

PERFORMANCE INVESTIGATIONS ON CONTROL STRATEGIES OF DFIG FED WIND ENERGY SYSTEM

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled "**Performance Investigations on Control Strategies of DFIG fed Wind Energy System**" in partial fulfillment of the requirements for the award of the Degree of Doctor of Philosophy and submitted in the Department of Electrical Engineering of the Maulana Azad National Institute of Technology, Bhopal is an authentic record of my own work carried out during the period from July 2019 to July 2023 under the supervision of Dr. Giribabu Dyanamina, Assistant Professor, Department of Electrical Engineering, Maulana Azad National Institute of Technology, Bhopal.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other Institution.

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ABSTRACT

Humans race towards luxurious benefits over the years lead to rise in electrical power demand globally and rapid depletion of natural resources. This has lead to even more problems mainly environmental and energy crises. To cater the increasing energy demand, there is need to search for alternate paths for increasing the energy production globally without disturbing the ecological balance, one such solution is to produce energy using naturally available renewable sources. Among all the renewable energy sources available naturally such as solar, wind, hydro, wave and ocean. The power generation using wind energy is very good alternative due its advantages such as easily available, cost effective, rapidly developing, more commercialized, and well proven technology. Power generation using wind energy systems is one of the crucial sources that can empower the globe in a realistic way out of its present critical condition. According to the Global Wind Report, 2020 was the second-best year ever for the wind energy industry. Growth in 2021 will be just 1.8% lower than in 2020. More than 94 GW of capacity was added despite the COVID-19 pandemic in its second year. This strongly indicates the remarkable perseverance and expansion trajectory of the global wind energy industry.

Wind energy conversion systems (WECS) harness the naturally available wind to generate electrical power. They efficiently and reliably convert the kinetic energy from the wind into electrical energy. The main components of a WECS can be categorized into mechanical, electrical, and control systems. The mechanical parts encompass various elements such as the tower, nacelle, rotor blades, rotor hub, gearbox, pitch drives, yaw drives, wind speed sensors, drive-train, and mechanical brakes. On the other hand, the electrical parts consist of the electrical generator, power converter, harmonic filters, step-up transformer, and a three-phase grid or collection point for distributing the generated power. Both the mechanical and electrical energy conversion systems rely on components present in the control system, which plays a crucial role in ensuring the smooth operation and coordination of the entire WECS.

In general wind turbines are classified as variable speed turbine (VST) and fixed speed turbine (FST). In recent years, DFIG based VST are perhaps the most commonly used WECS owing to advantages such as completely divorced real/reactive power control, maximum power acquisition ability, less mechanical-stress, smaller converter VA rating (usually 30 percent of generator capacity), and minimal power-loss compared to other generator configurations. These advantages are mostly achieved via back-to-back

(BTB) connection of power electronic converters. In DFIG based WECS stator windings of the generator are connected to the grid directly, where as the generator's rotor winding attached through two partially rated (30%) BTB converter known as the rotor side power electronic converter (RSPEC) and the grid side power electronic converter (GSPEC). The frequency and magnitude of current in the rotor windings can be easily controlled using this configuration and it also allows wider rotor speed variations and higher wind energy absorption capacity.

Wind energy conversion systems also classified as grid connected and standalone systems based on, they used. Grid connected wind are generally high power capacity generating station directly connected to grid. For grid connected WECS a small disturbance on the grid side leads to disconnection of generator from the power system network. In a DFIG based WECS as the stator terminals are directly connected to the grid any fault at the grid side forces the whole system into critical operating situation. Fault ride-through (FRT) operation is a critical concept in DFIG-based WECS that ensure the system's ability to withstand and recover from grid faults. During fault situations, such as a short circuit or voltage dip in the grid, the FRT capability allows the DFIG-based WECS to continue operation and remain connected to the grid without experiencing a complete shutdown. In the quest to improve Fault Ride Through (FRT) capabilities in wind turbines, a range of challenges are being addressed. These encompass concerns related to over-current in the stator and rotor windings of the generator, as well as over-voltage issues across the DC-link capacitor in the Back-to-Back (BTB) power converter of the DFIG. The DFIG system's limited power rating emphasizes the need to prioritize safeguarding the converter against potential damage resulting from short-circuit faults, which could lead to high currents in the generator's windings. Therefore, it becomes paramount to ensure the protection of the converter to enable the sustained operation and grid connection of the DFIG system, in full compliance with the requirements of the grid code. FRT techniques can classified as external retrofit and internal control modification-based control techniques. The present study implements both these FRT techniques to protect the generator during the fault and control the DFIG system.

External retrofit-based FRT techniques are classified as protection circuit and reactive power injecting devices. In this work protection circuit based FRT methods are implemented. Protection circuit based FRT are classified as rotor end series dynamic braking resistor (RSDBR), the DC link braking chopper (DCBC), rotor end parallel

resistance crowbar (REPRC), modulated SDBR (MSDBR), fault current limiter (FCL), energy storage systems (ESS) and series grid converter (SGC). To improve the performance of the DFIG based WECS during FRT operation a modified protection method has been proposed using fuzzy logic control, which integrates and coordinates the REPRC, DCBC, and RSDBR protection methodologies. The RSDBR provides primary protection, with the crowbar circuit being activated if the RSDBR is unable to protect during deteriorating scenario. Depending on the situation, the REPRC will only be activated initially or end of the fault. The DCBC is used to regulate the excessive voltage produced by the dc link but it is not required for fault ride-through operation; however, it does help to smooth the DC link voltage and expands the normal range of DFIG operation for higher active power imbalances between the converters.

In modern DFIG design, the variable frequency converter is built by two PWM converters; DFIG can capture maximum energy from the wind with high efficiency by controlling these converters. When compared with the squirrel-cage induction generator (SCIG) or synchronous generator (SG) which requires full-sized converters, the power converter of DFIG is rated at only a fraction of the machine nominal power, typically 30% of its nominal. The conventional control of DFIG has disadvantages such as significant torque/power ripples due to the high bandwidth of the hysteresis controllers, variable switching frequency of the converters, coordinate transformation and deterioration of the controller performance during the machine starting and low-speed operations. The dynamic response of a DFIG based WECS can be improved using model predictive methods, parameter sensitivity will also be reduced as compared to vector control. The DTC/DPC method controls torque/active and flux/reactive powers by directly selecting the appropriate voltages vectors of RSPEC/GSPEC.

Two-level converter has limitation at higher voltages due to maximum voltage withstand capability in switching devices and high stress in the windings as they cannot operate at high switching frequencies. High performance of doubly fed induction motor (DFIM) drive systems at increased power levels requires high quality inverter output with low harmonic loss and low torque ripple. Multi-level inverter (MLI) is an emerging technology used in high power applications because they provide high quality inverter output voltage with low harmonic distortion, low torque fluctuations and avoid the limitations of two-level voltage source inverter in vector control and direct control method drive system. There are three main topologies of MLI, namely Diode Clamped

Multi Level Inverter (DCMLI), Flying Capacitor Multi Level Inverter (FCMLI) and Cascaded H-bridge Multi Level Inverter (CHBMLI). The DCMLI, particularly the three-level, has drawn much interest in DFIM applications because it needs only one common voltage source.

In this study, both Model Predictive Direct Torque Control (MPDTC) and Model Predictive Direct Power Control (MPDPC) strategies collectively named as model predictive direct control method (MPDCM) are developed for a grid-connected DFIG based WECS. MPDCM offers excellent performance in terms of torque, active, reactive and flux control, reduced ripples, improved power quality, reduced sensitivity to parameter variations and fast dynamic response. It also enables high-efficiency operation, improved fault ride-through capabilities, and enhanced grid integration. Detailed simulation and experimental tests are carried out to investigate the performance of the wind energy system MPDTC for two-level and three-level diode clamped rotor side converter fed DFIG based WECS. The performance of the DFIG at variable speed operations for both converter configurations is simulated in MATLAB/SIMULINK. Further the simulation study and experimentation are also carried to control active and reactive power for grid connected DFIG based WECS. Similarly, MPDPC has been implemented for two level voltage source inverter (VSI) and three level diode clamped grid side inverter. The experimental implementation for validation of simulation study of proposed MPDCM has been performed on a 5 KW slip ring induction motor by developing prototype model using WAVCET 300 R&D control board for two-level and three-level BTB converter at variable wind speeds. The results obtained shows the improvement in the overall performance of the DFIG with faster settling time and lower peak overshoot and undershoot for proposed model predictive direct methods. Through this comprehensive approach of development, simulation, and hardware validation, the study aims to contribute to the advancement of control strategies for DFIG-based wind energy systems. The goal is to enhance the system's efficiency, stability, and fault tolerance, promoting the reliable integration of wind energy into the power grid and supporting the transition to a sustainable and renewable energy future.

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CONTENT

CANDIDATE’S DECLARATION	iii
ABSTRACT	iv
ACKNOWLEDGMENT	viii
LIST OF FIGURES	xiv
LIST OF TABLES.....	xx
ABBREVIATION.....	xxi
SYMBOLS	xxv
CHAPTER 1. INTRODUCTION.....	1
1.1 Overview of Wind Energy Penetration	1
1.2 Wind Energy Conversion System (WEC) Generator Technologies and Commercial Configurations	5
1.2.1 WECS Commercial Configuration	5
1.3 Research motivation	11
1.4 Objectives and Contributions of the Study:	12
1.5 Thesis Organization.....	13
CHAPTER 2. LITERATURE REVIEW	15
2.1 Introduction.....	15
2.2 DFIG modeling.....	16
2.3 Power converter modeling	18
2.4 FRT Capability of DFIG fed WECS	20
2.5 Control Strategies of the DFIG for the RSPEC	23
2.6 Control Strategies of the DFIG for the GSPEC.....	25
CHAPTER 3. MODELLING OF DFIG BASED WECS	29
3.1 Introduction.....	29
3.2 Induced Force/Torque	30
3.3 Slip Concept.....	31
3.4 Steady-State Equivalent Circuit of a DFIG	32
3.4.1 Power in the DFIG	35
3.4.2 Torque in the DFIG.....	36
3.5 Dynamic Modelling of DFIG	38
3.5.1 α - β Model	40

3.5.2	dq Model.....	44
3.6	CONTROL OF DFIG POWER CONVERTERS.....	46
3.6.1	Model of the 2L-VSI.....	47
3.7	MULTILEVEL VSC TOPOLOGIES	51
3.7.1	Model of Three-Level Neutral Point Clamped VSC Topology (3L-NPC)	51
3.8	Conclusion	54
CHAPTER 4. FRT METHODS FOR DFIG BASED WECS.....		55
4.1	Introduction.....	55
4.2	Grid Code Requirements for WECSs.....	56
4.3	Behaviour During Voltage Dips	61
4.3.1	DFIG Equivalent Circuits During Symmetrical Voltage Sags	61
4.3.2	DFIG Equivalent Circuits During Asymmetrical Voltage Dips	63
4.4	Enhancing Transient Stability in DFIG-WECSs using FRT Strategies	65
4.4.1	FRT Schemes Overview	65
4.4.2	External Retrofit Based FRT Techniques For DFIG	66
4.4.3	Internal retrofit based FRT Techniques for DFIG	82
4.5	Modified fuzzy logic based Parallel protection scheme	86
4.5.1	RSDBR and REPRC Resistance Values	91
4.6	Simulation Results.....	95
4.6.1	SYMMETRICAL FAULT CONDITION	97
4.7.2	Asymmetrical Fault Condition.....	105
4.7	RTS Results Discussion	114
4.8	Conclusion	123
CHAPTER 5. FCS-MP DTC FOR RSPEC OF DFIG FED WECS...		125
5.1	Introduction.....	125
5.2	Model Predictive Control.....	126
5.2.1	Predictive Control with Modulation	127
5.2.2	Predictive Control without Modulation	128
5.3	Features of Finite Control-Set Model Predictive Control	130
5.3.1	Main Features of FCS-MPC.....	130
5.4	Essential Principles of Model Predictive Control	133
5.4.1	Discrete Modeling Approach	133

5.4.2	Operating Principle	135
5.4.3	Design Procedure	137
5.5	FCS-MPC DTC Control of DFIG WECS	140
5.5.1	Introduction	140
5.5.2	Equivalent Circuit of DFIG	142
5.5.3	Correlation Between Rotor Currents and Control Objectives.....	145
5.5.4	DFIG Continuous-Time Dynamic Models	146
5.5.5	Dynamic Models of DFIG in Discrete-Time	150
5.5.6	Digital Control of BTB Converter-Based DFIG WECS	151
5.5.7	Predictive Torque Control For 2L-VSC of DFIG WECS	153
5.5.8	5.5.8 Control Algorithm for 2L-VSI.....	158
5.5.9	Predictive Torque Control FOR 3L-NPC-VSC of DFIG WECS ..	159
5.5.10	Control Algorithm for 3L-NPC-VSI	161
5.6	Simulation Results.....	162
5.6.1	Base Values	164
5.6.2	Transition to Per Unit System for Magnitudes and Parameters	165
5.6.3	Simulation Results and Performance Analysis	166
5.7	Experimental Setup	181
5.7.1	DFIG	181
5.7.2	DC MACHINE.....	182
5.7.3	WAVECT Real-Time Controller (RTC)	183
5.7.4	Inverter Stack	185
5.7.5	Procedure for Setting up a Grid-Connected DFIG-Based Wind Energy System in the Laboratory	186
5.8	Experimental Results.....	188
5.9	Conclusion	195
CHAPTER 6. FCS-MP DPC FOR GSPEC OF DFIG FED WECS...		197
6.1	Introduction.....	197
6.2	Construction and Controlling of the GSPEC	198
6.2.1	DESIGN OF PASSIVE COMPONENT	199
6.2.2	Designing the Reference DC-Bus Voltage.....	199
6.2.3	Establishing the Grid Power Factor	200
6.2.4	Orientation of Grid Voltage	200

6.3	Modeling of Three-Phase GSPEC	203
6.3.1	Modelling of Grid Currents and Powers in abc-Frame	203
6.3.2	Modelling of Grid Currents and Powers in the dq-Frame	206
6.3.3	Modeling of Grid Currents in the dq-Frame employing CT	206
6.3.4	Grid Active and Reactive power in the DQ-Frame employing CT	207
6.3.5	Transforming the dq-Frame CT Model of Grid Currents into a DT Model	207
6.3.6	Modelling Grid Active and Reactive Powers in the dq-Frame DT Model:	208
6.3.7	Modelling of VSI Output Voltages:.....	209
6.3.8	Modeling of the Output Voltages of a 2L-VSI:	209
6.3.9	Modelling of the Output Voltages of an NPC Inverter:	211
6.4	Calculation of Reference Grid-Side Variables	212
6.5	Predictive Power Control of 2L-VSI in dq-Frame	214
6.5.1	Procedure for Designing PPC Scheme:	215
6.5.2	Control Algorithm for 2L-VSI	216
6.6	Predictive Power Control of NPC based GSPEC Inverter.....	217
6.6.1	Procedure for Designing PPC Scheme	217
6.7	Simulation Results.....	221
6.8	Experimental Results.....	230
6.9	Conclusion	244
CHAPTER 7. CONCLUSIONS AND FUTURE SCOPE		247
7.1	Introduction.....	247
7.2	Conclusions.....	247
7.3	Future Scope	250
List of Publications		251
REFERENCES		253
APPENDIX-A		277
APPENDIX B.....		282
APPENDIX C.....		286

LIST OF FIGURES

Figure 1.1	New wind power capacity in 2022 and share of top 10 markets (%) [1]
Figure 1.2	Historic development of total installations of wind energy system in GW both offshore and onshore [2]
Figure 1.3	Evolution in the size of commercial wind turbines
Figure 1.4	Type 1 Fixed speed Configuration using SCIG WECS
Figure 1.5	Type 2 Semi-variable Speed Configuration using WRIG WECS
Figure 1.6	Type 3 Semi-variable Speed Configuration using DFIG WECS
Figure 1.7	Type 4 Full-variable Speed Configuration using PMSG WECS
Figure 1.8	Type 5 Direct Grid Connected Configuration using WRSG WECS
Figure 3.1	Fundamental arrangement of DFIG WECS
Figure 3.2	One-phase steady-state equivalent circuit of a DFIG
Figure 3.3	DFIG electrical equivalent circuit
Figure 3.4	Steady-state equivalent circuit of DFIG referred to stator
Figure 3.5	Power flow in a DFIG wind system Super-synchronous mode ($\omega_r > \omega_s$)
Figure 3.6	Power flow in a DFIG wind system Sub-synchronous mode ($\omega_r < \omega_s$)
Figure 3.7	Idealized three phase DFIG
Figure 3.8	Axes of two pole three phase DFIG
Figure 3.9	The equivalent dynamic circuit of the DFIG in $\alpha - \beta$ reference frames
Figure 3.10	dq Model of the DFIG in synchronous coordinate
Figure 3.11	Power circuit of three-phase 2L-VSI.
Figure 3.12	Two voltage levels of V_{ao}
Figure 3.13	Single phase leg of a 3L-NPC VSC
Figure 3.14	Operating modes of 3L-NPC VSC
Figure 4.1	Requirements for Voltage ride-through in accordance with the E. ON regulation
Figure 4.2	DFIG's stators' flux paths during symmetrical voltage sags (a) prior to sag (b) during sag (c) after sag
Figure 4.3	DFIG equivalent circuit model exposed to symmetrical voltage sag: (a) natural-machine and (b) forced-machine

Figure 4.4	Asymmetrical fault voltage on the grid (a) Single-phase to ground faults; (b) two-phase to ground fault and (c) two-phase fault
Figure 4.5	DFIG equivalent circuit model of the negative machine
Figure 4.6	Flux path of the stator in the event of an asymmetrical grid failure (a) Steady-state after a fault (b) the zero-flux state; and (c) the maximum natural flux state
Figure 4.7	FRT Techniques of DFIG-based WECS
Figure 4.8	Crowbar protection circuit for DFIG based WECS
Figure 4.9	Crowbar series RL protection circuit for DFIG based WECS
Figure 4.10	Conventional DC chopper protection circuit for DFIG based WECS
Figure 4.11	SDBR Protection Circuit for DFIG based WECS
Figure 4.12	MSDBR Protection circuit for DFIG based WECS
Figure 4.13	FCL classification for DFIG based WECS
Figure 4.14	ESS Protection circuit for DFIG based WECS
Figure 4.15	SGSC Protection Circuit for DFIG based WECS
Figure 4.16	DVR Circuit for DFIG based WECS
Figure 4.17	SVC Circuit for DFIG based WECS
Figure 4.18	STATCOM Circuit for DFIG based WECS
Figure 4.19	DFIG with Modified FL-based parallel protection scheme
Figure 4.20	Fuzzy System
Figure 4.21	Fuzzy Logic Interface Tools for System Analysis
Figure 4.22	Model of DFIG rotor equivalent circuit illustrating all protection schemes
Figure 4.23	Optimal value of resistance of RSDBR for protection
Figure 4.24	DFIG's dynamic behaviour in the absence of a protection system with Symmetrical Fault
Figure 4.25	DFIG's dynamic behaviour in the presence of Crowbar protection system with Symmetrical Fault
Figure 4.26	DFIG's dynamic behaviour in the presence of Proposed protection system with Symmetrical Fault
Figure 4.27	Peak Values of Voltage and Current during Symmetrical Faults
Figure 4.28	DFIG's dynamic behaviour in the absence of a protection system with Asymmetrical Fault (LL)

Figure 4.29	DFIG's dynamic behaviour in the presence of a protection system with Asymmetrical Fault (LL)
Figure 4.30	Peak Values of Voltage and Current during LL Faults
Figure 4.31	DFIG's dynamic behaviour in the absence of a protection system with Asymmetrical Fault (LLG)
Figure 4.32	DFIG's dynamic behaviour in the presence of a protection system with Asymmetrical Fault (LLG)
Figure 4.33	Peak Values of Voltage and Current during LLG Faults
Figure 4.34	RTS diagram of FRT of DFIG based WECS
Figure 4. 15	Illustration of Opening a Simulink Model in RT-LAB
Figure 4. 26	Simulink Model Structure with Master and Console Subsystems
Figure 4.37	Real-time simulator (RTS) results in the absence of protection system with Symmetrical Fault
Figure 4.38	Real-time simulator (RTS) results in the Presence of REPRC protection system with Symmetrical Fault
Figure 4.39	Real-time simulator (RTS) results of an improved FL based protection system with Symmetrical Fault
Figure 4.40	Real-time simulator (RTS) results of an improved FL based protection system with Asymmetrical Fault (L-L)
Figure 4.41	Real-time simulator (RTS) results of an improved FL based protection system with Asymmetrical Fault (L-L-G)
Figure 5.1	Block Diagram of Deadbeat predictive current control with a modulation stage
Figure 5.2	Graphical representations of the FCS-MPC scheme utilized to regulate load current
Figure 5.3	Fundamental characteristics of FCS MPC
Figure 5.4	Principle of Operation for Model Predictive Control (MPC)
Figure 5.5	dq Model of the DFIG in synchronous coordinate
Figure 5.6	Calculation of reference control variables for PTC of DFIG WECS
Figure 5.7	Block diagram of the PTC scheme for 2L-VSC-based DFIG.
Figure 5.8	Flowchart of PTC algorithm for 2L-VSC based DFIG
Figure 5.9	Flowchart of PTC algorithm for 3L-NPC VSC based DFIG
Figure 5.10	MATLAB/Simulink model of DFIG

Figure 5.11	Torque comparison of various techniques
Figure 5.12	Flux comparison of various techniques
Figure 5.13	DC Link Voltage variations
Figure 5.14	Rotor current waveform of MPDTC for the 2L VSC fed DFIG WECS
Figure 5.15	Rotor current waveform of MPDTC for the 3L VSC fed DFIG WECS
Figure 5.16	Rotor speed waveform
Figure 5.17	THD of 2L VSC Rotor current
Figure 5.18	THD of 3L NPC MLI Rotor current
Figure 5.19	Stator Current waveform of MPDTC for the 2L VSC fed DFIG WECS
Figure 5.20	Stator Current waveforms of MPDTC for the 3L NPC fed DFIG WECS
Figure 5.21	THD of 2L VSC Stator current
Figure 5.22	THD of 3L NPC MLI Stator current
Figure 5.23	Stator Active power in both the cases
Figure 5.24	Stator Reactive power in both the cases
Figure 5.25	Grid Active power in for the 2L VSC fed DFIG WECS
Figure 5.26	Grid Active power in for the 3L NPC fed DFIG WECS
Figure 5.27	Grid Reactive power in for the 2L VSC fed DFIG WECS
Figure 5.28	Grid Reactive power in for the 3L NPC fed DFIG WECS
Figure 5.29	Visualization of the DFIG Machine within the Laboratory Environment
Figure 5.30	DC machine used for wind emulation in the laboratory setup
Figure 5.31	(a) Front and (b) back view of the WAVECT Controller WCU300 as depicted in the WAVECT booklet. (c) Top and (d) front view of the WCU300 in a laboratory setting
Figure 5.32	(a) Front and (b) Top view of the 2L-VSC Stack. (c) Front and (d) Top view of the 3L-NPC Stack in a laboratory Setup
Figure 5.33	Prototype model Setup in Laboratory
Figure 5.34	Transient Response Analysis of FCS MPDTC Strategy with 2-Level VSC
Figure 5.35	Transient Response Analysis of FCS MPDTC Strategy with 3-Level NPC VSC
Figure 6.1	Grid voltage and current vectors in dq and $\alpha\beta$ frame
Figure 6.2	Schematic representation of grid voltage angle calculation under ideal grid conditions

Figure 6.3	Grid voltage angle estimation in the presence of distorted grid conditions
Figure 6.4	abc-frame standard model GSPEC representation
Figure 6.5	abc-frame simplified model GSPEC representation
Figure 6.6	dq-frame standard model GSPEC representation
Figure 6.7	dq-frame simplified model GSPEC representation
Figure 6.8	Schematic of a Three-Phase Grid-Connected NPC Inverter Power Circuit
Figure 6.9	Simplified representation of GSPEC with Generator-side MPPT control
Figure 6.10	Calculation of reference grid-side control variables with generator-side MPPT control.
Figure 6.11	Flowchart of the PPC algorithm for grid-connected 2L inverter
Figure 6.12	Flowchart of the PPC algorithm for grid-connected 3L NPC
Figure 6.13	MATLAB Simulink model of DFIG based WECS
Figure 6.14	An input Mechanical Torque
Figure 6.15	Reactive power Reference
Figure 6.16	DC Link Voltage Waveform
Figure 6.17	GPEC Current for DPC Technique
Figure 6.18	GPEC Current for MP-DPC Technique with 2L VSC
Figure 6.19	GPEC Current for MP-DPC Technique with 3L VSC MLI
Figure 6.20	DPC THD
Figure 6.21	PDPC THD
Figure 6.22	PDPC 3L THD
Figure 6.23	Grid Active power for the 2L-VSC and 3L NPV-MLI fed DFIG WECS
Figure 6.24	Grid Reactive power for the 2L-VSC and 3L NPV-MLI fed DFIG WECS
Figure 6.25	Stator Active power for the 2L-VSC and 3L NPC-MLI fed DFIG WECS
Figure 6.26	Stator Reactive power for the 2L-VSC and 3L NPC-MLI fed DFIG WECS
Figure 6.27	Stator and Rotor waveform for FCSMP-DPC 2L VSI in sub synchronous condition
Figure 6.28	Stator and Rotor waveform for FCSMP-DPC 3L NPC MLI in sub synchronous condition

- Figure 6.29 Stator and Rotor waveform for FCSMP-DPC 2L-VSI in super synchronous condition
- Figure 6.30 Stator and Rotor waveform for FCSMP-DPC 3L NPC MLI in super synchronous condition
- Figure 6.31 Transient Response Analysis of FCS MPDTC Strategy with 2-Level VSC
- Figure 6.32 Transient Response Analysis of FCS MPDTC Strategy with 3L NPC MLI

LIST OF TABLES

Table 1. 1	Consolidated overview of the five distinct configurations of wind energy systems.
Table 3. 1	Different Output Voltage Combinations of 2L-VSC
Table 3. 2	Switching sequence for one phase leg of a inverter
Table 4. 1	International standard governing the grid integration of wind power plants and their Fault Ride Through (FRT) capabilities
Table 4. 2	Comprehensive analysis of Grid Codes in various nations.
Table 4. 3	Symmetrical components of the grid voltage under asymmetrical
Table 4. 4	Comparative Analysis of Protection circuits-based FRT strategies
Table 4. 5	Comparative Analysis of Reactive power injecting devices-based FRT strategies
Table 4. 6	Comparative Analysis of Internal control modification-based control technique for DFIG
Table 4. 7	Coordination of Protection Techniques in Various Scenarios
Table 4.8	Comparative Performance Analysis Results during Symmetrical Fault
Table 4.9	Comparative Performance Analysis Results during LL Fault
Table 4.10	Comparative Performance Analysis Results during LLG Fault
Table 5. 1	Comparison of Torque results of various control method fed with 2L-VSC and 3L-VSC
Table 5. 2	Comparison of Flux results of various control method fed with 2L-VSC and 3L-VSC
Table 5. 3	Comparison of Torque and Flux ripples of various control method

ABBREVIATION

2L	Two-Level (Converter)
3L	Three-Level (Converter)
3	Three-Phase (Generator/Grid)
AC	Alternating Current
ADC	Analog to digital conversion
ANPC	Active Neutral Point Clamped
BTBC	Back-to-Back Converter
CSC	Current Source Converter
CT	Continuous-Time
DAC	Digital-to-Analog Conversion
DBPC	Deadbeat Predictive Control
DC	Direct Current
DCC	Diode-Clamped Converter
DD	Direct-Driven
DFIG	Doubly Fed Induction Generator
DFOC	Direct Field-Oriented Control
DG	Distributed Generation
DMC	Direct Matrix Converter
DPC	Direct Power Control
DSO	Distribution System Operator
DSP	Digital Signal Processor
DT	Discrete Time
DTC	Direct Torque Control
E+P	Estimation + Prediction
FC	Flying Capacitor
FCS-MPC	Finite Control-Set Model Predictive Control
FFT	Fast Fourier Transform
FOC	Field-Oriented Control
FPGA	Field-Programmable Gate Array
FRT	Fault Ride-Through
FSWT	Fixed-Speed Wind Turbine
GCT	Gate-Controlled Thyristor

GSPEC	Grid-side Power Electronic Converter
GSF	Generator Signal Feedback
GW	Gigawatt
HAWT	Horizontal-Axis Wind Turbine
HVAC	High-Voltage Alternating Current
HVDC	High-Voltage Direct Current
HVRT	High-Voltage Ride-Through
IFOC	Indirect Field-Oriented Control
IG	Induction Generator
IGBT	Insulated Gate Bipolar Transistor
IGCT	Integrated Gate-Commutated Thyristor
IM	Induction Machine
IMC	Indirect Matrix Converter
LPF	Low-Pass Filter
LTI	Linear Time-Invariant
LTV	Linear Time-Variant
LV	Low Voltage
LVRT	Low-Voltage Ride-Through
MIPS	Million Instructions Per Second
MPC	Model Predictive Control
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
MV	Medium Voltage
MW	Megawatt
NPC	Neutral-Point Clamped
OT	Optimal Torque
OTSR	Optimal Tip-Speed Ratio
PCC	Point of Common Coupling
PCC	Predictive Current Control
PDPC	Predictive Direct Power Control
PDVC	Predictive DC-Bus Voltage Control
PF	Power Factor
PGS	Passive Generator-side

P+P	Prediction + Prediction
PPC	Predictive Power Control
PSC	Predictive Speed Control
PSF	Power Signal Feedback
PTC	Predictive Torque Control
PVC	Predictive Voltage Control
PI	Proportional-Integral
PLL	Phase-Locked Loop
PMSG	Permanent Magnet Synchronous Generator
PWM	Pulse Width Modulation
RL	Resistive-Inductive
RMS	Root Mean Square
RPG	Reactive Power Generation
RSPEC	Rotor-side Power Electronic Converter
SCIG	Squirrel Cage Induction Generator
SFOC	Stator Flux-Oriented Control
SG	Synchronous Generator
SGCT	Symmetrical Gate-Controlled Thyristor
SHE	Selective Harmonic Elimination
SRF	Synchronous Reference Frame
STATCOM	Static Synchronous Compensator
SVC	Static VAR Compensator
SVM	Space Vector Modulation
SVOC	Stator Voltage-Oriented Control
TDD	Total Demand Distortion
THD	Total Harmonic Distortion
TSO	Transmission System Operator
TSR	Tip-Speed Ratio
UPF	Unity Power Factor
VAWT	Vertical-Axis Wind Turbine
VOC	Voltage-Oriented Control
VSC	Voltage Source Converter
VSI	Voltage Source Inverter

VSR	Voltage Source Rectifier
VSWT	Variable-Speed Wind Turbine
WECS	Wind Energy Conversion Systems
WF	Wind Farm
WFCP	Wind Farm Collection Point
WRIG	Wound Rotor Induction Generator
WRSG	Wound Rotor Synchronous Generator
WT	Wind Turbine
WTPC	Wind Turbine Power Curves
ZDC	Zero d-axis Current
ZOH	Zero-Order Hold
ZVRT	Zero-Voltage Ride-Through

SYMBOLS

Notation

P, Q	Active and reactive power
R, L, C	Resistance, inductance, and capacitance
v, i, ψ	Voltage, current, and flux linkage (peak values)
V, I, Ψ	Voltage, current, and flux linkage (rms values)
s	Switching signal

Superscripts for variable x

x^{op}	Optimal value of variable
x^p	Predicted variable
$\hat{x}$	Estimated variable
x^*	Reference variable
$\hat{x}^*$	Extrapolated reference variable

Subscripts for variable x

x_a, x_b, x_c	Natural (abc) frame variables
x_B	Base value
x_d, x_q	Synchronous (dq) frame variables
x_{dc}	DC/DC boost converter-related variable
x_g	Grid-related variable
x_i	Inverter-related variable
x_m	Mechanical system variable
x_{op}	Optimal value of variable
x_r	Rectifier/rotor related variable
x_R	Rated value
x_s	Generator (source in wind energy) related variable
x_T	Turbine-related variable
x_w	Wind-related variable
x_{WF}	Wind farm-related variable
x_α, x_β	Stationary ($\alpha\beta$) frame variables

Significant Symbols

α	Fortescue operator = $e^{j\frac{2\pi}{3}}$
A	State matrix in continuous time
A_r	WT rotor swept area
B	Input or control matrix in continuous time
B_m	WT and generator combined viscous friction
C	Output matrix in continuous time
C_{dc}	DC-link capacitance
C_{in}	Input DC-link capacitance of boost converter
C_p	Power coefficient of WT rotor blades
C_p^{op}	Optimal power coefficient of WT rotor blades
f_g	Grid frequency
f_s	Generator stator frequency
f_{sl}	Generator slip frequency
f_{sw}	Converter switching frequency
$f_{sw,i}$	Inverter switching frequency
$f_{sw,r}$	Rectifier switching frequency
g	Cost function for model predictive control
g_i	Cost function for current control
g_{id}	Cost function for d-axis current control
g_{iq}	Cost function for q-axis current control
$g_{i\alpha}$	Cost function for α -axis current control
$g_{i\beta}$	Cost function for β -axis current control
g_{PQ}	Cost function for active and reactive power control
g_{sw}	Cost function for converter switching frequency minimization
$g_{sw,r}$	Cost function for rectifier switching frequency minimization

$g_{sw,i}$	Cost function for inverter switching frequency minimization
$g_{T\psi}$	Cost function for electromagnetic torque and stator flux control
i_{ag}, i_{bg}, i_{cg}	Grid peak currents in abc-frame
I_{ag}, I_{bg}, I_{cg}	Grid rms currents in abc-frame
i_{ar}, i_{br}, i_{cr}	Generator peak rotor currents in abc-frame
I_{ar}, I_{br}, I_{cr}	Generator rms rotor currents in abc-frame
i_{as}, i_{bs}, i_{cs}	Generator peak stator currents in abc-frame
I_{as}, I_{bs}, I_{cs}	Generator rms stator currents in abc-frame
i_{dc}	DC branch current
i_{dg}, i_{qg}	Grid peak currents in dq-frame
i_{dr}, i_{qr}	Generator peak rotor currents in dq-frame
i_{ds}, i_{qs}	Generator peak stator currents in dq-frame
i_g	Grid peak current
I_g, V_g	Grid rms current and voltage
i_r	Generator peak rotor current
I_r	Generator rms rotor current
i_s	Generator peak stator current
I_s	Generator rms stator current
$i_{\alpha g}, i_{\beta g}$	Grid peak currents in $\alpha\beta$ -frame
$i_{\alpha r}, i_{\beta r}$	Generator peak rotor currents in $\alpha\beta$ -frame
$i_{\alpha s}, i_{\beta s}$	Generator peak stator currents in $\alpha\beta$ -frame
j	Switching state combination number
j_{op}	Optimal switching state combination number
k	Present sampling instant in discrete-time frame
$k-1$	Past sampling instant in discrete-time frame
$k+1$	Future sampling instant in discrete-time frame

k_i	Integral gain of PI controller
k_p	Proportional gain of PI controller
k_r	Generator rotor coupling coefficient
L	Load Inductance
L_{dc}	Inductance of boost converter DC choke
L_{ds}, L_{qs}	Generator dq-axes stator winding inductances
L_i	Inductance of inverter-side harmonic filter
L_{ls}, L_{lr}	Generator stator and rotor winding leakage inductances
L_m	Generator magnetizing inductance
L_s, L_r	Generator stator and rotor winding self-inductances
n_m	Generator mechanical speed (rpm)
N_p	Prediction horizon
n_{sw}	Number of switching changes in a converter
P_{dc}	DC-link power
P_g	Grid active power
P_g^*	Grid active power reference
P_{in}^*	Reference input DC power
P_m	Generator mechanical input power
P_r	Generator rotor output active power
P_s	Generator stator output active power
P_s^*	Generator stator active power reference
P_T	WT output power
pu	Per unit
Q_g	Grid reactive power
Q_g^*	Grid reactive power reference
Q_o	Overall WECS output reactive power
Q_r	Generator rotor output reactive power

Q_s	Generator stator output reactive power
Q_s^*	Generator stator output reactive power reference
R	Load resistance
r_{dc}	Internal resistance of DC inductor L_{dc}
r_i	Internal resistance of harmonic filter L_i
R_s, R_r	Generator stator and rotor winding resistances
S	Switching state combination for a power converter
s_a, s_b, s_c	Phase-abc switching signals for top switch in a two-level converter
$\bar{s}_a, \bar{s}_b, \bar{s}_c$	Phase-abc switching signals for bottom switch in a two-level converter
S_a, S_b, S_c	Phase-abc switching vectors
s_{aj}, s_{bj}, s_{cj}	Phase-abc switching signals, $j \in \{1, 2\}$
$s_{anj}, s_{bnj}, s_{cnj}$	Phase-abc switching signals with respect to neutral, $j \in \{1, 2\}$
s_{di}, s_{qi}	Inverter dq-axes switching signals
s_{dr}, s_{qr}	Rectifier dq-axes switching signals
S_g	Grid apparent power
S_s	Generator stator apparent power
s_x	Switching signal of phase-x top switch in a two-level converter, $x \in \{a, b, c\}$
$\bar{s}_x$	Switching signal of phase-x bottom switch in a two-level converter, $x \in \{a, b, c\}$
$s_{\alpha i}, s_{\beta i}$	Inverter $\alpha\beta$ -axes switching signals
$s_{\alpha j}, s_{\beta j}$	$\alpha\beta$ -axes switching signals, $j = \{1, 2\}$
$s_{\alpha r}, s_{\beta r}$	Rectifier $\alpha\beta$ -axes switching signals
T	Transformation matrix
$T_{abc/abcn}$	abc-frame to abc _n -frame transformation matrix

$T_{abc/dq}$	abc-frame to dq-frame transformation matrix
$T_{abc/\alpha\beta}$	abc-frame to $\alpha\beta$ -frame transformation matrix
$T_{dq/abc}$	dq-frame to abc-frame transformation matrix
$T_{dq/\alpha\beta}$	dq-frame to $\alpha\beta$ -frame transformation matrix
T_e	Generator electromagnetic torque
T_e^*	Generator electromagnetic torque reference
T_m	Generator mechanical input torque
$T_{\alpha\beta/abc}$	$\alpha\beta$ -frame to abc-frame transformation matrix
$T_{\alpha\beta/dq}$	$\alpha\beta$ -frame to dq-frame transformation matrix
v_{ag}, v_{bg}, v_{cg}	Grid peak voltages in abc-frame
V_{ag}, V_{bg}, V_{cg}	Grid rms voltages in abc-frame
v_{an}, v_{bn}, v_{cn}	Converter output voltages with respect to neutral n
v_{aN}, v_{bN}, v_{cN}	Converter output voltages with respect to negative DC-Bus N
v_{ar}, v_{br}, v_{cr}	Generator peak rotor voltages in abc-frame
V_{ar}, V_{br}, V_{cr}	Generator rms rotor voltages in abc-frame
v_{as}, v_{bs}, v_{cs}	Generator peak stator voltages in abc-frame
V_{as}, V_{bs}, V_{cs}	Generator rms stator voltages in abc-frame
v_{c1}, v_{c2}	Voltage across DC-link capacitors C_1 and C_2
v_{dc}	Net DC-bus voltage (voltage between positive and negative DC terminals)
v_{dg}, v_{qg}	Grid peak voltages in dq-frame
v_{dr}, v_{qr}	Generator peak rotor voltages in dq-frame
v_{ds}, v_{qs}	Generator peak stator voltages in dq-frame
v_g	Grid peak phase voltage
V_g	Grid rms phase voltage
v_r	Generator peak rotor phase voltage
V_r	Generator rms rotor phase voltage

v_s	Generator peak stator phase voltage
V_s	Generator rms stator phase voltage
v_w	Wind speed
$v_{\alpha g}, v_{\beta g}$	Grid peak voltages in $\alpha\beta$ -frame
$v_{\alpha i}, v_{\beta i}$	Inverter output voltages in $\alpha\beta$ -frame
$v_{\alpha r}, v_{\beta r}$	Generator peak rotor voltages in $\alpha\beta$ -frame
$v_{\alpha s}, v_{\beta s}$	Generator peak stator voltages in $\alpha\beta$ -frame
x	State vector in continuous and discrete time
β	Pitch angle of WT rotor blades
Γ_b	Input or control matrix in discrete time
Γ_w	Disturbance input matrix in discrete time
δ	Bandwidth of hysteresis controller (relay)
θ	Phase angle of space vector
θ_e	Generator electrical angle
θ_g	Grid voltage angle
θ_m	Generator mechanical rotor position angle
θ_r	Generator electrical rotor position angle
θ_s	Generator voltage angle
θ_{sl}	Generator slip angle
λ_{dc}	Weighting factor for balancing of DC-link capacitors voltage
λ_i	Weighting factor for current control
λ_{id}	Weighting factor for d-axis current control
λ_{iq}	Weighting factor for q-axis current control
$\lambda_{i\alpha}$	Weighting factor for α -axis current control
$\lambda_{i\beta}$	Weighting factor for β -axis current control
λ_p	Weighting factor for active power control
λ_Q	Weighting factor for reactive power control

λ_{sw}	Weighting factor for switching frequency minimization
λ_T	WT tip-speed ratio
λ_T^{op}	Optimal WT tip-speed ratio
ρ	Air density
σ	Generator leakage coefficient
τ_σ	Generator stator transient time constant
τ_r	Generator rotor time constant
Ψ_r	RMS value of rotor flux linkage
Ψ_s	RMS value of stator flux linkage
ω	Angular frequency of space vector
ω_g	Grid angular frequency
ω_r	Generator rotor electrical angular speed
ω_s	Generator stator electrical angular frequency
ω_{sl}	Generator angular slip frequency

Vectors

i	Current vector in natural frame $= [i_a \ i_b \ i_c]^T$
i_{dq}	Current vector in synchronous frame $= [i_d \ i_q]^T$
$i_{\alpha\beta}$	Current vector in stationary frame $= [i_\alpha \ i_\beta]^T$
i_g	Grid current vector in natural frame $= [i_{ag} \ i_{bg} \ i_{cg}]^T$
$i_{g,dq}$	Grid current vector in synchronous frame $= [i_{dg} \ i_{qg}]^T$
$i_{g,\alpha\beta}$	Grid current vector in stationary frame $= [i_{\alpha g} \ i_{\beta g}]^T$
i_r	Rectifier/rotor current vector in natural frame $= [i_{ar} \ i_{br} \ i_{cr}]^T$
$i_{r,dq}$	Rotor current vector in synchronous frame $= [i_{dr} \ i_{qr}]^T$
$i_{r,\alpha\beta}$	Rotor current vector in stationary frame $= [i_{\alpha r} \ i_{\beta r}]^T$
i_s	Generator current vector in natural frame $= [i_{as} \ i_{bs} \ i_{cs}]^T$
$i_{s,dq}$	Generator current vector in synchronous frame $= [i_{ds} \ i_{qs}]^T$

$i_{s,\alpha\beta}$	Generator current vector in stationary frame $= [i_{\alpha s} \ i_{\beta s}]^T$
v_g	Grid voltage vector in natural frame $= [v_{ag} \ v_{bg} \ v_{cg}]^T$
$v_{g,dq}$	Grid voltage vector in synchronous frame $= [v_{dg} \ v_{qg}]^T$
$v_{g,\alpha\beta}$	Grid voltage vector in stationary frame $= [v_{\alpha g} \ v_{\beta g}]^T$
$v_{r,dq}$	Rotor voltage vector in synchronous frame $= [v_{dr} \ v_{qr}]^T$
$v_{r,\alpha\beta}$	Rotor voltage vector in stationary frame $= [v_{\alpha r} \ v_{\beta r}]^T$
v_s	Generator stator voltage vector in natural frame $= [v_{as} \ v_{bs} \ v_{cs}]^T$
$v_{s,dq}$	Generator stator voltage vector in synchronous frame $= [v_{ds} \ v_{qs}]^T$
$v_{s,\alpha\beta}$	Generator stator voltage vector in stationary frame $= [v_{\alpha s} \ v_{\beta s}]^T$
s_i	Inverter switching state combination in natural frame $= [s_{ai} \ s_{bi} \ s_{ci}]^T$
s_r	Rectifier switching state combination in natural frame $= [s_{ar} \ s_{br} \ s_{cr}]^T$
ψ_r	Rotor flux linkage vector in natural frame $= [\psi_{ar} \ \psi_{br} \ \psi_{cr}]^T$
$\psi_{r,dq}$	Rotor flux linkage vector in synchronous frame $= [\psi_{dr} \ \psi_{qr}]^T$
$\psi_{r,\alpha\beta}$	Rotor flux linkage vector in stationary frame $= [\psi_{\alpha r} \ \psi_{\beta r}]^T$
ψ_s	Stator flux linkage vector in natural frame $= [\psi_{as} \ \psi_{bs} \ \psi_{cs}]^T$
$\psi_{s,dq}$	Stator flux linkage vector in synchronous frame $= [\psi_{ds} \ \psi_{qs}]^T$
$\psi_{s,\alpha\beta}$	Stator flux linkage vector in stationary frame $= [\psi_{\alpha s} \ \psi_{\beta s}]^T$

CHAPTER 1. INTRODUCTION

1.1 Overview of Wind Energy Penetration

The worldwide energy landscape is undergoing a dramatic change towards renewable energy sources, with wind power playing an important role in this transformation. Wind farms, which are made up of several wind turbines that work together, have been built all over the world, both onshore (located on the land) and offshore (located in the sea), to harness the plentiful wind resources. These wind farms have the potential to generate large amounts of renewable electricity, helping to diversify the energy mix and reduce dependency on fossil fuels. Furthermore, wind power has proven to be a cost-effective method for generating electricity. Wind energy's levelized cost has been significantly reduced as a result of technological breakthroughs, economies of scale, and favourable government policies. As a result, wind power has grown more competitive with traditional energy sources, making it an appealing option for utility-scale projects as well as dispersed generation.

Wind power's significance in the context of the global energy transition cannot be emphasised. As the world grapples with the issues of climate change and depleting fossil fuel resources, renewable energy sources like wind power provide a viable alternative to traditional electricity producing methods. Wind energy is almost endless because it is based on the Earth's natural atmospheric processes rather than finite resources such as coal, oil, or natural gas. Wind power's environmental friendliness is one of its most persuasive advantages. Wind energy generation, unlike fossil fuels, produces no direct emissions of greenhouse gases or air pollutants while in operation, contributing to considerable reductions in carbon dioxide emissions and better air quality. Wind power has emerged as a critical solution to the transition to a low-carbon economy as governments, organisations, and individuals work to battle climate change and minimise its effects [1].

Wind energy conversion (WEC) system has emerged as a crucial participant in the global pursuit of renewable energy sources, providing a sustainable and environmentally friendly alternative to meet the rising need for electricity. This renewable energy source, which harnesses the natural power of wind, has become an essential component of the global energy mix, playing a critical role in the transition to a cleaner and more

sustainable future. WECS is fundamentally concerned with converting kinetic energy from the wind into useful electrical energy. Wind turbines, which are designed to catch wind energy and turn it into rotational motion, are used to harness wind energy. Wind kinetic energy spins the turbine's rotor blades, propelling a generator that generates electricity.

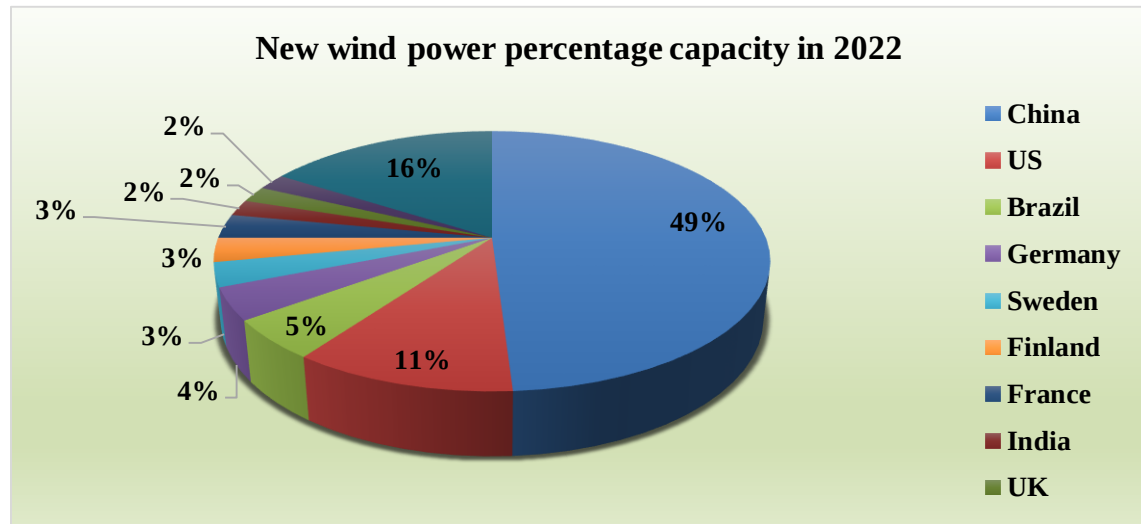


Figure 1.1 New wind power capacity in 2022 and share of top 10 markets (%) [1]

The wind sector installed a record 78 GW of new capacity in 2022, according to the Global Wind Energy Council (GWEC) report 2023, bringing total worldwide wind capacity to 906 GW. This represents a 9% increase over 2021, and it is the greatest of all power generation technologies. The data presented in Figure 1.1 highlights the dominant presence of China, the United States, Brazil, Germany, and Sweden as the top five markets for new installations in 2022, collectively accounting for a substantial 71% share of the global market. This emphasizes their pivotal roles in driving growth and adoption within the industry. Moving to Figure 1.2, which showcases the historical development of wind energy system installations, both offshore and onshore, a significant expansion of the wind sector is predicted over the next decade. By 2030, it is projected to reach an impressive 2 terawatts (TW). To achieve this target, an average annual installation of 136 GW between 2023 and 2027, followed by 143 GW between 2028 and 2030, will be necessary. This growth is primarily driven by energy system reform, carbon pricing, green recovery plans, corporate procurement, and technology innovation. These factors collectively contribute to the ongoing transition toward cleaner and more sustainable energy sources, solidifying the wind industry's crucial role in meeting global energy demands while mitigating climate change [2].

The GWEC-2023 report also highlights the regional trends and challenges for both onshore and offshore wind development. Onshore wind remains the dominant technology, with 93% of the total wind capacity in 2021, but offshore wind is catching up fast, with 7% of the total capacity and a potential to reach 10% by 2030. The report identifies North America, Europe, Africa/Middle East, Latin America and Asia-Pacific as the key regions for wind energy deployment, with different opportunities and barriers in each market [3].

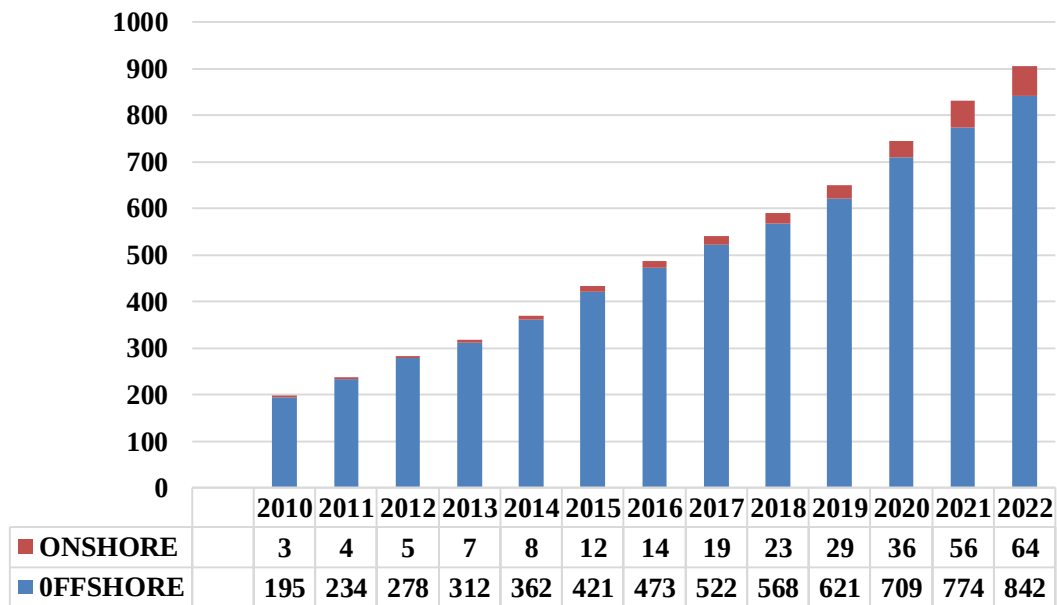


Figure 1. 2 Historic developments of total installations of wind energy system in GW both offshore and onshore [2]

A wind power system is made up of several components that work together to capture the kinetic energy in the wind and transform it into useful electrical energy. The wind turbine is the central component of a wind power system, converting wind energy into rotating mechanical energy. The rotor of the turbine, which normally has two or three blades, collects the energy from the wind as it travels over the blades, causing them to rotate. This rotating motion is subsequently sent to a generator inside the turbine's nacelle, where mechanical energy is converted into electrical energy [4]. Wind power systems use modern control systems to regulate numerous turbine parameters to optimise energy production and ensure safe operation. These control systems continuously monitor wind speed, direction, and other environmental conditions in order to optimise turbine performance and maximise energy harvest. Furthermore, grid integration is an important feature of wind power systems since it allows the generated electricity to be efficiently transmitted and delivered to users.

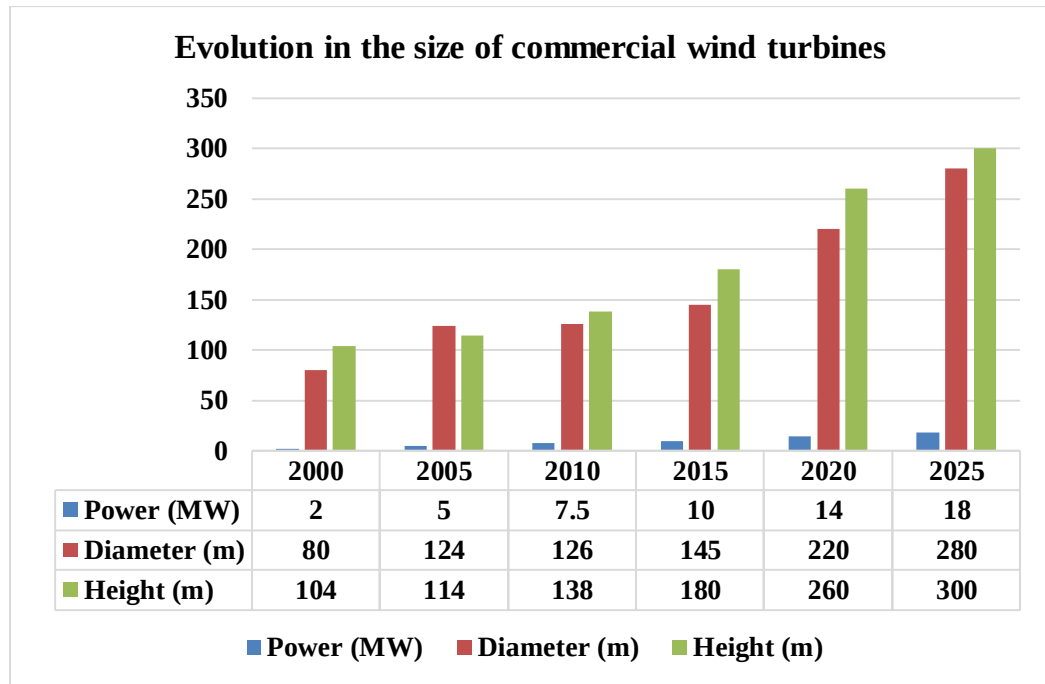


Figure 1. 3 Evolution in the size of commercial wind turbines

Wind farms have been built all over the world, ranging from onshore installations to offshore projects, and are made up of multiple wind turbines that work together. Individual turbines in these wind farms can have capacities ranging from a few hundred kilowatts to several megawatts. Wind turbine technology advancements such as larger rotor diameters, improved aerodynamics, and enhanced control systems have raised wind turbine efficiency and power output significantly. The power output of a wind turbine is proportional to the square of the rotor diameter and the cube of the wind speed, according to aerodynamic parameters [6], [7]. When compared to the small turbines, the huge turbines can capture more wind power while having reduced installation and maintenance expenses. As a result of this, the size of commercial wind turbines has expanded dramatically over the last 30 years, as can be seen in Figure 1.3. The capacity of the turbines has increased from 2MW in 2000 to 14MW in 2020. The diameter of wind turbine rotors has also expanded from 80 m in 2000 to 220 m in 2020. The GE Haliade-X is the world's largest wind turbine in terms of power rating, with a rated capacity of 14 MW and a rotor diameter of 220 m. This turbine's first prototype was erected in Rotterdam, Netherlands, in October 2019, and it was upgraded from 12 MW to 13 MW in October 2020, and then to 14 MW in October 2021. The Haliade-X has been chosen for various offshore wind projects, including Ocean Wind, Skipjack, and Vineyard Wind in the United States, and Dogger Bank in the United Kingdom [5]. The Mingyang Wind Power MySE 18.X-28X is the world's largest wind turbine by rotor diameter, with a rotor

diameter of almost 280 m and a swept area of 66,052 m². This turbine has an 18 MW rated capacity and is scheduled to go into commercial production in the first half of 2024 [5].

1.2 Wind Energy Conversion System (WEC) Generator Technologies and Commercial Configurations

Technologies for WECSs cover a broad spectrum of creative approaches for effectively converting wind power into electrical energy. The WECS generator is at the heart of these systems and is an integral part of any wind turbine's commercial setup. Commercial WECS configurations have improved in efficiency, dependability, and cost-effectiveness thanks to developments in generator design, materials, and control systems. This has sped up the development of wind power as a significant player in the world's renewable energy market [6].

There are various different generator types that can be employed in WECSs, each with unique benefits and drawbacks, such as doubly fed induction generators (DFIGs), permanent magnet synchronous generators (PMSGs), and squirrel cage induction generators (SCIGs). In order to regulate the transfer of energy from the wind turbine to the electrical grid, WECSs also feature power electronics such as inverters, converters, and controllers. To achieve the best possible performance and the highest possible amount of energy production, the planning and execution of a WECS must take into careful consideration a variety of criteria, including the average wind speed, the size of the turbines, and the integration requirements of the grid [7].

1.2.1 WECS Commercial Configuration

1.2.1.1 Type 1 WECS Fixed speed Configuration ($\pm 1\%$)

Type 1 corresponds to a fixed-speed WECS where the rotor speed remains constant, irrespective of the wind speed. Figure 1.4 provides an illustrative example of a Type 1 fixed-speed system featuring a squirrel-cage induction generator (SCIG) as the interface. In this configuration, the SCIG is directly connected to the grid through a soft-starter and step-up transformer, eliminating the need for power electronics in the system. A gearbox is typically required to synchronise the rotational speeds of the wind turbine and generator. Once the start-up process is over, the soft-starter is bypassed via a switch, allowing the system to run without the use of a power converter. The SCIG takes reactive

power from the grid in this configuration, necessitating the use of three-phase capacitor banks to compensate for this reactive power demand. As the wind speed changes, the rotor speed, as well as the generator output voltage and frequency, remain constant. Voltage and frequency are typically kept within 1% of nominal to provide stability and grid compatibility. There are still issues with this system design despite its low cost and ease of implementation. For instance, it performs poorly in low-wind conditions and cannot support the grid's reactive power. Furthermore, a Type 1 WECS may fall short of the requirements of modern grid codes and standards, which demand for more complex control and dynamic responses to grid disruptions.

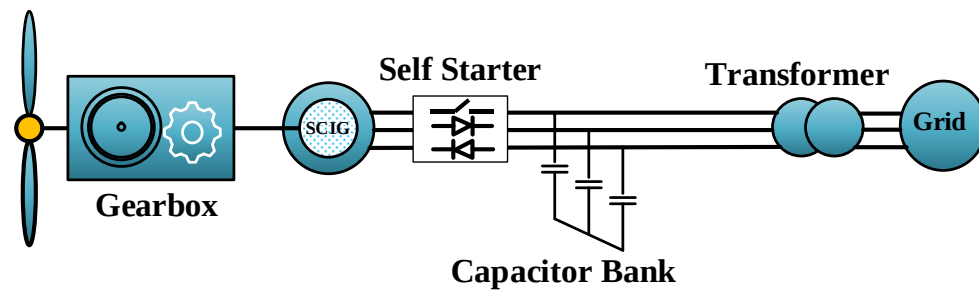


Figure 1. 4 Type 1 Fixed speed Configuration using SCIG WECS

1.2.1.2 Type 2 WECS Semi-variable Speed Configuration ($\pm 10\%$)

Type 2: semi-variable speed WECS is a kind of wind energy conversion system that enables some rotor speed adjustment based on wind speed. A Wound Rotor induction generator (WRIG) is commonly used in this type of system, which is connected to the electrical grid via a power converter as shown in Figure 1.5. The power converter enables control of the rotor speed as well as the generator output voltage and frequency, which may be modified to optimise wind energy capture while meeting grid requirements. The allowable range of rotor speed in a Type 2 WECS is 10% of the rated value. This offers some degree of flexibility and controllability over the output power as well as the reactive power, which can contribute to the stabilisation of the grid and reduce the impact of grid disruptions. Type 2 systems, on the other hand, present more implementation obstacles and higher costs as compared to Type 1 systems. Type 2 systems require specialised control algorithms and power electronics to achieve optimal performance, making them less popular among wind turbine manufacturers due to their limited speed range and lower energy conversion efficiency. As a result, this arrangement is losing relevance in the industry.

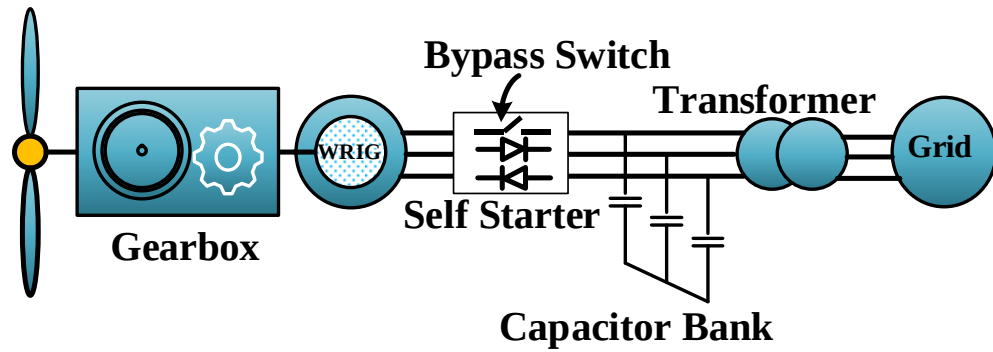


Figure 1. 5 Type 2 Semi-variable Speed Configuration using WRIG WECS

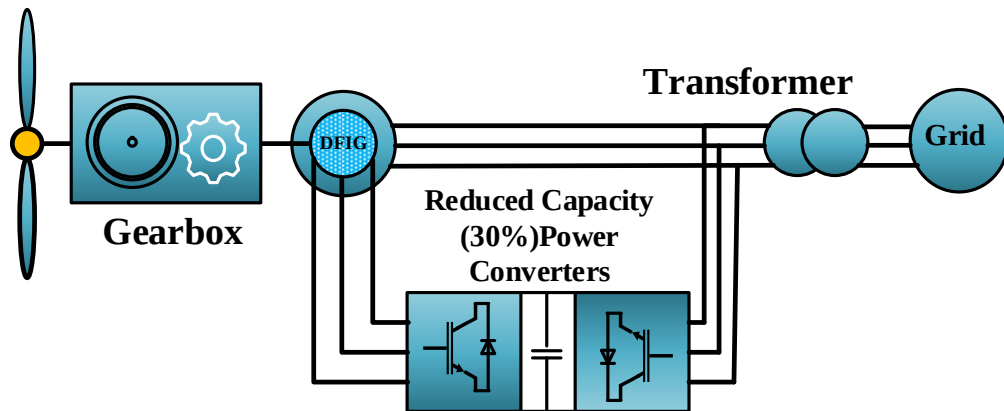


Figure 1. 6 Type 3 Semi-variable Speed Configuration using DFIG WECS

1.2.1.3 Type 3 WECS Semi-variable Speed Configuration ($\pm 30\%$)

Type 3 semi-variable-speed WECS, exemplified by Figure 1.6, provide substantial flexibility in rotor speed in response to varying wind speeds. These systems incorporate a doubly-fed induction generator (DFIG) that connects to the electrical grid through a power converter. Unlike Type 1 and 2 configurations, Type 3 turbines maintain the use of a gearbox and, the requirement for a soft starter and reactive power compensation is completely eliminated, paving the way for enhanced system efficiency and streamlined operations. In the world of wind energy, an ingenious power converter comes to life within the rotor circuit. Operating at a modest 30% of its full potential, this converter efficiently handles the slip power—approximately 30% of the generator's rated power. Its remarkable ability lies in granting precise control over the rotor's speed, the generator's voltage, and even the frequency. This control ensures optimal capturing of wind energy and compliance with the power grid. What sets it apart are the Type 3 WECSs, allowing the rotor to sway within a range of $\pm 30\%$ deviation from the rated value. This flexibility not only showcases outstanding performance but also grants resilience against disturbances in the power system. It is these extraordinary qualities that have established

the DFIG WECS technology as a true frontrunner, commanding an impressive market share of around 50% in the wind sector.

1.2.1.4 Type 4 WECS Full variable Speed Configuration (0%-100%)

WECSs of type 4 are also known as completely variable speed WECSs as shown in Figure 1.7. In contrast to Types 1, 2, and 3, Type 4 WECSs can operate at any wind speed between zero and rated wind speed. This type of WECS can control the generator's power electronics or modify the pitch angle of the blades to control rotor speed and power output. In this configuration, a Type 4 WECS comprising PMSG, WRSG, and SCIG with power ratings spanning from a few megawatts to several megawatts has been implemented. On the other hand, because the capacity of the power converter must correspond with that of the generator, the total size, cost, and complexity of the system all increase. In addition to this, there is an increase in power converter losses, which leads to a decrease in efficiency. Generators, on the other hand, are entirely detached from the grid and can operate at full capacity when equipped with full power converters. These WECSs are well-known for their great efficiency, their capacity to lower mechanical loads, and their support for grid stability through reactive power control.

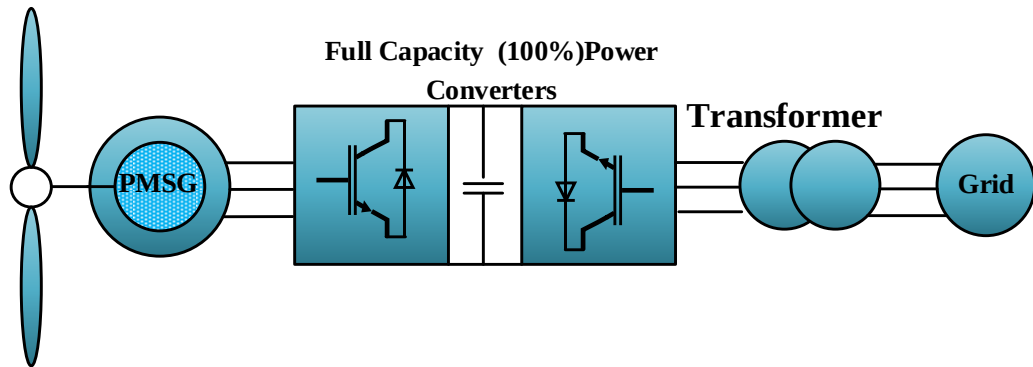


Figure 1. 7 Type 4 Full-variable Speed Configuration using PMSG WECS

1.2.1.5 Type 5 WECS Full variable Speed Configuration (0%-100%)

The Wound Rotor Synchronous Generators (WRSGs) are straight away connected to the grid as part of the variable speed WECS generators as shown in Figure 1.8. Innovatively, this earlier concept employs a mechanical converter instead of an electrical converter to achieve the desired variable speed operation. The task of converting the fluctuating wind turbine speed into a constant speed is performed by the torque/speed converter, also referred to as a variable ratio gearbox. The generator runs at a constant speed and is connected to the grid via a synchronising circuit breaker. Type 5 turbines offer the advantage of reduced overall system costs and space requirements compared to Type 4

turbines, primarily because they do not require a power electronic converter. This enables the generator to be directly connected to the medium-voltage (MV) collection point without the need for a step-up transformer, as there are no restrictions imposed by the power electronic converter, as seen in Type 4 turbines. However, despite the benefits associated with this configuration, Type 5 turbines are seldom employed in the wind energy industry due to limited knowledge and challenges related to the mechanical converter.

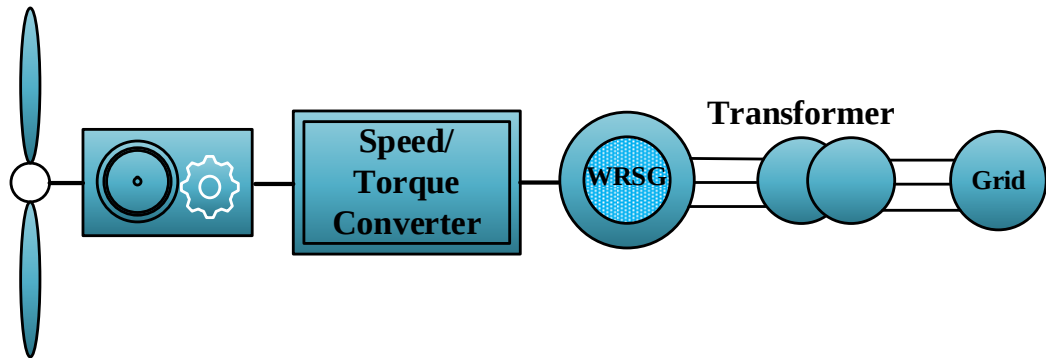


Figure 1. 8 Type 5 Direct Grid Connected Configuration using WRSG WECS

1.2.1.6 Comparison of WECS Configurations

Table 1 provides a comprehensive summary of the five turbine types, comparing various aspects such as the generator and power converters used, power electronics-converter capacity, reachable speed span, the need for soft-starters, gearboxes, and external compensation of reactive power, aero-dynamics control, MPPT ability, compliance with FRT requirements, technology status, and market penetration. Among these turbine types, Type 3 turbines emerge as the most favorable choice for megawatt-level applications. Hence, this thesis focuses on an in-depth investigation of the generator-converter configurations specific to Type 3 turbines, recognizing their promising potential and significance in the field.

Table 1. 1 Consolidated overview of the five distinct configurations of wind energy systems.

	Fixed Speed	Semi-Variable Speed		Full-Variable Speed	
Turbine Type	Type I Turbine	Type 2 Turbine	Type 3 Turbine	Type 4 Turbine	Type 5 Turbine

Generator	SCIG	WRIG	DFIG	PMSG/W RSG SCIG	WRSG
Power Converter	None	Diode + Chopper	AC/DC+D C/AC (or) AC/AC	AC/DC+D C/AC (or) AC/AC (or) AC/DC+D C/DC+DC /AC	None
Converter Capacity	0%	10%	30%	100% 100%	100%
Speed Range	$\pm 1\%$	$\pm 10\%$	$\pm 30\%$	0-100%	0-100%
Soft Starter	Required	Required	Not Required	Not Required Not Required	Not Required
Gear Box	3-Stage	3-Stage	3-Stage	3/2/1/0- Stage	2-Stage
Aero Dynamic Power Control	Active Stall, Stall, Pitch	Pitch	Pitch	Pitch	Pitch
MPPT Operation	Not Possible	Limited	Achievable	Achievable	Achievable
External Reactive Power Compensation	Needed	Needed	Not Needed	Not Needed	Not Needed
FRT Compliance	By External Hardware	By External Hardware	By Power Converter	By Power Converter	Unknown
Technology Status	Outdated	Outdated	Highly Mature	Emerging	Old Concept

Current Market Penetration	Few/No Installations	Few/No installations	>50% Share	2nd Highest Share	Few Installations
Example Commercial Wind Turbines	Vestas V82, 1.65 MW	Suzlon S88-2.1 MW	Repower 6M. 6.0 MW	Enercon E126, 7.5 MW Siemens SWT-3.6 3.6 MW	De Wind D82, 2.2 MW

1.3 Research motivation

The performance investigations on control techniques of DFIG (Doubly Fed Induction Generator) fed wind energy systems have gained substantial importance in the renewable energy market. This research is driven by the need to improve the overall efficiency, stability, and dependability of DFIG-based wind turbines, ultimately contributing to the advancement and optimisation of wind energy systems.

One important part of the research is the modelling of a multi-level inverter (MLI) fed DFIG-based wind energy conversion system. A deeper understanding of the interaction between the MLI and DFIG can be acquired by constructing a thorough model in MATLAB/SIMULINK. This modelling technique makes it possible to investigate and evaluate a variety of control systems, thereby providing insights into their performance as well as possible areas for development.

Model Predictive Direct Torque regulate (MPDTC) and Model Predictive Direct Power Control (MPDPC) systems have been developed to regulate the rotor-side and grid-side converters, respectively. These control algorithms have the ability to provide precise and efficient management of speed transient, torque ripples and power flow to the grid in DFIG-based WECS. The research examines and optimises control systems for two-level and multilevel converters to improve wind turbine system performance and stability.

Another key component of the research is the investigation of techniques to enhance the FRT capabilities of DFIG-based WECS. It is essential to comprehend and enhance the system's response to grid faults in order to guarantee dependable and uninterrupted operation. The research seeks to uncover efficient ways and offer

enhancements to the current fault mitigation approaches by conducting a thorough review of various FRT enhancement tactics.

Additionally, the study investigates symmetrical fault-based comparative analysis of DFIG which is connected through a grid and employing various protection circuits. This study helps in selecting and implementing effective protection techniques for DFIG-based wind turbines by providing useful insights into the performance and dependability of various protection schemes.

The research also investigates the hardware implementation of a proposed control scheme using a WVCET controller. This realistic implementation allows for the evaluation of the proposed control strategies and fault ride-through procedures in a real-world situation. The research contributes to the practical applicability and dependability of the proposed control strategies by validating the findings through hardware experiments.

In summary, the research motivation is to improve the performance, stability, and dependability of DFIG fed WECS. The research aims to contribute to the overall improvement and optimization of wind energy systems by investigating and optimising control strategies, exploring fault ride-through techniques, and conducting hardware implementations. This will, ultimately, support the widespread adoption and integration of wind power as a clean and sustainable energy source.

1.4 Objectives and Contributions of the Study:

The objectives of this thesis are centered around investigating and improving the performance and control strategies of a DFIG fed WECS. The study aims to address several key aspects of wind energy conversion, including modeling, control algorithms, FRT capability, and hardware implementation. The specific objectives and contributions of the study are as follows:

- Conducted an in-depth study on the grid-connected DFIG system and successfully carried out the DFIG mathematical modeling in the dq reference axis.
- Conducted an extensive literature survey on the FRT techniques of DFIG based wind energy systems, compared various FRT techniques, and proposed a modified protection technique for better protection compared to other methods.

- Developed a Model Predictive Direct Torque Control strategy for the rotor side converter of the DFIG fed WECS. Validated the model through extensive simulations in MATLAB and further tested it on a hardware prototype at different operating conditions using a WVCET 300 controller.
- Further, developed a Model Predictive Direct Power Torque Control strategy for the grid side converter of the DFIG fed wind energy system. Validated the simulation results with hardware prototype model at different operating conditions.

This study contributes to the advancement of knowledge and the development of practical solutions in the field of DFIG-based WECS. The study shows how the modelling, control algorithms, fault-ride-through techniques, and hardware implementation of these systems work. The established control techniques, which include MPDTC, MPDPC, and the enhanced FRT method based on fuzzy logic, have the potential to enhance grid integration, performance, and stability. The offered solutions can be used in real life and are reliable because they are based on a comparison of protection circuits and their implementation in hardware. The overall objective of this project is to improve the comprehension and optimisation of DFIG-based wind energy systems, supporting the more general objective of attaining a future powered entirely by renewable energy sources.

1.5 Thesis Organization

The thesis is organized as follows

Chapter 1 briefs about the introduction of the doubly fed induction generator based WECS and introduce the relevant control schemes for grid-connected DFIG system.

Chapter 2 presents the literature review on the controlling and fault ride through methods for doubly fed induction generator based WECS

. Further, this chapter also includes the research gaps and proposed objectives of the present research.

Chapter 3 describes the mathematical modeling of the grid-connected DFIG based WECS including the three level diode clamped inverter, wind turbine, and its open loop stability model using process reaction curve method in MATLAB/SIMULINK.

Chapter 4 presents the various fault ride through (FRT) methods for DFIG based wind energy systems and proposes the fuzzy based protection method for the FRT operation of DFIG. Further proposed FRT has been simulated in MATLAB/SIMULINK for different fault conditions and validated in Real-time with RTLAB 4500.

Chapter 5 describes the Model predictive direct torque control method for two level and three level converter fed rotor side power converter to control the speed and torque of the DFIG. The proposed model is initially simulated at various operating conditions and further, the simulated results are validated experimentally through a developed prototype model in the laboratory. The switching pulses for the converter are obtained by using WAVCET 300 controller.

Chapter 6 presents the Model predictive direct power control method for two level and three level inverter fed grid side power converter to control active and reactive power of the DFIG. The proposed model is simulated at various operating conditions and further, the simulated results are validated experimentally through a developed prototype model in the laboratory. The switching pulses for the inverter are obtained by using a WAVCET 300 controller.

Chapter 7 presents the concluding remarks along with the future scope of the research work.

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

Renewable energy sources are crucial for meeting the growing global energy demand and reducing greenhouse gas emissions. Among these sources, wind energy has gained popularity due to its abundance and affordability. Various configurations of wind turbines are used to harness wind energy for various applications and environmental conditions [8]. Wind energy is considered competitive to solar energy thanks to advancements in wind turbine technology [9]. A comprehensive investigation of the historical development of wind energy is presented in a review paper [10]. Furthermore, the current state of wind energy worldwide and the improvements in wind turbine designs are discussed in [11].

WECSs have been in use for more than three decades, and throughout that time, both fixed and variable speed technologies have been implemented. Former WECSs rely on a squirrel cage induction generator (SCIG) that directly connects to the electrical utility grid without the need for power conversion devices. Fixed-speed systems are advantageous due to their simplicity, excellent reliability, and low maintenance costs. However, they suffer from drawbacks such as low efficiency, significant power output fluctuations, and increased mechanical stress on components. On the other hand, variable-speed WECS are more efficient because they match the torque developed by the electrical generator to the highest amount of mechanical torque that is possible.

In the realm of variable-speed wind systems, three frequently employed generator types are the Doubly Fed Induction Generator (DFIG) [12], the Permanent Magnet Synchronous Generator (PMSG) [13], and the Wound Rotor Synchronous Generator (WRSG). In depth analysis was carried out in [14], and the results provide a comprehensive look at multi-MW wind turbine generators and power converters that are now available in the market as well as those that have been recently suggested. The pros and cons are compared and contrasted, and it is found that the DFIG model is the most popular choice because of its small converter size, low cost, and efficient operation under varying wind speeds. As a result, DFIG has evolved as a prominent area of research and development [14].

The doubly-fed induction generator (DFIG) model is probably the most common type of WECSs technology. This is due to its many advantages, such as operational flexibility with variable speed and fixed frequency, independent control over real and reactive power, increased capability for maximum power extraction, decreased mechanical strain, a small converter volt-ampere (VA) rating (typically 30% of the generator's capacity), and a reduction in power loss when compared with fixed-speed turbine (FST) induction generators or fully rated converter systems. These advantages are often realized by incorporating a back-to-back (BTB) converter [15].

In the DFIG configuration, the stator windings establish a direct connection to the electrical grid, while the rotor windings integrate with partially rated BTB power electronic converters (PEC). These are referred to as the rotor side power electronic converter (RSPEC) and the grid side power electronic converter (GSPEC). This configuration allows for precise control of the frequency and amplitude of current within the rotor windings. Furthermore, it allows for significant rotor speed variations, increasing the system's potential to absorb wind energy [16].

2.2 DFIG modelling

Several approaches can be utilized to illustrate the DFIG model, such as the stationary stator-reference frame, the rotor speed rotating reference-frame, and the synchronously rotating reference-frame. Ekanayake et al. in [17] opted for the synchronously rotating reference frame to streamline controller design, as it allows all currents and voltages to be expressed as direct current (DC) in nature. In contrast, the author Tapia et.al in [18] aligned both stator and rotor variables with their natural reference frames, resulting in the development of the "Quadrature-Phase Slip-Ring" model. In general, reduced-order models are used to express the DFIG model. These models can produce a third-order model when the derivative terms of the stator flux are ignored, or a first-order model when both the derivative terms of the stator flux and the rotor flux are ignored [19]. However, in [20], an enhanced third-order model that is considered with direct current (DC) components of stator currents was introduced. The authors compared this model to a full order model when the wind ramp was in effect. Alvaro Luna in [21] proposed a novel reduced third-order model. This model bypassed stator resistances and inductances by implementing the Laplace transformation. The

effectiveness of this model was then evaluated in a transient analytic environment against a full order model.

Numerous studies have focused on comparing full order models with reduced order models, as evidenced by various references [22]–[24]. Notably, the Abbaszadeh et al. in [25] undertook a thorough analysis that included both unsaturated and saturated full order models, as well as reduced order models, even considering saturated conditions. In addition, in [26], Pablo Ledesma compared a third-order model to a full-order model under short-circuit fault conditions, focusing on two extreme operation points: sub-synchronous speed and super-synchronous speed. It is worth noting that the key distinction between the models of squirrel-cage induction generators and doubly-fed induction generators lies in the rotor input. As a result, the utilization of simplified models for squirrel-cage induction generators can offer valuable perspectives that facilitate the understanding of reduced order models for DFIGs [27].

Several researchers, including Petersson (2005) and Xu (2007), have studied different ways to control DFIG systems using mathematical models they created [28], [29]. These methods include vector control, direct torque control, and direct power control. All of them are meant to make DFIG-based systems more efficient and reliable. Recognising the critical requirement for increased reliability, [30] conducted a thorough investigation of the mathematical modelling of DFIG under abnormal conditions. Their efforts culminated in the creation of sophisticated mathematical models capable of predicting, diagnosing, and mitigating a range of faults within DFIG systems. In addition, the investigation that was carried out by [31] shed light on the essential function that DFIG modelling plays within the scope of power system stability analysis. Their work on small-signal stability analysis provided important insight into the effects of DFIGs on the grid stability. The majority of the time, the current impedance modelling for DFIGs is focused on a single converter instance, such as the GSPEC or the RSPEC. As a result, the interaction between the RSPEC and the GSPEC, as well as the frequency coupling effect that is fundamental to the converter, is frequently neglected. This omission can compromise the precision of DFIG stability analysis. Consequently, this paper puts forth a comprehensive impedance model for the DFIG-focused WECS, taking into account coupling parameters (e.g., DC bus voltage dynamics, asymmetric current regulation in the dq frame, and PLL). In [31], the model was validated using numerical computations and Hardware-in-the-Loop (HIL) simulations on RT-Lab. The findings highlight that the

holistic impedance model with frequency coupling boasts greater accuracy and demonstrates an adeptness in precisely identifying potential resonance sites in the system. This is evidenced by the fact that the model is able to accurately pinpoint prospective resonance spots.

2.3 Power converter modelling

In the conventional setup of wind turbine-generator systems, a back-to-back two-level Pulse Width Modulation (PWM) converter has been traditionally utilized. This model, which encompasses a three-phase voltage source PWM converter, can be envisioned in both the stationary frame of reference to the rotating synchronous frame of reference. The latter frame is primarily devised to address control-related factors, highlighting the versatile nature of the model. In [32], a mathematical representation based on space vectors initially was used while operating within the ABC reference frame. Subsequently, [33] provided a comprehensive analysis of the conversion process of a PWM converter model, migrating from the stationary frame of reference to the rotating synchronous reference frame. A significant step forward was taken by Muller et al. (2003) as they proposed a more refined model in conjunction with a control method that makes use of power converters for the DFIG [34]. This study is notable for being one of the pioneering efforts that successfully controlled both the active and reactive power of a DFIG by implementing the use of power converters.

In an effort to boost system performance, new converter configurations have been suggested. A pioneering approach of back-to-back converter design was examined by Guo et al. (2010) with the aim of reducing the converter's size while increasing the system's efficiency [35]. An important area of research that has come under attention is grid integration. In response to this, Bojoi et al. (2012) put forth a superior model for grid integration that deployed power converters to maintain DFIG system stability during grid disruptions [36]. Recent years have seen an increase in the amount of focus placed in academic circles on the effects that converter nonlinearities on the performance of DFIG systems. In order to achieve this goal, the authors of [37] developed a model for power converters that takes into consideration the impacts of switching as well as conduction losses that occur within converters.

The domain of power electronics has seen significant progress, paving the way for the introduction of multilevel converters. [38] provided an extensive review of the use of

multilevel converters in DFIG systems. Multilevel converters offer a number of advantages over conventional two-level converters, including increased sinusoidal output voltage waveforms, decreased total harmonic distortion (THD), smaller and less expensive filters, fewer switching losses in the IGBTs, and reduced dv/dt [39]. These benefits stem from the capacity to generate output voltages with more than two voltage levels.

There have been a number of different layouts for multilevel inverters proposed, such as the diode-clamped, cascaded H-bridge, and flying capacitor types. Each configuration has its own set of advantages and disadvantages in the context of cost, complexity, and performance. These topologies were compared based on output voltage quality, total harmonic distortion (THD), power losses, and overall system efficiency [40], [41].

The control of multilevel inverters within DFIG systems is an essential aspect that impacts overall system stability and performance. Numerous control approaches have been suggested by researchers to ensure appropriate voltage and current regulation, enhanced power quality, and reliable functioning of the DFIG system. These strategies comprise pulse width modulation (PWM) [42][43], space vector modulation (SVM) [44][45], and model predictive control (MPC) [46]. The decision regarding the choice of the control approach is influenced by aspects such as system requirements, desired output waveform quality, switching frequency, and computational complexity [47][48].

Additionally, literature reviews examine modulation tactics, capacitor voltage balancing techniques, and control parameter tuning in relation to the optimisation of multilevel inverters. Different optimisation algorithms, like particle swarm optimisation (PSO), genetic algorithms (GA), and artificial neural networks (ANN), are used to find the best operating points and control factors for multilevel inverters in DFIG systems [49][50], [51]. Multilevel converters play a crucial role in DFIG-driven wind energy systems, as evidenced by the literature, which also highlights ongoing developments in control strategies, configurations, and applications. The consistent evolution in this domain suggests that multilevel converters are set to remain an integral part of future DFIG systems.

2.4 FRT Capability of DFIG fed WECS

FRT capabilities in DFIG wind turbines refer to their potential to maintain a grid connection even when the voltage level at the point common coupling (PCC) falls to as low as 20%. With the updated grid code standards globally, this characteristic has become critical, as the disconnection of the wind turbine (WT) from the grid during severe voltage drops could destabilize the power system. The strategies employed by utilities to enhance FRT capabilities in wind turbines address challenges such as excessive electrical current in the generator's stator and rotor circuit windings and surges in voltage across the DC-link capacitor in the DFIG system's back-to-back power converter. The protection of the converter against damage caused by short-circuit fault effects leading to high current variations in the generator's stator and rotor windings is prioritised because of the converter's comparatively low power rating in the DFIG system design. Hence, safeguarding the converter becomes essential to ensure the DFIG remains operational and connected to the grid, thus complying with the grid code requirements. Furthermore, the turbines are required to supply reactive power during voltage excursions into prescribed ranges [52]. A number of countries have released grid codes that are tailored expressly for wind turbines, with an emphasis on the ride-through capabilities of these turbines. These ride-through capabilities include FRT at the point of common coupling (PCC) for wind farms, as well as low voltage ride-through (LVRT) for wind turbine generators [53][54].

Extensive research has been conducted into the FRT capabilities of DFIG wind farms. The crowbar approach is a common method that is used to limit the amount of overcurrent that flows through the RSPEC [55]. This approach works by allowing rotor current to flow through an external resistor during faults, dissipating extra power caused by rotor over-current. However, the activation of the crowbar during a voltage sag corresponds with the deactivation of the RSPEC, which results in the DFIG being transformed into a typical SCIG that draws the reactive power from the grid. The crowbar resistor in a passive crowbar is connected to the rotor winding using a Thyristor that lacks a gate turn-off feature, while in an active crowbar, the resistor is externally connected to a three-phase rectifier circuitry and a semiconductor based power switch that has gate turn-off capability [56].

The positioning of a DC-chopper between the converters reduces the possibility of DC-link overvoltage [57] [58]. The DC-chopper can reduce overvoltage, however, it

is ineffective in reducing overcurrent. Integrating a crowbar protection circuit with a series R-L circuit can limit both rotor inrush current and DC-link overvoltage to predefined thresholds [59]. However, this plan partially converts the DFIG into WECSs based on a SCIG.

In contrast, a crowbar protection system integrated with a series dynamic resistor (SDR) can potentially save the RSPEC and DFIG-based WECS's DC-link [60]. By incorporating the superconducting storage devices can help to ease these difficulties, boosting FRT capabilities during outages or surges [61]. The fault current on the DFIG (stator end) can be reduced by using a resistive type-superconducting fault current limiter (SFCL), which can also improve the DFIG's FRT capabilities [62]. However, appropriate resistance levels need to be selected with great care in order to strike a compromise between power loss and FRT capacity. Moreover, a combined strategy using a crowbar, SDBR, and SMES can further enhance FRT capabilities by feeding real power into the network [63]. In recent studies, a novel approach was introduced to enhance the performance of combined Superconducting Magnetic Energy Storage (SMES) and Superconducting Fault Current Limiter (SFCL) systems [64], [65]. The primary objective of this approach was to mitigate fault currents and reduce power fluctuations. One notable modification in these investigations involved incorporating a superconducting coil (SC) within the SMES unit, typically connected in parallel to the system bus, and further connecting it in series with the transmission line via a rectifier. By doing so, the SC not only served as an energy storage component during normal operations but also functioned as a fault current limiter in case of short-circuit incidents within the power grid. Another research study [66] demonstrated that connecting the SC in series with the stator yielded superior FRT performance compared to series connection with the rotor. However, a significant drawback of this SC configuration is the increased cost it entails. This specific arrangement necessitates the use of three specialized transformers, each with a primary end voltage rating nearly identical to the line voltage, to maintain the desired voltage level during fault occurrences. Consequently, when this configuration is deployed in each Wind Turbine Generator (WTG) solely for steady-state power control, it results in a relatively low performance ratio.

A wide range of energy storage systems has been explored to enhance the LVRT performance in DFIG fed WECSs. These systems include batteries, supercapacitors, flywheels, and SMES. However, their practical implementation is prohibitively expensive

and fails to adequately address rotor current and torque oscillation issues. Furthermore, storage-based FRT technologies face challenges such as thermal runaway at high penetration and concerns regarding overcharging, resulting in high costs and low energy density. Among the critical problems hindering the continuous operation of DFIG-based WECSs, voltage stability issues stand out as the most crucial. To mitigate these issues, the utilization of reactive power-supporting devices has shown promise. The parallelly connected Flexible AC Transmission Systems (FACTS) devices, as investigated in [67], offer effective control of using PEC and provide enhancements in transient and voltage stability by reducing power oscillation [68]. Static Var Compensators (SVC) and Static Synchronous Compensators (STATCOM) are common devices to improve power transfer capability. Recent efforts have involved equipping Wind Turbines (WTs) with SVC and STATCOM devices to enhance transient stability and voltage regulation [69]. However, the adoption of FACTS devices for FRT operation incurs additional costs due to the requirement for high-rating switching equipment and efficient controllers [70 [71]].

Voltage sag issues can be quickly, flexibly, and effectively mitigated with the use of dynamic voltage resistors (DVR) which is installed at the PCC. DVRs inject the necessary reactive power to address sag effects [72]. While DVRs can effectively handle power quality disturbances [73], [74] they are unsuitable for systems experiencing sustained reactive power requirement leading to low voltage conditions or systems vulnerable to voltage collapse. Hence, implementing the DVR approach requires careful consideration of the load's nature and the transmission system's ability to withstand voltage fluctuations resulting from load changes [75]. Reference [76] proposes a Modulated Series DBR (MSDBR) based control scheme to improve the FRT capabilities of DFIG-fed WECS. This protective control scheme incorporates a voltage booster and provides a series voltage compensation that enables power evacuation to mitigate power imbalances during grid faults. This control scheme has low cost and straightforward to implement.

Apart from hardware-based techniques, alternative control approaches based on software have been suggested to enhance transient stability during faults. These include Blade Pitch control [77], Feedforward Transient Current control [78], Fuzzy Logic Control [79], Sliding Mode Control [80], and Predictive Control [81]. Software-based modified control approaches offer a cost-effective solution; however, their appeal is diminished due to the complexity and limitations associated with elevated fault currents.

2.5 Control Strategies of the DFIG for the RSPEC

The DFIG has gained significant popularity in WECS due to its advantageous features, such as independent control of active and reactive power and variable speed operation. The research literature has a wide variety of different control mechanisms that have been widely investigated and proposed for DFIGs. Although many advanced control techniques created for induction motors may be used with DFIGs, controlling a DFIG is trickier than controlling a typical induction motor. In the subsequent chapter 5 & 6, it will be demonstrated that any three-phase quantity, whether voltage, current, or flux linkage, can be represented as a single rotating vector [82].

Various control methods based on the DFIG's dynamic mathematical model have been described in the literature, like direct power control, vector control, direct torque control, predictive control, and non-linear control. Techniques for controlling rotor current vectors are frequently utilised in the conventional designs of DFIG control systems. Typically, these control systems are defined in the synchronous dq frame oriented to the stator flux [18], [82], the stator voltage (or grid flux) [83][84], or the gap flux [85]. Commonly used methods in DFIG control designs is stator-flux oriented control, in which the active power is controlled by the q-axis current component and the reactive power by the d-axis current component. Stator voltage-oriented control, in contrast, operates in the opposite manner, with the q-axis current component controlling reactive power and the d-axis component controlling active power. To evaluate system stability, the analysis of steady-state and dynamic performance, as well as controller design, rely on small signal stability requirements established from sophisticated DFIG-based wind turbine models. Vector Control (VC) is effective, but it requires precise estimation of machine parameters and extensive tuning to guarantee stability and a good response over the full working range [86].

Direct Torque Control (DTC) has emerged as an alternative scheme for achieving high-performance control in electric drives. It was first presented in the mid-1980s [87] and is lesser parameter dependence and tuning requirements than VC, as well as faster response. Conventional DTC employs two hysteresis comparators to regulate torque and flux directly by picking an appropriate voltage vector from a predetermined switching table based on rotor position and stator flux. The standard switching-table-based DTC does, however, have a few shortcomings, the most noteworthy one is substantial ripple in the torque output and the variable switching frequency [88]. Numerous techniques have

been suggested in the literature to solve these disadvantages and enhance steady-state performance while maintaining a fixed switching frequency. Space Vector Modulation (DTC-SVM) is a common method used in this context [89]. DTC-SVM improves steady-state performance but needs sophisticated computations, more machine parameters, and more tuning. Another technique is DTC-SVPWM, which provides constant switching frequency and reduced torque and flux disturbance in comparison to the lookup table method. Nevertheless, it adds another layer of complexity because it necessitates the tuning of proportional-integral controllers [90]. This strategy is somewhat comparable to Field-Oriented Control (FOC), which was described in [91]. [92] proposes a neuro-fuzzy-based Space-Vector Modulation (NF-SVM) technique for managing a two-level inverter supplying an induction motor. The NF-SVM makes use of an adaptive neuro-fuzzy inference system, also known as an ANFIS, in order to generate optimal switching states for the inverter. These states are determined by the stator's flux and torque errors.

Direct Power Control (DPC) is a control strategy that benefits from being easy to implement, requiring few sensors, being computationally simple, having a fast transient response, and requiring a simple machine model. A comparative study between VC and DPC for a Pulse-Width Modulation (PWM) rectifier was presented in [93]. Simulation results demonstrated the superiority of virtual-flux-based Direct Power Control over voltage-based DPC and VC [94]. In a different study [95], DPC was used in a wind turbine system powered by a DFIG that was operating with an uneven grid voltage. The authors presented a new form of DPC that relies only on stator flux, and the only values from the machine parameters that were necessary were the stator resistance value [96].

Predictive control methods have received a lot of interest recently in the context of wind turbine generating systems based on DFIG [97], [98]. Model Predictive Control (MPC) inside DTC approaches was proposed by researchers in [99], [100]. In this method, three voltage vectors are used at each sampling point. In spite of the fact that this method lowers torque ripple and improves dynamic behaviour, its control scheme is complicated and requires accurate estimations of the amount of time exerted for each voltage vector. Furthermore, it mandates the usage of two switching databases for DFIG control, one for sub-synchronous speeds and another for super-synchronous speeds. Finite Control Set Model Predictive (FCSMP) Control is a more straightforward, adaptable, reliable, and efficient option for controlling power electronics converters with a finite number of switching stages that has been popular in recent years [101]. FCSMP control

eliminates with the necessity for synchronised control mechanisms and modulation stages in a cascade, leading to superior steady-state reference tracking and rapid dynamic performance. In FCSMP control, the operational concepts of VC, DTC, and DPC schemes are leveraged to create Predictive Current Control (PCC), Predictive Torque Control (PTC), and Predictive Power Control (PPC), respectively. This allows FCSMP control to design Predictive Current Control (PCC), Predictive Power Control (PPC), and Predictive Torque Control (PTC). All of the VC, DPC, and DTC control variables can be regulated by these predictive control strategies without the need for additional external Proportional-Integral (PI) or hysteresis controllers. Moreover, the absence of a modulation stage in the FCSMP control methods allows for the flexibility of employing a diverse spectrum of switching frequencies. In both classical and predictive control schemes, the outer speed control loop of a generator is governed by a PI controller to maintain alignment with the desired reference value. The PCC, PPC, and PTC schemes necessitate quicker control actions compared to the relatively slower outer speed control loop, resulting in the replacement of the VC, DPC, DTC and internal control loops in these schemes. A recent advancement in this domain is the Predictive Speed Control (PSC) scheme, which eliminates the need for a speed PI controller and internal PI controllers, thereby simplifying the control structure and eliminating the cascade effect [102]. The generator speed and control variables are both controlled simultaneously by this scheme's internal PCC, PTC, or PPC.

2.6 Control Strategies of the DFIG for the GSPEC

In variable-speed WECSs, the management of grid-side power electronic converters (GSPECs) is accomplished through the use of a wide variety of strategies. Among these, the hysteresis control method stands out for its usage in modulating the grid-side converter's three-phase load currents. Hysteresis control, as a nonlinear control technique, involves the comparison between measured load currents and their corresponding reference currents. After that, the current errors that were produced are sent to relays, which are also referred to as hysteresis comparators or bang–bang controllers [103]. In each phase, the relay figures out the switching signals that are needed to keep the observed loads within the hysteresis bandwidth limits that the user has set. Hysteresis current control is regarded as one of the least complicated and most reliable approaches to controlling current. This is due to the fact that it does not call for any prior

knowledge on the part of the user or any specific system parameters or converter types. Since the inception of analog control platforms, this method has gained significant traction and widespread implementation within the power electronics sector [13]. Furthermore, the hysteresis control method circumvents the need for complex mathematical expressions, reference frame theory, intricate analog circuits, or high precision digital controllers. Although the uncontrolled switching frequency is a fundamental disadvantage of this controller, great progress has been made in minimising this problem. However, one persisting shortcoming of hysteresis control is its inability to accommodate constraints such as common-mode voltage reduction and spectrum shaping.

Sinusoidal Pulse Width Modulation (SPWM), also called carrier-based Pulse Width Modulation (PWM), is a common way to change the frequency of a signal in power converters. By comparing the carrier signal with the three-phase modulating signals, this approach estimates the duration of conduction time for the upper-leg switching devices. The inverter uses a low-cost control scheme employing SPWM technique to accomplish matching of rotor voltage, phase, and frequency with those of the grid, thereby facilitating power transfer via phase shifting. This scheme is specifically designed for super synchronous generation, avoiding complexity in the interface controller [104].

In grid-connected WECSs, Space Vector Modulation (SVM) serves as a widely employed modulation technique for the digital control of two-level Voltage Source Converters (2L-VSCs). SVM provides superior harmonic performance and DC-bus voltage utilisation in comparison to SPWM. The selection of vectors in Space Vector Modulation (SVM) is determined by calculating their proximity to the reference voltage vector. The dwell time calculation guides this selection process, enabling the generation of optimal gating signals through strategically designed switching schemes [105]. However, when applied to multilevel converters, the complexity of Space Vector Modulation (SVM) increases due to additional constraints such as improving load total harmonic distortion (THD), operating at low switching frequencies, minimizing common-mode voltage, and managing the DC-link neutral-point voltage. To improve the overall performance of GSPEC systems, the article [106] presents a control method that is centred on sliding-mode control, also known as SMC. The approach that is being proposed makes use of a double-loop structure, with a sliding-mode controller designed to improve the stability of the DC-link voltage being implemented in the outer loop, and

Direct Power Control (DPC), which is based on sliding-mode control, being utilised in the inner loop. This controller has the benefits of a straightforward structure, excellent control accuracy, quick reaction times, and substantial resilience. However, it is worth noting that this scheme has certain drawbacks, including complex mathematical modelling and the occurrence of chattering phenomena. Thus, the practical implementation of SMC is not as extensive as that of conventional control techniques.

A Fuzzy Logic Controller (FLC) replaces the Proportional-Integral (PI) controller commonly used in linear control systems, which is presented in reference [107] as a potential replacement. As a member of the nonlinear control techniques, Fuzzy Logic Controller (FLC) is widely regarded as one of the top choices among adaptive controllers. The fuzzy controller accepts the load current reference tracking error and its derivative as inputs and, using membership functions and "if-then" control rules, incorporates the designer's experience, knowledge, and intuition. However, it is crucial to consider that the effectiveness of this scheme's control performance relies heavily on the expert knowledge of the designers, which is based on heuristic reasoning, along with the utilization of specific control rules. Predictive control theory has become more popular recently. For the purpose of load current regulation, the method referred to as FCS-MPC is provided in reference [108]. In contrast to linear control, this methodology does not require linear PI regulators or modulation stages. As a result, it offers a fundamentally distinct method for controlling power converters in GSPEC systems. Field-Oriented Control (FOC) and Direct Power Control (DPC) schemes are implemented in variable-speed WECSs for governing GSPECs [109]. FOC ensures control of the grid currents, allowing management of the net DC-bus voltage (active power) and reactive power. In the DPC scheme, similar to the control applied to the generator side, independent control of grid active and reactive powers is achieved.

CHAPTER 3. MODELLING OF DFIG BASED WECS

3.1 Introduction

The section of the thesis titled "Modelling of DFIG based WECS" delves into an in-depth investigation of the mathematical models that have been established for DFIG-based wind power systems. This chapter's goal is to give a comprehensive analysis of the dynamic behaviour and performance characteristics displayed by DFIG systems, with a particular emphasis on steady-state as well as transient circumstances. Controlling a wind power system effectively requires an understanding of these models, which include the static and dynamic depiction of DFIGs and power converters. This is because these models encapsulate the operative relationships between variables in the DFIG power network, forming the cornerstone for the development of control designs in the subsequent chapters.

In the grid-connected mode of DFIG, the stator magnetic field is created by directly connecting the three-phase stator winding to the grid voltage, which has a constant magnitude and frequency. Figure 3. 1 illustrates the fundamental supply arrangement of DFIG [2], where a wind turbine is linked to the rotor shaft via a gearbox. The rotor windings, which are mounted on the rotor shaft, receive power of varying magnitude and frequency from a power electronic converter. This converter, standard in DFIG wind energy systems, is a BTB converter. It consists of two three-phase voltage source converters (VSC), known as the grid-side power electronic converter (GSPEC) and rotor side power electronic converter (RSPEC), which share the DC-link.

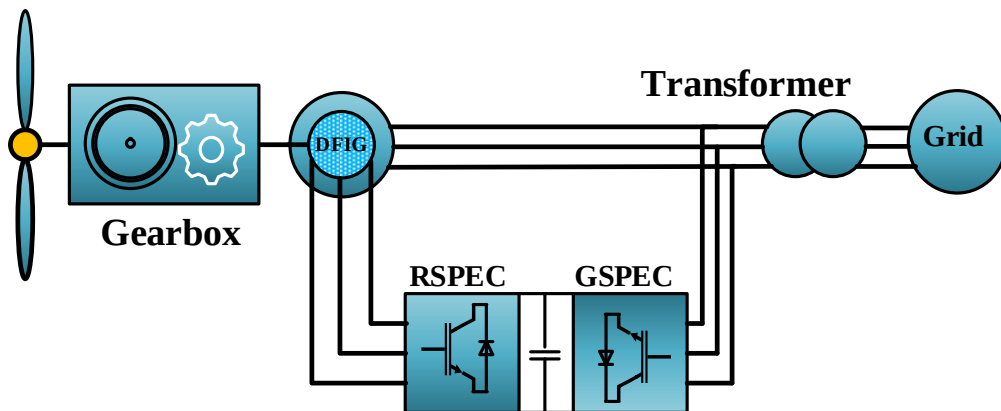


Figure 3. 1 Fundamental arrangement of DFIG WECS

The appropriate control approach allows the operating point of the converters to be adjusted, facilitating power transfer to the grid via the rotor and stator. Diverse configurations of power electronic hardware, like multi-level and matrix converters, have been designed to attain higher voltage levels while eliminating the requirement for a DC capacitor. In this chapter, we start off by introducing the steady-state model of the DFIG, which lays the foundation for our understanding. As we progress, we delve into the dynamic model of the DFIG and PEC. What makes it interesting is that we explore these models from different reference-frames like abc , $\alpha\beta$, and dq , giving us a well-rounded view. We also take the time to discuss how these dynamic models connect with each other across these diverse reference frames.

3.2 Induced Force/Torque

The DFIG, an innovative wind turbine design, incorporates two sets of windings with distinct functions: the rotor winding and the stator winding. Setting it apart from traditional induction machines with cage rotors, the DFIG utilizes external power sources for both windings. The grid supplies power to the stator winding, whereas the rotor winding is typically powered by a three-phase inverter. When constructing the steady-state model of the DFIG, we consider the rotor and stator windings to be connected in a star configuration. The grid supplies balanced three-phase voltages, which have a fixed amplitude and frequency. Similarly, the three-phase inverter provides the rotor with balanced three-phase voltages, ensuring a consistent frequency and amplitude as well. Under these conditions, the three phases of the DFIG are symmetrical, and the analysis can be simplified by focusing on the characteristics of a single phase of the machine. However, from a constructional standpoint, the DFIG rotor is larger and necessitates regular maintenance due to the wear and tear of the brushes and slip-rings.

Therefore, within the stator assembly, there are three windings arranged in a spatial distribution of 120° , accompanied by p pairs of poles. When a balanced 3-phase voltage with a frequency f_s energizes these stator windings, it gives rise to the induction of stator flux. This stator flux, in turn, rotates at a steady pace. In simpler terms, we can calculate the synchronous speed (n_s) using the following equation.

$$n_s = \frac{60f_s}{p} \text{ (rev/min)} \quad 3.1$$

Based on Faraday's law, the rotating stator flux fundamentally induces an electromotive force (emf) in the rotor windings:

$$e_{ind} = (v \times B)L \quad 3.2$$

Within the equation, the term e_{ind} represents the induced-emf experienced by a single conductor within the rotor. The variable v denotes the velocity of the conductor in relation to the rotational speed of the stator flux. B represents the vector that describes the density of the stator flux, while L signifies the length of the conductor.

As a consequence of the induced voltage in the rotor windings, together with the potential for externally supplied voltage via the brushes, a current is evoked within the rotor windings. In accordance with Laplace's law, this current gives rise to an induced force in the rotor of the machine.

$$F = i.(L \times B) \quad 3.3$$

In this context, F symbolizes the induced force (associated with the machine's induced torque), i represents the current flowing through the conductor of rotor, B denotes the stator flux density vector, and L stands for the conductor length.

3.3 Slip Concept

As discussed in the previous subsection, the rotor's induced voltage is influenced by the dynamic interaction between the rotational velocity of the stator flux and the rotor's motion. In fact, the angular frequency governing the induced voltages and currents within the rotor can be expressed by the following correlation.

$$\omega_{sl} = \omega_s - \omega_r \quad 3.4$$

In this formula, ω_m signifies the angular frequency characterizing the variations of voltages and currents within the winding of the rotor (measured in rad/s), ω_s denotes the angular frequency characterizing the variations of voltages and currents within the winding of the stator (also in rad/s), ω_r represents the rotor angular frequency (in rad/s).

$$\omega_r = p\Omega_r \quad 3.5$$

Here, Ω_r signifies the mechanical rotational speed at the rotor, measured in rad/s.

It's crucial to note that, under typical steady-state operation, as the induced currents and voltages within the rotor windings possess an angular frequency of ω_{sl} , the voltage supplied externally to the rotor must maintain the same angular-frequency ω_{sl} .

Therefore, the term often employed to depict the relationship between the stator's speed and the rotor's angular frequency is 'slip', denoted as s :

$$s = \frac{\omega_s - \omega_r}{\omega_s} \quad 3.6$$

Upon merging the equations (3.4) and (3.6), the correlation among the slip, the stator's angular frequency, and the rotor's angular frequency is revealed as follows:

$$\omega_{sl} = s\omega_s \quad 3.7$$

From this last equation, equivalently, the correlation among the frequencies can also be extrapolated:

$$f_{sl} = sf_s \quad 3.8$$

The sign of the slip allows us to categorize the machine's operation into three distinct modes:

$$\begin{aligned} \omega_r < \omega_s &\Rightarrow \omega_{sl} > 0 \Rightarrow s > 0 \Rightarrow \textit{Subsynchronous operation} \\ \omega_r > \omega_s &\Rightarrow \omega_{sl} < 0 \Rightarrow s < 0 \Rightarrow \textit{Hypersynchronous operation} \\ \omega_r = \omega_s &\Rightarrow \omega_{sl} = 0 \Rightarrow s = 0 \Rightarrow \textit{Synchronous operation} \end{aligned}$$

3.4 Steady-State Equivalent Circuit of a DFIG

A single-phase conceptual illustration of a DFIG is depicted in Figure 3. 2. In this figure, V_s and V'_r represent the voltage phasors for the stator and rotor, provided by the grid and inverter, respectively. I_s and I'_r symbolize the stator and rotor current phasors. L_m signifies the mutual inductance, while L_{ls} and L'_{lr} stand for the leakage inductance of the stator and rotor windings respectively. R_s and R'_r denote the resistances of the stator and rotor. Variables marked with a superscript ' refer to the variables on the rotor side.

It's essential to reemphasize that the frequencies of the voltage and currents in the stator and rotor circuits differ. The stator frequency (f_s) remains fixed if directly connected to the grid, whereas the frequency of the rotor voltages and currents (f_r) fluctuates and is dependent on the machine's speed as per expression (3. 8). As a result, the rotor impedance L'_{lr} is also speed-dependent. Within the idealistic model, the real-time

characteristics of the stator, including its voltages, currents, and fluxes, are visually represented in Figure 3. 3

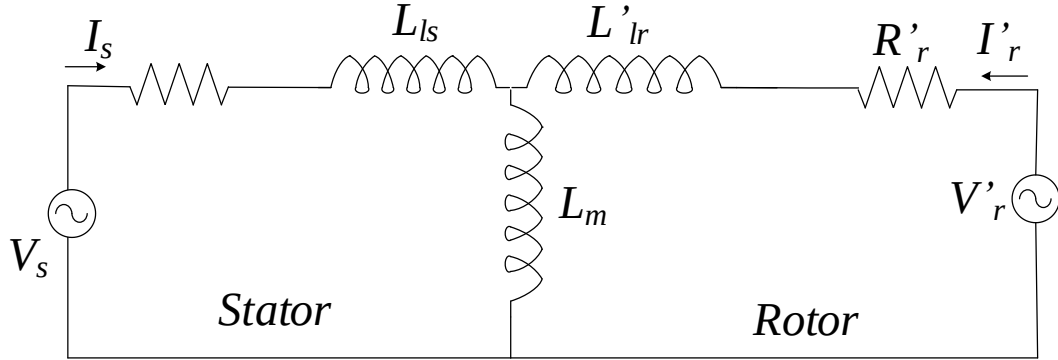


Figure 3. 2 One-phase steady-state equivalent circuit of a DFIG

$$v_{as} = R_s i_{as} + \frac{d\psi_{as}}{dt} \quad 3.9$$

$$v_{bs} = R_s i_{bs} + \frac{d\psi_{bs}}{dt} \quad 3.10$$

$$v_{cs} = R_s i_{cs} + \frac{d\psi_{cs}}{dt} \quad 3.11$$

In this context, R_s signifies the stator-resistance; i_{as} , i_{bs} , and i_{cs} represent the stator currents of phases A, B, and C, respectively; v_{as} , v_{bs} , and v_{cs} are the stator voltages applied; and ψ_{as} , ψ_{bs} , and ψ_{cs} correspond to the stator fluxes.

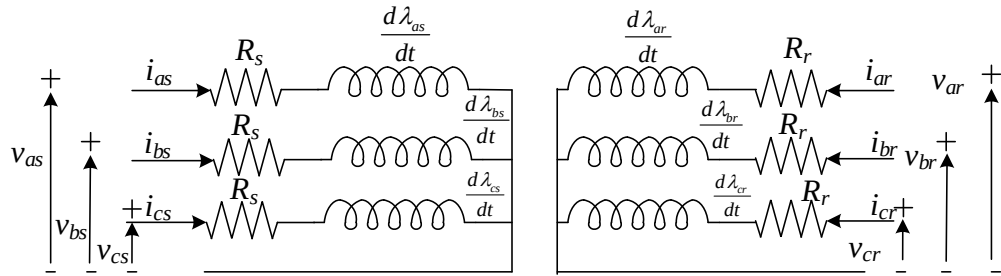


Figure 3. 3 DFIG electrical equivalent circuit

The stator side electrical quantities, under steady-state conditions, maintain a steady sinusoidal angular frequency ω_s , which is set by the grid. Likewise, the rotor's electrical equations can be outlined as follows:

$$v_{ar} = R_r i_{ar} + \frac{d\psi_{ar}}{dt} \quad 3.12$$

$$v_{br} = R_r i_{br} + \frac{d\psi_{br}}{dt} \quad 3.13$$

$$v_{cr} = R_r i_{cr} + \frac{d\psi_{cr}}{dt} \quad 3.14$$

In these equations, R_r signifies the rotor resistance; i_{ar} , i_{br} , and i_{cr} denote the rotor currents of phases A, B, and C, respectively; v_{ar} , v_{br} , and v_{cr} correspond to the rotor voltages applied; and ψ_{ar} , ψ_{br} , and ψ_{cr} represent the rotor fluxes.

Equations 3.9 through 3.14 elucidate the relationship between the voltage, current, and flux quantities in each phase of the stator and rotor windings. Figure 3. 4 illustrates the single-phase equivalent steady-state circuit of a DFIG in the frequency domain, with references to the stator side. Thanks to the machine's symmetry, the other two phases are essentially modeled as identical. The assumption is that the machine structure is balanced and magnetization is in the linear region. It's noteworthy that all variables are presented in the phasor ($j\omega$) model and referred to the stator side. In Figure 3. 4, the stator terminal is linked to a grid with constant voltage and magnitude (V_s), while the rotor terminal is connected to the rotor-side converter, which is fed with variable voltage and frequency V_r/s .

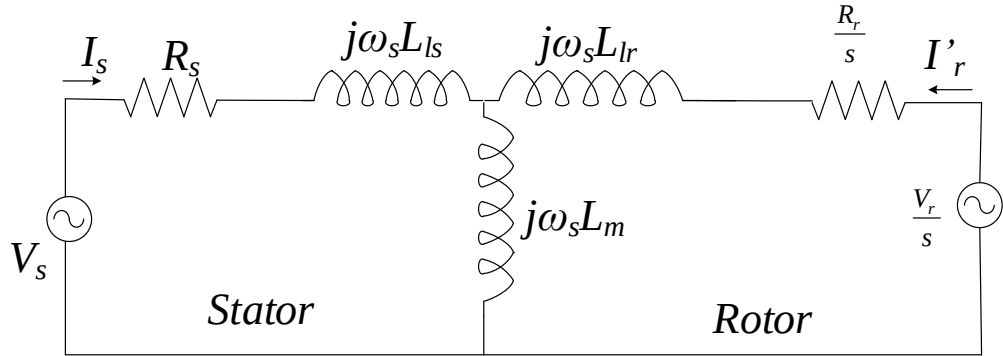


Figure 3. 4 Steady-state equivalent circuit of DFIG referred to stator

R_r are rotor resistor referred to stator side in Ohm (Ω), L_m , L_{ls} , L_{lr} are magnetizing inductance, stator leakage inductance and rotor inductance referred to stator side in Henry (H), respectively. Also, ω_s and s are stator frequency and slip, respectively. The electric equations of stator and rotor voltage and fluxes can be written using KVL on Figure 3. 4 as follows

In this case, R_r represents the rotor resistor referred to the stator side in Ohms (Ω), whereas L_m , L_{ls} , L_{lr} correspond to the magnetizing inductance, stator leakage inductance, and rotor inductance referred to the stator side in Henry (H), respectively. Moreover, ω_s and s denote the stator frequency and slip, respectively. Utilizing Kirchhoff's Voltage Law (KVL) on Figure 3. 4, the electrical equations for stator and rotor voltage, and fluxes can be formulated as follows:

$$V_s = R_s I_s + j\omega_s L_{ls} I_s + j\omega_s L_m (I_s + I_r) \quad 3.15$$

$$\frac{V_r}{s} = \frac{R_r}{s} I_r + j\omega_s L_{ls} I_r + j\omega_s L_m (I_s + I_r) \quad 3.16$$

$$\psi_s = L_m (I_s + I_r) + L_{ls} I_s = L_s I_s + L_m I_r \quad 3.17$$

$$\psi_r = L_m (I_s + I_r) + L_{lr} I_r = L_m I_s + L_r I_r \quad 3.18$$

Here, $L_s = L_m + L_{ls}$ represents the stator inductance, while $L_r = L_m + L_{lr}$ stands for the rotor inductance, referred to the stator side. Deriving from Equations 3.15 through 3.18, we can acquire the power flow in the DFIG under steady-state conditions.

DFIG incorporates three points of power conversion - the stator terminal, rotor terminals, and the rotor shaft. Power at the stator and rotor ports takes the form of both active and reactive power, while mechanical power is converted to active power at the shaft terminal. Power is additionally dissipated in stator and rotor winding resistors and the magnetic core. Utilizing Equations (3.15 through 3.18), the active power from the stator and rotor ports can be acquired by extracting the real parts of the apparent power S ($P = 3\{S\}$):

In this case, the superscript $*$ denotes the complex-conjugate of a space vector. After omitting the imaginary parts of equations (3.19) and (3.20): It is important to note that the identity $\{z^*\} = Im\{z\}$ where z is a member of the complex number set was utilized to simplify the expression. The mechanical power P_m captured by the DFIG can be represented as the total of the stator and rotor power:

3.4.1 Power in the DFIG

DFIG incorporates three points of power conversion - the stator terminal, rotor terminals, and the rotor shaft. Power at the stator and rotor ports takes the form of both active and reactive power, while mechanical power is converted to active power at the shaft terminal. Power is additionally dissipated in stator and rotor winding resistors and the magnetic core. Utilizing Equations (3.15 through 3.18), the active power from the

stator and rotor ports can be acquired by extracting the real parts of the apparent power S ($P = 3\{S\}$):

$$P_s = 3\text{Re}\{V_s I_s^*\} = 3\{R_s |I_s|^2 + j\omega_s L_{ls} |I_s|^2 + j\omega_s L_m (I_s + I_r) \cdot I_s^*\} \quad 3.19$$

$$P_r = 3\text{Re}\{V_r I_r^*\} = 3\{R_r |I_r|^2 + js\omega_r L_{lr} |I_r|^2 + js\omega_s L_m (I_s + I_r) \cdot I_r^*\} \quad 3.20$$

In this case, the superscript * denotes the complex-conjugate of a space vector. After omitting the imaginary parts of equations (3.19) and (3.20):

$$P = 3\text{Re}\{R_s |I_s|^2 + j\omega_s L_m I_r \cdot I_s^*\} = 3R_s |I_s|^2 - 3\omega_s L_m \text{Im}\{I_r \cdot I_s^*\} \quad 3.21$$

$$P_r = 3\text{Re}\{R_r |I_r|^2 + s\omega_s L_m I_s \cdot I_r^*\} = 3R_r |I_r|^2 - 3s\omega_s L_m \text{Im}\{I_s \cdot I_r^*\} \quad 3.22$$

In equations (3.21) and (3.22), the first term on the right-hand side corresponds to the resistive power losses occurring in both the stator and rotor windings. These losses are often considered negligible [5]. As a result, we can simplify equations (3.21) and (3.22) further, yielding the following simplified forms:

$$P_s = -3\omega_s L_m \text{Im}\{I_r \cdot I_s^*\} = -3\omega_s L_m \text{Im}\{I_s \cdot I_r^*\} \quad 3.23$$

$$P_r = -3s\omega_s L_m \text{Im}\{I_s \cdot I_r^*\} \quad 3.24$$

It's important to note that the identity $\{z^*\} = \text{Im}\{z\}$ where z is a member of the complex number set was utilized to simplify the expression. The mechanical power P_m captured by the DFIG can be represented as the sum of the stator and rotor power:

$$\begin{aligned} P_m &= P_s + P_r = 3\omega_s L_m \text{Im}\{I_s \cdot I_r^*\} - 3s\omega_s L_m \text{Im}\{I_s \cdot I_r^*\} \\ &= 3\omega_r L_m \text{Im}\{I_s \cdot I_r^*\} \end{aligned} \quad 3.25$$

3.4.2 Torque in the DFIG

The electromagnetic torque exerted on the machine's shaft, represented by T_e , can be deduced from Equation (3.25), neglecting mechanical power loss:

$$P_m = T_{em} \Omega_r = T_{em} \frac{\omega_r}{p} \quad 3.26$$

In this equation, p stands for pole-pair. Combining equation (3.25) and (3.26) results in:

$$T_{em} = 3L_m p \text{Im}\{I_s \cdot I_r^*\} \quad 3.27$$

The stator's active and reactive power can be derived from mechanical power $P_s \approx P_m / (1 - s)$ and $P_r \approx P_m s / (1 - s)$. Usually, the rotor speed of the DFIG varies from $0.7 \omega_s$ to

$1.3\omega_s$, corresponding to a slip of 30% to -30%. Depending on whether the slip is positive or negative, the rotor circuit can either draw power from or supply power to the grid. In the super-synchronous operation mode $\omega_r > \omega_s$, mechanical power P_m is transmitted from the shaft and delivered to the grid through both stator and rotor circuit ports, as depicted in Figure 3. 5. Disregarding losses in the generator and converters, the power delivered to the grid $|P_g|$ equals the generator's mechanical power $|P_m|$. Figure 3. 6 shows that for positive slip, known as the sub-synchronous operation mode ($\omega_r < \omega_s$), the rotor draws power from the grid.

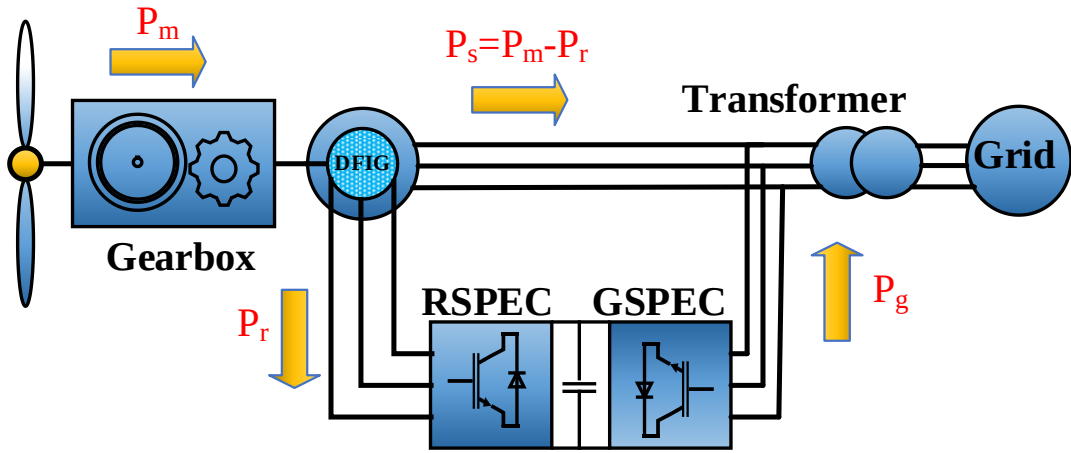


Figure 3. 5 Power flow in a DFIG wind system Super-synchronous mode ($\omega_r > \omega_s$)

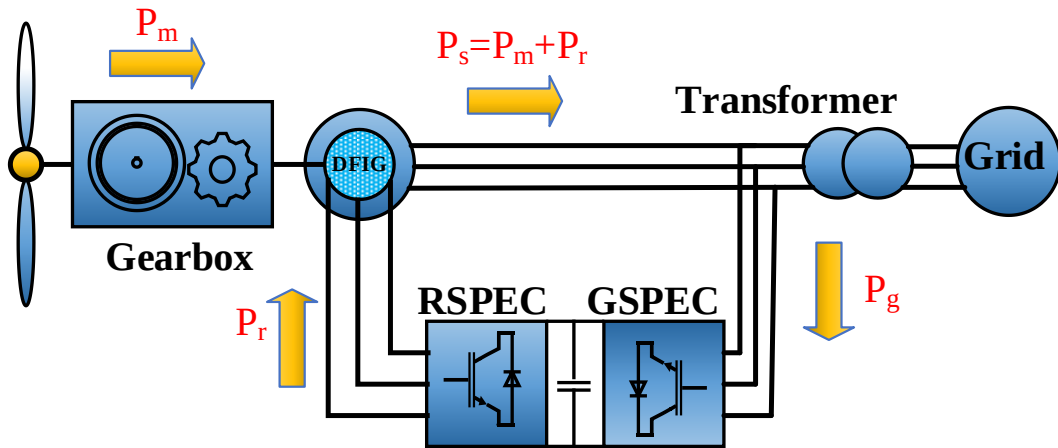


Figure 3. 6 Power flow in a DFIG wind system Sub-synchronous mode ($\omega_r < \omega_s$)

3.5 Dynamic Modelling of DFIG

In the preceding section, we discussed the per-phase steady-state equivalent circuit of the DFIG, with a focus on the steady-state model. However, to achieve a comprehensive understanding of the machine, this knowledge is insufficient. We must explore the dynamic and transient behaviors of the DFIG for accurate modeling and, crucially, for the subsequent development of machine control. These dynamic behaviors outline the machine's variable actions during transition periods and steady states. Normally, this dynamic behavior is investigated via a "dynamic model." This model enables us to continuously monitor the machine's performance (beyond the steady state), including torque, currents, and fluxes, under specific voltage supply conditions. By leveraging the insights provided by the dynamic model, we can anticipate the manner in which state transitions will unfold. This capability empowers us to detect potentially hazardous behaviors, such as instabilities or the occurrence of excessive transient currents. Additionally, during steady-state operation, the dynamic model provides additional system information, such as dynamic oscillations, torque, or current ripples, etc.

Several authors have developed models of AC machines, as discussed at the start of the previous chapter [7], [17], [23], [24], [30], [110], [111]. In the simplified and idealized model of the DFIG, the representation comprises a stator with three windings and a rotor with three windings as shown in Figure 3. 7. The complexity of the dynamic model stems from the rotational relationship between the three-phase rotor windings and the three-phase stator windings. Essentially, the DFIG can be seen as a three-phase transformer with a rotating secondary, where the coupling changes continuously based on the rotor position θ_r .

The relationships between the stator phases, their current conventions, and the angular orientation of different axes are depicted in Figure 3. 7. Additionally, the axis of a rotor phase is offset from the axis of the corresponding stator phase by an angle θ_r . As the rotor rotates at a rate of rad/s, the angle evolves over time, characterized by the expression

$$\theta_r = \omega_r t \quad (3.28)$$

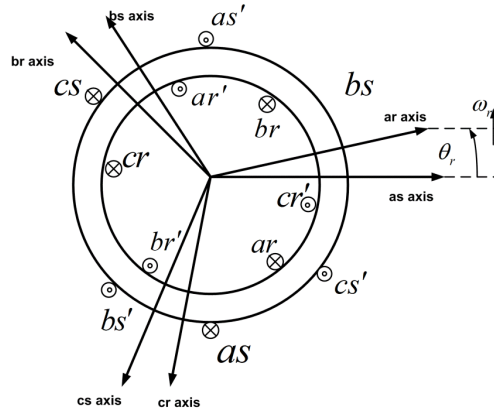


Figure 3. 7 Idealized three phase DFIG

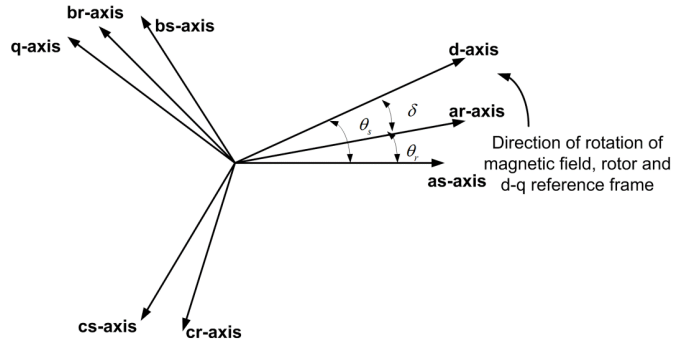


Figure 3. 8 Axes of two pole three phase DFIG

Using the unified circuit approach and motor nomenclature, the voltage equations for the magnetically interlinked stator and rotor circuits, as demonstrated in Figure 3. 8, can be articulated as follows:

$$v_{abcs} = i_{abcs} R_s + \frac{d\psi_{abcs}}{dt} \quad 3. 29$$

$$v_{abcr} = i_{abcr} R_r + \frac{d\psi_{abcr}}{dt} \quad 3. 30$$

In these equations, the 's' and 'r' subscripts refer to the stator and rotor circuits, respectively. Both are diagonal matrices, each containing identical non-zero elements. In a magnetically linear system, the flux linkages are portrayed as -

$$\begin{bmatrix} \psi_{abcs} \\ \psi_{abcr} \end{bmatrix} = \begin{bmatrix} L_s & L_{sr} \\ (L_{sr})^T & L_r \end{bmatrix} \begin{bmatrix} i_{abcs} \\ i_{abcr} \end{bmatrix} \quad 3. 31$$

The winding inductances are obtained through the derivation process, resulting in the following expressions: -

$$L_s = \begin{bmatrix} L_{ls} + L_{ms} & -\frac{1}{2}L_{ms} & -\frac{1}{2}L_{ms} \\ -\frac{1}{2}L_{ms} & L_{ls} + L_{ms} & -\frac{1}{2}L_{ms} \\ -\frac{1}{2}L_{ms} & -\frac{1}{2}L_{ms} & L_{ls} + L_{ms} \end{bmatrix} \quad 3.32$$

$$L_s = \begin{bmatrix} L_{lr} + L_{mr} & -\frac{1}{2}L_{mr} & -\frac{1}{2}L_{mr} \\ -\frac{1}{2}L_{mr} & L_{lr} + L_{mr} & -\frac{1}{2}L_{mr} \\ -\frac{1}{2}L_{mr} & -\frac{1}{2}L_{mr} & L_{lr} + L_{mr} \end{bmatrix} \quad 3.33$$

$$L_{sr} = \begin{bmatrix} \cos\theta_r & \cos\left(\theta_r + \frac{2\pi}{3}\right) & \cos\left(\theta_r - \frac{2\pi}{3}\right) \\ \cos\left(\theta_r - \frac{2\pi}{3}\right) & \cos\theta_r & \cos\left(\theta_r + \frac{2\pi}{3}\right) \\ \cos\left(\theta_r + \frac{2\pi}{3}\right) & \cos\left(\theta_r - \frac{2\pi}{3}\right) & \cos\theta_r \end{bmatrix} \quad 3.34$$

Here L_{ls} , L_{ms} , L_{lr} and L_{mr} denote the leakage and magnetizing inductances of the stator and rotor windings, and L_{sr} signifies the peak mutual inductance between the stator and rotor windings. Since the phase winding geometries, A, B, and C of the stator are stationary, the mutual inductance matrix L_s of the stator winding remains a constant matrix. This also holds true for the mutual inductance matrix L_r of the rotor winding. However, the mutual inductance matrix L_{sr} between the stator and rotor winding varies with the rotor angle θ_r , given that the flux linkage between the stator winding and the rotor winding changes as the angle θ_r fluctuates between the phase-A rotor winding and the phase-A stator winding.

The changes in both the stator flux and the rotor flux with respect to the rotor angle θ_r are apparent. As a result, the DFIG model in the ABC (abc) frame is considered a time-varying system. Analysing its dynamics in the ABC (abc) reference frame typically involves greater complexity.

3.5.1 α - β Model

Within this specific section, we delve into the derivation of the differential equations that encapsulate the DFIG model. To achieve this objective, we employ the space vector representation in the stator's frame of reference. The condition is such that

all three-dimensional space vectors satisfying it can be found on a subset within the three-dimensional space. In fact, this subset takes the form of a plane. Therefore, the three-phase variables can be conveniently represented as a complex vector on the complex plane, often referred to as the " $\alpha - \beta$ " or " abc " plane.

$$\begin{bmatrix} f_{\alpha\beta 0} \end{bmatrix} = \begin{bmatrix} T_{\alpha\beta 0} \end{bmatrix} \begin{bmatrix} f_{abc} \end{bmatrix} \quad 3.35$$

In this context, the variable 'f' can represent various phase-related quantities, such as the phase voltages, currents, or flux linkages of the machine and the transformation matrix $\begin{bmatrix} T_{\alpha\beta 0} \end{bmatrix}$, is given by

$$\begin{bmatrix} T_{\alpha\beta 0} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \sqrt{\frac{3}{2}} & -\sqrt{\frac{3}{2}} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} T_{abc} \end{bmatrix} \quad 3.36$$

Regarding the DFIG, the voltage equations 3.29-3.30 can be transformed into a complex vector equation form, represented as follows:

$$\overrightarrow{v}_s^s = \overrightarrow{i}_s^s R_s + \frac{d\overrightarrow{\psi}_s^s}{dt} \quad 3.37$$

$$\overrightarrow{v}_r^r = \overrightarrow{i}_r^r R_r + \frac{d\overrightarrow{\psi}_r^r}{dt} \quad 3.38$$

Here, $\overrightarrow{v}_s^s$ represents the stator voltage space vector, $\overrightarrow{i}_s^s$ denotes the stator current space vector, and $\overrightarrow{\psi}_s^s$ stands for the stator flux space vector. Equation 3.37 is represented in stator coordinates ($\alpha - \beta$ reference frame). On the other hand, the rotor voltage space vector is indicated by $\overrightarrow{v}_r^r$, the rotor current space vector by $\overrightarrow{i}_r^r$, and the rotor flux space vector by $\overrightarrow{\psi}_r^r$. Equation 3.38 is expressed in rotor coordinates (DQ reference frame). It should be pointed out that the superscripts "s" and "r" signify the reference frames to which the space vectors pertain, specifically the stator and rotor reference frames. Moreover, the correlation between the fluxes and currents, when articulated in space vector notation, can be represented by the ensuing equations:

$$\overrightarrow{\psi}_s^s = \vec{i}_s^s L_s + \vec{i}_r^s L_m \quad 3.39$$

$$\overrightarrow{\psi}_r^r = \vec{i}_r^r L_r + \vec{i}_s^r L_m \quad 3.40$$

Equation (3.39) is articulated in the stator reference frame, whereas Equation (3.40) is articulated in the rotor reference frame. When we take the coordinate transformation into account, the ensuing relationships hold true.

$$\overrightarrow{\psi}_s^s = \vec{i}_s^s L_s + \vec{i}_r^s L_m = \vec{i}_s^s L_s + e^{j\theta_r} \vec{i}_r^r L_m \quad 3.41$$

$$\overrightarrow{\psi}_r^r = \vec{i}_r^r L_r + \vec{i}_s^r L_m = \vec{i}_r^r L_r + e^{j\theta_r} \vec{i}_s^s L_m \quad 3.42$$

As a result, by referencing the associated space vectors to the stator-reference frame (through multiplication of Equation (3.38) by $e^{j\theta_r}$), we derive the $\alpha - \beta$ model of the DFIG via the subsequent equations in stator coordinates:

$$\overrightarrow{v}_s^s = \vec{i}_s^s R_s + \frac{d\overrightarrow{\psi}_s^s}{dt} \quad 3.43$$

$$\overrightarrow{v}_s^s = \vec{i}_r^s R_r + \frac{d\overrightarrow{\psi}_r^s}{dt} - j\omega_m \overrightarrow{\psi}_r^s \quad 3.44$$

$$\overrightarrow{\psi}_s^s = \vec{i}_s^s L_s + \vec{i}_r^s L_m \quad 3.45$$

$$\overrightarrow{\psi}_r^s = \vec{i}_r^s L_r + \vec{i}_s^s L_m \quad 3.46$$

Here, $\overrightarrow{v}_s^s = \overrightarrow{v}_{s\alpha}^s + j\overrightarrow{v}_{s\beta}^s$, and $\overrightarrow{v}_r^s = \overrightarrow{v}_{r\alpha}^s + j\overrightarrow{v}_{r\beta}^s$ represent the stator voltage and rotor voltage, respectively, in the $\alpha - \beta$ reference frame. On the other hand $\vec{i}_s^s = \vec{i}_{s\alpha}^s + j\vec{i}_{s\beta}^s$, $\vec{i}_r^s = \vec{i}_{r\alpha}^s + j\vec{i}_{r\beta}^s$, and $\overrightarrow{\psi}_s^s = \overrightarrow{\psi}_{s\alpha}^s + j\overrightarrow{\psi}_{s\beta}^s$, $\overrightarrow{\psi}_r^s = \overrightarrow{\psi}_{r\alpha}^s + j\overrightarrow{\psi}_{r\beta}^s$ denote the stator current, rotor current, stator flux, and rotor flux, respectively, in the $\alpha - \beta$ reference frame. It is important to note that the flux equations exhibit linearity, with all coefficients remaining constant throughout. The dynamic model in the $\alpha - \beta$ reference frames provides a simpler solution when compared to the ABC model. Equations (3.43) to (3.46) can be used to determine the equivalent circuitry of the dynamic mathematical model in the $\alpha - \beta$ reference frame, and this circuit is illustrated in Figure 3.9.

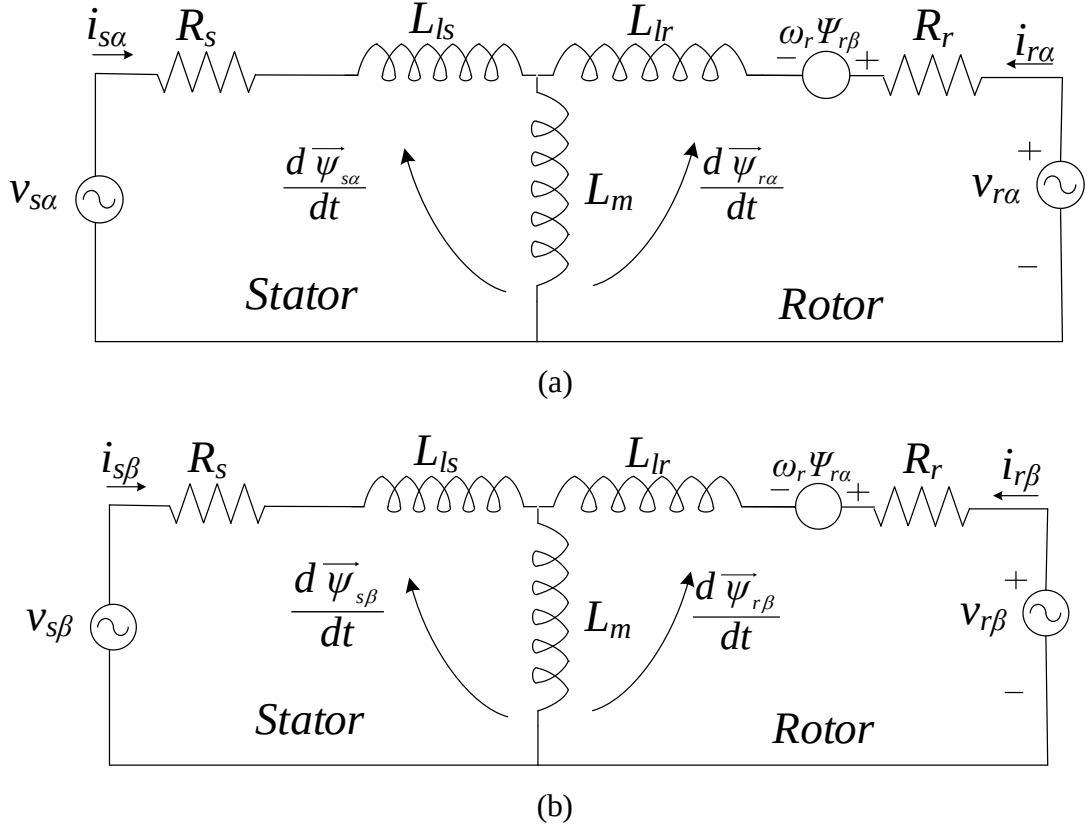


Figure 3. 9 The equivalent dynamic circuit of the DFIG in $\alpha - \beta$ reference frames:

In line with the dynamic model in the reference frame of $\alpha - \beta$, the computation of active and reactive powers for both the stator and rotor sides unfolds as follows:

$$P_s = \frac{3}{2} \text{Re}\{\bar{v}_s \bar{i}_s^*\} = \frac{3}{2} (v_{sa} i_{sa} + v_{sb} i_{sb}) \quad 3.47$$

$$P_r = \frac{3}{2} \text{Re}\{\bar{v}_r \bar{i}_r^*\} = \frac{3}{2} (v_{ra} i_{ra} + v_{rb} i_{rb}) \quad 3.48$$

$$Q_s = \frac{3}{2} \text{Im}\{\bar{v}_s \bar{i}_s^*\} = \frac{3}{2} (v_{sb} i_{sa} - v_{sa} i_{sb}) \quad 3.49$$

$$Q_r = \frac{3}{2} \text{Im}\{\bar{v}_r \bar{i}_r^*\} = \frac{3}{2} (v_{rb} i_{ra} - v_{ra} i_{rb}) \quad 3.50$$

In this context, the superscript $*$ symbolizes the complex conjugate of a space vector, which finds application in phasors. Ultimately, the determination of the electromagnetic torque can be achieved through:

$$T_{em} = \frac{3}{2} p \text{Im}\{\vec{\psi}_r \vec{i}_r^*\} = \frac{3}{2} p (\psi_{r\beta} i_{ra} - \psi_{ra} i_{r\beta}) \quad 3.51$$

Upon substituting Equations (3.45) and (3.46) into (3.51), alternative expressions emerge to facilitate the calculation of the electromagnetic torque:

$$T_{em} = \frac{3}{2} p \text{Im}\{\vec{\psi}_s \vec{i}_s^*\} = \frac{3}{2} p \frac{L_m}{L_s} \text{Im}\{\vec{\psi}_s \vec{i}_r^*\} \quad 3.52$$

3.5.2 dq Model

By incorporating a set of equations ranging from (3.43) to (3.51), the dynamic model of the DFIG undergoes a simplification when the reference frame is introduced. Assuming a constant value for ω_r , these equations exhibit linearity. Nevertheless, electrical variables associated with the DFIG, such as voltage, current, and flux in the $\alpha - \beta$ reference frame, retain their alternating current (AC) nature even in steady-state conditions. In the case of a balanced three-phase system, when we examine its complex vectors from a rotating reference frame, we can simplify them as steady vectors with their axis components representing direct current (DC) values. Considering that analyzing or designing the control of a DC system is notably simpler compared to an AC system, it becomes intuitive to convert the system with three phases into the rotating reference framework, commonly known as the dq rotating reference frame[112].

Now, let us introduce yet another frame of reference, namely the dq reference frame, that rotates with an angular frequency ω_s . The connection between the $\alpha - \beta$ reference frame and the dq reference frame can be established using a transformation called the Park transformation. This transformation can be mathematically represented as follows:

$$\begin{bmatrix} f_q \\ f_d \\ f_o \end{bmatrix} = [T_{qdo}(\theta_s)] \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \quad 3.53$$

In the given equation, the variable 'f' can represent various phase-related quantities, such as the phase voltages, currents, or flux linkages of the machine and the transformation matrix $[T_{dq0}]$, is given by

$$\left[T_{dq0}(\theta_s) \right] = \frac{2}{3} \begin{bmatrix} \cos\theta_s & \cos\left(\theta_s - \frac{2\pi}{3}\right) & \cos\left(\theta_s + \frac{2\pi}{3}\right) \\ -\sin\theta_s & -\sin\left(\theta_s - \frac{2\pi}{3}\right) & -\sin\left(\theta_s + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad 3.54$$

By implementing the dq rotating transformation in the case of the DFIG, Through simplification the derivation of the simplified dq model of the DFIG.

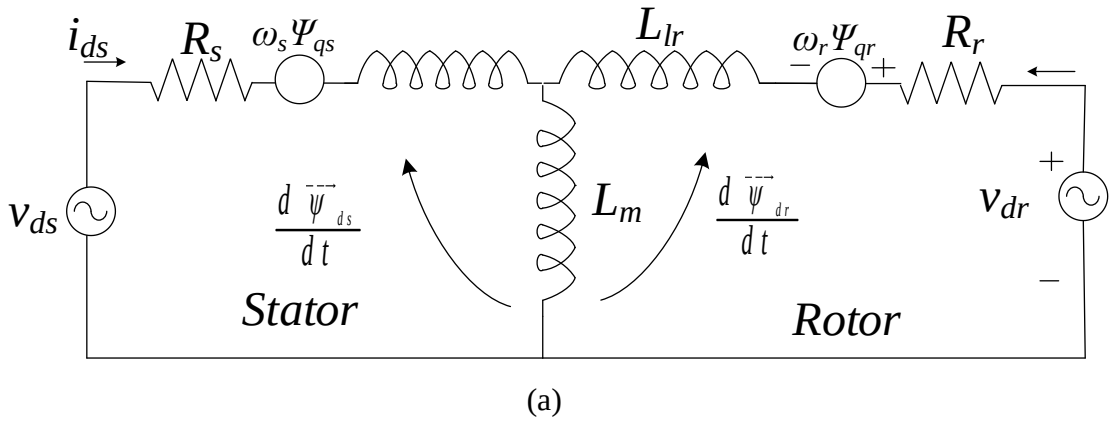
$$\vec{v}_s^a = \vec{i}_s^a R_s + \frac{d\vec{\psi}_s^a}{dt} + j\omega_s \vec{\psi}_s^a \quad 3.55$$

$$\vec{v}_r^a = \vec{i}_r^a R_r + \frac{d\vec{\psi}_r^a}{dt} + j(\omega_s - \omega_r) \vec{\psi}_r^a \quad 3.56$$

$$\vec{\psi}_s^a = \vec{i}_s^a L_s + \vec{i}_r^a L_m \quad 3.57$$

$$\vec{\psi}_r^a = \vec{i}_r^a L_r + \vec{i}_s^a L_m \quad 3.58$$

Within the scope of this discussion, the superscript "a" is representative of the space vectors that are associated with a frame that rotates synchronously. In the presence of sinusoidal voltage supply and under steady-state conditions, the dq components of voltages, fluxes, and currents remain constant, unlike the sinusoidal variations of the ab components. Hence, the dq circuit equivalent framework of the DFIG, when viewed in synchronous coordinates, is illustrated in Figure 3. 10.



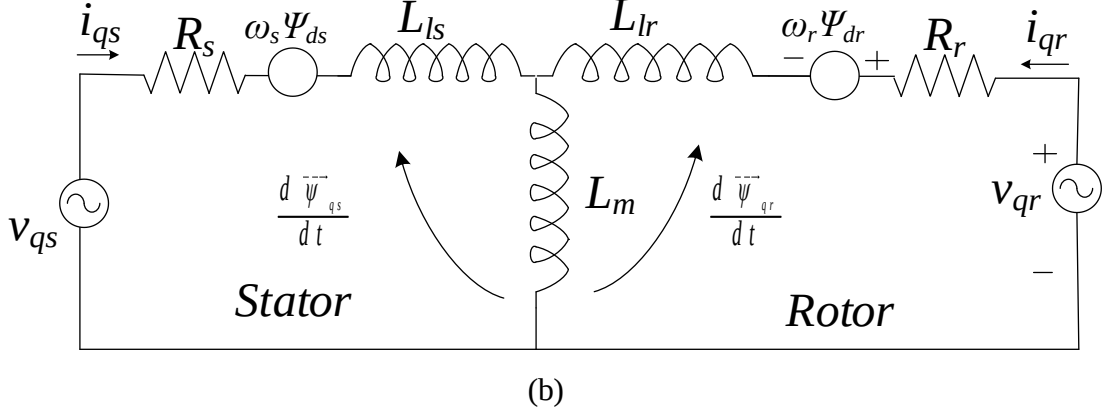


Figure 3. 10 dq Model of the DFIG in synchronous coordinate

The formulations for torque and power in the dq reference frame correspond to the $\alpha - \beta$ equations derived in the reference frame.

$$P_s = \frac{3}{2} \text{Re}\{\overline{v_s} \vec{i}_s^*\} = \frac{3}{2} (v_{ds} i_{ds} + v_{qs} i_{qs}) \quad 3.59$$

$$P_r = \frac{3}{2} \text{Re}\{\overline{v_r} \vec{i}_r^*\} = \frac{3}{2} (v_{dr} i_{dr} + v_{qr} i_{qr}) \quad 3.60$$

$$Q_s = \frac{3}{2} \text{Im}\{\overline{v_s} \vec{i}_s^*\} = \frac{3}{2} (v_{qs} i_{ds} - v_{ds} i_{qs}) \quad 3.61$$

$$Q_r = \frac{3}{2} \text{Im}\{\overline{v_r} \vec{i}_r^*\} = \frac{3}{2} (v_{qr} i_{dr} - v_{dr} i_{qr}) \quad 3.62$$

Hence, the expression for torque can also be derived accordingly.

$$T_{em} = \frac{3}{2} p \text{Im}\{\overline{\psi_r} \vec{i}_r^*\} = \frac{3}{2} p (\psi_{qr} i_{dr} - \psi_{dr} i_{qr}) \quad 3.63$$

3.6 CONTROL OF DFIG POWER CONVERTERS

In a DFIG-based WECS, the converters play a crucial role in achieving efficient power conversion. Initially, the thesis provides a comprehensive understanding of the back-to-back converter, which forms the backbone of the system. Once the fundamentals of the BTB converter are established, the focus shifts to the DFIG and its control strategies, with a specific emphasis on wind energy generation. The subject of this paper provides a description of the traditional and widely utilised two-level voltage source converter (2L-VSC), as well as a model analysis of it. However, as the power capacity and voltage requirements of wind turbines increase, the limitations of the two-level

converter become more apparent. To overcome these limitations and enable higher power handling, the study explores newer topologies, including multilevel converters. These advanced topologies offer numerous benefits, such as increased power and voltage handling capabilities, allowing wind turbines to generate power in the multimewatt range. Special attention is given to the most widely used multilevel topology—the three-level neutral point clamped (3L-NPC) VSC. By utilizing multiple voltage levels, these converters provide better waveform quality, reduced harmonics, and improved power quality for grid integration. The control strategies for the RSPEC and the GSPEC discussed in subsequent chapters, highlighting their role in controlling the DFIG. As WECSs continue to evolve, the use of multilevel inverters will likely become more prevalent, facilitating the efficient and reliable integration of wind power into the electrical grid [113].

This section outlines the significant facets of a BTB converter, primarily focused on the commonly implemented 2L-VSC. A BTB converter is composed of a RSPEC and a GSPEC, separated by a DC-link capacitor. The primary aim of the GSPEC is to minimize fluctuations in the DC-link voltage. Through controlling the generator-side converter, the torque and speed of a DFIG can be regulated, along with its real and reactive power at the stator terminals. This thesis leverages both the 2L-VSC and the 3L-Neutral Point Clamped (NPC) inverter, due to their widespread use as RSPECs and GSPECs in the WECS industry. The modelling of the 2L-VSC was undertaken first, followed by the 3L-NPC VSC.

3.6.1 Model of the 2L-VSI

A 3-phase 2-level Voltage Source Converter (VSC) serves as a critical component in various power electronic applications, including renewable energy systems, adjustable speed drives, and more. These converters facilitate the conversion of a DC voltage into a three-phase AC voltage output with controllable magnitude, frequency, and phase. A common practice in these converters is the use of Insulated-Gate Bipolar Transistors (IGBTs) as switching devices due to their ability to handle high voltages and currents, as well as their superior switching speeds. A 3-phase 2-level VSC generally comprises of six IGBTs, each paired with a diode, arranged in a 3-phase full-bridge topology. Figure 2.2 illustrates a simplified model of a three-phase power converter. In the setup where the grid is connected, energy transitions from the DC link over to the AC aspect of the converter, a phenomenon similar to what is typically seen in a passive load. Conversely,

in the instance of the generator, energy moves from the AC part of the converter to the DC link, showcasing a reversed direction when juxtaposed with a passive load. The IGBTs can be controlled to switch between two states: ON (conducting) and OFF (non-conducting). When an IGBT is ON, it behaves as a short circuit, allowing current to flow, whereas when it's OFF, it acts as an open circuit, blocking current flow.

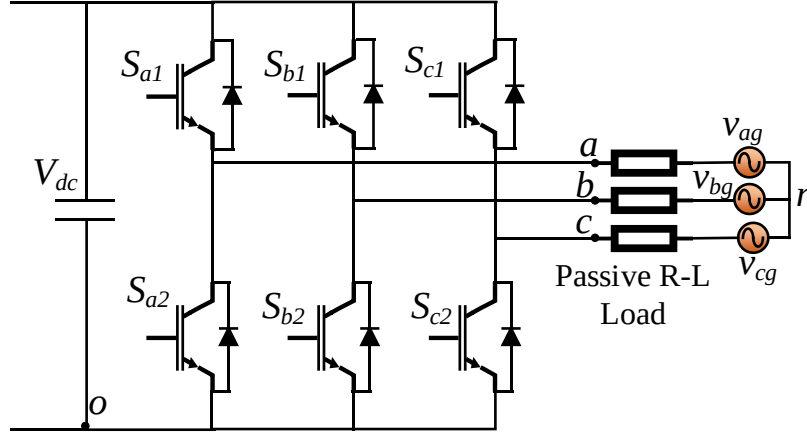


Figure 3. 11 Power circuit of three-phase 2L-VSI.

To model the 3-phase 2-level VSC, we can represent it using a set of state-space equations or transfer functions. The state of each IGBT switch, either 1 (ON) or 0 (OFF), is dictated by the control signal fed to its gate terminal. In each phase leg of the converter, two IGBTs (S_{x1} and S_{x2}) are switched in a complementary fashion (i.e., when S_{x1} is ON, S_{x2} is OFF, and vice versa). The switch signals then yield that $S_{x2} = \overline{S_{x1}}$. This property is extended to all three phases as $S_{x1} + S_{x2} = 1$ for all $x \in a, b, c$

Each phase's output voltage (V_a , V_b , and V_c for phases a, b, and c, respectively) can be formulated as:

$$\begin{aligned} V_a &= V_{dc} * S_{a1} \\ V_b &= V_{dc} * S_{b1} \\ V_c &= V_{dc} * S_{c1} \end{aligned}$$

Here, V_{dc} represents the DC link voltage, and S_{a1} , S_{b1} , and S_{c1} are the switching states of the upper IGBTs in each phase leg. The lower switches' states are simply the complementary of the upper ones. Thus, by different combinations of S_{a1} , S_{b1} , and S_{c1} . It is possible to create AC output voltages with a fundamental component of different amplitude and frequency. As depicted in Figure 2.3, this converter provides two possible voltage levels at each phase. The creation of AC output voltages with varying amplitude

and frequency is feasible. As illustrated in 3. 12, this converter offers two potential voltage levels for each phase.

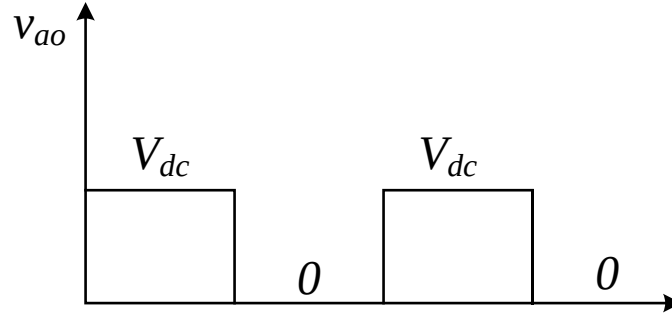


Figure 3. 12 Two voltage levels of v_{ao}

On a separate note, for modelling reasons, it is beneficial to understand the converter output voltages with reference to the neutral point (n) of the grid's three-phase system.

$$v_{xn} = v_{xo} - v_{no} \text{ with } x=a, b, c \quad 3. 64$$

The voltage between the neutral point (n) and the negative point of the DC bus (o) is required, so given a three-phase grid system that maintains, we can deduce

$$v_{an} + v_{bn} + v_{cn} = 0 \quad 3. 65$$

By substituting expression (3. 65) into the last expression, we obtain

$$v_{no} = \frac{1}{3}(v_{ao} + v_{bo} + v_{co}) \quad 3. 66$$

Inserting this last expression into Equation (3. 64) again, we finally get

$$v_{an} = \frac{2}{3}v_{ao} - \frac{1}{3}(v_{bo} + v_{co}) \quad 3. 67$$

$$v_{bn} = \frac{2}{3}v_{bo} - \frac{1}{3}(v_{ao} + v_{co}) \quad 3. 68$$

$$v_{cn} = \frac{2}{3}v_{co} - \frac{1}{3}(v_{bo} + v_{ao}) \quad 3. 69$$

Alternatively, straight from the order commands, we could write

$$v_{an} = \frac{V_{dc}}{3}(2S_a - S_b - S_c) \quad 3. 70$$

$$v_{bn} = \frac{V_{dc}}{3}(2S_b - S_a - S_c) \quad 3. 71$$

$$v_{cn} = \frac{V_{dc}}{3}(2S_c - S_b - S_a) \quad 3. 72$$

Eight potential output voltage combinations exist, matching the eight permissible state of switching of S_a , S_b , and S_c . Table 3.1 provides an overview of all of these different voltage arrangements. As indicated previously, the results are output voltages v_{ao} , v_{bo} , and v_{co} and utilise only two distinct voltage stages: V_{dc} and 0. This is the reason this converter is referred to as a "two-level converter." Matrix notation is employed to formulate the abc-frame Continuous time (CT) dynamic mathematical model of load current, specifically for a RL passive load. The formulation is expressed as follows:

$$\begin{bmatrix} v_{an}(t) \\ v_{bn}(t) \\ v_{cn}(t) \end{bmatrix} = \frac{2}{3} \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{bmatrix} + \begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{bmatrix} \quad 3.73$$

This expression can be further simplified as

$$v(t) = i(t)R + L \frac{di(t)}{dt} \quad 3.74$$

By applying the appropriate transformation matrices, the abc-frame model depicted in equation (

3. 73) can be converted into both $\alpha - \beta$ - and dq-frames.

Table 3. 1 Different Output Voltage Combinations of 2L-VSC

S_a	S_b	S_c	v_{ao}	v_{bo}	v_{co}	v_{an}	v_{bn}	v_{cn}
0	0	0	0	0	0	0	0	0
0	0	1	0	0	V_{dc}	$-\frac{V_{dc}}{3}$	$-\frac{V_{dc}}{3}$	$2\frac{V_{dc}}{3}$
0	1	0	0	V_{dc}	0	$-\frac{V_{dc}}{3}$	$2\frac{V_{dc}}{3}$	$-\frac{V_{dc}}{3}$
0	1	1	0	V_{dc}	V_{dc}	$-2\frac{V_{dc}}{3}$	$\frac{V_{dc}}{3}$	$\frac{V_{dc}}{3}$
1	0	0	V_{dc}	0	0	$2\frac{V_{dc}}{3}$	$-\frac{V_{dc}}{3}$	$-\frac{V_{dc}}{3}$
1	0	1	V_{dc}	0	V_{dc}	$\frac{V_{dc}}{3}$	$-2\frac{V_{dc}}{3}$	$\frac{V_{dc}}{3}$
1	1	0	V_{dc}	V_{dc}	0	$\frac{V_{dc}}{3}$	$\frac{V_{dc}}{3}$	$-2\frac{V_{dc}}{3}$
1	1	1	V_{dc}	V_{dc}	V_{dc}	0	0	0

3.7 MULTILEVEL VSC TOPOLOGIES

The evolution of power electronic technologies has paved the way for the development of Multi-Level Voltage Source Converters (MLVSCs), a type of VSC. MLVSCs are composed of Insulated Gate Bipolar Transistor (IGBT) switches, known for their high efficiency and fast switching characteristics. The inherent structure of MLVSCs allows for the synthesis of output voltages with better harmonic content and lower voltage stresses on the power devices.

The superiority of MLVSCs using IGBT switches in DFIG-based WECSs is becoming increasingly apparent. They facilitate better power control, have higher power capability, lower total harmonic distortion, and superior fault-tolerant capabilities, making them a highly effective solution for wind power conversion. While the 3L-NPC VSC remains the most prevalent topology, alternatives are gradually surfacing, including the FC (flying capacitor), cascaded H bridge, SMC (stacked multicell), and MMC (modular multilevel converter). These differing topologies are each designed to enhance various converter attributes, allowing for their application in diverse conditions. Consequently, this section introduces several multilevel VSC topologies best suited for DFIM-based wind turbines. However, a detailed exploration will be focused on the 3L-NPC VSC topology only.

Emerging MLVSCs topologies, apt for the back-to-back converter of a DFIG-based wind turbine, can be identified. Such topologies effectively enable the enhancement of operating voltages and powers with existing semiconductors, merely by augmenting the levels of the converter thereby circumventing the need for isolating transformers while preserving their power reversibility capability. However, as previously stated, this section is dedicated to an in-depth exploration of a predominantly employed multilevel topology: the 3L-NPC MLVSCs.

3.7.1 Model of Three-Level Neutral Point Clamped VSC Topology (3L-NPC)

The 3L-NPC VSC topology is a derivative of the classic two-level VSC, but with a notable distinction: it has three output voltage levels. These are typically positive, zero, and negative DC bus voltages. The structure of a 3L-NPC consists of four IGBTs and two diodes in each phase leg, clamped to the neutral point. This configuration allows for the clamping of the DC-link midpoint voltage, which results in a better voltage balance across the DC-link capacitors and reduces the voltage stress on the switches.

In the 3L-NPC VSC, the IGBTs work in pairs to control the flow of power, with each pair being responsible for one of the three output voltage levels. Figure 3. 13 displays a single-phase leg of a three-level diode-clamped inverter.

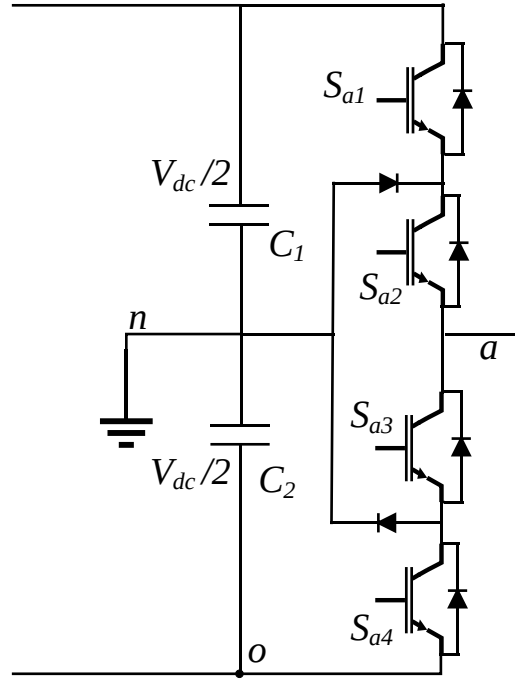


Figure 3. 13 Single phase leg of a 3L-NPC VSC

Within this circuit, the DC-bus voltage is divided into three levels through the use of two capacitors, C_1 and C_2 , which are connected in series. The neutral point, identified as "n," is located at the midpoint between the two capacitors. The output voltage V_{an} has three states: $\frac{V_{dc}}{2}$, 0 and $-\frac{V_{dc}}{2}$. Voltage level $\frac{V_{dc}}{2}$ requires turning on switches S_{a1} and S_{a2} while, for $-\frac{V_{dc}}{2}$, switches S_{a3} and S_{a4} need to be turned on, and for the 0 -voltage level, S_{a2} and S_{a4} need to be turned on.

The key components that distinguish this circuit from a conventional two-level inverter are D_1 and D_2 . These two diodes clamp the switch voltage to half the level of the DC-bus voltage. When both S_{a1} and S_{a2} are turned on, the voltage across 'a' and 'o' is V_{dc} , i.e., $V_{a0} = V_{dc}$. In this case, D_2 balances out the voltage sharing between S_{a3} and S_{a4} with S_{a3} blocking the voltage across C_1 and S_{a4} blocking the voltage across C_2 . Notice that the output voltage V_{an} is AC, and V_{a0} is DC. The difference between V_{an} and V_{a0} is the voltage across C_2 , which is $\frac{V_{dc}}{2}$. The three valid modes for phase leg of three-level

inverter are described schematically in Figure 3. 14. The switching sequence for obtaining output voltage levels is illustrated in Table 3. 2

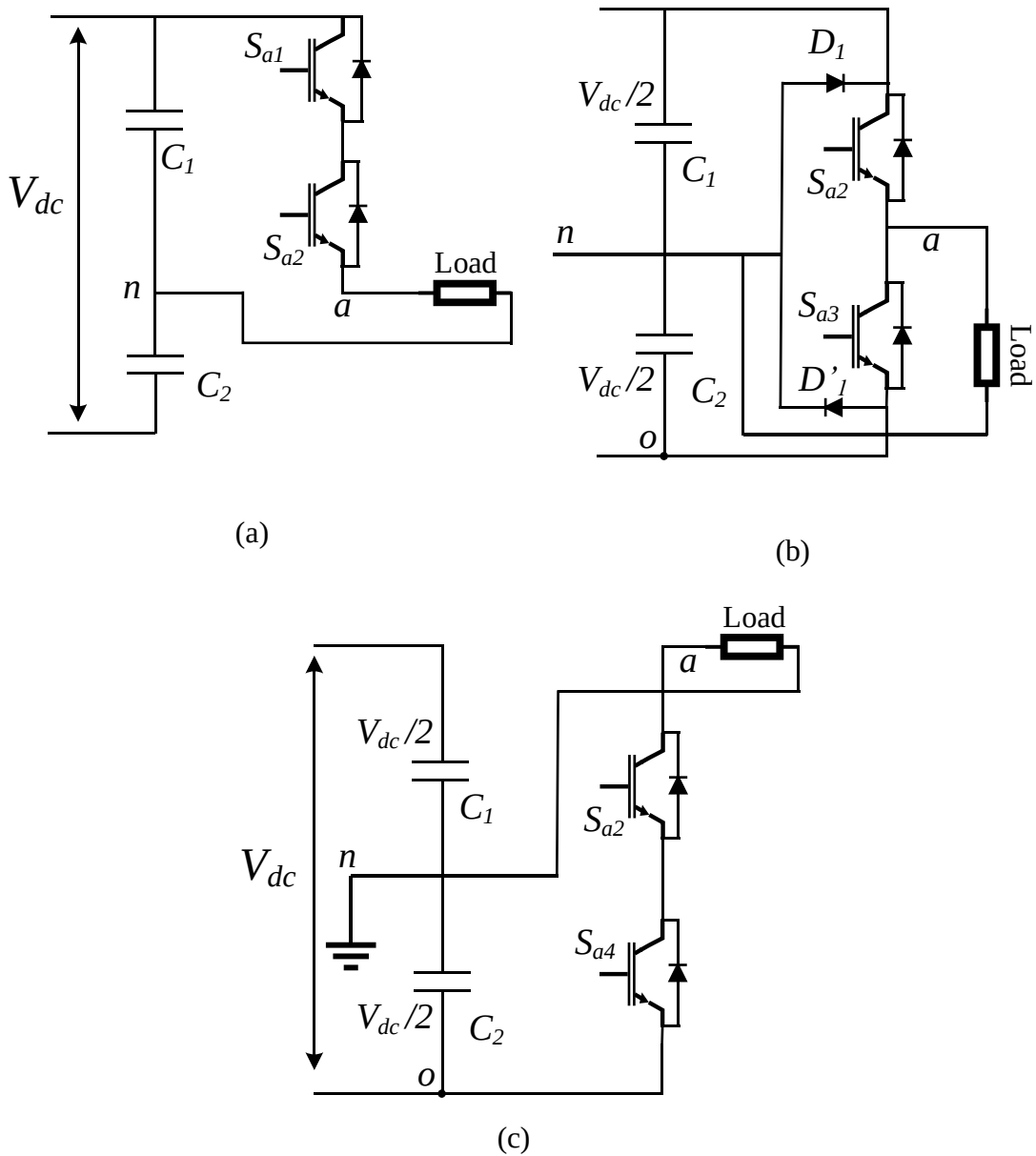


Figure 3. 14 Operating modes of 3L-NPC VSC

Table 3. 2 Switching sequence for one phase leg of an inverter

Output Voltage	S_1	S_2	S'_1	S'_2
$\frac{V_{dc}}{2}$	1	1	0	0
0	0	1	1	0
$-\frac{V_{dc}}{2}$	0	0	1	1

3.8 Conclusion

In conclusion, the "Modelling of DFIG based WECS" chapter has provided a thorough and detailed investigation of the mathematical models used to describe the dynamic behavior and performance characteristics of DFIG-based wind power systems. The comprehensive analysis presented here sheds light on the intricate relationships between variables in the DFIG power network, offering valuable insights into both steady-state and transient conditions. The significance of understanding these models cannot be overstated, as they serve as the foundation for effective control design in subsequent chapters. By accurately depicting the static and dynamic behavior of DFIGs and power converters, these models enable us to develop precise and efficient control strategies for wind power systems.

As renewable energy sources, particularly wind energy, play an increasingly crucial role in meeting global energy demands while minimizing environmental impact, the need for reliable and effective control methods becomes paramount. The rigorous exploration of DFIG-based wind power system models in this chapter equips researchers and engineers with the necessary tools to optimize and enhance the performance of wind energy systems. Furthermore, the knowledge gained from this chapter will aid in the development of advanced control techniques that can address various operational challenges faced by wind power systems, such as grid integration, stability, and fault management.

CHAPTER 4. FRT METHODS FOR DFIG BASED WECS

4.1 Introduction

WECSs have emerged as a critical participant in the renewable energy scene as the globe grapples with the pressing need to move to sustainable energy sources. With technological advancements and greater adoption, the necessity to maintain grid stability and reliability in the face of wind energy's intermittent and unpredictable nature has grown critical. This needs an extensive investigation of fault management systems, particularly FRT approaches for wind turbines using DFIG.

This chapter, entitled "FRT Methods for DFIG Based Wind Energy Systems," provides a comprehensive exploration of the topic. It is intended to shed light on the function and significance of FRT approaches in preserving grid stability and enhancing the overall reliability of wind energy systems. These methods become even more critical when the wind turbines are based on DFIGs, given their sensitivity to grid disturbances.

This first section provides an overview of the existing grid code requirements for WECSs, illuminating the grid integration restrictions and their effects on wind energy system design and operation. Grid codes specify the technical and operational requirements that a WECS must meet in order to be linked to the power grid and stay operational during grid outages. Understanding these standards provides us with a clear picture of the required FRT capabilities of wind turbines, particularly those using DFIG technology.

Following the grid code requirements, the chapter explores into a comprehensive description of various FRT schemes created and used in DFIG-based wind energy systems. These schemes play an important role in increasing the system's resilience to various fault scenarios, maintaining uninterrupted supply of electric power and limiting the potential damage that faults may impose on wind turbine generators. The chapter seeks to provide a full overview of the existing FRT solutions and their significance in maintaining grid stability by studying several FRT approaches, their operating principles, and their effectiveness under various fault scenarios.

The effective deployment and application of FRT technologies for DFIG-based wind turbines while adhering to grid code requirements is a critical step towards guaranteeing a stable and efficient renewable energy future. As we proceed through this

chapter, the important interlinkages that exist between grid code mandates, the conversion of wind energy, and FRT procedures will become clearly evident, thereby adding additional dimensions to our understanding of sustainable power systems.

Subsequent to the in-depth examination of grid codes and existing FRT schemes, this chapter introduces a novel fault mitigation approach based on fuzzy logic for DFIG-based wind energy systems. Recognizing the need for enhanced fault management strategies, we have proposed a modified protection scheme leveraging the adaptive and robust nature of fuzzy logic systems. The presented scheme aims to improve the FRT capabilities of DFIG-fed wind energy systems under various symmetrical and unsymmetrical fault scenarios.

The performance and efficiency of this proposed protection scheme are validated through extensive simulations. The MATLAB/Simulink environment is our primary tool for designing and testing this FRT method based on fuzzy logic. In addition, the chapter provides specifics regarding our extensive validation strategy in the real-time simulator OPAL-RT. This method contributes to the achievement of an even greater degree of precision and validates the scheme's robustness in conditions that are comparable to those seen in the real world. This extensive validation process, which includes virtual simulations as well as real-time emulations, is intended to ensure that the proposed FRT scheme can effectively manage diverse fault scenarios while adhering to grid code requirements, thereby improving the reliability and resilience of DFIG-based wind energy systems.

4.2 Grid Code Requirements for WECSs

Grid codes, also known as network codes or grid rules, are a collection of technical principles and requirements that power generating units are required to follow to in order to have a successful and safe connection to the electrical grid. Grid codes are also sometimes referred to as grid regulations. These regulations, which have been formulated by regulatory bodies, are aimed at ensuring the stability, dependability, and safety of the electricity system even under unusual or fault-prone circumstances. Grid codes, among other things, set criteria pertaining to power quality, fault management, frequency response, and voltage control.

Grid codes were traditionally created with a focus on large, centralised thermal or hydroelectric power plants, which are conventional power plants. Typically, synchronous

generators were used in these units because they naturally have strong FRT characteristics and may offer ancillary services like reactive power support. As a consequence of this, the requirements of the early grid codes were relatively simple and uncomplicated.

However, the global shift towards renewable energy sources in the late 20th century, particularly wind and solar power, led to a significant paradigm shift in power generation and distribution. Despite being essential for sustainability, these renewable energy sources presented additional difficulties because of their erratic nature and diverse technological foundations, particularly when it came to preserving the stability and security of the grid. Early models of WECSs were unable to handle disturbances properly or provide adequate ancillary services, resulting in disconnections during grid failures, which increased grid instability. Recognising the problem, grid operators and regulatory authorities all over the world began to modify and expand grid code standards to include WECSs, resulting in the contemporary, far more extensive grid codes we see today.

Modern grid codes impose rigorous requirements on WECSs to ensure they can contribute positively to grid stability and reliability. For instance, the FRT capability, which requires WECSs to stay connected and operational during and after grid faults, is a key grid code requirement in many countries. This is crucial to prevent the simultaneous disconnection of a large number of wind turbines during faults, which could lead to blackouts. Some specific criteria have been dictated by the grid code for overcoming the above scenario, known as FRT systems. These include high-voltage ride-through (HVRT), low-voltage ride-through (LVRT), and zero-voltage ride-through (ZVRT). The specifications in the LVRT and ZVRT are generally similar, with grid faults resulting in the voltage of the grid being zero in the ZVRT profile and the voltage of the grid in the LVRT profile being 15–25% of the nominal value. Other essential grid code requirements include reactive power provision, frequency response, and voltage control. Reactive power provision and voltage control ensure that WECSs can maintain the grid voltage within acceptable limits under different operating conditions. Frequency response, on the other hand, necessitates that WECSs contribute to system frequency regulation, particularly during large frequency deviations.

Table 4. 1 International standards governing the grid integration of wind power plants and their Fault Ride Through (FRT) capabilities

Standardized Code	Standard description
IEEE 1547	It provides guidelines for the design, testing, and operation of microgrid control systems. It outlines the requirements for microgrid control, including the necessary features and functions for safe and reliable operation of the microgrid. It also provides recommendations for the integration of distributed energy resources (DERs) and energy storage systems (ESSs) into microgrids, as well as guidelines for the testing and certification of microgrid control systems
IEEE 1688-2014	It is a recommended practice standard for conducting voltage-sag ride-through performance and compliance testing for electrical and electronic equipment that is connected to low-voltage power systems.
IEC-61000	The goal of these standards is to ensure that equipment and systems can operate reliably and without interference in the presence of electromagnetic disturbances.
IEC 61400-21	It checks how well wind turbines are connected to the power grid by measuring and evaluating the quality of power
IEC 61400-27	defines the information models and communication protocols for monitoring and controlling wind turbines.
IEC 61508	The standard provides a framework for assessing and managing safety risks associated with these systems throughout their entire lifecycle.
IEC 61400-21	It is intended to provide a common basis for assessing the power performance of wind turbines and facilitating comparison of results across different wind turbine types and sites.
ANSI/IEEE 1021-1988	It can be applied to wind turbine software development and verification and validation (V&V) activities.

	The standard can be used to ensure the quality, reliability, and safety of wind turbine software, which is critical for the operation and maintenance of wind turbines.
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Several worldwide standards for grid codes for WECSs have been established. These include International Electrotechnical Commission (IEC) standards such as IEC 61400-21, which outlines the technique for determining a wind turbine's electrical characteristics, including FRT capabilities, voltage and frequency regulation, and harmonics. Furthermore, regional standards, such as the European Network of Transmission System Operators for Electricity (ENTSO-E) in Europe and the Federal Energy Regulatory Commission (FERC) in the United States, have set thorough grid code requirements for WECSs. As our knowledge of wind energy systems and the difficulties that they provide to grid stability continues to expand, these standards are continuously being updated to reflect the latest developments. A comparison of different standards used for wind power plant grid integration and the FRT capability of wind systems is presented in Table 4. 2.

In accordance with the unique requirements of their respective communities, Transmission system operators (TSOs) and Distribution system operators (DSOs) from different countries have implemented specific FRT regulations. TSOs are obligated to implement either Low Voltage Ride Through (LVRT) or Zero Voltage Ride Through (ZVRT) operations due to the significant penetration of Renewable Energy (REN) sources. Furthermore, TSOs are compelled to enhance their LVRT capabilities due to the absence of essential equipment such as Automatic Voltage Regulators (AVR).

In 2003, the German transmission and distribution utility, E. ON, introduced regulations that have since been adopted as a standard. The requirements of both ZVRT and LVRT, as outlined in these E. ON regulations, are illustrated in Figure 4. 3. Instead of tripping off during transmission faults, E. ON's directive states that wind turbine generators should remain operational or "ride through." This FRT function is expected to kick in as soon as the grid voltage drops below 90% of the rated value. The regulations also stipulate that wind turbine generators should connect to the grid when the voltage lies above the ZVRT limit and below the High Voltage Ride Through (HVRT) limit. Conversely, generators should be disconnected from the grid if the voltage falls below the ZVRT or exceeds the HVRT limit, as advised by the utility operator. Furthermore,

should the voltage fail to restore to 90% of its rated value post the recovery period of 1500 ms, disconnection of the wind turbine generators is mandated[6][114].

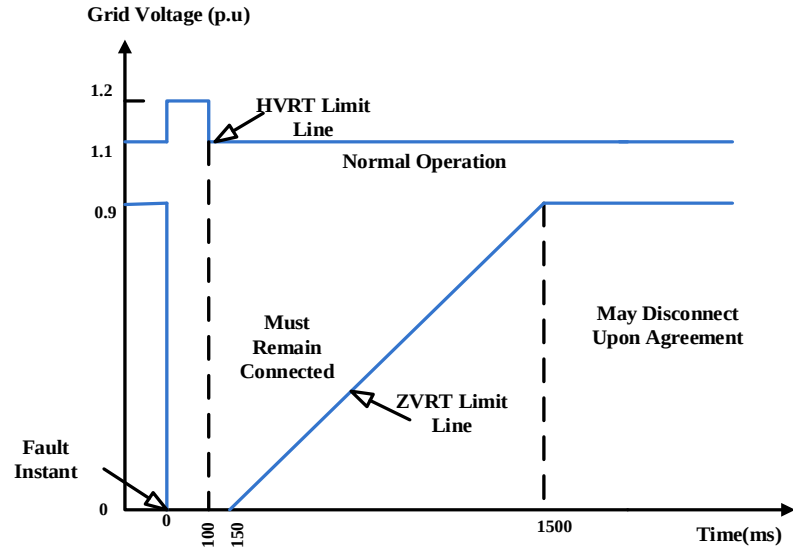


Figure 4. 3 Requirements for Voltage ride-through in accordance with the E. ON regulation

Across different countries and regions, the grid code specifications exhibit variability, with each system having its own set of requirements. These variations in technical specifications and restrictions outlined in the International Grid Codes (GCs) have a direct impact on both the level of wind energy penetration and the overall resilience of the grid [115]. The relevant details pertaining to frequency, Low Voltage Ride Through (LVRT), High Voltage Ride Through (HVRT), and power factor limits are presented in Table 4. 3, which encompasses multiple nations and encompasses both fault and post-fault scenarios[116].

Table 4. 3 Comprehensive analysis of Grid Codes in various nations.

Country	F (hz)	Frequency limits	Max. Time duration	LVRT				HVRT		Power factor	
				During fault		Post fault		During Fault			
				V _{min} • (p.u)	T _{max} . (s)	V _{min} • (p.u)	T _{max} . (s)	V _{max} . (p.u)	T _{max} (s)	Lag	Lead
Australia	50	47.5<f _{lim} <52.048	Continuous	0	0.10	0.7	2.0	1.3	0.06	0.95	0.95
		49.0< f _{lim} <51.0	10min.								
		48.0< f _{lim} <51.0	2min.								
		47.5< f _{lim} <52.0	9sec.								
Germany	50	49.0< f _{lim} <50.5	Continuous	0	0.15	0.85	1.0	-	-	0.9	0.95
		48.5< f _{lim} <51.5	30min.								
		47.5< f _{lim} <51.5	10min.								

		$46.5 < f_{lim} < 53.5$	10sec.								
Denmark	50	$48.5 < f_{lim} < 51.0$	Continuous	0.20	0.50	0.90	1.5	1.2	0.1	0.95	0.95
		$48.0 < f_{lim} < 51.0$	25min.								
		$47.5 < f_{lim} < 52.0$	5min.								
		$47.0 < f_{lim} < 52.0$	10sec.								
India	50	$49.5 < f_{lim} < 50.5$	Continuous	0.15	0.30	0.85	3.0	1.3	0.2	-	-
		$47.5 < f_{lim} < 51.5$	WECS remain connected								
Canada	60	$59.4 < f_{lim} < 60.6$	Continuous	0.0	0.15	0.85	1.0	-	-	0.90	0.95
		$58.5 < f_{lim} < 61.5$	11min.								
		$57.5 < f_{lim} < 61.7$	1.5min.								
		$56.5 < f_{lim} < 61.7$	2sec.								
		$55.5 < f_{lim} < 61.7$	0.35sec.								
USA	60	$60.0 < f_{lim} < 59.5$	Continuous	0.0	0.15	0.90	1.75	1.20	1	0.95	0.95
		$59.5 < f_{lim} < 59.3$	10min.								
		$59.3 < f_{lim} < 58.7$	10sec.								
China	50	$49.5 < f_{lim} < 50.2$	Continuous	0.2	0.625	0.90	2.0	1.3	0.5	0.95	0.95
		$47.5 < f_{lim} < 51.5$	10min.								

4.3 Behaviour During Voltage Dips

This section delves into the dynamic model of a DFIG operating under grid fault situations. The model's behavior when voltage drops due to asymmetrical and symmetrical grid failures will be examined.

Numerous nations around the globe have conducted studies on FRT requirements for WECS. The WECS are necessary to keep grid connectivity and offer reactive power compensation during grid outages. Grid faults typically result in voltage sags at the WECS terminal. In a WECS with a full-scale PEC, the generator will not "see" the voltage loss directly because the generator will be completely separated from the grid by the PEC. Therefore, the FRT capability of the system will be established according to the FRT capability of the PEC. However, in the case of a DFIG-fed WECS, in addition to affecting the GSPEC, the voltage sag also affects the generator since the DFIG's stator is linked directly to the grid [117][118]. This means that when there is a grid failure, the work of the DFIG will be more challenging. Before examining DFIG's FRT method and modified FRT method, it is crucial to understand the DFIG dynamic model during grid faults to evaluate the system's effectiveness during grid failures.

4.3.1 DFIG Equivalent Circuits During Symmetrical Voltage Sags

Voltage sag, often referred to as a voltage dip, is a short-term decrease in the RMS voltage level at a given point in the power system, dropping between 10% and 90% of

the nominal voltage, and lasting from half a cycle to one minute. Voltage sags are typically caused by system faults, sudden increases in load, or the starting of large motors.

In the context of FRT of DFIG based WECSs, voltage sag is a particularly relevant and challenging issue. This is because, during a grid fault leading to a voltage sag, high currents can be induced in the rotor winding of the DFIG due to the fast dynamics of the rotor voltage. These currents, if not properly managed, can lead to the tripping of the rotor-side converter, thereby disconnecting the wind turbine from the grid. Such disconnections can have detrimental impacts on the power system, potentially leading to instability or even widespread blackouts in extreme cases.

The underlying concept behind the DFIG during voltage sag is that the stator flux couldn't be changed abruptly. As a consequence, to maintain flux continuity, a stator natural flux (ψ_{sn}) will be added. Figure.4.2 depicts the stator flux evolution under symmetrical-voltage drops of 80%. Prior to voltage sags, the stator flux vector (ψ_s) rotates in conjunction with the voltage vector of the grid. When a dip occurs, the grid voltage vector's amplitude is decreased. However, because the flux of the stator cannot shift fast according to the principle of magnetic flux conservation, a natural flux (ψ_{sn}) will arise, as indicated in Figure 4.2 rotating in accordance with a grid voltage vector [119].

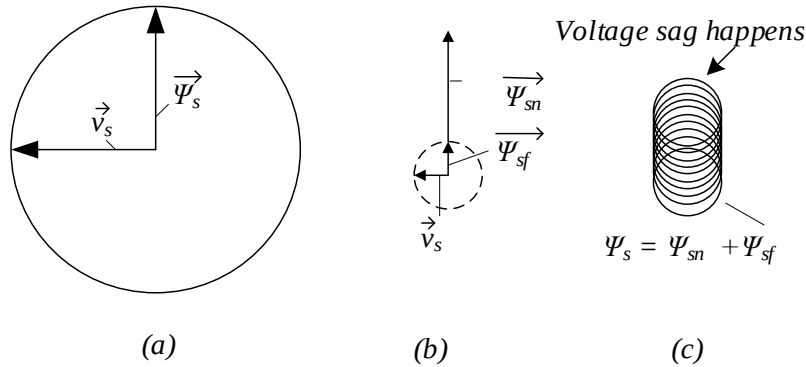


Figure 4. 4 DFIG's stators' flux paths during symmetrical voltage sags (a) prior to sag (b) during sag (c) after sag

The superposition principle can be used to describe the dynamic analysis of the DFIG under balanced voltage sags with two different equivalent circuits: the natural machine, in which the stator is short-circuited and the natural flux (ψ_{sn}) is present in the stator winding, and the forced-machine, in which the stator voltage is the remaining grid voltage and there is no transitory flux left, as shown in Figure 4.3.

Under normal conditions, the equivalent-circuit of the forced machine is identical to the DFIG's standard operating circuit. Figure 3(b) yields the distinct equation describing the relationship between stator natural-flux (ψ_{sn}) and rotor natural current (i_{rn}), as expressed in Eqs. (4. 1) and (4. 2):

$$\frac{d\psi_{sn}}{dt} = -\frac{R_s}{L_s}\psi_{sn} + \frac{L_s}{L_s}R_s i_{rn} \quad 4.1$$

$$\left(\frac{d}{dt} - j\omega_r\right)\psi_{sn} = v_{rn} - R_r i_{rn} - \left(\frac{d}{dt} - j\omega_r\right)\sigma L_r i_{rn} \quad 4.2$$

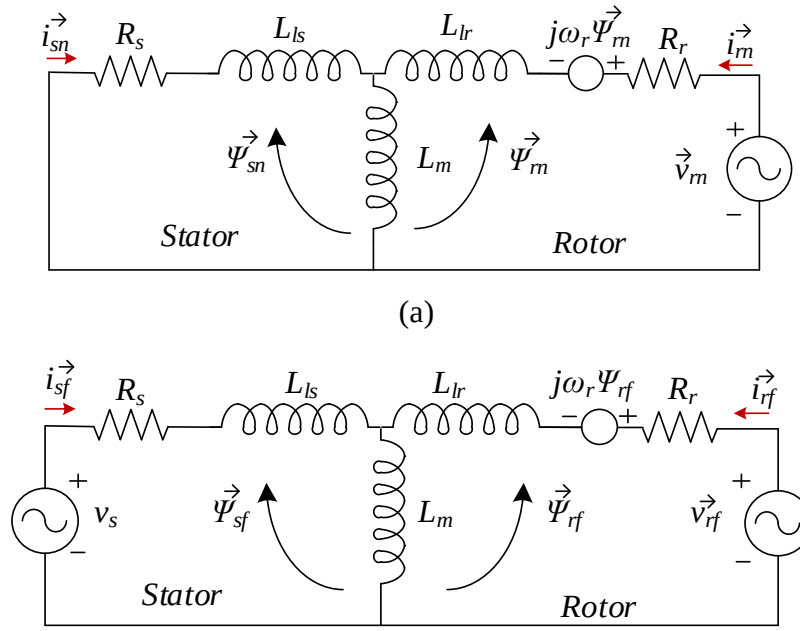


Figure 4. 5 DFIG equivalent circuit model exposed to symmetrical voltage sag:
(a) natural-machine and (b) forced-machine

4.3.2 DFIG Equivalent Circuits During Asymmetrical Voltage Dips

The symmetrical component approach can be used to divide the asymmetrical grid voltage into positive, negative, and zero sequence components. Figure 4. 6 depicts the voltage vectors for the three types of asymmetrical grid faults, and the grid voltage is categorized as positive sequence (V_{s+}), negative sequence (V_{s-}), or zero sequence (V_{s0}).

With the negative-sequence grid voltage, along with the natural flux ψ_{sn} and forced flux (ψ_{sf}), the negative-sequence grid voltage will also inject a stator negative flux (ψ_{sne}), which will have a frequency of $-\omega_s$, into the system. In addition to the

natural and forced machines, as shown in Figure 4. 7, the negative machine is another equivalent circuit that can be used to investigate the DFIG's operation [120].

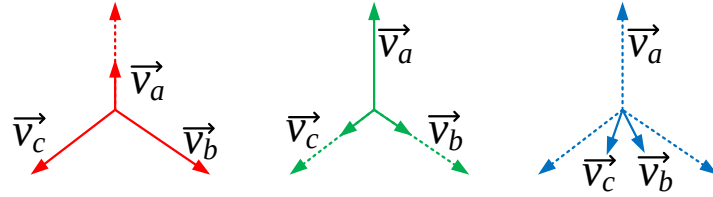


Figure 4. 6 Asymmetrical fault voltage on the grid (a) Single-phase to ground faults; (b) two-phase to ground fault and (c) two-phase fault

The negative machine's rotor equation is deduced as follows:

$$\left(\frac{d}{dt} - j\omega_r \right) \psi_{sne} = v_{rne} - R_r i_{rn} - \left(\frac{d}{dt} - j\omega_r \right) \sigma L_r i_{rne} \quad 4.3$$

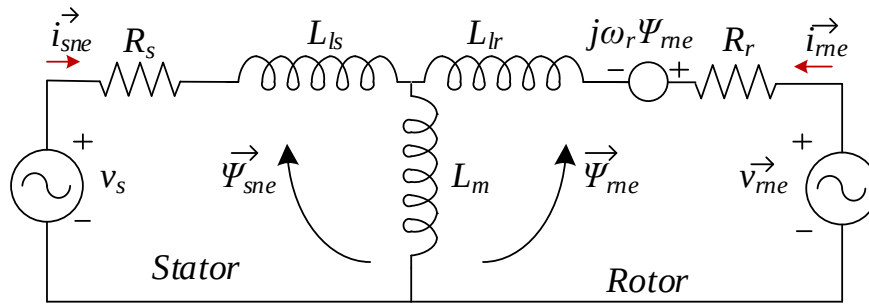


Figure 4. 7 DFIG equivalent circuit model of the negative machine.

Table 4. 4 Symmetrical component of the grid voltage under asymmetrical

Fault type	V_s^+	V_s^-	V_s^0
Single phase to ground	$1 - \frac{p}{3}$	$\frac{p}{3}$	$\frac{p}{3}$
Two phase	$1 - \frac{2p}{3}$	$\frac{p}{3}$	0
Two phase to ground	$1 - \frac{p}{2}$	$\frac{p}{2}$	0

The steady-state stator-flux path following an asymmetric grid fault is an ellipse owing to the presence of forced-flux and negative sequence flux. If there is a single-phase to ground fault, the stator flux will follow a specific path as shown in Figure 4. 8a. The natural flux of the stator during an asymmetrical grid fault is affected not only by the type of fault and the level of voltage loss but also by the timing of the fault, as depicted in Figure 4. 8 by the ' θ ' fault angle. If the fault occurs at an angle of $\theta = 90$ degrees and the positive and negative sequence grid voltages are in opposite directions, the resultant stator force and negative flux of the stator after the fault will be identical to the stator flux before

the fault. As a consequence, the ψ_{sn} will be zero, as shown in Figure 4. 8b. As illustrated in Figure 4. 8c, the ψ_{sn} will be at its highest point when the fault occurs at the value of zero it can be expressed as

$$\psi_{sn}(t_0)|_{\theta=0} = \frac{2pV_s}{3j\omega_s} \quad 4.4$$

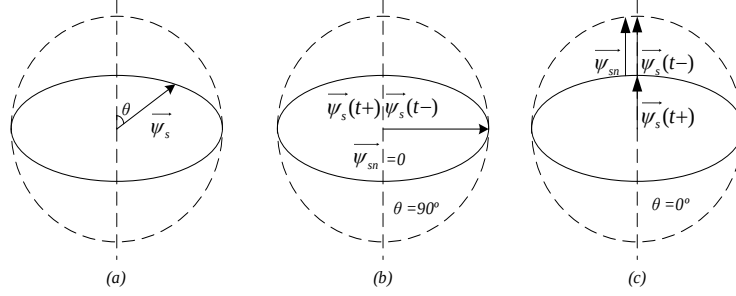


Figure 4. 8 Flux path of the stator in the event of an asymmetrical grid failure (a) Steady-state after a fault (b) the zero flux state; and (c) the maximum natural flux state.

4.4 Enhancing Transient Stability in DFIG-WECSs using FRT Strategies

This section explores a variety of FRT strategies, incorporating advanced control methods and hardware interventions. Advanced control approaches typically encompass technological tweaks that augment the DFIG's FRT performance, while hardware modifications, which use supplementary circuits, bolster the capacity of the DFIG WECS to withstand voltage reductions. Measures must be implemented to: (i) safeguard the power converter's semiconductor-switches against rotor overcurrent; (ii) protect the DC link capacitor from over-voltage; and (iii) ensure a reliable grid connection for the wind turbines [21,22]. To enhance the transient response of the DFIG-based WECS, the following measures are suggested:

- Utilization of protection devices in transient scenarios.
- Reactive power injection during transient states.
- Appropriate control system for both transient and steady state scenarios.

4.4.1 FRT Schemes Overview

This section provides a comprehensive overview of the various FRT strategies designed to bolster the transient response of the DFIG based WECSs. The principal aim of these strategies is to ensure the DFIG maintains its connection during fault occurrences, with a particular focus on Low Voltage Ride Through (LVRT) techniques.

These approaches can be broadly classified into two primary categories. One involves alterations in the hardware components, while the other encompasses modifications in the conventional converters utilized in the DFIG. The hardware-focused LVRT strategies can be further broken down into two sub-categories: those centered around the implementation of protective circuits, and those deploying devices for the injection of reactive power.

The classification of these diverse types of LVRT schemes, specifically for DFIG-based wind power plants, can be observed in Figure 4. 9. Following this, the section proceeds to elaborate on some of the most frequently implemented LVRT schemes in DFIGs. By understanding and implementing these diverse strategies, it is possible to significantly enhance the resilience and performance of DFIG-based wind energy systems under fault conditions.

4.4.2 External Retrofit Based FRT Techniques For DFIG

External retrofit based FRT techniques are modules that have been modified to alter the converter's design and can be categorized into two sections: as protection circuit-oriented FRT techniques and reactive power injection oriented FRT techniques.

4.4.2.1 External Protection circuit oriented FRT Techniques

The protection circuit-oriented FRT techniques are presented as

(a) Crowbar Circuit

The Crowbar Circuit is one of the most extensively utilised methods of resolving the FRT problem [121] [122]. As seen in Figure 4. 10 It involves a set of resistances installed on the slip-ring of the rotor-side with the help of semiconductor switches to bypass the RSPEC. Its general basic operation is explained as RSPEC gate signals are switched off at the voltage dip (for example, three-phase faults) and the rotor rings are shortened by the crowbar resistor or in other words the rotor current is then diverted to the crowbar which is shown by point F and throughout this instance, the rotor's transient current I_{rotor} becomes I_{rotor}^f (fault current) and it will dissipate in the resistance R_{crw} .

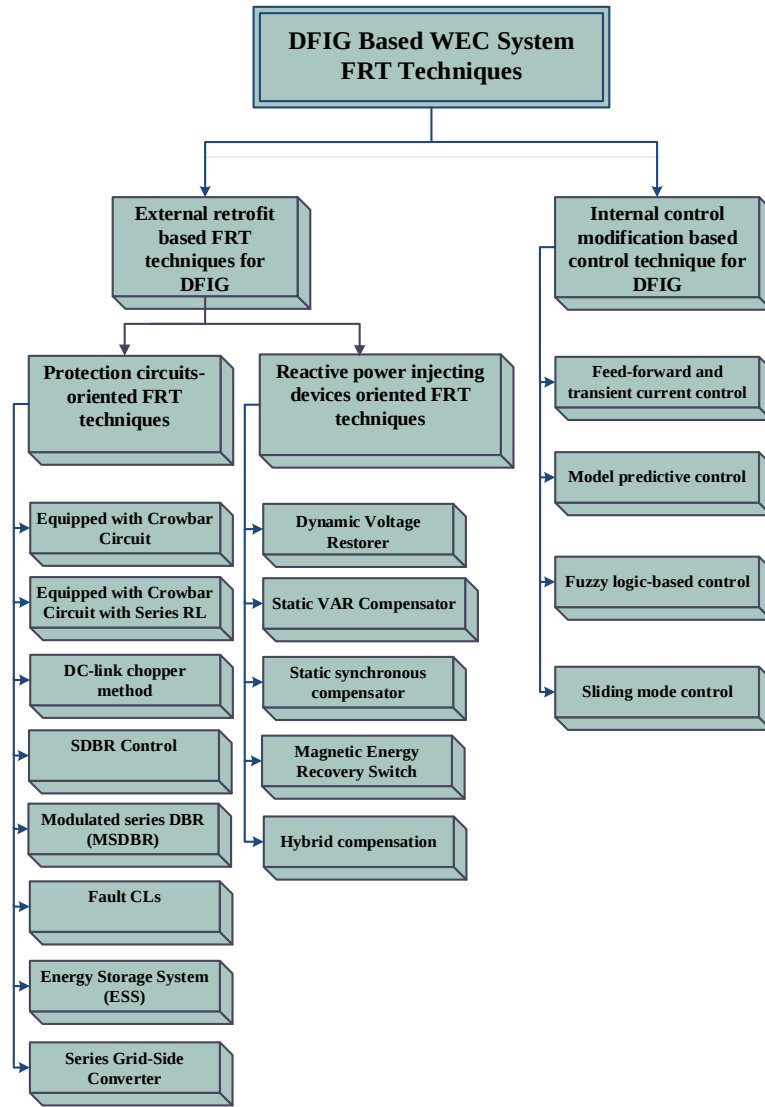


Figure 4. 9 FRT Techniques of DFIG-based WECS

Crowbar activation causes RSPEC and wind turbine (WT) to lose control over their ability to control active, reactive powers over a period of time. The issue with this technique is that the DFIG-WECS begins to operate as a reactive power consumption unit, such as an induction motor, resulting in a loss of grid voltage, so to overcome the limitations imposed by the crowbar installation, an improved model of the crowbar arrangement is proposed, which will be presented in the next section, which can ensure the concern of real and reactive power control. In addition, the crowbar circuit incorporated some active and passive compensators, a crowbar coordination concept with series dynamic resistance, and a crowbar with a DC-link chopper. These newer crowbar techniques attempt to reduce operating time and try to prevent DFIG from acting as SEIG [123]. The research in [124] investigates advancements in LVRT effectiveness of DFIG architecture with rotor crowbar taking grid impedance into account. In addition to this,

the mathematical concept for the crowbar resistance while taking into account the grid impedance is also determined.

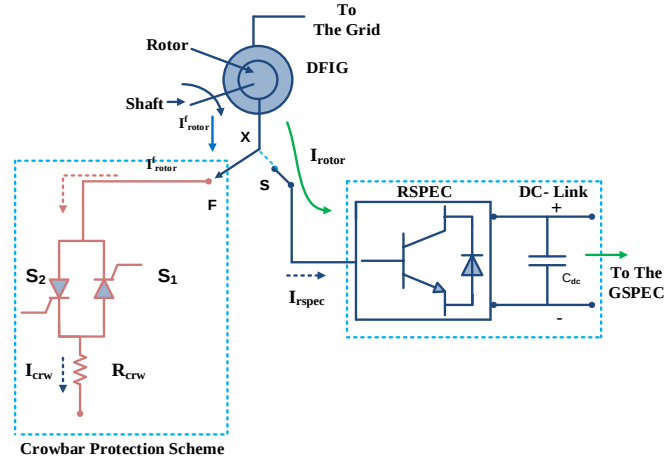


Figure 4. 10 Crowbar protection circuit for DFIG based WECS

(b) Crowbar series RL equipped circuit

The crowbar connects resistance in shunt with the DFIG's rotor field winding to restrict the rotor current. Alternative to this is to install reactance in series with the rotor windings of DFIG to restrict both the stator and rotor currents. The new scheme's circuit is shown in Figure 4. 11 to improve DFIG LVRT capability during grid disruptions. It's a hybrid model of an R-L circuit and a crowbar. At point C, the new crowbar series R-L circuit is attached to the rotor's winding. Whenever the rotor current reaches a threshold, the RSPEC connection is diverted to point S. Throughout this instance, the rotor's transient current (I_{fr}) is split in the two parts first is the current of the crowbar (I_{crw}), which is defined by the resistance of crowbar R_{crw}^{nps} , and second one is the RSPEC current (I_{rspec}), which is determined by the R-L series circuit impedance (Z_{seies}). At the event of failure and clearance, the RSPEC is always linked to the rotor-windings. When the control strategy is initiated, it implies that the crowbar, series equipped R-L circuit is triggered, further a portion of the generator rotor winding is shortened by the crowbar, and a portion of the generator rotor-winding is connected to the RSPEC. The RSPEC controller controls the generator's dynamic power, which would be a major benefit over conventional crowbars [125].

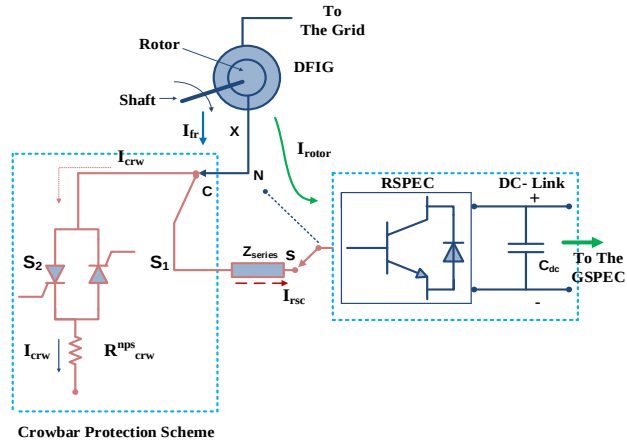


Figure 4. 11 Crowbar series RL protection circuit for DFIG based WECS

(c) Chopper technique for DC-links

The chopper circuit is the same as the rotor-side crowbar to minimize the overvoltage of the dc link. It is indeed a connection of the resistor to the DC link in shunt as shown in Figure 4. 12. The chopper circuit discharges surplus energy to obtain an acceptable DC link voltage. In [126] it discusses the use of a chopper as a single protection device. It can also be combined with other tools such as a super-conducting magnet, SBR [127] and SFCL [128]. In [58] an improved DC chopper topology that is competent of controlling the excessive transient rotor over-current and stator current in conjunction with handling the voltage of the DC link during a fault state without introducing any additional fault current limiting technique has been proposed. The improved DC chopper incorporates three additional switching devices that allow it to connect the DC chopper resistance in series or in parallel with the DC link, depending on the DC link cutoff voltage and current.

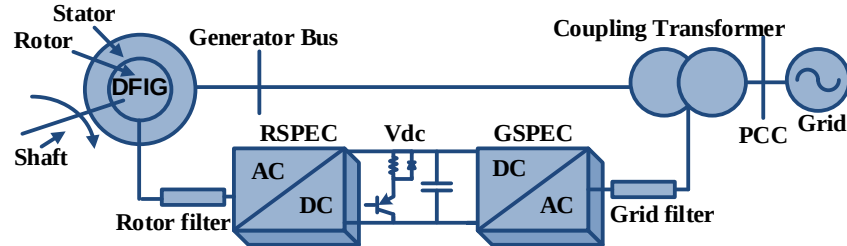


Figure 4. 12 Conventional DC chopper protection circuit for DFIG based WECS

(d) Series dynamic braking resistor (SDBR) control Scheme

A series connection of power electronic switches and series dynamic resistors connected to the stator or rotor terminal forms SDBR. SDBR is a series topology that is

associated with the stator terminal. The circuit depicted in Figure 4. 13 is ideal for extreme fault situations due to its high-power output and low residual voltage.

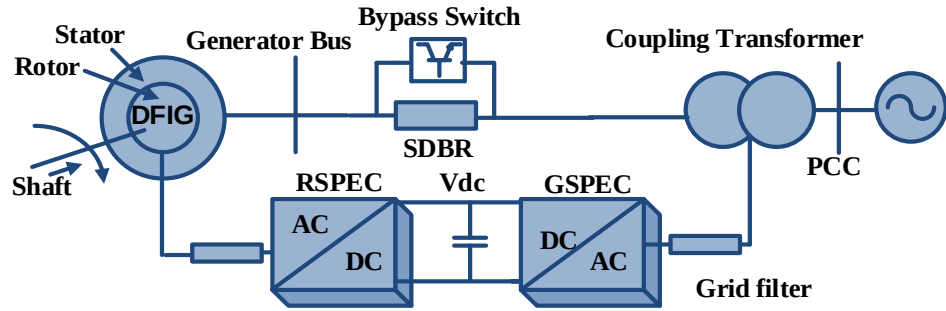


Figure 4. 13 SDBR Protection Circuit for DFIG based WECS

SDBR is distinguished from the crowbar's by its circuitry structure. Although SDBR has the advantage of regulating current magnitude, the DCLINK chopper/crowbar is shunt connected and controls voltage. Furthermore, the high voltage in the SDBR method is shared by resistance due to its structure of the series. As a result, the induced overvoltage cannot result in a loss of control over the converter. The SDBR regulates not only overvoltage of the rotor that might result in the RSPEC losing control, but also strongly restricts the high current of the rotor. Additionally, by restricting the rotor current, the charging current of the DC bus capacitor can also be brought down. Furthermore, the SDBR could manage the DFIG's real power, improving the wind generator's stability in the event of a fault. Also, during a voltage drop, the SDBR improves the generator output, decreasing its increased speed. This impact will enhance the DFIG system's and wind farm's post fault recovery, as the SDBR regulates and improves acceleration speed of the rotor during grid disturbance [60]. The mathematical formulation of fault current is developed in [129] using the SDBR and constant converter current regulation. Analytical analysis of the LVRT transient is done in order to characterize the LVRT effect. Focusing on an index integrating the DFIG's capacities to offer active power assistance and reduce electromagnetic torque oscillation, the resistance of the SDBR is optimized.

(e) Modulated series DBR (MSDBR)

In [130], a braking resistor that is comparable to both single- and multi-step braking resistors is described. It is based on modulated series DBR (MSDBR) technology. This control scheme is applied to maintain the desired terminal voltage consistent in the presence of both balanced and unbalanced voltage drops. Restoring the stator voltage helps GSPEC and RSPEC maintain controllability to avoid DC bus overvoltage,

rotor/stator short-circuit current, and DC bus capacitor overload. As a result, no extra protective devices, such as a DC-chopper, crowbar, or rotor braking resistance, are required. The continuous operation of a generator facility improves voltage response during the recovery period. The MSDBR module, as shown in Figure 4. 14, is made up of two antiserries insulated bipolar gate transistors that are connected in each phase parallel to the braking-resistor. The stator voltage controller's PWM signals independently regulate the voltage of the stator. Restoring the stator's voltage causes the GSPEC and RSPEC components of the circuit to compensate for the voltage and current overload caused by the direct current link.

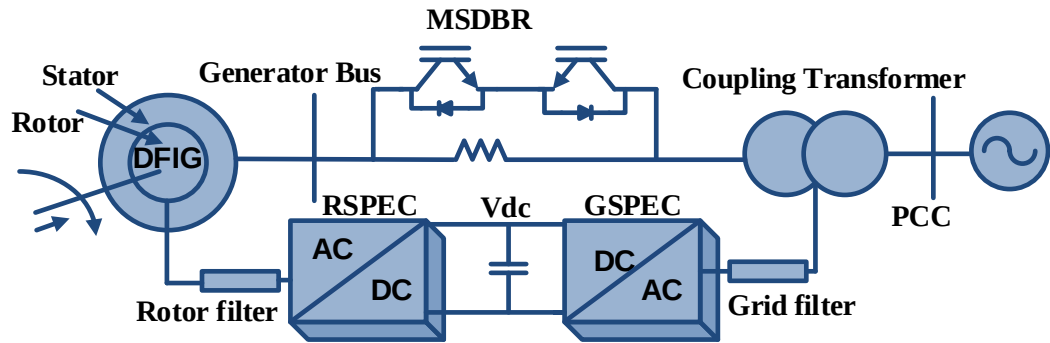


Figure 4. 14 MSDBR Protection circuit for DFIG based WECS

Figure 9. MSDBR Protection circuit for DFIG based WECS

(f) Fault CLs

Another type of protective approach employed for boosting the FRT capabilities of DFIG-oriented WECSs is the use of Fault Current Limiters (FCLs). The fault current level is limited by a 3-phase FCL, which includes an isolation-transformer and a high DC-inductance with a bypass-resistance situated on the DFIG stator-side [131]. To improve the transient stability of DFIG, a number of fault current limiter variations have been developed, and future research is ongoing on these limiters. However, FCLs are superior to the crowbar and dynamic braking resistor concept in terms of performance. Figure 4.13 illustrates all of the FCLs that were used to improve the FRT capacity of the DFIG.

FCL arrangements can be classified into two groups based on their impedance type and component arrangement. There are four types of FCLs based on their impedance: resistive, inductive, resistive-inductive, and resonance. Another classification exists depending on whether a superconductor is employed or not. The FCLs can be classified as either solid state or saturated core transformers based on their component type. The

FCL is located in different positions of the DFIG to increase the FRT capacity of the DFIG. In each position, the impact on the key-parameters of DFIG is related to the FCL impedance type. From the perspective of positioning, FCL is mainly located at the terminal and stator end of the DFIG. There are some FCL on the end of the rotor, and some other configurations on the Dc link. Further from the perspective of impedance, FCL is mainly resistive as seen in Figure.10 [132].

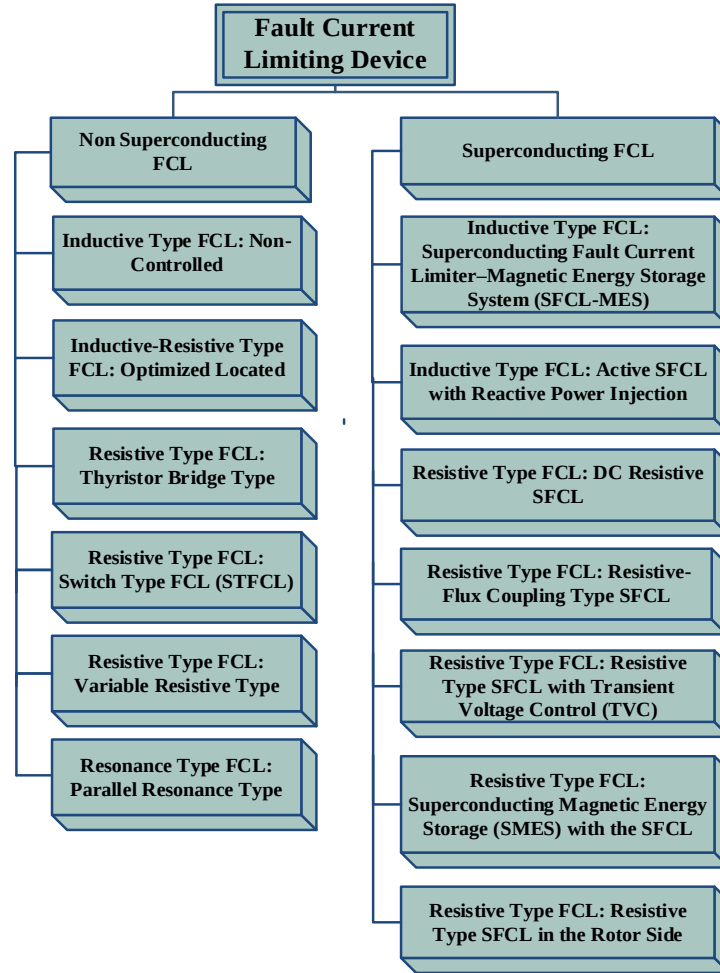


Figure 4. 15 FCL classification for DFIG based WECS

(g) Energy Storage Strategies (ESS)

An ESS improves the performance of a DFIG-based WECS by regulating the rotor current and power system transient stability (defined by the fault's critical clearing time) by providing reactive power assistance to the grid and protecting the DC-link from overvoltage's. In the steady state, ESS also controls DFIG's active power output. It can easily be incorporated into the DFIG configuration via a two-way DC/DC converter and a DC bus. Figure 4. 16 illustrates the physical structure of a DFIG equipped with energy storage. It has several advantages: it can be accessed anywhere under any operating

conditions, the machine's operation does not need to be reconfigured, it strengthens the LVRT and effectively improves transient state stability; The only limitation is that DFIG with energy storage is more expensive [133].

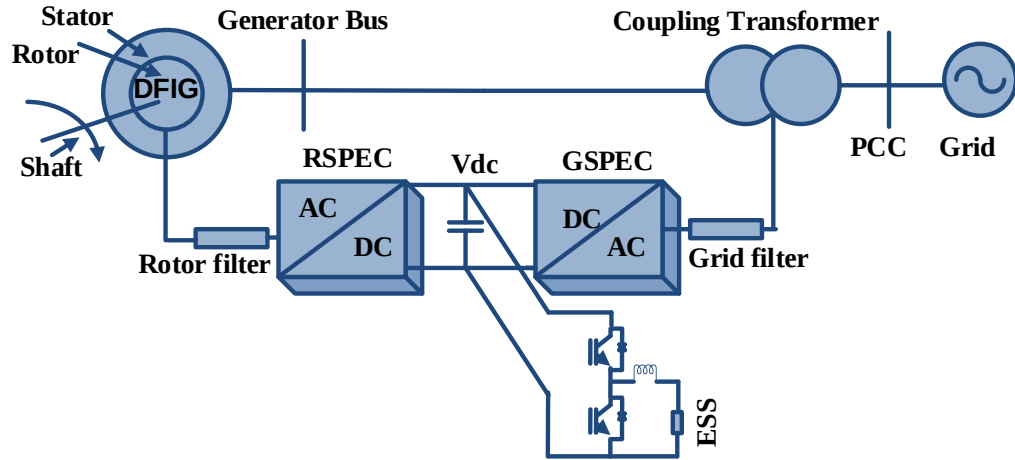


Figure 4. 16 ESS Protection circuit for DFIG based WECS

Wind energy implementation can utilise a range of different types of energy storage, including batteries, superconducting magnetic energy storage (SMES), supercapacitors (SC), and flywheels. When there is a fault, these batteries will assist in absorbing additional energy from the DC-link capacitor. After a fault has been cleared, ESS not only eliminates overvoltage difficulties in the DC-link capacitor, but it also supplies stored energy to the DFIG-WT. Several researchers have presented on the operation of batteries and supercapacitors in conjunction with turbines [134]. Supercapacitor has benefits over the other energy storage systems, including high energy density, longer lifetime, and lesser capital expense. As a result, the supercapacitor is taken into consideration as the most appropriate energy storage system for maintaining constant power output and mitigating wind turbine generator fluctuations [135]. A DFIG integrated with an electric double-layer capacitors-based energy storage system, which can improve LVRT capacity and ability and a transitory reactive power control strategy for the DFIG, is suggested in [136]. An innovative DFIG-based WECS is presented in [74] that incorporates the benefits of DVR and ESS, using a DVR in series on the end terminal of the generator and also throughout the system using the ESS.

(h) Series Grid-Side Converter

The Series Grid-Side Converter (SGSC), seen in Figure 4. 17, is a 2-way power semiconductor converter linked across the DC link. The SGSC controls the voltage by

delivering or consuming real power in an effort to manage the DC link voltage. The SGSC has another function that compensates stator harmonic voltages by harvesting the harmonic voltage content. SGSC injects series compensation voltage to compensate for the influence of negative sequence grid voltage by balancing the voltage of the stator. Additionally, the flux of the stator can also be regulated or controlled by SGSC serial-voltage injection [137].

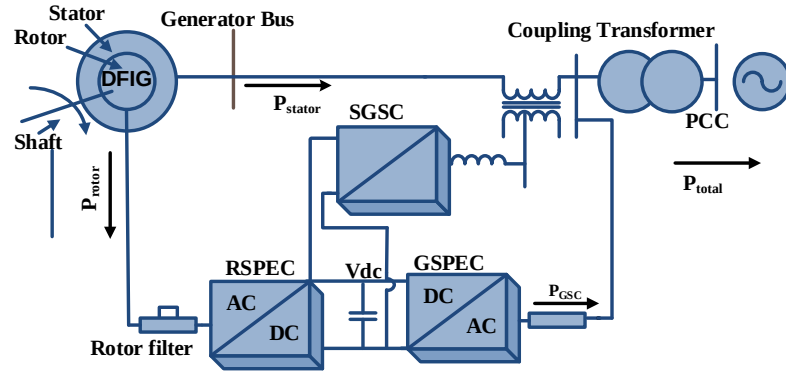


Figure 4. 17 . SGSC Protection Circuit for DFIG based WECS

To improve the utilisation of SGSC, [137] proposes a resonant adaptive controller, even in the presence of voltage imbalances throughout the switch network grid, hybrid controllers maintain a constant voltage on the stator. The DFIG-single WT's parallel-group-side corrector (PGSR) and SGSC architectural features are demonstrated in [138]. These technologies have been integrated and are attempting to share the same DC bus. PGSR supplies power to the circuit of the rotor during synchronous operation. To ensure the generator voltage never exceeds the nominal value, the SGSC maintains the optimal range of the stator flux. Table 4. 5 concludes with a comparative analysis of FRT techniques based on protection circuits.

Table 4. 5 Comparative Analysis of Protection circuits-based FRT strategies

S. No	Technique utilized	Benefits	Limitations
a.	Crowbar Technique [121] [122][123] [57]	It activates throughout the faults and helps to reduce overcurrent and prevent RSPEC.	When the crowbar is activated, RSPEC losses control.

b.	Crowbar with Series R-L [125]	The dynamic control of the active or reactive power of the stator is not lost.	Whenever a low series impedance is employed with the large resistance of the crowbar, the inrush current of the rotor may move through the converter through the R-L, resulting in abnormalities.
c.	DC-Link Chopper [126] [58]	Eliminates distortions and variations in voltage of DC-link and increases normal levels of DFIG operation.	The time required to disengage and restore the converter will be longer than a crowbar.
d.	SDBR [60] [129]	- Avoid using a crowbar regularly. Maximizes RSPEC operating time. - Offers low reactive current injection - Eliminates variations in torque.	- The quality of voltage is in be sufficient, depending on the SBR switching scheme. - Active power support is not required. - An additional equipment was required. Voltage oscillation in the DC-link
e.	MSDBR [130]	- This structure prohibits the use of both crowbar and DC chopper. - Compensation system sequence and power evacuation system.	- Behaviour of the scheme during injection of reactive power is not studied - Higher cost compared to the other schemes.
f.	FCL SFCL [131] [139] [132]	- Restrict fault current, strengthens RSPEC and improves its controllability. - Offers rapid action against fault current and automatic recovery - Quick quenching	- The price of STFCL is relatively high. - There isn't any support for reactive power. - Incapable of functioning at room temperature

g.	ESS [134] [135] [61] [74]	• Augments the transitional dynamics and stability of the generator during transient power network scenarios. • Regulates the steady-state mode's active power output.	• Challenges related to the performance and upkeep of battery systems • Self-discharge signifies an energy loss, as it remains idle while the system is in operation, thereby wasting stored power.
h.	SGSC [137] [138]	• Mitigates the oscillations in the stator flux synchronous frame, enabling its direct control.	• Struggles to uphold the power Balance within the dc-link.

4.4.2.2 Reactive Power Injecting Devices Oriented FRT Strategies

This segment elucidates the strategies FRT based on the reactive power injection capability.

(a) Dynamic Voltage Restorer

A Dynamic Voltage Restorer (DVR) is a series-circuit system designed to restore the voltage level to normal during voltage drop events. The DVR is utilized to mitigate voltage sags and swells, while also contributing to enhanced power efficiency[140]. The DVR is a series-connected FACTS (Flexible AC Transmission System) unit that possesses the capability to safeguard sensitive loads against abnormal and transient disturbances in the electric grid. The circuit arrangement of the DVR is illustrated in the provided Figure 4. 18. In general, the DVR is made up of two kinds of circuits: one for power injection and the other for control. The control circuitry is utilized to determine the magnitude, frequency, phase shift, and other parameters of the control signal that the DVR must inject. The injected voltage is produced by switching in the power-circuit in response to the control signal. An injection transformer, a high-speed PWM inverter, an AC harmonic filter, a DC power storage unit, and a control unit comprise the DVR power circuit.

When the voltage at the source end is interrupted, DVR is one of the most reliable methods for "restoring" the voltage quality at the load end. DVRs performed in three distinct modes, which are briefly described below:

- Bypass mode: This mode enables DVR to be bypass mechanically or electronically in the case of severe load currents or down - stream short circuits, while DVR does not inject voltage to achieve better voltage efficiency.
- Standby mode: This mode has a rated voltage, and the DVR is ready to handle a voltage drop. Throughout standby mode, the DVR may perform secondary tasks.
- Active mode: After detecting a voltage fall the DVR injects the lost voltage in this mode.

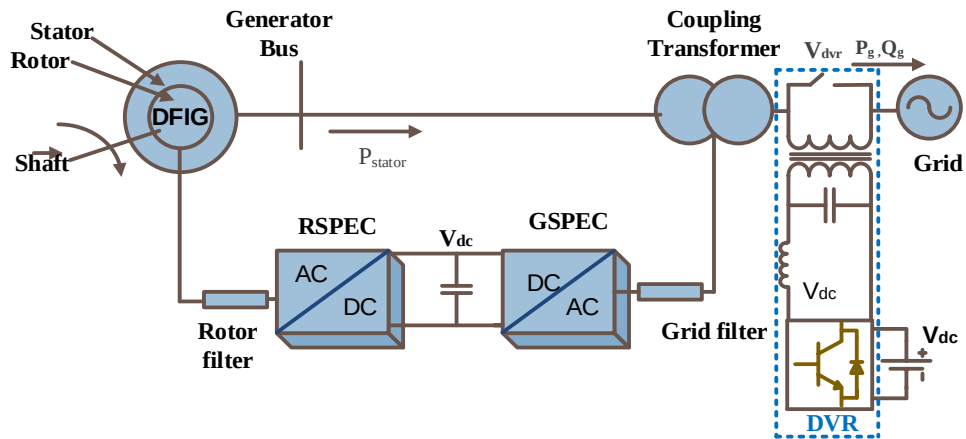


Figure 4. 18 DVR Circuit for DFIG based WECS

In [141], distinct DVR configurations are evaluated in terms of voltage and power ratings. The control systems centred on resonant controllers are addressed in [75] and [142] in order to compensate for non-symmetric voltages. [143] investigates the use of a DVR to enable uninterrupted FRT of voltage sags that meet GC requirements. [74] describes the development of a built-in DVR with an energy storage system (ESS) for wind farms based on DFIG. A Vanadium Redox Flow battery (VRF) is integrated into the DFIG back-to-back PWM converter in parallel with the DC connection capacitor. Through the bidirectional DC-DC converter, the ESS output charges the DC link capacitor. In addition, the DVR receives power from the same capacitor. The DC-TO-DC converter maintains a constant voltage on the DC link. A further solution for optimizing the efficiency and performance of DVR is explored in [144]. It uses a new asymmetrical multilevel inverter (MLI) centred on a Level Creator and an H-bridge inverter. An improved configuration of FCL DVR for grid and DFIG support during fault currents induced by significant voltage sags. The appropriate parameters for the construction of a

fault current limiting dynamic voltage restorer for DFIG systems are thoroughly examined in [72].

(b) Static VAR Compensator (SVC)

Since the early 1970s, SVC has been the most important component of FACTS devices. It is made up of traditional thyristors, which operate at a faster rate than mechanically-switched conventional devices and necessitate more sophisticated controllers. Shunt-connected SVC stands for reactive power generators or absorbers. By providing a controlled capacitive current or inductive current output, it can ensure the voltage level stability of the associated bus. SVC DFIG is shown in Figure 4. 19. SVC is a combination of a Thyristor Controlled Reactor (TCR) and a Thyristor Switched Capacitor (TSC). The TCR uses control of firing angle to continually decrease or increase inductive-current, although in TSR the attached inductors can be cut in and out step by step, eliminating the need to continuously control the firing angle[145]. Improving dynamic voltage management, thereby improving system load capacity and dampening system oscillations, may be one of the key reasons for installing SVC [146]. SVC will also be able to increase power transfer in the event of faults by holding the generator acceleration down and vice versa. This decreases the effect of the operational failure on the capacity of the generator to keep synchronous. The current SVCs are of varying susceptibility characteristic [147]. The traditional technology of SVC is losing its effectiveness because of low surge capability, poor dynamic efficiency, poor response speeds, etc.

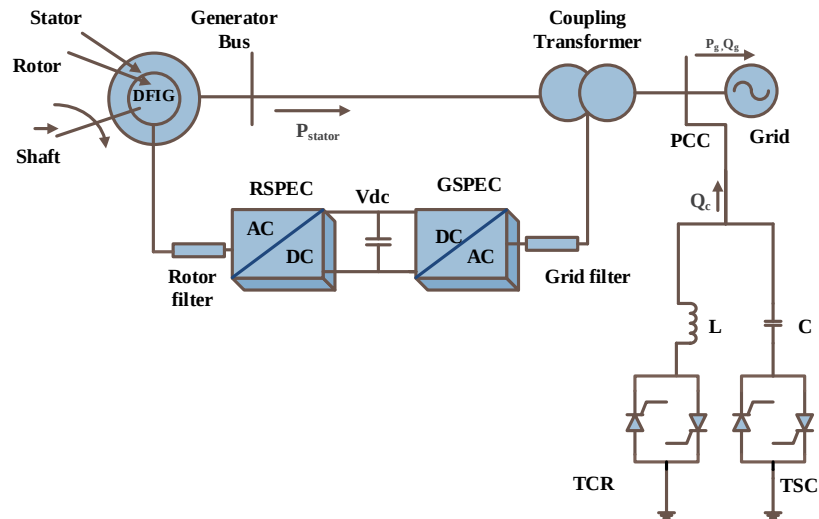


Figure 4. 19 SVC Circuit for DFIG based WECS

(c) Static synchronous compensator (STATCOM)

Another smart method to strengthen a wind energy system that can generate or consume reactive-power from the electric grid is to employ a static-synchronous compensator (STATCOM). A STATCOM should be inserted in the shunt as a synchronous solid-state condenser connected to an alternating current unit. The controller's power output is set up to control the voltage at each node or the reactive power sent to the bus.

STATCOM involves absorbing / injecting reactive power during the steady state to maintain the bus voltage and prevent variation. STATCOM injects the highest possible reactive currents to assist the electrical grid during transients, speed up the voltage recovery and restore the reliability of the voltage. It has similar quality compared to the synchronous condenser, but because it is an electrical appliance, there is no inertia, so it is superior to the synchronous condenser. Significant advantages of this system include relatively low capital costs, lower operational and service costs, and improved dynamics. Most VSCs are constructed with turn-off function thyristors, such as integrated gate commutated thyristors (IGCT) or gate turn-off (GTO) or insulated gate bipolar transistors (IGBT) [145]. STATCOM is capable of delivering greater transient margins compared to SVC. In addition, overloading capability can be enhanced. The geometry and control mechanisms of STATCOM differ in DFIG, as illustrated in Figure 4. 20. When RSPEC is deactivated by a crowbar, DFIG GSPEC supplies reactive power to operate through faults, similar to STATCOM. STATCOM provides superior voltage characteristics and they can provide greater reactive power adjustment when there are severe faults [147][148]. In [149], a combination strategy of low SDBR and STATCOM is suggested, with the capacity to control both real and reactive power. This setup can improve FRT performance and meet grid code requirements when the terminal voltage drops below the cutoff level.

(d) Magnetic Energy Recovery Switch (MERS)

Tokushima Institute of Technology's Shimada Laboratory was the first to create MERS [150]. MERS comprises of four diodes, a dc-capacitor and 4 forced commutated switches (such as GTOs) the MERS specification is similar to that of a complete 1-phase full-bridge inverter; however, the operating principle and application differ. The DC-capacitor capacitance is several times smaller compared to the standard 1-phase full bridge, and line frequency switching [151]. The device produces certain harmonics in line-strengths which do not have extreme consequences, but interfere with the system's

resonance frequency. By controlling the flow of current through the circuit, it is achievable to inject voltage for any current only within the device's rating, converting MERS into a series compensator. Additionally, MERS is a reactive power compensation device that functions similarly to SVC by providing continuous controlled capacitive power compensation via an easy-to-use interface. Findings suggest that comparing this model to other shunt compensator options, findings suggest that it offers an enticing alternative. So, more research needs to be done to see if the MERS approach can help DFIG's FRT capabilities.

Figure 4. 20 STATCOM Circuit for DFIG based WECS

It utilizes both series and shunt components. In DFIG WECS, the unified power flow controller (UPFC) and on a Unified Compensation System (UCS) are used as hybrid compensation devices. DFIG WECS utilizes a hybrid of shunt and series compensators to minimize voltage disturbances, harmonics, and flickers. It is a hybrid of STATCOM and Static Synchronous Series Compensator (SSSC) linked via DC-link. Both the real and reactive power of the DFIG system can be controlled using UPFC [152]. Table 4. 6 concludes with a comparative analysis of FRT techniques based on Reactive power injecting devices-based FRT strategies.

Table 4. 6 Comparative Analysis of Reactive power injecting devices-based FRT strategies

S. No	Method utilised	Advantages	Disadvantages
a.	Dynamic Voltage Restorer (DVR) [140][141]	• Perfectly capable for eliminating transients in generator currents. • Quick voltage retrieval and controllable supply of reactive power	• DVR needs additional active power. • Needs adequate power storage to minimize voltage drops.
b.	Static VAR Compensator (SVC)[146] [147]	• Reactive power compensation. • Continuous voltage regulator • Construction is uncomplicated, featuring reactive power injection.	• Voltage-dependent reactive control. • Faster response results in unstable voltage oscillations.
c.	Static synchronous compensator (STATCOM) [148] [149]	• Increased transient range and short-term overload potential during extreme voltage drop. • Reactive current control faster than the SVC. • Rapid response and adverse sequence voltage and current compensation.	• Increased running costs and expenditures. • Cannot provide active power.
d.	Magnetic energy recovery switch (MERS) [150][151]	• Eliminates reverse blocking. Efficient for deployment on a wide scale. • Low Losses for Switching	• Less stable control and has a by-pass mechanical transition.
e.	Hybrid compensation (UPQC) [152]	• Useful for both real and reactive power control. • Quick compensation for reactive power • Long time for critical clearing	• Consumes active power • A high DC-link capacitor was required.

4.4.3 Internal retrofit based FRT Techniques for DFIG

This section explains FRT strategies based on Internal retrofit are discussed

(a) Feed-forward and transient current control (FFTC)

The insertion of a feed-forward concept to the traditional current regulator results into the FFTC control system in the DFIG RSPEC. The output voltage of the RSPEC aligns with the induced transient voltage, decreases the current in rotor and significantly minimizes the interruption of the crowbar. With the assistance of an FFTC PI resonant-controller, the capability of the generator during LVRT is increased [153]. Transient feed-forward compensation terms are introduced both in the power-control loop and in the current-control loop, thus improving the ability to control the transient current and minimize the ripple in torque caused by faults at the grid. The dq transformation angle is given by a 3-phase phase lock loop (PLL) based on a synchronous-reference-frame with the q-axis tied to the positive-sequence stator voltage. Two FFTC functional blocks are added to the traditional vector-control technique to improve it.

(b) Model predictive control

Model predictive control (MPC) has grown in popularity as a potential alternative to modern control technology because it is centred on a system model to forecast the controlled variables' future behaviour follows optimization standards and implementation plans at each sampling moment and achieves the optimal control response. here are two main factors which classify the prediction algorithms of all AC drives: The pre-calculated duration (called the prediction range) and the method used to generate the reference signal Whereas some controllers take the inverter's discrete function is considered to compute the switching states directly without employing pulse width modulation (PWM), It is known as a finite control set (FCS) Other schemes route control signals through some modulator, such as PWM, and are referred to as continuous control set topologies (CCS). The FCS MPC selects switching states by considering the discrete operation of the inverters, and thus does not employ any modulation-scheme. This control analyses all possible switching scenarios and chooses the first one that meets the specified convergence criterion. As a result, the optimization approach is significantly easier than the one is using in the CCS-MPC. The CCS-MPC optimizes the inverter by considering its average model, with the goal of reducing the error between the predicted signal and the reference signal. The controller's output in this case is the reference duty- cycles, which is fed to the modulation technique [154][155].

In [156], the FCS-MPC algorithm used to increase the potential of DFIG LVRT in variable speed WECSs is discussed. This algorithm uses the inertia of the DFIG's rotor to maintain the excess energy during a sag in the grid's voltage. Simulation results show that the operational control scheme is suitable for ensuring the safe LVRT of the DFIG-based WECS also an active and reactive power generation unit while also meeting grid code standards. Because of the simplicity of the suggested control scheme, which requires no additional hardware, it outperforms traditional approaches in terms of performance and grid reliability enhancements, such as typical crowbar protection. In [157] a time-effective FCS-MPC strategy for DFIG system has been presented. The switching state of the RSPEC is used directly as a control input in this strategy. This enables the converter to carry out optimised control actions directly. Additionally, MPC-based study for LVRT potential in DFIG is not yet explored.

(c) Sliding mode control

Sliding Mode Control (SMC) is a powerful, stable, and highly nonlinear system control mechanism. SMC is characterized by its strong robust performance, quick convergence speed and easy implementation characteristics [158]. The SMC design concepts and their applications for drive systems were firstly suggested in [159]. It offers quick implementation, rejection of disruption, robustness and quick response, but the controlled condition may exhibit undesired chattering. Due to their robust external disturbances and non-linear dynamics of WECSs and generators, several second order SMC methods in aerodynamic control and power converter control in renewable energy applications have been proposed in [160][161]. In [160] a robust control sliding mode was proposed in order to regulate power generation in wind generators at variable speed. This can ensure the consistency and stability of the two operating areas, including high-speed and low-speed areas. The sliding mode control algorithms proposed in [162] for converters on the rotor and on the grid, end can let the WT run and operate effectively during uneven grid voltage conditions. They are also easy to use and do not require positive and negative voltage or current sequences for decomposition. Weakening high frequency chattering has always been a key problem in conventional sliding mode monitoring and that needs to be studied and resolved. By using this method, the efficiency of the control strategy has been established. However, the scenario with an unknown control direction remains unexplored.

(d) Fuzzy logic controller

The wind turbine converter topologies are conventionally controlled by PI controllers. PI controllers however provide less robustness and require precise knowledge of the dynamic model parameters for tuning. To tackle this limitation, a Fuzzy Logic Controller (FLC) is introduced. In a variety of ways, fuzzy logic is being used effectively to control DFIGs-based WT. Fuzzy logic is used in [163] to manage both active and reactive energy production. A fuzzy-logic gain modulator was employed in [164] to properly regulate the speed of the generator in order to maximise overall power production while also controlling real and reactive power generation via rotor side control scheme. In [165] a neuro fuzzy PI-gain scheduler with VC technique is introduced to make the system respond faster, settle down faster, and not make steady-state errors. Furthermore, it compares the efficiency and effectiveness of the DFIG system to that of a traditional PI controller. In [166] the introduction of an effective control scheme for the grid-connected DFIG with interval type-2 fuzzy sets (DFIG) with vector control technique is presented, DFIG is suitable for dealing with irregularities in the operating conditions of distributed systems, such as fault, load variations and wind velocity. The controller's output is evaluated by integrating it to an IEEE 34-bus test sample and accounting for multiple uncertainties. While the type-1 FLC can handle nonlinearity in the system, the type-2 FLC is far more efficient at dealing with system uncertainties. As a conclusion, these concepts open up a new field of application for the use of fuzzy control to enhance the FRT capabilities of DFIG using both active and passive techniques.

(e) Other Advanced control

Numerous new advanced techniques and modelling methodologies have been suggested to investigate and address DFIG's LVRT capacity. Newly proposed approaches include SMES based on FLC in [167] and a series linked current source converter dependent SMES in [168] to enhance the DFIG's LVRT performance. An adaptive learning control approach for WECSs with DFIG is presented in [169]. DFIG-LVRT WT's performance will also be improved with Heightened state-feedback predictive control as presented in [78]. In [170], a Novel controlled DFIG-WT crowbar is presented for fault level mitigation using adaptive neurofuzzy inference system. The study in [171] introduces a fuzzy-based technique for wind velocity prediction in Maximum Power Point Tracking (MPPT) configuration within normal circumstances and a coordinated Genetic Algorithm-based Active-Reactive (GA-PQ) controller incorporating DC chopper in FRT technique during grid failures. A transient reconfiguring approach for the DFIG

is presented and studied in [172] in order to improve its LVRT capacity. It is based on a modified rotor-voltage-reference technique.[173] provides an enhanced FRT systems for WECS equipped with DFIG that is based on proper stator voltage regulation and is capable of addressing symmetrical, unsymmetrical, and unbalanced grid voltage droops. This is achieved by using a correctly adapted topology of the standard WECS with DFIG, which allows the stator voltage to be regulated through the rotor power converters system.

A new robust fractional-order supertwisting sliding mode control was developed and suggested in [174] for supercapacitor-based power supplies in order to maintain a constant and smooth DC voltage and to rapidly improve the FRT and PQ capabilities of DFIG-based wind turbines. The frequency variation induced by the voltage dip is addressed in [175] using a P-Q coordination-based LVRT control technique for wind farms. By using an offline look-up table technique, the suggested strategy may adaptively deliver the active and reactive reference currents, thereby reducing the absence of active power generation and speeding up active power recovery during the LVRT interval. The study in[176] proposes a cooperative strategy using Virtual Inertia Control (VIC) and a redesigned GSPEC for Low Voltage Ride Through (LVRT) in order to meet Grid Code Requirements while also offering frequency support to the grid via synthetic inertia. Table 4. 7 concludes with a comparative analysis of FRT.

Table 4. 7 Comparative Analysis of Internal control modification-based control technique for DFIG

S.No	Control	Advantages	Disadvantages
a.	FFTCC [153]	By effectively controlling the transient current, the torque pulsation caused by the negative sequence current is significantly diminished.	- Involves intricate control mechanisms. - Requires input voltage sensing. - Exhibits sluggish response characteristics.
b.	MPC [154] [155]	- Accounts for the non-linearities and constraints within the system. - Demonstrates rapid and dynamic response capabilities.	- Significantly expensive. - Requires experimental validations for verification.

c.	Sliding mode control [161]	• Resilient to external disturbances. • Imposes no additional technical strain on the wind turbine drive train.	• The chattering effect induces oscillations. • The model exhibits complexity. • Control input signals may experience saturation.
d.	Fuzzy-based Control[164]	• Fuzzy control helps minimize insignificant transient overshoot.	• Associated with high costs. • Introduces complexity and increases power consumption. • Exhibits poor time response.

4.5 Modified fuzzy logic based Parallel protection scheme

A novel protection scheme is introduced to enhance the Fault Ride-Through (FRT) capabilities of the Doubly Fed Induction Generator (DFIG) based Wind Energy Conversion System (WECS). Leveraging the existing hardware components within a DFIG system, a Fuzzy Logic (FL) controlled, enhanced parallel protection approach is proposed. This scheme harmoniously unites a rotor-end series dynamic braking resistor (RSDBR), a DC link braking chopper (DCBC), and a rotor-end parallel resistance crowbar (REPRC) in a comprehensive topology. Each of these components, while interconnected in unique ways as shown in Figure 4.21, fall under the strategic control of a FL system. The RSDBR provides primary protection in this scheme, with the crowbar circuit being activated if the RSDBR is unable to protect due to a deteriorating scenario. Depending on the situation, the REPRC will only be activated at the beginning or end of the fault. The DCBC is used to regulate the excessive voltage produced by the dc link. However, a DCBC on the DC link is not required for FRT operation; however, it does help to smooth the DC link voltage and expands the normal range of DFIG operation for higher active power imbalances between the converters.

The coordination between REPRC, DCBC, and RSDBR can be accomplished through the use of a switching mechanism designed using FL controller. It is important to note the length, kind, and position of the fault in the DFIG's fed power system to analyze the severity of the over-current during disturbances in the three-phase rotor windings of the DFIG. Some faults may cause problems with excessive current, while

others may only cause problems with excessive voltage. If the protection systems are not precisely synchronized, overcurrents can damage the RSPEC's semiconductor switches and/or generate overvoltage's in the DC link capacitor.

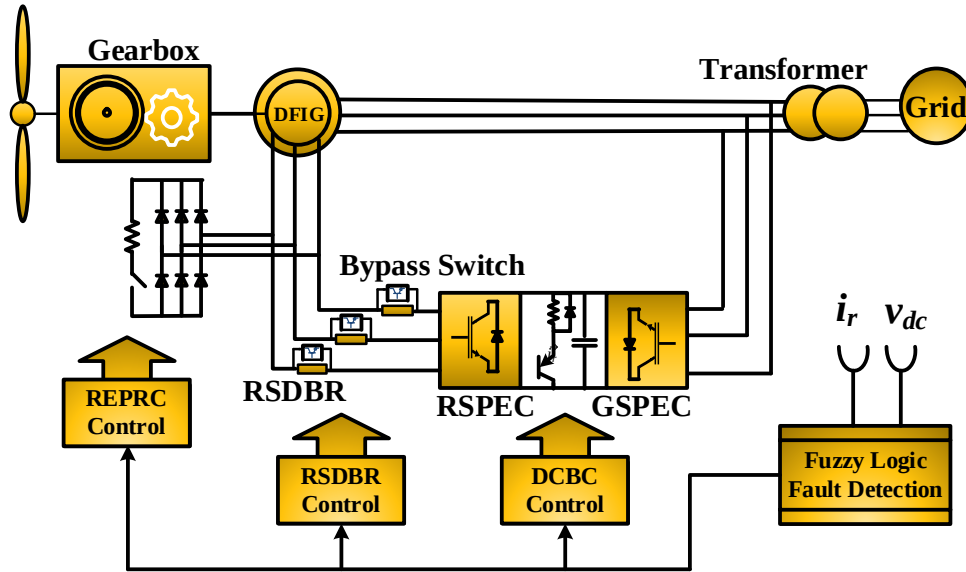


Figure 4. 21 DFIG with Modified FL-based parallel protection scheme

This paragraph describes the protection mechanism for a DFIG system in the event of faults. Table 2 shows scenarios for over-current and over-voltage problems, with the most vulnerable component of the DFIG identified in the third column, and the protection system that should be activated in the fourth column. If the first protective mechanism fails, the second system attempts to minimize the excess current or voltage, and if it still exceeds the maximum permissible value, the DFIG PECs are disconnected, according to the final column in Table 4. 8. Fuzzy logic (FL) is used to design the protection mechanism, with the Sugeno FL model suggested using MATLAB-Simulink, as it requires fewer hardware resources than standard Boolean logic.

Table 4. 8 Coordination of Protection Techniques in Various Scenarios

OC¹	OV²	MVP³	FPA⁴	SPA⁵	TPA⁶
No	No	-	-	-	-
Yes	No	RSPEC	RSDBR	REPRC	DCBC
No	Yes	DC Link	DCBC	RSDBR	REPRC
Yes	Yes	RSPEC and DC Link	RSDBR	DCBC	REPRC
High OC	No	RSPEC	REPRC	RSDBR	DCBC

	High OV	DC Link	DCBC	REPRC	RSDBR
High OC	High OV	RSPEC and DC Link	REPRC		DCBC

¹ Overcurrent, ² Overvoltage, ³ Most susceptible part, ⁴ First protective action, ⁵ Second protective action, ⁶ Third protective action

The protection system for converters is designed using fuzzy if-then rules as discussed in Table 2 with two input variables: rotor current and DC bus voltage. Each variable has a defined range with membership functions. The rules generate three output variables to determine if the protection system should be turned on or off. The following are the inputs:

- Rotor current
- DC Link Voltage

The first input's Membership function (MF) is defined as follows:

LOW

- MEDIUM
- HIGH
- NEGATIVEMID
- NEGATIVEHIGH

The first MF 'LOW' is placed in the acceptance limits that it does not destabilize the system. The second MF 'MEDIUM' is positioned in the system such that its current value is between the rated current and the current that can cause system damage. The third MF 'HIGH' has the current through the circuit is extremely high and has the potential to cause system damage. Similarly for the negative values membership functions is designed.

Similarly in the second input the Membership function is defined as follows

- LOW
- MEDIUM
- HIGH

The first membership function 'LESS' is placed in the acceptance limits so that it does not destabilize the system. The second membership function 'HIGH' is positioned in the system such that its voltage value is between the rated voltage and the voltage that can cause system damage. The third membership function 'VERY HIGH' has a voltage through the circuit that is extremely high and has the potential to cause system damage.

Three different outputs are used to map the different inputs of the membership function. They are as follows:

- RSDBR ON
- DCBC ON
- CROWBAR ON

This study uses the Takagi-Sugeno-Kang technique of fuzzy inference to identify the output, the only difference between it and mamdani is that the sugeno output function is either linear or constant, and in this study, the constant output membership function is used called as fuzzy singleton. A fuzzy singleton, is a fuzzy set with a membership function which is unity at one point in the universe and zero everywhere else. The basic conditions of the Sugeno fuzzy inference system are as follows:

If Input= p and Input 2 = q, then Output is $z = f(p, q)$

Usually $f(p, q)$ is a polynomial of the input variables p and q. but it can be any function. In this model 'f' is constant ($z=pa+qb+c$ where $a=b=0$) because of a fuzzy singleton case).

The output level z_i of each rule is weighted by the firing strength w_i of the rule. For example, for an AND rule with Input 1 = p and Input 2 = q, the firing strength is

$$w_i = \text{AND Method } (F1(p), F2(q))$$

Where $F1(p)$, $F2(q)$ are the membership functions for Inputs 1 and 2. The weighted mean of all rule responses, calculated as the final output of the system.

$$\text{Final Output} = \frac{\sum_{i=1}^N w_i z_i}{\sum_{i=1}^N w_i}$$

Where N is the number of rules. A Sugeno ruling functions as depicted in the Figure.4.20

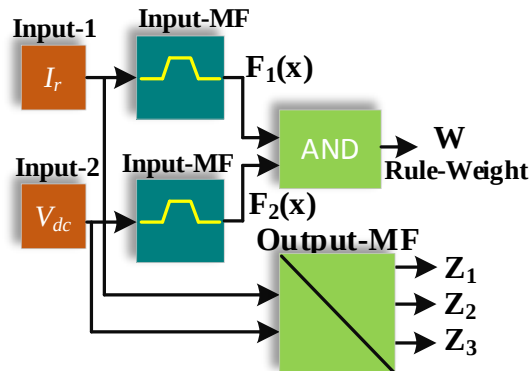


Figure 4. 22 Fuzzy System

For the first output variable, two membership functions are used to toggle the RSDBR protection SMALL and LARGE. Whereas SMALL defines Off state and LARGE denotes ON state. Similarly, the membership functions for the second and third outputs are SMALL and LARGE, the second output is used for CHOPPER switching, and the third output is used for CROWBAR. The following are the membership functions:

- SMALL
- LARGE

Lastly, the input membership functions and the output membership functions are plotted using well-defined sets of rules. If-then rules are used to set the following rules as shown in Figure 4. 23 Fuzzy Logic Interface Tools for System Analysis

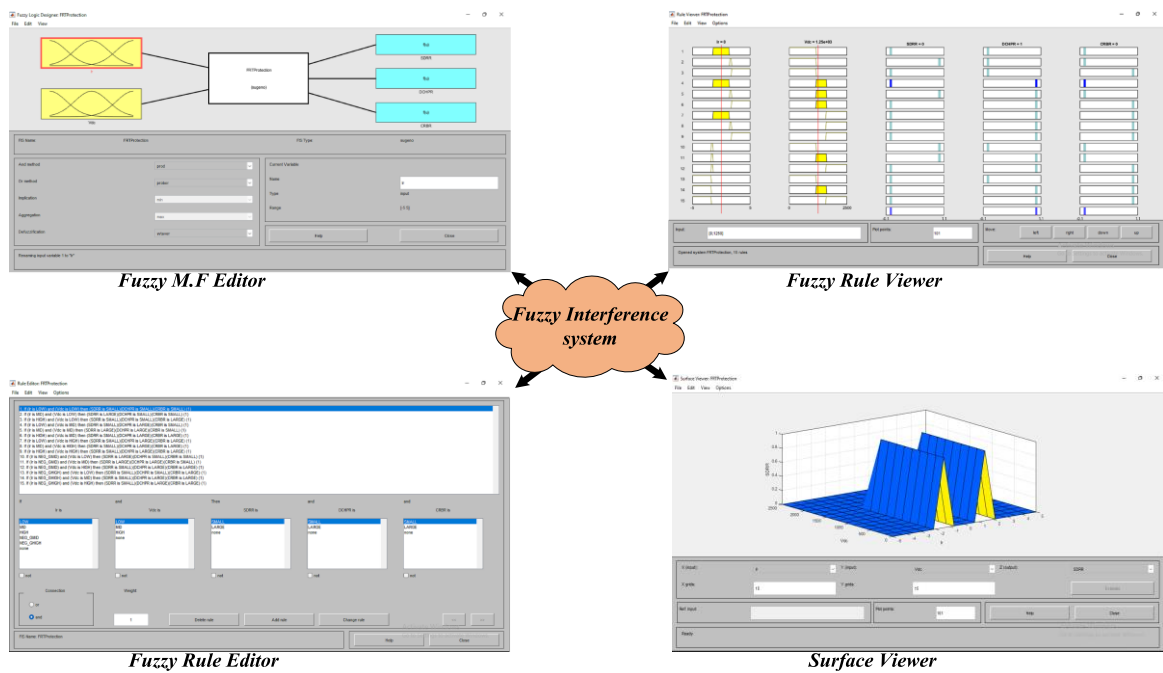


Figure 4. 23 Fuzzy Logic Interface Tools for System Analysis
Implementing this cohesive system, in conjunction with coupled crowbars, confers a number of significant benefits:

- It induces a reduction in the dc-link Voltage fluctuation range following the application of the improved control strategy, signaling the achievement of a rapid dynamic response. This is in contrast to the longer stabilization time required when relying solely on REPRC operations.
- Even with the rotor crowbar connected briefly, the dc-link voltage maintains stability. This underscores the value of employing the proposed enhanced technique, as this amalgamation can help curtail the dc voltage

fluctuation during a fault more promptly, thus minimizing the rotor crowbar switching time.

- The DFIG's uncontrolled operation period is curtailed, thereby preventing it from behaving like a Squirrel-Cage Induction Generator (SEIG) for extended periods. This facilitates quicker control over the machine's reactive power exchange with the grid.
- The coordinated strategy proposed reduces the magnitude of rotor and stator currents during fault scenarios.
- Upon implementing the suggested coordinated system, the torque oscillation of the generator exhibits less dampening, enabling the DFIG to deliver a higher quantity of reactive power to the grid during the post-fault transition phase.

The potency of this advanced protection technique has been scrutinized across an array of symmetrical and asymmetrical faults, such as single-phase, two-phase, and three-phase ground faults, revealing its robust performance in diverse fault conditions.

4.5.1 RSDBR and REPRC Resistance Values

The correct value of the resistance is usually the most crucial aspect in reducing the rotor current. It is not enough to determine the resistance value based only on the lower rotor current that occurs under fault conditions. Under faults, this selected value should be subject to a minimal DC voltage tolerance variation. It is important to select appropriate values for the resistor parameters. The RSDBR and REPRC resistance values can be determined from a transient study of stator voltage magnitude fluctuations, slip, and rotor speed. The resistance values are calculated under the worst conditions (with the highest peak current): Symmetric voltage drops up to 1.0p.u in the most severe condition. The expressions of the rotor-current are derived below:

As can be seen from Equation 3. 43-3. 46, RSPEC is a way to regulate the rotor voltage (v_r), which in turn is used to control the DFIG. First, remove i_s from Equation (3. 45) and (3. 46), then substitute it into Equation (3. 44). then, eliminate rotor flux ($\vec{\psi}_r$), which leads to the formula.

$$\vec{v}_r = \frac{L_m}{L_s} \left(\frac{d}{dt} - j\omega_r \right) \vec{\psi}_r + [R_r + \left(\frac{L_s L_r - L_m^2}{L_s} \right) \left(\frac{d}{dt} - j\omega_r \right)] \vec{i}_r \quad 4.5$$

Defining leakage factor as

$$\lambda = \frac{L_s L_r - L_m^2}{L_s} \quad 4.6$$

The voltage produced by the stator flux is then represented by a voltage source $\vec{v}_{ro}$

$$\vec{v}_{ro} = \frac{L_m}{L_s} \left(\frac{d}{dt} - j\omega_r \right) \vec{\psi}_r \quad 4.7$$

So Equation (4. 5) becomes

$$\vec{v}_r = \vec{v}_{ro} + [R_r + \lambda \left(\frac{d}{dt} - j\omega_r \right)] \vec{i}_r \quad 4.8$$

In Equation (4. 8), It is useful to interpret the rotor voltage in the rotor reference frame by multiplying both sides by $e^{-j\omega_r t}$

$$\vec{v}_r^r = \vec{v}_{ro}^r + R_r \vec{i}_r^r + \lambda L_r \frac{d\vec{i}_r^r}{dt} \quad 4.9$$

This Equation describes the connection between rotor voltage and current. As a result, the rotor circuit model is obtained and illustrated in with all earlier protection systems.

The voltage expression for phase 'a' is

$$v_{ra}(t) = \text{Re}\{\vec{v}_{ro}^r\} + R_r i_{ra}(t) + \lambda L_r \frac{di_{ra}^r(t)}{dt} \quad 4.10$$

For $i_{ra}(t)$ can be expressed in the form of a linear differential equation

$$i_{ra}'(t) + \frac{R_r}{\lambda L_r} i_{ra} = \frac{1}{\lambda L_r} [v_{ra}(t) - \text{Re}\{\vec{v}_{ro}^r\}] \quad 4.11$$

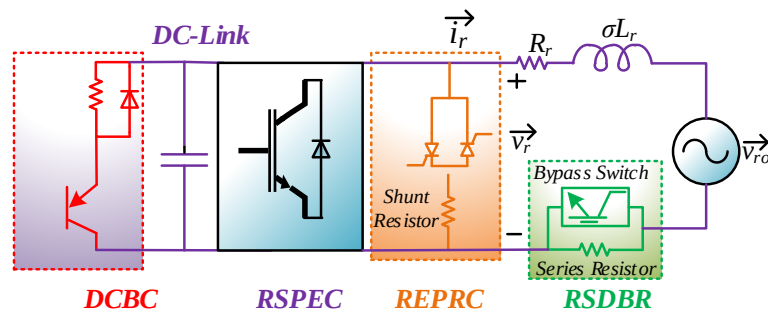


Figure 4. 24 Model of DFIG rotor equivalent circuit illustrating all protection schemes

Consequently, with the converter operational, $v_{ra}(t) = V_r \cos(s\omega_s t + \beta)$, where β is the phase-a rotor voltage angle at the time of loss.

For a symmetrical voltage interruption on the stator, if there will be a three-phase step magnitude transition from V_s to $(1-p) V_s$ (where p is the voltage sag ratio), $\vec{v}_{ro}^r$ in

Equation (4. 9) can surpass the upper limit voltage that the RSPEC can produce, causing the current control to fail. The voltage is

$$\overline{v_{ro}^r} = (1-p)V_s \frac{L_m}{L_s} s e^{js\omega_s t} - \frac{L_m}{L_s} \left(\frac{1}{\tau_s} + j\omega_r \right) \frac{pV_s}{j\omega_s} e^{-t/T_s} \quad 4.12$$

Considering that time constants are defined as

$$T_r = \frac{\lambda L_r}{R_r}, \quad T_s = \frac{L_s}{R_r}, \quad T = \frac{T_s T_r}{T_s - T_r} \quad 4.13$$

Equation (4. 11) can be modified by discarding $1/T_s$, which is negligible due to the minimal stator resistance of the generator; hence, $1/T_s$ can be omitted.

$$\overline{v_{ro}^r} \approx V_s \frac{L_m}{L_s} [s(1-p)s e^{js\omega_s t} - (1-s)p e^{-j\omega_r t} e^{-t/T_s}] \quad 4.14$$

From Equation (4. 11) and (4. 14), the final expression of $i_{ra}(t)$ can be solved and split into four parts.

$$\dot{i}_{ra}(t) = \dot{i}_{dc} + \dot{i}_{vr} + \dot{i}_{vrn} + \dot{i}_{vrf} \quad 4.15$$

Where the components are

$$\dot{i}_{dc} = \dot{i}_{ra}(t_0^-) - \frac{1}{\lambda L_r} \frac{T_r}{1+T_r^2(s\omega_s)^2} \times [V_r \cos \beta - V_s \frac{L_m}{L_s} s(1-p)] \quad 4.16$$

$$- \frac{1}{\sigma L_r} V_s \frac{L_m}{L_s} (1-s)p \frac{T}{1+T^2(\omega_r)^2} e^{\frac{-t}{T_r}}$$

$$\dot{i}_{vr} = \frac{V_r}{\lambda L_r} \left[\frac{T_r}{1+T_r^2(\omega_r)^2} \cos(s\omega_s t + \beta) + \frac{T_r^2}{1+T_r^2(\omega_r)^2} \sin(s\omega_s t + \beta) \right] \quad 4.17$$

$$\dot{i}_{vrf} = \frac{1}{\lambda L_r} V_s \frac{L_m}{L_s} s(1-p) \times \left[\frac{T_r}{1+T_r^2(s\omega_s)^2} \cos(s\omega_s t) + \frac{T_r s\omega_s}{1+T_r^2(s\omega_s)^2} \sin(s\omega_s t) \right] \quad 4.18$$

$$\dot{i}_{vrn} = \frac{1}{\lambda L_r} V_s \frac{L_m}{L_s} s(1-p) \times \left[\frac{T}{1+T^2\omega_r^2} \cos(\omega_r t) + \frac{T^2\omega_r}{1+T^2\omega_r^2} \sin(\omega_r t) \right] e^{\frac{-t}{T_s}} \quad 4.19$$

Due to the lower stator resistance, the relevant approximations are made: $e^{-t/T_s} \approx 1; T = T_r$. The components of the current are then written as a single trigonometric function as a

$$i_{dc} = i_{ra}(t_0^-) - \frac{1}{\lambda L_r} \frac{T_r}{1+T_r^2(s\omega_s)^2} \times V_r \cos\beta - \frac{1}{\lambda L_r} V_s \frac{L_m}{L_s} (1-s) p \frac{T}{1+T^2(\omega_r)^2} e^{\frac{-t}{T_r}} \quad 4.20$$

$$i_{vr} = \frac{V_r}{\lambda L_r} \left[\frac{T_r}{\sqrt{1+T_r^2(\omega_r)^2}} \sin(s\omega_s t + \beta + \delta) \right] \quad 4.21$$

$$i_{vrf} = 0 \quad 4.22$$

$$i_{vrn} = \frac{V_s}{\lambda L_r} \frac{L_m}{L_s} (1-s) \times \left[\frac{T_r}{\sqrt{1+T_r^2\omega_r^2}} \sin(\omega_r t + \delta) \right] \quad 4.23$$

Taking each component's amplitude at its maximum current value into consideration

$$i_{r\alpha, \max} = i_{ra}(t_0^-) - \frac{V_s}{\lambda L_r} \frac{L_m}{L_s} (1-s) \frac{T_r}{1+T_r^2(\omega_r)^2} + \frac{V_r}{\lambda L_r} \frac{T_r}{\sqrt{1+T_r^2(\omega_r)^2}} + \frac{V_s}{\lambda L_r} \frac{L_m}{L_s} (1-s) \frac{T_r}{\sqrt{1+T_r^2(\omega_r)^2}} \quad 4.24$$

In addition to this, the boundary conditions are

$$i_{r\alpha, \max} \leq I_{th_RSDBR}, \quad V_r \leq V_{th_RSPEC} \quad 4.25$$

As a result, (4.24) and (4.25) are Equation that T_r can be solved.

With the protective mechanisms

$$T_r = \frac{\lambda L_r}{R_r + R_{protection}} \quad 4.26$$

Finally, the crucial resistance value known as $R_{protection}$ can be determined. If the rotor fault currents are unable to be effectively restricted, the crowbar can be utilized as supplemental protection. $R_{protection}$ refers to total resistance, which comprises RSDBR and REPRC. RSDBRs provide current-limiting operation, so the critical condition for the crowbar resistance is the voltage across it must be within the limits of the rotor voltage to which it is connected in parallel: $R_{CB} \times i_{r, \max} \leq V_{r, \max}$. As a result, crowbar resistance contributes only a minor portion of total $R_{protection}$. This method of resistors with minimum and maximum levels is easier to use than crowbar protection alone. The rotor winding current limit sets the lowest value, and the converter terminal voltage limit sets the highest [177].

4.6 Simulation Results

In MATLAB Sim-Power Simulink, a WECS with six 1.5 MW DFIG-based wind turbines tied to a 25 kV distribution structure that transmits power to a 120 kV grid via a 30-km 25 kV feeder was modeled. The system was tested for dynamic response under various faults at "0.5 s". The system was initially tested without any protection, then with REPRC, and finally with the proposed coordinated protection scheme. The simulation time was kept short to check the system's rapid response. The findings are analyzed in the subsequent subsections. The appendix provides the generator parameters. The simulation was conducted with a constant wind speed of 15 m/s and the DFIG WECS supplying real power to the power system. The simulated fault condition is:

- 1) A symmetrical three-phase LLLG fault for 0.2 seconds
- 2) An Asymmetrical LL fault on two phases for 0.2 seconds
- 3) A Two phase to ground Asymmetrical LLG fault for 0.2 seconds

The values for the thresholds that are used in the calculation of R_{RSDBR} and R_{REPRC} are as follows: $I_{\text{th RSDBR}} = 1.5 \text{ p.u.}$, and $I_{\text{th REPRC}} = 1.8 \text{ p.u.}$ rotor slip is $s = -0.2 \text{ p.u.}$ for before the faults.

From Equation (4.25) and (4.26), $\tau_r = 0.26584 \text{ p.u.}$, $R_{\text{protection}} = 1.21 \text{ p.u.} = 0.4719 \Omega$. In summary, the total value of protection resistance should be 0.4719 ohm, and the task now is to find the optimal resistance value for the RSDBR in the DFIG system. This is important for maintaining LVRT capability, but increasing resistance can impact system efficiency and increase losses. The optimal value will be determined through MATLAB simulation during a 3-phase fault. In the system if the rotor fault currents cannot limit effectively, then only crowbar can be used as further protection. The total resistance is $R_{\text{protection}}$, includes RSDBR and REPRC. The current-limiting function is provided by the RSDBR, hence the critical criterion of crowbar resistance is that the voltage across it must be within the rotor voltage limit, for its shunt connection: $\text{REPRC} \times i_{r,\text{max}} \leq V_{r,\text{max}}$. Therefore, the crowbar resistance is a small contribution to the total $R_{\text{protection}}$. This is simpler than using crowbar protection alone, where the resistance has a lower and upper limit. The minimum value is restricted by the rotor winding current limit, while the maximum is set by the voltage limit.

To find the optimal value of resistance of RSDBR protection the additional simulation is conducted to investigate the impact of varying the RSDBR resistance on the LVRT capability of the system which is shown below in the form of graphs in the and it

shows that the optimum value for the RSDBR is 0.4ohm because the peak of stator, rotor current and DC Link voltage is minimum in the case of using 0.4 ohm and similarly the torque oscillation is minimum in the case of 0.4 ohm.

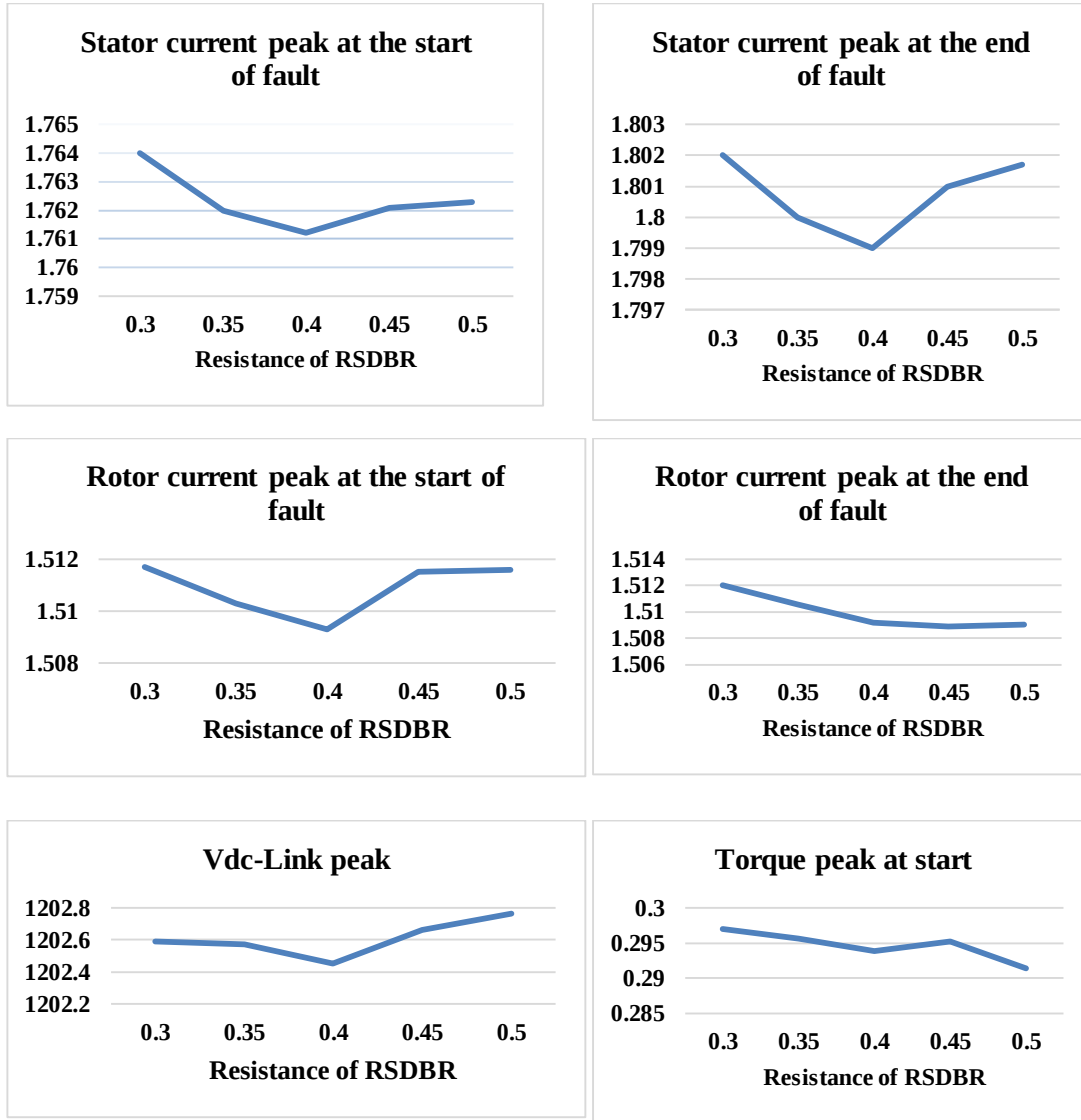


Figure 4. 25 Optmal value of resistance of RSDBR for protection

Then, the selected resistance values are $R_{RSDBR} = 0.4 \Omega$, $R_{REPRC} = 0.0719 \Omega$. Based on monitoring the maximum magnitude of dc voltage during the fault, the DCBC is activated. The relation between the charging activity and DCBC can be expressed as follows:

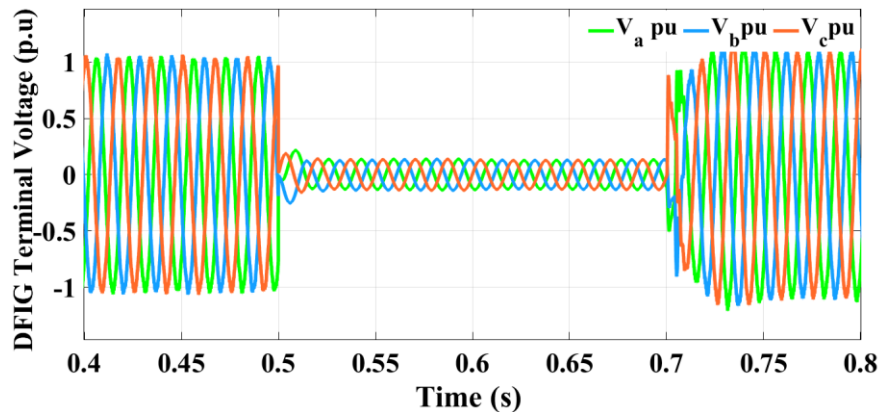
$$V_{r,max} - IR_{DCBC} - V_{DC} = 0 \quad 4. 27$$

According to Equation (32), it is possible to estimate the value of the DCBC " R_{DCBC} " by assuming that, in the event of a fault, the source voltage is zero (" $V_{r, max} = 0$ "). In this case, the current " I " through the resistor drops as the capacitor's loss of charge

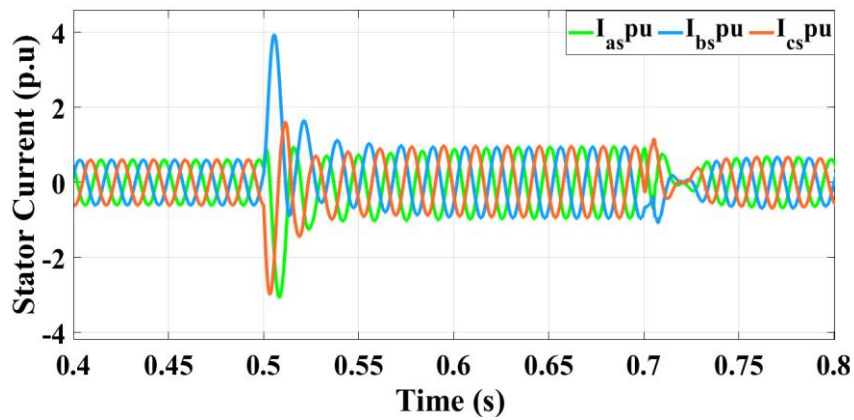
causes the voltage to drop. Upon reaching the nominal value of the capacitor's voltage, the dc-link crowbar resistance is determined, Therefore R_{DCBC} is taken as 0.5 ohm.

4.6.1 SYMMETRICAL FAULT CONDITION

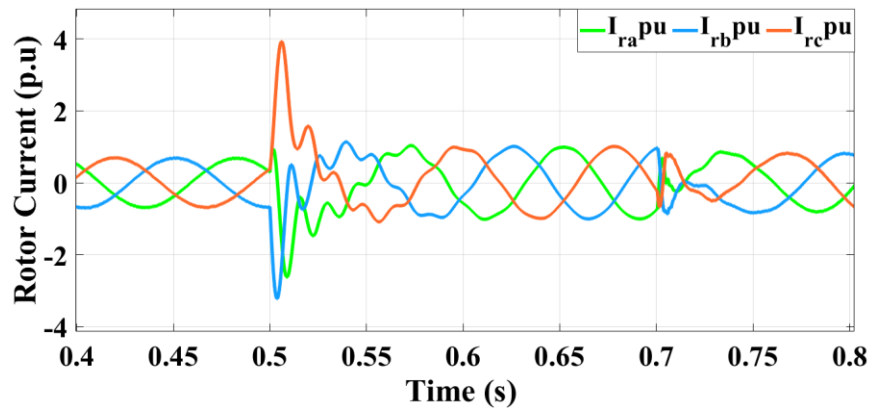
The simulation results from Figure 4.24 - 4.27 demonstrate the response of a DFIG during a LLLG symmetrical fault. Prior to the fault occurrence, the grid voltage and stator voltage remain constant, and the DFIG operates under normal conditions. The stator current and rotor current waveforms exhibit excellent performance, while the DC-link voltage remains constant, and the reactive power is maintained at nearly zero VAR. However, at time $t=0.5$ seconds, the grid fault instantaneously reduces the output voltage of the wind generator and decreases the stator voltage to 10% of its original value as can be seen in the Figure 4.24. This results in an abrupt increase in the rotor and stator current up to 4p.u, as well as an overvoltage in the DC-link bus voltage as shown in Figure 4.24. Without the protection system, the DFIG is unable to achieve FRT and can cause damage to the system's equipment due to the large failure voltages and currents.



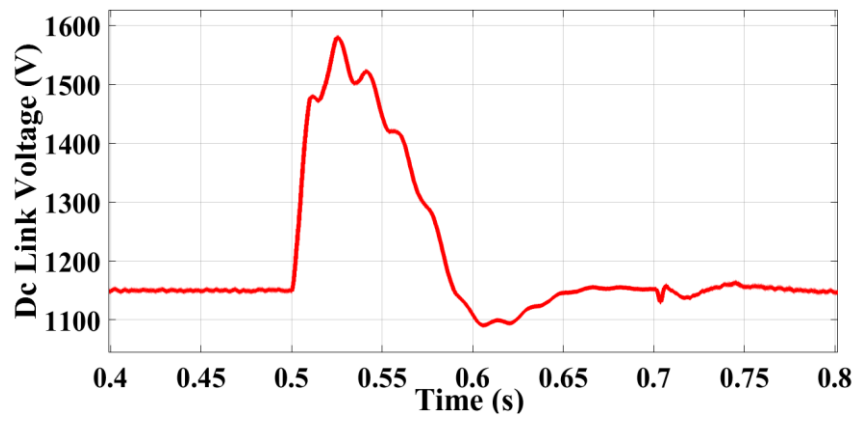
(a)



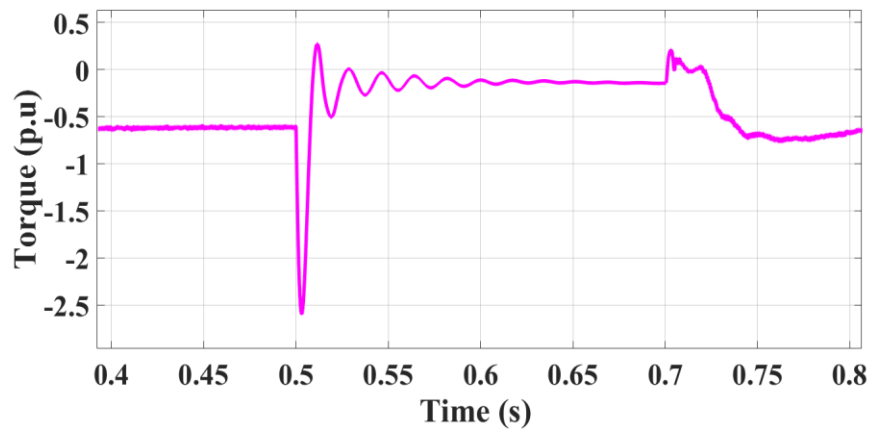
(b)



(c)



(d)



(e)

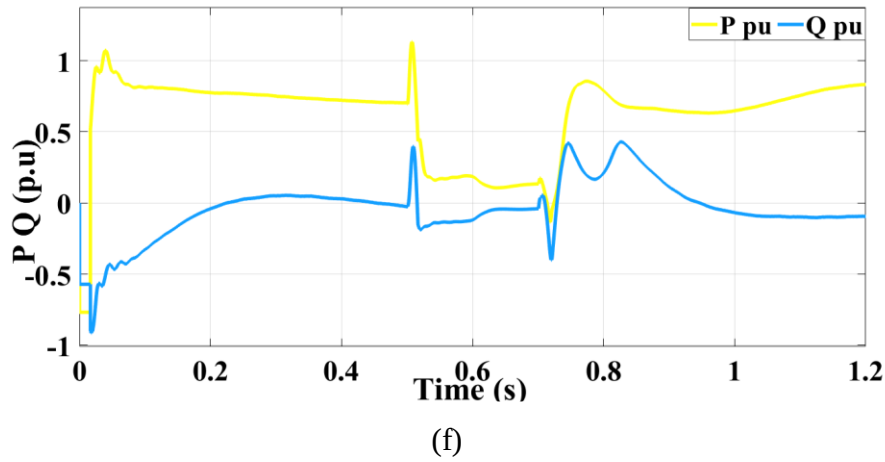
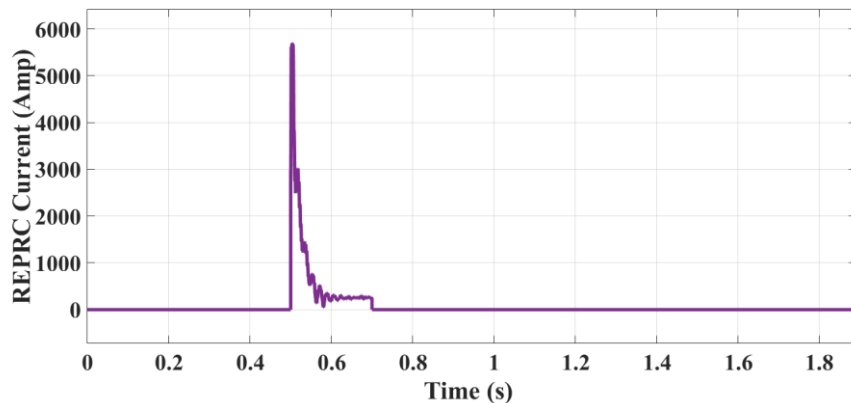
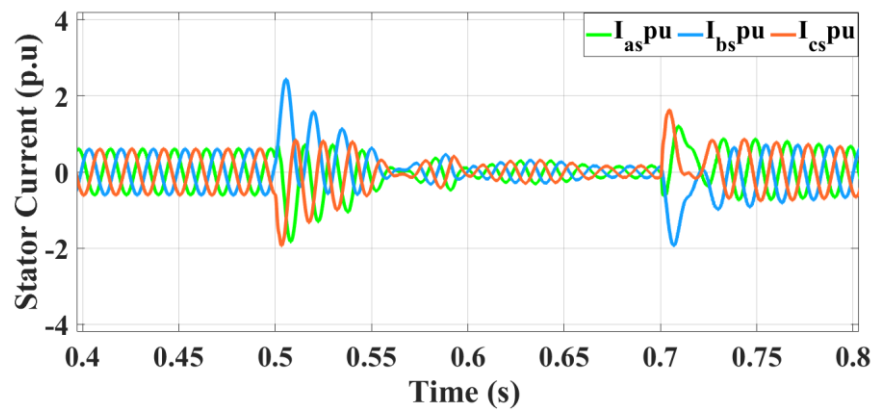


Figure 4. 26 DFIG's dynamic behavior in the absence of a protection system with Symmetrical Fault

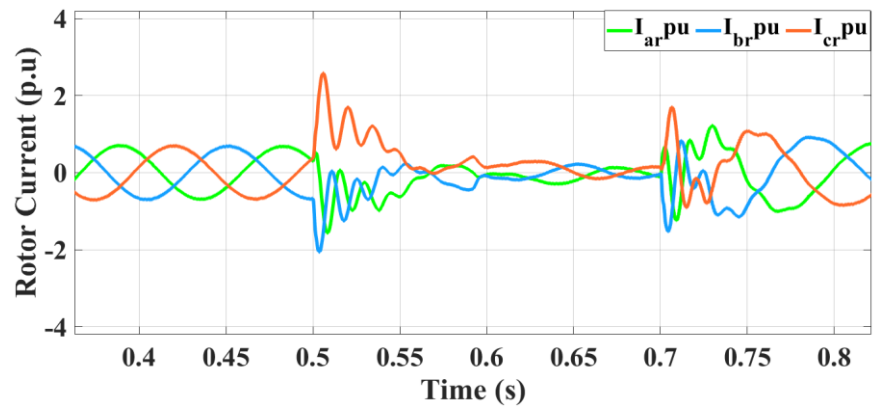
A traditional protection technique REPRC is used to protect a grid-connected DFIG-based system. This technique, however, has a disadvantage, its excitation causes the RSPEC and WT to lose control over their ability to control active and reactive power over the time. The REPRC technique is configured to activate whenever the rotor current exceeds 1.5 times the rated current; at this point, the RSPEC is short-circuited. The system detects stator-voltage losses at time $t=0.5$ seconds, triggering the REPRC and stopping the RSPEC. Figure 4.25 depicts the REPRC resistor current's behaviour, which rapidly increases and then rapidly decreases over time. This traditional protection technique has a substantial inhibiting effect on fault currents in the rotor and stator, limiting them within the DFIG system's permissible limits. also shows that with REPRC protection, the DC-link voltage drops significantly, especially when compared to Figure 4.24 **Error! eference source not found..** Although this traditional protection technique is effective in preventing system damage, its impact on active and reactive power control must be carefully considered.



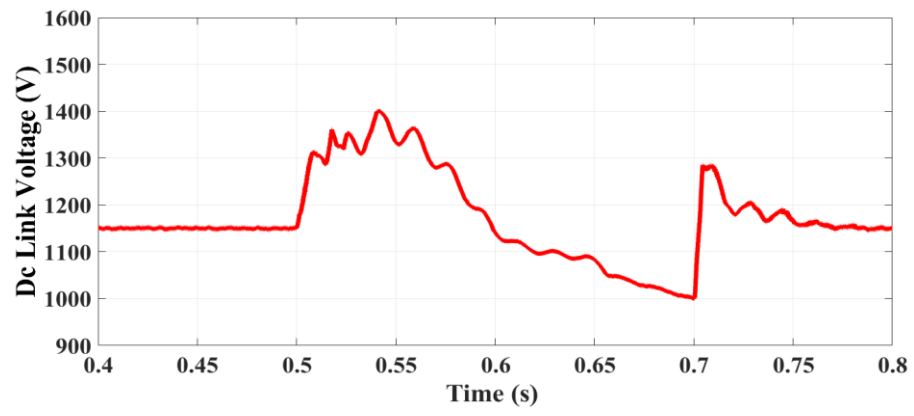
(a)



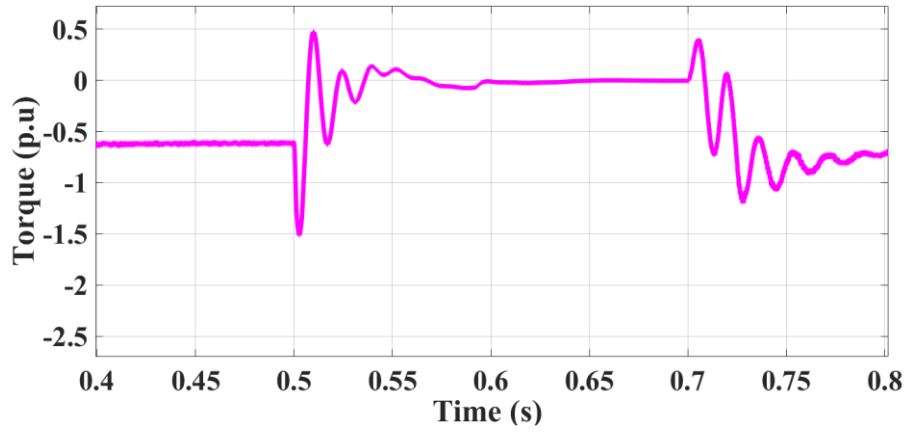
(b)



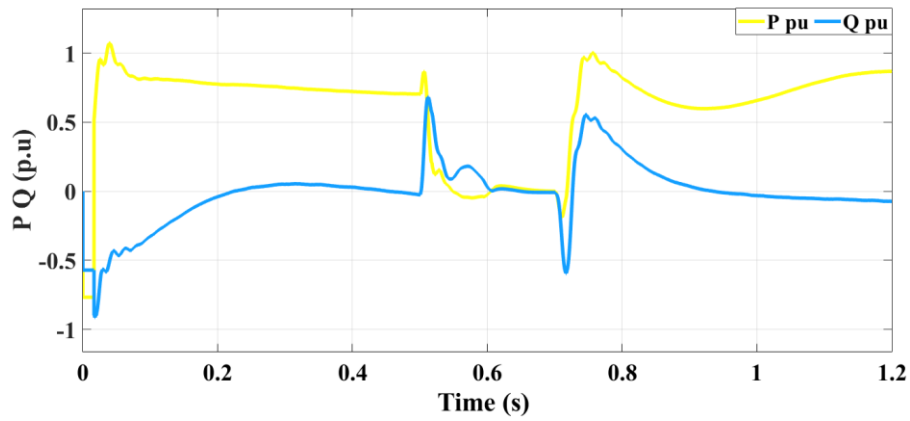
(c)



(d)



(e)

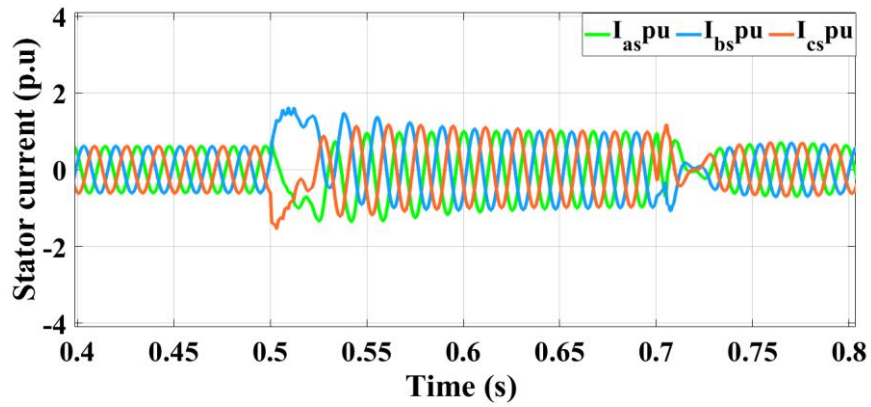


(f)

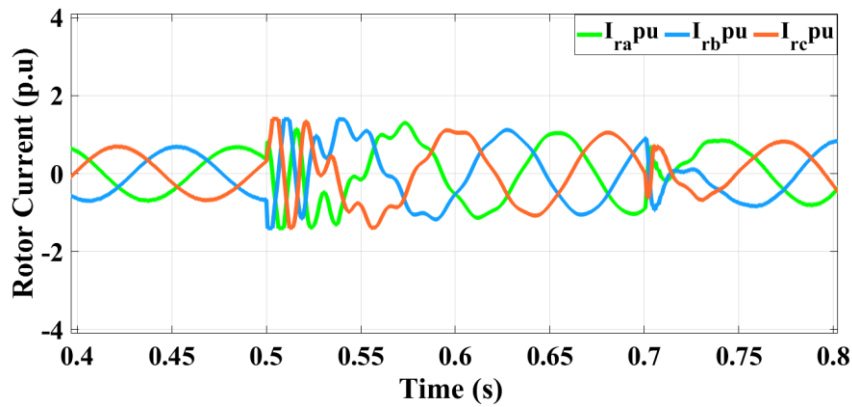
Figure 4. 27 DFIG's dynamic behavior in the presence of Crowbar protection system with Symmetrical Fault

Figure 4.26 depicts the switching of the Improved Parallel coordinated protection scheme, which shows that the RSDBR is engaged seven times to ensure that the rotor current is not exceeded. If the rotor current exceeds the REPRC threshold, the REPRC activates four times with the RSDBR engaged, while the DC Chopper protection is activated twice to ensure that the DC link voltage is within acceptable limits. According to the specifications, the improved parallel protection system method can effectively suppress the rotor current in less than 2 pu, implying that the FRT performance is superior to both no protection and REPRC protection, as shown in Figure 4.26. When using a REPRC alone, the DC-link voltage takes longer to reach a steady voltage level. When the parallel improved protection technique is used concurrently, this phenomenon is not observed. Even if the REPRC is only engaged for a brief period of time, the voltage on the dc connection becomes stable, and the dc-link voltage variation range is reduced to

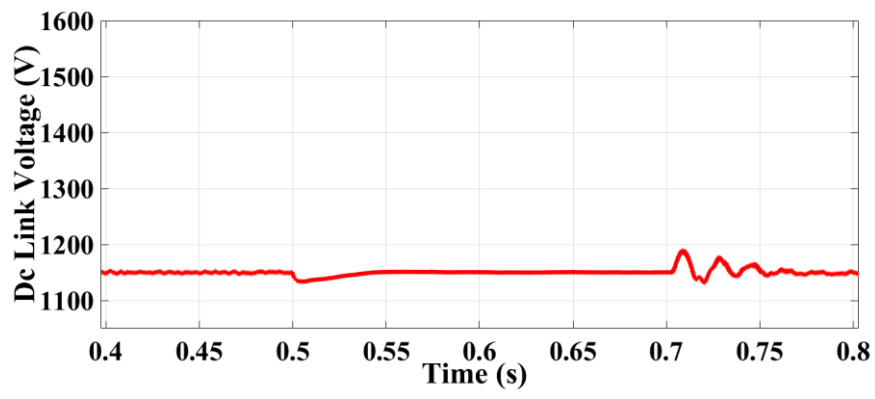
"30 V" with the parallel improved control protection technique, as illustrated in Figure 4.26. As a result, it is clear that the DCBC must be used in conjunction with the RSDBR and REPRC. This integration may aid in reducing the dc voltage swings that occur during a fault in a more efficient manner, thereby reducing the REPRC switching time. As a result, DFIG will not function as a SEIG for an extended period of time, resulting in the generator losing control in a relatively short period of time. As a result, when attempting to control its reactive energy exchange with the grid, the machine will have a faster response time. The simulation results in Figure 4.26 demonstrate the effectiveness of the improved method by limiting stator current and reducing dc bus voltage fluctuation to less than 1.2 times the rated value, ensuring that the converter is not affected. The comparative performance analysis is depicted in detail in Figure 4. 29 and Table 4.8.



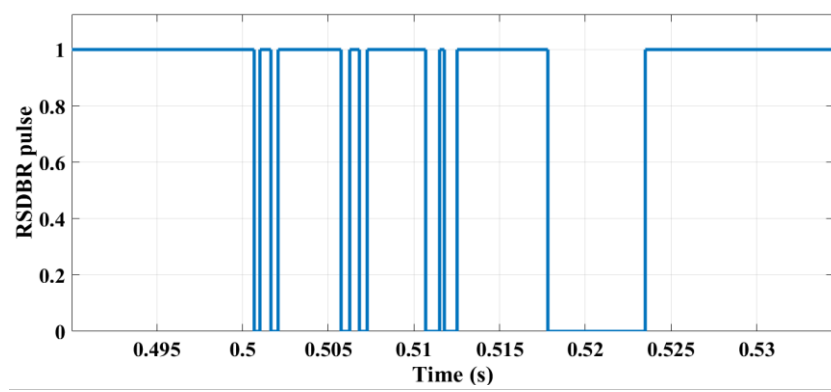
(a)



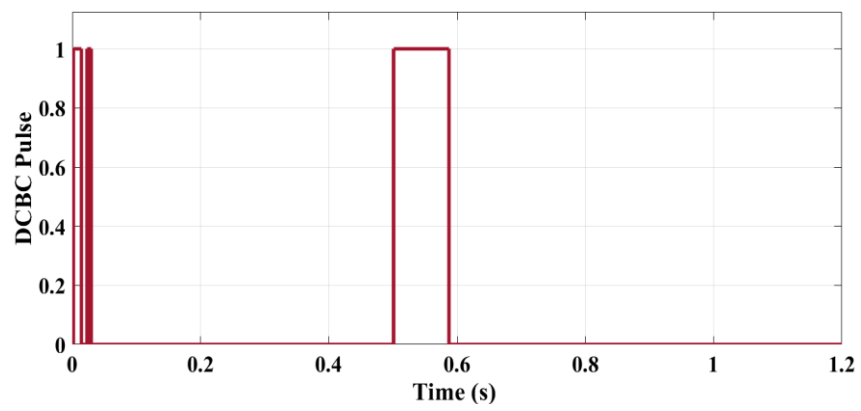
(b)



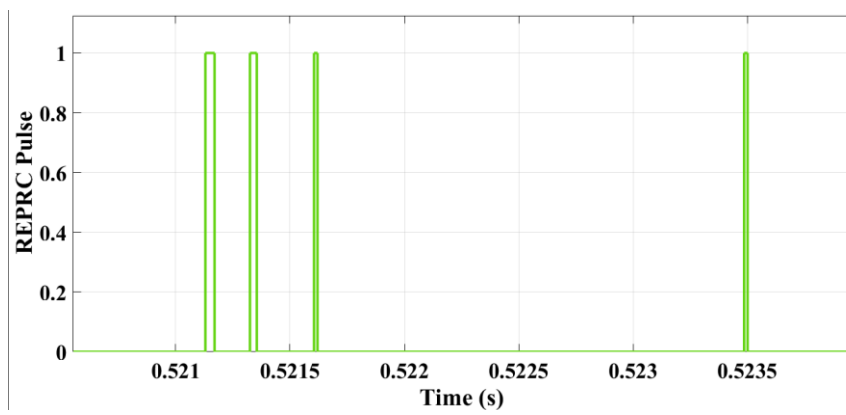
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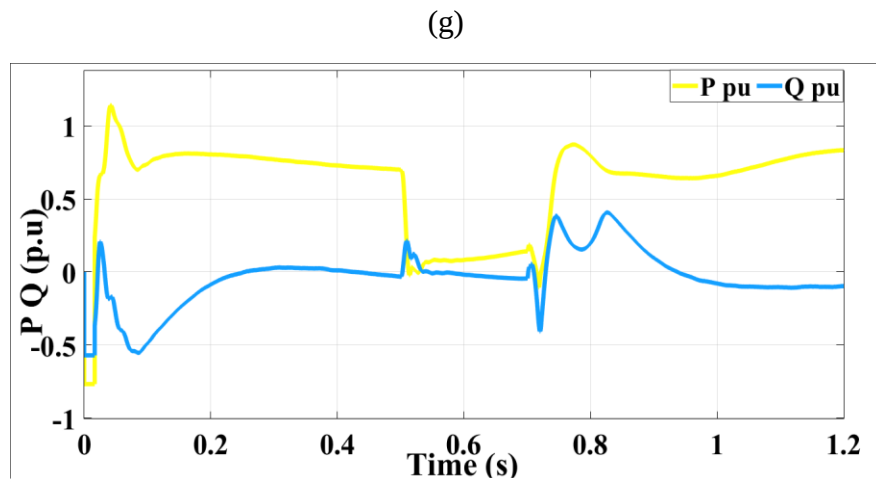
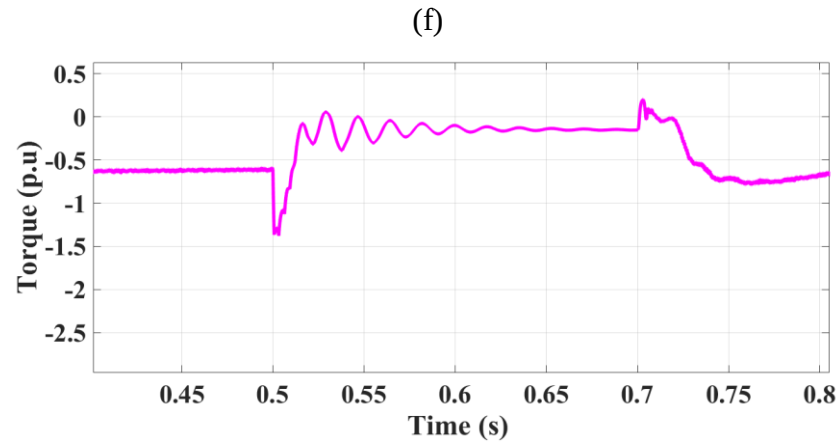


(d)



(e)





(h)

Figure 4. 28 DFIG's dynamic behavior in the presence of Proposed protection system with Symmetrical Fault

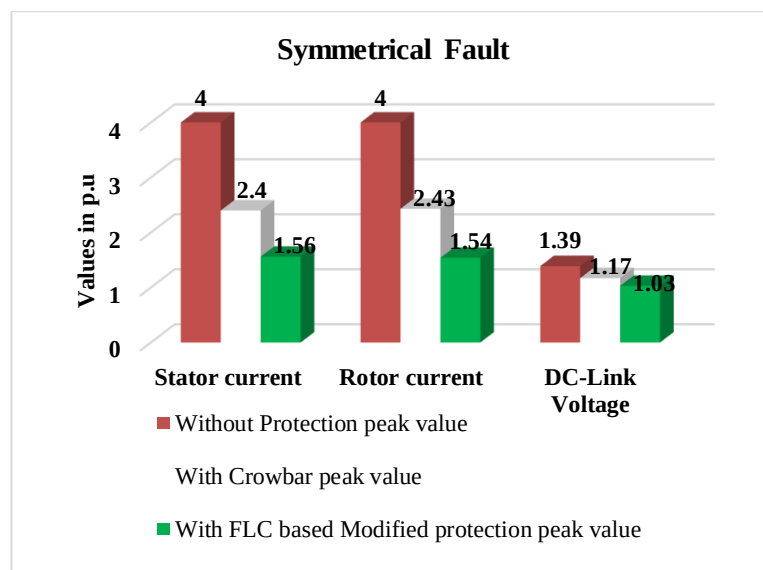


Figure 4. 29 Peak Values of Voltage and Current during Symmetrical Faults

Table 4.8 Comparative Performance Analysis Results during Symmetrical Fault

	Stator Current	Rotor Current	DC-Link Voltage
Without Protection Peak Value	4	2.4	1.56
With Crowbar Protection Peak Value	4	2.43	1.54
With FLC Based Modified Protection Peak Value	1.39	1.17	1.04

4.7.2 Asymmetrical Fault Condition

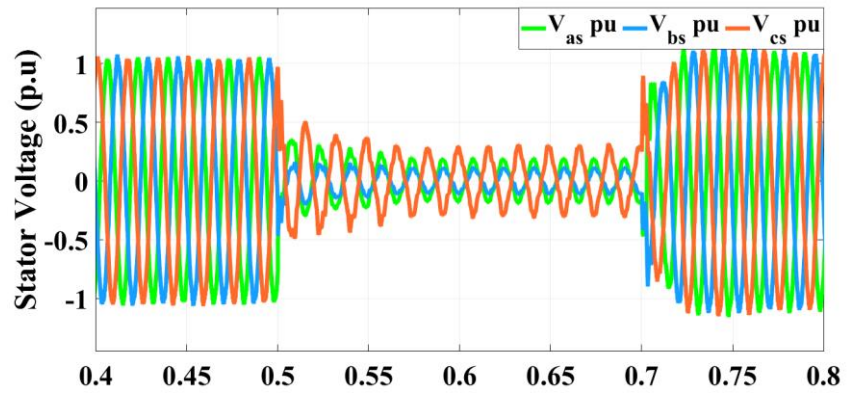
The functioning of the proposed coordinated technique in an asymmetrical fault condition is shown in this section. This section demonstrates the operation of the proposed coordination method under asymmetric fault conditions. The results obtained when using the modified coordinated protection strategy are included in this part of the paper and also in the absence of a protection system. The waveforms that are depicted in Figure 4.28 - 4.29 are those that are simulated if a two-phase short-circuit fault happens and the power system voltage drops to fifty percent without any protection technique and with protection technique.; and the waveforms depicted in

Figure 4. 32-31 are those that are generated in the event when a two-phase-to-ground short-circuit fault occurs and the grid voltage drops to fifty percent. Wind energy collected by wind turbines does not change significantly, resulting in an increase in the turbine's speed. A 2-phase short circuit and 2-phase grounding fault cause a short-term speed fall, signifying that the speed of the rotor is lesser than its synchronous speed at this moment. When the speed falls, the GSPEC is in the rectifier state; as the speed increases, the GSPEC shifts to the inverter state. The current of the rotor rises as the speed rises because the slip power increase through the RSPEC as shown in Figure 4.28 and

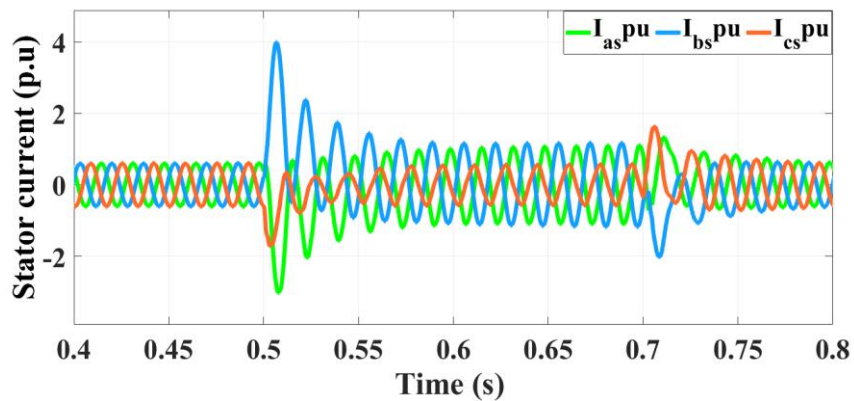
Figure 4. 32. Figure 4.28 -4.32 demonstrates that, prior to the occurrence of the fault, the grid voltage and stator voltage both remained constant, the DFIG is functioning normally, the waveforms of the stator current and rotor current are quite excellent, and the voltage of the DC-link voltage is also sustained constant and the reactive power has been almost maintained at 0 VAR. After the fault, the negative-sequence part of the stator flux linkage produces a surge current in the rotor current. In addition, stator current increased quickly up to 4p.u; the DC-link bus voltage also illustrates over-voltage

as can be seen in the Figures of the absence of protection technique which is Figure 4.28 and Figure 4.31. **Error! Reference source not found.** At time $t = 0.5\text{s}$, the Modified onfiguration recognizes the stator voltage loss and rise in rotor current and DC link bus voltage thus activating the protection system with the help of fuzzy logic control without stopping the RSPEC. The RSDBR has the distinctive advantage of being able to control the current directly. Furthermore, because the RSDBR is configured in series, the high voltage is shared by the resistance, so the induced excessive voltage does not cause RSPEC control to fail, and it also limits excessive rotor current. The modified control method can suppress the current and voltage surge, as shown in Figure 4.29 - 4.32. The Modified FL-based technique in this paper improves rotor current suppression during faults, and with the help of a FL-based controller, a wide range of conclusive results can be obtained as shown in

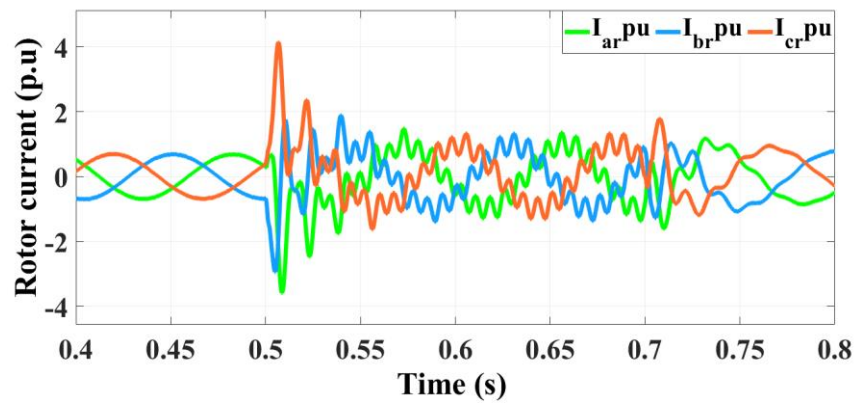
Figure 4. 32 and Figure 4. 35, and since the FL technique requires less hardware than traditional boolean values it is found to be acceptable and advantageous to use this technique. The comparative performance analysis is depicted in detail in Table 4.9. and Table 4.10



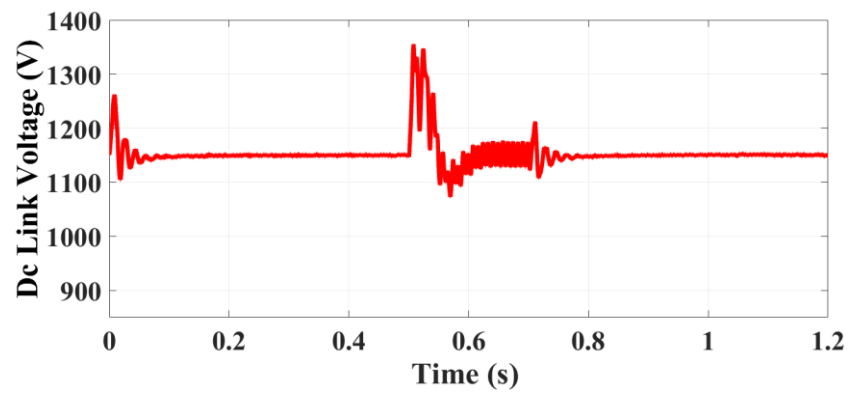
(a)



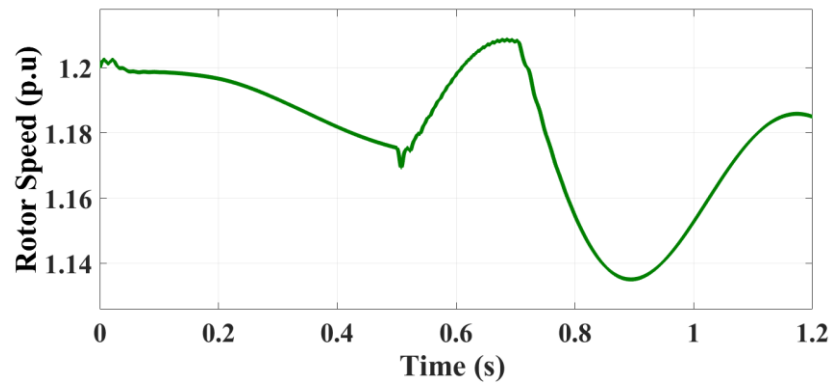
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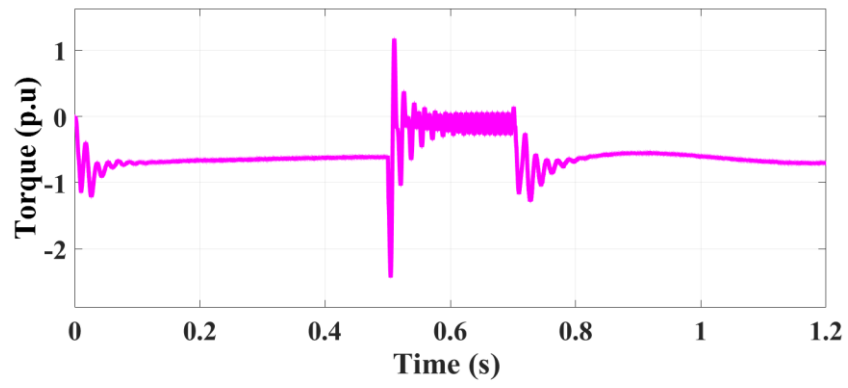
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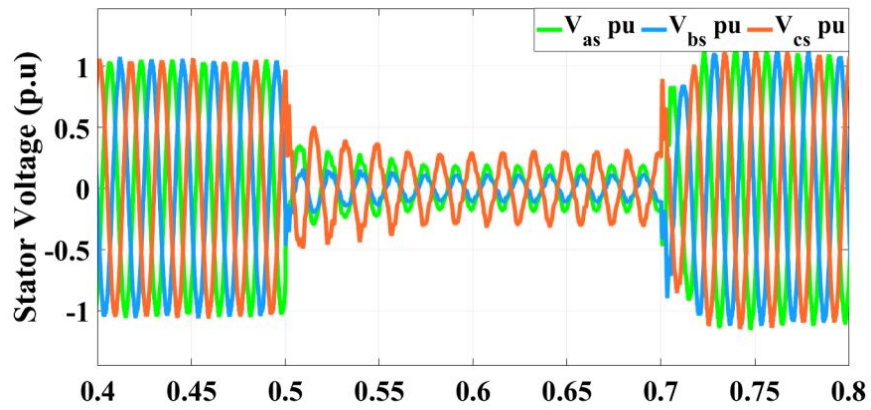


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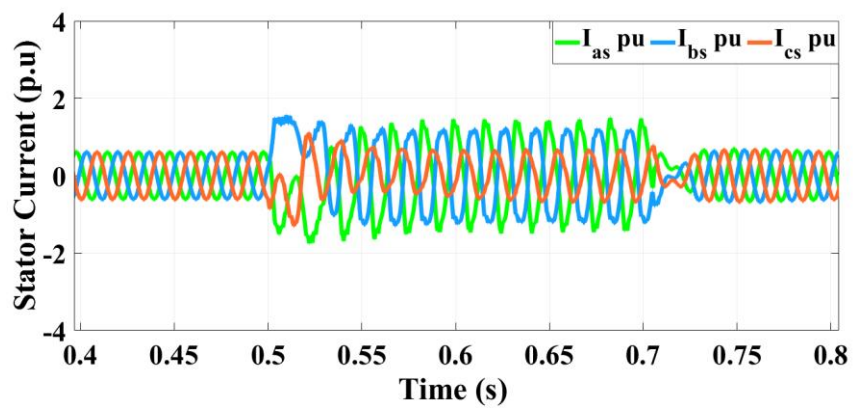


(f)

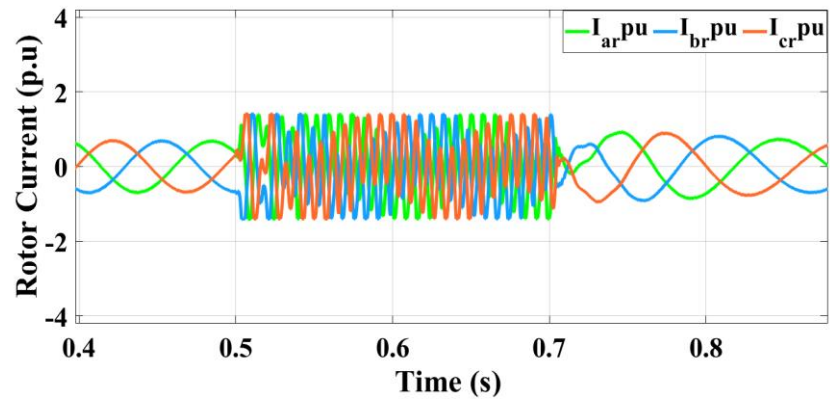
Figure 4. 30 DFIG's dynamic behavior in the absence of a protection system with Asymmetrical Fault (LL)



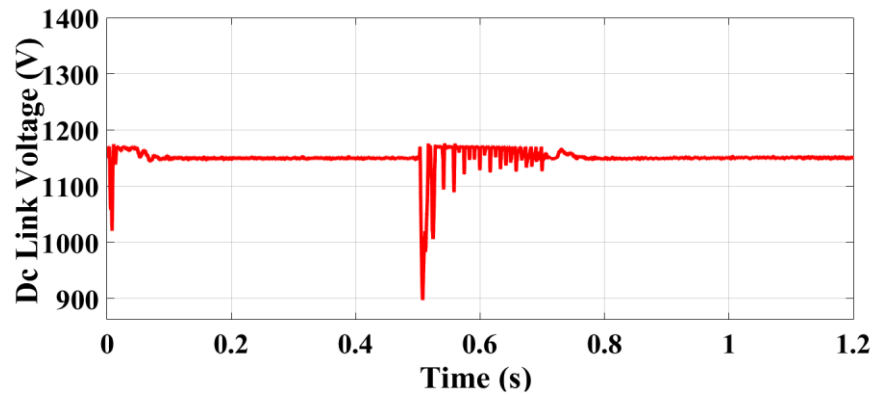
(a)



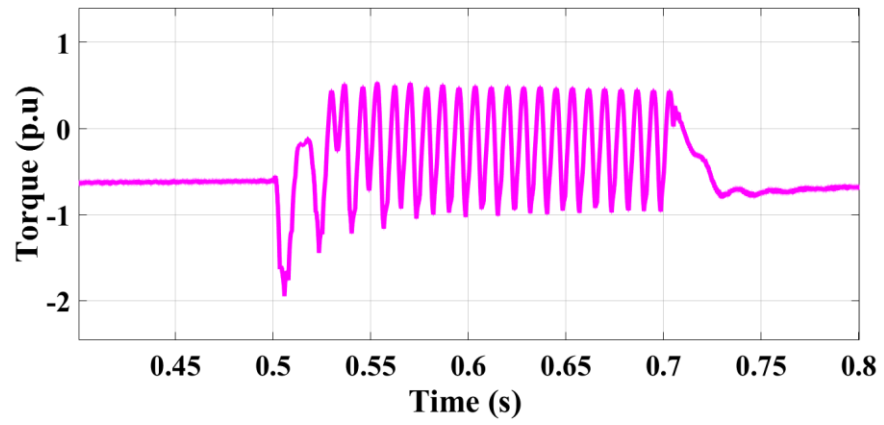
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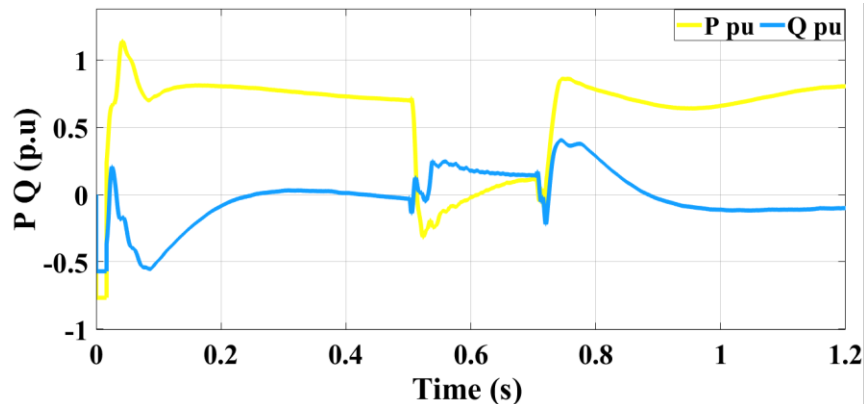
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(f)

Figure 4. 31 DFIG's dynamic behavior in the presence of a protection system with Asymmetrical Fault (LL)

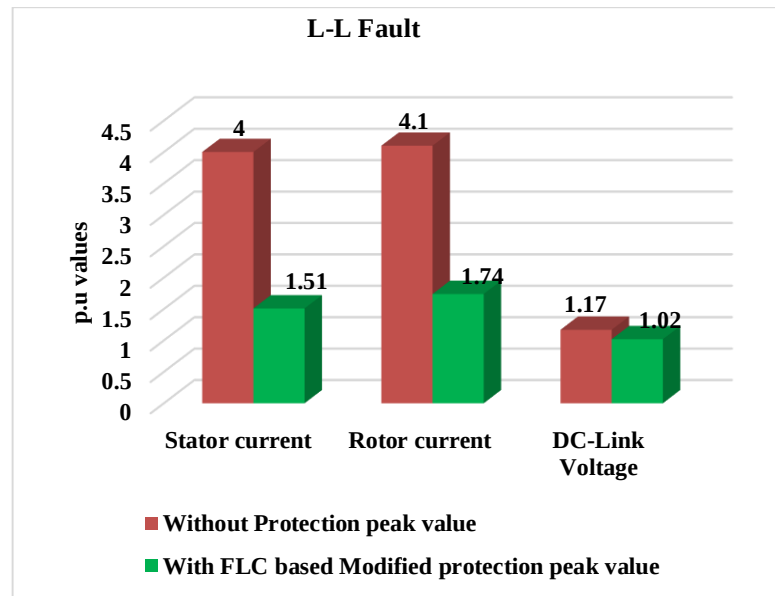
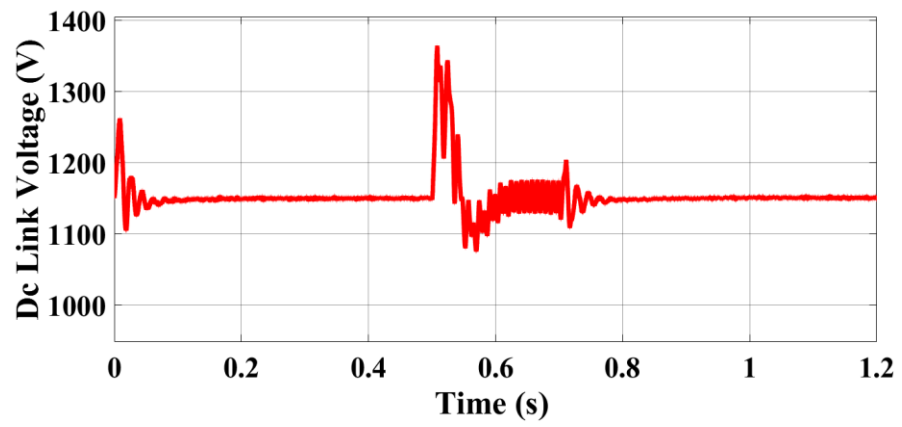
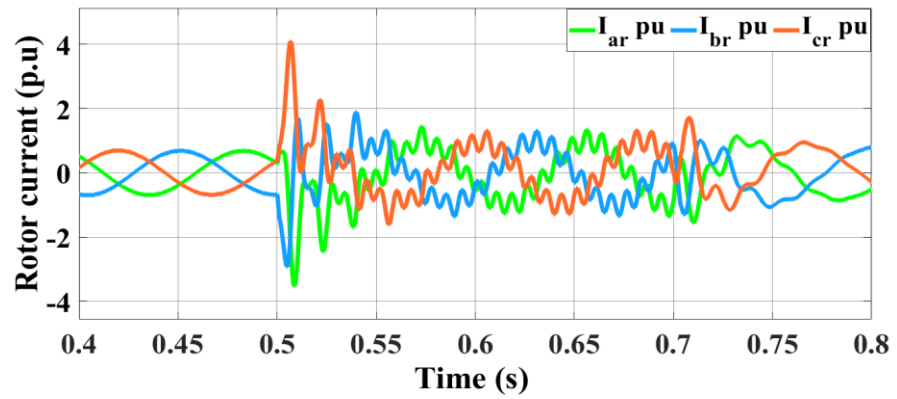
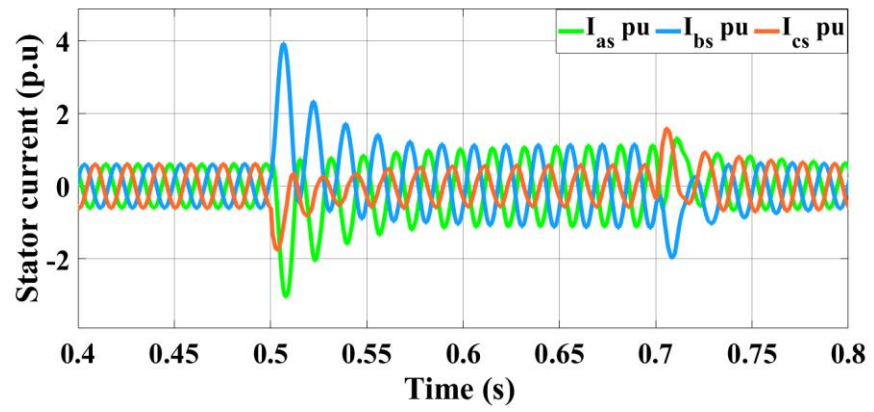
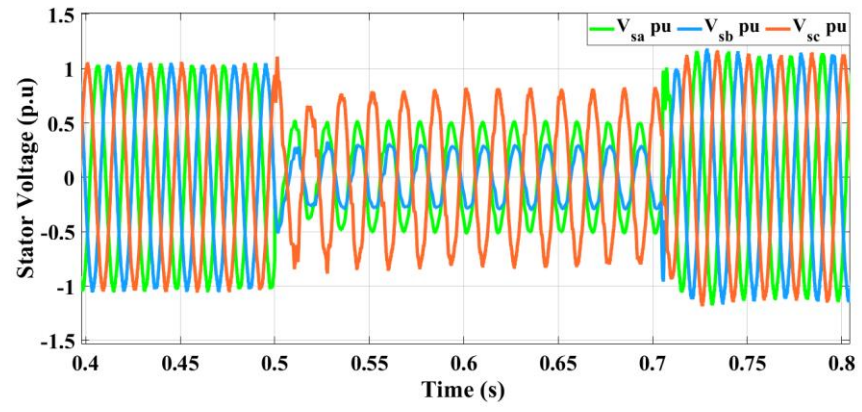


Figure 4. 32 Peak Values of Voltage and Current during LL Faults

Table 4.9 Comparative Performance Analysis Results during LL Fault

	Stator Current	Rotor Current	DC-Link Voltage
Without Protection Peak Value	4	4.1	1.17
With FLC Based Modified Protection Peak Value	1.51	1.74	1.02



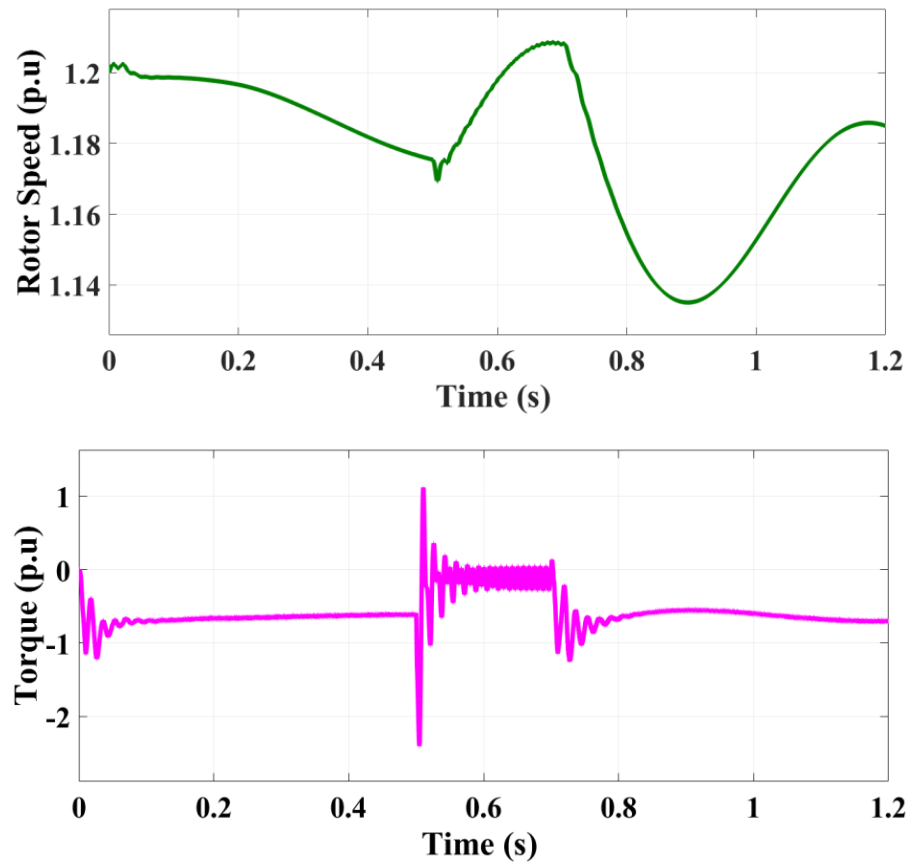
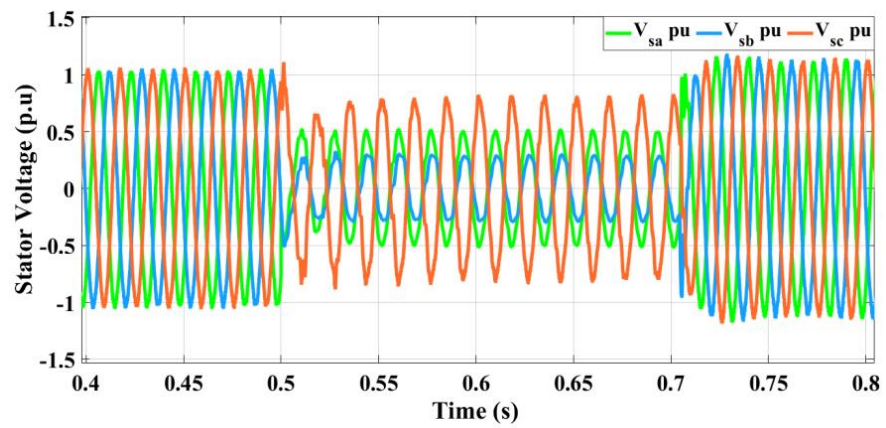
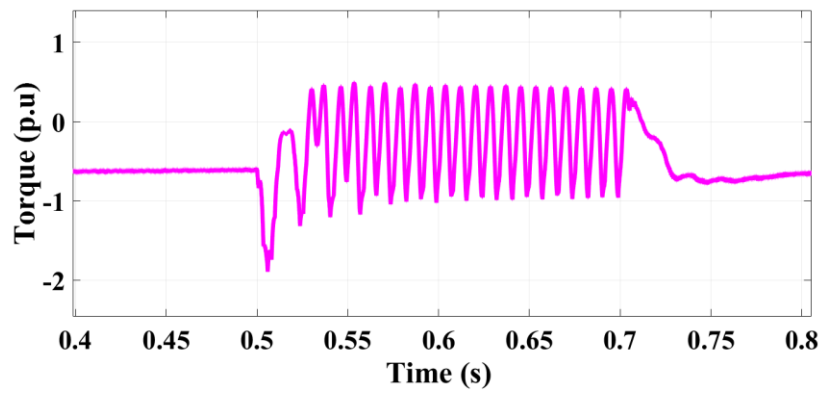
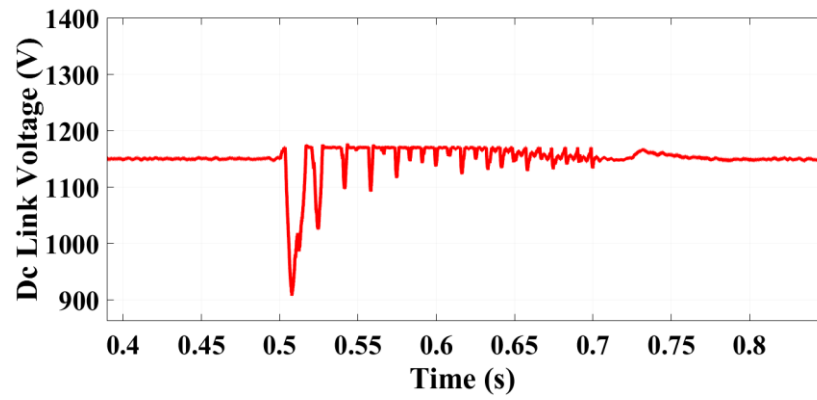
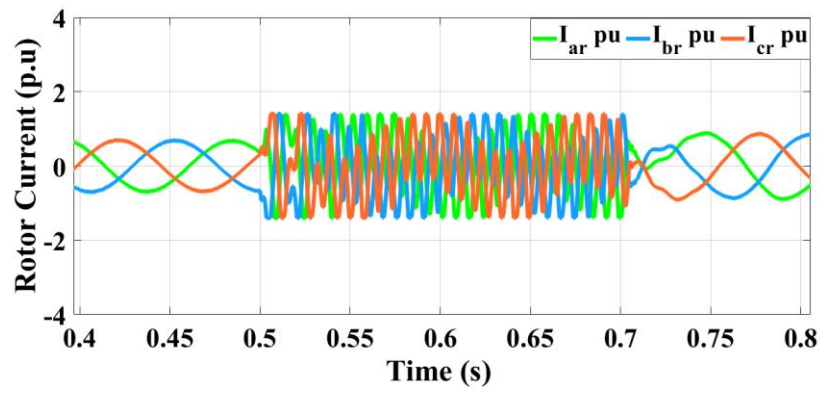
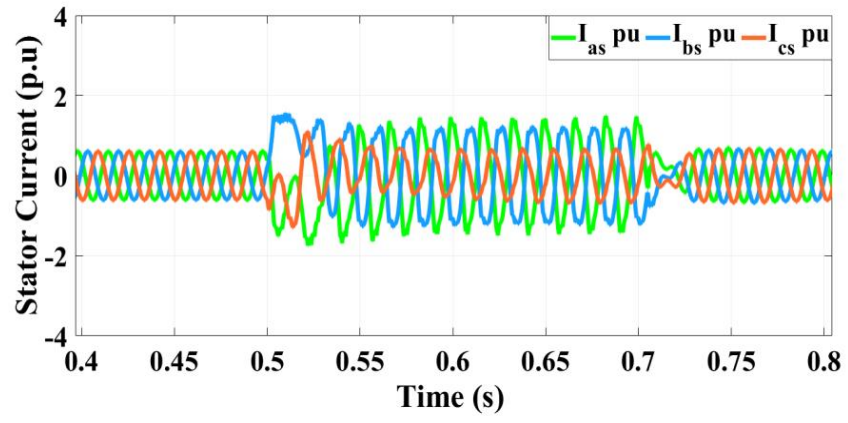


Figure 4. 33 DFIG's dynamic behavior in the absence of a protection system with Asymmetrical Fault (LLG)





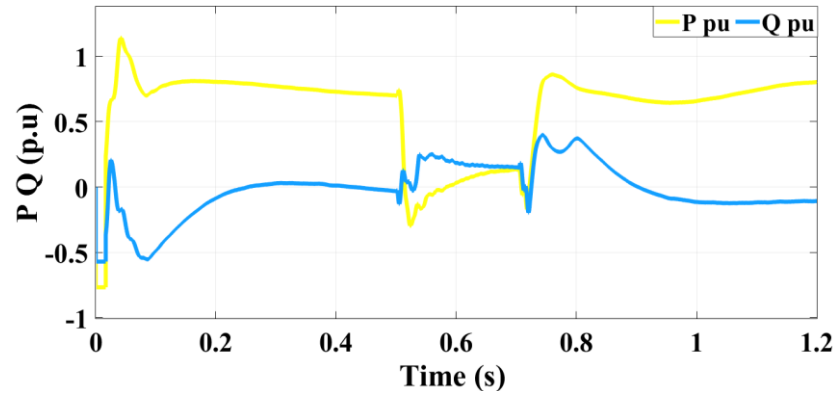


Figure 4. 34 DFIG's dynamic behavior in the presence of a protection system with Asymmetrical Fault (LLG)

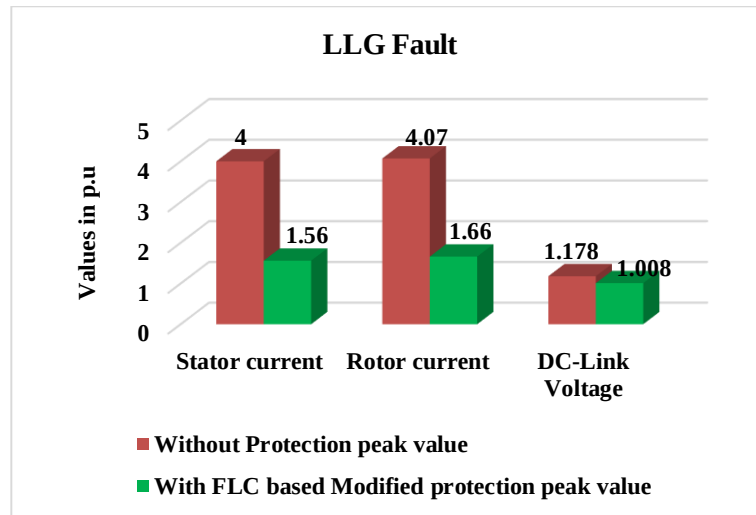


Figure 4. 35 Peak Values of Voltage and Current during Faults

Table 4.10 Comparative Performance Analysis Results during LLG Fault

	Stator Current	Rotor Current	DC-Link Voltage
Without Protection Peak Value	4	4.1	1.178
With FLC Based Modified Protection Peak Value	1.56	1.66	1.008

4.7 RTS Results Discussion

A case study was conducted in this section using a real-time simulator (RTS) to strengthen the credibility of antecedent analysis. RTS is a computer-based system that

allows engineers to simulate complex scenarios, observe system behavior, and test the effectiveness of protection and control schemes in real-time. With the advancement of hardware and software technologies, RTS has become an essential tool for power system analysis, power electronics, control system design, and renewable energy systems. In this context, this paper discusses the use of an RTS tool (OP4500) for simulating the behavior of a power system with a DFIG-based wind generator, with and without protection systems. The platform incorporates FL-based techniques and employs a range of components, including a host PC, DB-37 connector, BNC cables, HIL system, and GWinstek GDS-1104B DSO as depicted in Figure 4. 36. It is important to note that all parameters were expressed in per-unit form and assigned a multiplication factor of one.

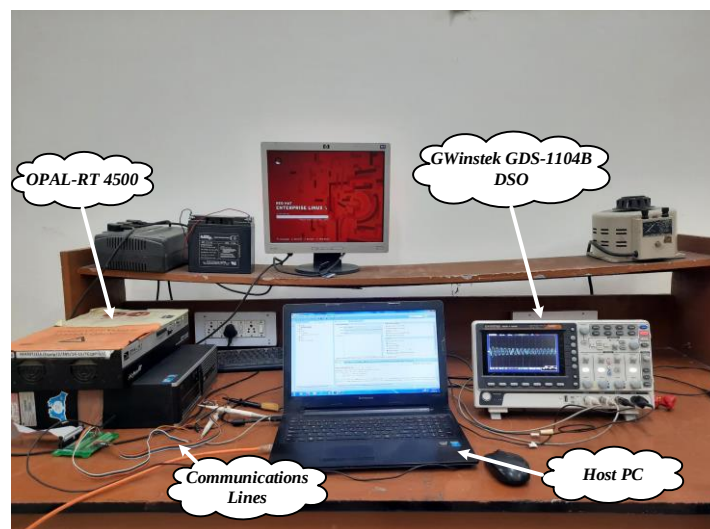


Figure 4. 36 RTS diagram of FRT of DFIG based WECS

Implementing a model from MATLAB to real-time using OPAL-RT involves a series of steps to ensure the proper simulation and execution of your system. The process described here is based on the provided content and expands upon it for a more comprehensive understanding.

1. Open a Model:

- Launch the OPAL-RT software and open the Simulink model you want to work with. You can do this through the Main Control window. The process of opening a Simulink model using RT-LAB is illustrated in [Figure 4.37](#).

2. Edit a Model in MATLAB:

- After opening your Simulink model within OPAL-RT, the next critical step is to make any necessary modifications or optimizations using MATLAB. However, it's

essential to remember that in the context of OPAL-RT, your Simulink model should adhere to a specific structure, consisting of two primary subsystems: the Master (SM) and the Console (SC) as shown in Figure 4.38.

2.1 Regroup into Subsystems:

- In OPAL-RT, the top-level of the Simulink model should not contain any mathematical content. To accommodate this requirement, your model must be organized into subsystems. Prefixes need to be added to these top-level subsystems, allowing OPAL-RT to effectively manage them during real-time execution. This structuring helps streamline the simulation process and ensures efficient utilization of Opal-RT's hardware.

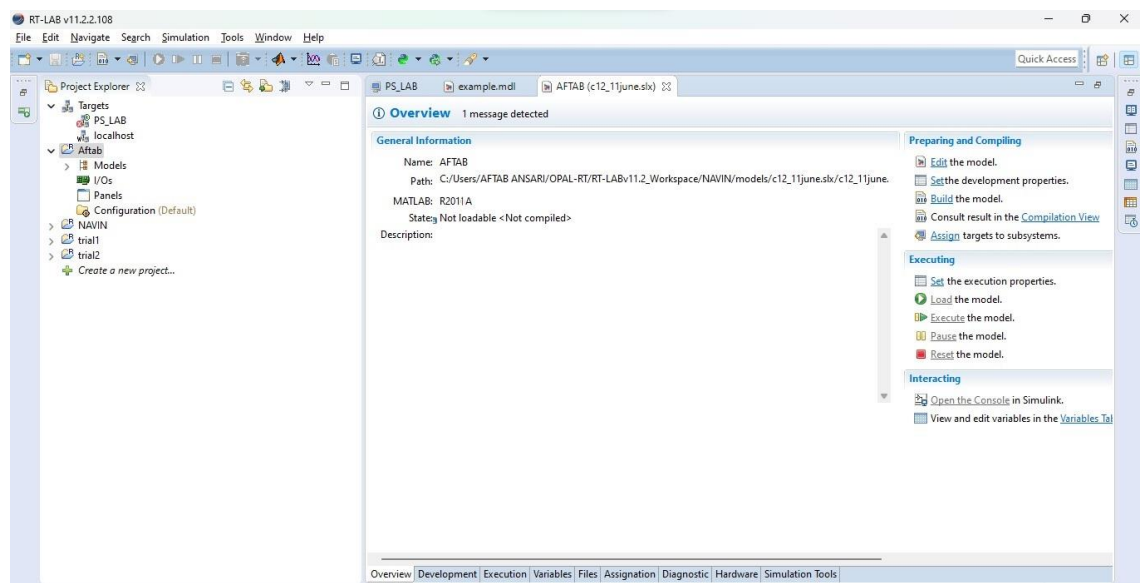


Figure 4. 37 Illustration of Opening a Simulink Model in RT-LAB

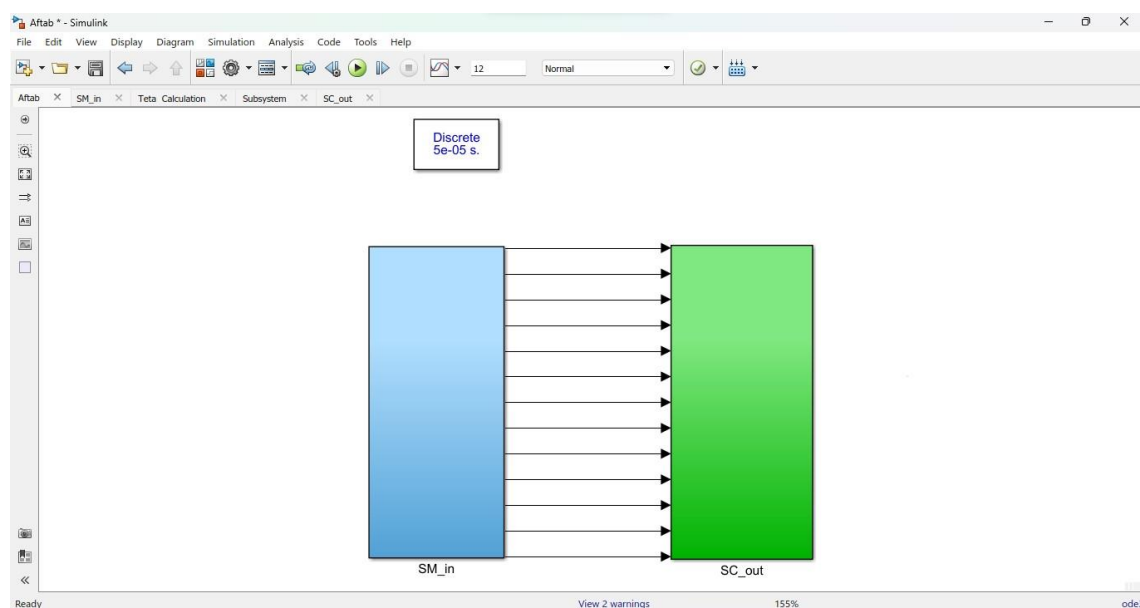


Figure 4. 38 Simulink Model Structure with Master and Console Subsystems

2.2 Three Types of Subsystems:

- There are three distinct types of subsystems that play specific roles in your simulation:

- SM Master Subsystem (Prefix Identifier: SM_)

- Number of SM subsystems allowed in a model: Always 1.

- Content: This is the primary subsystem responsible for housing all computational elements of the model. This includes mathematical operations, I/O blocks, signal generators, and more. Essentially, it encapsulates the core functionality of your model.

- Note: Every model must have precisely one SM subsystem, as it serves as the central hub of computations.

- SS Slave Subsystem (Prefix Identifier: SS_)

- Number of SS subsystems allowed in a model: Any (From 0 to...)

- Content: The SS subsystem houses additional computational elements of your model, similar to the SM subsystem. However, it comes into play when computational elements need to be distributed across multiple hardware nodes. Each SS subsystem corresponds to one computation node in Opal-RT's hardware setup.

- SC Console Subsystem (Prefix Identifier: SC_)

- Number of SC subsystems allowed in a model: 0 or 1

- Content: The SC subsystem is dedicated to user interface blocks, such as scopes, displays, switches, controls, and more. It facilitates interaction with the system while it's running. Unlike the SM and SS subsystems, the console subsystem runs asynchronously and is not linked to a specific computation node. Therefore, it shouldn't include signal generation or complex mathematical operations.

2.4 Add the OpComm Block:

- OPAL-RT utilizes OpComm blocks to manage and save communication setup information. These blocks enable communication between the console and computation nodes, as well as communication among multiple computation nodes in distributed simulations. All inputs of subsystems must pass through an OpComm block before any operations are performed on the associated signals. Typically, only one OpComm block is required, even if there are multiple inputs within a single subsystem.

2.5 Set the Real-Time Parameters:

- Real-time simulations in OPAL-RT operate in Fixed-Step mode. Careful consideration is needed when selecting the Fixed-Step size (fundamental sample time). This choice should align with the dynamics and requirements of your model, as well as the capabilities of the hardware and software being used. For instance, mechanical applications might require a step size around 1ms, while electrical systems might demand as little as 50 microseconds. To ensure the console (SC) runs indefinitely, set the simulation's stop time to 'inf'. This means that the console will only stop when you actively decide to reset your model, and it doesn't affect the simulation duration.

2.6 Target Platform Configuration:

- When developing a model in OPAL-RT, it's essential to set the target platform in "Red Hat mode." This configuration ensures compatibility and proper functioning within the OPAL-RT environment.

By following these steps and adhering to the outlined structure and requirements, you can effectively prepare your Simulink model for real-time execution using OPAL-RT, enabling you to simulate, analyze, and optimize your systems with precision and efficiency.

3. Compilation:

- Click on the Compile button in the Main Control window to compile your Simulink model. This step prepares your model for real-time execution. OPAL-RT's compilation process ensures that your model can run in real-time.

4. Assign Nodes:

- Use the Assign Nodes button in the Main Control window to link your model's subsystems to specific target nodes. This step helps OPAL-RT manage the distribution of computations across hardware nodes efficiently. You should consider the hardware capabilities when making these assignments.

5. Synchronization Mode:

- Select an appropriate synchronization mode based on your simulation requirements:

- Simulation: No synchronization; runs as fast as possible.
- Software Synchronized: Real-time simulation synchronized using the internal RTOS timer.
- Hardware Synchronized: Real-time simulation synchronized using an external hardware timer.

- Simulation with Low Priority (Rare): Lower priority mode for background simulations (Windows-based target).

6. Loading:

- Click on the Load button to load your Simulink model onto the target hardware.

This is the final step before executing the model in real-time. The console will open, providing a user interface for interaction during execution.

7. Execution / Pause:

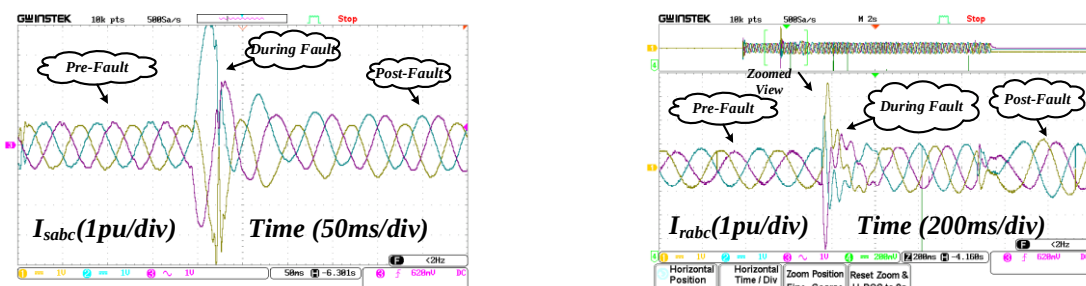
- Use the Execute button in the Main Control window to start the execution of your Simulink model in real-time. During execution, you can:
 - Change controls within the console.
 - Monitor changes displayed in scopes, displays, etc.
 - Pause the execution at any time for analysis or adjustments.

8. Reset:

- When you want to stop the model definitively, use the Reset button in the Main Control window. This will halt the acquisition (both software and hardware), and the console will close.

It is essential to keep in mind the specific requirements and dynamics of your model when configuring synchronization modes and choosing the appropriate sample time (fixed-step size). Additionally, consider hardware limitations and capabilities when assigning nodes for distributed simulations.

The results of a symmetrical voltage dip in a 1.5 MW DFIG WECS without any protective measures are demonstrated in Figure 4. 39. In the event of a minor disturbance at 0.5s, the grid voltage plummets to 0.2pu, as evident from the graph. At $t = 0.5s$, the grid failure instantaneously reduces the output voltage of the wind generator, along with a drop in the stator voltage to 10% of its current value, which is depicted in Figure 4. 39(a). Furthermore, the stator and rotor currents exhibited a rapid increase, and the DC-link bus indicated over-voltage, as shown in Figure 4. 39(c).



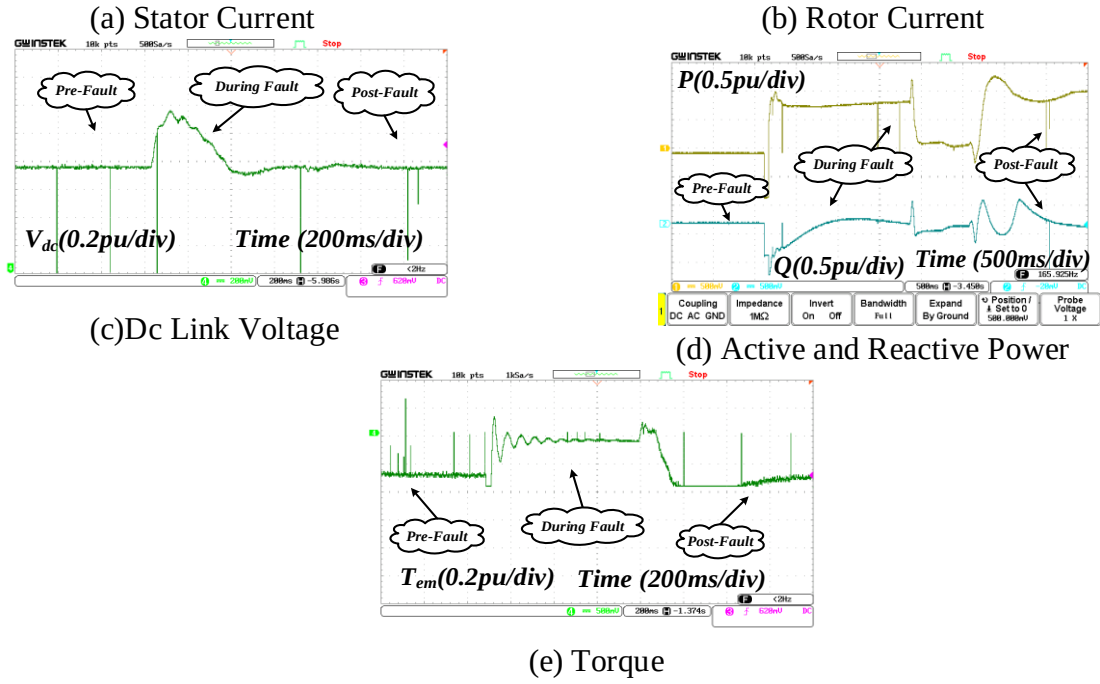
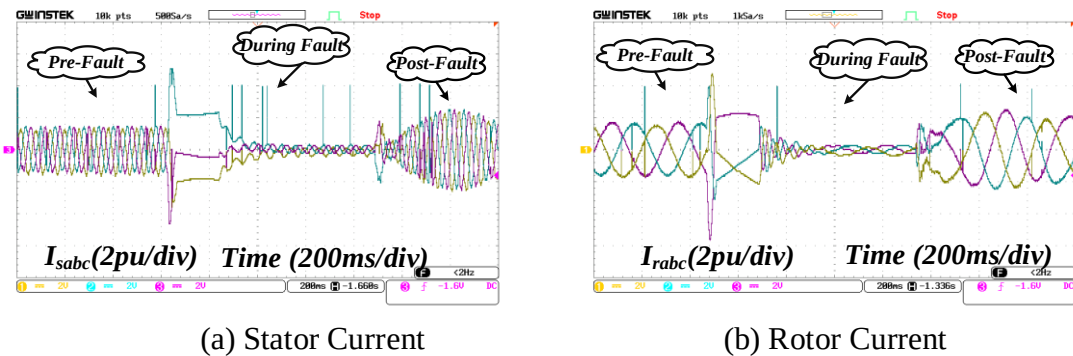
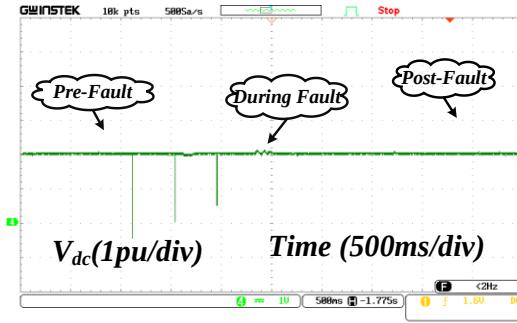


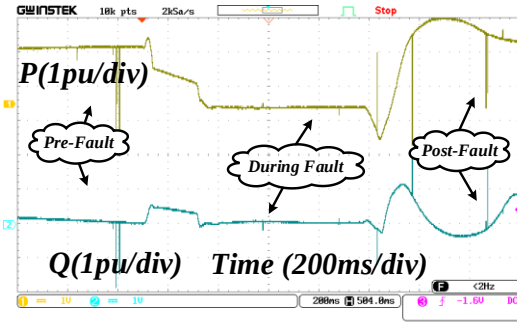
Figure 4. 39 Real-time simulator (RTS) results in the absence of protection system with Symmetrical Fault

Now a modified FL based coordinated protection technology is used as the protection unit. The RTS result with modified strategy shown in Figure 4. 408-4.41 for both the Asymmetrical and Symmetrical faults shows that for the entire fault time, the peak rotor and stator current never surpassed the estimated maximum limit of 2 p.u. Modified configuration detects a sudden rise in rotor current and Dc Link bus voltage and activates the security mechanism with the help of the FL tool without interfering with the RSPEC. The Modified technique demonstrated remarkable efficacy in curbing the stator and rotor's three-phase current within the permissible limit of 2 pu, as illustrated in Figure 4. 40-4.41. In addition, the modified methodology obliterates the substantial torque fluctuations linked with fault activation, as evidenced by the simulation and RTS outcomes. Furthermore, the modified technique manifests its potential to mitigate the PEC's potential harm by ensuring stator current regulation and containing dc-bus voltage fluctuations to a maximum of 1.5 times the rated value.

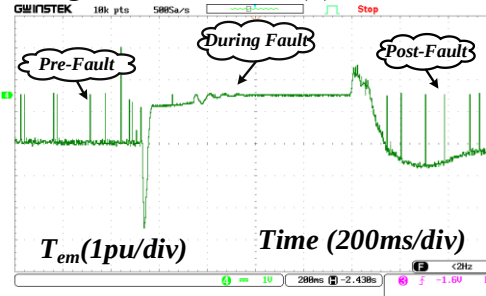




(c) Dc Link Voltage

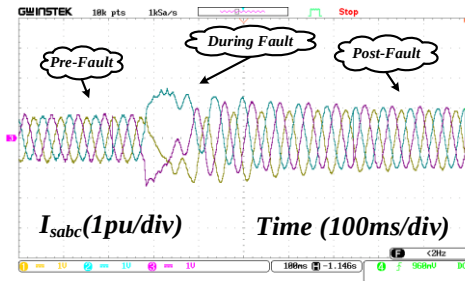


(d) Active and Reactive Power

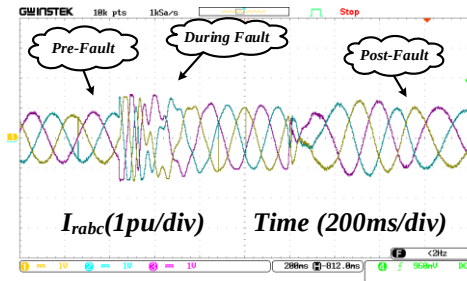


(e) Torque

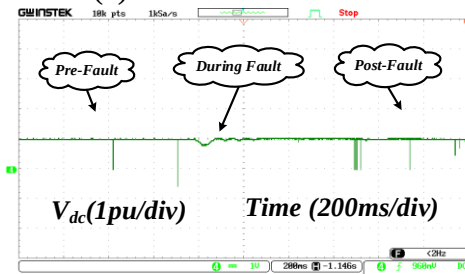
Figure 4. 40 Real-time simulator (RTS) results in the Presence of REPRC protection system with Symmetrical Fault



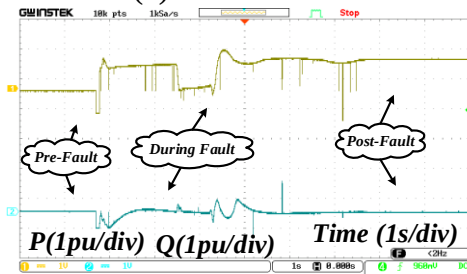
(a) Stator Current



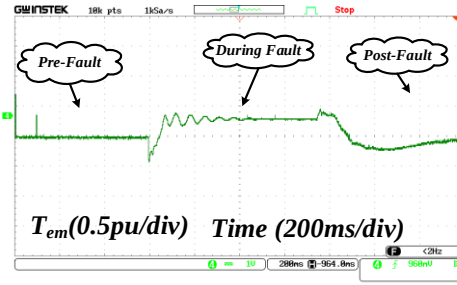
(b) Rotor Current



(c) Dc Link Voltage

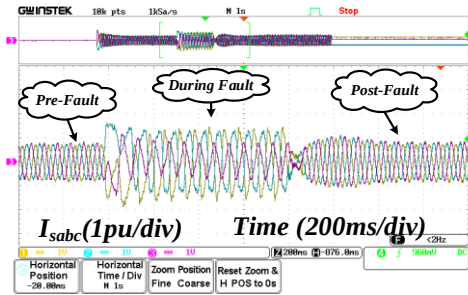


(d) Active and Reactive Power

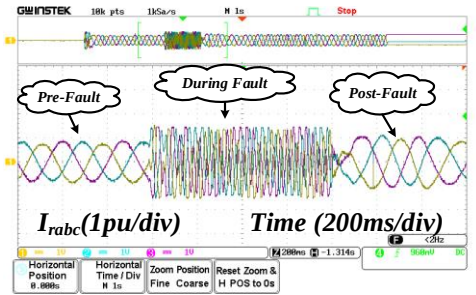


(e) Torque

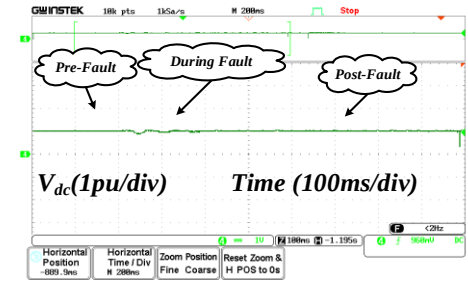
Figure 4. 41 Real-time simulator (RTS) results of an improved FL based protection system with Symmetrical Fault



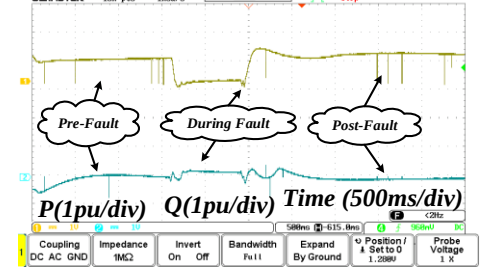
(a) Stator Current



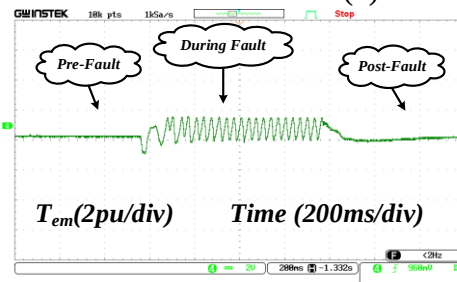
(b) Rotor Current



(c) Dc Link Voltage



(d) Active and Reactive Power



(e) Torque

Figure 4. 42 Real-time simulator (RTS) results of an improved FL based protection system with Asymmetrical Fault (L-L)

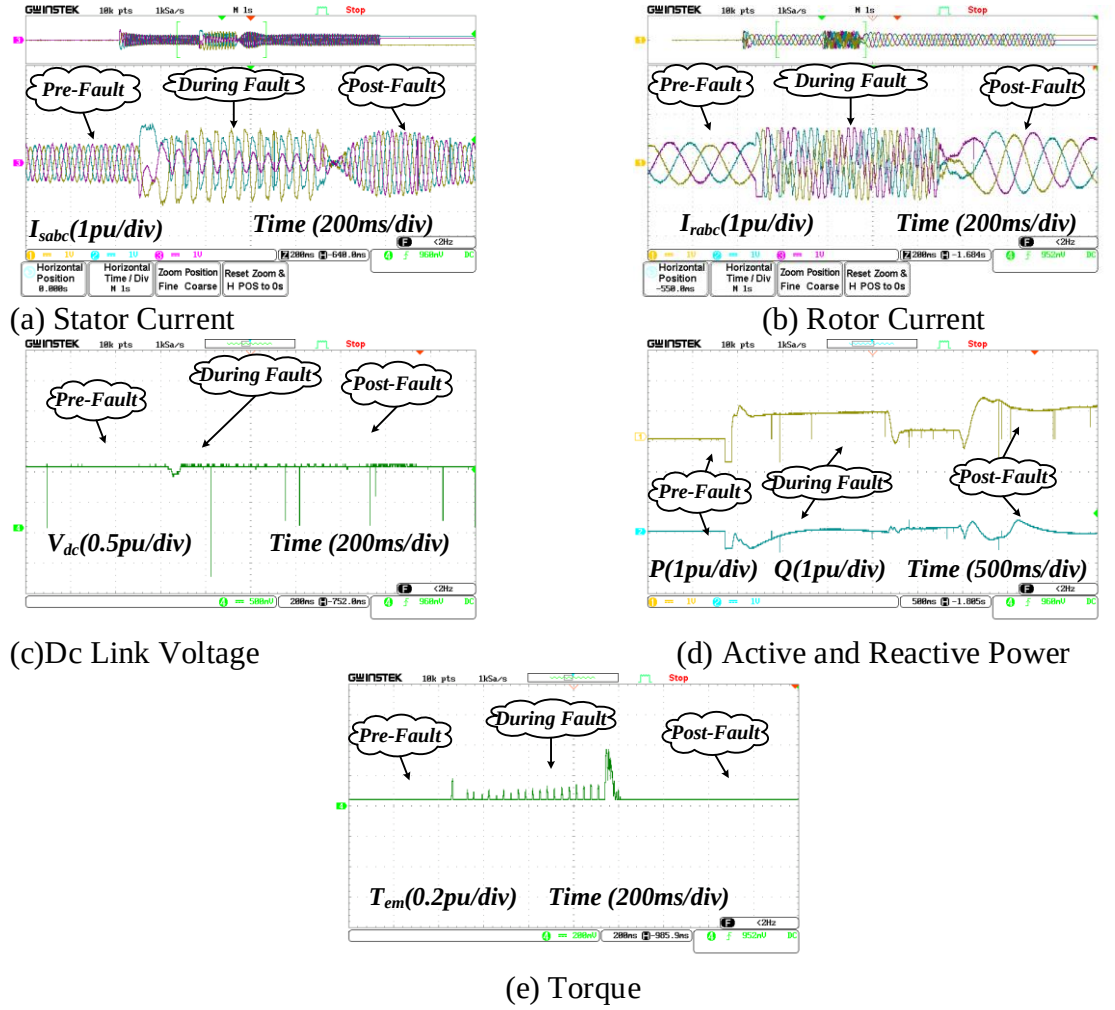


Figure 4. 41 Real-time simulator (RTS) results of an improved FL based protection system with Asymmetrical Fault (L-L-G)

4.8 Conclusion

In conclusion, this chapter has provided a comprehensive exploration of FRT methods for DFIG-based wind energy systems, focusing on their importance in maintaining grid stability and enhancing overall system reliability. Understanding and complying with grid code requirements are essential for the successful integration of wind energy systems into the power grid, especially considering the sensitivity of DFIG-based turbines to grid disturbances.

The chapter has covered various existing FRT schemes utilized in DFIG systems, emphasizing their role in increasing system resilience, ensuring uninterrupted power supply, and minimizing the impact of faults on wind turbine generators. By studying different FRT approaches and their effectiveness under various fault scenarios, we have

gained valuable insights into their significance in maintaining grid stability. Recognizing the need for enhanced fault management strategies, we have proposed a novel fault mitigation approach based on fuzzy logic for DFIG-based wind energy systems. The adaptive and robust nature of fuzzy logic systems makes it an attractive choice for improving FRT capabilities. Extensive simulations in MATLAB/Simulink, as well as real-time emulations in the OPAL-RT environment, have validated the performance and efficiency of proposed FRT method, ensuring its adherence to grid code requirements and its ability to manage diverse fault scenarios.

The effective deployment and application of FRT technologies in DFIG-based wind turbines are crucial steps towards achieving a stable and efficient renewable energy future. This chapter has highlighted the interlinkages between grid code mandates, wind energy conversion, and FRT procedures, providing a deeper understanding of sustainable power systems. As the demand for renewable energy continues to rise, ensuring the reliable and stable operation of wind energy systems becomes paramount. The research presented in this chapter contributes valuable insights and advancements in FRT methods, playing a vital role in shaping the future of wind energy systems and their integration into the broader power grid. By developing and validating effective FRT solutions, pave the way for a more sustainable and resilient energy landscape.

CHAPTER 5. FCS-MP DTC FOR RSPEC OF DFIG FED WECS

5.1 Introduction

In this chapter, the exploration and application of Finite Control Set Model Predictive Control (FCS-MPC) for DFIG based wind energy systems has been presented. The need for optimized control and utilization of renewable energy systems, particularly wind energy, is of paramount importance in today's era of energy transition. With the global quest for clean and sustainable energy sources gaining momentum, the significance of efficient control techniques in these systems cannot be overstated.

The backbone of this chapter is the exploration of FCS-MPC and its effective application to DFIG based wind energy systems. The FCS-MPC, a modern and highly efficient control technique, stands out due to its predictive nature, taking advantage of the known control set to directly calculate and optimize future behavior. This feature makes it an attractive choice for DFIG systems, facilitating an optimized and efficient control mechanism. Further extending the boundaries of exploration, FCS-MPC can be applied to a standard two-level fed DFIG-based wind energy system, but also venture into its application in a multilevel fed DFIG-based system. The multilevel approach offers a higher level of flexibility, better harmonic performance and lower switching losses, while the application of FCS-MPC aims to enhance system performance and operational efficiency.

A critical part of exploration involves the verification of theoretical findings with practical results. MATLAB simulations to visualize, evaluate, and validate the efficiency and effectiveness of FCS-MPC in the context of DFIG fed WECS was performed. This computational modeling and simulation platform provides an ideal environment to develop and test the control algorithms, prior to their application in real-world scenarios. To facilitate a tangible demonstration and application of work, hardware prototype of this system also developed. This prototype is equipped with a WAVECT Controller, a state-of-the-art control system designed specifically for wind turbines, which is renowned for its reliability, precision, and robustness. The successful integration and operation of the WAVECT Controller in system further consolidates the validity of work.

5.2 Model Predictive Control

MPC has emerged as one of the most significant advances in the field of control systems engineering. MPC was developed in response to the demand for more efficient, safe, and precise control systems in the chemical and petroleum sectors. It has now grown into a key methodology used in a wide range of industries. Its origins can be traced back to the late 1970s and early 1980s, when the fundamental algorithms were created to control complicated industrial processes with various inputs and outputs. MPC provides an optimum control strategy that calculates control signals based on future predictions about system behaviour [178]. Its strength is its capacity to deal with multivariable systems, restrictions, and trade-offs between competing objectives.

In the field of power electronics and electrical drives, the application of MPC has become increasingly prevalent due to its ability to optimize the performance of these systems dynamically and in real-time. The adoption of MPC in power electronic devices and electrical drives, where it provides solutions for complex issues like efficiency enhancement, power quality improvement, and mitigating the effects of parameter uncertainties and external disturbances, has been fuelled by the rise of advanced computational capabilities.

During the exploration of Chapter 2 (Literature survey), we encountered an extensive levels of predictive control approaches featuring diverse concepts for control that have evolved over time. Predictive control techniques within the realm of power converters can be generally characterized into two distinct sets. The first set consists of modulator-based predictive control, which also includes continuous control-set MPC, generalised predictive control, and direct current control. Also included in this collection is deadbeat predictive control. The second category includes modulator-free predictive control approaches such as FCS-MPC, trajectory-tracking MPC, direct MPC, and hysteresis-based MPC [179]. Irrespective of the specific technique employed, all predictive control methods share a common fundamental principle: they utilize the Discrete Time (DT) model of the system to anticipate future plant behavior and subsequently execute optimal control actions based on predetermined control objectives. This section delves into an elucidation of the two most frequently employed predictive control strategies.

5.2.1 Predictive Control with Modulation

The deadbeat predictive control scheme is showcased in Figure 5. 1, incorporates a modulation stage and is commonly referred to as the single-step predictive control. In this setup, the deadbeat controller is used in place of the more widespread PI regulator typically used in linear control [180][181]. Deadbeat control, the earliest form of predictive controller devised for PEC [182], holds significant prominence in the field. Leveraging the load and converter models, the deadbeat controller forecasts forthcoming current activities within each period. After that, the controller will identify the most appropriate reference voltage vector, which will be denoted as v^* , and then it will apply vector to the modulation stage. Gating signals are generated and sent to the power converter by way of the PWM/SVM modulator. This enables the power converter to maintain consistent functioning at a predetermined switching frequency.

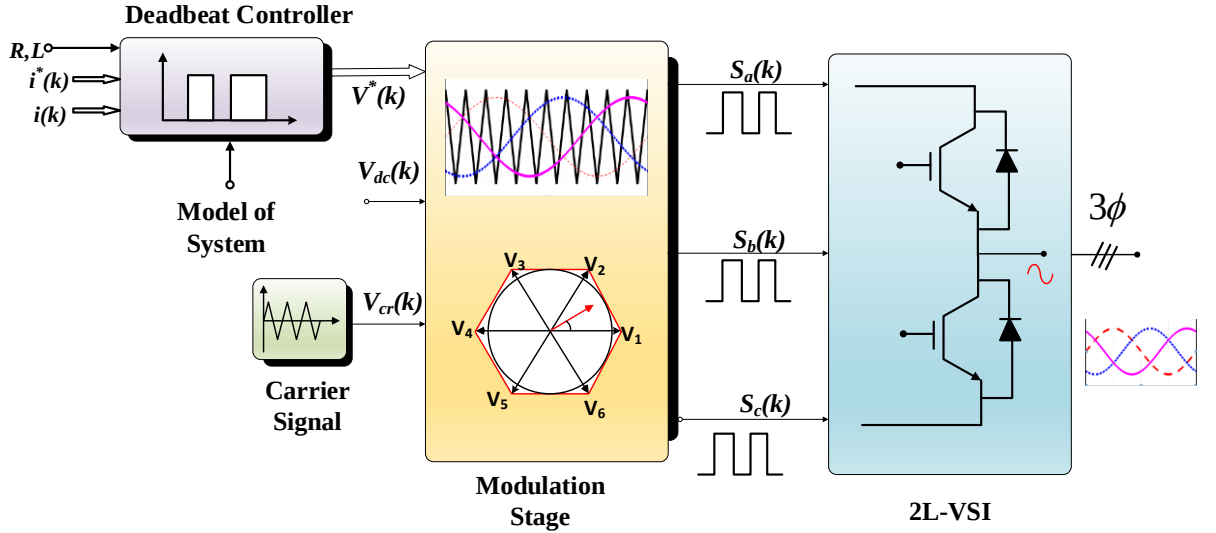


Figure 5. 1 Simplified Block Diagram of Deadbeat PCC

Taking into account the state variables representing the dynamics of the load current, which are obtained from the converter model showcased in Figure 3. 11, the following modified expressions are obtained:

$$\frac{di(t)}{dt} = -\frac{R}{L}i(t) + \frac{1}{L}v^*(t) \quad 5.1$$

From the above CT dynamic model, we construct the following discrete time (DT) model of the load current, which is optimised for a T_s sampling time.

$$i(k+1) = \phi i(k) + \Gamma v(k) \quad 5.2$$

Where ϕ and Γ are the discrete equivalents of the CT parameters $\frac{R}{L}$ and $\frac{1}{L}$ respectively, and $i(k+1)$ is the future load current. The upcoming section provides a comprehensive explanation of discretization methods.

According to the DT model presented, $v^*(k)$ is computed as

$$v^*(k) = \Gamma^{-1} [i^*(k+1) - \phi i(k)] \quad 5.3$$

In this context, $i^*(k+1)$ is being used to stand in for the reference current that was extrapolated (or calculated). In the context of deadbeat control, the goal is to achieve a reference voltage vector with the value $v^*(k)$ such that the current error at the subsequent sampling instant $(k+1)$ is zero. This control technique operates on a straightforward principle, devoid of tuning or optimization procedures. Consequently, deadbeat control exhibits rapid dynamic response when compared to classical controllers. Nevertheless, challenges arise in the form of system parameter fluctuations, disturbances, measurement noise, and control delays, this can potentially undermine the performance of the fundamental deadbeat control and give rise to instability concerns.

5.2.2 Predictive Control without Modulation

A regulatory approach for load current control, referred to as FCS-MPC, is illustrated in Figure 5. 2 [108]. This strategy offers a distinct concept compared to linear control by abolishing the necessity for linear PI regulators and a modulation stage. Unlike previous techniques that respond to errors after they occur, FCS-MPC adopts a proactive approach by implementing protective control arrangements even before a significant current error happens. The FCS-MPC scheme primarily comprises the following procedure: The procedure involves extrapolating current of reference from the k^{th} to the $(k+1)$ sampling instant, followed by utilizing a predictive model to compute future load currents. Following this, a cost function is utilised to provide gating signals and evaluate the accuracy of the predictions that were made.

By employing the predictive model outlined in equation (5. 2), the future load current values are predicted through consideration of the restricted number of switching states, which can be enumerated for all viable system states. In order to assess the

accuracy of these predictions, a cost function is employed, measuring the total error between the reference, and forecast load currents.

$$g(k) = \left| i^*(k+1) - \hat{i}(k+1) \right| \quad 5.4$$

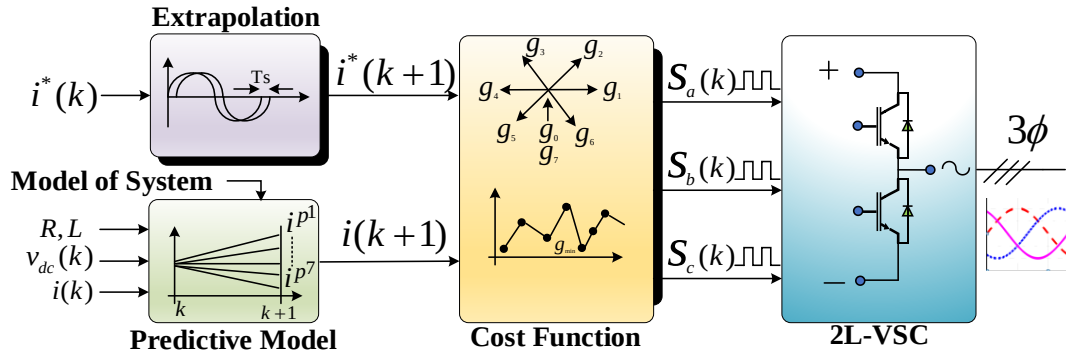


Figure 5. 2 Graphical representation of the FCS-MPC scheme utilized to regulate load current.

An optimal actuation is determined by picking the switching state that is most appropriate for the situation. The goal of this is to reduce the magnitude of current error at the subsequent sample. After that, the switching state that was selected is applied immediately to the converter. FCS-MPC demonstrates swifter dynamics in comparison to traditional control techniques, all while ensuring admirable tracking of steady-state references in contrast to conventional methods. Unlike deadbeat predictive control, FCS-MPC presents a more adaptable criterion for choosing optimal switching signals, allowing for the integration of multi-objective control considerations, including system non-linearities and constraints. In deadbeat control, the reference vector $\hat{v}^*(k)$ is directly calculated using measurements and system parameters, without the need for online optimizations or iterations, as detailed in equation (5. 3). Although FCS-MPC involves additional online optimizations that increase computational demands, modern digital control platforms are capable of addressing the required computational capacity without significant challenges [183].

When it comes to the implementation of dq-frame linear control, the road ahead leads to the incorporation of compensating terms as well as SVM. The literature review delves into a wide variety of methods, but the one that stands out as the easiest to implement is hysteresis control, with FCS-MPC coming in a close second. Hysteresis and intelligent control are distinguished from one another by the fact that they are not dependent on any system models or parameters; rather, they rely on the intuition and

background knowledge of the designers. On the other hand, other schemes require these models and parameters. Sliding mode control (SMC) and FCS-MPC both allow constraints to be incorporated into the controller architecture, but it is FCS-MPC that proves to be more flexible and easily implementable. Hysteresis and FCS-MPC showcase exceptional dynamic responses due to their modulator-free operation. Although the switching frequency in both techniques is variable, FCS-MPC allows for the modification of the cost function to control this frequency. In envisioning the future prospects of advanced control schemes, two pivotal factors come into play: (1) the ease of digital implementation and (2) superior performance in comparison to classical control methods. In fulfilling these criteria, FCS-MPC emerges as a frontrunner, presenting a straightforward and instinctive methodology for digital implementation, while simultaneously delivering optimal performance across diverse operational scenarios. Anticipate the forthcoming convergence of simplicity and excellence within the realm of control as FCS-MPC paves the way for a promising future [184].

5.3 Features of Finite Control-Set Model Predictive Control

The application of FCS-MPC in power converter-based energy processing applications offers numerous advantages, rendering it an appealing choice for researchers in both industry and academia [185]. Notably, recent studies have showcased the versatility of FCS-MPC, demonstrating its successful implementation across a wide array of PECs encompassing various adjustable-speed motor drives, output harmonic filter configurations, power quality enhancement, HVDC systems, and PV and wind energy conversion applications[186]. This section delves into a detailed analysis of the key features and challenges associated with FCS-MPC.

5.3.1 Main Features of FCS-MPC

The conceptual framework of FCS-MPC is made up of eight fundamental characteristics, as shown in Figure 5.3. The following is a brief explanation of these major features.

- **Discrete Control Actions:** Unlike conventional MPC where the control actions are continuous, in FCS-MPC, the control actions are finite and discrete, coming from a predefined control set. For example, in the case of power converters, the control set would include all possible switch states.

- **Clear and Accessible for Comprehension:** The concept behind FCS-MPC is straightforward and easy to grasp. No matter the control application, FCS-MPC consistently utilizes four primary subsystems, which are as follows:
 1. Calculation of References
 2. Extrapolation,
 3. Predictive Modelling
 4. Minimization of the Cost Function.
- **Optimization:** During each sampling moment, the control algorithm assesses the cost function for every available control action within the control set. The action that yields the lowest cost function is chosen for execution. The optimization algorithm iterates a number of times based on the potential switching states ($s(k)$) of the converters. The number of switching possibilities or states for every given converter is constrained to a finite set using this method, which ensures an optimisation process. For instance, the 2L-VSC converter offers 8 switching states, while the NPC converter provides 27 switching states.
- **Direct Action:** The selected control action is applied directly to the system, without the need for any modulator, hysteresis regulators, linear PI controllers, and the lookup table in the control loop unlike traditional control strategies. This leads to a very fast dynamic response.
- **Addresses System Disturbances and Time Delays:** FCS-MPC effectively handles disturbances in power conversion systems, compensates for dead-times in power converters, and effectively manages voltage drop in semiconductor switches. The controller's ability to select a switching state with the least cost function error enables it to mitigate perturbations, even when the parameters of the output harmonic filter and internal DC-link filter undergo variations.
- **Modelling Flexibility:** FCS-MPC is versatile and can be applied to linear or non-linear, and single-input-single-output (SISO) or multiple-input-multiple-output (MIMO) systems, providing great modeling flexibility. An outstanding aspect of FCS-MPC lies in its ability to seamlessly integrate the power converter's nonlinearities and limitations within the system

model. The cost function can be tailored to accommodate various constraints and technical specifications, including but not limited to maximum current limitations, reduced switching frequency, spectrum shaping, minimization of common-mode voltage, decreased power losses, THD control, and boundary limits for mechanical and electrical variables. These design and operational considerations are paramount in achieving a secure and dependable operation.



Figure 5. 3 Fundamental characteristics of FCS MPC

- **Multi-variable Control:** It allows for the control of multiple variables simultaneously, giving it the ability to perform complex tasks in systems where multiple variables interact. FCS-MPC excels at addressing the challenges of multivariable control problems in diverse systems by employing a decoupled approach within the control loop, eliminating the need for external compensation terms. By intelligently selecting weighting

factors, FCS-MPC effortlessly incorporates both "soft constraint" and "hard constraint" handling within a multivariable control framework. This capability is particularly advantageous in electro-mechanical energy conversion applications, where FCS-MPC efficiently manages control variables from both the electrical and mechanical domains.

- **Constraints Handling:** FCS-MPC can handle constraints in a straightforward way, allowing for the direct inclusion of constraints in the formulation of the control problem.

5.4 Essential Principles of Model Predictive Control

MPC, also known by various names such as horizon control, planning in motion, control with dynamic matrices, algorithmic model control, generalized predictive control, and dynamic linear programming [187], operates on a shared principle: the ability to anticipate future events and make control decisions based on minimizing an objective function.

Numerous research studies have addressed concerns regarding predictive control in power electronics, resulting in several established solutions for selecting cost functions, designing weighting factors, compensating for control delays, extrapolating reference variables, and determining real-time implementation sampling intervals. This section presents the fundamental principles of FCS-MPC as a supplementary resource to enhance understanding of the core concept of FCS-MPC.

5.4.1 Discrete Modeling Approach

This section deals the fundamental concept of the discrete sampled-data model, which plays a vital role in the design and analysis of FCS-MPC within a digital time (DT) framework. In a sampled-data system, a digital device controls a CT plant. To bridge the gap between continuous functions, models, and equations, and their discrete counterparts, a mathematical process called discretization is employed. Discretization, rooted in discrete mathematics, enables the transformation from CT to DT domain. FCS-MPC harnesses an online optimization algorithm developed in the DT domain, utilizing a consistent sampling interval T_s , to attain peak control performance. Consequently, intricate sampled-data models, derived from their corresponding CT models, are frequently utilized to guarantee precise control outcomes.

Consider the following general power conversion system, which is characterised by a first-order CT model:

$$\frac{dx(t)}{dt} = Ax(t) + Bu(t) \quad 5.5$$

The CT parameters of the PEC, including factors like resistance of load, filter inductance, and DC-link capacitance, are represented by the variables A and B. The state vector to be controlled, which could be voltage, current, torque, power, or flux, is denoted by $x(t)$. Additionally, the input vector in continuous time, consisting of variables like DC voltage and grid voltage, is represented by $u(t)$. The classification of discretization methods is commonly divided into two main categories: exact and approximate methods. Exact methods provide the highest level of precision when converting models. The matrix exponential method, also referred to as the zero-order hold (ZOH) method, is utilized for exact discretization. On the other hand, approximate methods encompass techniques such as forward Euler, backward Euler, truncated Taylor series, and bilinear transformation [188].

The state equations of Model (5. 5) exhibit a first-order nature, allowing us to approximate the derivative using the forward Euler method. The study also incorporated the forward Euler method by considering both the present sample (k) and the future sample ($k + 1$), as illustrated in the following example.

$$\left\{ \frac{dx(t)}{dt} \right\}_{t=k} \approx \frac{x(k+1) - x(k)}{T_s} \quad 5.6$$

The step-size for discretization, typically represented as T_s , plays a crucial role in the following transformations.

Through the substitution of equation (5.6) into equation (5.5), derives an approximate discrete-time (DT) model, which can be expressed as:

$$\frac{x(k+1) - x(k)}{T_s} = Ax(k) + Bu(k) \quad 5.7$$

Further simplification leads us to:

$$x(k+1) = \phi x(k) + \Gamma u(k) \quad 5.8$$

With

$$\phi \approx 1 + AT_s, \Gamma \approx BT_s \quad 5.9$$

In this expression, the matrix I represents a unitary matrix with a dimension equivalent to that of the state matrix A .

It is worth noting that the exact discretization technique yields a DT model similar to the one depicted in equation (5.8). However, the accurate computation of matrices ϕ and Γ necessitates the utilization of matrix exponential, as showcased in the following demonstration:

$$\phi = e^{AT_s}, \Gamma = \int_0^{T_s} e^{A\tau} d\tau B = A^{-1}(\phi - I)B \quad 5.10$$

Considering Equation (5.5), if the parameters A and B remain constant over time, the system is classified as a linear time-invariant (LTI) system. On the other hand, in situations where A and B vary with time, as observed in systems like the induction machine, the system is referred to as a linear time-variant (LTV) system. In the case of LTI systems, matrices and can be precomputed offline, enabling the use of either the forward Euler or zero-order hold (ZOH) method without introducing additional complexity. However, for LTV systems, achieving exact discretization becomes significantly intricate and may even be unattainable in certain cases. In such circumstances, the forward Euler method provides a straightforward approach[189].

5.4.2 Operating Principle

The fundamental operating principle of Model Predictive Control (MPC) is shown in Figure 5.4. In order to streamline the analysis, the reference control trajectory x^* is maintained at a constant value. The MPC approach formulates the control problem in a discrete-time (DT) framework, where variables are allowed to change their values only at discrete sampling instants. Unlike classical hysteresis and linear control techniques that rely on past and present variable values, MPC takes into account past, present, and future values of the variable. This means that MPC anticipates future errors and implements proactive control actions to prevent the system from experiencing significant errors, thereby enhancing overall system robustness. The principle of MPC is composed of three key components, as illustrated below [190].

5.4.2.1 Prediction: Anticipatory Stage of MPC

The fundamental principle of Model Predictive Control (MPC) revolves around numerical optimizations and online iterations. This stage primarily centers on the

discrete-time (DT) model, akin to the one outlined in (5. 8). Predictions for the future outcomes of the state variable x and the control input sequence u are made using the system model and feedback observations at the current time instance (k), with a prediction horizon N_p in mind.

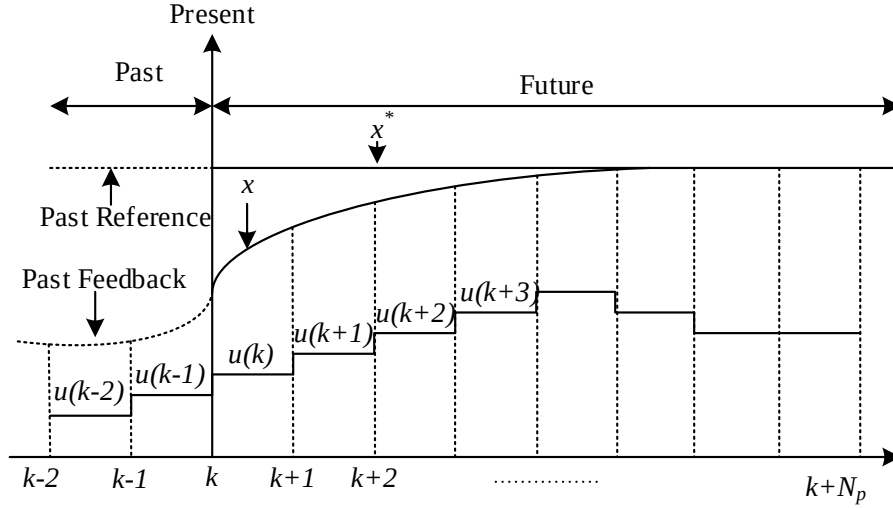


Figure 5. 4 Principle of Operation for Model Predictive Control (MPC)

5.4.2.2 Optimization: Evaluation of Predictions

After that, the anticipated values are evaluated with the help of a cost function, which specifies the control objectives or the desired system behaviour. This cost function is often a nonlinear function that includes reference, anticipated, and input events.

$$J(k) = f [x^*(k), \dots, x^*(k + N_p), x(k), u(k), \dots, u(k + N_p)] \quad 5. 11$$

The input actuation will be determined by selecting the optimal control order that will result in the lowest value for the objective function $J(k)$.

$$u^{op}(k) = \arg \min_u J(k) \quad 5. 12$$

5.4.2.3 Receding Horizon Strategy: Dynamic Control Approach

The first step of the optimal input sequence, which is denoted by the equation $u(k) = u^{op}(k)$, is carried out on the plant as part of the receding horizon technique. Therefore, the state variable x moves closer and closer to the intended reference trajectory, which is denoted by x^* . During each sample interval, we will go through this process of monitoring new feedback variables, forecasting the behaviour of the system, and optimising the cost of performance. The approach known as "receding horizon" is characterised by its fundamental iterative process.

In the context of a plant described by the DT model outlined in (4.4), the objective is to maintain the state variable x at its designated set point, denoted as x^* . To accomplish this control goal, the control input u is strategically chosen as a steering variable, as exemplified below:

$$x^*(k+1) - x(k+1) = 0 \Rightarrow \underbrace{x^*(k+1)}_{\text{Set point}} - \underbrace{\phi x(k)}_{\text{Feedback}} - \underbrace{\Gamma u(k)}_{\text{Steering}} = 0 \quad 5.13$$

By dynamically adjusting the $u(k)$ value at each sampling interval, even in the presence of minor variations in ϕ and Γ , the state variable is effectively kept at its desired set-point value. This ability of MPC to robustly handle modeling errors and uncertainties contributes to its reliability.

5.4.3 Design Procedure

In a previous section (5.2.1), the FCS-MPC method for load current regulation has been explored. This section delves deeper into the concept, providing a complete step-by-step approach for implementing FCS-MPC. It gives the control method in the natural (abc) reference frame to assist analysis. The FCS-MPC scheme consists of five key subsystems: (1) reference current estimation, (2) extrapolation of a reference currents, (3) generation of a comprehensive list of possible state switching combinations, (4) development of a discrete-time predictive model, and (5) cost function minimization. The primary goal of this control strategy is to assure precise tracking of the load currents (i) to the reference currents (i) across a wide range of operating situations. The design process described below is comprised of five critical steps, which are as follows [191]:

5.4.3.1 Obtaining Feedback Measurements:

In this initial stage, the focus is on capturing the necessary feedback variables, namely the DC-link voltage v_{dc} and the three-phase load currents (i_a , i_b , and i_c). These measurements are acquired and seamlessly integrated into the digital control system via the analog-to-digital converter (ADC) channels. For balanced loads, the sum of the instantaneous three-phase currents is zero, allowing for straightforward deduction of the i_c value based on the measurements of i_a and i_b . Consequently, the design of the digital current control system utilizing FCS-MPC necessitates only a single voltage sensor and two current sensors.

5.4.3.2 Determining Reference Currents:

Moving on, the next stage includes computing the three-phase reference currents, which are represented by the notation $i(k)$. These currents are suited to the particular application that is being considered at this time. The RSPEC and GSPEC reference currents are calculated using the FOC or VOC approaches, respectively. The $i(k)$ values in this example have been generated using customised by users three-phase sinusoidal sources. This adaptable control method can be easily modified to a variety of power conversion applications by simply adjusting the reference currents to meet the unique needs.

5.4.3.3 Estimating Future Reference Currents:

In order to facilitate the calculation of current error at the $(k + 1)$ sampling instant, the reference currents (specifically, not the load currents) are extrapolated from the $(k)^{th}$ instant to the $(k + 1)$ sampling instant. This extrapolation step is essential for supporting the cost function, allowing for accurate assessment of the current error at the desired time point. By extrapolating the reference currents, the control algorithm gains the necessary information to optimize the control action and ensure effective current regulation.

5.4.3.4 Prediction of State Variables

Within this stage, the following sub-steps are involved in predicting the load currents:

1. Obtaining the Continuous-Time (CT) Load Current Model: As demonstrated in (3.74) in Chapter 3, the CT load current model is derived. It's important to note that this model varies depending on the specific power conversion application.

$$\frac{di(t)}{dt} = \frac{1}{L} [v(t) - Ri(t)] \quad 5.14$$

2. Mapping CT Model to Discrete-Time (DT): By employing the forward Euler approximation method as depicted in (5.6), the CT model in (4.11) is mapped to the discrete-time domain.

$$i^P(k+1) = \underbrace{\left(1 - \frac{RT_s}{L}\right)}_{\phi} i(k) + \frac{T_s}{L} v^P(k) \quad 5.15$$

This process involves utilizing the predicted variable superscript p to denote the future load currents.

3. Computation of DT Parameters ϕ and Γ : The DT parameters ϕ and Γ , which are essential for the predictive model subsystem, are computed offline using R , L , and T_s . These parameters serve as inputs to facilitate the prediction of load currents.
4. Identifying Possible Switching State Combinations: To predict the converter voltages $v^p(k)$, it is crucial to determine the possible switching state combinations. By referring to the modelling of the 2L-VSC in Section 3.6.1, the converter voltages $v(k)$ is found to be correlated with the switching states $s(k)$. Table 3.1 provides insight into the eight potential switching signal combinations.
5. Prediction of PEC Voltages and Load Currents: Using the measured DC-link voltage and the eight possible switching states, the converter voltages with respect to the load neutral are predicted. A combination of equations (3.69) and (3.71) leads to accurate predictions.

$$v^p(k) = \begin{bmatrix} v_{an}(t) \\ v_{bn}(t) \\ v_{cn}(t) \end{bmatrix} = v_{dc}(k) \begin{bmatrix} \frac{2}{3} & \frac{-1}{3} & \frac{-1}{3} \\ \frac{-1}{3} & \frac{2}{3} & \frac{-1}{3} \\ \frac{-1}{3} & \frac{-1}{3} & \frac{2}{3} \end{bmatrix} \begin{bmatrix} s_a(t) \\ s_b(t) \\ s_c(t) \end{bmatrix} \quad 5.16$$

The limited set of switching state combinations in the FCS-MPC scheme significantly simplifies the online iterations required. As a result, these combinations produce eight distinct predictions for output voltages of PEC, ultimately resulting in 8 different predictions for the load currents.

5.4.3.1. Minimization of the Cost Function: Final Design Step

In this concluding design step, the focus is on minimizing the cost function $g(k)$, which evaluates the absolute error between the eight predicted currents $i^p(k+1)$ and the extrapolated reference currents $i^*(k+1)$.

$$g(k) = i^*(k+1) - i^p(k+1) \quad 5.17$$

In an idealised scenario in which all conditions are optimal, achieving a cost function value of zero would signify that load currents have been perfectly controlled. In reality, though, this perfect goal is almost impossible to reach. The evaluation of the cost function, as shown in equation (5.16), yields a total of eight different values, ranging from g_0 to g_7 . Finding the smallest cost function value and the accompanying switching state arrangement is the goal of the cost function optimisation subsystem. During the course of the design process, the ideal switching state is figured out and then applied to the converter during the subsequent sampling moment. This happens during the k th sampling interval, which occurs during the design phase. The FCS-MPC methodology, in particular, eliminates the requirement for PI controllers and a modulation mechanism.

5.5 FCS-MPC DTC Control of DFIG WECS

5.5.1 Introduction

The control of Doubly-Fed Induction Generator (DFIG) WECSs is of great significance in maximizing the power generation capabilities and ensuring efficient operation. In particular, the RSPEC plays a crucial role in regulating the electrical power exchanged between the DFIG and the grid. One approach that has shown promising results in achieving effective RSPEC control is the FCS-MPC strategy. FCS-MPC offers several advantages in terms of its ability to handle the nonlinear and time-varying characteristics of the DFIG system, as well as its capability to consider system constraints and dynamic behaviors.

In the FCS-MPC control scheme for DFIG WECSs, the objective is to maintain optimal power generation while meeting the grid code requirements and ensuring safe operation of the system. The control algorithm utilizes a finite control set approach, where a pre-defined set of control actions is employed to determine the optimal control trajectory over a specified prediction horizon.

The FCS-MPC control scheme incorporates a predictive model of the DFIG system, capturing the dynamics of both the rotor and stator sides. The model takes into account various parameters such as rotor speed, stator currents, and grid voltage, among others, to accurately predict the future behavior of the system. By considering these predictions, the control algorithm optimizes the control actions, including the selection of the converter's switching states, to achieve the desired power output and maintain the system within safe operating limits [192].

The FCS-MPC approach applied to DFIG WECSs for RSPEC incorporates various subsystems to achieve effective control. These include calculating reference currents, extrapolating reference currents, selecting switching state configurations, predicting converter voltages, and optimising a cost function to identify the best control actions. Through this comprehensive control approach, the FCS-MPC technique offers robust and precise control of the DFIG system, enabling enhanced power generation performance and efficient grid integration. Direct Torque Control (DTC) is a control strategy widely employed in the field of electrical machines to achieve precise torque and flux control. When applied to DFIGs, DTC can enhance the performance and efficiency of the RSPEC operation.

In recent years, the integration of DTC with FCS-MPC has gained significant attention for the control of DFIGs with RSPEC. This hybrid approach combines the benefits of both DTC and FCS-MPC, resulting in improved torque and flux control with enhanced dynamic response and reduced torque ripples. In the FCS-MPDTC scheme for DFIGs, the objective is to control the torque and flux at the rotor side while maintaining optimal power generation and grid synchronization. The control algorithm employs a predictive model of the DFIG system, considering factors such as rotor speed, stator currents, and voltage references to anticipate future behavior. By utilizing this predictive model, the FCS-MPDTC algorithm optimizes the control actions, including the selection of voltage vectors, to achieve accurate torque and flux regulation. The FCS-MPDTC strategy eliminates the need for traditional PI controllers, offering a more direct and dynamic control approach. By directly controlling the torque and flux components, the FCS-MPDTC scheme provides faster response times and improved transient performance. Furthermore, by utilizing the FCS-MPC framework, the control algorithm can incorporate various constraints and system limitations, ensuring safe and reliable operation.

The control of the rotor side converter in the FCS-MPDTC scheme involves multiple steps, including the calculation of reference torque and flux values, determination of voltage vectors based on the predictive model, and the minimization of a cost function to select the optimal voltage vector. This process is repeated in each control cycle, allowing for real-time adaptation to changing operating conditions. Overall, the FCS-MPC-DTC strategy for the rotor side converter of DFIGs offers advanced control capabilities, combining the benefits of DTC with the predictive capabilities of FCS-MPC.

By achieving precise torque and flux control while considering system constraints, the FCS-MPDTC approach enhances the performance and efficiency of DFIG systems, making them more suitable for various renewable energy applications.

In the previous part of this section, we covered the numerous frames, such as abc , $\alpha\beta$, and dq , in which it is possible to conduct an analysis of the DFIG. The stator and rotor variables in the DFIG display separate angular frequencies, denoted by the ω_s and ω_{sl} . The design of Predictive Control allows for the selection of the $\alpha\beta$, abc , or dq frames. Nevertheless, utilising the $\alpha\beta$ and abc frames can result in digital control that is more complicated and has more coupling concerns. The use of dq -frame control, on the other hand, causes all stator and rotor variables to become DC. This simplifies the computation and enables decoupled control.

This section now concentrates on the modelling of DFIG using the stator voltage vector (SVOC) scheme. Both the steady-state and dynamic versions of the DFIG are shown, with a focus on how important they are for designing PTCs. Furthermore, the relationship among rotor currents and stator active and reactive powers is determined, contributing to a comprehensive understanding of the system.

5.5.2 Equivalent Circuit of DFIG

In the implementation of FCS-MPC DTC (Finite Control Set Model Predictive Control Direct Torque Control) for Doubly-Fed Induction Generators (DFIGs), it is beneficial to represent the DFIG using an equivalent circuit in the d - q reference frame. This d - q reference frame simplifies the analysis and control of the machine by decoupling the rotor and stator variables. Figure 5. 5 depicts the equivalent circuits of the dynamic dq -axes that are used by DFIG.

Implementing FCS-MPC DTC for DFIG involves modeling the DFIG system using the equivalent circuit in the d - q reference frame. This model enables the prediction of the d - q axis currents and voltages based on the applied control actions. By considering the constraints and objectives of the control scheme, the FCS-MPC DTC algorithm determines the optimal control strategy to regulate the torque and flux of the DFIG.

With reference to Figure 5. 5, the stator and rotor voltage vectors are defined according to [193].

$$v_{s,dq} = R_s i_{s,dq} + \frac{d\psi_{s,dq}}{dt} + j\omega_s \psi_{s,dq} \quad 5.18$$

$$v_{r,dq} = R_r i_{r,dq} + \frac{d\psi_{r,dq}}{dt} + j(\omega_s - \omega_r) \psi_{r,dq} \quad 5.19$$

Where

In the DFIG system, we utilize the following vectors and parameters:

- The stator voltage vector, represented as $v_{s,dq} = \begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix}$, and the rotor voltage vector, denoted as $v_{r,dq} = \begin{bmatrix} v_{dr} \\ v_{qr} \end{bmatrix}$. Both are measured in volts.
- The stator current vector, $i_{s,dq} = \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix}$, and the rotor current vector, $i_{r,dq} = \begin{bmatrix} i_{dr} \\ i_{qr} \end{bmatrix}$. These vectors indicate the current flow in the stator and rotor windings, respectively, and are measured in amperes.
- The stator flux vector, $\psi_{s,dq} = \begin{bmatrix} \psi_{ds} \\ \psi_{qs} \end{bmatrix}$, and the rotor flux vector, $\psi_{r,dq} = \begin{bmatrix} \psi_{dr} \\ \psi_{qr} \end{bmatrix}$. These vectors represent the flux in the stator and rotor circuits, respectively, and are measured in Weber.
- R_s and R_r represent the stator and rotor winding resistances, respectively, measured in ohms.
- The slip angular speed, $\omega_{sl} = (\omega_s - \omega_r)$, is calculated as the difference between the stator angular speed (ω_s) and the rotor angular speed (ω_r), both measured in radians per second.

These vectors and parameters provide essential information for analyzing and controlling the DFIG system. By monitoring and manipulating these variables, we can effectively regulate the operation of the DFIG, ensuring efficient energy conversion and reliable performance.

In the state of steady-state operation, the derivative terms in Equations (5.18) and (5.19) become negligible. As a result, the stator flux vector can be determined using Equation (5.18) in the following manner:

$$\psi_{s,dq} = \frac{v_{s,dq} - R_s i_{s,dq}}{j\omega_s}$$

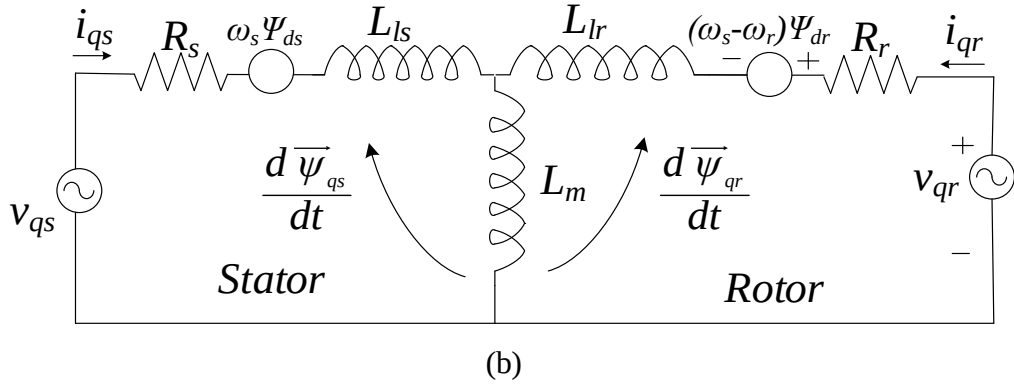
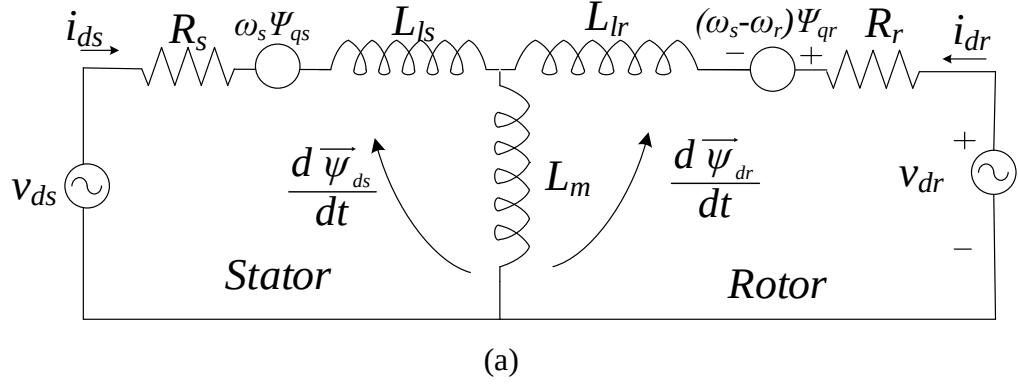


Figure 5. 5 dq Model of the DFIG in synchronous coordinates

Alternatively, an alternative representation can be employed using the stator and rotor flux linkage vectors, defined as follows:

$$\psi_{s,dq} = i_{s,dq} L_s + i_{r,dq} L_m \quad 5. 21$$

$$\psi_{r,dq} = i_{r,dq} L_r + i_{s,dq} L_m \quad 5. 22$$

The expression for the electromagnetic torque can be derived as follows:

$$T_{em} = \frac{3}{2} p \text{Im}\{\vec{\psi}_r \vec{i}_r^*\} = \frac{3}{2} p (\psi_{dr} i_{qr} - \psi_{qr} i_{dr}) \quad 5. 23$$

Under the implementation of the stator voltage-oriented control (SVOC) strategy, the stator voltage vector v_s is aligned with the d-axis and the stator's q-axis voltage is nullified.

$$v_{qs} = 0, \quad v_{ds} = \sqrt{v_s^2 - v_{qs}^2} \quad 5. 24$$

Consequently, changes are observed in the stator's active and reactive power in the following manner:

$$P_s = \frac{3}{2} \text{Re}\{\vec{v}_s \vec{i}_s^*\} = \frac{3}{2} (v_{ds} i_{ds}) \quad 5.25$$

$$Q_s = \frac{3}{2} \text{Im}\{\vec{v}_s \vec{i}_s^*\} = -\frac{3}{2} (v_{ds} i_{qs}) \quad 5.26$$

5.5.3 Correlation Between Rotor Currents and Control Objectives

In the context of DFIG WECSs, achieving Maximum Power Point Tracking (MPPT) and adjusting the Wind Farm Control Panel Power Factor (WFCP-PF) are crucial control objectives. These objectives are accomplished by regulating the rotor currents through digital control of the RSPEC. Hence, it is important to understand the relationship between the rotor currents and the control variables, including T_e , P_s , and Q_s .

Resolving Equations (5. 20), (5. 21-5. 22), and (

5. 23) allows for the expression of the electromagnetic torque in relation to the dq-axes rotor currents. Additionally, under the SVOC scheme, the maintenance of zero q-axis stator voltage is ensured. In the case of a high-power DFIG, the resistance of the stator winding, denoted as R_s , becomes essentially negligible, simplifying the representation of the electromagnetic torque as outlined below:

$$T_{em} = \frac{-3}{2} p \frac{L_m}{\omega_s L_s} i_{dr} v_{ds} \quad 5.27$$

The rotor currents can be defined in terms of stator active and reactive powers by resolving Equations (5. 20), (5. 21-5. 22), and (

5. 25-

5. 26) [194-195]:

$$\begin{aligned} i_{dr} &= \left(-\frac{2L_s}{3v_{ds}L_m} \right) P_s - \left(\frac{R_s}{\omega_s L_m} \right) i_{qs} \\ i_{qr} &= \left(+\frac{2L_s}{3v_{ds}L_m} \right) Q_s + \left(\frac{R_s}{\omega_s L_m} \right) i_{ds} - \left(\frac{1}{\omega_s L_m} \right) v_{ds} \end{aligned} \quad 5.28$$

The aforementioned expressions can be made even simpler by ignoring the stator winding resistance.

$$i_{dr} = \left(-\frac{2L_s}{3v_{ds}L_m} \right) P_s \quad 5.29$$

$$i_{qr} = \left(+\frac{2L_s}{3v_{ds}L_m} \right) Q_s - \left(\frac{1}{\omega_s L_m} \right) v_{ds}$$

As shown in Equations (5.27) and (5.29), it becomes evident that T_e exhibits a direct proportionality with i_{dr} , P_s demonstrates a direct proportionality with i_{dr} , and Q_s showcases a direct proportionality with i_{qr} . Precise rotor current management in the dq-axis allows for the independent control of the DFIG's electromagnetic torque, stator active power, and stator reactive power.

5.5.4 DFIG Continuous-Time Dynamic Models

To utilize predictive control strategies, acquiring dynamic models for the stator current and stator flux in the DFIG is crucial. The desired state-space format for the Induction Machine (IM) model should be presented as follows:

$$\begin{aligned} \frac{d[i_s, \psi_r]}{dx} &= F \{ [A], [i_s, \psi_r], [B], [v_s, v_r] \} \\ \frac{d[i_s, \psi_s]}{dx} &= F \{ [C], [i_s, \psi_r] \} \end{aligned} \quad 5.30$$

As a result, the purpose of this part is to ascertain the parameter matrices A, B, and C that are necessary for DFIG modelling. The rotor voltages mentioned in (5. 18-5. 19), stator flux-linkages in (5. 21), and rotor flux-linkages in (5. 22) all require information about the rotor current. However, capturing this data is quite challenging. To bypass this issue, the rotor currents are defined in relation to stator currents, facilitated by Equation (5. 22):

$$i_r = \frac{\psi_r - L_m i_s}{L_r} \quad 5.31$$

By substituting Equation (5. 31) into Equation (5. 21), can express the stator flux-linkages as:

$$\psi_s = \sigma L_s i_s + k_r \psi_r \quad 5.32$$

Here, k_r represents the rotor coupling coefficient, σL_s denotes the total leakage inductance, σ refers to the total leakage coefficient, and k_s represents the stator coupling coefficient [179]. The values of these parameters are characterized as:

$$k_r = \frac{L_m}{L_r}, k_s = \frac{L_m}{L_s}, \sigma = 1 - (k_s k_r) = 1 - (k_s \frac{L_m^2}{L_s L_r}) \quad 5.33$$

Similarly, by substituting Equation (5.35) into Equation (5.28), can derive the dynamics of the rotor flux as:

$$\frac{d\psi_r}{dt} = \frac{L_m i_s}{\tau_r} - \left[\frac{1}{\tau_r} + (\omega_s - \omega_r) \right] \psi_r + v_r \quad 5.34$$

Here, τ_r represents the rotor time constant.

$$\tau_r = \frac{L_r}{R_r} \quad 5.35$$

The subsequent step involves determining the stator current dynamics. By substituting Equation (5.32) into Equation (5.18) and simplifying the equation, the stator current dynamics can be expressed as:

$$\frac{di_s}{dt} = \frac{1}{\sigma L_s} - \left[(R_s + j\omega_s \sigma L_s) i_s - j\omega_s \psi_r k_r - k_r \frac{d\psi_r}{dt} \frac{1}{\tau_r} + v_r \right] \quad 5.36$$

In Equation (5.36), the term $\frac{d\psi_r}{dt}$ is undesired and needs to be replaced with its equivalent to achieve the state-space model. By substituting Equation (5.34) into Equation (5.36), we obtain the following expression [179]:

$$\frac{di_s}{dt} = - \left(\frac{1}{\tau_\sigma} + j\omega_s \right) i_s + \frac{k_r}{\sigma L_s} \left(\frac{1}{\tau_r} - j\omega_r \right) \psi_r + \frac{1}{\sigma L_s} v_s - \frac{k_r}{\sigma L_s} v_r \quad 5.37$$

The variables r_σ and τ_σ are of significant importance in the context of the above equations. These variables correspond to the equivalent resistance and stator transient time constant, respectively, and are defined as follows:

$$r_\sigma = R_s + R_r, \tau_\sigma = \frac{\sigma L_s}{r_\sigma} \quad 5.38$$

The precise definition of the dq-frame space phasor is given by:

$$f = (f^d + j f^q), f \in \{v, i, \psi\} \quad 5.39$$

By substituting the aforementioned expression into Equation (5.37), can derive the following result:

$$\begin{aligned} \frac{d(i_{ds} + j i_{qs})}{dt} = & - \left(\frac{1}{\tau_\sigma} + j\omega_s \right) (i_{ds} + j i_{qs}) + \frac{k_r}{\sigma L_s} \left(\frac{1}{\tau_r} - j\omega_r \right) (\psi_{dr} + j\psi_{qr}) + \\ & \frac{1}{\sigma L_s} (v_{ds} + jv_{qs}) - \frac{k_r}{\sigma L_s} (v_{dr} + jv_{qr}) \end{aligned} \quad 5.40$$

By isolating the real and imaginary elements from the aforementioned formula, we obtain the following [180]:

$$\frac{di_{ds}}{dt} = -\frac{1}{\tau_\sigma} i_{ds} + \omega_s i_{qs} + \frac{k_r}{\sigma L_s \tau_r} \psi_{dr} + \frac{k_r \omega_r}{\sigma L_s} \psi_{qr} + \frac{1}{\sigma L_s} v_{ds} - \frac{k_r}{\sigma L_s} v_{dr} \quad 5.41$$

$$\frac{di_{qs}}{dt} = -\omega_s i_{ds} - \frac{1}{\tau_\sigma} i_{qs} - \frac{k_r \omega_r}{\sigma L_s} \psi_{dr} + \frac{k_r}{\sigma L_s \tau_r} \psi_{qr} + \frac{1}{\sigma L_s} v_{qs} - \frac{k_r}{\sigma L_s} v_{qr} \quad 5.42$$

Likewise, by resolving Equation (5.34), derives the dq-frame rotor flux dynamics as follows:

$$\frac{d\psi_{dr}}{dt} = \frac{L_m i_{ds}}{\tau_r} - \frac{1}{\tau_r} \psi_{dr} + (\omega_s - \omega_r) \psi_{qr} + v_{dr} \quad 5.43$$

$$\frac{d\psi_{qr}}{dt} = \frac{L_m i_{qs}}{\tau_r} - (\omega_s - \omega_r) \psi_{dr} - \frac{1}{\tau_r} \psi_{qr} + v_{qr} \quad 5.44$$

Ultimately, the dq-frame stator flux-linkages are extracted from Equation (6.36):

$$\psi_{ds} = \sigma L_s i_{ds} + k_r \psi_{dr} \quad 5.45$$

$$\psi_{qs} = \sigma L_s i_{qs} + k_r \psi_{qr} \quad 5.46$$

By integrating Equations (5.41) to (5.46), presents the CT state-space model within the dq reference frame as indicated below [196]:

$$\frac{d}{dt} \begin{bmatrix} i_{ds} \\ i_{qs} \\ \psi_{dr} \\ \psi_{qr} \end{bmatrix} = A \begin{bmatrix} i_{ds} \\ i_{qs} \\ \psi_{dr} \\ \psi_{qr} \end{bmatrix} + B \begin{bmatrix} v_{ds} \\ v_{qs} \\ v_{dr} \\ v_{qr} \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} \psi_{ds} \\ \psi_{qs} \end{bmatrix} = C \begin{bmatrix} i_{ds} \\ i_{qs} \\ \psi_{dr} \\ \psi_{qr} \end{bmatrix} \quad 5.47$$

and

$$A = \underbrace{\begin{bmatrix} -\frac{1}{\tau_\sigma} & \omega_s & \frac{k_r}{\sigma L_s \tau_r} & \frac{k_r \omega_r}{\sigma L_s} \\ -\omega_s & -\frac{1}{\tau_\sigma} & \frac{k_r \omega_r}{\sigma L_s} & \frac{k_r}{\sigma L_s \tau_r} \\ \frac{L_m}{\tau_r} & 0 & -\frac{1}{\tau_r} & \omega_{re} \\ 0 & \frac{L_m}{\tau_r} & -\omega_{re} & -\frac{1}{\tau_r} \end{bmatrix}}_{A(t)} \quad 5.48$$

$$B = \underbrace{\begin{bmatrix} \frac{1}{\sigma L_s} & 0 & -\frac{k_r}{\sigma L_s} & 0 \\ 0 & -\frac{1}{\tau_\sigma} & \frac{k_r \omega_r}{\sigma L_s} & \frac{k_r}{\sigma L_s \tau_r} \\ \frac{L_m}{\tau_r} & 0 & -\frac{1}{\tau_r} & \omega_{re} \\ 0 & \frac{L_m}{\tau_r} & -\omega_{re} & -\frac{1}{\tau_r} \end{bmatrix}}_B \quad 5.49$$

$$C = \begin{bmatrix} \sigma L_s & 0 & k_r & 0 \\ 0 & \sigma L_s & 0 & k_r \end{bmatrix} \quad 5.50$$

The continuous-time (CT) dq-frame dynamic model of DFIG is provided below for the purpose of examining the dynamic model of rotor current:

$$\frac{d}{dt} \begin{bmatrix} i_{ds} \\ i_{qs} \\ \psi_{dr} \\ \psi_{qr} \end{bmatrix} = \underbrace{\begin{bmatrix} -\frac{1}{\tau_\sigma} & \omega_s & \frac{k_r}{\sigma L_s \tau_r} & \frac{k_r \omega_r}{\sigma L_s} \\ -\omega_s & -\frac{1}{\tau_\sigma} & \frac{k_r \omega_r}{\sigma L_s} & \frac{k_r}{\sigma L_s \tau_r} \\ \frac{L_m}{\tau_r} & 0 & -\frac{1}{\tau_r} & (\omega_s - \omega_r) \\ 0 & \frac{L_m}{\tau_r} & -(\omega_s - \omega_r) & -\frac{1}{\tau_r} \end{bmatrix}}_{A(t)} \begin{bmatrix} i_{ds} \\ i_{qs} \\ \psi_{dr} \\ \psi_{qr} \end{bmatrix} + \underbrace{\begin{bmatrix} \frac{1}{\sigma L_s} & 0 & -\frac{k_r}{\sigma L_s} & 0 \\ 0 & -\frac{1}{\tau_\sigma} & \frac{k_r \omega_r}{\sigma L_s} & \frac{k_r}{\sigma L_s \tau_r} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}}_B \begin{bmatrix} v_{ds} \\ v_{qs} \\ \psi_{dr} \\ \psi_{qr} \end{bmatrix}$$

In the model described above, the most critical state variables are the dq-axes stator currents and rotor flux linkages. Consequently, it is crucial to establish a continuous-time (CT) output model that links the dq-axis rotor currents with the state variables defined in Equation (5.51). For analytical support, the expression in (5.31) is transformed into a state-space equation, as illustrated below:

$$\begin{bmatrix} i_{dr} \\ i_{qr} \end{bmatrix} = \underbrace{\begin{bmatrix} \frac{L_m}{L_r} & 0 & \frac{1}{L_r} & 0 \\ 0 & -\frac{L_m}{L_r} & 0 & \frac{1}{L_r} \end{bmatrix}}_C \begin{bmatrix} i_{ds} \\ i_{qs} \\ \psi_{dr} \\ \psi_{qr} \end{bmatrix} \quad 5.52$$

where C represents the output matrix in Continuous-Time (CT).

The dq-axes rotor voltages, v_{dr} and v_{qr} , as stated in (5.51), are regulated by the RSPEC. This control subsequently directs both the stator currents and rotor flux linkages, and indirectly manages the rotor currents. As such, the state-space models present in Equations (5.51) and (5.52) are known as the indirect dynamic models of the rotor currents.

5.5.5 Dynamic Models of DFIG in Discrete-Time

The time-varying nature of the state matrix A(t) introduces temporal variability in the dynamic models of the indirect and direct rotor currents. To streamline the discretization procedure, sampled data models are derived through the utilization of the forward Euler approximation. This approximation technique provides an estimation of the first-order derivative, as outlined below [196]:

$$x(k+1) = x(k) + T_s \left\{ \frac{dx(t)}{dt} \right\}_{t=k}, \quad x \in \{i_{ds}, i_{qs}, i_{dr}, i_{qr}\} \quad 5.53$$

By integrating Equations (5.51), (5.52), and (5.53), the formulation of the dynamic model for the discrete-time (DT) indirect rotor current is expressed as follows:

$$\begin{bmatrix} i_{ds}(k+1) \\ i_{qs}(k+1) \\ \psi_{dr}(k+1) \\ \psi_{qr}(k+1) \end{bmatrix} = \underbrace{\begin{bmatrix} 1 - \frac{T_s}{\tau_\sigma} & \omega_s(k)T_s & \frac{k_r T_s}{\sigma L_s \tau_r} & \frac{k_r T_s \omega_r(k)}{\sigma L_s} \\ -\omega_s(k)T_s & 1 - \frac{T_s}{\tau_\sigma} & \frac{-k_r T_s \omega_r(k)}{\sigma L_s} & \frac{k_r T_s}{\sigma L_s \tau_r} \\ \frac{L_m T_s}{\tau_r} & 0 & 1 - \frac{T_s}{\tau_r} & \omega_{sl}(k)T_s \\ 0 & \frac{L_m T_s}{\tau_r} & -\omega_{sl}(k)T_s & 1 - \frac{T_s}{\tau_\sigma} \end{bmatrix}}_{\phi(k)} \begin{bmatrix} i_{ds} \\ i_{qs} \\ \psi_{dr} \\ \psi_{qr} \end{bmatrix} + \quad 5.54$$

$$\underbrace{\begin{bmatrix} \frac{T_s}{\sigma L_s} & 0 & -\frac{k_r T_s}{\sigma L_s} & 0 \\ 0 & \frac{T_s}{\tau_\sigma} & 0 & -\frac{k_r T_s}{\sigma L_s} \\ 0 & 0 & T_s & 0 \\ 0 & 0 & 0 & T_s \end{bmatrix}}_{\Gamma_b} \begin{bmatrix} v_{ds} \\ v_{qs} \\ v_{dr} \\ v_{qr} \end{bmatrix}$$

With

$$\begin{bmatrix} i_{dr}(k) \\ i_{qr}(k) \end{bmatrix} = \underbrace{\begin{bmatrix} -\frac{L_m}{L_r} & 0 & \frac{1}{L_r} & 0 \\ 0 & -\frac{L_m}{L_r} & 0 & \frac{1}{L_r} \end{bmatrix}}_H \begin{bmatrix} i_{ds}(k) \\ i_{qs}(k) \\ \psi_{dr}(k) \\ \psi_{qr}(k) \end{bmatrix} \quad 5.55$$

where T_s represents the control sampling time. The relationship between the CT and DT matrices is characterized by the following:

$$f(k) \approx (I + A(t)T_s), \Gamma_b \approx BT_s, H = C \quad 5.56$$

Here, I stand for the identity matrix.

5.5.6 Digital Control of BTB Converter-Based DFIG WECS

To develop a digital control system for traditional or predictive control of DFIG WECSs, a comprehensive understanding of the control scheme's block diagram, control requirements, and computation of reference control variables is essential. This segment of the discussion delves into the digital control system's advancement for DFIG WECSs, encompassing both RSPEC and PTC approaches.

In the DFIG configuration, the stator terminals are directly connected to the Wind Farm Collection Point (WFCP), while the rotor terminals are linked to the WFCP through a Back-to-Back Voltage Source Converter (BTB VSC), a harmonic filter, and a step-up transformer. The stator voltage (v_s) of the DFIG is equivalent to the voltage (v_o) at the WFCP, which represents the output of the wind turbine. While the currents in the rotor circuit are capable of flowing in both directions depending on the speed of the rotor, the currents in the stator flow in just one direction, which is from the stator to the WFCP.

The separation of duties between RSPEC and GSPEC makes it possible for two distinct digital control systems to function in a manner that is completely autonomous from one another. In order to function properly, the RSPEC and GSPEC digital control

systems require feedback signals from the stator, rotor, grid sides, and DC-link. To facilitate the application of motor models for generator operation, stator currents are measured in the opposite direction. The reference for GSPEC reactive power (Q_g^*) is set to zero, indicating that GSPEC does not handle the overall WECSs Power Factor (PF) control [197]. The reference for stator reactive power (Q_s^*) is determined to enable RSPEC to control the total reactive power (Q_o) of the WECS. The reference command for stator reactive power (Q_s^*) can be adjusted to achieve unity PF, positive for leading PF, or negative for lagging PF of the WFCP. The digital control systems for RSPEC and GSPEC are employed to fulfill the technical and operational requirements of the DFIG WECS. The Maximum Power Point Tracking (MPPT) operation and the WFCP PF are both managed by managing the currents flowing through the rotors, while the overall DC-bus voltage is kept at its reference through the regulation of the currents flowing through the GSPEC side.

5.5.6.1 Reference Control Variable

The process for obtaining the reference torque is outlined in the block diagram presented in Figure 5.6. The reference for the electromagnetic torque, denoted as T_e^* , is determined using either the optimal tip-speed ratio (OTSR) or optimal torque (OT) Maximum Power Point Tracking (MPPT) methods [172-176].

The OTSR MPPT method derives an estimate of the reference speed ω_m^* by making use of the observed value of the wind speed v_w in conjunction with the previously computed coefficient K_{op1} . This reference speed is then compared to the measured mechanical speed ω_m .

A Proportional-Integral (PI) controller processes the deviation between the rotor mechanical speed and the reference speed to generate the reference torque T_e^* , ensuring that ω_m follows the desired ω_m^* trajectory. On the other hand, the OT algorithm directly computes T_e^* based on the feedback of the rotor speed ω_m and the coefficient K_{op2} . Alternately, an OT power curve-based MPPT or an OT power signal feedback MPPT could be used in place of the OTSR and OT algorithms. Both of these MPPTs are based on wind turbine power curves.

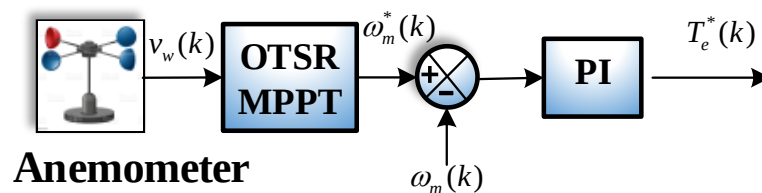


Figure 5. 6 Calculation of reference control variables for PTC of DFIG WECS

This section embark on an in-depth analysis of the digital control strategy for RSPEC, with the overarching objective of achieving robust control over the DFIG WECS. The primary aim for the RSPEC control schemes is to consistently track the designated reference torque across various operating conditions.

5.5.7 Predictive Torque Control For 2L-VSC of DFIG WECS

This section presents the block diagram of the dq-frame Predictive Torque Control (PTC) scheme for a DFIG equipped with RSPEC as illustrated in Figure 5. 7. By employing optimal gating signals for RSPEC, the torque and rotor flux of the DFIG can be independently controlled. The Maximum Power Point Tracking (MPPT) operation is confined to a speed range of $\pm 30\%$. The reference torque $T_e^*(k)$ is determined following the OT MPPT control method, and the rotor flux reference $\psi_r^*(k)$ is kept constant. The prediction of electromagnetic torque and rotor flux, as well as the computation of the cost function, are both important significant design steps that are involved in the PTC scheme. The subsequent sections will go into additional information regarding these design stages.

Within this section, we unveil a distinctive block diagram of the dq-frame PTC scheme, specifically tailored for a DFIG that incorporates RSPEC. This novel configuration is graphically represented in Figure 5. 7. By skillfully employing optimal gating signals for RSPEC, independent control over the torque and rotor flux of the DFIG can be achieved. It's worth noting that the MPPT operation is confined within a speed range of $\pm 30\%$. The reference torque $T_e^*(k)$ is meticulously determined through the application of the OT MPPT control method, while the rotor flux reference $\psi_r^*(k)$ is held constant. As part of the intricate design process of the PTC scheme, significant stages involve the prediction of electromagnetic torque and rotor flux, along with the precise calculation of the cost function [179]. These pivotal design stages will be further elucidated in subsequent sections.

5.5.7.1 Collection and Processing of Feedback Signals:

In order to create the PTC scheme, it is necessary to take measurements of the wind speed v_w , the voltage of the DC-link capacitor $V_{dc}(k)$, the stator currents $i_s(k)$, the stator voltages $v_s(k)$, and the mechanical speed of the generator rotor $\omega_m(k)$.

The three-phase stator currents $i_s(k)$ are gauged in the direction opposing the original flow, as the "predictive model" subsystem employs motor-corresponding

dynamic equations. The mechanical speed $\omega_m(k)$ is multiplied by the DFIG pole pairs p to obtain the equivalent rotor electrical speed $\omega_r(k)$. The Stator Voltage Oriented Control (SVOC) scheme is used to estimate the stator voltage angle θ_s , slip angle θ_{sl} , and stator angular frequency ω_s . The dq-axes rotor flux linkages are also estimated. The stator voltage angle θ_s aids in the conversion of three-phase stator voltages and currents into equivalent dq-frame voltages and currents ($v_{s,dq}$ and $i_{s,dq}$). Due to the stator voltage orientation, we have $v_{ds} = v_s$, and $v_{qs} = 0$. The slip angle θ_{sl} contributes to the estimation of dq-axes rotor flux linkages ψ_{dr} and ψ_{qr} .

The "predictive model" subsystem uses motor-specific dynamic formulae to measure the three-phase stator currents $i_s(k)$ in the opposite direction of the original flow. The electrical speed of the rotor, $\omega_r(k)$, is calculated by multiplying the mechanical speed, $\omega_m(k)$, by the number of pole pairs, p in the DFIG. It is possible to estimate the stator voltage angle θ_s , the slip angle θ_{sl} , and the stator angular frequency ω_s with the use of a control method called Stator Voltage Oriented Control (SVOC). This also make estimates for the rotor flux connections along the dq-axes. The stator voltage angle θ_s helps convert three-phase stator voltages and currents to equivalent dq-frame voltages and currents ($v_{s,dq}$ and $i_{s,dq}$). Due to the orientation of the stator voltage, we have $v_{ds} = v_s$, and $v_{qs} = 0$. The slip angle, denoted by θ_{sl} , is a factor that plays into the calculation of the rotor flux linkages, denoted respectively by ψ_{dr} and ψ_{qr} .

5.5.7.2 *Prediction of Future Behaviour of DFIG Rotor Currents for the calculation of future values of torque*

The predictive model block is crucial in calculating future torque values by accounting for dq-axes rotor currents. To accomplish this, a multi-step process is used that incorporates various factors such as the DFIG and RSPEC's Discrete-Time (DT) model, estimations of the dq-axes flux linkages of the rotor $\psi_{r,dq}(k)$, measurements of the dq-axes stator current and voltage levels $i_{s,dq}(k)$ and $v_{s,dq}(k)$, tracking of rotor angular speed $\omega_r(k)$ and angular stator frequency $\omega_s(k)$, in addition to taking into account the slip angle $\theta_{sl}(k)$ and conducting an analysis of the recorded DC-link voltage $V_{dc}(k)$, it is essential to explore all of the possible switching state combinations of RSPEC. In the following sections, the step-by-step technique for estimating the dq-axes rotor currents is discussed.

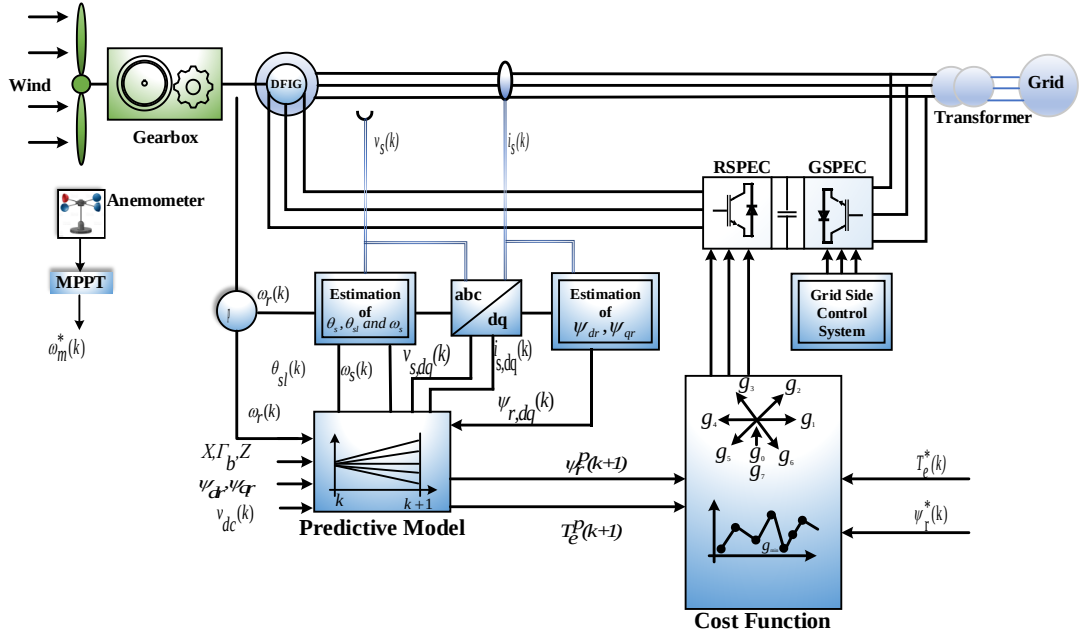


Figure 5. 7 Block diagram of the PTC scheme for 2L-VSC-based DFIG.

The output voltages of the RSPEC, represented by v_{dr} and v_{qr} , correspond to the rotor voltages of the DFIG, as depicted in Figure 5.7. Anticipating the RSPEC voltages in the dq-frame enables the estimation of forthcoming values for stator currents and rotor flux linkages. This is exemplified by a simplified portrayal of the Discrete-Time (DT) model in equation (5.54) as presented below:

$$\begin{bmatrix} i_{ds}(k+1) \\ i_{qs}(k+1) \\ \psi_{dr}(k+1) \\ \psi_{qr}(k+1) \end{bmatrix} = \phi(k) \begin{bmatrix} i_{ds}(k) \\ i_{qs}(k) \\ \psi_{dr}(k) \\ \psi_{qr}(k) \end{bmatrix} + \Gamma_b \begin{bmatrix} v_{ds} \\ v_{qs} \\ v_{dr}^p \\ v_{qr}^p \end{bmatrix} \quad 5.57$$

The predicted variables in the equation are denoted with the superscript "p." In order to minimize online calculations, the parameters ϕ and Γ_b are pre-defined offline, excluding the $\omega_r(k)$ and $\omega_{sl}(k)$ terms. This optimization enhances computational efficiency. The rotor voltages mentioned in the previous equation are estimated by considering the dq-axes RSPEC switching signals and the measured voltage of DC-link capacitor. This modelling process is summarized by the following equation:

$$\begin{bmatrix} v_{dr}^p(k) \\ v_{qr}^p(k) \end{bmatrix} = v_{dc}(k) \begin{bmatrix} s_{dr}^p(k) \\ s_{qr}^p(k) \end{bmatrix} \quad 5.58$$

In this equation, the switching signals for the dq-axes are derived from the switching signals for the natural frame as well as the slip angle $\theta_{sl}(k)$, is illustrated in the following equation:

$$\begin{bmatrix} s_{dr}^p(k) \\ s_{qr}^p(k) \end{bmatrix} = \underbrace{\begin{bmatrix} \cos\theta_{sl}(k) & \sin\theta_{sl}(k) \\ -\sin\theta_{sl}(k) & \cos\theta_{sl}(k) \end{bmatrix}}_{T_{\alpha\beta/dq}} \frac{2}{3} \underbrace{\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}}_{T_{abc/\alpha\beta}} \begin{bmatrix} s_{ar1}^p \\ s_{br1}^p \\ s_{cr1}^p \end{bmatrix} \quad 5.59$$

The switching signals initially exist in the natural frame and are subsequently transformed into the $\alpha\beta$ -frame. They are further converted into the dq-frame utilizing the $\theta_{sl}(k)$. This technique effectively reduces the computational load for online operations. By combining Equations (5.47) and (5.48), For the purpose of making precise predictions regarding the future values of dq-axes stator currents and rotor flux linkage in response to RSPEC switching signals, an exhaustive sampled data model has been developed. This predictive model is shown below:

$$\begin{bmatrix} i_{ds}^p(k+1) \\ i_{qs}^p(k+1) \\ \psi_{dr}^p(k+1) \\ \psi_{qr}^p(k+1) \end{bmatrix} = \phi(k) \begin{bmatrix} i_{ds}(k) \\ i_{qs}(k) \\ \psi_{dr}(k) \\ \psi_{qr}(k) \end{bmatrix} + \Gamma_b \begin{bmatrix} v_{ds} \\ v_{qs} \\ v_{dc}(k)s_{dr1}^p(k) \\ v_{dc}(k)s_{qr1}^p(k) \end{bmatrix} \quad 5.60$$

By advancing the variables in Equation (5.55) by one sample period, the redicted future value of rotor currents can be computed using stator currents and rotor flux linkages as illustrated in Equation (5.60). That is,

$$\begin{bmatrix} i_{dr}^p(k+1) \\ i_{qr}^p(k+1) \end{bmatrix} = H \begin{bmatrix} i_{ds}^p(k+1) \\ i_{qs}^p(k+1) \\ \psi_{dr}^p(k+1) \\ \psi_{qr}^p(k+1) \end{bmatrix} \quad 5.61$$

The expected value of electromagnetic torque in the future is determined from the cross product of the projected dq-frame rotor currents and rotor flux linkage as depicted in (5.61) and (5.61) respectively. The model for $T_{em}^p(k+1)$ is established as follows:

$$T_{em}^p(k+1) = 1.5p \left[\psi_{dr}^p(k+1)i_{qr}^p(k+1) - \psi_{qr}^p(k+1)i_{dr}^p(k+1) \right] \quad 5.62$$

5.5.7.3 Minimizing the Cost Function:

By establishing a cost function, we simultaneously manage the DFIG's rotor flux and electromagnetic torque. The formulation of the cost function is as follows:

$$g_r(k) = \lambda_1 \left[T_{em}^*(k+1) - T_{em}^p(k+1) \right] + \lambda_2 \left[\psi_r^*(k+1) - \psi_r^p(k+1) \right] \quad 5.63$$

Where λ is the weighting factor. The weighting factors λ_1 and λ_2 are related to the primary goal of controlling the dq-frame torque, hence they are set to one. Taking into account the eight combinations mentioned above for switching signals, we can generate eight distinct predictions for i_{dr} , i_{qr} , ψ_{dr} , and ψ_{qr} , resulting in eight distinct future values of T_{em} . During each sampling interval, the most appropriate switching states for RSPEC are chosen based on the smallest cost function value, ensuring precise alignment of torque with respective reference torque. During the $(k+1)$ sample time, the selected switching states are applied to the RSPEC.

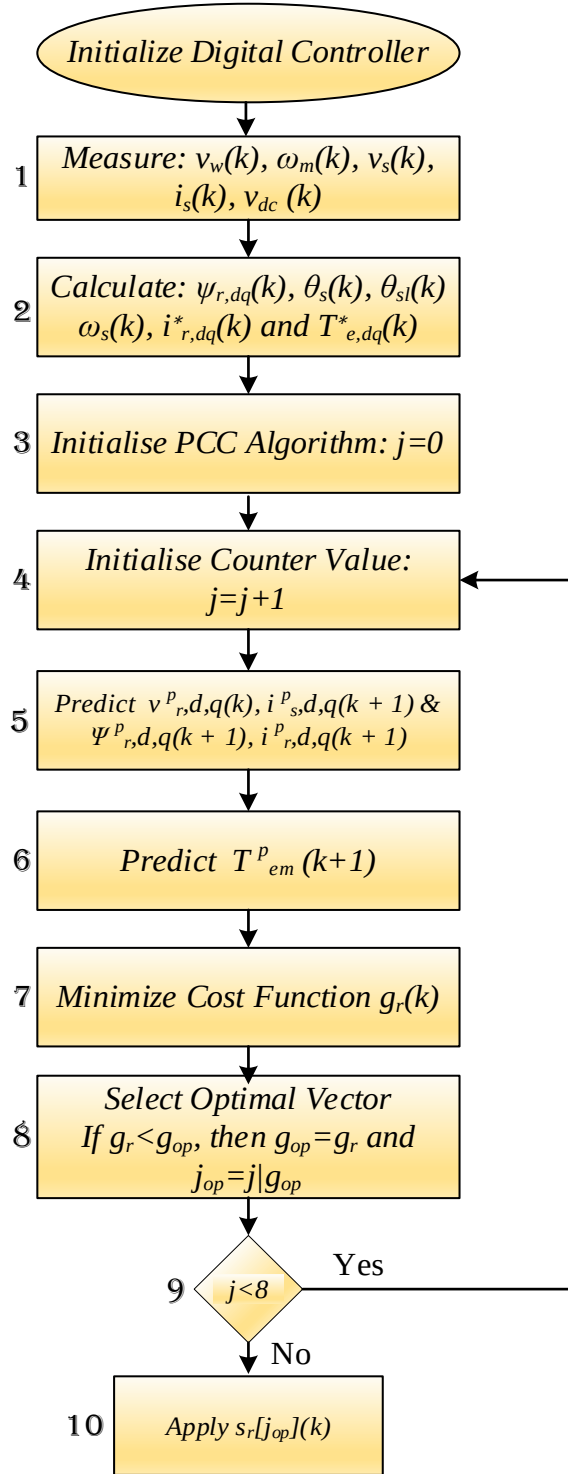


Figure 5. 8 Flowchart of PTC algorithm for 2L-VSC based DFIG

5.5.8 Control Algorithm for 2L-VSI

Figure 5. 8 illustrates the flowcharts of the PTC algorithms for RSPEC in the dq-frame. The design and digital implementation of the PTC algorithms involve 10 main blocks/steps. Block 1 acquires the necessary feedback measurements. Block 2 calculates the reference Torque as well as the rotor flux linkages, stator voltage angle, slip angle,

and stator angular frequency required for the RSPEC TCC algorithm. Block 3 initiates the PTC algorithm, which then enters an iterative loop at block 4 and concludes at block 9. Block 5 predicts the dq-frame RSPEC output voltages and rotor current. Block 6 predicts the rotor flux and torque with the assistance of block 7, which evaluates the RSPEC cost function. The optimal vector j_{op} , corresponding to the minimum cost function value, is stored in block 8. After completing the iterative loop for eight counter values, block 10 generates the switching signals that correspond to j_{op} and directly applies them to the RSPEC.

5.5.9 Predictive Torque Control FOR 3L-NPC-VSC of DFIG WECS

The discussion in this segment pertains to the Predictive Torque Control strategy associated with BTB NPC converter-based DFIG WECSs. An illustration of the PTC, specifically catered to an NPC rectifier-based DFIG WECS, is depicted in Figure 5.9. The structure of this control system mirrors the PTC addressed in Section 5.5.7, barring two alterations: firstly, the 2L VSC is supplanted by an NPC rectifier, and secondly, the DC-link is composed of a pair of DC-link capacitors.

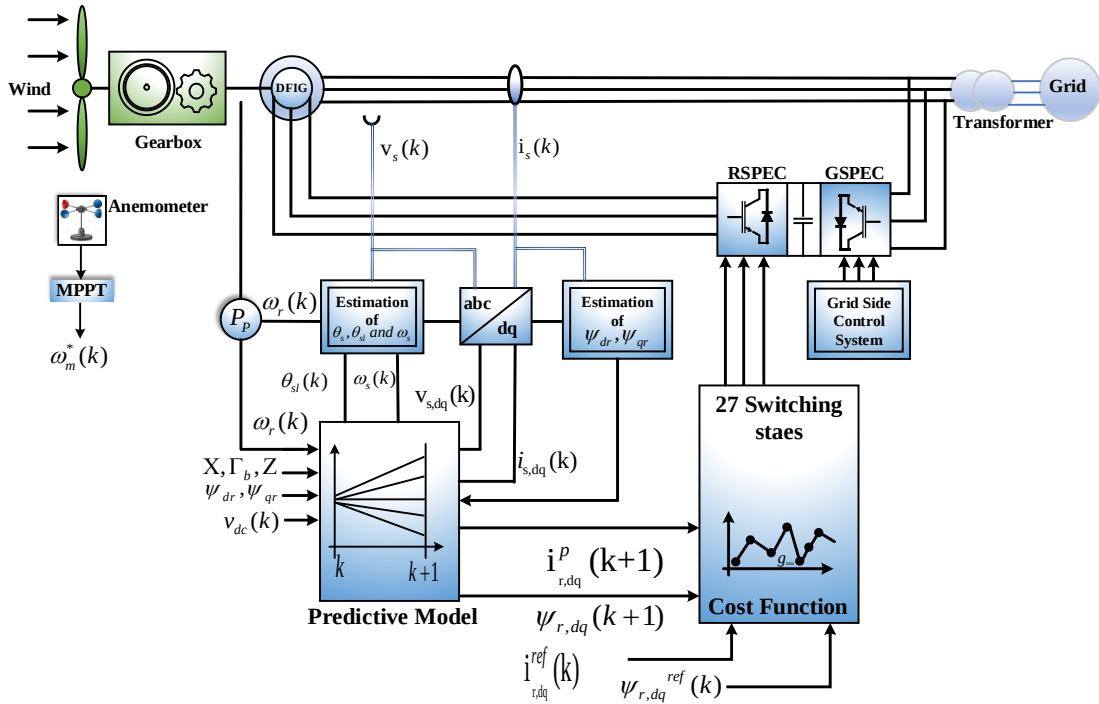


Figure 5. 9 Block diagram of the PTC scheme for 3LNPC MLI-based DFIG.

The reference torque $T_e^*(k)$ computation is performed in line with OT MPPT control, and a constant reference for the rotor flux, denoted as $\psi_r^*(k)$, is set. The reference

rotor flux extrapolation $\psi_r^*(k+1)$ is rendered equal to $\psi_r^*(k)$. Given that $T_e^*(k)$ is unvarying in a steady-state, there is no need for extrapolation. There are other crucial elements in the PTC with BTB NPC converter strategy, which include forecasting the voltage of the DC-link capacitors, the electromagnetic torque, and the rotor flux, in addition to the formulation of the cost function [39]. The detailed exploration of these design steps is given in the following sections.

5.5.9.1 Prediction of Future Behavior of DFIG Torque and Flux

The future values of rotor flux, electromagnetic torque, and DC-link capacitors voltage are deduced through the subsequent design procedures:

- The DT model outlined in Equation (5. 54) is employed to anticipate the dq-frame stator currents and rotor flux linkages for the future. This model utilizes $v_{ds}(k)$ and $v_{qs}(k)$, the output voltages of the DFIG (or NPC converter). These are conceived in relation to the DC-link capacitors voltage and dq-frame switching signals, as delineated below:

$$\begin{bmatrix} v_{dr}^p(k) \\ v_{qr}^p(k) \end{bmatrix} = v_{dc1}(k) \begin{bmatrix} s_{dr1}^p(k) \\ s_{qr1}^p(k) \end{bmatrix} + v_{dc2}(k) \begin{bmatrix} s_{dr2}^p(k) \\ s_{qr2}^p(k) \end{bmatrix} \quad 5.64$$

The dq-frame switching signals are interconnected with the natural frame signals in the following manner:

$$\begin{bmatrix} s_{drj}^p(k) \\ s_{qrj}^p(k) \end{bmatrix} = \underbrace{\begin{bmatrix} \cos\theta_{sl}(k) & \sin\theta_{sl}(k) \\ -\sin\theta_{sl}(k) & \cos\theta_{sl}(k) \end{bmatrix}}_{T_{\alpha\beta/dq}} \underbrace{\frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}}_{T_{abc/\alpha\beta}} \begin{bmatrix} s_{arj}^p \\ s_{brj}^p \\ s_{crj}^p \end{bmatrix}, j \in \{1,2\} \quad 5.65$$

By integrating (5. 64) into (5. 54), we acquire the comprehensive sampled-data model for the stator currents and rotor flux linkages as detailed:

$$\begin{bmatrix} i_{ds}^p(k+1) \\ i_{qs}^p(k+1) \\ \psi_{dr}^p(k+1) \\ \psi_{qr}^p(k+1) \end{bmatrix} = \phi(k) \begin{bmatrix} i_{ds}(k) \\ i_{qs}(k) \\ \psi_{dr}(k) \\ \psi_{qr}(k) \end{bmatrix} + \Gamma_b \left[v_{dc1}(k) \begin{bmatrix} s_{dr1}^p(k) \\ s_{qr1}^p(k) \end{bmatrix} + v_{dc2}(k) \begin{bmatrix} s_{dr2}^p(k) \\ s_{qr2}^p(k) \end{bmatrix} \right] \quad 5.66$$

By advancing the variables in Equation (5. 55) by one sample period, the anticipated future value of rotor currents can be computed using stator currents and rotor flux linkages as illustrated in Equation (5. 60). That is,

$$\begin{bmatrix} i_{dr}^p(k+1) \\ i_{qr}^p(k+1) \end{bmatrix} = H \begin{bmatrix} i_{ds}^p(k+1) \\ i_{qs}^p(k+1) \\ \psi_{dr}^p(k+1) \\ \psi_{qr}^p(k+1) \end{bmatrix} \quad 5.67$$

The anticipated future value of electromagnetic torque is derived from the cross product of the projected dq-frame rotor currents and rotor flux linkages as depicted in (5.61) and (5.61) respectively. The model for $T_{em}^p(k+1)$ is established as follows:

$$T_{em}^p(k+1) = 1.5p \left[\psi_{dr}^p(k+1)i_{qr}^p(k+1) - \psi_{qr}^p(k+1)i_{dr}^p(k+1) \right] \quad 5.68$$

5.5.9.2 Minimizing the Cost Function:

By establishing a cost function, the DFIG's rotor flux and electromagnetic torque can be simultaneously managed. The formulation of the cost function is as follows:

$$g_r(k) = \lambda_1 \left[T_{em}^*(k+1) - T_{em}^p(k+1) \right] + \lambda_2 \left[\psi_r^*(k+1) - \psi_r^p(k+1) \right] \quad 5.69$$

The factor λ is a weighting element. The weighting components λ_1 and λ_2 are fundamentally linked to the primary objective of controlling the dq-frame torque, and as a result, are assigned a value of one. The PTC method shares similarities with the traditional DTC approach. This technique retains the quick dynamic response of torque and flux, while reducing digital implementation complexities. The typical DTC requirements for hysteresis controllers and lookup tables are made redundant in the PTC approach. The generator and converter models, along with 27 potential switching state combinations, are used to predict NPC converter voltages for i_{dr} , i_{qr} , ψ_{dr} , and ψ_{qr} , yielding twenty-seven possible future values of T_{em} .

5.5.10 Control Algorithm for 3L-NPC-VSI

Figure 5.10 showcases the flowcharts depicting the PTC algorithms for RSPEC in the dq-frame. The design and digital implementation of these algorithms encompass ten key blocks/steps. Block 1 acquires the necessary feedback measurements, while Block 2 calculates various parameters essential for the RSPEC PTC algorithm, such as the reference torque, rotor flux linkages, stator voltage angle, slip angle, and stator angular frequency. Block 3 initiates the PTC algorithm, which then proceeds through an iterative loop starting at Block 4 and concluding at Block 9. Within this loop, Block 5 predicts the

output voltages and rotor current in the dq-frame for RSPEC. Block 6 predicts the rotor flux and torque, aided by Block 7, which evaluates the RSPEC cost function. The optimal vector j_{op} , corresponding to the minimum cost function value, is stored in Block 8. Upon completing the iterative loop for Twenty seven counter values, Block 10 generates the switching signals associated with j_{op} and directly applies them to the RSPEC.

5.6 Simulation Results

This section presents the MATLAB/Simulink simulation results for a grid-connected DFIG based WECSs, evaluating the performance of the MPDTC of the Rotor Side Power Electronic Converter (RSPEC). The investigation compares the behaviour of two different types of converters, the 2-level and 3-level Neutral Point Clamped (NPC) converters.

MATLAB/Simulink is an ideal framework for modelling and simulating complicated power electronic systems, allowing for in-depth research of their dynamic behaviour. In particular, the MPDTC of the RSPEC is taken into account in this context due to its importance in controlling the power flow between the DFIG and the grid and to reduce the ripple content in the torque and flux, hence influencing the overall efficiency and performance of the WECS.

The 2-level and 3-level NPC converters have been selected for comparison because they are widely used in WECS. These converters are critical in controlling and optimising the energy flow in the system, ensuring efficient wind energy conversion and transmission to the grid. The simulation study involves subjecting the system to a variety of operating circumstances in order to evaluate the response and performance of the converters.

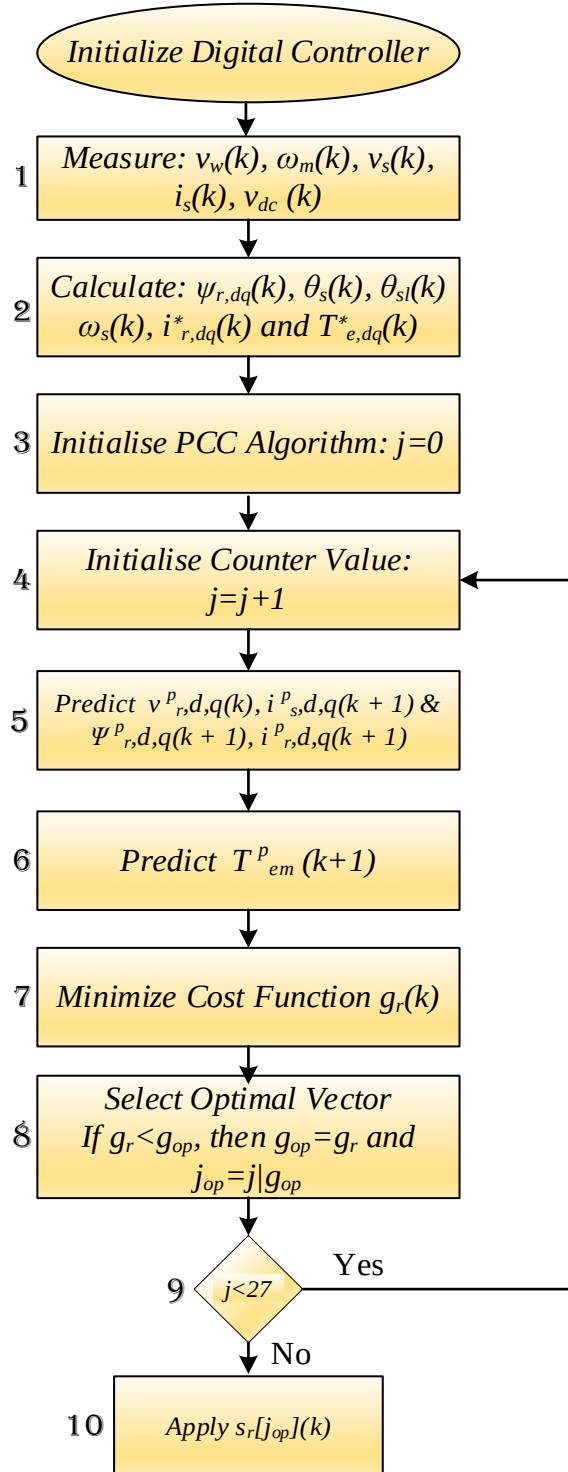


Figure 5. 10 Flowchart of PTC algorithm for 3L-NPC VSC based DFIG

This section will go over observations about system stability, dynamic response, efficiency, and the quality of power delivered to the grid in depth. The simulation results of the 2-level and 3-level NPC converters under MPDTC of the RSPEC can be compared to gain useful insights into their different advantages and problems. These findings will

help researchers make more informed decisions about the selection and design of power electronic converters for grid-connected DFIG-based WECS.

Delving deeper into the approach to be utilized for the simulation study, the per unit (p.u.) methodology has been adopted to facilitate the comparison of different machine parameters and magnitudes. Employing this technique offers the benefit of indicating the deviation of variables from their base or rated values, thus enhancing comprehension of system performance without the need for precise nominal values at first glance.

5.6.1 Base Values

Thus, the initial step in simulation approach is to perform p.u. transformations on the machine parameters and magnitudes. Normalisation is accomplished by dividing the actual value of a given parameter by a base value. For example, the per unit voltage (V_{pu}) is calculated by dividing the actual voltage (V) by the base voltage (V_{base}). The subscript "pu" represents magnitude p.u. values [199].

$$V_{pu} = \frac{V}{V_{Base}} \quad 5.70$$

For the sake of this investigation the stator rated RMS values of voltages and currents as the base values are used for calculations:

$$\text{Base Voltage : } V_{Base} = |V_s|_{rated} \dots\dots(V) \quad 5.71$$

$$\text{Base Current : } I_{Base} = |I_s|_{rated} \dots\dots(A) \quad 5.72$$

$$\text{Base AngularFrequency : } \omega_{Base} = \omega_{s rated} (rad / s) \quad 5.73$$

From these three fundamental base values can be derive from the remaining base values. The following section will showcase MATLAB model and discuss the simulation outcomes under these normalized conditions. By employing this methodological approach aims to present a thorough and comprehensible performance analysis of the 2-level and 3-level NPC converters under MPDTC of the RSPEC.

$$\text{Base Flux : } \psi_{Base} = \frac{V_{Base}}{\omega_{Base}} \quad 5.74$$

$$\text{Base Impedance : } Z_{Base} = \frac{V_{Base}}{I_{Base}} \quad 5.75$$

$$\text{Base Inductance : } L_{Base} = \frac{\psi_{Base}}{I_{Base}} \quad 5.76$$

$$\text{Base Power : } S_{Base} = 3V_{Base}I_{Base} \quad 5.77$$

$$\text{Base Speed : } \omega_{m Base} = \frac{\omega_{Base}}{p} \quad 5.78$$

$$\text{Base Torque : } T_{Base} = \frac{S_{Base}}{\omega_{m Base}} \quad 5.79$$

5.6.2 Transition to Per Unit System for Magnitudes and Parameters

Following the establishment of base values, transforms parameters into per unit values. This can be accomplished by using the expressions described in the subsequent discussion.

$$\text{Stator voltage in pu : } V_s \text{ pu} = \frac{V_s}{V_{Base}} \quad 5.80$$

$$\text{Stator current in pu : } I_s \text{ pu} = \frac{I_s}{I_{Base}} \quad 5.81$$

$$\text{Stator flux in pu : } \psi_s \text{ pu} = \frac{\psi_s}{\psi_{Base}} \quad 5.82$$

$$\text{Stator active power in pu : } =P_s \text{ pu} = \frac{3\text{Re}\{V_s \cdot I_s^*\}}{S_{Base}} \quad 5.83$$

$$\text{Stator reactive power in pu : } =Q_s \text{ pu} = \frac{3\text{Im}\{V_s \cdot I_s^*\}}{S_{Base}} \quad 5.84$$

The magnitudes of the phasors undergo transformation to per unit values; in other words, the angle remains constant during this conversion process. This principle is also applicable to the rotor, as indicated by the following expressions:

$$\text{Rotor voltage in pu: } V_r \text{ pu} = \frac{V_r}{V_{Base}} = \frac{V_r' \cdot u}{V_{Base}} \quad 5.85$$

$$\text{Rotor current in pu: } I_r \text{ pu} = \frac{I_r}{I_{Base}} = \frac{I_r'}{V_{Base} \cdot u} \quad 5.86$$

$$\text{Rotor flux in pu: } \psi_r \text{ pu} = \frac{\psi_r}{\psi_{Base}} \quad 5.87$$

$$\text{Rotor active power in pu: } =P_r \text{ pu} = \frac{3\text{Re}\{V_r \cdot I_r^*\}}{S_{Base}} \quad 5.88$$

$$\text{Rotor reactive power in pu: } =Q_r \text{ pu} = \frac{3\text{Im}\{V_r \cdot I_r^*\}}{S_{Base}} \quad 5.89$$

It's important to emphasize per unit values for rotor voltage and currents are calculated based on stator referred voltages and currents. Consequently, can deduce the following for torque and speed:

$$\text{Torque in pu: } T_{em} \text{ pu} = \frac{T_{em}}{T_{Base}} \quad 5.90$$

$$\text{Speed in pu: } \omega_m \text{ pu} = \frac{\omega_m}{\omega_{Base}} \quad 5.91$$

In conclusion, the machine's parameters can be converted into per unit values using the following transformations:

$$\text{Resistances in pu: } r = \frac{R}{Z_{Base}} = \frac{RI_{Base}}{V_{Base}} \quad 5.92$$

$$\text{Inductances in pu: } l = \frac{L}{L_{Base}} = \frac{LI_{Base}}{V_{Base}} \omega_{Base} \quad 5.93$$

It is important to observe that parameters converted into per unit values are denoted in lowercase letters. Similarly, to the magnitudes, both stator and rotor parameters undergo per unit transformation using the same base value.

5.6.3 Simulation Results and Performance Analysis

In the context of the WECSs, a critical component is a 1.5 MW wind turbine connected to a power source. This turbine incorporates a DFIG, composed of a WRIG coupled with an AC/DC/AC IGBT-based PWM converter. A unique characteristic of

DFIG technology is its ability to extract optimal energy from the wind during periods of low wind speed by precisely adjusting the turbine speed. This feature also minimizes the mechanical stresses experienced by the turbine during sudden wind gusts.

In order to validate our hypothesis and establish a performance benchmark for the FCS-MPDTC, we developed a comprehensive simulation model using MATLAB, as depicted in Figure 5. . This model encompasses various components such as a DFIG connected to the grid, a wind turbine model, a Phase-Locked Loop (PLL), a control block for the converter system (RSPEC and GSPEC), as well as filter circuits and scope for signal display.

The primary focus of analysis revolves around comparing the torque performance of different techniques to the proposed FCS-MPDTC. Specifically, examine the most utilised technique that is Conventional Direct Torque Control (DTC) and Space Vector Modulation DTC (SVM-DTC) techniques. By employing varying input mechanical torque values, aims to evaluate how each technique performs in terms of tracking the reference torque. Special attention to transient overshoot, undershoot, ripple factor and settling time, as Overshoot pertains to the extent to which the system's output surpasses its final consistent value in a steady-state condition. Excessive overshoot might compromise system stability and potentially risks harming components or apparatus in the system. Likewise, undershoot is an indication of how significantly the system's output dips beneath its ultimate steady-state value. Much like overshoot, a considerable undershoot may provoke instability or create harmful scenarios within the system. Furthermore, settling time serves as a metric for the duration required for a system's output to remain within a specified range around its final steady-state value following the application of a step input. A shorter settling time signifies a more rapid system response, though it may incite instability if it's excessively brief. Conversely, an overly prolonged settling time might cause the system to respond sluggishly to alterations.

Simultaneously, another important parameter is the ripple factor. This measures the degree of torque fluctuations or 'ripples' over a given timeframe. A high ripple factor points to a greater extent of torque inconsistencies within the system. This could potentially lead to complications in a DFIG system, and hence, a steady torque signal is imperative. Lower ripple factors indicate a smoother, more stable DC signal, which is preferable, these factors provide valuable insights into the overall effectiveness of each technique.

Through this comprehensive comparison, aims to gain a deeper understanding of the advantages offered by the FCS-MPDTC approach. By evaluating its performance in relation to established techniques such as Conventional DTC and SVM-DTC, we can ascertain its potential to enhance torque tracking accuracy while minimizing undesirable transient behaviour. Figure 5. 92 illustrates the comparative study. When observing the startup transients where the reference torque is set at -0.5pu, conventional DTC has high transient overshoot and settling time. SVM-DTC performs better but still falls short when compared to FCS-MPDTC with a 2-Level Voltage Source Converter (2L-VSI). With this technique, both the transient overshoot and settling time are reduced. Incorporating a multilevel inverter, such as a 3-Level Neutral Point Clamped converter (3L-NPC), further enhances the performance, as evidenced by a significant decrease in transient overshoot and settling time.

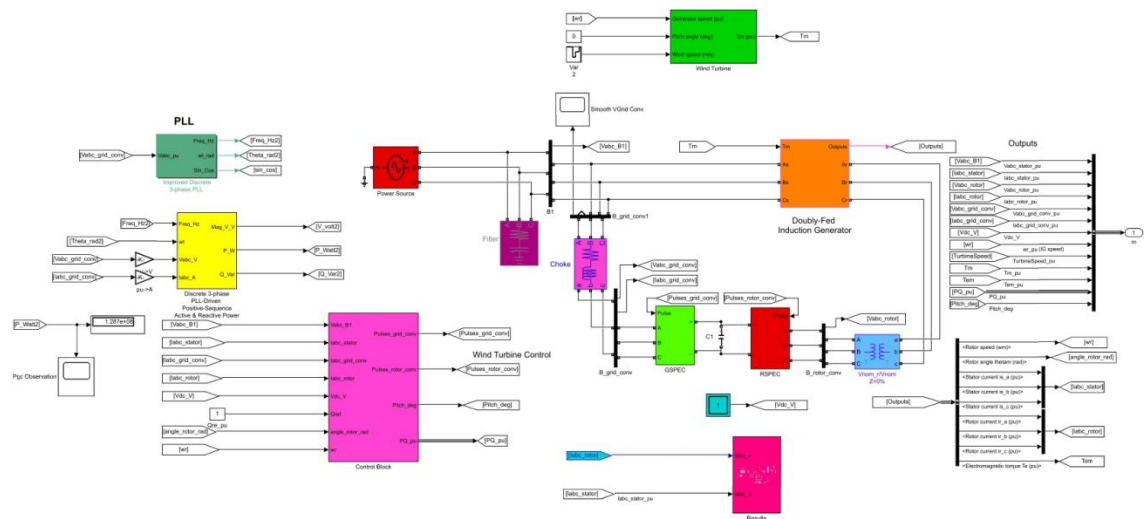


Figure 5. 11 MATLAB/Simulink model of DFIG

Further to test the performance of these techniques during a step change in the input torque at time $t=2$ sec, simulating an increase in wind speed. Once again, the FCS-MPDTC excels in minimizing ripple content. The same result holds when wind speed and input torque are increased again, pushing the generator into supersynchronous speed. In contrast, when wind speed is decreased and input torque increases, FCS-MPDTC continues to perform well, reducing ripple content, peak overshoot, and settling time. The 3L-NPC equipped DFIG still emerges as the best performer in these conditions.

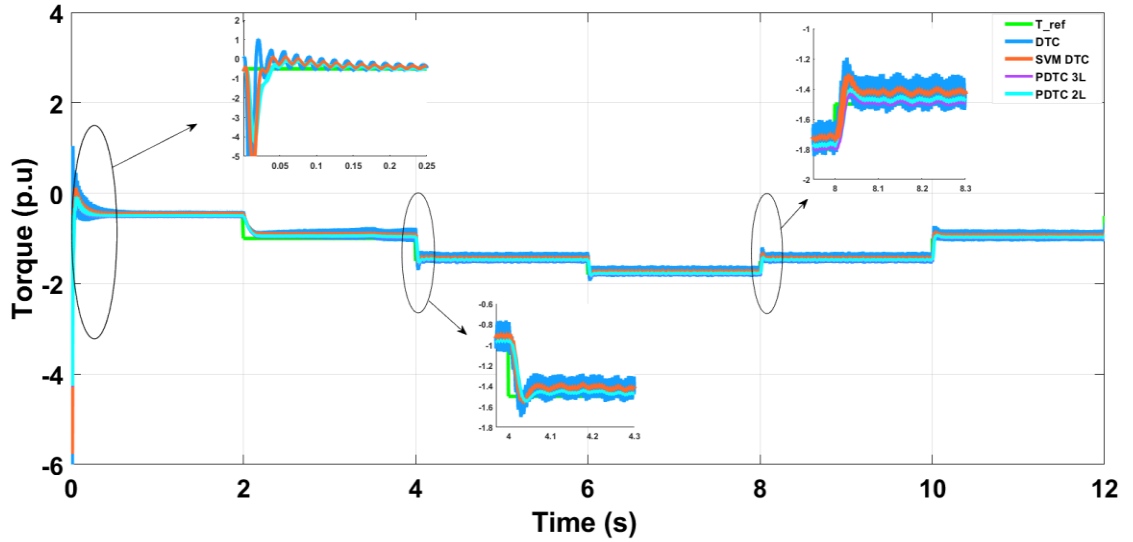


Figure 5.92 Torque comparison of various techniques

A comparative summary of all these techniques is presented in Table 5.1, where it's clear that for torque control, FCS-MPDTC with a 3L-NPC VSC is the most efficient. In essence, findings suggests that the ripple content associated with conventional DTC is quite high due to the use of the hysteresis comparator for control. Though SVM-DTC shows an improvement over conventional DTC, the FCS-MPDTC outperforms both by significantly reducing the ripple content. The replacement of the 2L inverter with a multilevel inverter further improves performance, with FCS-MPDTC driving the 3L NPC converter resulting in the lowest ripple content, overshoot, and undershoot among all tested techniques.

To evaluate the rotor flux comparison among various techniques and the proposed method altered the flux reference to examine the actual flux's tracking behavior. This is visualized in Figure 5.10, which presents a collective view of flux variations in relation to the reference flux, as accounted for by all techniques. During the starting transient, the reference flux is set at 0.3pu. All techniques initiate their process, striving to follow the reference flux. However, the conventional DTC exhibits high ripple content and an appreciable overshoot, despite its short settling time. When compared to conventional DTC, the SVM DTC operates with reduced ripple content, indicating an improved performance. Significantly, when the gate pulse is introduced through the FCS MPDTC Technique utilizing a 2 Level VSC, we observe a substantial reduction in ripple content. Moreover, replacing the 2L VSI with a 3-level NPC converter further curtails the ripple content and exhibits superior performance against all other techniques.

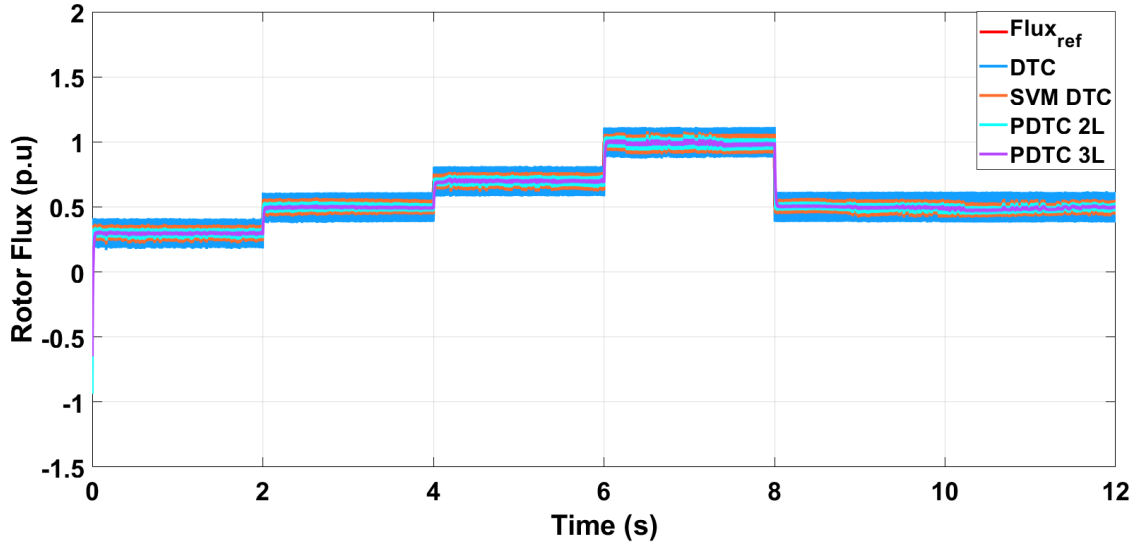


Figure 5. 10 Flux comparison of various techniques

To assess the dynamic performance of these control techniques, we implement a step change in the input flux at timestamps $t=2$ sec, $t=4$ sec, and $t=6$ sec. All techniques adequately track their respective references, with DTC showing an impressively short settling time, albeit with high ripple content. Similar performance is observed when the flux reference is decreased; all techniques effectively track their references. Yet, across all these scenarios, the FCS MPDTC for 3L NPC emerges as the superior performer in terms of flux. A detailed comparison concerning the ripple factor is exhibited in Table 5.2 and Table 5.3.

In Table 5.3, a comprehensive comparative analysis of various control techniques applied to a DFIG is presented. These techniques encompass DTC, SVM-DTC, Predictive FCS MPDTC using 2L VSC, and FCS MPDTC using 3L NPC MLI. The primary objective of this analysis is to discern the extent of torque and flux ripple associated with each control method.

Torque ripple signifies the fluctuations or variations in the DFIG's torque during its operation, while flux ripple denotes changes in the magnetic flux within the DFIG. These ripples can have significant consequences for DFIG performance and efficiency. Upon examining the results, it becomes evident that "FCS MPDTC using 3L NPC MLI" stands out as the control technique that yields the lowest percentages of torque and flux ripple, approximately 1.37% and 1.33%, respectively. These exceptionally low values indicate a high degree of stability and precision in controlling the motor's torque and flux.

However, as transition from "FCS MPDTC using 3L NPC MLI" to "FCS MPDTC using 2L VSC," "SVM DTC," and finally "DTC," a gradual increase in both

torque and flux ripple percentages is observed. This trend implies that the earlier control techniques exhibit diminishing effectiveness in mitigating undesirable torque and flux fluctuations. The drawbacks associated with higher torque and flux ripple percentages are notable. First, increased ripple can lead to reduced system efficiency, as more energy is dissipated in the form of unwanted torque variations. This can result in higher losses within the DFIG. Additionally, higher torque ripple levels can exert greater mechanical stress on the machine and connected mechanical components, potentially reducing their operational lifespan.

Conversely, the advantages of achieving low ripple percentages are significant. Enhanced machine performance and precision are among the most notable benefits. In wind turbine generators precise control is paramount, low ripple translates to smoother and more efficient operation. Furthermore, reduced torque and flux ripple contribute to diminished audible noise and vibration, enhancing the comfort and usability of systems. In the end, Table 5.3 underscores the critical importance of selecting an appropriate control technique for DFIG systems. Control methods that result in lower torque and flux ripple percentages, exemplified by "PDTC using 3L NPC," offer superior motor performance, reduced energy losses, and decreased mechanical stress. In contrast, higher ripple percentages, as seen in "DTC," signify less precise control and potential operational inefficiencies within the system.

Observing the DC link voltage variation in response to input torque changes, as illustrated in Figure 5.14, highlights key differences between the techniques. The conventional DTC demonstrates substantial ripple content in the DC link voltage when there are variations in input torque. This trend is accompanied by significant peak overshoot and lengthy settling times.

Comparatively, SVM DTC demonstrates better performance, outshining conventional DTC. However, examining the DC link voltage under the control of FCS MPDTC, witness an even more impressive operation. It exhibits superior performance in all categories: ripple content, peak overshoot, undershoot, and settling time. Taking a step further by replacing the 2L VSC with a 3L MLI results in a remarkable performance improvement. This is particularly noticeable during step changes in torque variation, which typically triggers sudden peaks in the DC link voltage. Yet, the FCS-MPDTC showcases exceptional performance across all techniques. For a more detailed evaluation,

refer to Table 5.1, Table 5.2 and Table 5.3, which provides an in-depth comparison of these techniques under varying operational conditions.

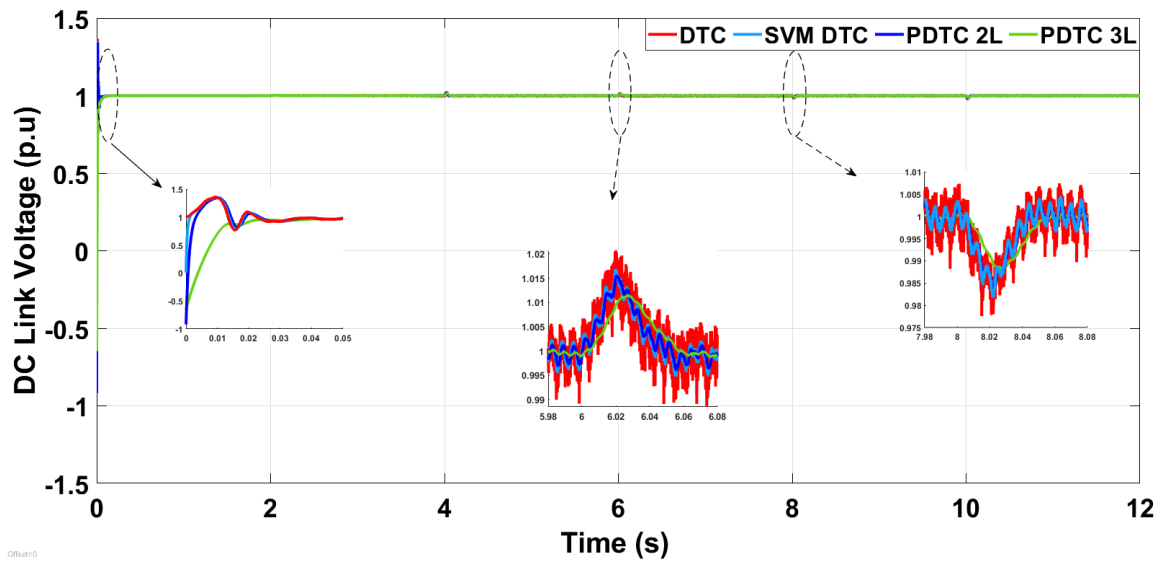


Figure 5.114 DC Link Voltage variations

Table 5.1 Comparison of Torque results of various control method fed with 2L-VSC and 3L-VSC

Operating Condition	Parameter	DTC	SVM DTC	PDTC using 2L VSC	PDTC using 3L NPC MLI
During starting	%Overshoot/Undershoot	32	26	14	5
	Settling Time (s)	0.87	0.82	0.73	0.64
Change in reference torque (-0.5pu to -1pu)	%Overshoot/Undershoot	22.74	11	9	3
	Settling Time (s)	0.91	0.83	0.78	0.74
Change in reference torque (-1pu to -1.5pu)	%Overshoot/Undershoot	16.68	8.3	5.8	5.4
	Settling Time (s)	0.67	0.62	0.45	0.40
Change in reference torque (-1.5pu to -1.8pu)	%Overshoot/Undershoot	11.5	8	7	4
	Settling Time (s)	0.66	0.64	0.45	0.42
Change in reference torque (-1.8pu to -1.5pu)	%Overshoot/Undershoot	21	7.3	5.8	5.90
	Settling Time (s)	0.68	0.70	0.56	0.50
	%Overshoot/Undershoot	23	8.53	5.86	5.64

Change in reference torque (-1.5pu to -1pu)	Settling Time (s)	0.66	0.84	0.7	0.59
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Table 5.2 Comparison of Flux results of various control method fed with 2L-VSC and 3L-VSC

Operating Condition	Parameter	DTC	SVM DTC	PDTC using 2L VSC	PDTC using 3L NPC MLI
During starting	%Overshoot/Undershoot	38	26	14	5.33
Change in reference flux (-0.5pu to -1pu)	%Overshoot/Undershoot	24.74	10.39	9.23	3.40
Change in reference flux (-1pu to -1.5pu)	%Overshoot/Undershoot	15.68	10.25	6.71	3.14
Change in reference flux (-1.5pu to -1.8pu)	%Overshoot/Undershoot	13.5	8.1	5.90	2.54
Change in reference flux (-1.8pu to -1.5pu)	%Overshoot/Undershoot	21	16.8	12	4.60

Table 5.3 Comparison of Torque and Flux ripples of various control method

Operating Condition	DTC	SVM DTC	PDTC using 2L VSC	PDTC using 3L NPC MLI
Torque Ripple %	18.54	9.03	2.7	1.37
Flux Ripple %	14.01	7.02	3.9	1.33

Having thus far explored the comparative analysis of various direct control techniques, have seen the FCS MPDTC consistently outperforming the others. This superior performance is discernible across all parameters under consideration, substantiating claim that suggested technique exhibits the best overall operation. From this point forward, focus will narrow to a comparison between FCS MPDTC powered by 2L VSC and 3L NPC VSC. Further goal is to further investigate and assess the performance of these configurations across all remaining parameters.

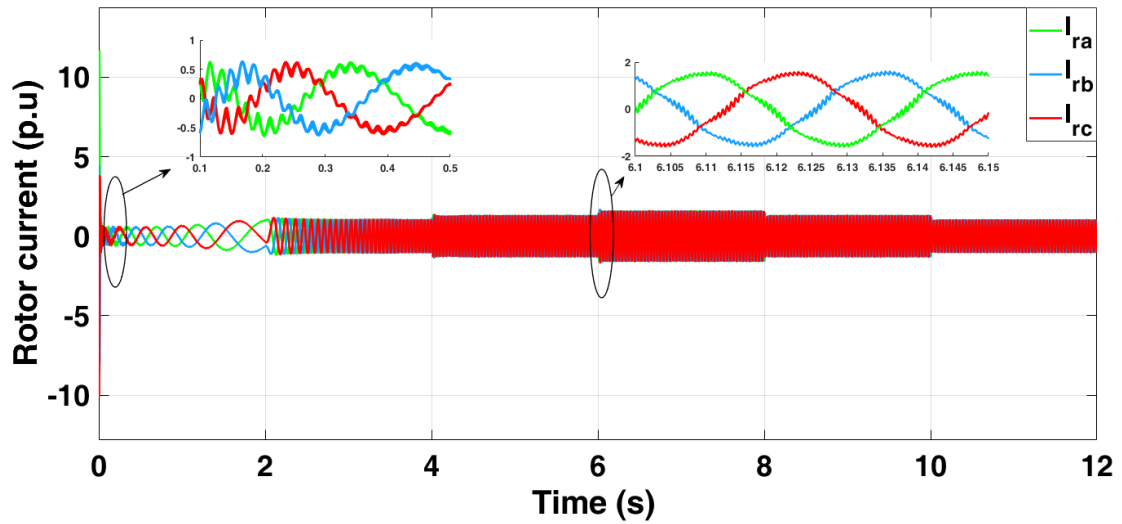


Figure 5. 12 Rotor current waveform of MPDTC for the 2L VSC fed DFIG WECS

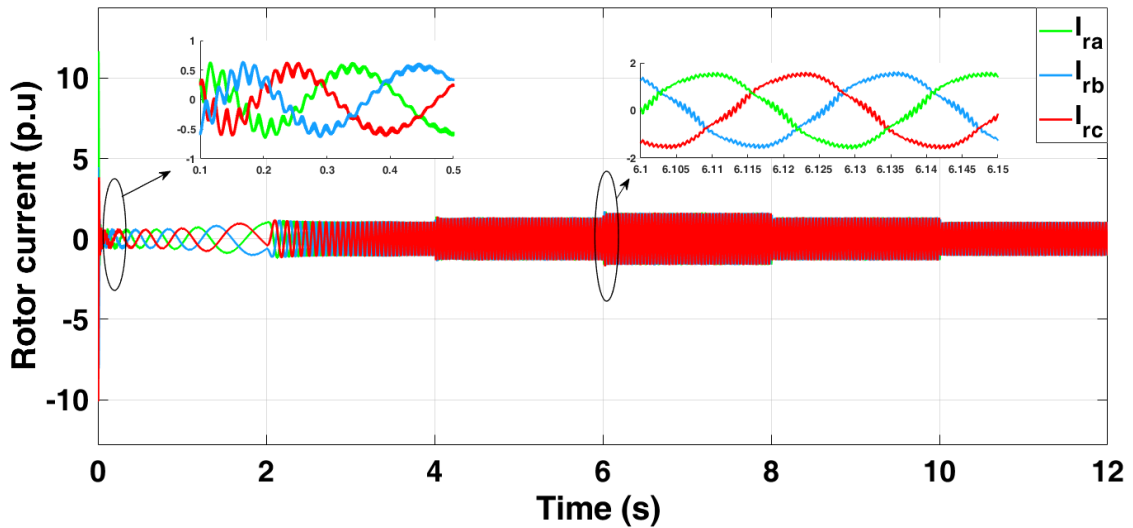


Figure 5. 13 Rotor current waveform of MPDTC for the 3L VSC fed DFIG WECS

The Figure 5. 12 and Figure 5. 13 showcase the rotor current waveforms for both 2L and 3L NPC-powered DFIG in wind converter systems, accommodating for the previously depicted torque variations. An intriguing observation from these waveforms is the variable frequency of the rotor current. The frequency inconsistency stems from the rotor current frequency's unique relation to the differential between the rotor's mechanical speed and the electrical speed of the grid, often referred to as the slip frequency. In essence, the slip represents the difference between the stator's synchronous speed determined by the grid frequency and the generator's pole pair count and the rotor's mechanical speed.

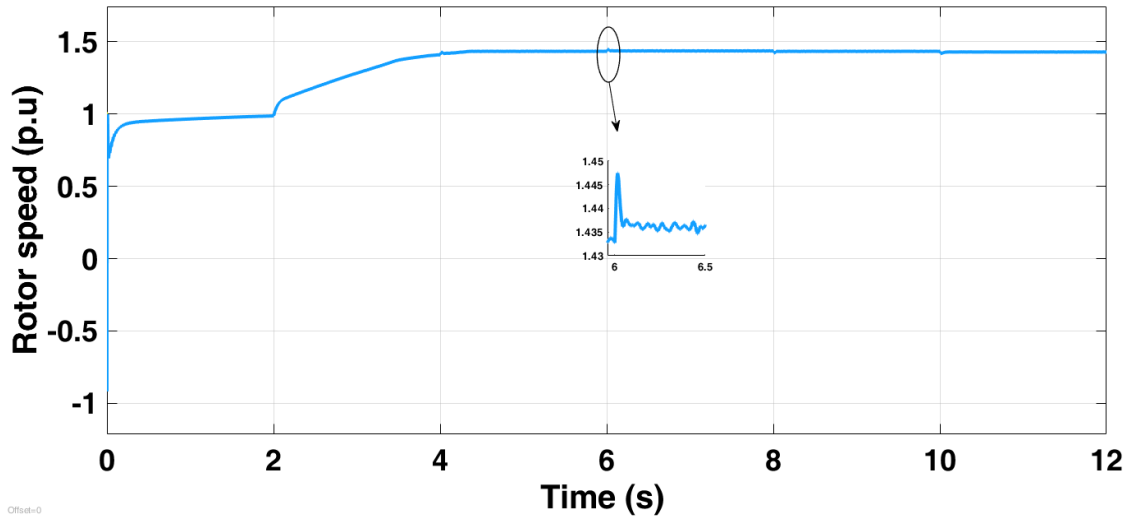


Figure 5. 14 Rotor speed waveform

In standard DFIG operations, the rotor speed adjusts to accommodate fluctuating wind speeds, causing the slip and consequently, the rotor current frequency, to change accordingly. Therefore, the rotor current frequency is not static, which is evidenced in the figures. This is particularly clear when contrasting the rotor current frequency at subsynchronous speeds (when the generator operates below the synchronous speed) to supersynchronous speeds (when the generator operates above the synchronous speed). The latter state arises when wind speed accelerates, thereby increasing the input mechanical torque and subsequently, the rotor speed as shown in Figure 5. 14 .

Upon a closer inspection of the rotor current waveforms for both configurations, it's apparent that the ripple content for the 2L VSC-powered DFIG is significantly higher. This is primarily due to the heightened distortion, clearly visible in the waveform and further substantiated by the zoomed-in section included for enhanced clarity. The higher distortion for the 2L VSC-powered DFIG, in contrast to the 3L NPC-powered DFIG, is further supported by the THD (Total Harmonic Distortion) analysis presented in Figures 5.18 and 5.19. The findings confirm a higher THD for the 2L system compared to the 3L system, thereby proving the superior performance of a DFIG system powered by a MLI.

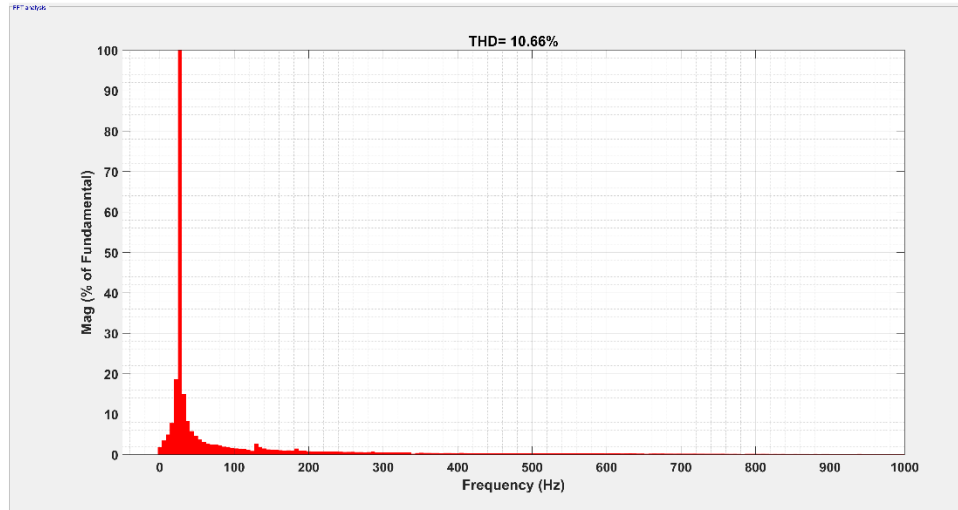


Figure 5. 15 THD 2L VSI Rotor current

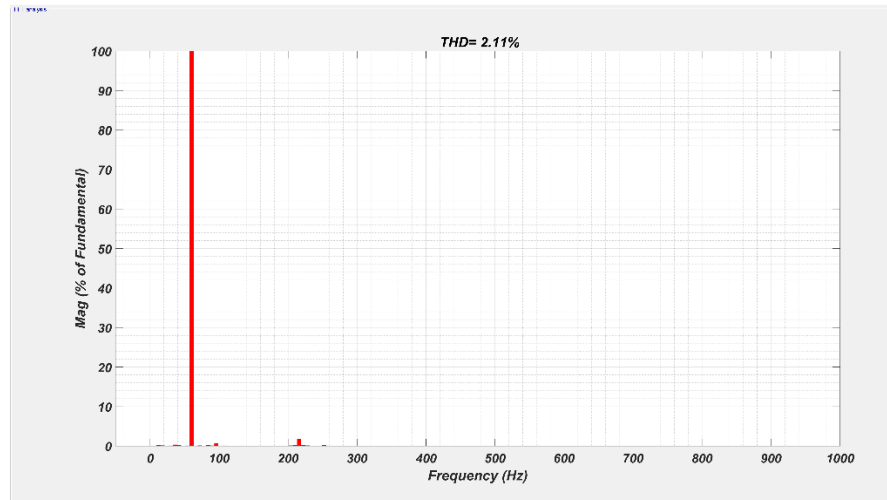


Figure 5. 16 THD 3L NPC MLI Rotor current

The stator current waveforms, vividly depicted in Figures 5.20 and Figures 5.21, offer additional insights into presented analysis. These figures reveal a smoother stator current for the 3L NPC-fed DFIG system in comparison to the 2L VSC-fed counterpart. To ensure a more thorough understanding a magnified segment of the waveform that illustrates this discrepancy in a clearer manner has been included. Furthermore, it's important to note that the current variation seen in the stator current waveforms aligns with the input torque variations as discussed previously.

To validate observations performed a THD analysis. The results unequivocally support conclusion: the 3L NPC-fed DFIG system exhibits a lower THD when compared to the 2L VSC-fed DFIG system as can be seen Figure 5.22 and Figure 5.23. Consequently, this confirms the superior performance of the 3L NPC-fed DFIG system in terms of stator current smoothness and reduced harmonic distortion.

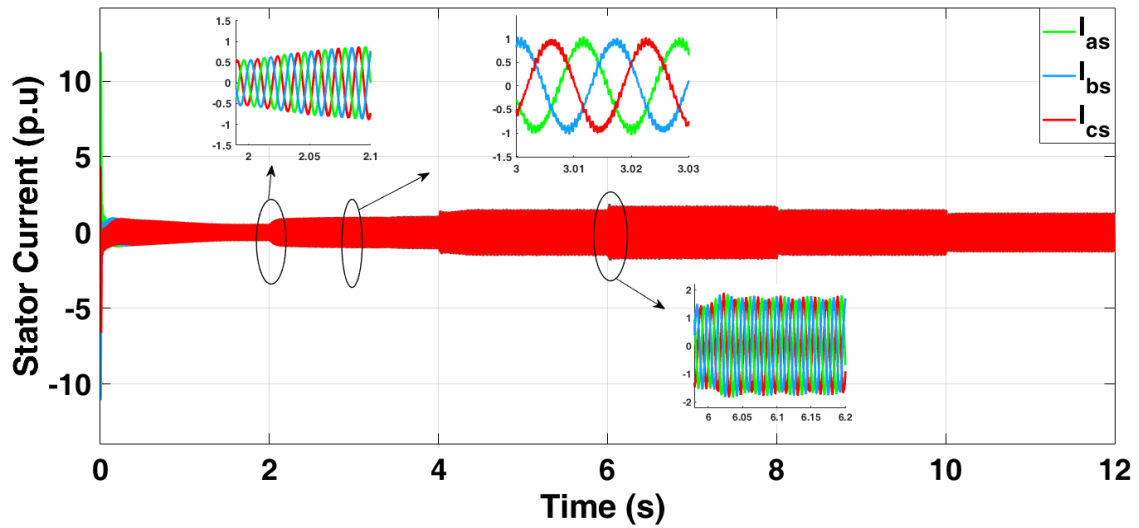


Figure 5. 17 Stator Current waveform of MPDTC for the 2L VSC fed DFIG WECS

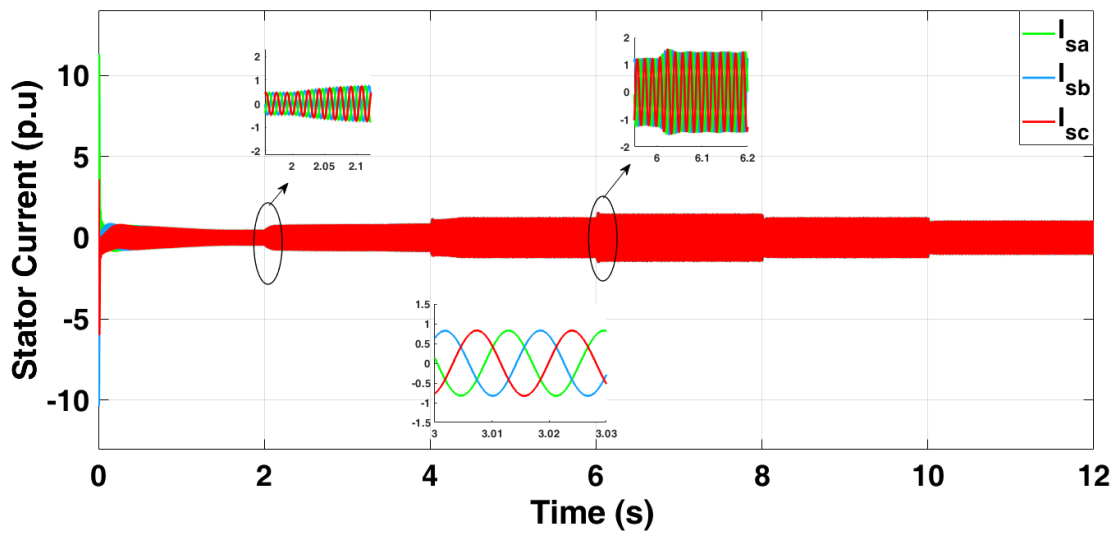


Figure 5. 18 Stator Current waveform of MPDTC for the 3L NPC fed DFIG WECS

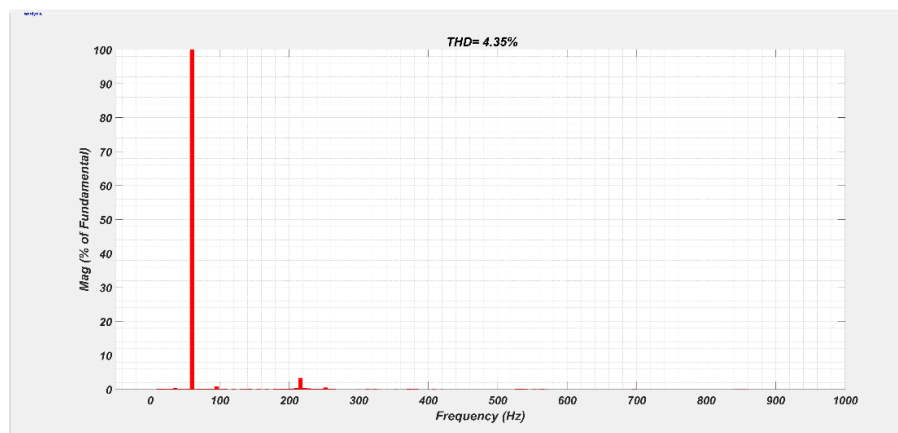


Figure 5. 19 THD 2L VSI for Stator current

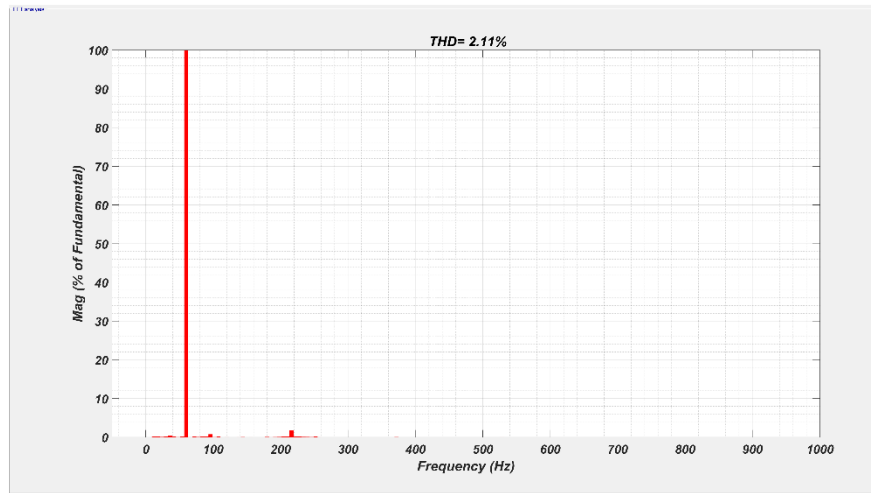


Figure 5. 20 THD 3L NPC MLI for Stator current

To deepen analysis the stator's active and reactive power, as well as the grid's active and reactive power are plotted as depicted in Figure 5.24 to Figure 5.29. Although the power variations in both scenarios appear minor when measured in per unit (p.u), it's essential to remember that these power values actually represent figures in the magnitude of megawatts (MW) and megavolt-amperes reactive (MVAR). As such, even a slight difference can translate into substantial variations within the real-world system.

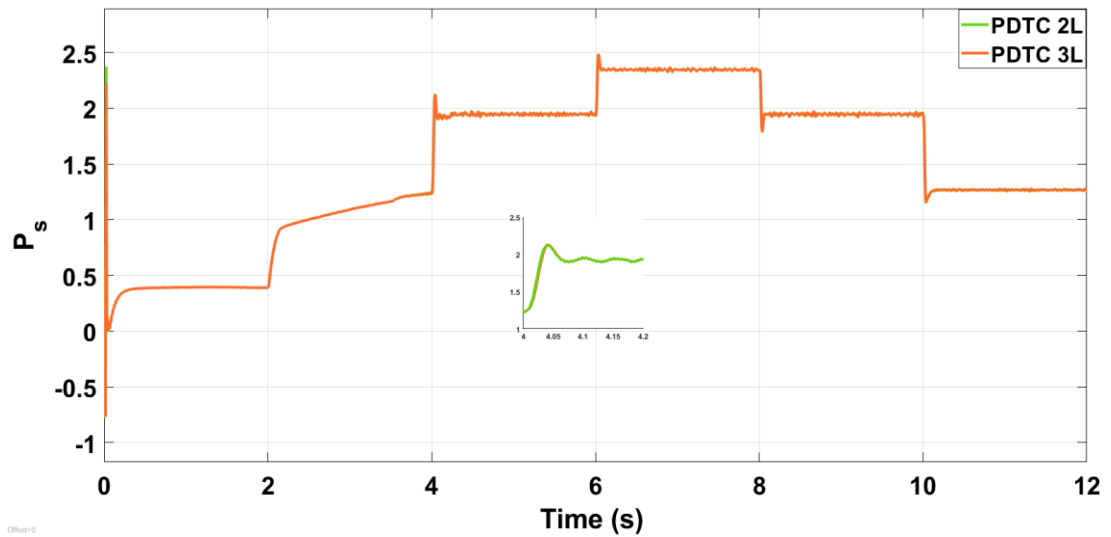


Figure 5. 21 Stator Active power in both the cases

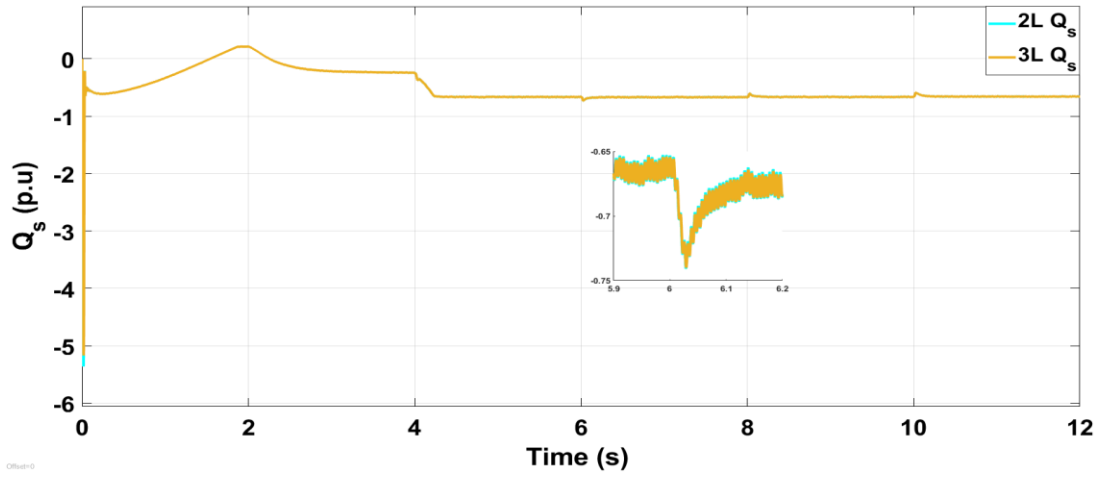


Figure 5. 22 Stator Reactive power in both the cases

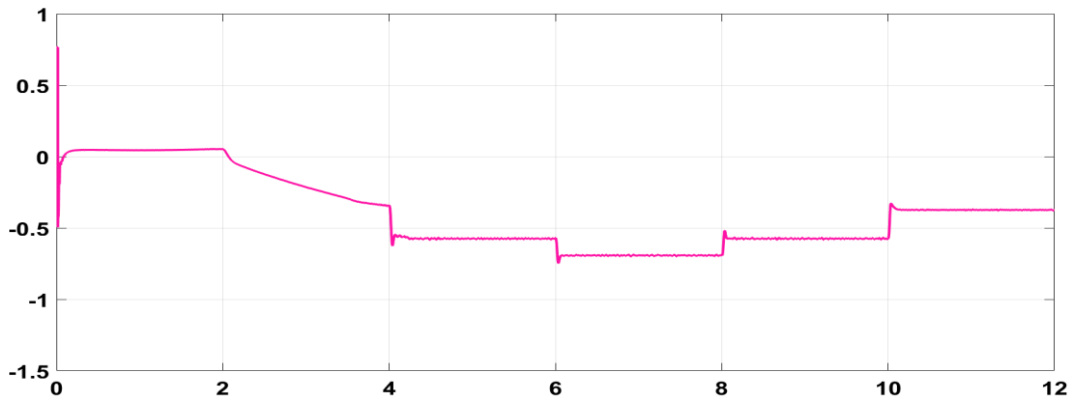


Figure 5. 26 Grid Active power in for the 2L VSC fed DFIG WECS

To examine these variations it is observed that the degree of distortion, or the ripple effect or fluctuations in power, is noticeably lower in the 3L NPC-fed DFIG system compared to its 2L VSC counterpart. This reaffirms the superior performance of the 3L NPC system, underlining its ability to provide a more stable power output with reduced oscillations.

In order to validate the theoretical findings and lend tangible credibility to control strategy, have embarked on the design and construction of a hardware prototype for experimental validation. This practical approach provides with a real-world platform to critically assess the behavior and effectiveness of our control technique under various operational conditions. By examining the results generated by this physical setup can draw concrete conclusions on the practical applicability and benefits of proposed strategy. The subsequent experimental results serve as empirical evidence, reinforcing the theoretical assertions made throughout study.

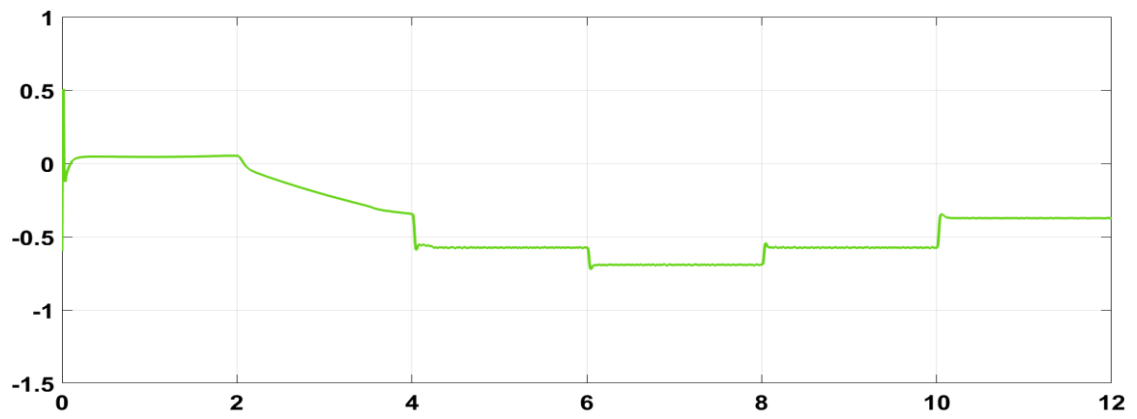


Figure 5. 27 Grid Active power in for the 3L NPC fed DFIG WECS

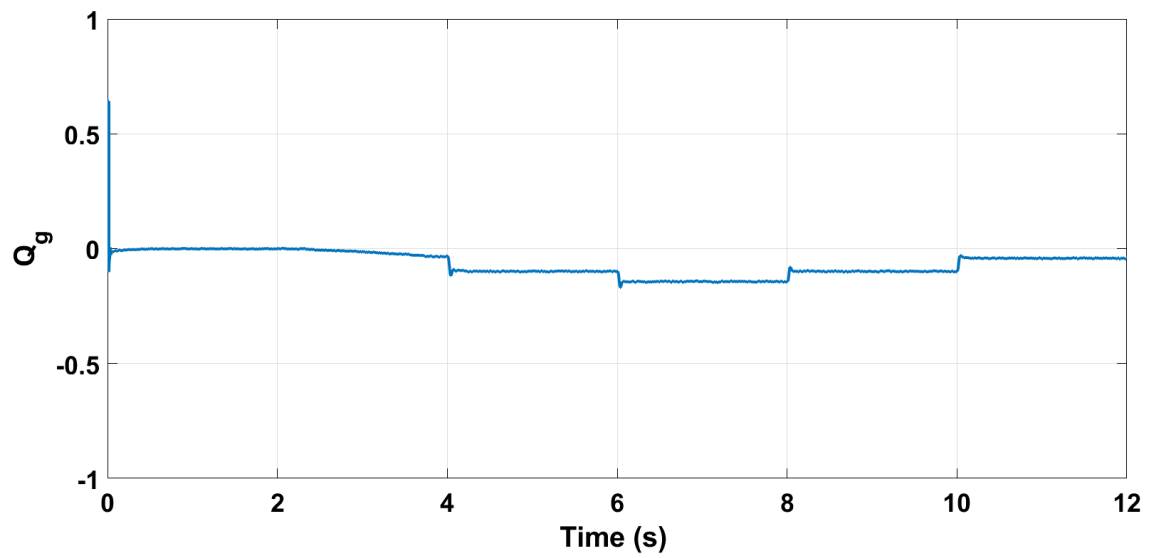


Figure 5. 238 Grid Reactive power in for the 2L VSC fed DFIG WECS

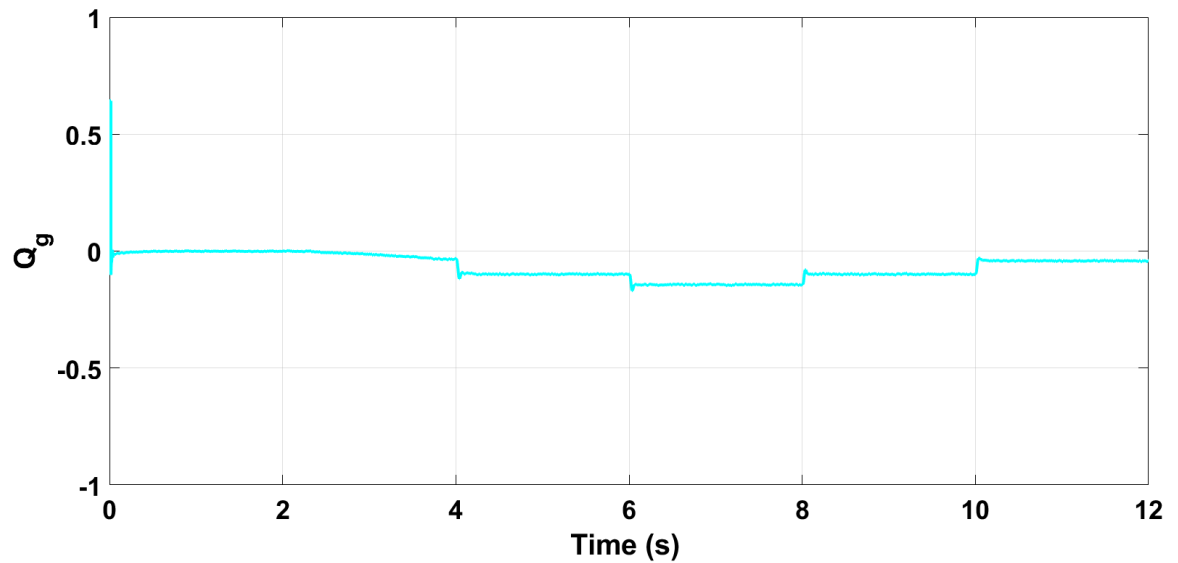


Figure 5. 249 Grid Reactive power in for the 3L NPC fed DFIG WECS

5.7 Experimental Setup

Practical testing of the schemes developed in this work is implemented in real time by developing an experimental platform using a 2.2KW three phase DFIG, and a 2.5 KW, 220 V, 1500 RPM, separately excited DC Motor which behave or mimic as wind emulator and two back to back power electronic converter of 2 level VSC and 3 Level VSC, reactor and filter, and WAVECT WCU300 Real Time Controller. The layout of the experimental setup is shown in the upcoming section.

5.7.1 DFIG

The 3-phase induction motor utilized in this study is a Doubly Fed Induction Generator (DFIG) manufactured by Crompton Greeves Power and Industrial Solutions Limited. This motor is rated for an output power of 2.2KW and operates at a voltage rating of 415V with a tolerance of $\pm 10\%$. The rated current for the motor is 5A, and it runs at a rated speed of 925 RPM with 6 poles. The frequency range of operation is 50Hz with a tolerance of $\pm 5\%$. The winding connection of the motor is configured as Stator-(Delta) and Rotor-(Star). The figure depicted as Figure 5. 25 visually illustrate the DFIG machine housed within the laboratory setting.

To accurately model and analyze the motor's behavior, the equivalent circuit parameters of the machine were determined through a series of tests. These tests include the DC test, which is employed to calculate the stator resistance value. The no-load test is performed to determine the magnetizing inductance, as well as the core and mechanical losses. Lastly, the locked rotor test is conducted to calculate the stator and rotor leakage inductances, along with the rotor resistance. These test results are essential for accurately representing the motor's characteristics and performance in various operating conditions.

The utilization of this DFIG motor, with its specific rated parameters and connection configuration, allows for precise control over its generated power, making it well-suited for applications where variable speed and reactive power control are required. The determined equivalent circuit parameters enable accurate modeling and analysis of the motor, facilitating optimization and enhancing its performance for optimal power generation and utilization.



Figure 5. 25 Visualization of the DFIG Machine within the Laboratory Environment

5.7.2 DC MACHINE

The ASHC132M DC motor, manufactured by CG Power and Industrial Solutions Limited, is a powerful 2.5 KW motor designed to operate at 220 V. It operates at a base speed of 1500 RPM, with a maximum speed capability of 1800 RPM. This particular motor belongs to the separately excited category, where the armature current is 13.0 DC and the excitation type is separately excited with an excitation current of 0.45 A DC. Figure 5. 26 illustrates the DC Machine for wind emulation purposes within the laboratory setting.

In the laboratory Setup, this DC machine utilized as a wind emulator in experimental setups. By employing appropriate control strategies, the DC machine simulate the behavior and characteristics of a wind turbine. This is achieved with the assistance of a DC-DC converter, by modifying its duty cycle. By precisely modulating these parameters, the DC machine is capable of simulating the variable speed and torque characteristics typically observed in real wind turbines. This emulation allows to study and analyze the behavior of wind energy systems in a controlled laboratory environment, enabling us to develop innovative control strategies and evaluate the performance of these systems with greater precision.

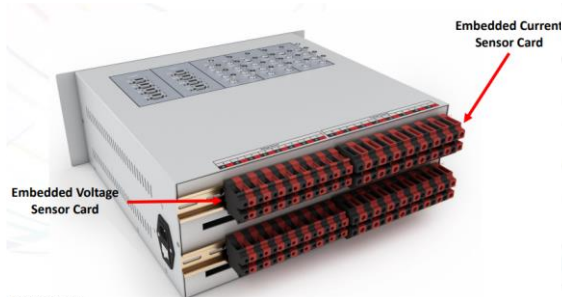


Figure 5. 26 DC machine used for wind emulation in the laboratory setup

5.7.3 WAVECT Real-Time Controller (RTC)

The WAVECT Real-Time Controller (RTC) controller model WCU300 is a Xilinx Zynq SoC-based device that offers advanced control and management capabilities for power electronic systems. It features full user control function execution on the FPGA fabric, allowing for precise and efficient control. With a fast step time of 10/25/50 ns and a PWM switching frequency of up to 2 MHz with 5 ns resolution, the WCU300 ensures high-speed and accurate control operations. It incorporates embedded voltage and current sensors, PWMs, analog I/O, digital I/O, and more, providing comprehensive monitoring and control functionalities.

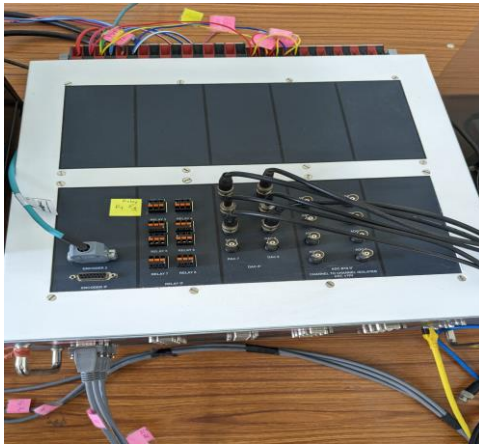
The WCU300 supports model-based design with MATLAB/Simulink HDL Coder and Xilinx System Generator (XSG) support, eliminating the need for manual coding. With a single click, users can generate binary and configuration files, simplifying the development process. The WAVECT Suite Software offers control function tuning, analysis and measurement functions, data logging, scripting support, and program management for the WAVECT controller. This suite enhances the flexibility and ease of use for users, enabling efficient system configuration and optimization. In this study, the WAVECT Controller WCU300 Figure 5. 27 (Figure (a) and (b) from the WAVECT booklet) was utilized. Furthermore, the laboratory experiments incorporated the WCU300 (Figure (c) and (d)), with Figure (c) representing the top view and Figure (d) displaying the front view.



(a)



(b)



(c)



(d)

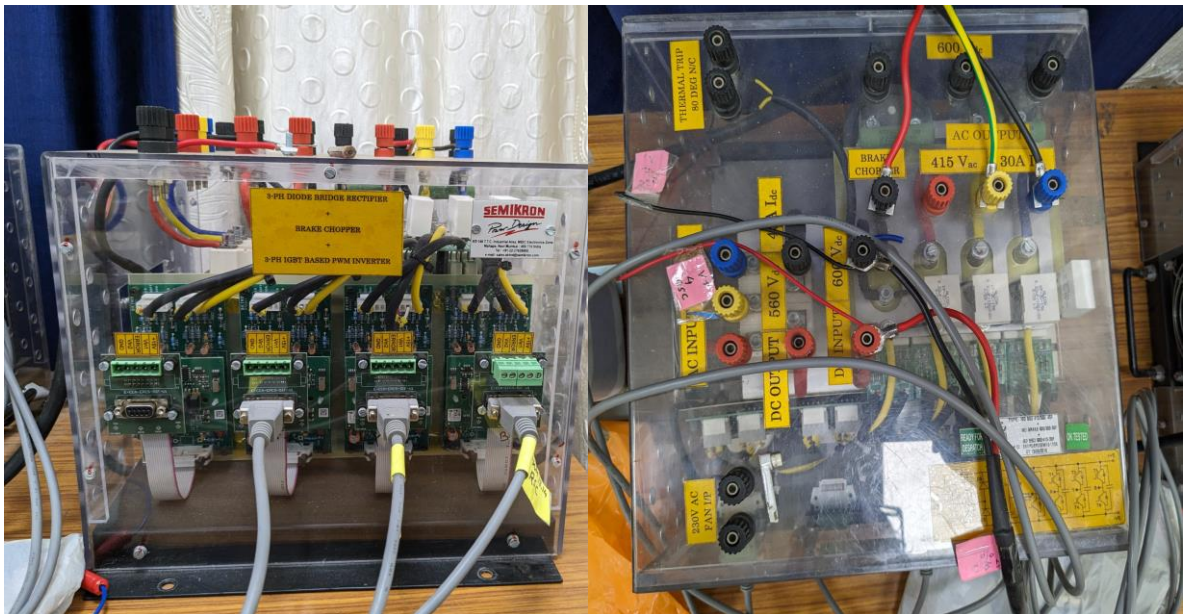
Figure 5. 27 (a) Front and (b) back view of the WAVECT Controller WCU300 as depicted in the WAVECT booklet. (c) Top and (d) front view of the WCU300 in a laboratory setting.

The WCU300 is equipped with IO cards that include 8 VI sensors, 8 high current sensors, analog input, encoder input, PWM output, analog output, relay output, and digital input/output. These IO cards provide versatile connectivity options, allowing for seamless integration with external sensors, actuators, and control devices. This extensive range of IO capabilities enables users to interface with different components of their power electronic systems and facilitates comprehensive system monitoring and control.

Overall, the WAVECT Real-Time Controller WCU300 is a powerful and feature-rich device that combines the flexibility of FPGA-based control with user-friendly software and versatile IO options. It empowers users to achieve precise and efficient control over their power electronic systems, facilitating system optimization and enhancing overall performance.

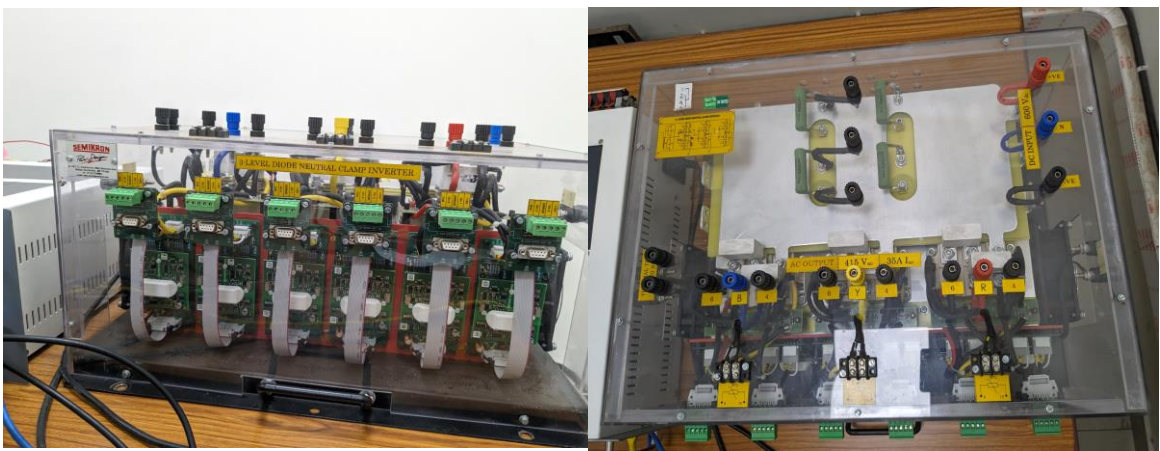
5.7.4 Inverter Stack

Semikron, a prominent manufacturer of power electronics, has developed these inverter stacks with a strong focus on delivering exceptional performance, reliability, and efficiency. These products are meticulously designed to seamlessly integrate into various system architectures and endure demanding operating conditions. Our utilization comprises two categories of Semikron inverter stacks: the first one being an IGBT-based two-level voltage source converter (VSC), and the second one being an IGBT-based three-level inverter stack. The generation of PWM (Pulse Width Modulation) pulses for these stacks is facilitated by the WAVECT Controller. The laboratory setup of the Semikron inverter stacks is depicted in Figure 5. 28



(a)

(b)



(c)

(d)

Figure 5. 28 (a) Front and (b) Top view of the 2L-VSC Stack. (c) Front and (d) Top view of the 3L-NPC Stack in a laboratory Setup.

5.7.5 Procedure for Setting up a Grid-Connected DFIG-Based Wind Energy System in the Laboratory

The experimental setup involved the implementation of a Finite Control Set Model Predictive Direct Torque Control (FCS-MPDTTC) for a grid-connected DFIG based wind energy system is shown in Figure 5.33. The primary component utilized in the setup was a DC Machine, which acted as a Wind Emulator. To control the speed of the DC Machine, a Machine side PEC (MSPEC) DC-DC Converter was employed, allowing precise adjustment of the duty cycle.

In addition to the DC Machine, another crucial component was the DFIG Machine. The stator of the DFIG Machine was directly connected to the grid, while the rotor was connected to the grid through a Back-to-Back converter consisting of an RSPEC and GSPEC module. The SEMIKRON manufactured STACK was employed to facilitate this connection. To monitor and measure various parameters, a Multimeter was utilized. It was used to measure the DC Link voltage and the excitation voltage of the DC Machine. Maintaining a constant excitation voltage was crucial, especially when running the DFIG Machine above its synchronous speed. As the speed increased, the excitation voltage tended to drop. Therefore, continuous measurement and adjustment were required to maintain the excitation voltage at the rated level.

To control the RSPEC converter and generate PWM gate pulses for both converters, a WAVECT Controller was employed. It played a vital role in ensuring accurate control and synchronization of the DFIG Machine with the grid. Additionally, a Digital Storage Oscilloscope (DSO) was utilized to display various quantities such as voltage, current, gate pulse, wind speed, and more. The entire experimental setup was coordinated and controlled by a host PC. The MATLAB model was programmed on the host PC, allowing verification of the system through simulations before proceeding to the physical implementation. Once the simulation results were satisfactory, the HDL (Hardware Description Language) code for the WAVECT Controller was generated for validation and integration with the hardware prototype.

Here's a general step-by-step process for a laboratory setup of a grid-connected DFIG-based wind energy system:

1. **Component Connection:** Connect the components including the DC Machine, DFIG, AC/DC/AC converter, DC link, transformer, and grid system. The DFIG consists of a rotor and a stator, where the stator is directly connected to the grid, and the rotor is connected to the grid through a back-to-back AC/DC/AC converter that is RSPEC and GSPEC.
2. **Control System Configuration:** Implement the control system. This usually involves a RSPEC, GSPEC, and a DC machine side converter. The RSPEC is used to control the active and reactive power of the DFIG, the GSPEC is used to maintain the DC-link voltage constant, and the DC machine side PEC (DC-MSPEC) is used to control the wind turbine's mechanical power.
3. **System Initialization:** Start the DFIG at no load condition (the DFIG is not connected to the grid). This is typically done by allowing the wind turbine to rotate the rotor of the DFIG.
4. **Grid Synchronization:** Before the DFIG can be connected to the grid, the voltage and frequency of the stator must be matched to the grid. This is achieved by controlling the rotor currents using the RSPEC. A PLL is usually used to synchronize the stator voltage with the grid voltage.

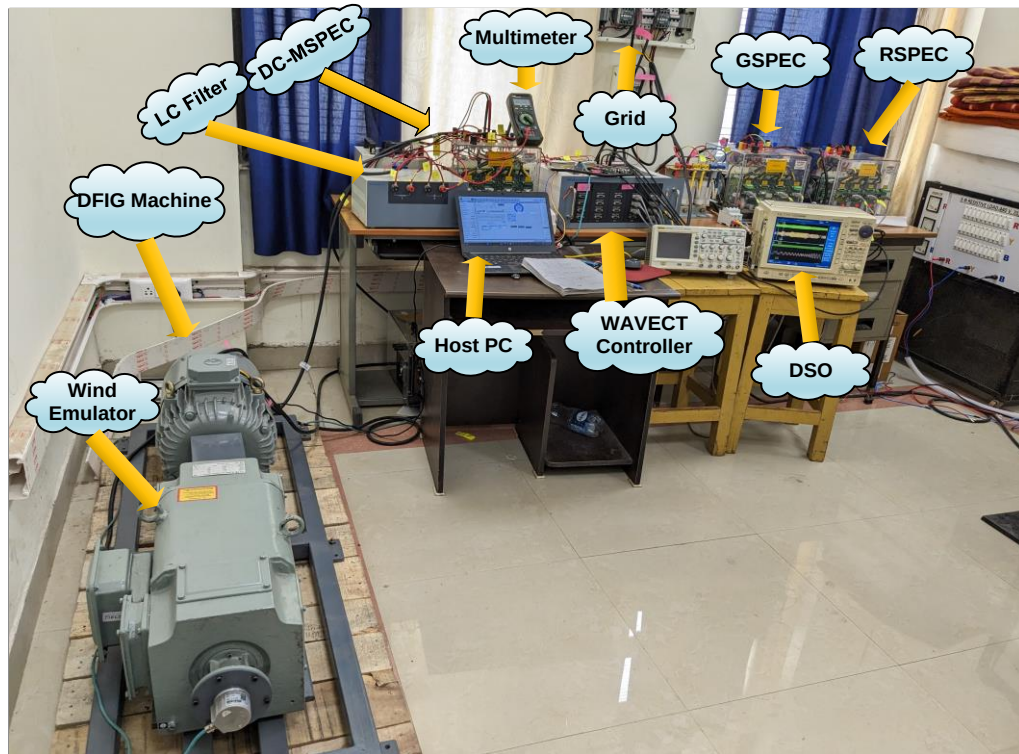


Figure 5. 29 Prototype model Setup in Laboratory

5. **Grid Connection:** Once the stator voltage is synchronized with the grid, the DFIG can be connected to the grid. At this point, the DFIG will start to feed power into the grid.
6. **MPPT Tracking:** Implement Maximum Power Point Tracking (MPPT) algorithm to extract maximum power from the wind. This is usually achieved by continuously adjusting the turbine speed based on wind speed.
7. **Monitoring and Adjusting:** Regularly monitor the system performance. Adjust the control parameters as necessary to maintain maximum efficiency and power quality.
8. **Active and Reactive Power Control:** The active and reactive power supplied to the grid can be controlled by adjusting the rotor current. This can help to improve the stability and power quality of the grid.

5.8 Experimental Results

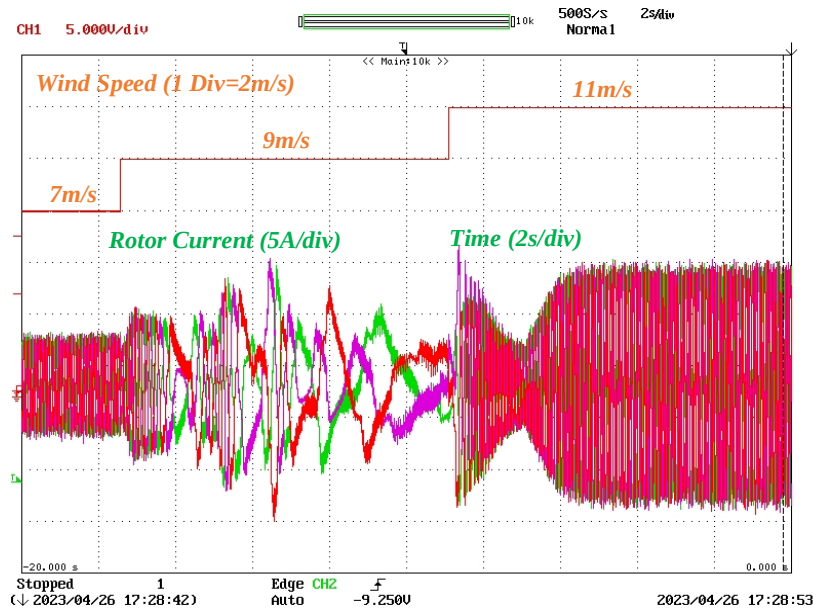
The analysis of a grid-connected Doubly-Fed Induction Generator (DFIG) based wind energy system, particularly when considering variable wind speeds and the transition from a 2-level converter to a 3-level Neutral Point Clamped (NPC) Converter in the rotor side converter (RSPEC), necessitates a thorough understanding of multiple variables. These variables include rotor and stator currents, stator power, grid power, and their respective effects on RSPEC and grid side converter (GSPEC) operations.

To begin, it is important to clarify that conducted a dynamic analysis by varying the wind speed of the system from subsynchronous to supersynchronous. We presented experimental results from a Digital Storage Oscilloscope (DSO) for both the 2-level VSC RSPEC and the 3-level NPC MLI, initiated the setup with a wind speed of 7m/s, as depicted in Figure 1, focusing on the quality of the rotor current waveform.

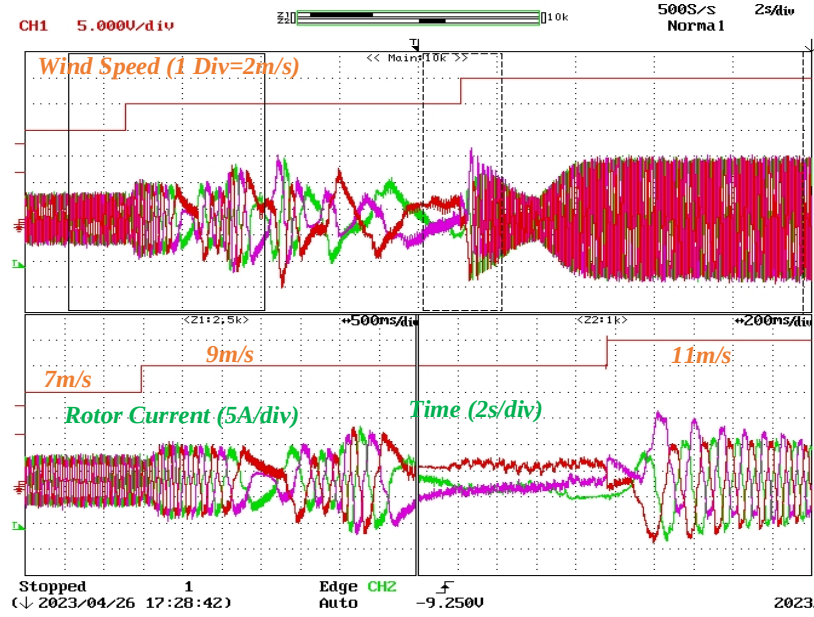
The analysis commences with the DFIG operating in a subsynchronous mode at a wind speed of 7m/s (as depicted in Figure 5. 30 (a) and Figure 5. 31(a)), thereby functioning in a subsynchronous mode. Here, the DFIG draws power from the grid from GSPEC, and the GSPEC functions as a rectifier. The RSPEC functioning the role of an inverter, transmuting Direct Current (DC) to Alternating Current (AC) for the rotor. At this juncture, the rotor current waveform, especially with a 2-level converter, may exhibit high switching harmonics, leading to suboptimal waveform quality (Figure 5. 30 (a)). In contrast, the adoption of a 3-level NPC converter in the RSPEC introduces a marked improvement in the rotor current waveform by reducing harmonic distortions and delivering superior current quality as can be seen in Figure 5. 31(a).

Increasing the wind speed to near-synchronous conditions at 9m/s leads to an interesting transformation. The rotor speed elevates (Figure 5. 30 (c)), rendering the slip near zero. As a result, the frequency of the rotor current (product of slip and stator frequency) approaches zero. This is visible in the zoomed version of the rotor current waveform presented in Figure 5. 30 (b). As the RSPEC doesn't need to supply or absorb power, the grid-side power generation is nullified. Despite these changes, the 2-level converter still leads to higher distortion compared to the 3-level NPC converter in terms of rotor current quality.

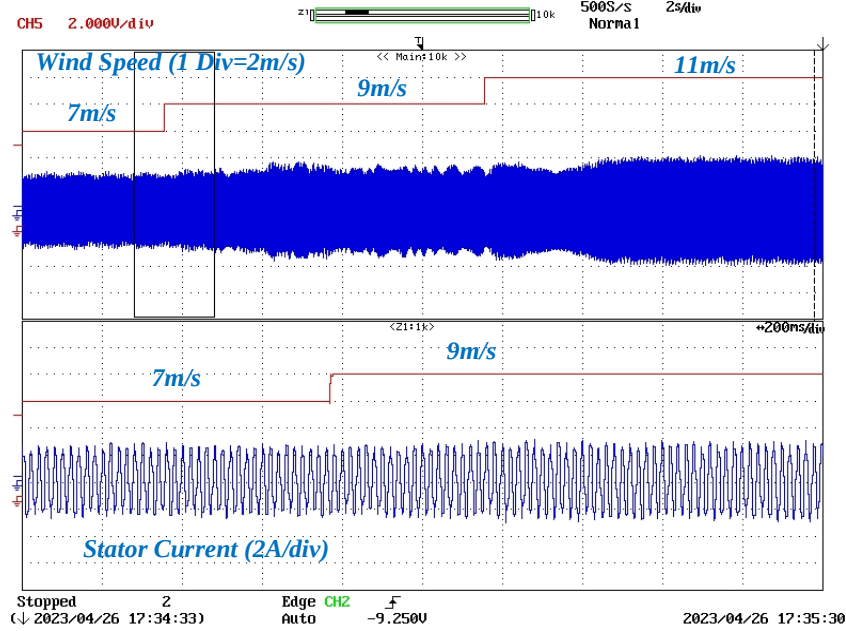
To escalate to a super-synchronous wind speed of 11m/s, the DFIG assumes a power-generating role also from the GSPEC, harnessing power from both the rotor and the stator. The rotor current frequency enhances (Figure 5. 30 (a)), with the RSPEC operating as a rectifier, converting rotor AC power to DC. In such conditions, a 3-level NPC converter enhances the rotor current waveform by reducing harmonic distortions.



(a) Rotor Current



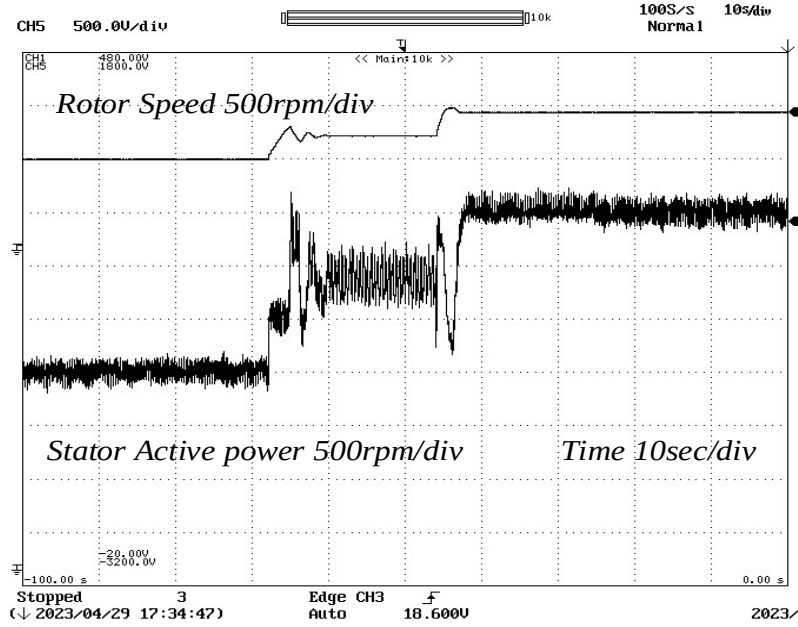
(b) Zoomed Version of Rotor current



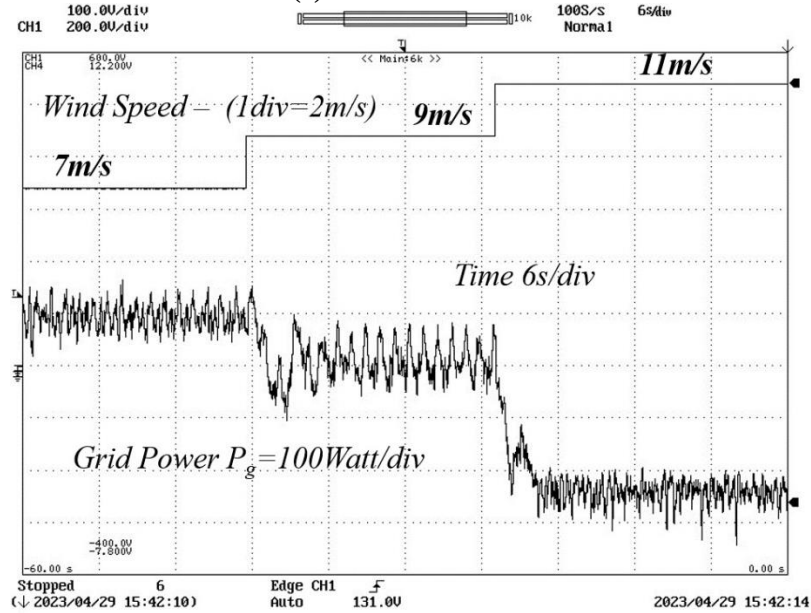
(c) Stator Current

The quality of the stator current and the level of harmonic distortion are crucial for the DFIG's performance and the power fed into the grid in any wind energy conversion system. In the case of the 2-level VSC at subsynchronous speed (7m/s), the power drawn from the grid affects the stator current, resulting in higher distortion due to the inherent switching harmonics of the 2-level converter as shown in Figure 5. 30 (c) . Comparatively, the 3-level NPC converter significantly reduces stator current distortion, providing a more sinusoidal waveform with improved quality as can be seen in Figure 5. 30 (c). As the wind speed increases to 9m/s and the DFIG transitions into power generation from the rotor side, the quality of the stator current improves, albeit

with slight amplitude increase. However, the presence of switching harmonics from the 2-level converter still limits its quality. On the other hand, the 3-level NPC converter greatly enhances stator quality by producing a stepped output waveform that closely resembles a sine wave, resulting in significantly reduced total harmonic distortion (THD).



(d) Stator Active Power



(e) Grid Active Power

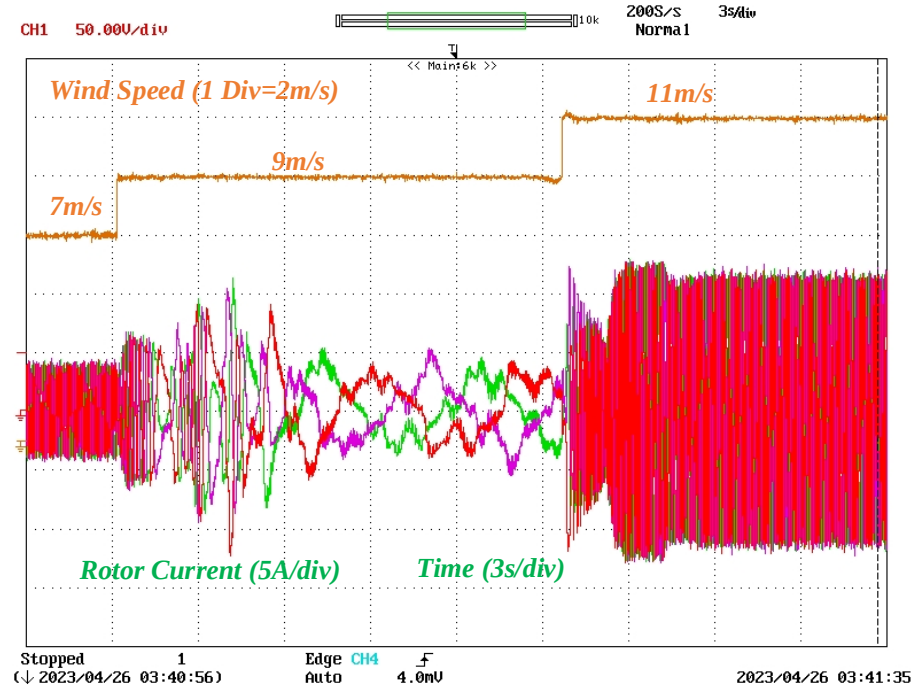
Figure 5. 30 Transient Response Analysis of FCS MPDTC Strategy with 2-Level VSC

When the wind speed reaches super-synchronous (11m/s), the DFIG operates as a generator, supplying power to the grid. In this mode, the stator current experiences the highest degree of distortion with a 2-level converter, primarily due to the switching

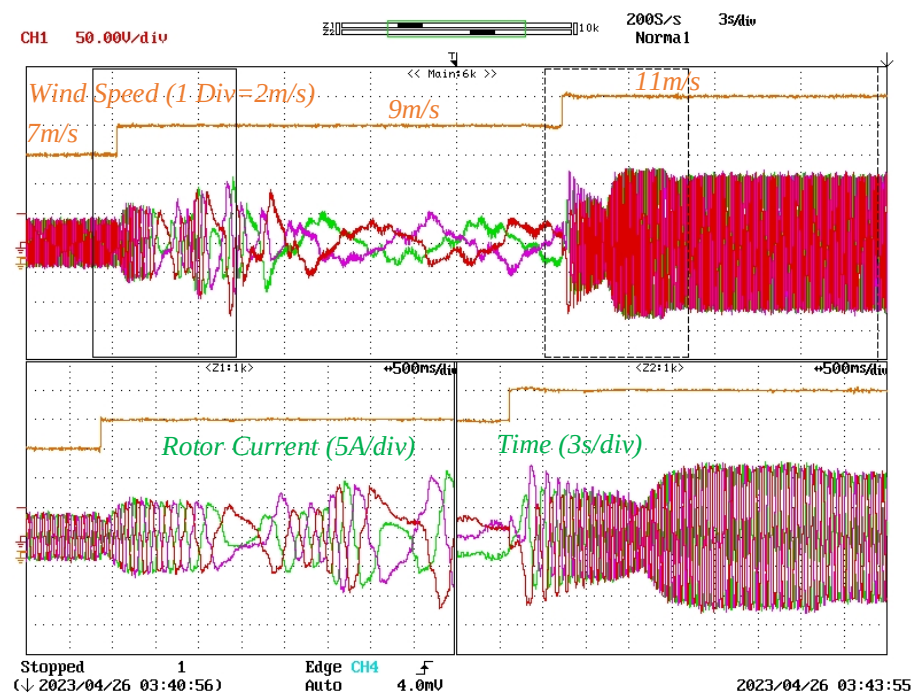
harmonics inherent in this type of converter. Despite operating at the highest wind speed, the stator current's quality remains superior with the 3-level NPC converter, thanks to the smoother waveform generated, thereby reducing distortion and maintaining high-quality power feed to the grid.

Stator power generation increases with the wind speed. In all cases, whether in subsynchronous, synchronous, or supersynchronous modes, the stator generates power while the grid absorbs power in the subsynchronous mode, generates power in the supersynchronous mode, and registers zero power in the synchronous mode. Notably, the fluctuations in power or harmonics in both stator and grid power are more pronounced with the 2-level VSC compared to the 3-level NPC MLI.

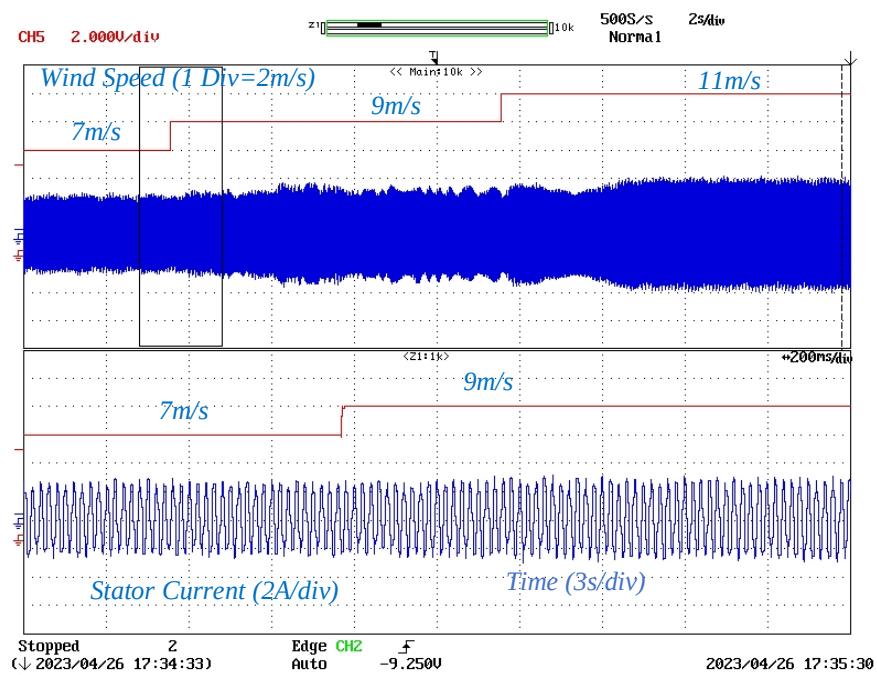
In conclusion, the utilization of a 3-level NPC converter with FCS-MPC-DTC control technique enhances the quality of the rotor current, stator currents, stator power, and grid power. It reduces harmonic distortion, providing superior control over power flow between the grid, stator, and rotor under varying wind speeds.



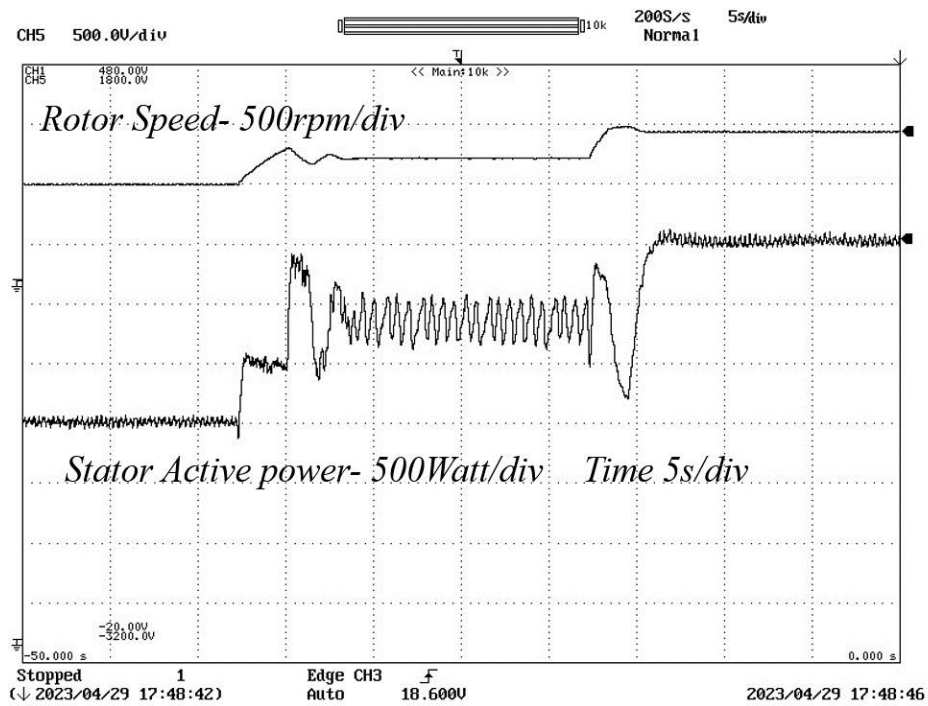
(a) Rotor Current



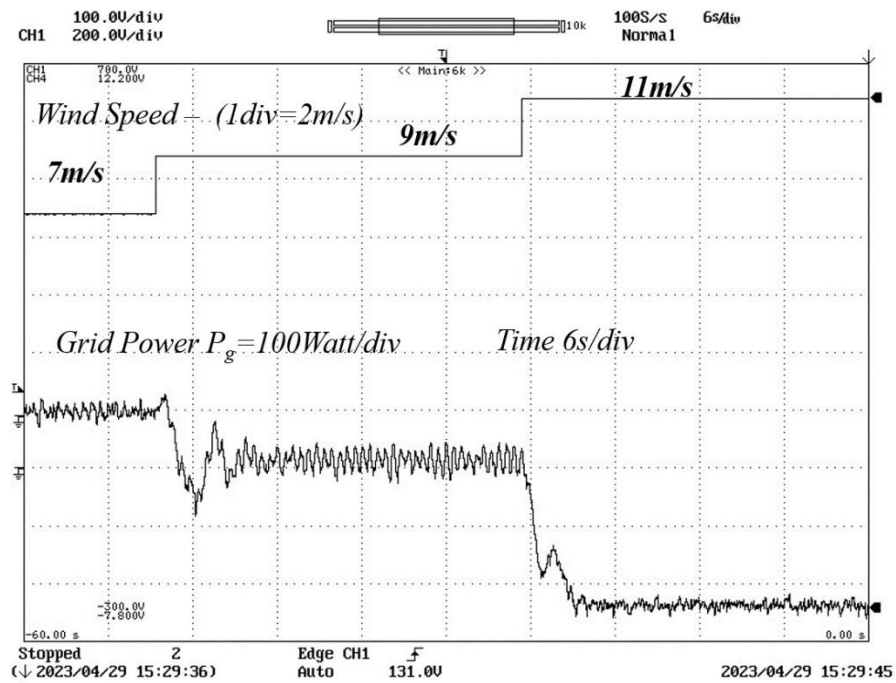
(b) Zoomed Version of Rotor current



(c) Stator Current



(d) Stator Active Power



(e) Grid Active Power

Figure 5. 31 Transient Response Analysis of FCS MPDTC Strategy with 3-Level NPC MLI

5.9 Conclusion

In conclusion, this chapter has focused on the exploration and application of Finite Control Set Model Predictive Control (FCS-MPC) in DFIG based wind energy systems. The predictive nature of FCS-MPC, along with its ability to directly calculate and optimize future behavior, makes it an attractive choice for controlling DFIG systems efficiently. By extending investigation to include both standard two-level fed DFIG-based wind energy systems and multilevel fed DFIG-based systems also demonstrated the flexibility and potential benefits of FCS-MPC in various configurations.

To validate theoretical findings and ensure the practical viability of FCS-MPC, used MATLAB simulations as a powerful tool to visualize and evaluate the control algorithm's performance under different operating conditions. These simulations provide crucial insights and offer a safe environment for developing and refining control strategies before real-world implementation. Taking research beyond simulation, have successfully developed a hardware prototype that incorporates the WAVECT Controller, a cutting-edge control system tailored for wind turbines. The successful integration and operation of the WAVECT Controller with FCS-MPC further underscore the effectiveness and reliability of our approach.

In summary, this chapter has shed light on the potential of FCS-MPC as an efficient and robust control technique for DFIG based wind energy systems. The combination of theoretical analysis, MATLAB simulations, and practical implementation has provided valuable evidence of the benefits of FCS-MPC in enhancing system performance and operational efficiency. As the demand for sustainable energy solutions continues to grow, FCS-MPC holds promise in contributing to the advancement of wind energy systems, making them more reliable and effective sources of clean power.

CHAPTER 6. FCS-MP DPC FOR GSPEC OF DFIG FED WECS

6.1 Introduction

MPC is a powerful technique used in modern control systems. It predicts and optimizes system behaviour over a future time horizon. One application of MPC is for power control of GSPEC of DFIG in wind energy systems.

The utilization of DFIG-based WECS is prevalent owing to their remarkable adaptability and high efficiency. The DFIG enables wind turbines to operate efficiently across a range of speeds, thereby optimizing power extraction in varying wind conditions. This system consists of two key components: the stator, which is directly linked to the grid, and the rotor, which is connected to the grid through a converter system encompassing the RSPEC and the GSPEC. The primary function of the GSPEC is to stabilize the DC-link voltage while ensuring the continuous supply of total active power (the sum of stator and rotor power) to the grid.

Control strategies for GSPEC are essential for the efficient functioning of the DFIG system. Among the available strategies, Finite Control Set Model Predictive Control (FCS-MPC) has gained a lot of attention in recent years due to its ability to handle multi-variable control and constraints, its fast dynamic response, and its robustness against parameters variations and grid disturbances. It differs from traditional control strategies in that it includes the power electronic converter's switching nature directly into the control problem formulation.

FCS-MPC for the DPC of the GSPEC in DFIG systems is an emerging research area. This method allows direct control of active and reactive power and yields faster response and more robust to disturbances compared to conventional techniques. In FCS-MPC based DPC, at each sampling instant, a prediction model is used to forecast the future behaviour of the system for every possible combination of converter switching states. An optimization algorithm is useful to select the switching state that minimizes the error among the predicted and reference powers.

The main pro is, it allows for simultaneous control of various outputs, such as active, reactive power, and DC-link voltage. This enables more efficient and stable operation of the WES system, mainly under variable wind conditions and grid

disturbances. Moreover, the use of this technique in DPC eliminates the need of separate PI controllers and PWM modulators, which simplifies the whole control system and reduces the computational burden.

In this chapter, the details of FCS-MPDPC and its application to the GSPESC of DFIG systems is presented. The theoretical aspects of proposed method and its benefits in achieving precise control of the active and reactive power exchanged with grid. In an effort to further understanding and knowledge its application beyond the traditional two-level fed DFIG-WES also extended its use to multilevel converters to DFIG technology. To validate the theoretical findings and demonstrate the performance of FCS-MPDPC MATLAB simulations are performed. The simulation study provides visual representation of the control algorithm and allows evaluating its performance under various operating conditions. The simulation results are validated further by developing a hardware prototype to demonstrate the practical application of the work. This hardware prototype incorporates a WAVECT Controller, a cutting-edge digital control system specifically designed for wind turbines. The hardware prototype allows observing the real-time performance of the system and validating the applicability in an actual wind turbine setup. Through extensive testing the control accuracy, stability, and response of the system under various operating conditions can be evaluated. This practical demonstration serves as tangible evidence of the practicality and efficacy of technique.

Through this comprehensive exploration the potential and practical application of FCS-MPDPC for the GSPESC of DFIG systems is demonstrated. The combination of theoretical analysis, practical implementation, and simulation results provides valuable insights into the performance and benefits of FCS-MPDPC, contributing to the advancement of control techniques in the field of wind energy systems.

6.2 Construction and Controlling of the GSPEC

In this construction and management of the GSPEC including the assembly of passive components (DC-link capacitors and AC-side harmonic filter), the configuration of the net DC-bus voltage magnitude reference, defining the power factor (PF) of the grid, and the orientation of the grid voltage (synchronization with the grid).

6.2.1 DESIGN OF PASSIVE COMPONENT

The GSPEC requires passive elements on both the DC and AC sides to carry out storage and filtering roles. A DC capacitor is employed being its value determined from below equation [8]:

$$C_{dc} = \frac{T_r \Delta P_{dc}}{2V_{dc} \Delta V_{dc}} \quad 6.1$$

C_{dc} , denoting the capacitance of the DC-link capacitor and computed using variables T_r , the control delay owing to filtering of the DC-bus voltage and AC current control; ΔP_{dc} , the highest permissible DC power fluctuation; V_{dc} , the nominal DC-bus voltage; ΔV_{dc} , is the permissible DC-bus voltage ripple. Similarly the above variables are balanced considering factor such as dynamic response, size, and cost to configure the DC-link capacitor. For high-power applications DC-link capacitor value is taken as 4.0 pu to accommodate a reasonable balance between various design factors.

The AC side passive components will have relatively minor role in storing energy, which is approximately 5% of the overall system energy. The harmonic filter on the AC-side is either an inductive (L) filter or an inductive-capacitive-inductive (LCL) filter. Although the latter one offers improved grid current quality compared to the former but may have filter resonance concerns during significant changes in operating conditions [200]. This discussion critically focuses on the design and control of the GSPEC based on the L-filter configuration. In commercial Wind Turbines (WTs) with 2L-VSCs, its value is computed in conjunction with the leakage inductance of the step-up transformer (if present), typically ranging from 0.1 to 0.25 pu [200]. Further its value decreases with multilevel converters.

6.2.2 Designing the Reference DC-Bus Voltage

The grid connected Voltage Source Inverter (VSI) operating with a modulation index (MI) m_a having a range from zero to one will ensure proper functioning. The V_{dc} must surpass the peak line-to-line voltage $V_{g,l-l}$ of the grid. The selection of the reference DC-bus voltage v_{dc}^* can be computed from both MI and the root mean square (rms) phase voltage V_g of the grid. This relationship is illustrated in the below equation [201]:

$$v_{dc}^* = \frac{\sqrt{2}V_{g,ll}}{m_a} = \frac{\sqrt{2}V_g}{m_a}, 0 \leq m_a \leq 1 \quad 6.2$$

The V_g , corresponds to the rms value of the fundamental frequency component of the grid inverter phase voltage, V_{il} . To choose an appropriate v_{dc}^* , it is essential to consider the fluctuations and transients in the grid voltage occur during dynamic operations. The MI is chosen as 0.8, a reasonable 20% margin is provided for accommodating adjustments in transient conditions. Therefore v_{dc}^* is established in relation to the grid phase voltage as illustrated below:

$$v_{dc}^* = \frac{\sqrt{6}V_g}{0.8} \quad 6.3$$

The crucial factor in controlling of the inverter in BTB converter is maintaining value of reference DC voltage independent of operating conditions, to achieve this PI controller is employed in the outer control loop by regulating net bus voltage.

6.2.3 Establishing the Grid Power Factor

The GSPEC is having bidirectional power transfer characteristics elaborated in two modes namely depending on transfer of power from grid to DC bus and from DC bus to grid. During normal operation power flows as mentioned in mode one and during system starting the rectifier operation (mode two) is utilized to pre-charge the DC-link capacitors and initiate the magnetization of current for the DFIG. The active and reactive powers exchanged with the grid are precisely illustrated as below:

$$\begin{aligned} P_g &= V_g I_g V \cos \theta_g \\ Q_g &= V_g I_g V \sin \theta_g \end{aligned} \quad 6.4$$

In the above θ_g represents the Power Factor (PF) angle, i.e., the angle between the voltage and the current vectors of the grid. The DC link functions as a source during mode one operation or as a load during mode two operations.

6.2.4 Orientation of Grid Voltage

The use of either V_g or grid flux orientations can exercise independent control over the grid currents or the active and reactive power components. The critical useful points in digital control controlling the GSPECs are [202]:

- A control method similar to FOC of high-performance drives named as Voltage-Oriented Control (VOC) to independently control grid current.

- A parallel control method having similarities to DTC of drives known as Voltage-Oriented Direct Power Control (V-DPC) which allows the decoupled control of grid's active and reactive power.
- Other method using rotor flux to regulate grid current is Virtual Flux-Oriented Control.
- Finally, other control technique using virtual flux component and DPC known as Virtual Flux-Oriented Direct Power Control to independently control grid's active and reactive power.

The VOC technique is a closed-loop current control using dq frame. In this three-phase currents (i_{ag} , i_{bg} , and i_{cg}) and voltages (v_{ag} , v_{bg} , and v_{cg}) are sensed through Hall Effect sensors and coordinated to SRF grid currents (i_{dg} and i_{qg}) and voltages (v_{dg} and v_{qg}). Echoing the methodology employed in wind generator modeling (Refer to Equations (3. 59) and (3. 61) in Chapter 3), the stator active and reactive powers of the grid are computed as follows:

$$\begin{aligned} P_g &= \frac{3}{2} \text{Re}\{S_g\} = \frac{3}{2} (v_{dg} i_{dg} + v_{qg} i_{qg}) \\ Q_g &= \frac{3}{2} \text{Im}\{S_g\} = \frac{3}{2} (v_{qg} i_{dg} - v_{dg} i_{qg}) \end{aligned} \quad 6.5$$

S_g is the apparent power, active power is P_g and reactive power is Q_g of the grid.

The control method is elaborated by setting q axis grid voltage as zero and allowing direct link between P_g and i_{dg} , also Q_g and i_{qg} , by maintaining d axis grid voltage a constant value. This is referred as the SRF's d-axis with the grid voltage. This is graphical represented in Figure 6.1.

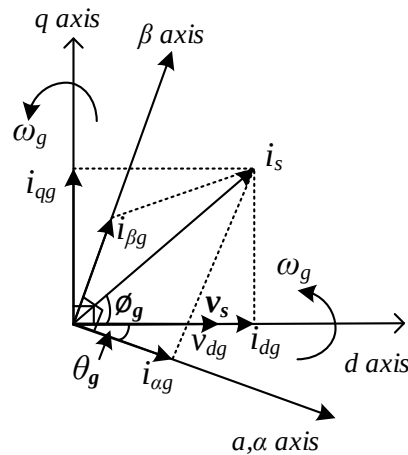


Figure 6. 1 Grid voltage and current vectors in dq and $\alpha\beta$ frame

The vector v_g also computed similarly by taking v_{qg} as zero, the active and reactive power of the grid can be encapsulated as:

$$\left. \begin{aligned} P_g &= \frac{3}{2}(v_{dg}i_{dg}) \\ Q_g &= -\frac{3}{2}(v_{dg}i_{qg}) \end{aligned} \right\} \text{for } v_{qg} = 0 \quad 6.6$$

The grid voltage angle is denoted as θ_g , it is critical aligned to v_{dg} , with grid voltage magnitude, v_s this will play a critical role in WECS for synchronization of inverter and grid connection smoothly. Also this angle plays a pivotal role in coordinate transformation of variables and designing the digital control system. Under ideal grid voltage conditions, the angle can be derived from the stationary frame voltages, designated as $v_{\alpha g}$ and $v_{\beta g}$, as follows:

$$\theta_g = \tan^{-1} \left(\frac{v_{\beta g}}{v_{\alpha g}} \right) \quad 6.7$$

The frame grid voltages $v_{\alpha g}$ and $v_{\beta g}$ can be derived from the three-phase grid quantities as below:

$$\begin{bmatrix} v_{\alpha g} \\ v_{\beta g} \end{bmatrix} = \frac{2}{3} \underbrace{\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}}_{T_{abc/\alpha\beta}} \begin{bmatrix} v_{ag} \\ v_{bg} \\ v_{cg} \end{bmatrix} \quad 6.8$$

The formation of grid angle from three phase voltage quantities through coordinate transformation is detailed through a schematic representation as illustrated in Figure 6.2. The computed grid angle θ'_g oscillates between $-\pi$ and $+\pi$. For aligning peak of a phase grid voltage v_{ag} , with the apex of the phase angle, a modulus function varying 0 to 360 degrees is used. This makes the final grid voltage angle synchronously varying along with instantaneous variation in v_{ag} .

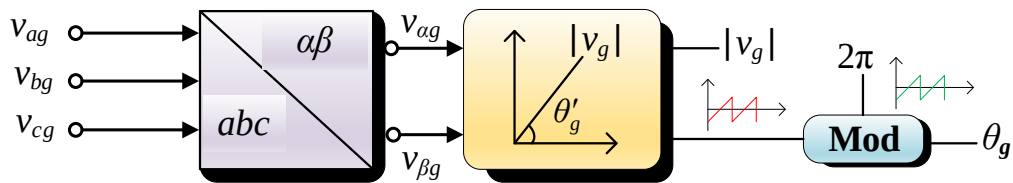


Figure 6. 2 Schematic representation of grid voltage angle calculation under ideal grid conditions

In presence of harmonic content, practically grid voltages are prone to more distortions. To limit this Synchronous Reference Frame -Phase Locked Loop (SRF-PLL) is used as illustrated in Figure 6.3. Where in, the 3-phase voltages are changed to the dq quantities with the help feedback angle θ_g , also a low-pass filter (LPF) is used to shift the grid voltage error, and a PI controller to make the v_{qg} to zero. For improvement in the initial dynamic performance a feed-forward angular frequency term (ω_o) is added to PI controller. Following this, an integrator is also employed to transform ω_g into θ_g and an absolute function is used to vary θ_g with in specified limits ranging from 0 and 2π .

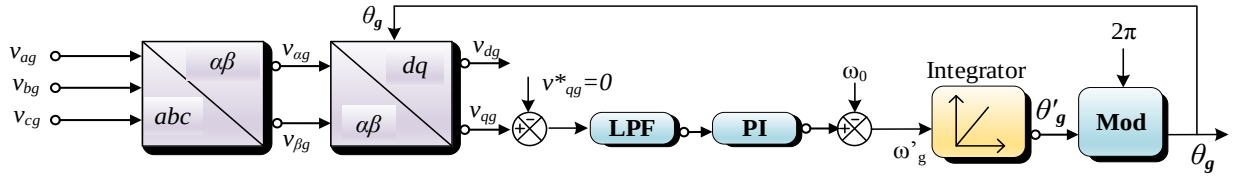


Figure 6. 3 Grid voltage angle estimation in the presence of distorted grid conditions

6.3 Modeling of Three-Phase GSPEC

Two prominent converters in the realm of GSPECs for the WECS are the 2L-VSI and 3L-NPC. These converters are important to manage the active and reactive power fed to the grid. This can be accomplished either directly or indirectly via the oversight of grid currents. The operation in CT and DT modelling of grid currents and power in different transformations are presented. To shed light on the interconnection among the switching states of power converters and the dynamics of grid variables, a switching table based on the operation of GSPEC in terms grid voltages is also presented [203].

With a conventional VOC scheme the currents in the SRF are regulated through PI tuning and minimizing steady-state errors but in MPC scheme, the steady-state current/power errors are virtually made identical across three reference frames.

6.3.1 Modelling of Grid Currents and Powers in abc-Frame

Inductive filter is considered to simplify the mathematical analysis of the system. Figure 6. 4 and Figure 6. 5 provide a clear representation of the connection of grid inverter. The voltage variables v_{ao} , v_{bo} , and v_{co} stand for the voltages of the 2L-VSI or NPC inverter with reference to the –ve DC-rail (o).

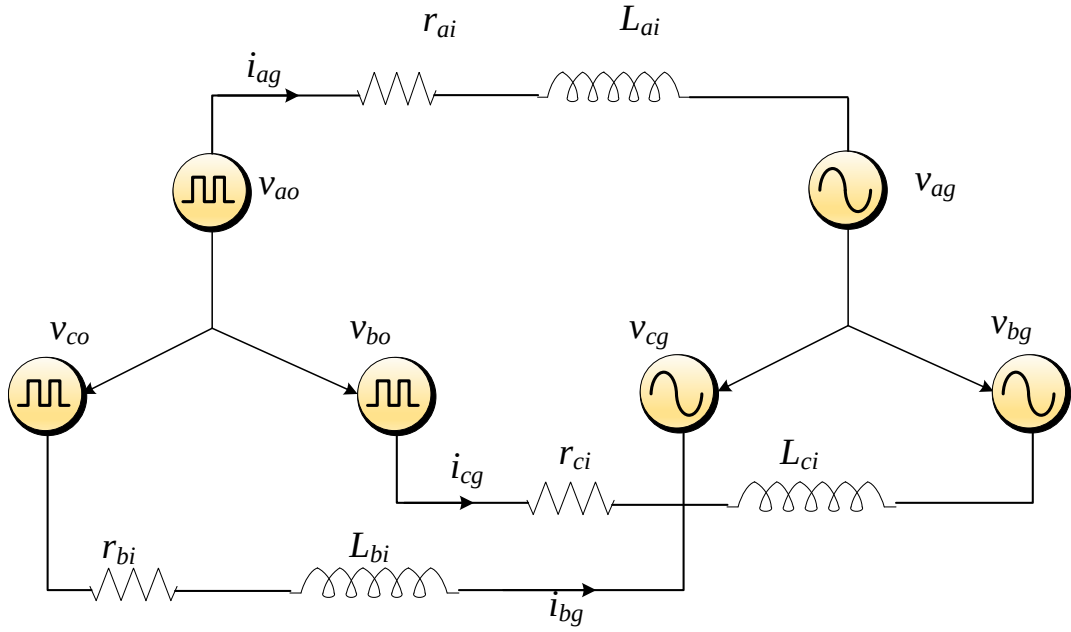


Figure 6. 4 abc-frame standard model GSPEC representation

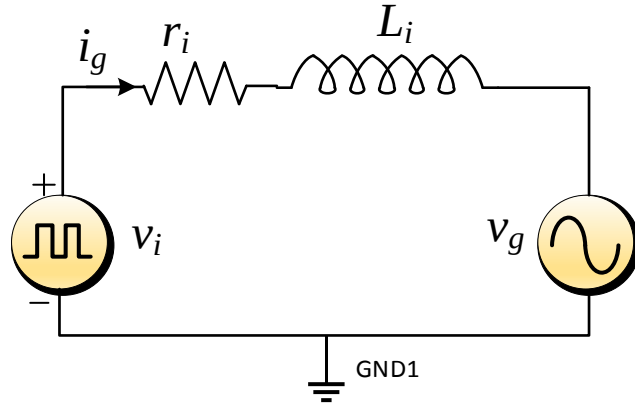


Figure 6. 5 abc-frame simplified model GSPEC representation

The three-phase grid voltages are represented by v_{ag} , v_{bg} , and v_{cg} , while i_{ag} , i_{bg} , and i_{cg} signify the three-phase grid currents. The terms L_{ai} , L_{bi} , and L_{ci} are grid-filter inductance for three phases. The internal resistance of the grid filter and the leakage resistance of the step-up transformer are denoted as r_{ai} , r_{bi} , and r_{ci} . Also v_{no} represents the neutral point voltage measured between negative inverter DC-rail and neutral point. The Grid Current Modeling in three phase CT approach is presented as: The analysis is simplified by making the following assumptions:

$$\begin{aligned}
r_{ai} &= r_{bi} = r_{ci} = r_i \\
L_{ai} &= L_{bi} = L_{ci} = L_i \\
v_{ag} + v_{bg} + v_{cg} &= 0 \\
i_{ag} + i_{bg} + i_{cg} &= 0
\end{aligned} \tag{6.9}$$

Expressing the VSI AC-side voltages in terms of grid voltages, grid currents, and filter parameters is achievable by applying Kirchhoff's voltage law to Figure 6. 4

$$\begin{bmatrix} v_{ao} \\ v_{bo} \\ v_{co} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} r_i & 0 & 0 \\ 0 & r_i & 0 \\ 0 & 0 & r_i \end{bmatrix} \begin{bmatrix} i_{ag} \\ i_{bg} \\ i_{cg} \end{bmatrix} + \begin{bmatrix} L_i & 0 & 0 \\ 0 & L_i & 0 \\ 0 & 0 & L_i \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_{ag} \\ i_{bg} \\ i_{cg} \end{bmatrix} + \begin{bmatrix} v_{ag} \\ v_{bg} \\ v_{cg} \end{bmatrix} + \begin{bmatrix} v_{no} \\ v_{no} \\ v_{no} \end{bmatrix} \tag{6.10}$$

Determining the grid neutral voltage v_{no} is possible by utilizing the following approach for a three-phase balanced grid.

$$\frac{v_{ao} + v_{bo} + v_{co}}{3} = v_{no} \tag{6.11}$$

Formulating the VSC output voltages in matrix notation, considering the grid neutral voltage v_{no} , can be achieved by substituting equation (6.11) into equation (6.10).

$$\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} = \begin{bmatrix} v_{ao} - v_{no} \\ v_{bo} - v_{no} \\ v_{co} - v_{no} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} r_i & 0 & 0 \\ 0 & r_i & 0 \\ 0 & 0 & r_i \end{bmatrix} \begin{bmatrix} i_{ag} \\ i_{bg} \\ i_{cg} \end{bmatrix} + \begin{bmatrix} L_i & 0 & 0 \\ 0 & L_i & 0 \\ 0 & 0 & L_i \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_{ag} \\ i_{bg} \\ i_{cg} \end{bmatrix} + \begin{bmatrix} v_{ag} \\ v_{bg} \\ v_{cg} \end{bmatrix} \tag{6.12}$$

This expression can be further simplified. The voltage and current vectors in the above equation are defined as follows:

$$v_i = r_i i_g + L_i \frac{di_g}{dt} + v_g \tag{6.13}$$

Expressing the dynamics of the abc-frame CT grid current from Equation (6.12) yields the following formulation:

$$\underbrace{\frac{d}{dx} \begin{bmatrix} i_{ag}(t) \\ i_{bg}(t) \\ i_{cg}(t) \end{bmatrix}}_{\dot{x}(t)} = \underbrace{\begin{bmatrix} -\frac{r_i}{L_i} & 0 & 0 \\ 0 & -\frac{r_i}{L_i} & 0 \\ 0 & 0 & -\frac{r_i}{L_i} \end{bmatrix}}_A \underbrace{\begin{bmatrix} i_{ag}(t) \\ i_{bg}(t) \\ i_{cg}(t) \end{bmatrix}}_{x(t)} + \underbrace{\begin{bmatrix} \frac{1}{L_i} & 0 & 0 \\ 0 & \frac{1}{L_i} & 0 \\ 0 & 0 & \frac{1}{L_i} \end{bmatrix}}_{B_I} \underbrace{\begin{bmatrix} v_{an}(t) \\ v_{bn}(t) \\ v_{cn}(t) \end{bmatrix}}_{v_i(t)} + \underbrace{\begin{bmatrix} -\frac{1}{L_i} & 0 & 0 \\ 0 & -\frac{1}{L_i} & 0 \\ 0 & 0 & -\frac{1}{L_i} \end{bmatrix}}_{B_g} \underbrace{\begin{bmatrix} v_{ag}(t) \\ v_{bg}(t) \\ v_{cg}(t) \end{bmatrix}}_{v_g(t)} \tag{6.14}$$

This expression can be further simplified as below

$$\frac{di_g}{dt} = -\frac{r_i}{L_i} i_g + \frac{1}{L_i} v_i - \frac{1}{L_i} v_g = A i_g + B_i v_i + B_g v_g \quad 6.15$$

6.3.2 Modelling of Grid Currents and Powers in the dq-Frame

In dq-frame all the variables are in DC in nature. The terminal voltages of the 2L-VSI or NPC inverter are symbolized as v_{di} and v_{qi} . The grid voltages of dq-frame are denoted as v_{dg} and v_{qg} , also the grid currents are represented by i_{dg} and i_{qg} . Figure 6. 6 represents the standard and simplified structure GSPEC in d-q axis. The term ω_g is indicative of the grid's angular frequency and terms $-\omega_g L_i i_{qg}$ and $\omega_g L_i i_{dg}$ account for the induced speed voltages computed from coordinate transformation of variables.

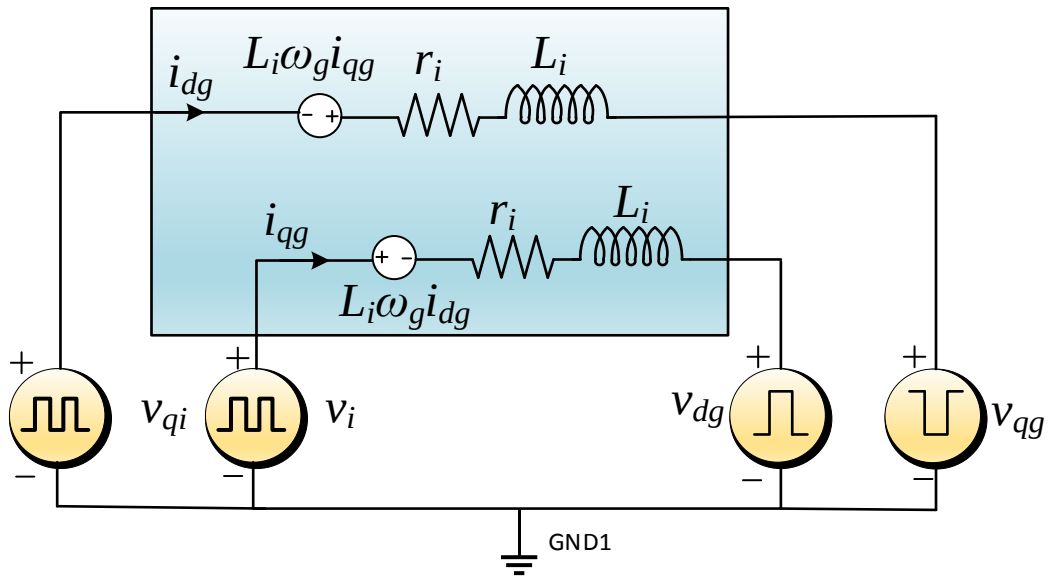


Figure 6. 6 dq-frame standard model GSPEC representation

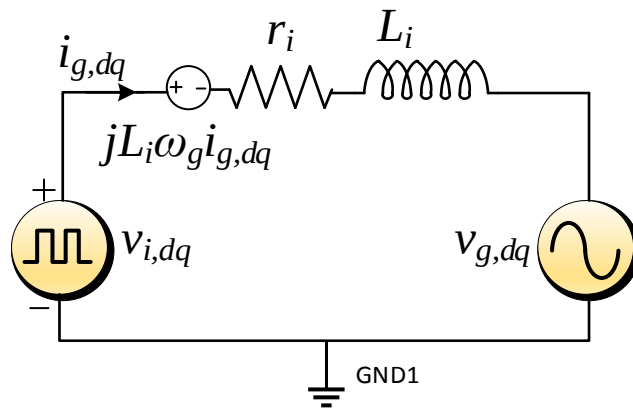


Figure 6. 7 dq-frame simplified model GSPEC representation

6.3.3 Modeling of Grid Currents in the dq-Frame employing CT

To obtain the dq-frame inverter voltages, Equation (6.10) is multiplied by the abc/dq transformation matrix presented in equation (3. 54) this leads to expression:

$$\begin{bmatrix} v_{di} \\ v_{qi} \end{bmatrix} = \begin{bmatrix} r_i & -\omega_g L_i \\ \omega_g L_i & r_i \end{bmatrix} \begin{bmatrix} i_{dg} \\ i_{qg} \end{bmatrix} + \begin{bmatrix} L_i & 0 \\ 0 & L_i \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_{dg} \\ i_{qg} \end{bmatrix} + \begin{bmatrix} v_{dg} \\ v_{qg} \end{bmatrix} \quad 6.16$$

Simplifying the representation, we have:

$$v_{i,dq} = (r_i + j\omega_g L_i) i_{g,dq} + L_i \frac{di_{g,dq}}{dt} + v_{g,dq} \quad 6.17$$

In the above equations, the dq-frame voltage and current vectors are defined as follows:

$$\begin{aligned} v_{i,dq} &= (v_{di} + jv_{qi}) = \begin{bmatrix} v_{di} \\ v_{qi} \end{bmatrix} \\ v_{g,dq} &= (v_{dg} + jv_{qg}) = \begin{bmatrix} v_{dg} \\ v_{qg} \end{bmatrix} \\ i_{g,dq} &= (i_{dg} + ji_{qg}) = \begin{bmatrix} i_{dg} \\ i_{qg} \end{bmatrix} \end{aligned} \quad 6.18$$

The dynamic model of the dq-frame grid current can be derived from Equation (6.18) in the following manner:

$$\frac{d}{dt} \begin{bmatrix} i_{dg}(t) \\ i_{qg}(t) \end{bmatrix} = \underbrace{\begin{bmatrix} -\frac{r_i}{L_i} & \omega_g \\ -\omega_g & -\frac{r_i}{L_i} \end{bmatrix}}_A \underbrace{\begin{bmatrix} i_{dg}(t) \\ i_{qg}(t) \end{bmatrix}}_{x(t)} + \underbrace{\begin{bmatrix} \frac{1}{L_i} & 0 \\ 0 & \frac{1}{L_i} \end{bmatrix}}_{B_i} \underbrace{\begin{bmatrix} v_{di}(t) \\ v_{qi}(t) \end{bmatrix}}_{v_i(t)} + \underbrace{\begin{bmatrix} -\frac{1}{L_i} & 0 \\ 0 & -\frac{1}{L_i} \end{bmatrix}}_{B_g} \underbrace{\begin{bmatrix} v_{dg}(t) \\ v_{qg}(t) \end{bmatrix}}_{v_g(t)} \quad 6.19$$

6.3.4 Grid Active and Reactive power in the DQ-Frame employing CT

The representation of the grid's active and reactive powers in the dq-frame, based on the CT model, is defined in the following manner according to [186].

$$\begin{aligned} P_g &= \frac{3}{2} (v_{dg} i_{dg} + v_{qg} i_{qg}) \\ Q_g &= \frac{3}{2} (v_{qg} i_{dg} - v_{dg} i_{qg}) \end{aligned} \quad 6.20$$

6.3.5 Transforming the dq-Frame CT Model of Grid Currents into a DT Model

The MPC algorithm is an optimization tool. For successful implementation of this scheme, it is mandatory to change the parameters from CT models into their DT counterparts. The CT grid current model, as laid out in Equation (6.19) is having linear

and time-invariant behaviour thanks to constant terms used in state matrix A. These results to exact and approximated DT terms offline computation. In Section 5.5.5, it was mentioned as discrete error between the exact method and the forward Euler method is negligible, especially for small values of r_i and T_s . For simplification forward Euler approximation method is only focused considering both the present sample (k) and the future sample ($k+1$), as outlined below:

$$\left\{ \frac{dx(t)}{dt} \right\}_{t=kT_s} \approx \frac{x(kT_s + T_s) - x(kT_s)}{T_s}, x \in \{i_{dg}, i_{qg}\} \quad 6.21$$

The above expression can be further simplified as:

$$x(k+1) = x(k) + T_s \left\{ \frac{dx(t)}{dt} \right\}_{t=k} \quad 6.22$$

In above equation T_s is the sampling time employed in the DT conversion. By substituting equation (6.22) into equation (6.19), DT grid current model in the dq frame can be obtained:

:

$$\begin{bmatrix} i_{dg}(k+1) \\ i_{qg}(k+1) \end{bmatrix} = \Phi \begin{bmatrix} i_{dg}(k) \\ i_{qg}(k) \end{bmatrix} + \Gamma_i \begin{bmatrix} v_{di}(k) \\ v_{qi}(k) \end{bmatrix} + \Gamma_g \begin{bmatrix} v_{dg}(k) \\ v_{qg}(k) \end{bmatrix} \quad 6.23$$

The forward Euler approximation leads DT equivalent matrices in the below manner:

$$\Phi \approx [I + AT_s] \approx \begin{bmatrix} 1 - \frac{r_i T_s}{L_i} & \omega_g T_s \\ -\omega_g T_s & 1 - \frac{r_i T_s}{L_i} \end{bmatrix} \quad 6.24$$

$$\Gamma_i \approx B_i T_s \approx \begin{bmatrix} \frac{T_s}{L_i} & 0 \\ 0 & \frac{1}{T_s} \end{bmatrix}, \Gamma_g \approx B_g T_s \approx \begin{bmatrix} -\frac{T_s}{L_i} & 0 \\ 0 & -\frac{1}{T_s} \end{bmatrix}$$

6.3.6 Modelling Grid Active and Reactive Powers in the dq-Frame DT Model:

The grid active and reactive powers in DT can be computed relatively easily because the power terms in CT model are not having derivative terms. The future

behaviour of the grid power variables can be obtained by shifting the variables to its next sampling instant i.e. $(k + 1)$.

$$\begin{aligned} P_g(k+1) &= 1.5p \left[v_{dg}(k+1)i_{dg}(k+1) + v_{qg}(k+1)i_{qg}(k+1) \right] \\ Q_g(k+1) &= 1.5p \left[v_{qg}(k+1)i_{dg}(k+1) - v_{dg}(k+1)i_{qg}(k+1) \right] \end{aligned} \quad 6.25$$

Assuming that the grid voltages in the dq-frame, represented by $v_{dg}(k+1)$ and $v_{qg}(k+1)$, exhibit a DC nature in the SRF, we can simplify the analysis by considering that $v_{dg}(k+1)$ is approximately equal to $v_{dg}(k)$, and $v_{qg}(k+1)$ is approximately equal to $v_{qg}(k)$.

6.3.7 Modelling of VSI Output Voltages:

The grid active and reactive powers in DT models as explained in above equation related to the future values of grid currents: $i_{dg}(k+1)$ and $i_{qg}(k+1)$. These terms in DT models are depend on the VSI output voltages: $v_{dg}(k)$, and $v_{qg}(k)$ as seen in Equation (6.23). For the design of Predictive Power Control (PPC) and Predictive Current Control (PCC) schemes with 2L-VSI and NPC inverters it is essential to represent the output voltages of GSPEC in three frames for switching state computed. The output voltages of the 2L-VSI and NPC inverter must be measured in terms of DC-link voltage and the switching states in the three frames mentioned earlier.

6.3.8 Modeling of the Output Voltages of a 2L-VSI:

The GSPEC includes a 2L-VSI having insulated gate bipolar transistor (IGBT) switches. The power circuit has been clearly discussed in section 3.6.1, accompanied by a pictorial representation in Figure 3.11. Every phase leg is equipped with two active switches, and the switching signals for each phase will have a complementary pattern this can be specified as $S_{a2} = \overline{S_{a1}}$, $S_{b2} = \overline{S_{b1}}$, and $S_{c2} = \overline{S_{c1}}$. The three phase grid output terminals establish a connection to the positive or negative (P or N) of DC-bus owing to values of the switching signals. The voltage of DC-link capacitor is identical to the overall DC-bus voltage ($v_{c1} = V_{dc}$). The inverter out level has two switching states ('0' and '1') at the output side of each phase thus it can have total eight potential combinations for a

three-phase 2L-VSI as (2³). The terminal voltages of the VSI w.r.t the negative DC-bus “o” can be generated from the DC-link capacitor voltage and switching signals this relationship can be formulated as follows [203]:

$$\begin{bmatrix} v_{ao}(k) \\ v_{bo}(k) \\ v_{co}(k) \end{bmatrix} = V_{dc} \begin{bmatrix} S_{a1}(k) \\ S_{b1}(k) \\ S_{c1}(k) \end{bmatrix} \quad 6.26$$

For implementing the PCC and PPC schemes in the abc-frame, the inverter voltages are expressed terms of the grid neutral n, Therefore above expression can be modified as:

$$\begin{bmatrix} v_{an}(k) \\ v_{bn}(k) \\ v_{cn}(k) \end{bmatrix} = V_{dc} \underbrace{\begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ -\frac{1}{3} & \frac{2}{3} & -\frac{1}{3} \\ -\frac{1}{3} & -\frac{1}{3} & \frac{2}{3} \end{bmatrix}}_{T_{abc/abcn}} \begin{bmatrix} S_{a1}(k) \\ S_{b1}(k) \\ S_{c1}(k) \end{bmatrix} = V_{dc} \begin{bmatrix} S_{an1}(k) \\ S_{bn1}(k) \\ S_{cn1}(k) \end{bmatrix} \quad 6.27$$

For reducing the computational burden on digital controller the above computations are performed offline. The terminal voltages in stationary frame are derived from above expression as:

$$\begin{bmatrix} v_{\alpha}(k) \\ v_{\beta}(k) \end{bmatrix} = V_{dc} \underbrace{\frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}}_{T_{abc/\alpha\beta}} \begin{bmatrix} S_{a1}(k) \\ S_{b1}(k) \\ S_{c1}(k) \end{bmatrix} = V_{dc} \begin{bmatrix} S_{\alpha1}(k) \\ S_{\beta1}(k) \end{bmatrix} \quad 6.28$$

The terminal voltages in SRF are determined from Equation (6.26) in the subsequent manner:

$$\begin{aligned} \begin{bmatrix} v_d(k) \\ v_q(k) \end{bmatrix} &= V_{dc} \underbrace{\begin{bmatrix} \cos\theta_g(k) & \sin\theta_g(k) \\ -\sin\theta_g(k) & \cos\theta_g(k) \end{bmatrix}}_{T_{\alpha\beta/dq}} \begin{bmatrix} S_{a1}(k) \\ S_{b1}(k) \\ S_{c1}(k) \end{bmatrix} \\ &= V_{dc} \begin{bmatrix} S_{d1}(k) \\ v_{q1}(k) \end{bmatrix} \end{aligned} \quad 6.29$$

6.3.9 Modelling of the Output Voltages of an NPC Inverter:

The power circuit of a NPC inverter includes IGBT switches as depicted in Figure 6. 8. Each phase leg comprises of 4 active switches and 2 clamping diodes. The top switches of each phase operate in a complementary manner with bottom switches resulting following relationships $S_{a3} = \overline{S_{a1}}$, $S_{a4} = \overline{S_{a2}}$, $S_{b3} = \overline{S_{b1}}$, $S_{b4} = \overline{S_{b2}}$, $S_{c3} = \overline{S_{c1}}$ and $S_{c4} = \overline{S_{c2}}$.

The grid output terminals connected to the positive, mid, or negative (P, Z, or N) DC bus based on the switching signals. The DC-link comprises two identical capacitors, their midpoint (or neutral point) being tied to the midpoint of the clamping diodes of each phase. The cumulative DC-bus voltage is uniformly divided between the DC-link capacitors yielding $v_{C1} = v_{C2} = V_{dc}/2$. In NPC there are 3 switching states per phase, the total number of combinations for a three-phase NPC inverter finalised to 27.

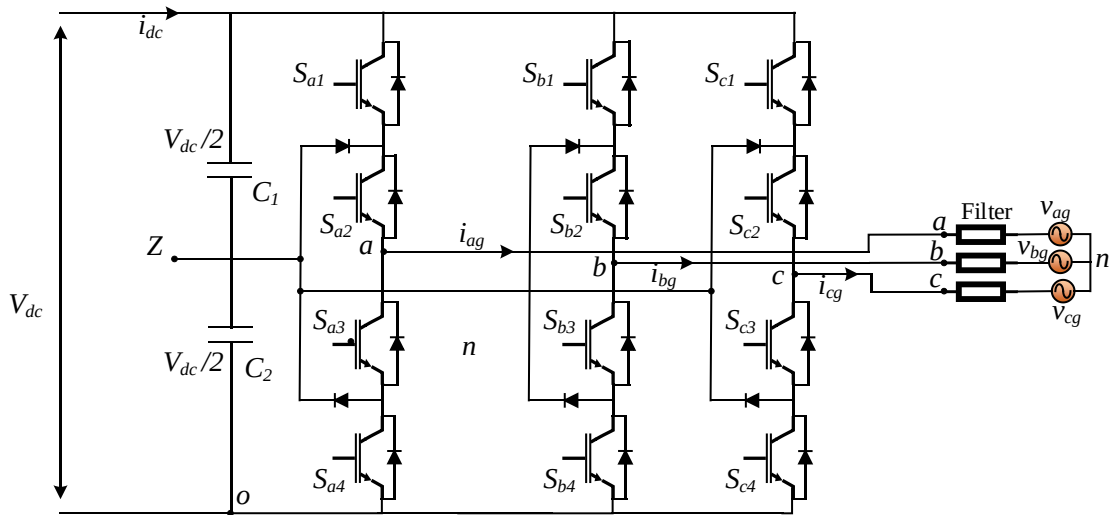


Figure 6. 8 Schematic of a Three-Phase Grid-Connected NPC Inverter Power Circuit

In an NPC inverter, the relation between output voltages and negative DC-link (o) needs knowledge of DC-link capacitor voltage and the switching signals, this can be formulated as below [204]:

$$\begin{bmatrix} v_{ao}(k) \\ v_{bo}(k) \\ v_{co}(k) \end{bmatrix} = \frac{V_{dc}}{2} \begin{bmatrix} S_{a1}(k) \\ S_{b1}(k) \\ S_{c1}(k) \end{bmatrix} + \frac{V_{dc}}{2} \begin{bmatrix} S_{a2}(k) \\ S_{b2}(k) \\ S_{c2}(k) \end{bmatrix} \quad 6.30$$

The inverter output voltages w.r.t grid neutral (n) can be computed as:

$$\begin{aligned}
\begin{bmatrix} v_{an}(k) \\ v_{bn}(k) \\ v_{cn}(k) \end{bmatrix} &= \frac{V_{dc}}{2} \underbrace{\begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ -\frac{1}{3} & \frac{2}{3} & -\frac{1}{3} \\ -\frac{1}{3} & -\frac{1}{3} & \frac{2}{3} \end{bmatrix}}_{T_{abc/abcn}} \begin{bmatrix} S_{a1}(k) \\ S_{b1}(k) \\ S_{c1}(k) \end{bmatrix} + \frac{V_{dc}}{2} \underbrace{\begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ -\frac{1}{3} & \frac{2}{3} & -\frac{1}{3} \\ -\frac{1}{3} & -\frac{1}{3} & \frac{2}{3} \end{bmatrix}}_{T_{abc/abcn}} \begin{bmatrix} S_{a2}(k) \\ S_{b2}(k) \\ S_{c2}(k) \end{bmatrix} \\
&= \frac{V_{dc}}{2} \begin{bmatrix} S_{an1}(k) \\ S_{bn1}(k) \\ S_{cn1}(k) \end{bmatrix} + \frac{V_{dc}}{2} \begin{bmatrix} S_{an2}(k) \\ S_{bn2}(k) \\ S_{cn2}(k) \end{bmatrix}
\end{aligned} \tag{6.31}$$

The NPC voltages in the stationary frame can be computed from:

$$\begin{aligned}
\begin{bmatrix} v_{\alpha}(k) \\ v_{\beta}(k) \end{bmatrix} &= \frac{V_{dc}}{2} \begin{bmatrix} T_{abc/\alpha\beta} \end{bmatrix} \begin{bmatrix} S_{a1}(k) \\ S_{b1}(k) \\ S_{c1}(k) \end{bmatrix} + \frac{V_{dc}}{2} \begin{bmatrix} T_{abc/\alpha\beta} \end{bmatrix} \begin{bmatrix} S_{a2}(k) \\ S_{b2}(k) \\ S_{c2}(k) \end{bmatrix} \\
&= \frac{V_{dc}}{2} \begin{bmatrix} S_{\alpha1}(k) \\ S_{\beta1}(k) \end{bmatrix} + \frac{V_{dc}}{2} \begin{bmatrix} S_{\alpha2}(k) \\ S_{\beta2}(k) \end{bmatrix}
\end{aligned} \tag{6.32}$$

Similarly, inverter terminal voltages in SRF can be acquired as:

$$\begin{aligned}
\begin{bmatrix} v_d(k) \\ v_q(k) \end{bmatrix} &= \frac{V_{dc}}{2} \begin{bmatrix} T_{\alpha\beta/dq} \end{bmatrix} \begin{bmatrix} T_{abc/\alpha\beta} \end{bmatrix} \begin{bmatrix} S_{a1}(k) \\ S_{b1}(k) \\ S_{c1}(k) \end{bmatrix} + \frac{V_{dc}}{2} \begin{bmatrix} T_{\alpha\beta/dq} \end{bmatrix} \begin{bmatrix} T_{abc/\alpha\beta} \end{bmatrix} \begin{bmatrix} S_{a2}(k) \\ S_{b2}(k) \\ S_{c2}(k) \end{bmatrix} \\
&= \frac{V_{dc}}{2} \begin{bmatrix} S_{d1}(k) \\ S_{q1}(k) \end{bmatrix} + \frac{V_{dc}}{2} \begin{bmatrix} S_{d2}(k) \\ S_{q2}(k) \end{bmatrix}
\end{aligned} \tag{6.33}$$

6.4 Calculation of Reference Grid-Side Variables

Operating WECSs at an optimal performance level mandates meticulous control of variables, such as MPPT control, (2) net DC-bus voltage control, and (3) grid reactive power control. Figure 6.9 illustrates the exchange of these control variables between the RSPEC and GSPEC.

Initially MPPT control is achieved by the RSPEC, whereas the GSPEC regulates DC voltage and grid reactive power. The wind generator combining with rectifier acts as a variable DC current source which is proportional to the active power extracted from the wind. For effective control of WECS, the GSPEC plays critical role to control

current/power. The traditional VOC deploys i_{dg} and i_{qg} as reference control variables for the GSPEC, while the V-DPC relies on P_g and Q_g . In the PPC scheme, P_g and Q_g^* functions are used as the reference control variables, which results to the calculation of reference control variables similar to classical control methods. This sketches an overview of the calculation procedure for reference currents, reference active and reactive powers in three frames [205].

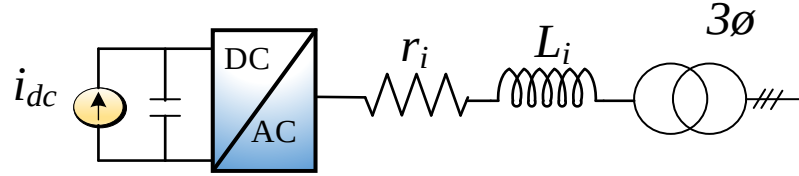


Figure 6. 9 Simplified representation of GSPEC with Generator-side MPPT control

GSPEC control is used for regulating the V_{dc} at its reference value V_{dc}^* and Q_g based on the grid reference power (Q_g^*). The below block diagram shown in Figure 6. 10 illustrate the computational procedure for obtaining the reference grid currents, the reference grid active and reactive power w.r.t generator-side MPPT control.

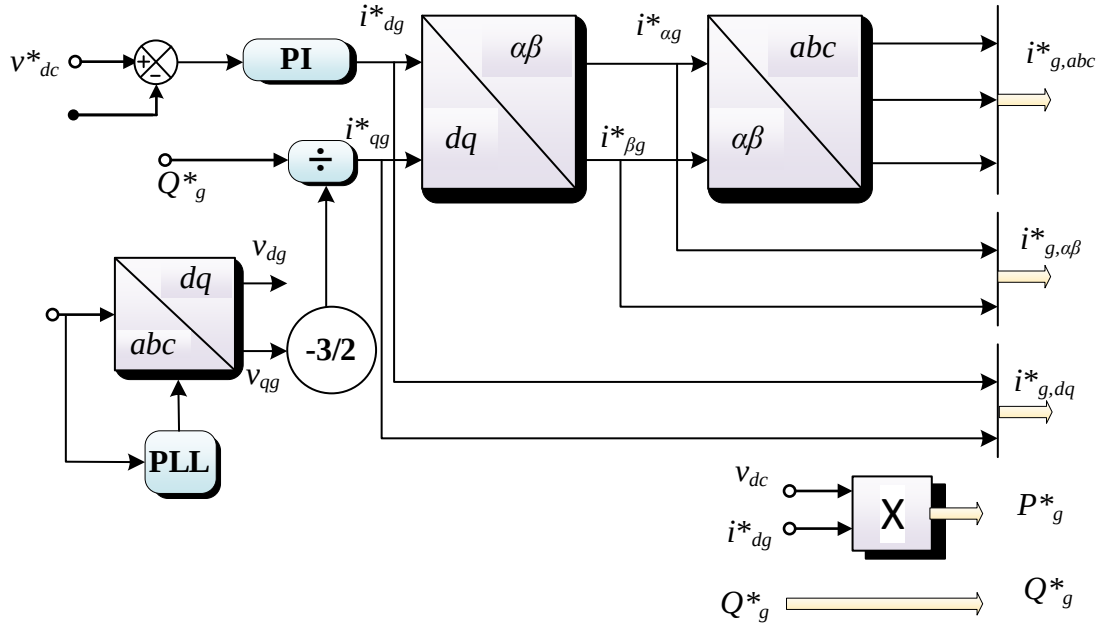


Figure 6. 10 Calculation of reference grid-side control variables with generator-side MPPT control.

To maintain the measured V_{dc} at its reference value V_{dc}^* , a PI controller is utilized. The PI controller generates the reference d-axis grid current, i_{dg} , where the controller

gains, k_p and k_i , are proportional and integral gains, respectively. The PI controller operation is governed by the Laplace operator, 's'.

$$i_{dg}^* = (K_p + \frac{K_i}{s})(V_{dc}^* - V_{dc}) \quad 6.34$$

Omitting the losses in the GSPEC, P_g on the AC is equal to the DC, mathematically; this relationship can be expressed as:

$$P_g = \frac{3}{2}(v_{dg}i_{dg}) = V_{dc}i_{dc} \quad 6.35$$

The reference d-axis grid current, $i_{dg}^*(k)$, generated by the PI controller, varies based on the operating conditions. For a WES, the RSPEC injects current, i_{dc} , depending on the maximum energy extracted from the wind. When the wind speed is below the cut-in speed, i_{dc} supplied by the RSPEC is zero. Similarly, when it is rated value i_{dc} is rated. To simulate variable-speed WECSs, a variable DC current source is considered, as shown in Figure 6.9. The reference Q_g^* is taken as reference value provided by the grid operator set as zero for unity power factor (PF), -ve for leading PF, and +ve for lagging PF. From Equation (6.6) the, i_{qg} , is calculated based on Q_g^* and, the reference P_g is obtained by multiplying i_{dg} with V_{dc} .

$$i_{qg}^* = \frac{2Q_g^*}{-3v_{dg}} \quad 6.36$$

6.5 Predictive Power Control of 2L-VSI in dq-Frame

Figure 6.11 presents the implementation of a PPC scheme for a grid-connected 2L-VSI. The main motive of PPC is to accomplish decoupled control of the active and reactive powers flowing into the grid by efficiently controlling the grid currents on the dq-axis. The power flow is primarily from the GSPEC to the grid.

The GSPEC governs the net DC-bus voltage and grid reactive power by generating suitable gating signals for the 2L-VSI. Decoupled control over both the grid's active power (P_g) and reactive power (Q_g) is achieved through precise control over the dq-axis grid currents. This enables the independent control facilitating efficient and effective operation of the grid-connected inverter system.

6.5.1 Procedure for Designing PPC Scheme:

The PPC scheme depicted in Figure 6.11 offers a straightforward and intuitive design approach. It involves the following five steps:

6.5.1.1 Measurement and Synthesis of Feedback Signals:

The v_g , i_g , and V_{dc} are measured from Hall Effect sensors; θ_g is obtained using the SRF-PLL technique using the sensed grid voltages and utilised for coordinate transformation. Aligning v_{dg} with the grid voltage vector, v_{qg} is set to zero.

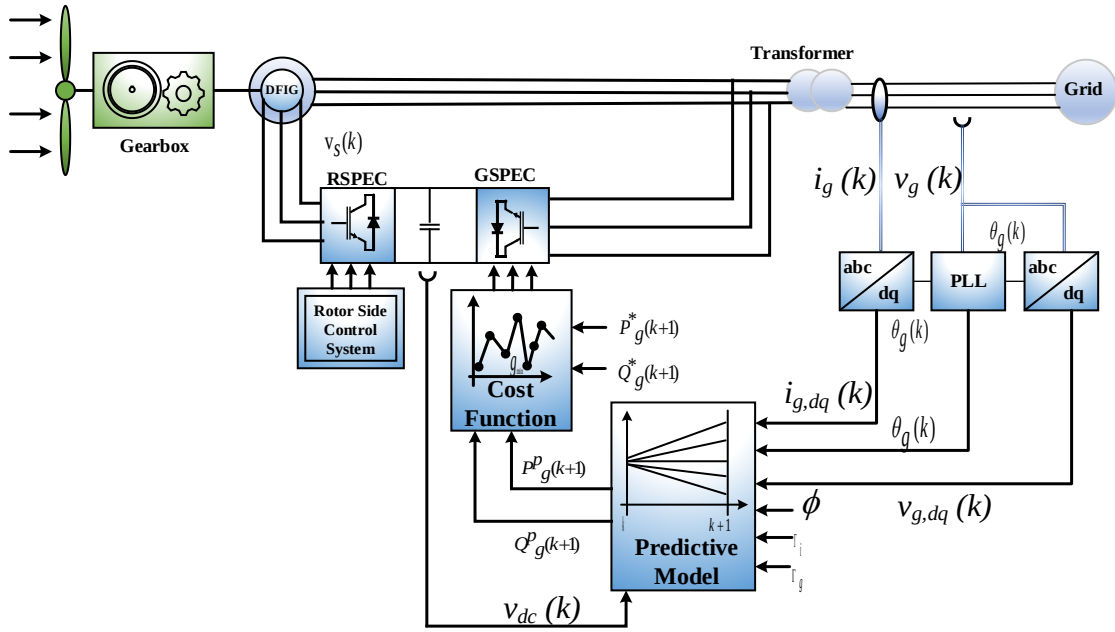


Figure 6.11 Block diagram of the PTC scheme for 2L-VSC-based DFIG

6.5.1.2 Calculation of Reference Powers:

For implementing PPC on generator-side MPPT, the reference currents are determined based on the V_{dc} and Q_g loops. The reference d-axis grid current is generated by the PI controller in the DC-link, maintaining the active power extracted from the wind and ensuring V_{dc} remains at its desired reference value (V_{dc}^*). This design is pertinent to both classical and predictive control strategies and can be employed for both VSI and NPC inverters. The Q_g^* is supplied by the grid operator. It can be fine-tuned to ensure a unity, leading, or lagging power factor, as per the requirements. The P_g^* is derived from MPPT algorithm. From GSPEC point the algorithm uses a conventional approach of WT power curve. These design steps yield the process of PPC scheme, giving effective control and coordination of power in different control schemes and inverter configurations.

6.5.1.3 Extrapolation of Reference Powers:

During steady-state operation, as the reference powers in WECS are DC quantities extrapolation is not needed. However, in practical WECSs, the wind speed and active power reference exhibit dynamic changes therefore extrapolation method is required.

6.5.1.4 Predicting the Future Behavior of Grid Powers:

The DT model for grid active and reactive powers is derived from Equation (6.37) as:

$$\begin{aligned} P_g(k+1) &= 1.5p \left[v_{dg}(k+1)i_{dg}(k+1) + v_{qg}(k+1)i_{qg}(k+1) \right] \\ Q_g(k+1) &= 1.5p \left[v_{qg}(k+1)i_{dg}(k+1) - v_{dg}(k+1)i_{qg}(k+1) \right] \end{aligned} \quad 6.37$$

The future grid voltages in the dq-frame, represented by $v_{dg}(k+1)$ and $v_{qg}(k+1)$, exhibit a DC nature in the synchronous reference frame (SRF), thus can simplify the analysis by considering that $v_{dg}(k+1)$ is approximately equal to $v_{dg}(k)$, and $v_{qg}(k+1)$ is approximately equal to $v_{qg}(k)$. hence, no extrapolation is needed.

6.5.1.5 Minimizing the Cost Function:

To achieve control objectives, involving the regulation of grid active and reactive power, the objectives are incorporated into a cost function in the following manner:

$$g_r(k) = \lambda_1 \left[P_g^*(k+1) - P_g^p(k+1) \right] + \lambda_2 \left[Q_g^*(k+1) - Q_g^p(k+1) \right] \quad 6.38$$

The weighting factors λ_1 and λ_2 are assigned to control the active and reactive power respectively. As both active and reactive power control are considered primary objectives, these weighting factors are typically set to 1.

6.5.2 Control Algorithm for 2L-VSI

Figure 6.12 illustrates the progression diagram of the Predictive Power Control (PPC) algorithm used for a 2L inverter. Dimensions for measuring DC-link capacitors voltage, grid voltages, and currents are performed using the initial block. The $(k+1)$ state reference for active and reactive power, as well as the weighting factor $\lambda_{dc,i}$, are calculated in block 2. An iterative cycle runs between these blocks. From the third to the ninth block, the predicted values of the output voltages $v_g^p(k)$ from the 2L Voltage Source Converter

(VSC), dq-axes grid currents $i_g^p(k+1)$, active power $P_g^p(k+1)$, and reactive power $Q_g^p(k+1)$ are computed. The cost function minimization $g_i(k)$ is undertaken for each of the 8 potential switching states. The optimal vector j_{op} , along with its associated switching signals, is selected and immediately applied to the 2L VSC inverter within the eighth to tenth blocks. The PPC algorithm enables the concurrent control of grid active and reactive power.

6.6 Predictive Power Control of NPC based GSPEC Inverter

The principal aim of the PPC approach is to secure decoupled control of grid active and reactive powers via the managing dq-axis grid currents. Similarly, the decoupled control of active power P_g and reactive power Q_g can be accomplished through the control of $\alpha\beta$ -axes grid currents, according to reference [206].

6.6.1 Procedure for Designing PPC Scheme

The construction of the Predictive Power Control (PPC) scheme for the Neutral Point Clamped (NPC) inverter parallels the PPC design for 2L VSI demonstrated in previous Figures 6.11. The crucial design steps are elaborated upon below.

6.6.1.1 Measuring and Compiling Feedback Signals:

The three phase grid voltages and currents (v_g and i_g) are measured and then converted into $v_{g,dq}$ and $i_{g,dq}$ with the help of θ_g and predictive model block employs the measured DC-link capacitors voltage. For the successful implementation of the MPPT wind speed v_w , is also required.

6.6.1.2 Computation of Reference Powers:

The grid operator supplies the reference reactive power command ($Q_g^*(k)$), which can be set to zero for unity power factor, negative for leading power factor, and positive for the lagging power factor. The MPPT algorithm provides the active power reference, $P_g^*(k)$ as previously mentioned, the WT power curves-based MPPT algorithm can be deployed.

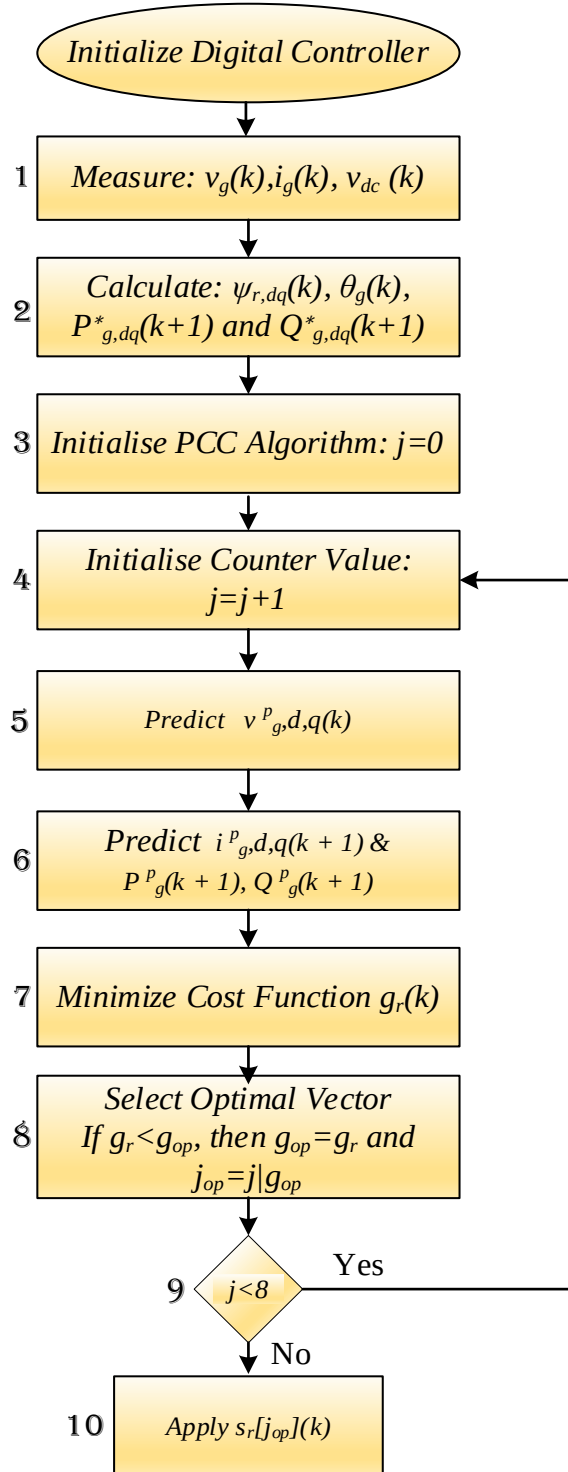


Figure 6. 11 Flowchart of the PPC algorithm for grid-connected 2L inverter

6.6.1.3 Predicting the Future Behavior of Grid Powers:

The DT model for grid active and reactive powers is derived from Equation (6.37) in the following manner:

$$\begin{aligned}
P_g(k+1) &= 1.5p \left[v_{dg}(k+1)i_{dg}(k+1) + v_{qg}(k+1)i_{qg}(k+1) \right] \\
Q_g(k+1) &= 1.5p \left[v_{qg}(k+1)i_{dg}(k+1) - v_{dg}(k+1)i_{qg}(k+1) \right]
\end{aligned} \tag{6.39}$$

The grid voltages in the dq-frame, represented by $v_{dg}(k+1)$ and $v_{qg}(k+1)$, exhibit a DC nature in the synchronous reference frame (SRF), we can simplify the analysis by considering that $v_{dg}(k+1)$ is approximately equal to $v_{dg}(k)$, and $v_{qg}(k+1)$ is approximately equal to $v_{qg}(k)$. hence, no extrapolation is needed.

For a NPC inverter, the future dq-axes grid currents are acquired by amalgamating the Equation (6.34) following formula.

$$\begin{bmatrix} i_{dg}(k+1) \\ i_{qg}(k+1) \end{bmatrix} = \Phi \begin{bmatrix} i_{dg}(k) \\ i_{qg}(k) \end{bmatrix} + \Gamma_g \begin{bmatrix} v_{dg}(k) \\ v_{qg}(k) \end{bmatrix} + \Gamma_i \left\{ \frac{V_{dc}}{2} \begin{bmatrix} S^p_{d1}(k) \\ S^p_{q1}(k) \end{bmatrix} + \frac{V_{dc}}{2} \begin{bmatrix} S^p_{d2}(k) \\ S^p_{q2}(k) \end{bmatrix} \right\} \tag{6.40}$$

6.6.1.4 Minimizing the Cost Function:

To achieve control objectives, which involve the regulation of grid active and reactive power, these objectives are incorporated into a cost function in the following manner:

$$g_r(k) = \lambda_1 \left[P_g^*(k+1) - P_g^p(k+1) \right] + \lambda_2 \left[Q_g^*(k+1) - Q_g^p(k+1) \right] \tag{6.41}$$

The weighting factors λ_1 and λ_2 are assigned to control the active and reactive power respectively. As both active and reactive power control are considered primary objectives, these weighting factors are typically set to 1.

6.6.1.5 Control Algorithm for 3L-NPC-VSI

Figure 6.13 illustrates the progression diagram of the Predictive Power Control (PPC) algorithm used for a NPC inverter. Measurements of DC-link capacitors voltage, grid voltages, and currents are performed within the initial block. The $(k+1)$ -state reference for active and reactive power, as well as the weighting factor $\lambda_{dc,i}$, are computed within the subsequent block 2. An iterative cycle occurs between these blocks. From the third block to the ninth block, the predicted values of the output voltages $v_g^p(k)$ from the NPC, dq-axes grid currents $i_g^p(k+1)$, active power $P_g^p(k+1)$, and reactive power $Q_g^p(k+1)$

are computed. The cost function minimization $g_i(k)$ is undertaken for each of the 27 potential switching states. The optimal vector j_{op} , along with its associated switching signals, is selected and immediately applied to the NPC inverter within the eighth to tenth blocks. The PPC algorithm enables the concurrent control of grid active and reactive power.

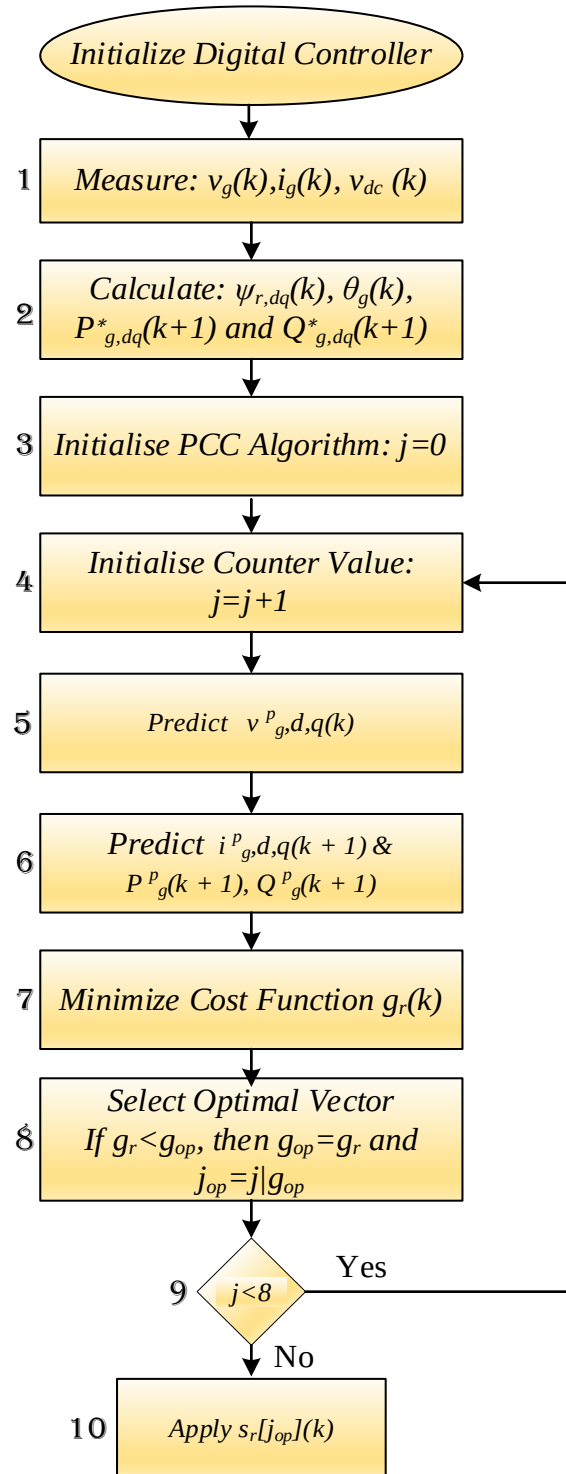


Figure 6.12 Flowchart of the PPC algorithm for grid-connected 3L NPC

6.7 Simulation Results

In the context of WECS, a crucial component is a 1.5 MW wind turbine connected to a power source. This turbine incorporates a DFIG consisting of a WRIG coupled with an AC/DC/AC IGBT-based PWM converter. The unique feature of DFIG technology is its ability to optimize energy extraction from low wind speeds by precisely adjusting the turbine speed. This feature also reduces mechanical stress during sudden wind gusts.

This section primarily focuses on the control mechanisms of GSPEC for the DFIG, suggesting the use of the FCS-MPDPC technique. This technique provides direct, decoupled control of active and reactive power, offering numerous advantages as discussed earlier.

To validate our hypothesis and establish a performance benchmark for FCS-MPDPC, we developed a comprehensive simulation model using MATLAB, as shown in Figure 6.14. The model encompasses various components, including a DFIG connected to the grid, a wind turbine model, PLL, a converter system control block (RSPEC and GSPEC), filter circuits, and signal display scopes.

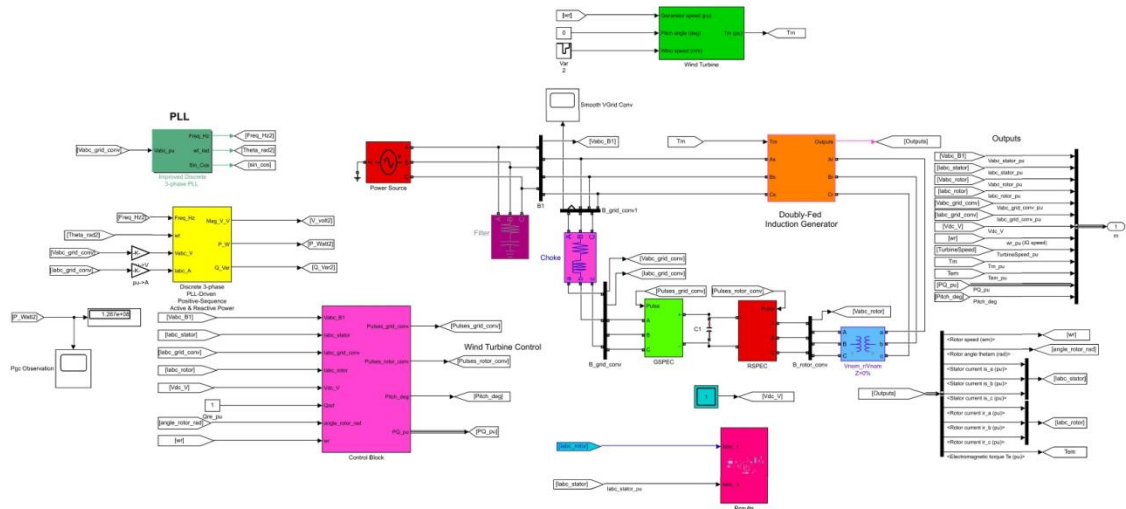


Figure 6. 13 MATLAB Simulink model of DFIG based WECS

Analysis primarily focuses on comparing the DPC performance with FCS-MPDPC using both 2-level and 3-level NPC techniques. By varying the input mechanical torque values aims to evaluate how each technique tracks the reference torque. Particularly attention to transient overshoot, undershoot, ripple factor, and settling time. This comprehensive comparison aims to gain a deeper understanding of the advantages offered by the FCS-MPDPC approach. By evaluating its performance in relation to

established techniques such as Conventional DPC can determine its potential for enhancement. Analyze the DC Link voltage ripple, grid-side converter current (power flow), and overshoot and settling time of various power components such as stator active and reactive power and grid active and reactive power.

The comparative study of the DC Link voltage provides an instructive view of the responses offered by DPC, FCS-MPDPC with a 2-L VSC and FCS-MPDPC with a 3-L NPC-MLI. These comparisons are drawn in the context of increasing wind speed, with input torque variations observed at $t=3$ seconds and $t=6$ seconds (as shown in Figure 6. 14), and changes in reactive power reference marked at $t=9$ seconds as shown in Figure 6. 15.

Under such dynamic conditions, the DC Link voltage encounters a series of fluctuations and spikes, influenced by the alterations in input torque and reactive power as shown in Figure 6. 16. An analysis of these voltage deviations under different control techniques brings to light discernible differences.

The DPC exhibits substantial oscillations and overshoot in the DC Link voltage, signifying the relative instability of this technique in handling rapid changes in operating conditions. A marked improvement is seen with the FCS-MPDPC employing a 2L VSC, with a noticeable reduction in the overshoot, indicating an enhanced capability to contain voltage fluctuations. The FCS-MPDPC with a 3L-NPC MLI presents the most stable performance among the three techniques. It demonstrates the smallest overshoot and the most robust response to alterations in input torque and reactive power. After the change in reactive power reference, an increase in DC Link voltage fluctuation is evident in the DPC technique. Meanwhile, the voltage under both FCS-MPDPC techniques remains stable, underscoring their superior control performance. In summary, the 3L-NPC MLI coupled with the FCS-MPDPC technique offers superior DC Link voltage regulation in the face of varying input torque and reactive power, thereby enhancing the operational stability of the overall system.

An analysis of the grid-side converter current reveals notable distinctions between the traditional DPC, MPDPC with a 2L inverter, and MPDPC with a 3L-NPC MLI. A closer inspection of the transient inrush at the commencement phase indicates a pronounced transient in the DPC case as shown in Figure 6. 17, which diminishes considerably in the case of the MPDPC with a 2-level converter shown in Figure 6. 18.

The transient response is most refined with MPDPC using a 3L-NPC MLI shown in Figure 6. 19.

The grid-side converter current undergoes a marked change when a step input torque variation is introduced at $t=3$ seconds. In the case of subsynchronous operation, this alteration induces a high degree of harmonics and distortion in the grid-side current. The zoomed waveform section for DPC vividly delineates the high harmonic distortion inherent in conventional DPC operation illustrated in Figure 6. 17 .

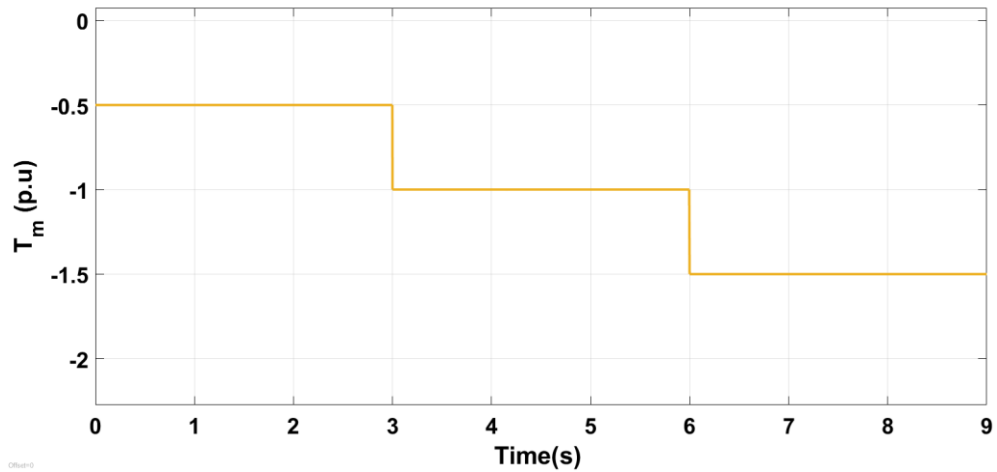


Figure 6. 14 An input Mechanical Torque

Implementing Finite Control Set Model Predictive Direct Power Control (FCS-MPDPC) with a 2L converter demonstrates an impressive reduction in the starting transient as well as a diminished harmonic distortion at regular time intervals and during step changes. This outcome, visually captured in the zoomed waveform, underscores the robustness and superior performance of the FCS-MPDPC technique in comparison to the conventional DPC.

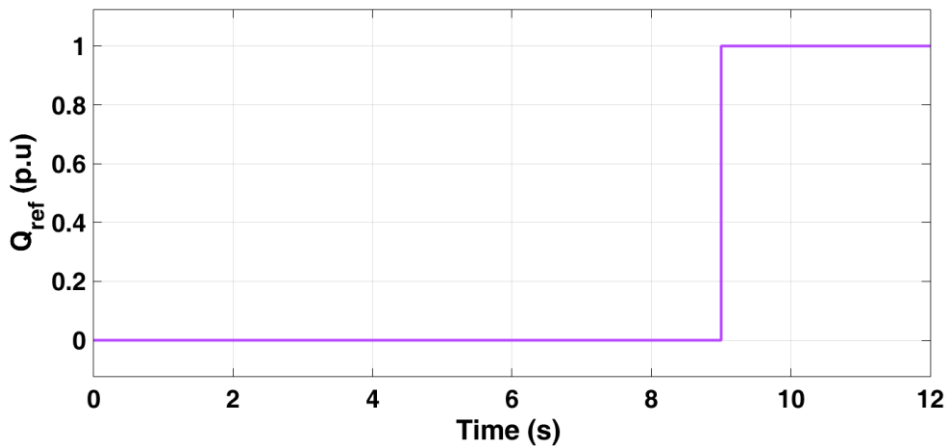


Figure 6. 15 Reactive power Reference

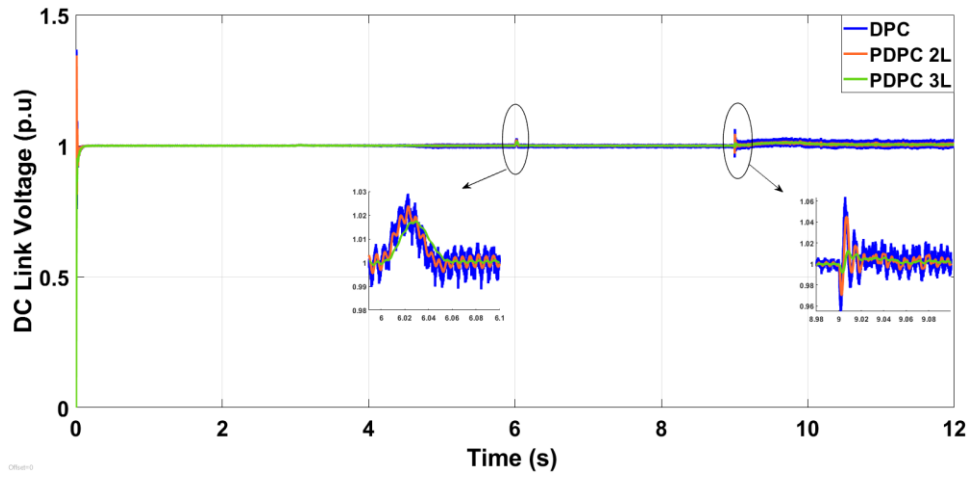


Figure 6. 16 DC Link Voltage Waveform

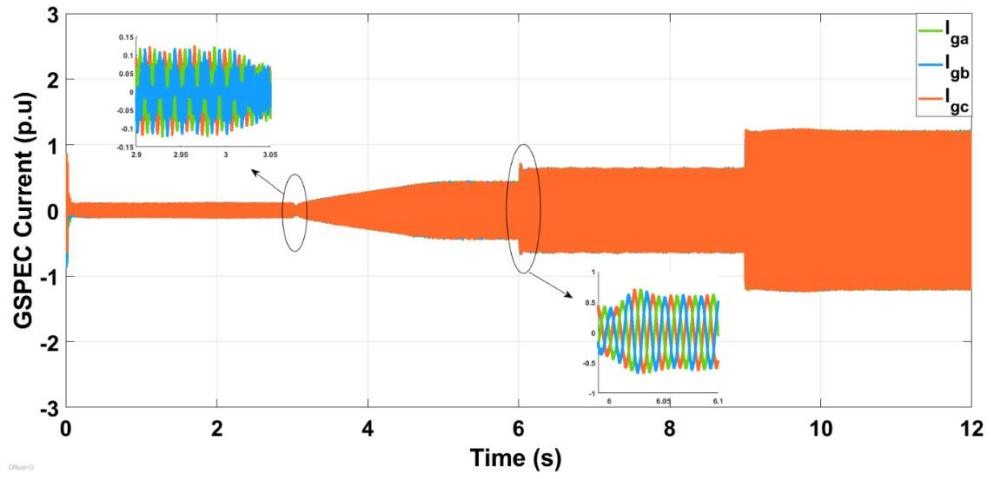


Figure 6. 17 GSPEC Current for DPC Technique

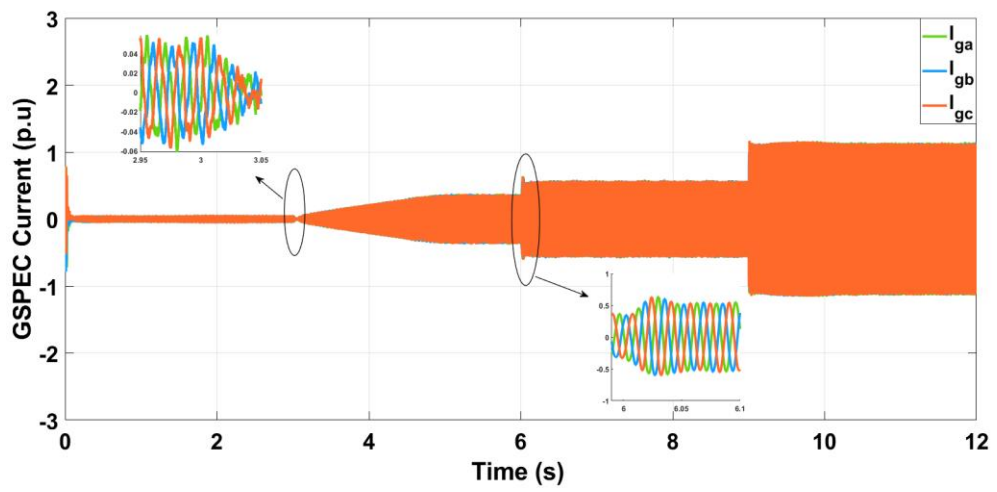


Figure 6. 18 GSPEC Current for MP-DPC Technique with 2L VSC

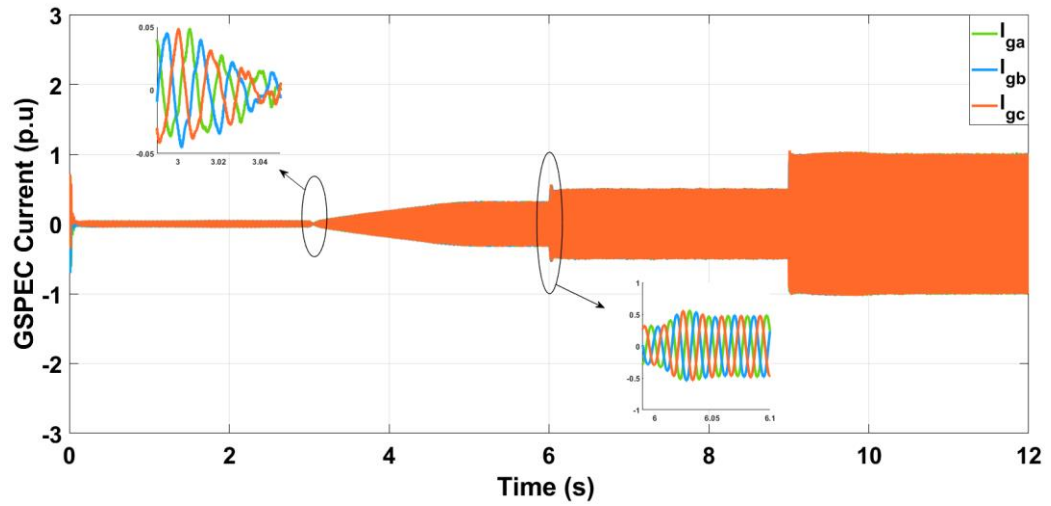


Figure 6. 19 GSPEC Current for MP-DPC Technique with 3L VSC MLI

When replaced the 2L-VSC with a 3L-NPC MLI, the waveform quality (Figure 6. 19) shows significant improvement over both the conventional DPC and FCS-MPDPC with 2L-VSC. The current waveform appears markedly smoother, further mitigating distortion and harmonics. Examining the THD of these waveforms lends quantitative credence to these observations. THD of the 3L-NPC MLI is shown in Figure 6.22 when fed to a DFIG with the FCS-MPDPC technique shown in

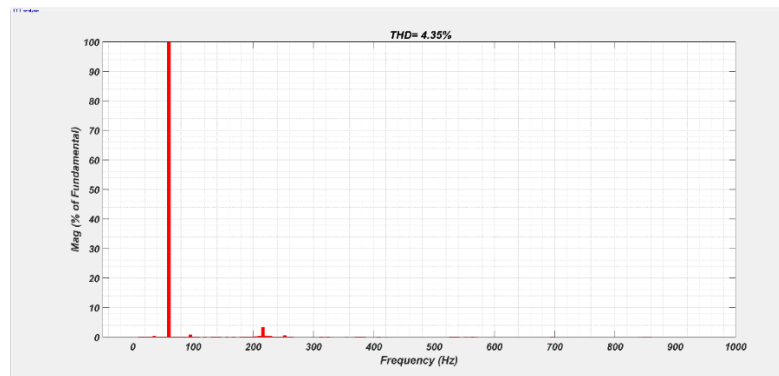
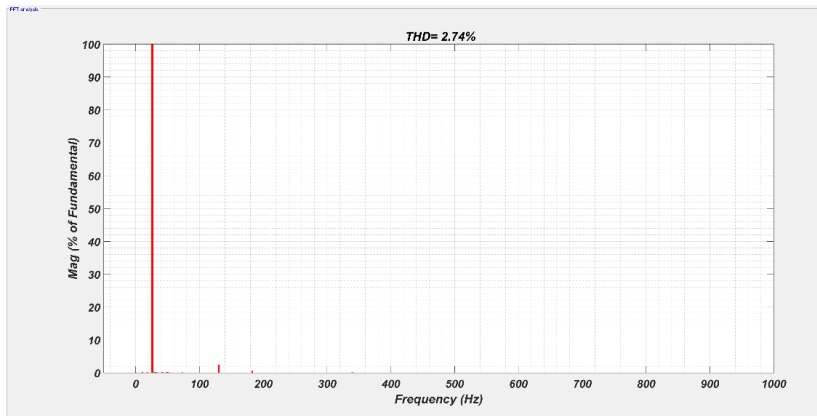


Figure 6. 22,

Figure 6. 21, is notably lower compared to the other two approaches. The conventional DPC, in contrast, presents the highest THD among all as shown in

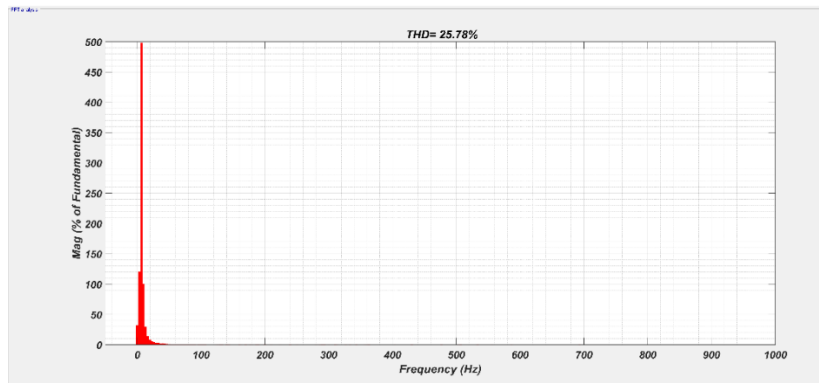


Figure 6. 20.

In summary, the use of FCS-MPDPC with a 3-level NPC MLI offers a considerable improvement in grid-side converter current quality, resulting in reduced harmonics and distortion. This illustrates the efficacy of advanced control techniques and higher order converters in enhancing the overall performance of a DFIG-based WECS.

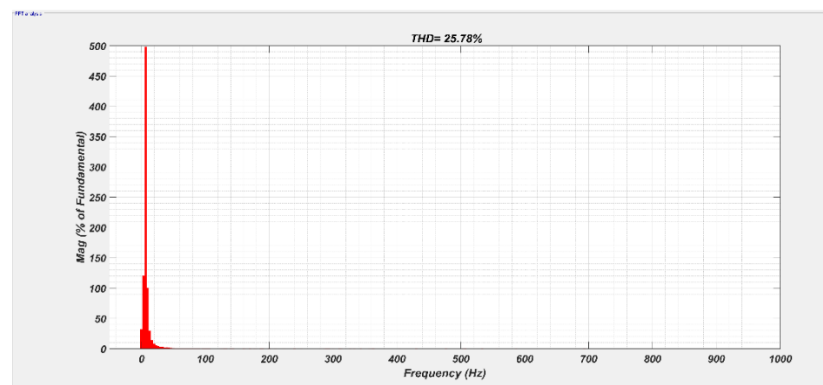


Figure 6. 20 DPC THD

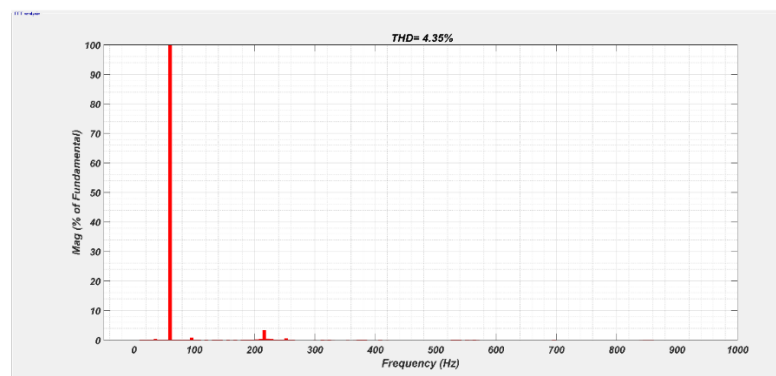


Figure 6. 21 PDPC THD

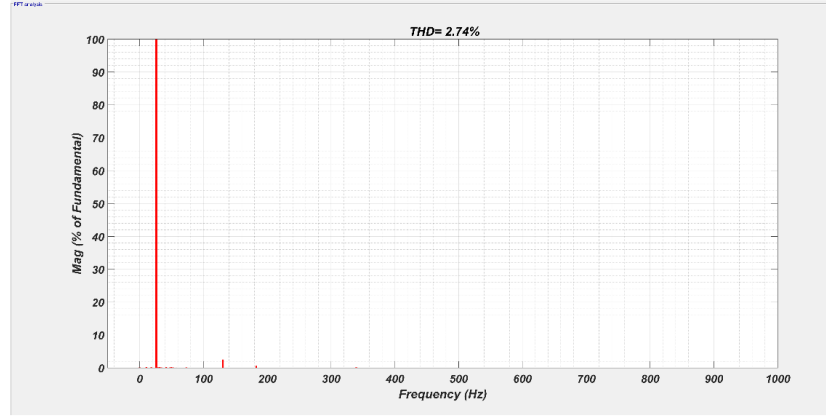


Figure 6. 22 PDPC 3L THD

The power generated by the GSPEC can be deeply explored through the prism of various configurations and control techniques. This exploration provides valuable insights into the efficiency and adaptability of these systems in handling energy conversion tasks. Focus is to compare the power generated when a 2L-VSC coupled with a FCS-MPC-DPC technique is utilized and 3L-NPC MLI.

Utilizing the FCS-MP-DPC technique with a 2L-VSC marks a substantial improvement in the power output of the GSPEC compared to conventional control methods. The FCS-MP-DPC strategy ensures superior power flow control, which enhances the system's adaptability to abrupt shifts in operational conditions, such as variations in wind speed or load demand. The power produced under these scenarios tends to be stable, with minimal transient effects, which underscores the robustness of this control methodology.

Now, delving into the simulation, the input torque of the machine altered at $t=3$ sec and then again at $t=6$ sec. As a result, changes can be observed primarily in the active power of the grid, as depicted in the associated figure shown in Figure 6. 23 , while the grid's reactive power remains relatively unaffected shown in Figure 6. 24 . This simulation indicates minimal power fluctuation or ripple effect. The overshoot in 3-level NPC is minimal compared to the 2-level VSC, demonstrating the former's better performance. The undershoot is also reduced in the case of 3L VSC, as depicted in the zoomed segment of the P_g figure.

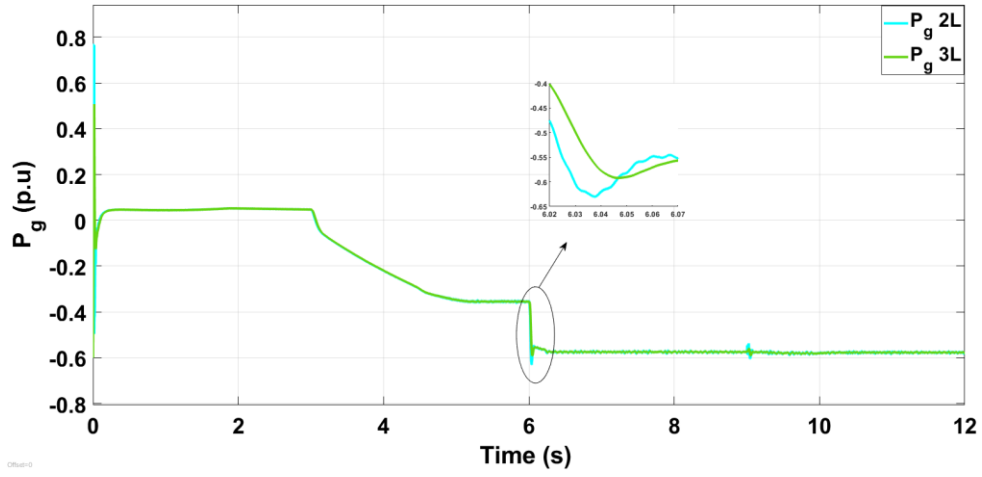


Figure 6. 23 Grid Active power for the 2L-VSC and 3L-MLI fed DFIG WECS

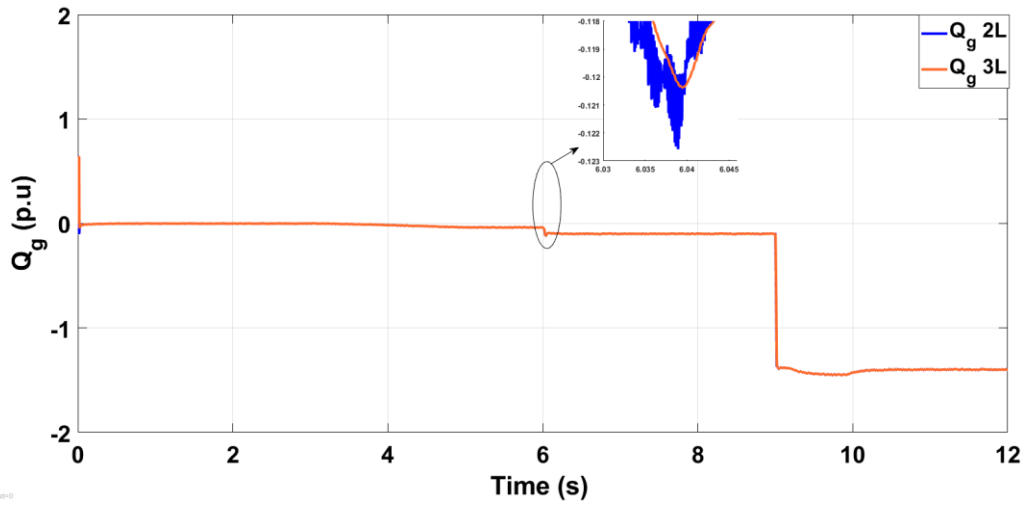


Figure 6. 24 Grid Reactive power for the 2L-VSC and 3L NPV-MLI fed DFIG WECS

At $t=9$ sec, introduced a step change in the Q_{ref} , previously set at zero value, and observed the effect primarily on Q_g and not on P_g , reinforcing the decoupling nature of both powers. Upon examining the Active power generated by the GSPEC, a slight spike is noted at the time of Q_{ref} change in the 2L VSC case. This spike is significantly smaller in the case of the 3L NPC MLI, indicating its superior robustness and stability.

However, the 2L-VSC, while improving overall performance, still encounters challenges related to power quality due to harmonic distortion. Despite the excellent control offered by FCS MP DPC, the harmonic profile tied with the 2L-VSC can be mitigated only to a degree, potentially limiting the overall power transfer efficiency. Switching to a 3L NPC MLI observed a significant improvement in power quality. The multilevel structure of the 3L-NPC MLI enables a more sinusoidal voltage waveform,

effectively reducing harmonic distortions and thereby improving power quality. This enhanced power quality ensures a cleaner, more reliable power transfer into the grid.

Additionally, when the 3L NPC MLI is paired with the FCS-MP DPC technique, it exhibits superior dynamic performance under varied operating conditions. The amalgamation of the control technique's inherent responsiveness and the improved voltage profile offered by the 3L-NPC MLI assures that the power produced by the GSPEC remains consistent and stable, even during rapid changes in wind speed or load demand.

Now the effect on stator active and reactive power due to using different configurations and control techniques in a DFIG can be analyzed by observing changes under two conditions as discussed earlier. Now considering the same, First one is one when increasing input torque that represent real-world conditions under which a wind turbine often operates. The active power generated by the DFIG is directly proportional to the torque. Thus, an increase in input torque (or wind speed) which is done at $t=3$ sec and $t=6$ sec which will lead to an increase in stator active power as can be seen in FIG. However, this might cause voltage fluctuations in a traditional control scheme, but with the FCS MPC DPC technique, the DFIG can better manage these changes but if we used 2L VSC then as compared to 3L NPC MLI then its peak overshoot is more as can be seen in the zoom part of the P_s waveform shown in Figure 6. 25. Now at $t=9$ sec a step change is given in the reactive power reference which does not affect the Stator Active power only a very small change is noticed this shows the decoupled nature of both the powers now if we see that a step change in Q_{ref} , on the other hand, can cause the reactive power to fluctuate as can be seen in Figure 6. 26 if we see the comparison in betwnn 2VSC and 3L NPC MLI the overshoot and settling time of reactive stator power is more which is also shown in the Figure 6. 26 especially in the zoom part of this whereas it is less in the case of 3L MLI. Once again, the FCS MP DPC technique, especially when paired with a 3L NPC MLI, proves to be more efficient in handling this abrupt change, maintaining a stable grid voltage by controlling the reactive power more accurately

In conclusion, a 3L-NPC MLI paired with the FCS MP DPC control technique offers considerable advantages over a 2L-VSC in terms of stator active and reactive power grid active and reactive power generation in a DFIG. This configuration provides better power quality, less harmonic distortion, and superior adaptability to changing operational conditions, including variations in input torque and Q_{ref} .

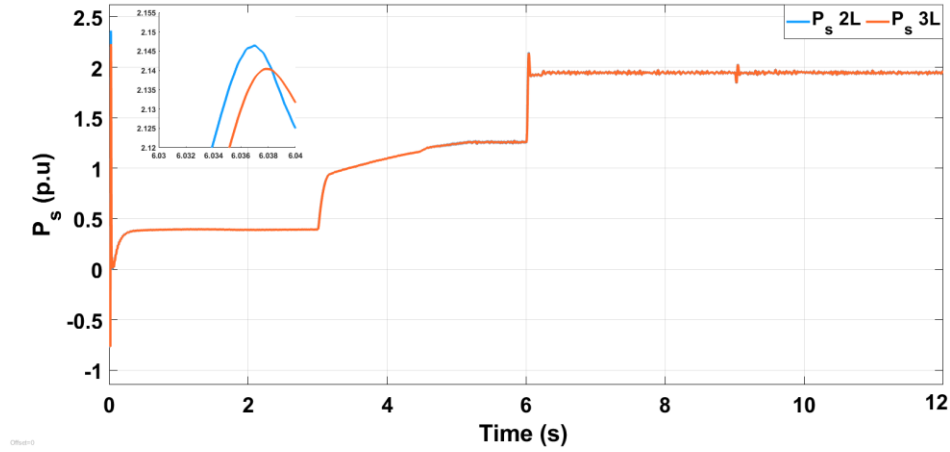


Figure 6. 25 Stator Active power for the 2L-VSC and 3L NPC-MLI fed DFIG WECS

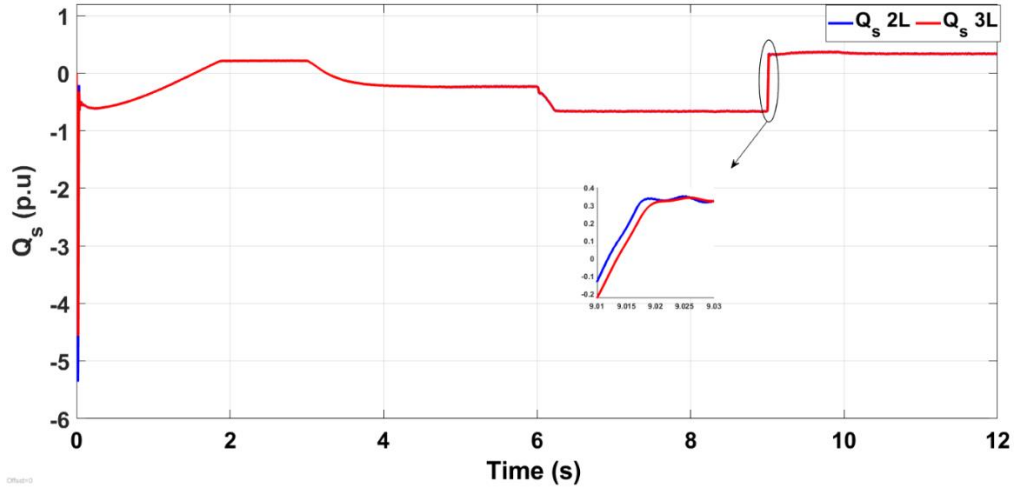


Figure 6. 26 Stator Reactive power for the 2L-VSC and 3L NPC-MLI fed DFIG WECS

6.8 Experimental Results

The analysis of a grid-connected DFIG based WECS, particularly when considering variable wind speeds and the transition from a 2L-VSI to a 3L-NPC MLI GSPEC, necessitates a thorough understanding of multiple variables. These variables include rotor and stator currents, stator power, grid power, and their respective effects on RSPEC and grid side converter (GSPEC) operations.

The performance and behavior of a DFIG vary significantly based on the design of its GSPEC and its operating mode. Investigating DFIG equipped with a 2L-VSC and then replacing it with a 3L-NPC MLI. Both configurations utilize the same control strategy: FCS-MP-DPC. This exploration covers the machine's operation in both

subynchronous and supersynchronous modes under the steady state and then for the dynamic analysis have change the wind speed of the DFIG Setup and then analysis the setup again with its voltage, current and power parameters.

First in the Steady state Analysis, in the sub synchronous mode, the rotor speed is lower than the synchronous speed, implying that the DFIG consumes power from the GSPEC and generate power only from the stator side and the GSPEC functions as a rectifier. The RSPEC functions as an inverter, transmuting DC to AC for the rotor. The generated stator and rotor currents typically exhibit higher harmonics, with increased THD, when using a 2L-VSC as the GSPEC as shown in Figure 6. 27. This effect arises due to the switching characteristics of the 2L-VSC. However, upon switching to the FCS-MP-DPC control strategy, the stator and rotor currents' THD improves notably. This improved performance is due to the superior control offered by FCS-MP-DPC, which enhances the dynamic response of the GSPEC.

When the 2L-VSC is replaced with a 3L-NPC MLI under the same control strategy, the harmonic content in the stator and rotor currents diminishes even further. The 3L-NPC MLI, due to its multilevel output voltage waveform, naturally reduces the harmonic distortion, resulting in a lower THD for the same operating conditions as can be seen in the Figure 6.28. Consequently, the 3L-NPC MLI proves to be a more efficient GSPEC for DFIG in the subynchronous mode.

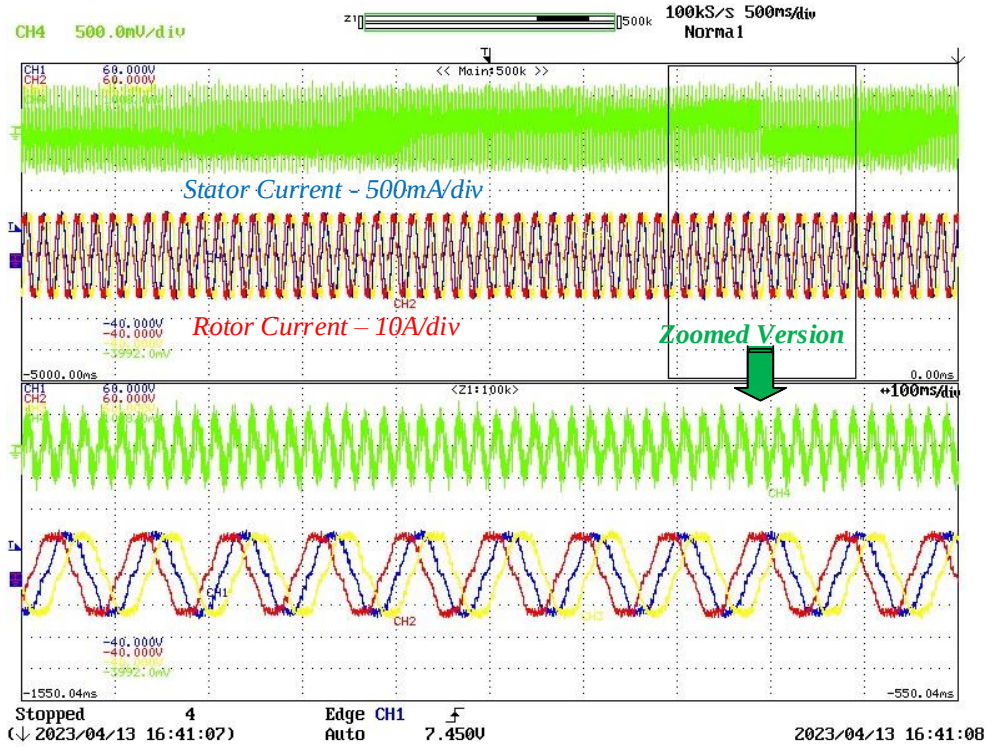


Figure 6. 27 Stator and Rotor waveform for FCSMP-DPC 2L VSI in sub synchronous condition

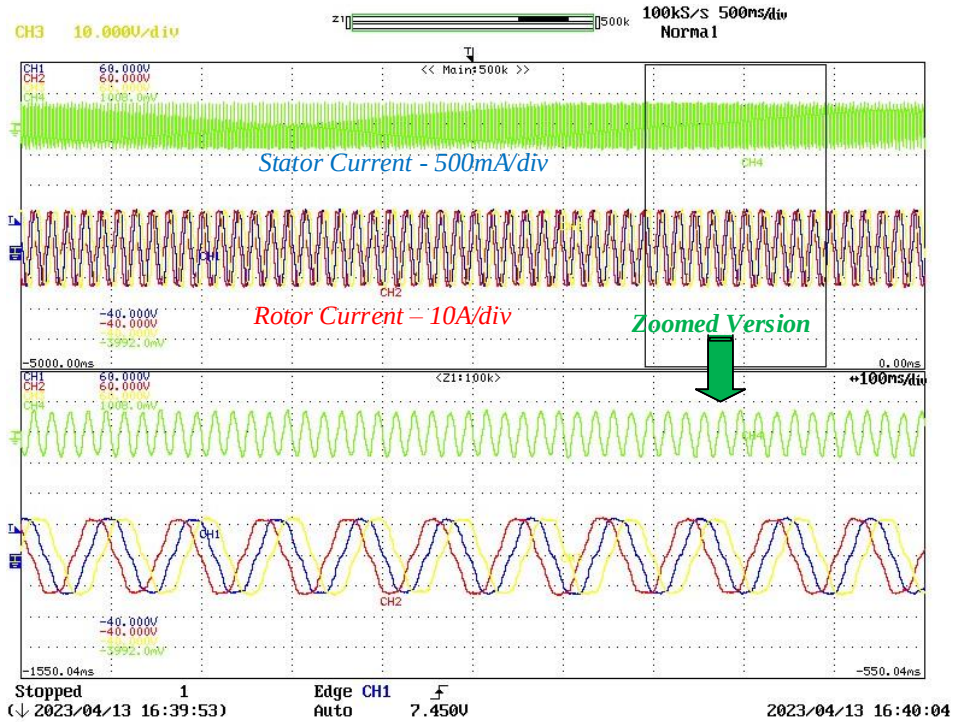


Figure 6. 28 Stator and Rotor waveform for FCSMP-DPC 3L NPC MLI in sub synchronous condition

Transitioning to the supersynchronous mode, where the rotor speed is higher than the synchronous speed, the DFIG supplies power to the grid. Similar to the sub

synchronous mode, the stator and rotor currents show higher harmonic content and THD when using the 2L VSC. Nonetheless, the FCS-MPC-DPC control strategy significantly improves the harmonic profile in the supersynchronous mode as well as shown in Figure 6. 29. Upon replacing the 2L VSC with a 3L NPC MLI, there's a clear decrease in the harmonic content in the stator and rotor currents, leading to an improved THD as can be seen in Figure 6. 30 Stator and Rotor waveform for FCSMP-DPC 3L NPC MLI in super synchronous condition. This improvement is more profound in the supersynchronous mode, making the 3L NPC MLI an advantageous choice for GSPEC in DFIG applications.

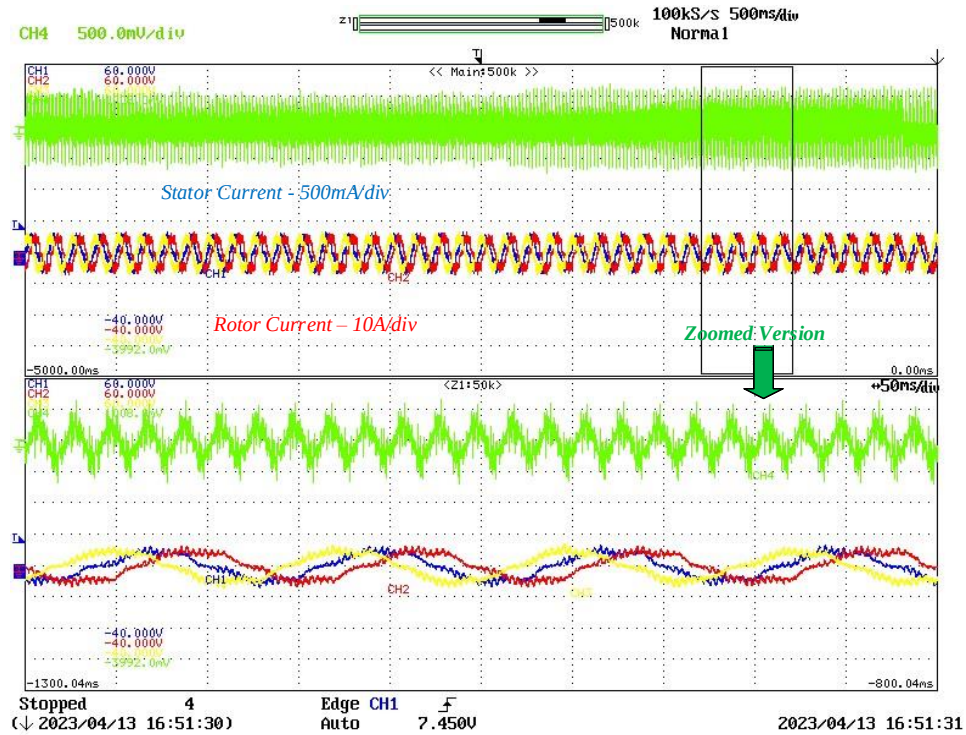


Figure 6. 29 Stator and Rotor waveform for FCSMP-DPC 2L-VSI in super synchronous condition

In both sub and super synchronous modes, the rotor current frequency of the DFIG varies. In the sub synchronous mode, the rotor frequency is the difference between the grid frequency and the electrical rotor speed, while in the super synchronous mode, it is the sum of the two. This variation can affect the harmonic content and THD. Yet, regardless of the mode, the 3L NPC MLI consistently outperforms the 2L VSC in terms of harmonic distortion and THD, highlighting its efficacy in enhancing the overall performance of the DFIG.

The performance of a DFIG significantly varies under transient conditions, such as changes in wind speed. DFIG using a FCS-MP-DPC technique using a 2L VSC as its GSPEC, and then with a 3L NPC MLI.

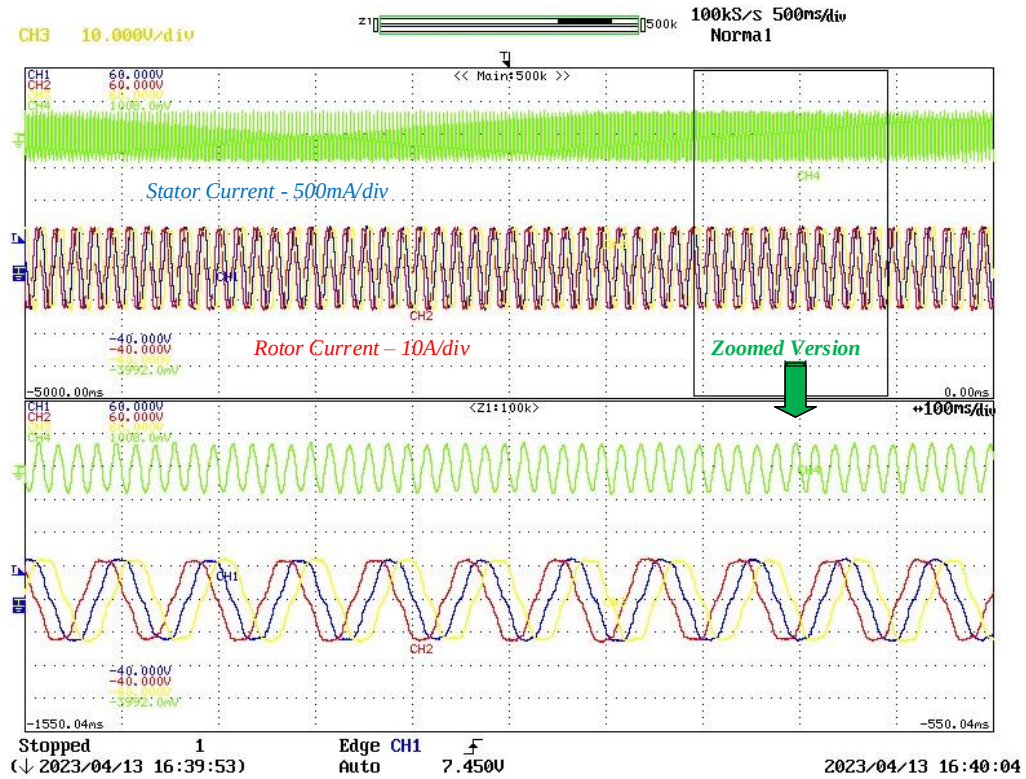


Figure 6. 30 Stator and Rotor waveform for FCSMP-DPC 3L NPC MLI in super synchronous condition

Starting our analysis with the DFIG in a subsynchronous mode at a wind speed of 7m/s (referenced in Figure 6. 31(e)), the generator is consuming power from the grid via the GSPEC, which acts as a rectifier and generate from the stator. RSPEC operates as an inverter, converting DC to AC for the rotor. At this stage, the rotor current waveform, when using a 2-level converter, can contain high switching harmonics, resulting in an inferior waveform quality (Figure 6. 31 (a)) have shown all the zoom part of rotor and stator current form subsynchronous to synchronous and then synchronous to super synchronous and then again form super synchronous to synchronous to subsynchronous. However, when replaced the 2L converter with a 3L-NPC MLI converter in the RSPEC can see a noticeable improvement in the rotor current waveform. The 3L NPC converter lowers harmonic distortions, thus enhancing current quality, as visible in Figure 6. 32

When the wind speed increases to near-synchronous conditions at 9m/s, a compelling shift occurs. The rotor speed rises, causing the slip to approach zero. Consequently, the frequency of the rotor current, which is the product of the slip and

stator frequency, also gets close to zero. This phenomenon is evident in the magnified version of the rotor current waveform in Figure 6. 31(b). Since the RSPEC neither needs to supply nor absorb power in these circumstances, the power generation from the grid side becomes negligible as can be seen in Figure 6. 31 (e). However, even in this state, the 2L converter results in a higher distortion in rotor current quality compared to the 3L-NPC converter as visible in Figure 6. 32 (a)

Transitioning to a super-synchronous wind speed of 11m/s, the DFIG starts generating power from the GSPEC as well, thereby deriving power from both the rotor and the stator. This situation increases the rotor current frequency (see Figure 6. 31 (a)), and the RSPEC serves as a rectifier, transforming the AC power from the rotor into DC. In these conditions, a 3L-NPC converter provides significant enhancements to the rotor current waveform by reducing harmonic distortions.

The quality of the stator current and the extent of harmonic distortion have significant implications for the performance of the DFIG and the quality of power delivered to the grid in any wind energy conversion system. When operating with a 2-level VSC at subsynchronous speed (7m/s), the power extracted from the grid influences the stator current, inducing higher distortion due to the intrinsic switching harmonics of the 2-level converter as depicted in Figure 6. 31 (c). In contrast, the 3L NPC converter remarkably reduces stator current distortion, generating a more sinusoidal waveform with an enhanced quality, as evident in Figure 6. 32(c).

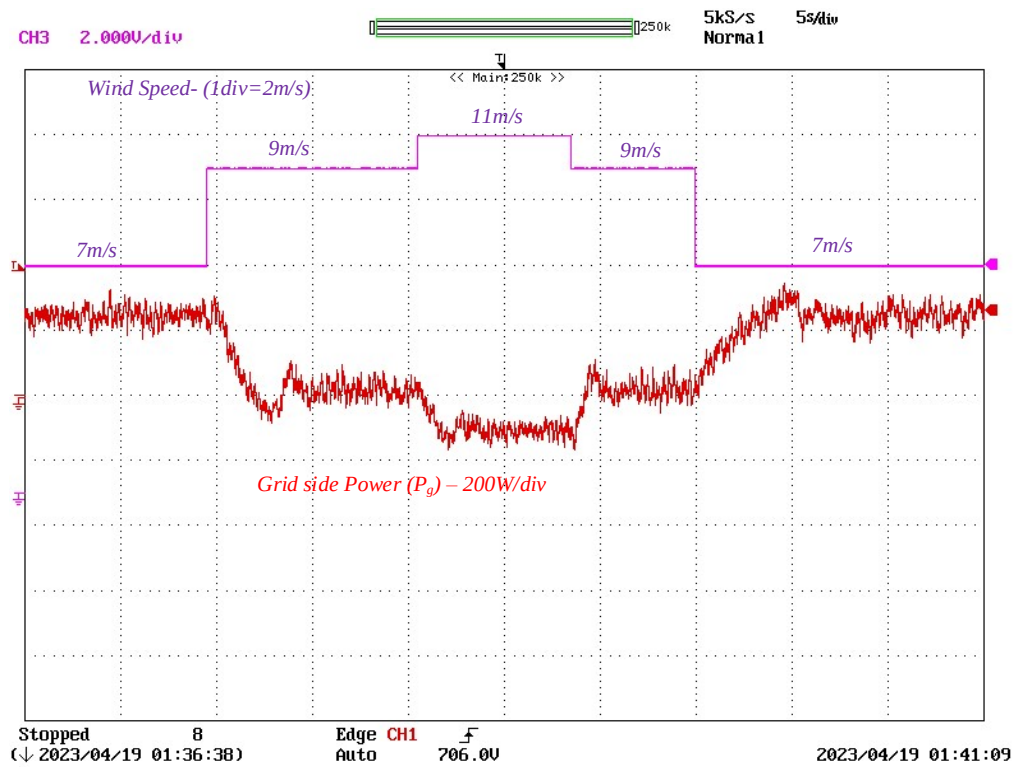
As the wind speed escalates to 9m/s and the DFIG shifts into the power generation mode from the rotor side, the stator current quality sees an improvement, although accompanied by a slight increase in amplitude. Nevertheless, the persistent presence of switching harmonics from the 2L- converter continues to limit the overall quality of the stator current. Conversely, the 3L-NPC converter significantly boosts the quality of the stator current, generating a stepped output waveform that closely emulates a sine wave. This leads to a considerable reduction in the THD.

As the wind speed reaches super-synchronous speeds (11m/s), the DFIG functions as a power generator, delivering energy to the grid. During this operational mode, the stator current with a 2L- converter experiences the highest distortion, primarily due to the switching harmonics inherent to this converter type. Nevertheless, despite operating at elevated wind speeds, the quality of the stator current remains markedly superior with the

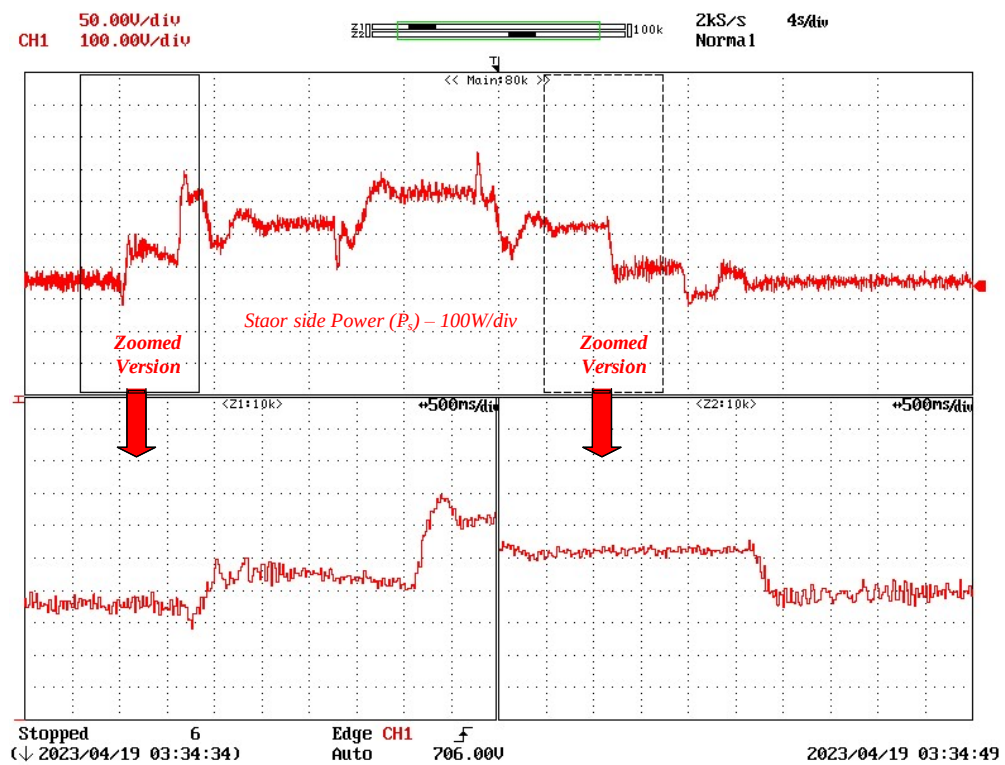
3L-NPC converter. This is attributable to the production of a smoother waveform, which mitigates distortion, thereby preserving high-quality power delivery to the grid.

The power generated by the stator intensifies with the wind speed. Irrespective of whether the DFIG operates in subsynchronous, synchronous, or supersynchronous modes, the stator continuously produces power. Simultaneously, the grid absorbs power during the subsynchronous mode, generates power in the supersynchronous mode, and records null power during the synchronous mode. Importantly, the fluctuations in power and the associated harmonics in both stator and grid power are significantly more pronounced with the 2L-VSC compared shown in Figure 6. 31 (e) & (f) to the 3L-NPC MLI shown in Figure 6. 32.

In summary, the deployment of a 3L-NPC MLI coupled with the FCS-MP-DTC control strategy, enhances the quality of both rotor and stator currents, as well as stator and grid power. It effectively mitigates harmonic distortion, providing superior control over the power interchange between the grid, stator, and rotor under varying wind conditions.

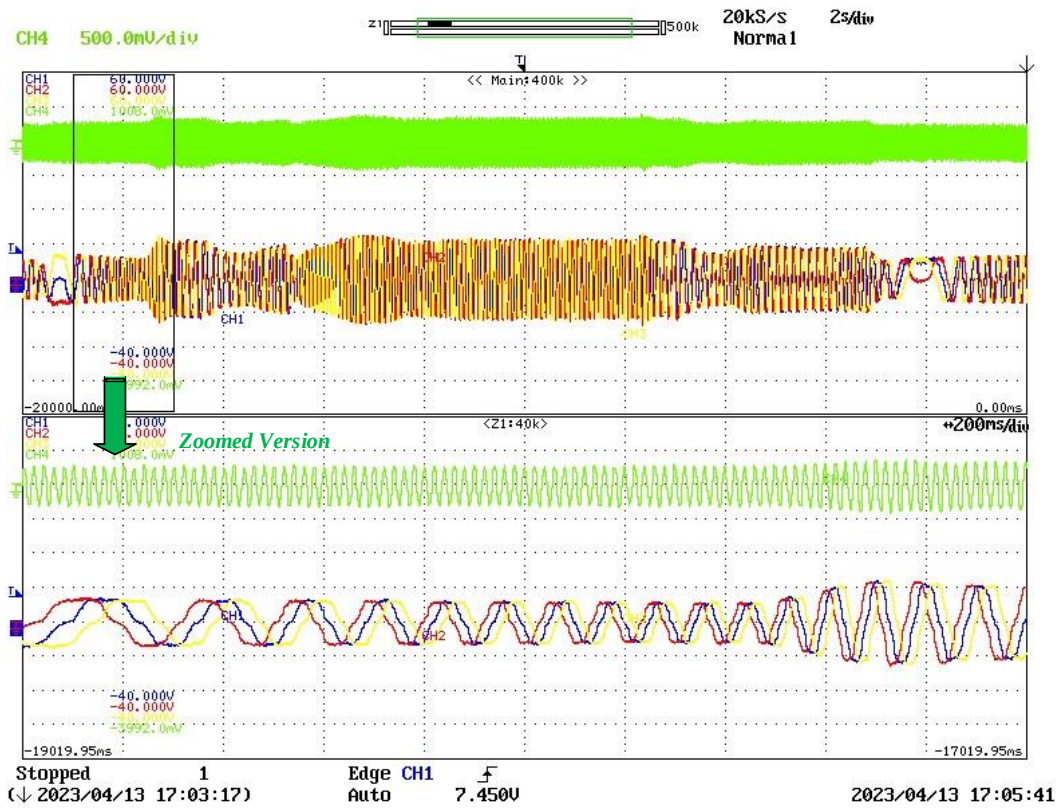


(e) Grid Side Active power

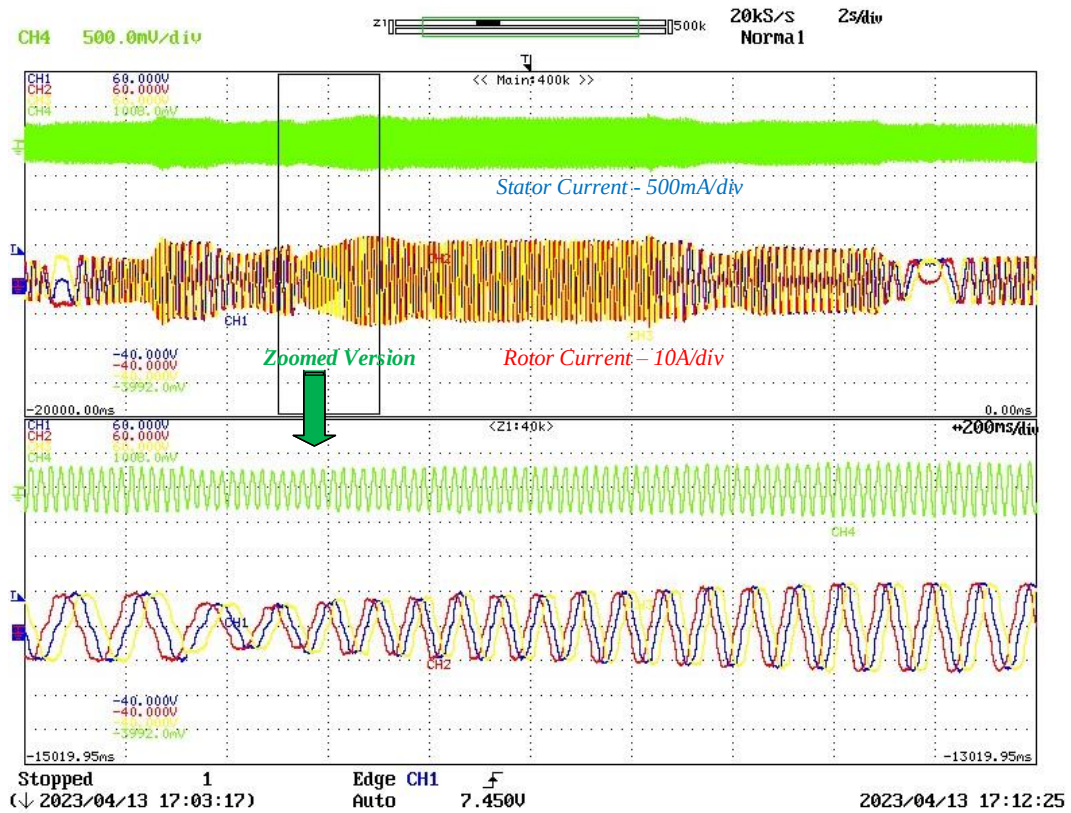


(f) Stator Side Active power

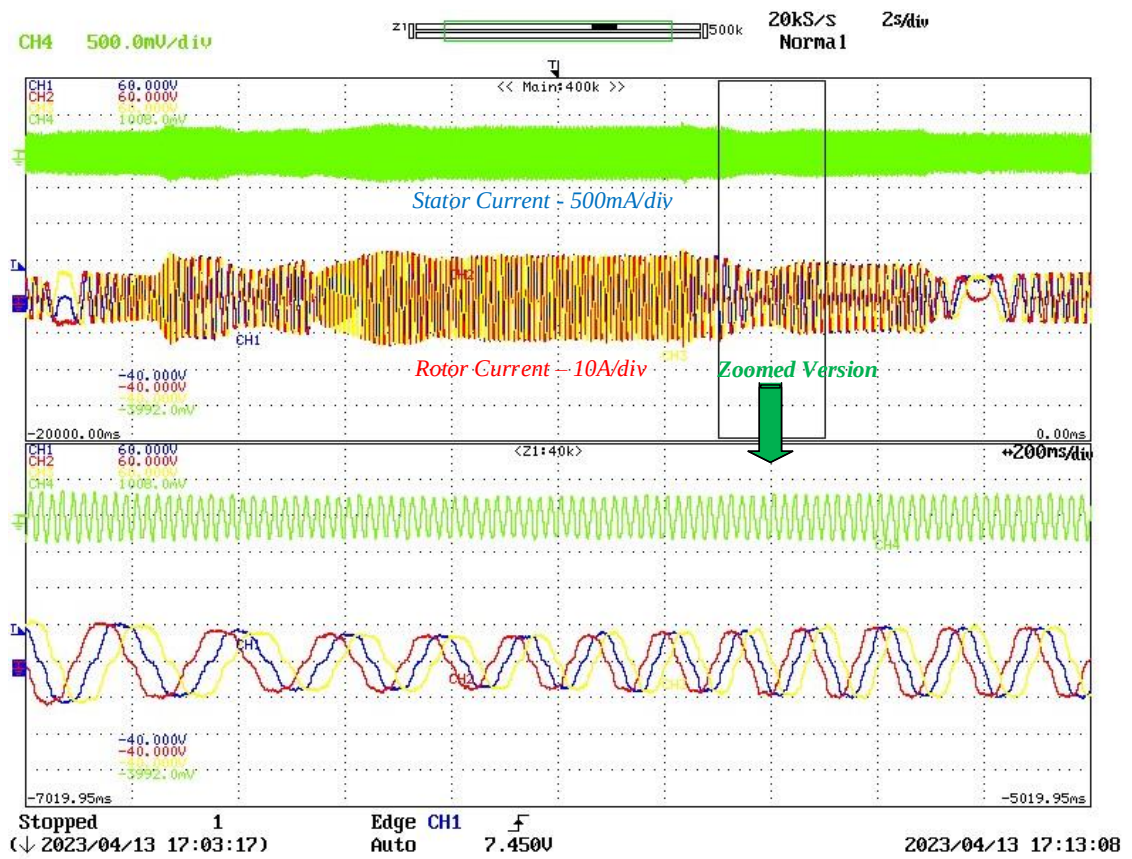
Figure 6. 31 Transient Response Analysis of FCS MPDPC Strategy with 2-Level VSC



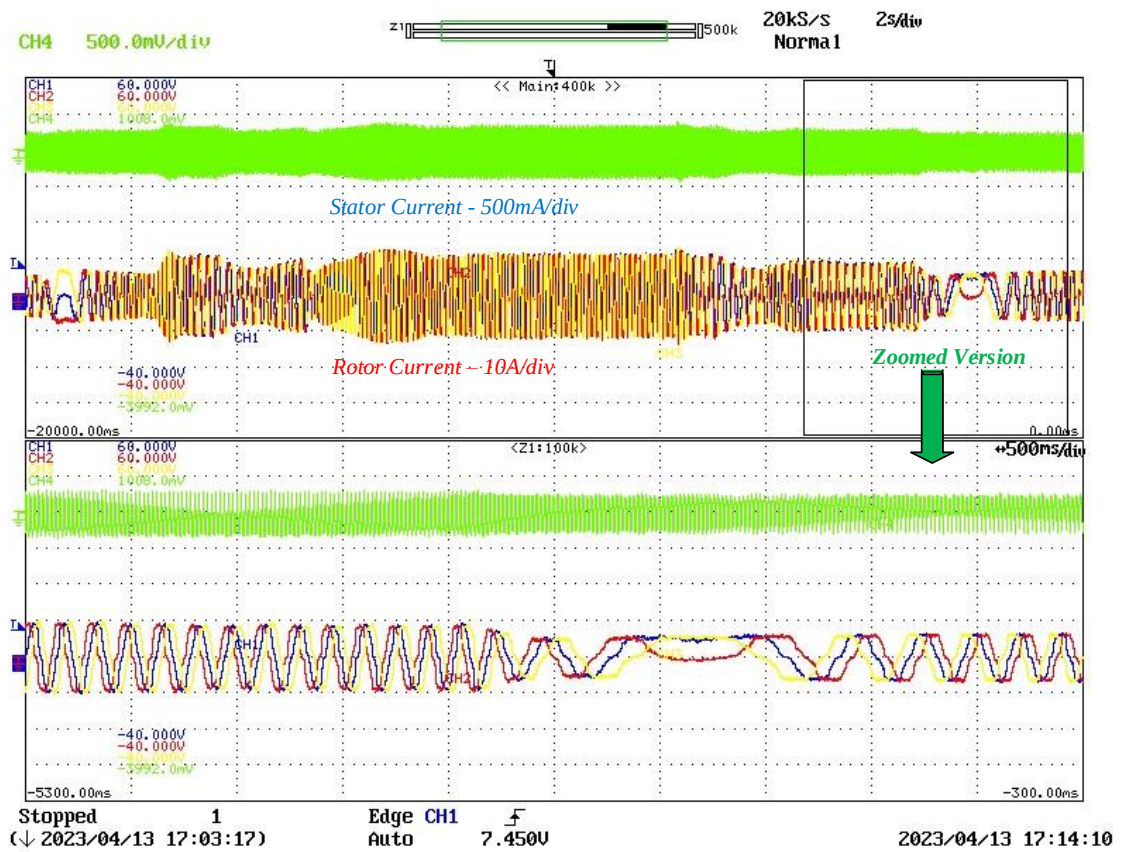
(a) Stator and Rotor current with zoom from Sub synchronous to synchronous



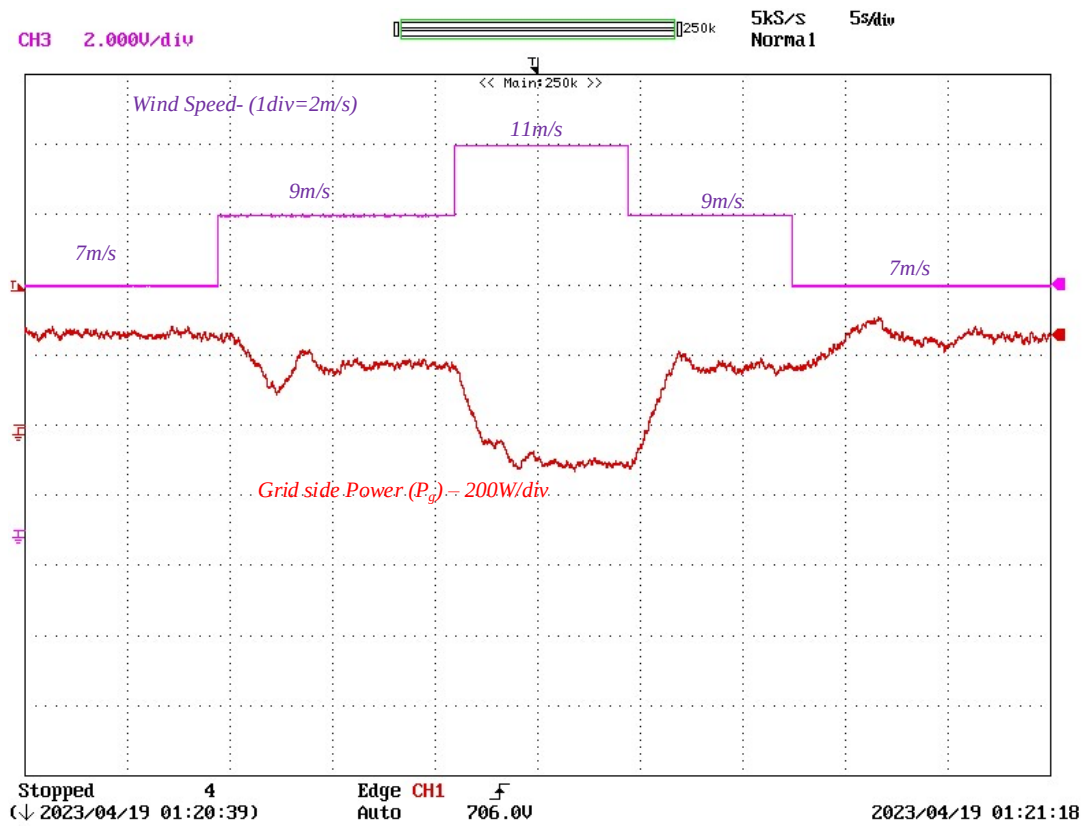
(b) Stator and Rotor current with zoom from Synchronous to Supersynchronous



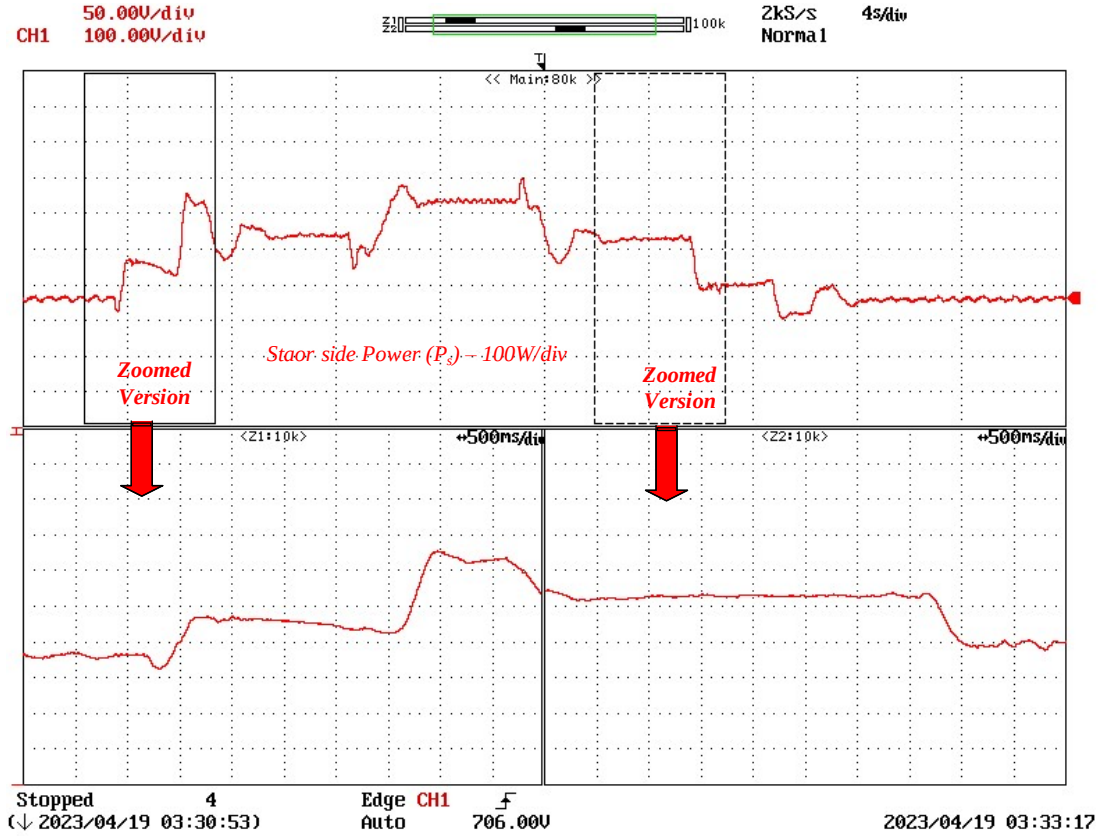
c) Stator and Rotor current with zoom from Supersynchronous to Synchronous



(d) Stator and Rotor current with zoom from Synchronous to Subsynchronous



(e) Grid Side Active power



(f) Stator Side Active power

Figure 6. 32 Transient Response Analysis of FCS MPDPC Strategy with 3L NPC MLI

6.9 Conclusion

In conclusion, this chapter has presented a comprehensive study on FCS-MPDPC and its application to the GSPEC of DFIG systems for wind energy. The theoretical aspects of FCS-MPDPC have been explored highlighting its benefits in achieving precise control over active and reactive power exchanged with the grid. In pursuit to enhance the understanding of FCS-MPDPC extended its application beyond the conventional two-level fed DFIG-based WECS to include multilevel converter. This expansion has allowed assessing the flexibility and efficiency of FCS-MPDPC in various system configurations and across different voltage levels, demonstrating its versatility in wind energy systems.

To validate the theoretical analysis and ascertain the effectiveness of FCS-MPDPC conducted MATLAB simulations under diverse operating conditions. By comparing the simulation results with theoretical predictions confirmed the capability of FCS-MPDPC

in regulating power flow and achieving optimal control in DFIG-based WECS. Further developed hardware prototype model to practically demonstrate the applicability of FCS-MPDPC in a real-world wind turbine setup. Through this implementation, incorporating the cutting-edge WAVECT Controller has achieved successful operation and control of the system. The hardware prototype provided tangible evidence of the practicality and efficacy. The real-time performance observations and extensive testing of the system have enabled to evaluate the control accuracy, stability, and response under various operating conditions. These practical demonstrations validate the potential of FCS-MPDPC as a robust and efficient control strategy for GSPESC in DFIG-based WECS.

Overall, this chapter's findings contribute to the advancement of control techniques in the field of wind energy systems. The combination of theoretical analysis, simulation studies, and practical implementation sheds light on the capabilities and benefits of FCS-MPDPC, providing valuable insights for researchers and engineers seeking more efficient and sustainable solutions in the realm of renewable energy. As renewable energy continues to gain prominence in addressing global energy challenges, FCS-MPDPC stands out as a promising control strategy that can significantly enhance the performance and reliability of wind energy systems in the future.

CHAPTER 7. CONCLUSION AND FUTURE SCOPE

7.1 Introduction

The research work in this thesis has focused on the application of model predictive direct control methods to three-level diode clamped back to back converter fed doubly fed induction generator based wind energy conversion system. The main objective was to investigate different control strategies to improve transient performance of the DFIG based WECS during FRT and variable wind speed operations. Fuzzy logic controller based coordinated protection scheme have been developed and tested on software and real time using OPAL RT 4500 controller and MPDCM for two and three level BTB converters at variable wind speed operation has been simulated and validated through experimental implementation. This chapter summarizes the investigations and findings of the research, presents conclusions and a direction for future studies.

7.2 Conclusions

The generators in wind energy conversion systems (WECS) plays critical role by converting the mechanical energy from the rotating wind turbine into electrical energy. The choice of generator technology depends on various factors such as turbine size, wind conditions, efficiency requirements, and cost considerations. Type-III based WECS using DFIG has become most popular recently due its advantages over other generators, therefore DFIG based WECS was considered in the present study.

The induction motor modeling in the synchronous reference frame based on the dq axes theory has presented. Principle of direct torque control is also illustrated based on the machine model derived in the synchronous reference frame. Multi level inverter is an emerging technology that allows the drive system to operate at increased power level, high quality inverter output with low harmonic loss and generates low torque fluctuations. The MATLAB/Simulink model simulation of DTC of induction motor drive fed with two-level and three-level inverter was carried out. Three level diode clamped BTB converter configuration has been considered in the study and compared with two-level BTB converter for controlling the speed, torque, power and DC voltage of grid connected DFIG.

Grid code requirements for integrating the wind turbines to grid are discussed. FRT ability is one the most grid code requirement for a generating station connected to grid. The classification of different FRT methods has been presented; these FRT methods are classified as internal protection circuits, external protection circuits using reactive power injection systems. The contributions and unique characteristics of these configurations were analyzed and compared. External systems are used to update the converter configuration and are most commonly used for pre-installed WECS. Internal control strategies make use of the latest innovative control methods to improve the overall DFIG-WECS FRT capability. The improvement of the internal control system may lead to the improvement of the control effect during the voltage sag in the grid. Because there is no need to use external additional circuits, it can even enhance the effectiveness of the DFIG based WECS during low voltage ride through. Therefore, internal control methods are favored in newly installed wind farms, and they have a huge growth potential in the long run. In view of the real-time obstacles faced, the research focused on ways to further improve FRT capabilities. Finally based on case study performance evaluation comparison of the RSDBR, DCBC and REPRC was performed. To improve the performance of the DFIG based WECS during FRT operation a modified protection method has been proposed using fuzzy logic control by integrating the REPRC, DCBC, and RSDBR protection methodologies. In the proposed method, RSDBR provides primary protection and with the crowbar circuit being activated if the RSDBR is unable to protect during deteriorating scenario. Depending on the situation, the REPRC will only be activated initially or end of the fault. The DCBC is used to regulate the excessive voltage produced by the dc link but it is not required for FRT operation; however, it does help to smooth the DC link voltage and expands the normal range of DFIG operation for higher active power imbalances between the converters. The robustness of the proposed FRT method was tested. The proposed scheme is simulated on MATLAB/SIMULINK platform and the OPAL-RT application for different fault conditions. Real time implementation of proposed Fuzzy based coordinated protection scheme on real time simulator OPAL RT 4500 controller for different fault conditions such as LL and LLL has done. The proposed scheme has shown better performance during these fault operations with better oscillatory response compared to conventional schemes.

Using indirect vector control to control speed, torque power and DC voltage has shown poor performance. Therefore, direct control methods are used which offers greater

advantages. In conventional DTC, two hysteresis comparators are used to regulate the torque and flux directly by selecting an appropriate voltage vector from a predefined switching table according to the position and stator flux. However, there are some drawbacks of conventional switching-table based DTC and the two most notable drawbacks are large torque ripple and variable switching frequency. Incorporating space vector modulation in DTC/DPC may solve the problem of achieving the constant switching frequency; however it has drawbacks such as weak robustness to parameter variation, requirements of PI controllers and difficulty to implement multilevel inverter in WECS. The use of model predictive control is an alternative to these conventional direct control methods. MPC voids proportional-integral and hysteresis controllers. Model predictive direct torque control (MPDTC) and model predictive direct power control (MPDPC) work in the same manner but the predicted values being the rotor flux and electromagnetic torque in the former, and the stator reactive and active powers in the latter.

In the present thesis MPDTC for rotor side converter where for both two-level and three level diode clamped converter are implemented on MATLAB/SIMULINK software has been simulated for variable wind speed operations. The performance of the MPDTC at variable wind speed has been recorded with simulation and experimental results and their comparison at different performance parameters are tabulated. Similarly, MPDPC for grid side inverter for both two-level and three level diode clamped inverter are implemented on MATLAB/SIMULINK software has been simulated for variable wind speed operations. Three level inverter fed DFIG has been more robust at transient conditions during variable wind speeds which are validated via practical and software implementation and their comparison at different performance parameters are tabulated.

The prototype model of proposed DFIG based WECS for MPDCM has been developed and is implemented practically in real time using WACET 300 R&D controller board on wind emulator consists of DC machine prime mover and semikron make two level and three BTB converters. Experimental tests at variable wind speeds were carried out to investigate the performance of the proposed scheme in grid connected mode of operation. The three level BTB converter connected DFIG based WECS using MPDCM has shown better performance at various transient operations.

A detailed comparison between the performances of the two and three level BTB converter fed DFIG based WECS for MPDTC and MPDPC methods at variable wind

speed operation has been made. Further comparative investigation between conventional FRT protection method and proposed fuzzy based coordinated protection scheme for different fault scenario's has been done with proposed coordinated scheme showing better results compared to its counterpart. Finally, using MPDCM for multi level BTB converter and fuzzy logic has shown great capabilities for significantly improved performance of grid connected DFIG based WECS.

7.3 Future Scope

The field of model predictive control (MPC) for grid-connected DFIG based wind energy systems offers several potential avenues for future research and development. Some possible future scopes in this area include:

- Explore and develop advanced MPC strategies that can further improve the performance, efficiency, and FRT capability of the DFIG system. This could involve incorporating advanced optimization techniques, adaptive algorithms, and machine learning approaches to enhance control performance under varying operating conditions and system dynamics.
- Developing improved MPC strategies for improving grid stability, power quality and frequency regulation. This may involve the coordination of multiple DFIG systems, considering grid code requirements, and addressing challenges related to grid faults and disturbances.
- Investigating the integration of energy storage systems (such as batteries or super capacitors) to DFIG systems and developing MPC strategies to optimize their combined operation. This allows better management of power fluctuations, enhancing energy production capabilities, and improving systems stability and reliability.

LIST OF PUBLICATIONS

International Journals

1. Ansari AA, Dyanamina G “Fault Ride-Through Operation Analysis of Doubly Fed Induction Generator-Based Wind Energy Conversion Systems: A Comparative Review.” *Energies*, Vol 15 issue 21, PP, 2022. <https://doi.org/10.3390/en15218026> (SCI- Q1)
2. Ansari AA, Dyanamina G, “Real-Time Implementation of The Fuzzy Logic Controlled Parallel Protection Technique to Enhance the DFIG System’s Fault Ride through Capability,” *Scientia Iranica, International Journal of Science and Technology*, PP.1-26, 2023. (SCI-Q2, Accepted under Publication)
3. Ansari AA, Dyanamina G, “Neural Network Based Direct Torque Control for Doubly Fed Induction Generator fed Wind Energy System”, *Advances in Computational Design, an International Journal*, PP.1-9, 2023. (ESCI/ Scopus-Q3, Accepted under Publication).
4. Ansari, A.A., Dyanamina, G. “Comparative Analysis of Controlling Methods for Doubly Fed Induction Generator Based Wind Energy System” in Kumar, S., Singh, B., Singh, A.K, *Recent Advances in Power Electronics and Drives. Lecture Notes in Electrical Engineering, Springer, Singapore*, Vol 852, PP. 493-507, 2022. https://doi.org/10.1007/978-981-16-9239-0_37 (Scopus-Q4)

International Conferences

1. Ansari, A.A., Dyanamina, G “A Study on the Impact of SDBRs on the Fault Ride-through Capability of DFIG based Wind Farms”, *IEEE International Conference on Computer, Electronics and Electrical Engineering and Their Applications*, NIT Uttarakhand, PP 1-6, June 2023 (Accepted).
2. Ansari, A.A., Dyanamina, G “FCS-MPC based predictive current control of grid connected DFIG based Wind Energy System” *IEEE IAS Global Conference on Emerging Technologies (GlobConET)*, Loughborough University, London, PP. 1-6, May 2023.
3. A. A. Ansari, G. Dyanamina and A. A. Ansari, “Decoupled Control of Rotor Side Power Electronic Converter for Grid Connected DFIG Based Wind Energy System”, *IEEE International Students' Conference on Electrical, Electronics and Computer Science (SCEECS)*, MANIT Bhopal, pp. 1-6, February 2023, doi: 10.1109/SCEECS57921.2023.10063093.
4. Ansari, A. A., & Dyanamina, G, “MATLAB Simulation of FRT Techniques for DFIG-based Wind Farms” *IEEE International Conference on Control, Automation, Power and Signal Processing (CAPS-2021)*, IITDM Jabalpur, India PP 1-6, September 2021. doi: [10.1109/CAPS52117.2021.9730674](https://doi.org/10.1109/CAPS52117.2021.9730674).

5. Ansari, A. A., & G. Dyanamina, “State of Art and Comprehensive Study on Smart Meter Networking” *Lecture Notes in Electrical Engineering (LNEE) Book Series*. 2nd Conference on Flexible Electronics on Electric Vehicle (FlexEV-2021), Jaipur, India PP 1-6, 2021.

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APPENDIX-A

A.1 Clark Transformation

The Clark transformation is basically employed to transform three-phase to two-phase quantities. The two-phase variables in a stationary reference frame are sometimes denoted as α and β . As shown in Figure A. 1 the α axis coincides with the a-axis and the β axis lags the a-axis by 90° .

$$\begin{bmatrix} f_{\alpha\beta 0} \end{bmatrix} = \begin{bmatrix} T_{\alpha\beta 0} \end{bmatrix} \begin{bmatrix} f_{abc} \end{bmatrix} \quad \text{A.1}$$

Where the transformation matrix $\begin{bmatrix} T_{\alpha\beta 0} \end{bmatrix}$, is given by

$$\begin{bmatrix} T_{\alpha\beta 0} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad \text{A.2}$$

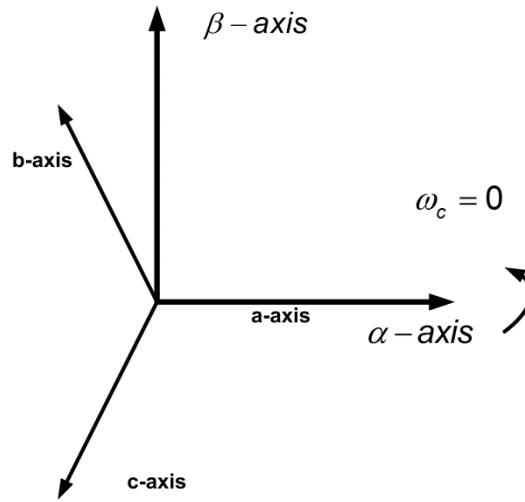


Figure A. 1: Relationship between $\alpha\beta$ - abc quantities

and the inverse transformation is

$$\left[T_{\alpha\beta 0}\right]^{-1} = \frac{2}{3} \begin{bmatrix} 1 & 0 & 1 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & 1 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & 1 \end{bmatrix} \quad \text{A.3}$$

A.2 Parks Transformation

The Park's transformation is a well-known transformation that converts the quantities to two-phase synchronously rotating frame. The transformation is in the form of:

$$\begin{bmatrix} f_{dq0} \end{bmatrix} = \begin{bmatrix} T_{dq0}(\theta_d) \end{bmatrix} \begin{bmatrix} f_{abc} \end{bmatrix} \quad \text{A.4}$$

Where $dq0$ transformation matrix is defined as

$$\begin{bmatrix} T_{dq0}(\theta_d) \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta_d & \cos\left(\theta_d - \frac{2\pi}{3}\right) & \cos\left(\theta_d + \frac{2\pi}{3}\right) \\ -\sin\theta_d & -\sin\left(\theta_d - \frac{2\pi}{3}\right) & -\sin\left(\theta_d + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad \text{A.5}$$

and the inverse transformation is given by

$$\begin{bmatrix} T_{dq0}(\theta_d) \end{bmatrix}^{-1} = \frac{2}{3} \begin{bmatrix} \cos\theta_d & -\sin\theta_d & 1 \\ \cos\left(\theta_d - \frac{2\pi}{3}\right) & -\sin\left(\theta_d - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta_d + \frac{2\pi}{3}\right) & -\sin\left(\theta_d + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \quad \text{A.6}$$

Where θ_d is the transformation angle.

The positive q-axis leads the positive d-axis by 90° in the original Park's transformation. Some authors define the q-axis as lagging the d-axis by 90° . The transformation with q-axis lagging d-axis is given by:

$$\left[T_{qdo}(\theta_q) \right] = \frac{2}{3} \begin{bmatrix} \cos \theta_q & \cos\left(\theta_q - \frac{2\pi}{3}\right) & \cos\left(\theta_q + \frac{2\pi}{3}\right) \\ \sin \theta_q & \sin\left(\theta_q - \frac{2\pi}{3}\right) & \sin\left(\theta_q + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad \text{A.7}$$

And the inverse transformation matrix is

$$\left[T_{qdo}(\theta_q) \right]^{-1} = \frac{2}{3} \begin{bmatrix} \cos \theta_q & \sin \theta_q & 1 \\ \cos\left(\theta_q - \frac{2\pi}{3}\right) & \sin\left(\theta_q - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta_q + \frac{2\pi}{3}\right) & \sin\left(\theta_q + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \quad \text{A.8}$$

Where θ_q is transformation angle when q-axis is leading.

The relationship between θ_d and θ_q is:

$$\theta_q = \theta_d + \frac{\pi}{2} \quad \text{A.9}$$

One can show that both $\left[T_{dqo}(\theta_d) \right]$ and $\left[T_{qdo}(\theta_q) \right]$, are basically same, except the ordering of the d and q variables [10, 14]. Both alternatives are shown in Figure A. 2.

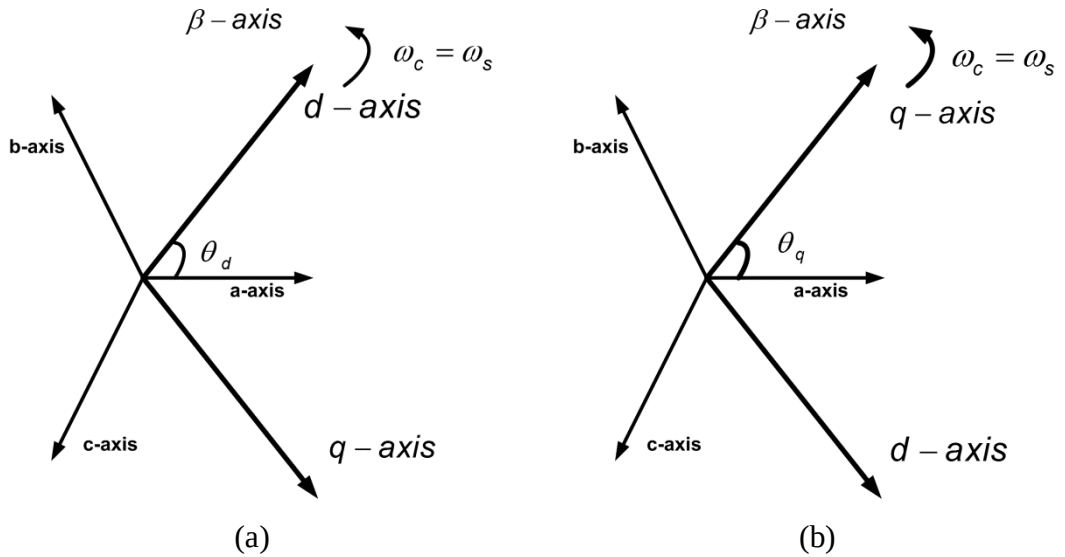


Figure A. 2: Relationship between (a) dq -abc quantities (b) qd -abc quantities

A.3 Reference Frames

Generally an arbitrary reference frame is used to simulate the induction motor which is laborious. But it is useful to convert a unified model to other frames. The most

commonly used ones are, two marginal cases of the arbitrary rotating frame, stationary reference frame and synchronously rotating frame [10, 14].

Arbitrary reference frame voltage equations when written in matrix form

$$\begin{bmatrix} v_{qs}^c \\ v_{ds}^c \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_s + L_s p & \omega_c L_s & L_m p & \omega_c L_m \\ -\omega_c L_s & R_s + L_s p & -\omega_c L_m & L_m p \\ L_m p & (\omega_c - \omega_r) L_m & R_r + L_r p & (\omega_c - \omega_r) L_r \\ -(\omega_c - \omega_r) L_m & L_m p & -(\omega_c - \omega_r) L_r & R_r + L_r p \end{bmatrix} \begin{bmatrix} i_{qs}^c \\ i_{ds}^c \\ i_{qr}^c \\ i_{dr}^c \end{bmatrix} \quad \text{A.10}$$

and torque is written as

$$T_e = \frac{3}{2} \frac{P}{2} L_m (i_{qs}^c i_{dr}^c - i_{ds}^c i_{qr}^c) \quad \text{A.11}$$

A.3.1 Stationary or Stator Reference Frame

The speed of reference frame is stator, which is equal to zero: hence $\omega_c = 0$ is substituted in the **Error! Reference source not found.** then

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_s + L_s p & 0 & L_m p & 0 \\ 0 & R_s + L_s p & 0 & L_m p \\ L_m p & -\omega_r L_m & R_r + L_r p & -\omega_r L_r \\ \omega_r L_m & L_m p & \omega_r L_r & R_r + L_r p \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \quad \text{A.12}$$

The torque equation is

$$T_e = \frac{3}{2} \frac{P}{2} L_m (i_{qs} i_{dr} - i_{ds} i_{qr}) \quad \text{A.13}$$

A.3.2 Synchronous Reference Frame

The speed of reference frame is $\omega_c = \omega_s$. Where ω_s is stator supply frequency.

By substituting the $\omega_c = \omega_s$ in **Error! Reference source not found.** the induction motor model in the synchronous reference frame is obtained. The superscript e denotes an electrical synchronous reference frame, the equation is given by:

$$\begin{bmatrix} v_{qs}^e \\ v_{ds}^e \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_s + L_s p & \omega_s L_s & L_m p & \omega_s L_m \\ -\omega_s L_s & R_s + L_s p & -\omega_s L_m & L_m p \\ L_m p & (\omega_s - \omega_r) L_m & R_r + L_r p & (\omega_s - \omega_r) L_r \\ -(\omega_s - \omega_r) L_m & L_m p & -(\omega_s - \omega_r) L_r & R_r + L_r p \end{bmatrix} \begin{bmatrix} i_{qs}^e \\ i_{ds}^e \\ i_{qr}^e \\ i_{dr}^e \end{bmatrix} \quad \text{A.14}$$

and torque equation is

$$T_e = \frac{3}{2} \frac{P}{2} L_m (i_{qs}^e i_{dr}^e - i_{ds}^e i_{qr}^e) \quad \text{A.15}$$

A.3.3 Rotor Reference Frame

The speed of the rotor reference frame model is $\omega_c = \omega_r$ and angular position is $\theta_c = \theta_s$. By substituting the $\omega_c = \omega_r$ in **Error! Reference source not found.** the induction motor model in the rotor reference frame is obtained [10, 14]. The superscript r denotes a rotor reference frame and is given by:

$$\begin{bmatrix} v_{qs}^r \\ v_{ds}^r \\ v_{qr}^r \\ v_{dr}^r \end{bmatrix} = \begin{bmatrix} R_s + L_s p & \omega_r L_s & L_m p & \omega_r L_m \\ -\omega_r L_s & R_s + L_s p & -\omega_r L_m & L_m p \\ L_m p & 0 & R_r + L_r p & 0 \\ 0 & L_m p & 0 & R_r + L_r p \end{bmatrix} \begin{bmatrix} i_{qs}^r \\ i_{ds}^r \\ i_{qr}^r \\ i_{dr}^r \end{bmatrix} \quad \text{A.16}$$

The torque equation is as

$$T_e = \frac{3}{2} \frac{P}{2} L_m \left(i_{qs}^r i_{dr}^r - i_{ds}^r i_{qr}^r \right) \quad \text{A.17}$$

APPENDIX B

B.1 Fuzzification

Fuzzification is a process where all the inputs are mapped to fuzzy set, membership functions are assigned to all these sets. The fuzzy logic action is based on linguistic variables. In this process each point of the input space (universe of discourse) is assigned a membership value μ (degree of membership), which is in the range of 0 and 1; when it is zero no membership value is assigned, for $\mu = 1$ full membership is assigned to fuzzy set.

There are many types of membership functions; some are smooth such as Gaussian and Sigmoid and others are non-smooth such as triangular and trapezoidal as shown in Figure B. 1. The choice of suitable membership function is not unique. However, simple membership functions such as triangular and trapezoidal are used in various applications due to their linear characteristics [65].

B.2 Knowledge Base

The knowledge base consists of the database and the linguistic-control rule base. The database provides the information which is used to define the linguistic control rules and the fuzzy data manipulation in the fuzzy-logic controller. The rule base (expert rules) specifies the control goal actions by means of a set of linguistic control rules. In other words, the rule base contains rules which are those which would be provided by an expert. The FLC looks at the input signals and by using the expert rules determines the appropriate output signals (control actions) [65]. The rule base contains a set of *If-Then* rules. The main methods of developing the rule base are:

- Using the experience and knowledge of an expert in the application and the control goals;
- Modeling the control action of the operator;
- Modeling the process;
- Using a self-organized fuzzy controller;
- Using artificial neural networks.

When the initial rules are obtained by using expert physical considerations, these can be formed by considering that the three main objectives to be achieved by the fuzzy-logic controller are:

- Removal of any significant errors in the process output by suitable adjustment of the control output;
- Ensuring a smooth control action near the reference value (small oscillations in the process output are not transmitted to the control input);
- Preventing the process output exceeding user specified values.

B.3 Fuzzy Inference Engine

The fuzzy inference engine is used to generate the fuzzy outputs by connecting the fuzzified inputs to the output fuzzy sets based on linguistic rules. This mimics human reasoning which can be described by an *If-Then* rules: If x is A_i and/or y is B_i then z is C_i where, x and y are the first and the second fuzzy inputs respectively and A_i and B_i are the membership functions for each input, z is the controller output, C_i is the membership function of the output.

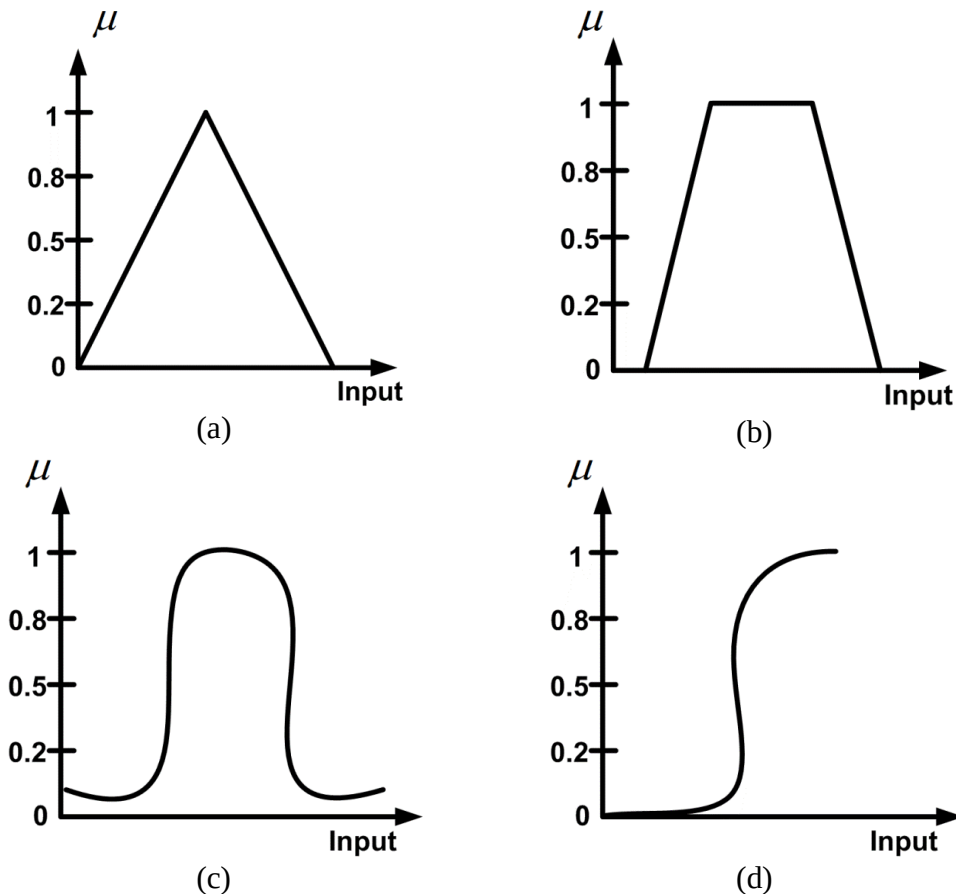


Figure B. 1: Fuzzy membership functions (a) triangular (b) trapezoidal (c) gaussian

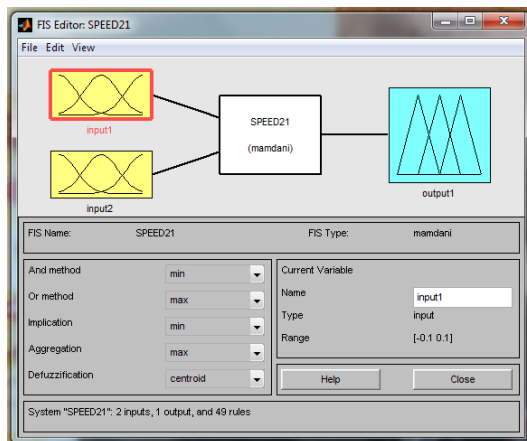
(d) sigmoid

B.4 Defuzzification

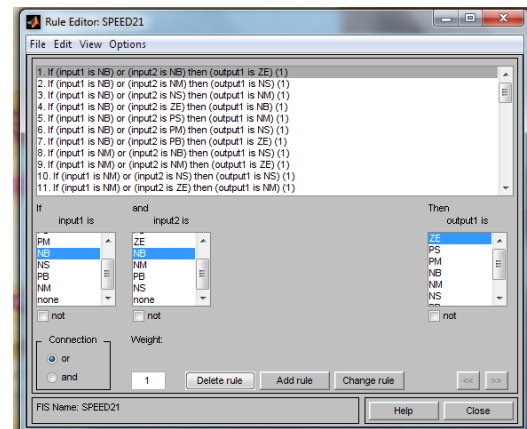
The last step of the FLC is the defuzzification process where the output fuzzy set is transformed back to a real value. Different methods can be used for the defuzzification such as: maximum, mean of maxima, center of the area and center of gravity. Usually scaling factors are used in the input and the output of the FLC to normalize the value of the controller input and to de-normalize the controller output. More often the tuning of these parameters is performed off-line using any optimization technique such as Genetic Algorithm (GA). After the tuning process these parameters remain constant during the normal operation of the controller. Improvement in the controller performance and robustness, these parameters can also be alerted online. If such an on-line tuning of scaling factors, fuzzy rules or membership functions is performed the controller becomes an adaptive fuzzy controller [20].

B.5 Fuzzy Logic Controller Implementation

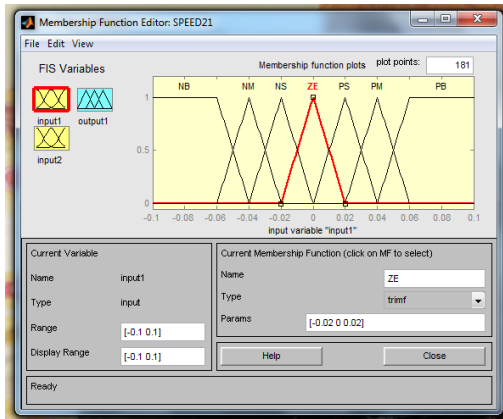
The most frequently used FL system is the Mamdani-type which consists of three main parts: Fuzzification, inference engine and defuzzification. FLC can be modeled using the MATLAB fuzzy logic toolbox graphical user interface GUI as shown in Figure B. 2. This allows an easy way to build the FLC graphically. Five primary GUI tools are provided to help building and editing the FLC: Fuzzy Inference System (FIS) editor, membership function editor, rule editor, rule viewer and surface viewer. These GUI tools are dynamically linked so that any change in one will affect the others. The FIS editor is used to determine number and names of inputs and outputs, membership function editor defines shapes of different membership functions and inputs outputs range, rule editor is used for editing the FL rules. Rule viewer and surface viewer are read-only tools and are used to look at the FIS characteristics [25].



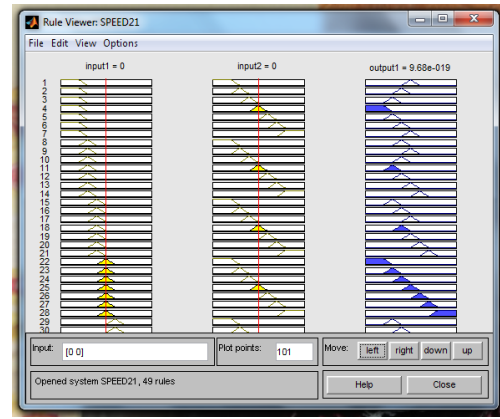
(a)



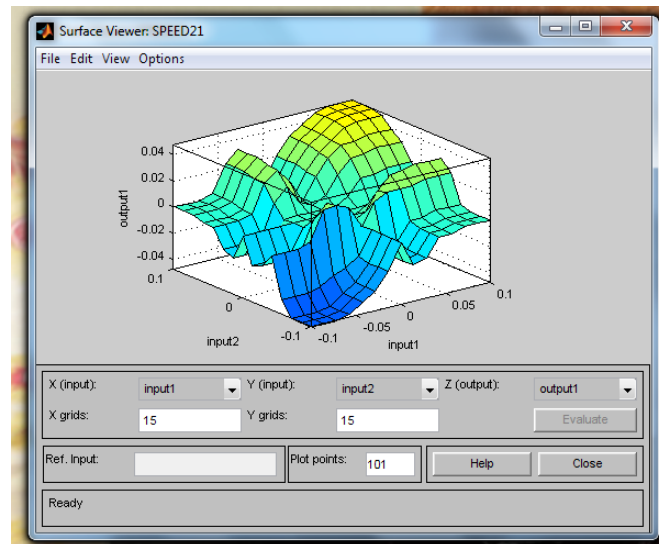
(b)



(c)



(d)



(e)

Figure B. 2: Fuzzy logic modelling using MATLAB (a) fuzzy inference system (FIS) editor (b) membership function editor (c) rule editor (d) rule viewer (e) surface viewer.

APPENDIX C

C.1 Simulation Parameter of DFIG

Parameters	Value
Rated Power	1.5 MW
Rated R.M.S. line-to-line voltage (stator)	575 V
Rated R.M.S. line-to-line voltage (rotor)	1975 V
Frequency	50 Hz
Stator resistance	0.01965 p.u
Rotor resistance	0.01909 p.u
Stator leakage inductance	0.0397 p.u
Rotor leakage inductance	0.0136 p.u
Magnetizing inductance	1.354 p.u
Pair of poles	3
Inertia constant	0.09526
Friction Factor	0.05479
Nominal Dc Voltage	1150 V
DC Bus Capacitor	0.01 F

C.2 Experimental Parameter of DFIG

Parameters	Value
Rated Power	2.2 KW
Rated Voltage	415 $\pm$ 10% V
Rated Current	4.97 A
No. of Poles	6
Rated Speed	925 RPM
Frequency	50 $\pm$ 5% Hz
Efficiency	77% at full load
Rated Torque	2.32 kg-m
Stator resistance	1.99 ohm
Rotor resistance	1.84 ohm
Magnetizing inductance	0.37 H

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