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**INVESTIGATION OF POWER CONVERTERS FOR
AC AND DC POWER COLLECTION IN WIND
TURBINE SYSTEMS**

MD SHAFQUAT ULLAH KHAN

SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution.

17 November 2019

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Md Shafquat Ullah Khan

Supervisor Declaration Statement

I have reviewed the content and presentation style of this thesis and declare it is free of plagiarism and of sufficient grammatical clarity to be examined. To the best of my knowledge, the research and writing are those of the candidate except as acknowledged in the Author Attribution Statement. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

17 November 2019

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Dr. Ali Iftexhar Maswood

Authorship Attribution Statement

This thesis contains material from [7] papers published in the following peer-reviewed journal(s) where I was the first and/or corresponding author.

Chapter 3 is published as [1] J. Kavil Kambrath, M. S. U. Khan, Y. Wang, A. I. Maswood and Y. Yoon, "A Novel Control Technique to Reduce the Effects of Torsional Interaction in Wind Turbine System," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 7, no. 3, pp. 2090-2105, Sept. 2019.

The contributions of the co-authors are as follows:

- Dr. A. I. Maswood and Dr. Y. Wang provided the initial project direction.
- The conceptualization the paper was ideated by M.S.U. Khan.
- The modeling and design of power electronic components and converter control was carried out by M.S.U. Khan in Matlab/Simulink and J. K. Kambrath carried out modeling in SIMPAC. The co-simulation platform was created as a joint effort.
- The simulation and experimental work were performed at the School of Electrical and Electronic Engineering at Nanyang Technological University by M.S.U. Khan and J. K. Kambrath.
- The manuscript was prepared and corresponded by M.S.U. Khan.
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- Dr. A. I. Maswood provided the initial project direction.
- The manuscript drafts preparation and the basic modeling of the system was carried out at the School of Electrical and Electronic Engineering in Nanyang Technological University by M.S.U. Khan.
- I and Dr. H. D. Tafti carried out the simulation of the system in co-simulation platform of PSIM and Matlab/Simulink.
- Dr. H. D. Tafti edited the manuscript and M. Tariq revised the manuscript from the technical writing perspective.
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- Dr. A. I. Maswood provided the initial direction for the work.
- The manuscript drafts proposing the topology was prepared and primarily edited by M.S.U. Khan.
- The basic simulations and modeling of the system have been carried out by M.S.U. Khan.
- M.S.U. Khan and M. Tariq carried out the literature review and conceptualized the basic application of technology.
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The contributions of the co-authors are as follows:

- Dr. A. I. Maswood provided the initial direction for the work.
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- T. Iqbal curated the basic concepts in regards to the application of the technology.
- K. Sathpathi modeled the control of WRSG excitation system.
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- The equations required carried out the required numerical calculations were formulated by M.S.U. Khan.
- Dr. A. Tripathi revised the manuscript from a technical perspective.

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INVESTIGATION OF POWER CONVERTERS FOR AC AND DC POWER COLLECTION IN WIND TURBINE SYSTEMS

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A thesis submitted to Nanyang Technological University
in partial fulfillment of the requirements for the degree of
PhD of Engineering

2019

*Dedicated to
my affectionate mother,
my encouraging father,
my loving and supportive wife,
my adorable sister,
family and friends.*

*Remembering: Mr. Irfan Siddiquie
(for his encouragements in engineering research)*

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Abstract

Wind turbine systems (WTSs) have become one of the significant contributors to renewable energy and pledges the formidable reduction of global dependence on fossil fuel. With the overall increase in wind power production, individual wind turbines are also getting bigger producing power rating as high as 20 MW. WTSs are a complex electro-mechanical system, and as the wind turbines are getting bigger, vibration issues are becoming one of the concerning issues. Torsional vibration is one of the dominant contributors of failures pertinent to mechanical aspects which statistically causes the highest downtime to the WTS. Though the electrical system has lower downtime than the mechanical system, the power electronic components in the system add to the highest annual failure rate. As the installation of WTS is on a high in offshore scenarios, the reliability, and failure contingencies become one of the major concerns for the utilities. The research world is continuously striving for solutions in this regards for high power applications. Wind dynamics and grid side disturbances affecting the stability of the system required further analysis more than ever before.

This thesis focuses on both control and topological aspects of WTS. Addressing the challenges in electro-mechanical scenario the active damping techniques of torsional vibrations in WTSs are investigated for a voltage source converter (VSC) based back to back (B2B) WTS. A novel control algorithm for the front end converter called speed difference damping controller (SDDC) is proposed, which reduces the effect of load dynamics and transient torsional oscillations caused due to wind dynamics. SDDC is designed based on segregated control of natural frequency and damping. The appropriateness of the converter control is verified in a comparative forum with other available algorithms. The system is emulated in simulation and experimentation for dynamic conditions from input wind speed, and output integrated grid.

With the high power produced by the large wind turbine generators, the voltage and

current rating for the power electronic converters are very high as well. Traditional semiconductor switches are failing to keep up with the ever-increasing voltage, and current ratings as their physical limits are reached. As a solution, newer elements are being explored and researched alongside advanced converter topologies. Multilevel converter topologies are becoming a popular solution as it accommodates off-the-shelf devices for high power applications. A three-level neutral-point-clamped (3L-NPC) converter is one of the most prominent in the research of multilevel converter topologies for B2B WTS applications. This topology is investigated in this dissertation addressing the dc-link aberrations related to the wind variations and grid-dynamics. The effect of wind variations and grid-side disturbances destabilize the dc-link voltage due to the varying active and reactive power flow demands. This problem is solved by the integration of an energy storage system (ESS) via a bidirectional dc-dc converter. An algorithm is analyzed for the operation of the dc-dc converter. The algorithm for control is implemented first via PI-controller. A simplistic model predictive deadbeat control based dynamic reference tracking method is also implemented for the dc-dc converter current control. The dynamic reference design tracks the dc-dc inductor current reference within one step of predictive horizon making it fast in response. The two control techniques are discussed based on the results of simulation analysis.

Offshore wind farms showcase several advantages over onshore ventures. And going offshore dc-power collection configurations have superiority over ac power collection configurations in many regards. For offshore scenario, converters with simple configuration aiding to lower computational power requirement, lower switch count, simpler cooling system, and higher reliability are convenient and highly preferred. The aspect of simpler generator side converter in the offshore scenario is addressed and thus in this dissertation studies a topology with three-phase diode rectifier with auxiliary circuitry called unity power factor rectifier (UPFR). Considering application in high power scenarios as above, the parallel unity power factor rectifier (PUPFR) topology is proposed as a plausible front end converter for offshore WTS. The control objective of the PUPFR includes the input current control to ensure unity power factor operation which is done using hysteresis current control; current imbalance control between the parallel branches to ensure equal power-sharing, and dc-link voltage control assuring constant dc-link voltage with capacitor voltage balancing. The viability of the converter is investigated in simulation, and the simulation results are validated in scaled-down experimentation for wind dynamics and grid side variations.

In this dissertation, VSC, parallel VSC (PVSC), 3L-NPC, UPFR, and PUPFR are investigated for front end converter topologies for WTS. Component failure based reliability estimation provides an outline or superficial idea of applicability of a power converter in a specific scenario. The component failure based reliability analysis of all the converter topologies discussed in the dissertation is carried out in a comparative platform. The reliability estimation analysis is done based on individual component failure data obtained from a tool book. For the topology of PUPFR and UPFR, an economic feasibility study is conducted, which includes cost-estimations, power loss economics, component failure dynamics, and capacity factor estimation.

Thus it can be concluded saying that the SDDC for torsional vibration decouples the natural frequency control and the damping control providing the system with a higher degree of freedom to the control of the front end converter. Integration of an ESS via a dc-dc converter is analyzed for its control for application in 3L-NPC based grid-connected WTS. A simpler PUPFR is proposed as a plausible topology for high power offshore WTS. Reliability estimation investigation carried out to investigate the applicability and economic aspects of PUPFR application in offshore WTSs.

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List of Acronyms and Notations

A. List of Acronyms

ANPC	Active Neutral Point Clamped Converter
ASVM	Adaptive Space Vector Modulation
B2B	Back-to-Back
BSB	Bidirectional Switching
DFIG	Doubly Fed Induction Generator
ESS	Energy Storage System
GSF	Generator Speed Feedback
HCC	Hysteresis Current Control
IGBT	Insulated Gate Bipolar-junction Transistor
MPC	Model Predictive Control
MPPT	Maximum Power Point Tracking
MTBF	Mean Time Between Failure
MTTF	Mean Time To Failure
NPC	Neutral Point Clamped
PI	Proportional Integral
PMSG	Permanent Magnet Synchronous Generator
PR	Proportional Resonant
PUPFR	Parallel Unity Power Factor Rectifier
PVSC	Parallel Voltage Source Converter
SCIG	Squirrel Cage Induction Generator
SDDC	Speed Difference Damping Controller
SVM	Space Vector Modulation
UPFR	Unity Power Factor Rectifier
VIDC	Virtual Inertia Damping Controller
VSC	Voltage Source Converter
WRSG	Wound Rotor Synchronous Generator
WTS	Wind Turbine System

B. List of Notations

δ_{res}	Damping ratio
λ_{igbt}	Failure rate of IGBT
$\lambda_{p.d.bsb}$	Failure rate of BSB
$\lambda_{p.d.rec}$	Failure rate of passive three phase diode rectifier
ω_g	Wind turbine generator speed
ω_{res}	Resonant frequency
ω_t	Wind turbine speed.
B_i	Damping co-efficient
C_1 and C_2	Upper and lower dc-link capacitors
C_F	Capacity Factor
E_C	Actual Output Energy of Wind Turbine System
E_R	Rated Output Energy of Wind Turbine System
f	Frequency
$i_{gen-(abc)}$	Generator Output Current
$i_{sw-(abc)}$	Current through switches
J_i	Inertia
K_i	Stiffness co-efficient
K_i	Integral control gain
K_p	Proportional control gain
P	Number of Poles
P_{gen}	Generator output power
T_{comp}	Compensating torque
T_s	Sampling time
T_g	Generator torque
$v_{dc.ref}$	dc-link reference voltage
v_{dc}	dc-link voltage
$v_{gen-(abc)}$	Generator Output Voltage
$v_w ind$	Wind speed

Chapter 1

Introduction

The first chapter contains the trends in the renewable energy industry with a focus on the promises of wind energy as a dependable power source for the future. The overview of wind power industry and its development is presented in respect to some statistical data. The aspects and promises of the wind turbine inciting to the motivation of this research are stated. The major contributions of the dissertation are summarized. Finally the overall organization of the thesis is described in detail.

1.1 Contemporary Wind Power Industry

The power industry is focusing on accommodating renewable energy sources to curtail the adverse effects of fossil the fuel based power industry. The year 2017 marked the largest annual increase of renewable power generation capacity, with approximately 178GW installation completed worldwide [1] Fig. 1.1 represents the estimate of the renewable energy share of global electricity production. Overall, there is an increase of 7% of net addition of renewable energy to global power capacity in 2017 compared to the preceding year. [1] Worldwide renewable power capacity is estimated to appease 26.5% of global electricity demand, with wind power providing about 5.6%. [1]

Wind power has emerged to be one of the most feasible renewable sources of energy. In the last few decades wind power production has escalated from 6MW in 1996 and is expected to reach up to 800GW by 2021 [8]. This surge in the wind energy sector is realized by virtue of the increased capacity of individual wind turbine systems

Figure 1.1: Estimate of renewable energy share of global electricity production by the end of year 2017 [1].

(WTS). Presently industries manufacturing wind turbines generators are capable of production of generators rated as high as 10MW [9] and it is expected to double in the coming decade [2]. Fig. 1.2 presents the evolution of WTSs in terms of its size and generation capability. With these mammoth wind turbines built with startling power ratings, the power electronics industry for power conversion faces a constant challenge. The high current and high voltage rated devices are reaching horizons of its physical operating range commensurate with the wide band gap semiconductor-physics limitations. New devices based on experimental semiconductor ores are getting popular and is widely researched. [10,11]

Figure 1.2: Chronological development of wind turbines in terms of size and power rating [2].

In terms of the annual wind power capacity installations, the last two terms of 2015-2016 and 2016-2017 were fairly modest. But still, this sector has gone through its

third strongest annum where above 52GW of generation capacity has been added globally. These data are depicted in a comparative bar diagram in Fig. 1.3. The rise in the market is highly influenced by contraction of Chinese wind power expansion but Europe and India had record years. The encouraging factor has been the continuous trend towards greater market diversity with the influx of several smaller markets globally.

Figure 1.3: Cumulative and annual global installed wind capacity from 2001 to 2017 [3]

With the availability of consistent and high wind speed, offshore WTSs are being preferred over the onshore options. Offshore wind farms are now fairly mature in Europe in terms of technicality and market reliance. It has taken the shape of an alluring investment option for individuals and commercial institutions. Cumulative offshore installations have been in steady increase for 5 years from 2011, but there has been a substantial upsurge in 2017. Going offshore, wind turbines experience challenges of maintenance, installations, and power transmission. Reliability of the power electronic converters become a major concern. Recent trends for complex front-end converters are investigated for their ruggedness in such scenarios. For transmission of power, dc-power collection and high voltage direct current (HVDC) transmission are gaining popularity due to numerous advantages over the high voltage alternating current (HVAC) transmission system but its technological maturity is still under scrutiny [12, 13].

Overall, the escalating market of wind power is highly motivating. With the leveled cost of energy (LCOE) coming down, wind power can play an important role com-

bating the high carbon dioxide level of the world. There are challenges to address in terms of installation time, LCOE, fault ride through, grid integration, accommodation of power converters in the nacelle of high power turbines, electromechanical faults, incorporation of the energy storage systems (ESSs), etc. This dissertation represents the research work addressing the challenges in term of power electronic converters, control, ESS, converter reliability and electromechanical aspects.

1.2 Research Motivations

The wind is an auspicious source of renewable energy and carries a promise of a greener future. Belonging to a country with a shortage of power, my initial research interest has always been towards sustainable and renewable power sources. The prospects of wind power, it's availability, it's capability of high power production from each turbine and the maturity of the associated technology motivates this research. The dissertation has evidence of motivation in regards to the understanding of the power converter configurations, electromechanical interactions, wind farm power collection schemes, and control schemes. The urge to propose new technologies with the aim of improving the prevailing WTS status is another general motivation of the research work performed.

Vibration related issues have always accompanied wind turbines irrespective of its application. Along with it the wind turbine systems being a complex electromechanical system brings in several operational adversities. In variable speed WTS, effect of wind variations has implications in both electrical and mechanical aspects. One of such mechanical phenomenon is torsional vibration in the drive train of the WTS. In order to obtain the vibration mode, the drive train characteristics, electrical coupling with grid and load characteristics can be investigated. Eagerness to address these problems in high power, grid connected WTS has been one of the driving motivations of this dissertation.

Wind has always been a stochastic source of energy. With a high penetration of wind power into the grid, the challenges of grid integration have always been a major research focus. The anomalies of grid and wind speed variations can be addressed via innovative power electronic control and application of energy storage systems. Addressing wind dynamic issues with the application of ESSs is one of the motivations

for this work.

Wind speed variability in an offshore scenario tends to be lower compared to the offshore situations. The aspects of space concern, wind speed variations, landscape aesthetics and close human proximity has made offshore wind farms popular and feasible for future generation unit expansions. In the offshore scenario, the transmission of power in high voltage dc (HVDC) links provides advantages over HVAC. Factors of a longer converter lifetime and simplicity of converter in offshore scenarios are also very essential. These challenges invoke inspiration for further investigations and if possible provide solutions with advanced topologies and control.

The converters used in WTSs are all prone to faults and failure. These faults are both instigated by mechanical and electrical anomalies. For utilities investing in offshore wind farms, these factors play a major role. The implications of converter reliability and feasibility have also been a motivation for this dissertation.

1.3 Research Objectives

The principle objective for this research is the instigation of power electronic applications in wind turbines and its improvements. The objectives of the dissertation can be laid down in points as:

- Understanding the operation of a wind turbine system from both electrical and mechanical perspectives.
- Modeling of wind turbines for replicating the rotating torque translated from kinetic energy. The rotating torque emulates the input to generators in WTS. Simulation of the model of wind turbine.
- Analyzing the advantages and disadvantages of ac-power and dc-power transmission for different modes of wind power collection in offshore and onshore scenarios.
- Detailed analysis of popular power converters for suggesting improvements to curtail wind dynamics and grid variations. Addressing the problem from the electromechanical perspective, the objective is to introduce a control algorithm to mitigate torsional vibrations.

- From power electronic perspective investigate probable integration of energy storage system, to lessen the effects of wind variations and grid faults.
- Suggest a simplistic power converter topology for high power high current generators in offshore WTS. The converter simplicity would be defined by the operation, control computational load and number of semiconductor switches associated with a given topology.
- Investigate plausible techniques to accommodate power converter topologies with lower voltage or current rating so as the physical semiconductor limits are not challenged.
- A detailed assessment of different power converters in terms of reliability and economic feasibility to determine the most plausible front end power converter for a WTS.
- Development of an experimental setup for validating different results proposed in theoretical or simulation analysis.

1.4 Major Contributions

The research objectives have been addressed in details rendering to several contributions in this dissertation. The dissertation has two directions, first is the investigation of an active power converter based WTS and the second is passive rectifier based WTS. The dissertation finally concludes with a overall converter topology study in terms of their reliability. The major contributions of this thesis are given below in a summarized manner.

□ Active electromechanical vibration damping in VSC based back to back Wind Turbine Systems.

The damping control and natural frequency control of back to back voltage source converter based wind turbine system is studied. A convoluted novel control technique called speed difference damping controller (SDDC) for a WTS is proposed. In this work the effect of load dynamics and transient torsional oscillations in a WTS is reduced the utilizing proposed SDDC. A detailed theoretical analysis is carried

out. Simulation and hardware experimentation of the proposed controller is tested for different case scenarios in a detailed multi-inertia model that emulates a WTS drive-line. A comparative analysis along with a parametric variation uncertainty analysis is performed for the available and proposed controller.

Author publication:

- J. K. Kambrath, **M. S. U. Khan**, Y. Wang, A. I. Maswood and Y. Yoon, "A Novel Control Technique to Reduce the Effects of Torsional Interaction in Wind Turbine System," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*.

□ **Parallel Unity Power Factor Rectifier Operation for Wind Turbine Systems**

Parallel operation of a passive rectifier with an auxiliary circuit is proposed for the application of dc-power collection in offshore wind power systems. The proposed system topology is controlled with the objective of a constant dc-link voltage with balanced capacitor voltages under all operating conditions. The generator output current is controlled to ensure unity power factor operation. This is achieved by hysteresis current control and it ensures a balanced current division between the parallel branches making the topology viable for higher generator current applications.

Author publication:

- **M. S. U. Khan**, A. I. Maswood, M. Tariq, H. D. Tafti and A. Tripathi, "Parallel Operation of Unity Power Factor Rectifier for PMSG Wind Turbine System," in *IEEE Transactions on Industry Applications*, vol. 55, no. 1, pp. 721-731, Jan.-Feb. 2019.

- **M. S. U. Khan**, A. I. Maswood and M. Tariq, "Operation of parallel Unity Power Factor Passive Front End rectifier for PMSG based offshore wind turbine system," *2016 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES)*, Trivandrum, pp. 1-5.

- **M. S. U. Khan**, A. I. Maswood, K. Satpathi, M. T. Iqbal and A. Tripathi, "Analysis of Brushless Wound Rotor Synchronous Generator with Unity Power Factor Rectifier for Series Offshore DC Wind Power Collection," *IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society*, D.C., USA, pp. 1693-1698.

□ **Componet failure based reliability estimation study for front end converters in Wind Turbine Systems.**

The converters (PUPFR, UPFR, 3L-NPC, 2L-VSC and parallel 2L-VSC (PVSC)) studied in this dissertation are compared based on the reliability and economic feasibility in order to determine the most convenient front end converter topology for a wind turbine system. The reliability is equated based on the calculation of failure rate for individual components in the converters to quantify the overall converter failure rate, mean time between failure and availability. Then two converter topologies with least failure rates are selected for power loss analysis and analysis in terms of economy. Detailed economic analysis is carried out based on the initial cost of the selected component, operational cost, power loss, and economic analysis.

Author publication:

• **M. S. U. Khan**, A. I. Maswood, M. Tariq, H. D. Tafti and A. Tripathi, "Reliability and Economic Feasibility Analysis of a Novel Parallel Unity Power Factor Rectifier for Wind Turbine System," in *IET Renewable Power Gen.*.

□ **Analysis of integration of ESS with three-level neutral-point-clamped converter-based back to back Wind Turbine Systems.**

A full-scale 3L-NPC converter is analyzed in simulation based study for a grid-connected wind turbine system. The proportional resonant controller, along with adaptive space vector modulation, were implemented as a control technique for the rectifier and the inverter. This work focused on curtailing effects of the wind speed variations and grid dynamics via integration of an energy storage system at dc-link through a bidirectional dc-dc converter. The viable topology of dc-dc converter is selected. An plausible algorithm is tested for the control of the selected the dc-dc converter. The algorithm is implemented with conventional PI control and a model predictive control based dynamic reference tracking control technique is designed, implemented and compared with the PI-controller performance in simulation studies.

Author publication:

- **M. S. U. Khan**, A. I. Maswood, H. D. Tafti, M. M. Roomi and M. Tariq, "Control of bidirectional DC/DC converter for back to back NPC-based wind turbine system under grid faults," *4th International Conference on the Development in the Renewable Energy Technology (ICDRET)*, Dhaka, 2016, pp. 1-6.
- **M. S. U. Khan** (2018), Multilevel Converter based Wind Power Conversion, In Maswood, A. I.(Ed) and Tafti, H. D. (Ed) *Advanced Multilevel Converters and Applications in Grid Integration*. Hoboken, NJ: Wiley; 2018.

The contribution of the author in terms of publications are associated with the corresponding chapters through the tabular representation represented below in Table 1.1.

Table 1.1: The association between thesis chapters and author publications. The numbering refers to the section - List of Publication^[7.3]

Chapter Number	Author Publication Number
2	[1]-[7]
3	[2]
4	[4,5]
5	[1,6,7]
6	[3]

1.5 Thesis Organization

The research presented in this dissertation is organized in thesis format expanded through 7 chapters. The schematic outline of thesis organization is shown in Fig. 1.4. Furthermore, a short summary of individual chapters is chronologically arranged below:

Chapter 1: Overview of the wind power industry and future promises are presented in this chapter. The research motivations inspired by the promises are presented followed by the research objectives and the major novel contributions in this dissertation. This chapter ends with the description of the thesis organization.

Chapter 2: This chapter reviews the state-of-art wind turbine system, its configuration types and modes of power collection. This chapter also includes details of

Figure 1.4: Outline of the dissertation organization

the electromechanical domains of WTSs. The reliability study methods of power converters based on individual component failure modes are summarized as well.

Chapter 3: This chapter focuses on the electromechanical iterations specifically torsional vibrations in WTSs. A control algorithm for a voltage source converter based front end rectifier called speed difference damping control (SDDC) is proposed. SDDC reduces the effect of load dynamics and transient torsional oscillations caused by wind dynamics. The proposed controller is compared in detail with other available controllers in the literature. The controller operation is validated in simulation for various case scenarios. An experimental hardware setup is established and the case scenarios are validated.

Chapter 4: This chapter discusses the implementation of a full-scale back to back three-level neutral point clamped converter, for grid-connected wind turbine system. The converters are controlled based on established techniques of proportional resonant and adaptive space vector modulation techniques. The system discussed is supported by a energy storage system (ESS) connected at the dc-link. The ESS is connected via a bidirectional dc-dc converter. The dc-dc converter is controlled for active/reactive power injection to the grid or active power storage during grid and wind speed dynamics. A bidirectional dc-dc converter is selected and controlled via

proportional integral (PI) and predictive deadbeat controller. Simulation results of the different operating condition and system performance with different controllers are analyzed.

Chapter 5: This chapter introduces a detailed analysis of an auxiliary circuit based three-phase diode rectifier and proposes the parallel use of the converter topology for dc-power collection in offshore WTS. The control of the converter is performed based on hysteresis current control and dc-link voltage control. The simulation investigates dynamic scenarios which could disrupt the converter operation and control. The hardware experimentation validates the simulation study in a 2.5kW laboratory setup.

Chapter 6: This chapter focuses on the component failure based reliability estimation analysis of the converter topologies discussed in the thesis. The analysis is carried out in a comparative forum. VSC, PVSC, 3L-NPC, UPFR, and PUPFR are equated for failure probability depending on individual component failures. The reliability analysis is based on the data provided in MIL-HDBK-217, Military Handbook, Reliability Prediction of Electronic Equipment. For the analyzed topology in Chapter 5, the economic feasibility, power loss implications and capacity factor are analyzed.

Chapter 7: The main contributions of the thesis are summarized and concluded in this chapter. This chapter includes possible future works to the dissertation in different paradigms. Chapter 7 is followed by the List of author's publications and Bibliography related to this dissertation.

Chapter 2

Literature Review

This chapter reviews the available research studies in the literature about WTS. Firstly, the basic concepts and types of the WTS are reviewed. The wind turbine model used for the later chapters is designed and discussed in details. This chapter reviews different types of power converter topologies which are already established, trending and promising for application in offshore and onshore scenarios. The challenge of vibrations faced by wind turbine system is also reviewed in terms of different control algorithm available. The method of reliability analysis of the power converter of the WTS is also presented. The chapter ends with a summary focusing on the identified research gaps from the literature review.

2.1 Basic Concepts of Wind Turbine System

The wind is one of the basic elements of nature, and it is available all over the world. The behavior of wind varies geographically. Based on its availability, the wind speed has been utilized historically for irrigation, heavy object relocation, transportation in navy and aviation, whatnot. The wind has also been utilized for electrical energy production. Wind turbine systems convert the kinetic energy of incident wind into rotational mechanical energy. This rotational energy is fed to the generator as input to produce electrical power. Two main configurations of WTS are popular and prevailing in the industry; vertical axis wind turbines (VAWT) and Horizontal axis wind turbines (HAWT) [14]. Both have their share of advantages and disadvantages. For large scale industrial application there are several obstacles for VAWTs. Inherently

VAWTs are not as sturdy as HAWT. Though VAWT has fewer components, it is prone to higher wear and requires periodic repairs. Thus HAWT are widely installed for high power onshore and offshore wind power applications.

For the configuration of HAWTs, the blades are connected to a central hub and the hub is attached to the top section of the tower. The nacelle contains the drive train, generator, and the power conversion devices. Based on voltage rating the WTS can be categorized into low voltage (LV) and medium voltage (MV) [15]. Based on the region of installation, the definitions of LV and MV varies as shown in Table below:

Table 2.1: Region Classification of voltage levels [7]

Region	Standard	Voltage Class
Europe	IEC60038	Low Voltage Class ($< 1000\text{V}$): 220, 400, 690V
		Medium Voltage Class (1- 35kV): 3.3, 6.6, 11, 22, 33 kV
North America	ANSI C84.1	Low Voltage Class ($< 600\text{V}$): 208, 120, 120, 480, 575V
		Medium Voltage Class (600 to 35kV): 2.4, 4.16, 6.9, 12.47, 13.81, 21, 34.5kV

The wind is a stochastic energy source. Based on wind speed, there are three defined zones of wind turbine operation. They are (i) cut-in speed, (ii) rated speed and (iii) cut out speed. These zones of operation are depicted in Fig 2.1. The values in x -axis refer to the general standard value of wind speed for WTS operation.

Figure 2.1: Wind speed operating range [4]

Higher wind speed does not always result in higher power produced. Other than the

limitation of generator rating, there is another factor called the Betz limit. Betz limit is defined by the amount of power which can be extracted by any wind turbine from incident wind flow. Theoretically, the limit is can me calculated as $\mu = 16/27 \approx 59\%$. This Betz-limit is the theoretical maximum efficiency at which a wind turbine can convert the incident linear wind power into rotational power. The minimum speed for which the wind turbines generates usable power is called the cut-in speed. Rated speed is the constant zone of power production from the WTS where the system produces the rated power. Out of range wind speed are adverse for both mechanical and electrical equipment associated with WTS. The cut-out speed or furling refers to the speed beyond which wind power production is at a halt.

2.1.1 Major Components of Wind Turbine Systems

A WTS consists of generally two types of components: Electrical and Mechanical. The mechanical components are comprised of the tower, rotating blades, nacelle, gear box, pitch drive, yaw drive and few controlling equipments [14]. The electrical sector in this case is made up of mainly the generator and power converters. Based on different configuration there are harmonic filters, power conditioner devices, etc. Thus WTS has a complex electromechanical control platform.

The three bladed rotors are more unproblematic in terms of their vibrational behavior and thus suitable for gigantic high power WTS [16]. The nacelle includes the electrical generator and power converters providing them with the exoskeleton protecting the electrical equipment. The heavy nacelle suspended over the tower provides a balance to the heavy rotating blade dynamics. The high power turbines run at a low speed and high torque. Generators are coupled via a gearbox. Gearbox requires maintenance and cause reduced lifespan and efficiency. Such characteristics are highly implausible for offshore scenarios. Torsional vibration reduction and mechanical damping is required to extend the operating lifetime of the WTS. Wind generators with no gearbox and direct coupling are called direct-drive WTS. Such system alleviates the complexities of the gearbox. The low rotating speed is compensated by bigger and heavier generators [17].

Several types of generators have been proposed and investigated for WTS. Based on the variation of application and power rating, different generators are selected for

different WTS. Different generators and their comparison are later discussed in this chapter. The generator output varies with wind variation. In order to mitigate the effects of variable speed, various power electronic equipment is installed to condition the power produced and transfer to the grid [2,17]. Later on different types of power converters for wind turbines are investigated in details.

As mentioned earlier WTS is a complex electromechanical system. A detail electromechanical control system is required for the steady-state and dynamic operation. The control is generally implemented via computer-based devices with signal processing ability. General factors of mechanical control are yaw drive control and pitch control. From the electrical perspective, generator torque control, dc-link voltage control and grid integration related control are mainly examined.

2.1.2 Wind Turbine Modeling

Mechanical power obtained from the rotating input of the wind turbine is converted into electrical energy by the generator. The generated electrical power is conditioned by the power electronic interfaces with the aim to keep control of different parameters. The potential power obtained from a wind turbine is represented by the equation,

$$P_{mech} = \frac{1}{2} \rho_w A_T C_p(\lambda, \beta) v_{wind}^3 \quad (2.1)$$

here, $\frac{1}{2} \rho_w A_T v_{wind}^2$ signifies the input power to the wind turbine where ρ_w represents the air density (kg/m^3), v_{wind} represents wind speed (m/s), A_T is the area swept by rotating turbine blades with radius R_T ($A_T = \pi R_T^2 \text{ m}^2$), C_p represents the coefficient of performance and λ is a function of blade pitch angle (β) and tip speed ratio ($\lambda = \omega_r / v_{wind}$). C_p is called turbine power coefficient and it illustrates the overall turbine efficiency ($C_p = \frac{P_{in}}{P_{mech}}$). The power coefficient is a dimensionless measure and this defines the efficiency of a wind turbine in extracting the energy of the incident wind stream. C_p signifies the wind power captured by the rotor blades. Different wind turbine utilities defines the values of C_1 to C_6 and x which depends on the model of the wind turbine [18]. These parameters are used to extract the value of C_p . In equation, C_p which can be modeled as the Eq. 2.2 and Eq. 2.3 [18,19]:

$$C_p(\lambda, \beta) = C_1(C_2 - C_3\beta - C_4\beta^x - C_5)e^{-C_6} \quad (2.2)$$

The values of C_1 to C_6 depend on the different types of wind turbine. The numerical values are considered in accordance to literature that considered similar wind turbine sizing [18, 20]. $C_1 = 0.5$, $C_2 = 116/\lambda_i$, $C_3 = 0.4$, $C_4 = 0$, $C_5 = 5$ and $C_6 = 21/\lambda_i$. λ_i is intermittent tip speed ratio and it is related to tip speed ratio and β . λ_i can be equated as,

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (2.3)$$

Similar to the PV systems, WTS are designed to extract maximum power. WTS was previously designed to be operating at constant wind speed. Advancements in technologies associated with power conversion have made it possible to operate the system in variable wind speed conditions [21]. WTS is expected to operate close to the optimum tip speed ratio (TSR) to attain a maximum coefficient of performance (C_p).

Variation of the rotor speed of the generator varies the TSR of the system. Other common control methods performing maximum power point tracking (MPPT) for WTS are Power Signal Feedback (PSF) control and Hill Climbing Searching (HCS) control [22, 23].

Figure 2.2: Torque co-efficient curve i.e. Lambda vs C_T curve for WTS.

Limitations are there for every energy conversion technology. For heat engines there

is Carnot efficiency, bandgap for photovoltaic cells, Gibbs free energy for fuel cells and for WTS there is a limit for conversion of kinetic energy to mechanical power, which defined earlier as Betz limit. In practicality, the limit is in a range of 40 % to 45% [24].

2.2 Types of Wind Turbine System

Wind turbine generation configuration can be categorized into four types for the different combinations of generator and power converter topologies [24, 25]. These topologies mainly consider AC power collection and transmission. For an MVDC or HVDC type transmission system the configurations would be void of inverters. The types of WTS configurations are listed below:

- Type-A: Fixed speed WTS.
- Type-B: Limited variable speed or semi-variable speed WTS.
- Type-C: Variable speed WTS with partial scale converter.
- Type-D: Variable speed WTS with full-scale converter.

2.2.1 Type-A : Fixed-speed WTS

Shown in Fig.2.3 is the fixed speed WTS, where the SCIG is connected to the grid through a soft starter [8]. A step-up transformer follows soft-starter and the system is free of any power converter interface. For this type of configuration, a gearbox is essential which compensates the rotational speed difference between generator and the turbine. The principle of fixed speed WTS is to maintain constant frequency so as to inject power directly to the AC grid. After generator start-up, the soft-starter is bypassed by a switch, and the system works without any power converter. SCIG draws reactive power from the grid and thus three-phase capacitor banks are pertinent. These WTS require stall control, pitch control, or active stall control [24, 26]. The main feature of this type of configuration is simplicity, low costs and reliability. The key downsides are lower efficiency, variation in the wind speed are directly affects the grid and grid faults cause tremendous stress on the wind turbine.

In order to comply with the grid codes FACTS devices and bulky capacitor banks are deployed [27, 28].

Figure 2.3: Fixed Speed WTS with Squirrel Cage Induction Generator

2.2.2 Type-B : Semi-variable-speed WTS

Variable-speed operation increases the energy conversion efficiency by increasing percentage of wind power capturing ability at higher wind speeds. It also reduces stress on mechanical drive-train caused by sudden wind gusts and thus longevity of the system is increased. As shown in Fig.2.4, semi-variable speed WTS is composed of WRIG which provides 0-10% variable speed operation. Rotor resistance control by slip rings is called Optislip control [29], which ensures optimum slip to maintained for specific wind speed. Like Type-A, this configuration also requires a gearbox, soft starter, and reactive power compensation devices. The system can capture more power but it has higher energy losses contributed by rotor resistance losses. Restricted speed range and low energy conversion efficiency are the main drawbacks of such a system.

Figure 2.4: Semi Variable speed WTS with Wound Rotor Induction Generator

2.2.3 Type-C: Variable-speed WTS with Partial-scale Power Conversion

For Type-C configuration doubly fed induction generator (DFIG) are used. Power from the generator is fed through both stator and rotor windings. Size of the converters is approximately 30% of the nominal generator power [30]. For steady-state operations, this configuration (Fig.2.5) neither require any soft-starter nor reactive power compensation devices. The power converters allow bidirectional power flow in the rotor circuit increasing the speed range of the generator. MPPT operation further increases system efficiency. DFIG based partial-scale WTS is one of the dominating topologies in today's industry with about half of the market share [24, 31, 32]. The major drawbacks of these turbines are limited fault ride through (FRT) capability and high maintenance cost for offshore applications [33].

Figure 2.5: DFIG based variable speed WTS with partial power conversion

2.2.4 Type-D: Variable speed WTS with Full-scale Conversion

The back to back full-scale (100%) power converter topologies gained much popularity for its advantages in grid-connected and standalone AC-AC systems [34]. In such a system, the AC-DC rectifier is followed by a DC-link. The DC-link feeds inverter which connects to AC power collection or any AC load. Full-scale power converter enables generator to be fully decoupled from grid and its disturbances. The transients and aberrant outputs of the generator are not reflected to the grid due to the decoupling of the rectifier and inverter through the dc-link block [35–37] Type-D (Fig.2.6) have advantages over other types in aspects of higher efficiency, fault ride through capability and the capability to accommodate higher power. Back-to-back topologies

are also suitable for low wind speed operations with direct drive system topologies.

Figure 2.6: Variable speed WTS with full scale power conversion

These different types of WTS described above have varying characteristics. Over time the WTSs have matured with higher efficiency, bigger size, higher power density, etc. The types of WTS are represented in a comparative table form below in Table 2.2.

Table 2.2: Comparison of different types of WTS configurations

Wind Turbine Type	Type-A	Type-B	Type-C	Type D	
Generator Type	SCIG	WRIG	DFIG	PMSG	WRSG
Starter	Soft Starter	Soft Starter	N/A	N/A	N/A
Speed Range	N/A	$\pm 10\%$	$\pm 30\%$	100%	100%
Converter	N/A	3-ph Diode and DC/DC OR none	AC/AC OR AC/DC and DC/AC	AC/AC OR AC/DC and DC/AC	AC/AC OR AC/DC and DC/AC
Converter Capacity	N/A	10%	30%	100%	100%
Mechanical Control	Stall & Pitch	Pitch	Pitch	Pitch	Pitch
MPPT	N/A	Partial	Obtained	Obtained	Obtained

2.3 Importance of STATCOM in Full-scale WTS

The surge in the capacity of individual wind turbines, the wind farms voltage at the point of common coupling (PCC) varies with the wind speed for variable wind

speed operation. If not compensated, these variations cause several stability issues and ultimately result in system shutdown. The wind farm operators have been provided with tight guidance to comply with grid codes and thus limit the effects of wind power fluctuations on network quality and stability [38–40].

This voltage instability is caused by the inability of the grid side power converter to meet the reactive power demand of the grid. The solution is provided by various reactive power compensation techniques [41, 42]. One of the optimal solutions for reactive power compensation is the application of a dedicated power electronics unit called static synchronous compensator (STATCOM). Over the years, STATCOMs have proved to be the ideal solution for reactive power compensation by the virtue of their characteristics of fast response, lower harmonic distortion and smaller reactor requirement.

Full scale back to back (B2B) connected wind turbine systems are designed to operate under variable wind speed operation and they are connected directly to supply the ac power grid. WTS equipped with B2B power converters are capable of generating reactive power and thus regulate the voltage of the wind farm PCC. However, the limited current-carrying capability of the grid-side converter imposes a cap on the active and reactive power conversion capability. Thus due to these limitations, a STATCOM would still be a requirement for wind farms with full-scale B2B converters. The STATCOMs in B2B configured WTS would be smaller than regular as the reactive power compensation would be shared between the grid-side converter and STATCOM.

2.4 Wind Power Converters

Wind turbine generators generate electrical power translated from the rotating wind turbines mechanical power. The WTS power converters are mostly deployed in Type C and Type D. The generator side converter is a rectifier which converts the ac into dc charging up the dc-link. The main aim of control of the generator side converter remains speed and torque control. The load side converter or grid side converter is an inverter that converts the dc to ac. The control aspects of the grid side or load side converter is compliance with the grid or load [25]. With time and technological advancement, there have been several converter topologies proposed

for WTS. Innovative topologies are proposed with the aim of increasing efficiency at lower costs. For diverse proposals in literature and industry, a definitive classification of WTS power converters is not possible [8].

2.4.1 Active Converters Topologies

Converters with active switches like MOSFET, IGBTs, etc are called the active converters. Active converters bring in the advantage of controllability over the system. But for high power applications, there are several challenges to be addressed. The active converters are widely discussed in the literature for WTS in both ac and dc power collection.

2.4.1.1 Two level Voltage Source Converters(2L-VSC)

Formed with six semiconductor switches, the two-level voltage source converters (2L-VSC) are popular for B2B topology for full-scale power conversion. The dc-link in between the inverter and rectifier is made of series and parallel capacitors. 2L-VSC are known for its simplicity, technological maturity in low voltage applications and high efficiency. As discussed earlier, full scale power conversion can be realized by the use of PMSG, WRSG and also SCIG [34, 43, 44]. B2B topology is also be used for Type-C WTS with DFIG [30] where the required converter rating is lower than other types of WTs. The dc-link decouples the generator from the grid. 2L-VSC are suitable for low voltage and low power level.

Figure 2.7: Voltage source converter in B2B topology used for WTS

In higher power applications, 2L-VSC can be applied in parallel networks or by connecting the switching devices in series. Parallel networks with independent dc-link give the system higher modularity but it adds in complexities like circulating current, power imbalance and bigger nacelle for converter related circuitry accommodation

(gate-drivers, heat-sink, etc) [45]. With a common dc-link or using an open winding transformer at the grid side, the intricacy of circulating currents can be avoided [46,47]. Connecting switching devices in series does make the system applicable for MV level, but the physical mismatch between the IGBTs make this solution further challenging in terms of practicality [48].

Figure 2.8: Paralleled back to back VSC in WTS: (a) with individual dc-links and (b) with common dc-link.

These types of power conversion topologies are operable with all types of WTS. For the 2L-VSC topologies, switching losses are dependent on the switching frequency and it is maintained within a range of 1-3 kHz to achieve lower losses [43]. In order to meet the grid codes requirements specially to ensure the FRT ability of the system, grid side filters are used.

2.4.1.2 Multi-level Voltage Source Converters

With high power high, medium voltage and high current rating for gigantic generators installed, WTS utilities have made it a compulsion for the research industry to bring about alternate converters topologies. Various types of multilevel converters are proposed in literature but few of them are commercialized bringing in industrial challenges of implementation. Some of the multilevel VSC popular in research and has applicability in WTS are neutral point clamped (NPC) converter, flying capacitor (FC) converter and active neutral point clamped (ANPC) converter [49,50].

Three level NPC (3L-NPC) or diode clamped multilevel converter topology has been widely addressed in several research articles as one of the most promising WTS con-

verter topology [51–56]. One NPC converter unit has six sets of dual series-connected IGBTs. The midpoints of the IGBTs are clamped with dual series of diodes. The midpoint of the clamped diodes meets at a common point which is generally connected to the mid point of two dc-link capacitors. 3L-NPC converter has three level of ac power thus it brings in the advantage of reduced filter size for grid-connected operations [57–61]. Using 3L-NPC as the generator side converter adds size reduction advantage of a step-up transformer. There are various controller algorithms proposed for 3L-NPC, but with space vector modulated (SVM) pulse width modulation technique, the redundant switching state selection can be avoided. Being high voltage converter module, 3L-NPC converter can support 6MW. For similar power range around 10 parallel branches of 2L-VSC would have been required. Alongside the advantages, there are few drawbacks of this topology. With this high number of switching action capacitor voltages balancing becomes a challenge [51, 62–65]. Imbalanced capacitor voltages pose higher stress of switches affecting operation and lifetime. Literature provides a solution to this problem with use of external hardware [66]. In nacelle of WTS, the addition of any other hardware means larger size and way higher cost of production, installation, and reduction of system reliability. With various modulation schemes this problem can also be addressed. Carrier based pulse width modulation (CPWM) with zero-sequence voltage injection is a plausible solution. Space vector modulation or adaptive space vector modulation techniques also provide solutions in this regard [61, 67, 68]. But adhering to high switching frequency the converter switching loss increases drastically [69].

Replacing the clamped diodes in NPC converters with capacitors gives us the multi-level converter topology called flying capacitor (FC) converter [70–72]. FC converters are simple in configuration and bring in the advantage of easier dc-link voltage balance and redundant switching states [73]. But the requirement of pre-charging circuits of all capacitors makes a topological hassle and the reliability in heavy duty is questionable. Though promising, this topology has not yet been commercially implemented for WTS applications.

Issues like uneven power loss and problems related to variable frequency in NPC can be eliminated by replacing the clamping diodes with active switches i.e. IGBTs. This gives the converter freedom to sustain with equal switching frequency avoiding the mismatch. This topology is termed as ANPC converter [71].

Figure 2.9: Popular multilevel back to back converters researched for grid connected WTS: (a) 3L-NPC, (b) 3L-ANPC and (c) 3L-flying capacitor converter.

Some of the other multilevel topologies investigated in literature are four-level NPC (4L-NPC), five-level, seven-level and nine-level ANPC (5L-ANPC, 7L-ANPC and 9L-ANPC) [59, 74]. A higher level of NPC and ANPC converters aid to reduced filter sizing but the voltage stress for the semi-conductor switches remain the same. Using such a high number of active switches increases failure contingencies and the complex control required demands higher computational ability of the system. Such converter topologies could be considered for onshore applications for its advantages in grid integration but realizing it for the generator side converter in the offshore scenario is superfluous and impractical.

2.4.1.3 Current Source Converters

In current source converters (CSC), the polarity of the dc-side current is retained and thus the power flow direction is determined by the dc-side voltage polarity [25]. CSC has a dc-link for B2B operation which eventually decouples the generator from the grid. Unlike VSC dc-link in CSC is formed of dc-choke. CSCs have certain advantages during fault scenarios, slightly lower cost of production and even lower maintenance cost. But CSC has slower dynamics due to lower switching frequency operation of the bulky dc-choke operation in high power applications [8]. The CSCs

are already applied in high power drive applications but it has not yet been adapted for the WTS applications [75].

2.4.2 Passive Converters Topology for WTS

Three-phase uncontrolled diode-rectifiers are most simple and rugged front-end converter topology. Diodes being the most basic, available, and sturdy power electronic devices make the passive rectifier a good choice for high power applications. Power flow in WTS is unidirectional. The power produced from the generator is supplied to the grid. Thus in order to make generator side converters simple and more reliable, the passive uncontrolled diode rectifiers are also applicable for WTS as they are also unidirectional [76–78]. PMSG and WRSG can actually accommodate these rectifiers as do not need magnetizing current but SCIG has restriction on using passive generator-side converters. Reduced complexity in topology leads to simpler control complexity as well. Higher cost-cutting can be achieved for savings in simpler control platform and the lesser number of gate drivers associated. The diode bridge rectifiers have some serious disadvantages as well. They have an innate characteristic of injecting current harmonics in the system, which raises the THD of the system. Using it as generator end rectifier will result in electromagnetic torque ripple. Though the torque ripple is not translated to inverter output, it reduces the lifetime of generator [79].

Twelve-pulse passive series type or parallel rectifier improves the harmonic performance [80]. In order to accommodate it, the power needs to be conditioned with passive filtering and bulky generator side transformers. This is not at all acceptable for offshore WTS.

Passive rectifiers can also be deployed accompanied by a dc-dc converter [8, 81] as shown in Fig. 2.10(a). This gives some controllability to the front end converter of the WTS. The dc-dc converter is used to control for MPPT. based on the power level the dc-dc converter can be chosen to be of multilevel topology [57]. Though this topology provides controllability the passive rectifier still distorts the generator output current and causes the torque ripples.

The Vienna rectifier topology proposed by Kolar [82]; provides unity power factor operating rectifier with three semiconductor switches. Research has considered these

Figure 2.10: Passive three-phase diode rectifier based power electronic converters for front end generator converter applications in WTS : (a) 3-phase diode rectifier followed by dc-dc converter, (b) 3-phase diode rectifier with auxiliary circuit for UPF operation and (c) Vienna type UPF rectifier.

topologies for the application of WTS as well as shown in Fig. 2.10(c). [83,84]. But for this type of converters, any switch related fault associates with the dismantling of the converter and thus higher downtime is always on the cards. Another variant of Vienna rectifier is available which has two anti-parallel switches connected to form a bidirectional switching link between the input and mid-point of dc-link. But the number of switches used is same as VSC. These topologies have been considered for high power applications [85,86]. Literature [76,87] supports the topology to be a better performing rectifier over the 2L-VSC due to its improved THD performance with lesser number of switches involved. Aditya in [6], proposed a UPF rectifier topology to be used as front end converters for WTS depicted in Fig. 2.10(b). This topology has been primarily conceptualized and published by Mehl and Barb in [88]. For this UPF rectifier (UPFR) the primary ac-dc conversion is done by three-phase diode rectifier. This topology has bidirectional switching blocks (BSB) as the auxiliary circuits. These BSBs are used to control the rectifier and improve the THD and PF as compared to the three-phase diode rectifier topology. Furthermore, commuting major percentage of power through the diode rectifier provides more rigidity to the system [89–93]. These rectifiers have similar power circuit as Vienna rectifier and have similar THD performances. But it is more suited for offshore wind power systems as separate BSB administer modularity in comparison to Vienna rectifier and lower switch count compared to its variants.

The topology proposed by Aditya [6] for stand-alone system is promising and can be further investigated for high power grid-connected or dc-power collection applications. For high power application, this topology can be used in parallel. Such operation has not yet been addressed in the literature.

2.5 Overview of Power Converter Control in WTS

Diodes are semiconductor devices that work on natural commutation. Diodes connected in a certain format aided to the creating of three-phase diode rectifiers. As like as its unit component, the diode rectifiers are also naturally commuted and does not require external control. Various ratings of such rectifiers can be designed based on the physical characteristics of the semiconductor but controllability is null. With controllable high power inverter, diode rectifiers are still a good choice of front end rectifier topology for wind turbine systems. In quest of controllability in power electronic devices, several semiconductor switches have been developed [94–98]. One of the simplest of the device providing controllability is thyristor. By controlling the firing angle of thyristor gates the output voltages can be controlled [99]. But thyristor has the drawback of the controlled turn-on but the turn-off is naturally controlled based on the line frequency. Thyristor controlled rectifier based WTSs have been implemented and studied but it has the shortcoming associated with its characteristics. Insulated-gate bipolar transistors (IGBTs) are the next upgraded categories of power devices which are completely controllable [97]. Numerous other semiconductor devices have been engineered for their plausible applications in power electronic devices. Few of such devices are the insulated gate commutated thyristor (IGCT), gate turn-off thyristor (GTO), metal oxide semiconductor field effect transistor (MOSFET) and many more. With the availability of control over the switches the control theories and supporting platforms have evolved at a quick pace as well.

Proportional-integral (PI) controllers are most commonly used along with different modulation schemes like pulse width modulation (PWM), selective harmonic elimination (SHE) and space vector modulation (SVM) [61, 100–124]. For using the PI controller, the measured currents are compared to the generated references to obtain the error signal. The error signal is processed by the PI regulators to obtain the reference. The reference signal is compared to the triangular signal to generates the

switching signals for the power converter [100, 109, 111, 112, 125].

Commendable performance of the converter is obtained when the assumed linear model is designed with higher band-width modulation. However, this scenario causes higher switching losses due to high frequency operation. In the application of WTS, this means high computational power for the power converter controller which is not always expected in the industry. If the switching frequency is lowered, the power quality declines and bigger filters are required [126, 127]. This again will cause higher weight for individual WTS which will just add to the burden.

PI and PID controllers are linearized control system which is simpler in regards of the implementation. There are few shortcomings in implementation of PI or PID, as for example, the requirement of multiple frame transformations. Multiple frame transformation results higher computational load and complexity. Due to the steady-state error at the stationary frame, it becomes compulsory to decouple the phase dependency for application in three-phase systems. Stationary reference frame values can be acquired directly from the two independent PR controllers without inverse Park transformation [128, 129].

A hysteresis current control is a nonlinear control method [95, 130–133]. In HCC, input currents are measured and compared with a reference current. The error is tracked within a hysteresis band, and the switching signals are generated. This is an effective and simple concept but widely applicable in WTS. An HCC with PI regulator can provide current shaping, dc-link voltage control and capacitor voltage balancing [78, 93, 134]. The disadvantage of this method is the variable switching frequency. [135]

Several advanced control techniques like sliding mode control, fuzzy logic control, artificial neural network, predictive control, etc are widely studied in literature as plausible solutions to high power electronics [8, 136, 137]. But the high computational load, less sturdy electronic equipment, sensitive components, etc make it a mammoth challenge to apply in remote locations like offshore WTS [138, 139].

2.6 Generators in Wind Turbine System

Doubly fed induction generator (DFIG) based WTS are widely deployed. But with the advancements and flexibility of full-scale power converters, the squirrel cage induction generators (SCIG), permanent magnet synchronous generator (PMSG) and wound rotor synchronous generator (WRSG) would eventually outnumber DFIG based WTS [140–142]. PMSG has been the most popular for its simplicity of operation, smaller size and expansion scale possibilities in terms of variable speed wind power production. Though popular for onshore wind farms, the induction generators require bigger mechanical drive systems composed of multistage high ratio gearboxes making the modules heavy and prone to higher maintenance [143]. Thus for offshore applications synchronous generators are more advantageous. In spite of these advantages, research has been conducted on alternatives of PMSG due to the highly unpredictable market of permanent magnets (PM) [144]. PMs are one of the earliest functional materials. With the discoveries of rare earth material, there was a significant drop in prices. China being main producers (over 95%) of it took advantage of global high demands and created a market monopoly escalating the PM price to its peak [145]. Of all the PM core materials, Nd-based (Neodymium) based ones are most popular. Material research have advanced in with alternative to Nd based PMs, but in order to get similar performance requires challenging environmental conditions which are far fetched from present day practicality. Thus electrically excited synchronous generator (EESG) or the wound rotor synchronous generator (WRSG), is thus gaining much importance as it is free from economic dependence of PM market. Unlike PMSG, WRSG is not very robust but it has added a degree of freedom of field control. SCIG is also advantageous in this regard as the capital cost is low, no dependence on PMs, etc. A detailed comparison between the generators is provided below in Table 2.3.

From the current market trend and advancement in technology, it is obvious that most of the Type-A deployed system would soon be outnumbered and replaced by SCIG, PMSG or WRSG based WTS. Thus in this dissertation 3 types of promising generators would be investigated in different operating scenarios, for the diversity of applications and in-depth knowledge in this field.

Table 2.3: Comparison of different types of generators in WTS

Type	Advantages	Disadvantages
SCIG	<ul style="list-style-type: none"> *Cheaper generator construction expense. *Simplistic rugged machine. *Higher availability for large scale applications *Efficient in damping pulsating torque for wind gusts. *Comparatively smaller and lighter. *Can achieve high output levels without increasing size *Lower maintenance cost. 	<ul style="list-style-type: none"> *Full scale converters required. *High rated converter resulting in higher converter power loss *Requires reactive power and thus increasing converter complexity *High inrush current once connected to grid.
PMSG	<ul style="list-style-type: none"> *Speed regulation achievable without gearbox *High torque achievable at low speeds. *No requirement of excitation system. 	<ul style="list-style-type: none"> *High production cost depending on the unstable PM market. *Unpredictable forecast of future rare earth PM availabilities. *Damage due to demagnetizing PM in case of severe overloading and short circuit. *Use of only passive diode rectifier reduces the controllability.
WRSG	<ul style="list-style-type: none"> *Low mechanical wear due to slow machine rotation *Direct drive can further reduce cost with gearbox elimination *Allow reactive power control as reactive power injection in not required. *Independent control of both real and reactive power 	<ul style="list-style-type: none"> *Synchronizing relay required for proper grid synchronization. *Higher maintenance costs than that of an IG * Small PM dependence for exciter machine. *Added control complexity due to excitation control.
DFIG	<ul style="list-style-type: none"> *Lower rated converter required *Lower converter losses due to low rated converters 	<ul style="list-style-type: none"> *Susceptible to grid dynamics and failures. *Higher expense of generator production than IG. *Higher maintenance due to use of slip ring. *Not viable for offshore wind farm applications.

2.7 Basics of Wind Power Collection

As discussed each wind turbines producing high power, challenges of power collection have prevailed since the beginning. Primarily, the Type A WTS would not operate in varying wind speed to be able to synchronize with the grid directly. With variable speed operations, the challenges of grid integration is taken up by advanced power electronic devices. Due to ease of installation, WTS used to be installed onshore and the generation plant is referred as an onshore wind farm. In onshore scenario ac-power collection with high power inland heavy power conditioning devices was more feasible and practiced [13,146]. Offshore wind power prospects are even more alluring. In the offshore scenario, the wind is steady and stronger. The visual impacts and noise pollution does not also affect the neighboring human habitat [147,148]. Several interconnections of WTSs are proposed in literature. Based on the type of power given by the WTS for transmission, the wind farm configurations can be broadly categorized in two sections: (i) ac-power transmission or collection (ii) dc-power transmission or collection.

Type A, B, and C WTS configurations can be interconnected for ac power collection. But for dc coupling and dc-power collection, only Type D WTS can be deployed. Type of power transmission to be chosen also depends on the distance between the grid and wind farm.

2.7.1 AC-power Transmission / Collection

The ac-power collection or transmission is mostly viable for onshore WTS. Wind farms output power can be transmitted to the grid via high voltage alternating current (HVAC) links using step-up and step down transformers in places required. For offshore wind farms placed several kilometers into the sea, such scheme is not viable as additional static compensator (STATCOM) or other heavy power electronic devices are required at both ends of the HVAC line for efficient power transmission [4]. This affects the reliability and feasibility of the overall system as well. One of the challenges for WTS grid integration is to meet the grid codes and assess the behavior of the system for grid side dynamics [149,150]. Grid codes include active and reactive power control for frequency and voltage regulation, power quality aspects, fault ride through behavior and system protection.

Figure 2.11: ac power collection: (a)ac power collection with HVAC link and (b)dc power collection with HVDC link.

Thus for grid connected system it is imperative to investigate the effect of grid dynamics and input wind dynamics on the WTS transients.

2.7.2 DC-power Transmission / Collection

Several dc-power transmission configurations are implemented in offshore wind farms. Back to back power converters are considered for parallel ac based high voltage direct current (HVDC) transmission. For this type of configuration current source or voltage source converters can be used. For high power wind turbines, advanced multilevel converters or paralleled two level voltage source converters are used [12, 151].

For the case of dc-power collection, there are few added advantages. Firstly, the inverters for the dc-ac power conversion can be placed onshore. This reduces the

offshore wind turbine system nacelle weight and lowers the nacelle component counts as well. Henceforth, the system reliability increases with reduction in failure contingencies. For the paralleled configuration shown in Fig. 2.12(b), the generator end rectifier requires a supplementary dc-dc converter. The dc-dc converter increases the output voltage to medium voltage dc (MVDC) scale [4]. The dc-dc converter thus replicates the function of the step-up transformer used in ac power transmission configurations depicted in Fig. 2.11. Another added advantage of using dc-dc converter is that it weighs lesser compared to the three-phase low/medium frequency ac transformers.

Figure 2.12: dc power collection: (a) series connected dc wind farms and (b) parallel connected dc wind farms.

Another interconnection approach is the series connection of the ac-dc converters as shown in Fig. 2.12(a) [152–155]. This configuration is prone to a vulnerability of complete shutdown for a single point failure. In order to avoid such scenarios each generator-converter unit is equipped with a bypass switch to isolate the dc link.

But the challenge prevails for a multiple-fault-event scenario where numerous units might be required to be segregated and the overall dc-voltage limit falls below the lower threshold triggering a full-scale shutdown. However, such multiple-fault-event scenario would cause all other discussed configurations in Fig. 2.11 and Fig. 2.12(b) to shutdown as well.

In comparison to the power collection topologies presented in Fig. 2.11 and Fig. 2.12(b), it can be seen that a lower number of power converters and power transformers are required for the configuration Fig. 2.12(a). In addition to that, the central wind farm substation is not required for the configuration presented in Fig. 2.12(a) [8]. These factors bring in several cost-cutting opportunities. In addition to that, with a lesser number of high power components in the system, the overall system efficiency is expected to be higher in the series dc-power collection configuration [152]. The statement of reliability emphasizes on similar aspects as well. A lower number of high power devices aids to lower failure contingencies and thus reliability of the system increases as well.

2.7.3 Energy Storage System Integration

There has been abundant research carried out recently focusing on the energy storage system (ESS) integration with renewable energy sources [156,157]. ESS provided the stochastic sources like wind or solar, a cushion from the source dynamics. Even for cases of grid fault surplus energy can be stocked up in ESS. Another advantage of ESS application is its role in helping WTS attain fault ride through (FRT) compliance. ESS for such purpose could be mechanical, electrical, electrochemical or hybrid.

The ESS are generally connected via dc-dc converter at the dc-link. It can also be placed as a power back before the grid but then it has to be connected via a bidirectional ac-dc power converter. The lengthy charging time and discharging time of the electrical batteries make them partially effective for fast dynamic wind variations or grid variations. Again deployment of supercapacitors which has fast discharging time, might disrupt the stability of the complex WTS if not controlled properly. Researchers have proposed several hybrid topologies for ESS to make them applicable for WTS [157].

Though advantageous for application in megawatt (MW) range WTS, the viability

of the system in terms of sizing and expense is always under scrutiny. And the reliability of such a system becomes a matter of high priority for application in offshore scenarios. But still, this is an interesting application to be considered for stochastic onshore WTS.

The control of the dc-dc converter connecting the ESS has some challenges to meet. For the dc-link connected ESS, dynamics of the dc-dc controller might affect the stability of the dc-link. If not controlled properly, the power injected or absorbed from the system can adversely affect the power balance from the generator to the grid. Conventional PI-controller has been effective to carry out the control of the dc-dc converter in this regards, but for hybrid ESS it becomes a challenge. For faster dynamics model predictive control (MPC) is also an option to investigate. MPC has recently presented promising results in power electronic application especially dc-dc power converters [158–160]. MPC has also been applied in renewable energy applications as well [161–163]. Advantage of MPC lies with its independence on the linearized average system model and its ability to include several constrains into account. A simplistic MPC method is implemented in [164] for dynamic reference design, and its applied for active front end rectifier in drive or motor applications. This method is not complex and considers only one step of predictive horizon. It has not been investigated for application of dc-dc converter for ESS integration for any renewable applications.

2.8 Vibration Problems in WTS

Alongside generator, converter and control complicities few other issues of WTS can be addressed in terms of power electronics. One of such issue is the electro-mechanical torsional vibration observed in the drive-train. History if vibration problem with WTS goes long back. For modern wind turbines, the tower has a slim construction which makes it further prone to vibrations. The drive train of the WTS is composed of rotating masses which are prone to vibration. These vibrations can be swayed upon by both the input side and transmission side dynamics. One of the ideal cases of torsional vibration is the turbulent incident wind that creates cyclic variations of torque at the rotor. Beside creating mechanical noise, this electro-mechanical phenomenon employs considerable impact on output power quality and dynamics of

load side components. It has also been researched that one of the main reason for such long wind turbine downtime and gearbox failures are related to the torsional vibration. For this case, the drive-line is excited at the first natural frequency under extreme conditions [165].

In solution to this problem, various electromechanical control involving the generator side power electronic converter to absorb the transient energy of the torsional vibration is researched and addressed widely in literature [35,166,167]. Under classical control scheme, authors in [35,166–169] studied the effect of closed-loop speed controller and indirect torque control on torsional vibrations. The discussed methods improve the system reliability and serve as the basis for the development of active vibration damping techniques in the wind industry. The generator speed information filtered using a band-pass filter has been used to provide damping to the WTS [170–173]. This method titles generator speed feedback (GSF) has been successful in providing damping to the first torsional frequency. In [174], dc-link voltage control based technique and in [35] a power balance based methods are proposed to provide damping to the WTS. These methods have resemblance with GSF, as the power balance and voltage balance are dependent on similar parameter i.e. generator speed. G.Mandic *et.al.* in [175] used a method called stress-damping-controller (SDC) which utilizes the generator side acceleration information as the feedback signal. SDC provides a certain amount of damping to the first natural frequency. In [176] the authors proposed virtual-inertia-damping-controller (VIDC). VIDC is designed with additional turbine side speed information as the feedback signal. VIDC resembles with the load acceleration control proposed in [177]. With the additional sensor, VIDC offers better damping performance compared to GSF and SDC [176].

Literature [178–181] used variations of GSF, SDC, and VIDC to provide the WTS with enhanced damping capability. But in VIDC, the natural frequency and damping cannot be controlled separately. VIDC requires the feedback of acceleration information which is obtained by differentiating the turbine speed. In order to obtain the optimal damping ratio, the control gain is varied over a large range, and in the process, the differentiation amplifies the switching and measurement noises over the whole wide range.

This problem can be solved by segregating the natural frequency control and damping control. Such a solution has not yet been proposed nor investigated.

2.9 Importance of Reliability Analysis of Power Converters in WTS

Manufacturers of wind turbines consider the aspect of reliability in designing and development of power converters and other sub-assemblies [5, 182, 183]. With the increase of capacity of individual wind turbines, the failure rates of each component are increasing. Thus the studies related to reliability of the system is becoming furthermore compulsive. Accessibility, fault reporting and repair - all these factors play a major role in offshore WTS reliability assessment [184]. As discussed in the last section the vibration and mechanical interaction aspects in WTSs have become research concern of higher interest as the wind turbines are built larger. In Fig 2.13, the failure rate and the downtime rate of different components of the WTS are represented.

Figure 2.13: Annual failure rate and downtime of different components of a WTS

The reliability studies can be categorized in three major levels going from broader context to component level i.e. (1) data analysis and optimization based on available fault data [185, 186], (2) system level analysis considering various stress scenarios and (3) component failure based reliability studies [2, 183, 187, 188]. While each level of analysis has its own importance, from power electronic perspective the component level analysis is significant [189]. The primary component failure study is composed of device physics, parts count analysis, parts stress analysis, etc. The study is further extended to operational context considering power loss calculations, thermal analysis, etc [190, 191]. The literature discusses various studies relating factors of wind speed and temperature with component failure dynamics [192]. Some study relates field-specific power electronic component failure data with various transient operating

conditions [193]. Thus it can be implied that component failure study and prediction models shape the base reliability analysis for power electronic components in WTS.

2.9.1 Power Electronic Reliability Analysis

Diodes and IGBTs are the basic composites of almost all power electronic converters used in WTS. Diodes are basic rugged power electronic devices which are self-commuted and prone to lesser failure compared to IGBTs. But compare to other active switching devices IGBTs have the advantage of high current density though it is a voltage controlled device. It is essential understanding the IGBT failure mechanism in order to assess the converter lifetime and WTS reliability [188]. The power converter failure to cost ratio is fairly within the sustainable limit for some redundant converters but for drive applications, the ratio fairly increases [194]. This is translated in to the lifetime of the converters, for example, some converters are built with a lifetime of 30 years, whereas for drive applications similar converter would yield around 10-20 years of a lifetime [195]. WTS being high power drive application makes power electronic reliability assessment a compulsory analysis [189]. In this thesis, generator side rectifiers are investigated and topology is proposed as one of the viable offshore WTS converter solutions. Thus the assessment of the reliability of the rectifiers become obligatory.

2.9.2 Component Lifetime based Reliability Estimation Analysis

As discussed above of several steps of reliability assessment, component lifetime prediction and failure analysis creates the primary platform to build upon. Lifetime prediction of IGBTs for high power application can be a good measure to estimate viability of the converter. IGBT lifetime prediction model can be broadly categorized into the analytical model and physical models. Several IGBT condition monitoring studies has been carried out in the literature. But for WTS, no study is found to focus on the component failure based reliability analysis especially for the front end converters. Thus for all the converter topologies discussed for this dissertation a detail component failure based reliability analysis is to be carried out.

“Military Handbook, Reliability Prediction of Electronic equipment (MIL-HDBK-217F),” is established in order to maintain uniform and consistent of estimating reliability [196]. This basically works as a tool to assess the reliability of new electronic of power electronic equipment designed [197].

After identification of component failure contingencies, the study can be extended to operational context bringing aspects of thermal factor into consideration. In order to do that, thermal reliability prediction can be investigated with detailed finite element method (FEM) based models and detailed power electronics thermal model analysis. In order to assess the viability of the parallel power converter proposed for WTS in 5, the MIL-HDBK-217 is used as a tool. In literature no study related to the referred topology reliability study in WTS is available. It must be noted that MIL-HDBK-217F helps to get an overview of the power converter reliability and the operational context is not considered. The component failure based reliability study of the power electronic converters discussed in this thesis are compared and the results are summarized in 6.

2.10 Summary

In Chapter 1 the present trends and market scenario of WTS were discussed. This chapter introduces the basic concept related to the operation and construction of WTS. The operating range of WTS based on wind speed is discussed as well. The major components of WTS are discussed in terms of mechanical and electrical segments. The modeling of the wind turbine is described with mathematical interpretations. This model is used in simulation in all the following chapters.

Different types of WTS configurations are introduced along with references of available utilities adopting them. The configuration type leads the way to the investigation of types of power converters popular in this industry. The converter types were broadly categorized based on active and passive semi-conductor switches used. As several generators are proposed literature and used in industry, generators were comparatively evaluated based on their advantages and disadvantages.

Due to high boost of offshore wind farm installations, the dc-power collection has become a major topic of research in this field. Thus the modes of power collection for

WTS were also discussed. Energy storage system integration with WTS also plays a major role in WTS dynamics and it has been discussed in this section as ESS is also a mode of power collection.

Addressing one of the major issues pertaining to mechanical failure, the vibration problems of WTS has been reviewed. The methods of active damping of torsional vibration were introduced as well.

From the performed literature review several gaps and opportunities of research were observed. In this dissertation, the generators i.e. SCIG, PMSG and WRSG are addressed in separate configurations for the diversity of knowledge in regards to its application in WTS. This dissertation constantly strives to address the better generator side power converter through the chapters. Finally, in the chapter preceding conclusion, the discussed front end converters are compared articulately with respect to reliability and feasibility.

The electromechanical issues of the gearbox can be power electronically addressed and the improvements in this sector are addressed in the following chapter, i.e. Chapter3. The power electronic configuration considered is the popular B2B 2L-VSC.

Chapter 3

Active Damping Control of Torsional Vibration in WTS

This chapter introduces a control algorithm for active front end rectifiers in wind turbine system based on the electromechanical interactions. A speed difference damping controller is proposed which reduces the effect of load dynamics and transient torsional oscillations caused due to wind dynamics. The proposed controller is compared in details with other available controllers in literature. The controller operation are validated in simulation analysis for various test case scenarios. Experimental hardware setup is constructed and the simulated test case scenarios are validated. The summary of the work is presented with argumentative discussion in Section 3.7.

3.1 Introduction

Wind turbines are complex electro-mechanical systems. The mechanical structure comprises of rotating blades, pitch control system and sensitive drive-train components. These component failures add adverse economical scenarios with reduction of revenue generation with the escalating maintenance cost. This maintenance cost becomes even higher in offshore scenarios. Research suggests that the main reason for such failures are related to the torsional vibration; in which, the first natural frequency is excited in the drive-line under extreme conditions like a resonant wind excitation, hard stop, wind gust, unbalanced masses, and shaft misalignment, etc. [165].

As discussed in Chapter 2, there are various electromechanical control techniques involving the generator side converter that absorbs the transient energy of the torsional vibration. These topics are researched and addressed widely in [35, 166, 167]. From literature, we can obtain active damping control methods as generator speed feedback (GSF) [170–173], stress-damping-controller (SDC) [175] and [176] virtual-inertia-damping-controller (VIDC). In [178, 178–181] variations of GSF, SDC and VIDC are used to provide the WTS with enhanced damping capability. The methods could garnish better results if the approach segregates the natural frequency control and damping control.

This chapter addresses the issue of damping control and natural frequency control proposing a convoluted novel control technique called speed difference damping controller (SDDC) for WTS. SDDC is designed upon on the speed difference between the high-speed gear shaft speed and generator shaft speed. The novelty and contributions of this research can be summarized in the following points:

- The reduction of the effect of load dynamics and transient torsional oscillations in WTS utilizing the proposed SDDC.
- The claim is supported by a detailed theoretical analysis, designing the control gains with a derived two-inertia model.
- The simulation and hardware experimentation of the proposed controller is tested for validation of the claim, in a detailed multi-inertia model that emulates a WTS drive-line.
- A detailed comparative analysis along with parametric variation uncertainty is presented for the VIDC, SDC, GSF and proposed SDDC control.

Theoretical, simulation and experimental analysis demonstrates superior performance of SDDC in protecting drive-line under extreme conditions serially followed by VIDC, SDC, and finally GSF.

Furthermore, this chapter is organized in the following order. Section 3.2 describes the system modeling with an overview of the wind turbine modeling, Eigen analysis of mechanical model and electrical modeling. In Section 3.3, the proposed control technique i.e. SDDC is discussed in details. Section 3.4 outlays a comparative study of the active vibration damping schemes. Section 3.5 and Section 3.6 describes the

Figure 3.1: System architecture of back to back voltage source converter based WTS with proposed SDDC controller.

simulation results and experimental results respectively. The summary is drawn in the Section 3.7.

3.2 System Modeling

A basic component of the generation unit of a geared WTS consists of the rotational turbine blades, rotor, multiple stage planetary gearbox, and generator. The generator is followed by the power electronic interface and finally the grid. The system considered for this study is illustrated in Fig. 3.1. The gearbox is controlled by the pitch controller which depends on the generator-side shaft's angular speed (ω_g). The generator side converter i.e. the rectifier is controlled based on the proposed controller. The generator torque reference is obtained from the torque-speed charac-

Table 3.1: Wind Turbine Parameters

Parameter	Annotation	Value
Power	P_{gen}	2.5MW
Radius	R	50m
Wind speed	v_{wind}	10m s^{-1}
Generator Speed	ω_g	600rpm
Turbine Speed	ω_t	17.14rpm

teristics of the WTS. The grid side inverter is controlled based on the requirements of voltage and frequency demands from the grid.

The system modeling addresses firstly the modeling of wind turbine with its characteristics, followed by the mechanical modeling with detailed Eigen analysis of the system, and the electrical system modeling. For simulation analysis, the modeling is carried out in a co-simulation environment using SIMPACK and Matlab® software interface.

3.2.1 Mechanical System Model and Eigen Analysis

For this study, the tower vibration and bending moments are not considered. The wind velocity profile drives the multi-inertia model which is controlled by the pitch controller and the generator electromagnetic torque. The mechanical model is made in SIMPACK and the velocity profiles, the pitch angle, and generator electromagnetic torque is given as input to the SIMPACK from Matlab®. For the modeling of shafts and gearboxes, simplification of the scenario is requisite to curtail the computational burden. The present state-of-the-art analysis of shafts and gearboxes with high fidelity use finite-element-modeling (FEM) approach. However, for torsional interaction investigations, it is not mandatory to use FEM [198], as the frequencies of interest are around the synchronous region. The adhered approach to mechanical system model for this study is lumped-parameter-modeling. In this approach, a complicated system is simplified into the spring-inertia model with matching dynamics [198].

In [198], a six-mass five-stiffness is modeled and represented and similar modeling procedure is replicated and extended to obtain the present system model. In research findings [199], more detailed model of WTS is available, where it is represented as an eight-inertia seven-stiffness (8J-7S) system, where the inertia and the stiffness are transferred to the generator side as depicted in Fig. 3.2. In the figure, J_1 represents the wind turbine rotor inertia and J_8 represents generator rotor inertia [198, 200]. The 8 inertia 7 stiffness model is the physical representation of the dominant inertias in the wind turbine system. The inertias can be mentioned as: turbine along with the turbine shaft together (J_1), low speed gear carrier(J_2), low speed gear planet (J_3), the medium speed shaft (J_4), high speed gear carrier(J_5), high speed gear planet(J_6),

high speed shaft with coupling(J_7) and the generator(J_8). The simplification of this 8 inertia 7 stiffness model is done by using the Eigen analysis. The behavior of the 8 inertia system model when checked at the first torsional frequency is representable by a two inertia model. The first of which includes J_1 to J_7 together and the other one being J_8 .

Table 3.2 presents the data used for the proposed model. It includes the generator side values for inertia, stiffness and shaft damping. The mechanical system parameters of poles, natural frequencies and damping ratio are also included in Table 3.2.

Figure 3.2: Inertia, stiffness and material damping representation of the 8J-7S system.

Table 3.2: Parameters for Mechanical Modeling

INDEX (i)	Parameters referred to Generator-side			Parameters referred to Mechanical System			
	Inertia (J_i)	Stiffness Coeffi- cient (K_i)	Damping Coeffi- cient (B_i)	Pole (P)	Damping Ratio	Natural Fre- quency (f)	Time Con- stant
—	kg m ²	N m rad ⁻¹	N m s rad ⁻¹	rad s ⁻¹	—	Hz	s
1	2.311×10^4	7.7854×10^7	500	3.316×10^{-9}	1	—	3050
2	5.60	4.624×10^7	500	$-0.398 \pm 45.6j$	8.74×10^{-3}	7.26	2.51
3	3.86	1.1328×10^7	500	$-11.8 \pm 375j$	3.14×10^{-2}	34.12	8.47×10^{-2}
4	15.51	1.137×10^7	500	$-21.3 \pm 1060j$	2.0×10^{-2}	168.70	4.7×10^{-2}
5	9.80	7.86×10^7	500	$-49 \pm 1860j$	2.6×10^{-2}	296	2.04×10^{-2}
6	3.74	2.615×10^7	500	$-73.6 \pm 2860j$	2.57×10^{-2}	455.20	1.36×10^{-2}
7	24.19	1.53×10^6	500	$-154 \pm 5290j$	2.86×10^{-2}	859.44	6.48×10^{-3}
8	680	—	—	$-153 \pm 5900j$	2.59×10^{-2}	939.01	6.53×10^{-3}

Eigen Analysis of the Eight-Inertia-Seven-Stiffness System

Eigen mode analysis of the eight-inertia-seven-stiffness system is shown in Fig. 3.3. The x -axis value displays the ‘Index’ in Table 3.2 which corresponds to various poles in the system. At the index value 1, all the inertia speed amplitudes are the same with a normalized value of 1, and all inertias are in phase. A single joined inertia can approximate the system behavior at the first pole. For the index value 2 (7.26Hz), inertia- 8 (J_8) has an amplitude 1, while all other inertias have amplitude

Figure 3.3: Eigen analysis of the multi-inertia system

Table 3.3: Two-inertia system parameters referred to the Machine side

INDEX (<i>i</i>)	Inertia (J_i)	Stiffness Coefficient (K_i)	Damping Coefficient (B_i)
—	kg m ²	N m rad ⁻¹	N m s rad ⁻¹
1	2373.42 (J_t)	1.53×10^6 (K_{sh})	500 (B_{sh})
2	680 (J_g)	—	—

neering 0.2pu. From the Eigen-phase analysis, it is observed that inertia- 8 (J_8) is moving anti-phase to inertias- 7 (J_7) to inertia- 1 (J_1). There is a torsional twisting point between inertia- 8 (J_8) and inertia- 7 (J_7). The behavior at this Eigen-value can be approximated as a two inertias with inertia- 8 (J_8) being the first and second being the combined inertia of inertia- 7 (J_7) to inertia- 1 (J_1). In this way, two-inertia representation can be used for the control system analysis of WTS at the first torsional resonance frequency. The revised two-inertia representation of the multi-inertia model described above can be represented by the calculated values given in Table 3.3. Similarly, the behavior at other natural frequencies can be deduced from the Eigen analysis. At the second natural frequency, J_8 and J_1 have an amplitude near to 0 pu, while inertias J_2 to J_7 have the amplitude varying from 1 pu to 0.5 pu. These inertias are 180° apart with respect to the phase of J_8 and J_1 . Thus two torsional twisting points are observed. In this procedure of analysis, further twisting points can be located with reference to higher natural frequencies.

3.2.2 Electrical System Modeling

The rotational torque from the wind turbines are utilized by the gear-box to rotate the shaft of the electric machine at rated speed. In Chapter 3, a permanent magnet synchronous generator has been investigated for the WTS. In this study, for simplicity and diversity in the research study, the generator considered is a squirrel

cage induction generator (SCIG). But the analysis can be extended to evaluate the other wind-generators in regards of damping and torsional oscillations. The SCIG is also rated at 2.5 MW. The machine parameters are represented in Table 3.4 along with other electrical parameters. The modeling equations in dq -reference frame for the induction machine is obtained from the literature [198, 200–202] and represented below:

$$v_{sd} = (r_s + \sigma L_s p) i_{sd} + \frac{L_m}{L_r} p \psi_r + \omega_s \sigma L_s i_{sq} \quad (3.1)$$

$$v_{sq} = (r_s + \sigma L_s p) i_{sq} + \frac{L_m}{L_r} \omega_s \psi_r + \omega_s \sigma L_s i_{sd} \quad (3.2)$$

$$T_g = \frac{3}{2} \cdot \frac{P}{2} \cdot \psi_r \cdot i_{sq} \quad (3.3)$$

Here Eq. 2 and 3 represents the d -axis and q -axis voltage representations respectively. In the equations r_s refers to the stator resistance, L_s is the stator inductance, σ is the leakage coefficient, L_m is the magnetizing inductance, and L_r is rotor inductance. Eq. 4 represents the electromagnetic torque where ψ_r is the flux, P represents the number of machine poles and i_{sq} is the q -axis current. Induction machine is followed by the power electronic interface. The power electronic interface of the system would convert the generated ac-power to dc charging up the dc-link capacitor and it would be again converted back to ac-power feeding directly to the grid. Similar full-scale conversion study has been carried out in Chapter 3 with 3L-NPC converters. The main focus of this study lies with the electromechanical interactions between the electrical and mechanical system. Thus for simplicity, a two-level voltage-source-converter (2L-VSC) based back to back topology makes up the power electronic interface. This chapter contributes to the control of the generator side converter taking the reference q -axis current from the proposed control technique. The power generated is fed to the grid through an inverter which is also chosen as 2L-VSC. This configuration is commonly known as back-to-back 2L-VSC (B2B 2L-VSC) [9]. The switching frequency of the grid side converter is set to 3kHz. The output of the inverter is connected to the ac-grid through an LCL-filter [203]. The capacitor value is selected based on converter hold up time [204]. The electrical parameters for the generator, dc-link and grid side filters are given in Table 3.4.

Table 3.4: Electrical System Parameters

Generator Ratings		Generator Electrical Parameters		dc-bus and grid-side filter parameters	
Parameters	Values	Parameters	Values	Parameters	Values
Power	2.5MW	Stator Resistance	2.38m Ω	dc-link voltage	1200V
Gear Ratio	1: 35	Stator Leakage Inductance	0.0316mH	dc-link capacitance	10mF
Rated Voltage	690V	Magnetizing Inductance	1.896mH	Filter Inductance	0.14mH
Rated Speed	600rpm	Rotor Resistance	1.43m Ω	Filter Resistance	0.01 Ω
Pole Pairs	3	Rotor Leakage Inductance	0.0316mH	Filter Capacitance	0.380mF
—	—	—	—	Damping Resistance	0.0861 Ω

Figure 3.4: Two inertia representation of WTS.

3.3 Proposed Speed Difference Damping Controller

As observed in the Eigen analysis in Section 3.2, the multi-inertia wind turbine model can be simplified to a two-inertia model to describe the first torsional frequency. In the designed two-inertia model, the driving inertia is the generator inertia (J_g) and driven inertia is the turbine inertia (J_t). Using the gear ratio, the obtained value of J_t is referred to generator side. The turbine is driven with high-speed shaft coupling stiffness represented as the connecting element. The two inertia representation of the wind turbine is shown in Fig. 3.4.

The modeling state equations of the system can be represented as,

$$\frac{d}{dt} \begin{bmatrix} \omega_g \\ \omega_t \\ \theta_g - \theta_t \end{bmatrix} = \begin{bmatrix} -\frac{B_{sh}}{J_g} & \frac{B_{sh}}{J_g} & -\frac{K_{sh}}{J_g} \\ -\frac{B_{sh}}{J_t} & -\frac{B_{sh}}{J_t} & \frac{K_{sh}}{J_t} \\ 1 & -1 & 0 \end{bmatrix} \begin{bmatrix} \omega_g \\ \omega_t \\ \theta_g - \theta_t \end{bmatrix} + \begin{bmatrix} \frac{1}{J_g} \\ 0 \\ 0 \end{bmatrix} [T_g] + \begin{bmatrix} 0 \\ -\frac{1}{J_t} \\ 0 \end{bmatrix} [T_{aero}] \quad (3.4)$$

The state variables are ω_g , ω_t and $\theta_g - \theta_t$. The generator torque (T_g) is the control input, and wind turbine aerodynamic torque (T_{aero}) is the non-measurable input. ω_g and ω_t are the speeds measured using the speed encoder system. The two-inertia system is characterized by the resonant-frequency and damping-ratio. The equation interpretation for resonant-frequency and damping ratio of the two-inertia system is given as,

$$\omega_{res} = \sqrt{K_{sh} \cdot \frac{J_g + J_t}{J_g \cdot J_t}} \quad (3.5)$$

$$\delta_{res} = \frac{B_{sh}}{2} \sqrt{\frac{J_g + J_t}{K_{sh} \cdot (J_g \cdot J_t)}} \quad (3.6)$$

The SDDC is having the feedback input from the difference between the generator speed and high speed gear. The aspiration of the proposed control is the reduction of the speed inequality between generator and components of the drive-line. By reducing the dynamic speed difference, the adverse effects of the torsional frequency can be mitigated. The block diagram for SDDC implementation is depicted along with the system diagram in Fig. 3.1. The control block diagram of SDDC is shown in Fig. 3.5.

Figure 3.5: Control block diagram for proposed control method (SDDC).

In the proposed SDDC method, a compensating torque (T_{comp}) is added to the gen-

erator counter torque command ($f(\omega)$). T_{comp} is a function of speed difference and it mitigates the first natural frequency torsional vibration. This method balances the wind turbine torque. The generator torque T_g and T_{comp} can be mathematically realized in Eq. 3.7 and Eq. 3.8.

$$T_g = f(\omega) + T_{comp} \quad (3.7)$$

$$T_{comp} = -K_p (\omega_g - \omega_t) - \frac{K_i}{s} (\omega_g - \omega_t) \quad (3.8)$$

From Eq. 3.4 and Fig. 3.4, the transfer function of generator speed to generator torque is described in Eq. 3.9 given below,

$$\frac{\omega_g(s)}{T_g(s)} = \frac{1}{sJ_g} \cdot \frac{(s^2 + \frac{sB_{sh}}{J_t} + \frac{K_{sh}}{J_t})}{(s^2 + sB_{sh}(\frac{1}{J_g} + \frac{1}{J_t}) + K_{sh}(\frac{1}{J_g} + \frac{1}{J_t}))} \quad (3.9)$$

The transfer function between the wind turbine and generator electromagnetic torque is derived and interpreted as,

$$\frac{\omega_t(s)}{T_g(s)} = \frac{1}{sJ_gJ_t} \cdot \frac{(sB_{sh} + K_{sh})}{(s^2 + sB_{sh}(\frac{1}{J_g} + \frac{1}{J_t}) + K_{sh}(\frac{1}{J_g} + \frac{1}{J_t}))} \quad (3.10)$$

As defined above the SDDC is designed based on the speed difference of generator and wind turbine, taking the difference between the transfer functions in Eq. 3.9 and Eq. 3.10 we obtain the transfer function for $\Delta\omega$. With proportional and integral controller $K_p + K_i/s$, the open-loop transfer function is derived and represented in Eq. 3.12.

$$\frac{\Delta\omega(s)}{T_g(s)} = \frac{1}{J_g} \cdot \frac{s}{(s^2 + sB_{sh}(\frac{1}{J_g} + \frac{1}{J_t}) + K_{sh}(\frac{1}{J_g} + \frac{1}{J_t}))} \quad (3.11)$$

$$G_{\Delta\omega}(s) = \frac{1}{J_g} \cdot \frac{sK_p + K_i}{(s^2 + sB_{sh}(\frac{1}{J_g} + \frac{1}{J_t}) + K_{sh}(\frac{1}{J_g} + \frac{1}{J_t}))} \quad (3.12)$$

Therefore, a new control variable is defined; speed difference at the resonant frequency $\Delta\omega_{res}$. The resonant frequency components are obtained from the speed difference using a bandpass filter. Thus, closing the loop of the resonant speed difference feedback, the ratio of $\Delta\omega_{res}$ concerning the regulator speed reference $\Delta\omega_{res}^*(s)$

is

$$\frac{\Delta\omega_{res}(s)}{\Delta\omega_{res}^*(s)} = \frac{\frac{sK_p+K_i}{J_g}}{\left(s^2 + sB_{sh}\left(\frac{1}{J_g} + \frac{1}{J_t} + \frac{K_p}{J_g \cdot B_{sh}}\right) + K_{sh}\left(\frac{1}{J_g} + \frac{1}{J_t} + \frac{K_i}{J_g \cdot K_{sh}}\right)\right)} \quad (3.13)$$

From the closed-loop transfer function presented in Eq. 3.13, the proportional controller results in changes in the coefficients of 's' and the integral controller results in changes in the constant term in the denominator. This concludes to the fact that the damping and natural frequency can be controlled independently using the controller. In the transfer function of closed-loop control (Eq. 3.13), keeping the integral gain zero and increasing the proportional gain can increase the damping ratio up to unity. On the contrary, the increase in integral gain keeping the proportional gain zero can cause the natural frequency to increase up to infinity. The closed-loop transfer in Eq. 3.13 root locus and bode plot is shown in Fig. 3.6(a) and (b). The effect of the controller gains on the natural frequency and damping ratio can accurately determine by using the root locus tool which is shown in Fig. 3.6(a). The root locus diagram gives the relative movement of poles of a transfer function with the increase in control gains. The movement is from poles of the denominator to the zeros of the numerator. The increase in integral gain results in the movement of the poles parallel to the imaginary axes which are shown with the straight line parallel to imaginary axes. This means that the zeros are situated at the infinity and the poles are moving to the infinite location where the zeros are situated. This movement can improve the natural frequency over a very large range. The small half circle represent the movement of the poles with the increase in the proportional gain. The two poles in Eq. 3.13 i.e $\frac{1}{s+\delta_{res}\omega_{res}+j\omega_{res}\sqrt{1-\delta_{res}^2}} + \frac{1}{s+\delta_{res}\omega_{res}-j\omega_{res}\sqrt{1-\delta_{res}^2}}$ which are shown as blue squares in Fig. 3.6(a) moved up to zeros one at the origin at the other at infinity with a breakaway point at $-\omega_{res}$ in the real axis. The breakaway point in the real axes represents the highest damping achievable with a damping ratio of unity. Thus the increase proportional gain can improve the damping ratio up to unity and will not create any change in the natural frequency. When the combination of both integral and proportional controllers are taken which is shown with the big circle in Fig. 3.6, both the natural frequency increase and damping ratio improvement can be achieved. The two poles in Eq. 3.13 which are shown as blue squares in Fig. 3.6(a) can be moved up to two zeros one at $K_p s + K_i$ (indicated as red circle) and the other zero at infinity with a break way point in the real axis. From these movements, the

change of natural frequency is from $\sqrt{K_{sh} (\frac{1}{J_g} + \frac{1}{J_t})}$ to $\sqrt{K_{sh} (\frac{1}{J_g} + \frac{1}{J_t}) + \frac{K_i}{K_{sh} J_g}}$ and the damping ratio can be altered from $\frac{B_{sh}}{2} \sqrt{\frac{(J_g + J_t)}{K_{sh} (J_g \cdot J_t)}}$ to $\frac{B_{sh}}{2} \cdot \frac{(\frac{1}{J_g} + \frac{1}{J_t} + \frac{K_p}{B_{sh} \cdot J_g})}{\sqrt{K_{sh} (\frac{1}{J_g} + \frac{1}{J_t} + \frac{K_i}{K_{sh} \cdot J_g})}}$.

Figure 3.6: Control design of proposed SDDC- K_{pi} method applied to derived two-inertia system: (a) Root locus referred to Eq. 3.13 and (b) bode plot.

The corresponding dynamic torque reduction can be analyzed by using the bode plot which is shown in the right hand side of the Fig. 3.6(b). With the increase integral control gain K_i shown with the dotted line, the natural frequency peak moves towards the high frequency region. This illustrates the increase in closed loop natural frequency, and hence any excitation at the original natural frequency will be having lesser torque amplitude. The increase K_p gain is resulting in the reduction of the resonant peak in the downward direction which is shown with solid lines. Thus, with the combination of both K_p and K_i (shown with the hyphenated line), both damping ratio improvement and natural frequency shift can be achieved. These improvements in control design would eventually result in the alleviation of the dynamic effects of torsional vibrations. The integral control gain (K_i) for changing the natural frequency from ω_{res_old} to ω_{res_new} is further represented in Eq. 3.14 followed by the proportional control gain (K_p) for changing the damping ratio from δ_{res_old} to δ_{res_new} in Eq. 3.15

$$K_i = J_m(\omega_{res_new}^2 - \omega_{res_old}^2) \quad (3.14)$$

$$K_p = 2J_m \left(\delta_{res_new} - \frac{\delta_{res_old} \cdot \omega_{res_old}}{\omega_{res_new}} \right) \cdot \omega_{res_new} \quad (3.15)$$

Figure 3.7: Torque-speed characteristics of the wind turbine system.

The control parameters in WTS are generator speed, electromagnetic torque, blade pitch angle, DC link voltage and now the speed difference. The generator torque reference for the control action is obtained through a predefined torque-speed characteristic shown in Fig. 3.7. When the generator speed is reaches to 315rpm, the electromagnetic torque is switched in. From 450rpm to 600rpm the generator torque operates to keep the wind turbine at the peak of C_T vs λ curve to follow a square law. Above 600rpm, the generator electromagnetic torque is maintained at rated value. During the rated operation, the wind turbine is controlled using the pitch controller. The pitch regulation mechanism can be represented using a second-order transfer function as shown in Eq. 3.16 which is described in [203].

$$\frac{\beta}{\beta_{ref}} = \frac{sK_p + K_i}{s^2 + 2\delta\omega_{pitch} + \omega_{pitch}^2} \quad (3.16)$$

Application of the proposed SDDC control technique to multiple torsional modes

The proposed SDDC control technique is primarily designed to reduce torsional interactions at the first natural frequency. The first torsional frequency is the dominant value with highest torque amplitude. This frequency is excited in the drive-line under extreme conditions like wind gust, hard stop, shaft misalignment, and unbalanced masses [165]. With proposed SDDC control it is possible to improve the damping ratio up to unity for the first torsional frequency. When SDDC control is

Figure 3.8: Root-locus diagram for SDDC control applied to multiple torsional modes.

applied to mitigate the effects of second and third natural frequencies, only a limited level of improvements are possible. Above third natural frequencies, improvements are negligible. The improvements of higher order frequency are illustrated with the root-locus diagram in Fig. 3.8. The damping improvement of second and third natural frequency follows a parabolic curve with maxima and minima. The control gain should be designed to keep the poles to the farthest left hand point in order to achieve maximum damping. The proposed SDDC control improve the damping ratio of second and third natural frequency when the supplementary speed sensor is placed at the right location, as for example at J_7 in this detailed wind turbine model. The best place for placing the new speed sensor is near to the lowest stiffness element which is a flexible coupling link in the wind turbine drive-line. Inaccurate positioning of the additional speed sensor can make the second and third natural frequency to move to the right hand direction which would eventually result in the decrease of the damping

ratio and cause torque amplification.

3.4 Comparative Analysis of Active Vibrational Damping Schemes

The SDC and VIDC methods have some similarities in their operating principles. These control methods work on the basis of the feedback component of acceleration. Acceleration parameter depends on the system inertia and can effectively alter it. The proposed SDDC method uses torsion (speed difference) as the feedback variable. Hence, the stiffness and material damping parameters can be controlled efficiently. GSF method is a limited combination of SDDC and SDC, where the generator speed information is used. In this study, all these control methods are tuned to the first natural frequency using a bandpass filter, and therefore the control action is limited to the first natural frequency only. Their operating principles and effective improvement can be analyzed using the expression of natural frequency and damping ratio given in Eq. 3.17 and Eq. 3.18.

$$\omega_{res} = \sqrt{\frac{K_{sh_eq}}{J_{eq}}} \quad (3.17)$$

$$\delta_{res} = \frac{B_{sh_eq}}{2} \sqrt{\frac{1}{K_{sh_eq} \cdot J_{eq}}} \quad (3.18)$$

In the equations above, J_{eq} , K_{sh_eq} and B_{sh_eq} are the equivalent inertia, stiffness, and material damping respectively. In SDC, the equivalent inertia J_{eq} is increased from the original value. Since both natural frequency and damping ratio has an inverse square relationship with equivalent inertia, their value decrease. In the VIDC method, J_{eq} is reduced which increases the natural frequency and damping ratio. But the variation in damping and natural frequency in both these control methods depends on single control gain, and hence independent control is not possible. The proposed SDDC methods have two controller gains and the effects can be analysed independently. The proportional controller increases equivalent material damping

B_{sh_eq} . Since the natural frequency is independent of B_{sh_eq} , there will not be any changes in natural frequency with the proportional gain. The material damping has a linear relationship with the damping ratio. As a result, the increase in proportional gain results in a direct rise in damping ratio. On the other hand, the integral controller results in an increase in the equivalent stiffness K_{sh_eq} which increase the natural frequency and reduces damping ratio. To compensate for the reduction in damping ratio, the integral controller needs to be used along with a proportional controller gain at all times. In GSF method, J_{eq} is increased and B_{sh_eq} is slightly increased. Hence, the natural frequency is reduced and damping factor varies with a parabolic shape with maxima and minima. The natural frequency shift and the damping ratio cannot be independently controlled in GSF which is similar to SDC and VIDC. In SDDC, damping and natural frequency shift are decoupled whereas in all other control methods they are coupled. The comparison results of the proposed SDDC with SDC, VIDC, and GSF is given in Table 3.5. In the table ‘NF’ refers to ‘Natural Frequency’ and ‘DR’ refers to ‘Damping Ratio’.

Table 3.5: Comparison of Active Vibrational Damping Systems in WTS

Con- oller Type	Operating Principle	Differen- tiator	Change of variable	Change of frequency	Change of damping factor	Extra sensor	Indep- -endent control of NF and DR
SDC	Accel- -eration feedback	Required	Increases equivalent inertia	Limited frequency change from $\sqrt{K_{sh}(\frac{1}{J_g} + \frac{1}{J_t})}$ to $\sqrt{\frac{K_{sh}}{J_t}}$	Low. From $\frac{B_{sh}}{2} \sqrt{\frac{(J_g + J_t)}{K_{sh}(J_g \cdot J_t)}}$ to $\frac{B_{sh}}{2} \sqrt{\frac{1}{K_{sh} \cdot J_t}}$	No required	Not possible.
VIDC	Accel- -eration feedback	Required	Reduces equivalent inertia	Large frequency change from $\sqrt{K_{sh}(\frac{1}{J_g} + \frac{1}{J_t})}$ to ∞	High. Upto damping ratio of 1.	Speed sensor to measure turbine side speed (difficult to obtain)	Not possible.
GSF	Speed feedback	Not required	Increases equivalent inertia and slightly increases equivalent material damping	Limited frequency change from $\sqrt{K_{sh}(\frac{1}{J_g} + \frac{1}{J_t})}$ to $\sqrt{\frac{K_{sh}}{J_t}}$	Low. Damping factor increase is parabolic with a minimum value of $\frac{B_{sh}}{2} \sqrt{\frac{1}{K_{sh} \cdot J_t}}$	Not required	Not possible.
SDDC	Torsion feedback	Not required	Increases equivalent shaft stiffness and equivalent material damping	Large frequency change from $\sqrt{K_{sh}(\frac{1}{J_g} + \frac{1}{J_t})}$ to ∞	High. Upto damping ratio of 1.	Extra speed sensor required (obtained via encoder installed at rear end of high speed gear shaft)	Possible

3.5 Simulation Results

The effectiveness of the proposed control scheme is analyzed using the integrated wind turbine model connected to the grid under different wind profiles. The tests have been planned to address the resonant wind issues and extreme wind gusts which concerns wind-turbine operators. In course of emulating the real and extreme wind scenarios following test conditions are simulated: (i) sinusoidal-wind input, (ii) impulse-wind input and grid-dynamics, (iii) real-time data wind input. In order to validate the superiority of the proposed SDDC, a quantitative characterization study called the parametric uncertainty is performed for varying non-linear parameters i.e. the varying stiffness for this study. The gains used for simulation are tabulated in Table 3.6. As discussed earlier, the control variables for SDC and VIDC are acceleration whereas for the proposed SDDC and GSF control variables are speed information. Large variation in controller gains are seen because of the different control variables. The speed sensor for the SDDC is installed at J_7 in Fig. 3.2, which corresponds to planetary gear shaft end in the actual system. For VIDC, the extra speed sensor is placed at J_1 which corresponds to the turbine rotor in the actual system.

Table 3.6: Active Protection and Controller Gains

Controller gain	GSF	SDC	VIDC	SDDC (K_p)	SDDC (K_p and K_i)
Controller gain	1.9×10^4	470	1.6×10^3	1.2×10^4	$K_p = 1.5 \times 10^4, K_i = 5.3 \times 10^5$
New frequency	6.2	6	9	7.52	9
Modified damping	9.5×10^{-3}	7.2×10^{-3}	1.9×10^{-2}	0.15	0.14

The grid side converter control has the objective of maintaining a constant dc-link voltage by using outer dc-link voltage regulation loop and inner current control loops [19, 203]. The angular information is obtained using phase-locked-loop (PLL). The generator torque controller and inner current controller are designed in reference to [198, 204]. The parameters of the dc-link and grid side electrical components are tabulated in Table 3.4.

Figure 3.9: Sinusoidal wind input:(a) wind velocity and (b) aerodynamic torque.

Scenario I: Sinusoidal Wind Input

Firstly, the performance of different controllers is compared for a hypothetical sinusoidal wind excitation. A constant wind speed of amplitude 10 m s^{-1} is applied for 5 s to initialize the wind turbine model. A sinusoidal wind profile with an amplitude of 0.36 m s^{-1} and frequency of 7.52 Hz is superposed over the base wind speed at $t = 5$ s. The corresponding v_t profile and the aerodynamic torque input are shown in Fig. 3.9. From $t = 5$ s to $t = 95$ s the aerodynamic torque oscillates between -44 kNm to -36 kNm with a frequency corresponding to the resonant wind excitation. The WTS produces a steady torque of -44 kNm and a fluctuating component of -4.0 kNm due to the superposed resonant wind.

All the control methods under investigation are tested for the above-described wind input and the obtained results are depicted in Fig. 3.10 and Fig. 3.11. For time period $5 \text{ s} < t < 20 \text{ s}$, the wind-turbine system operates without any active control, the controllers are activated for the following time periods: GSF ($20 \text{ s} < t < 35 \text{ s}$), SDC ($35 \text{ s} < t < 50 \text{ s}$), VIDC ($50 \text{ s} < t < 65 \text{ s}$), SDDC with K_p ($65 \text{ s} < t < 80 \text{ s}$), and SDDC with K_p and K_i ($80 \text{ s} < t < 95 \text{ s}$). The torque transferring through the shafts T_{sh1} , T_{sh3} , T_{sh5} , and T_{sh7} are presented and the zoomed view at the instant of switching between different control schemes are shown in Fig. 3.10 (a) to (g) for convenience.

When the sinusoidal wind excitation is applied at $t = 5$ s, a fluctuating component of torque of increasing amplitude adds to the drive-line shaft torque and the amplitude oscillates between -20 kNm to -60 kNm. Such large torque amplitude with oscillating nature can induce serious reliability issues to the drive-line components especially gear-teeth, bearings and the couplings. The lower and upper peaks of oscillation with different control methods are observed to be as follows: GSF (-36 kNm and -44 kNm), SDC (-37 kNm and -43 kNm), VIDC (-38 kNm and -42 kNm). With

Figure 3.10: Comparison of transmitted drive-train shaft torque under sinusoidal wind excitation with different control schemes: (a) shaft torque with different controls, (b) shaft torque with resonant wind excitation, (c) switching from uncontrolled to GSF, (d) switching GSF to SDC (e) SDC to VIDC, (f) VIDC to SDDC- K_p and (g) SDDC- K_p to SDDC- K_{pi} .

the proposed SDDC method and K_p gain, it is seen that the fluctuating component limited to 1 kN m which was previously lowest for VIDC at 4 kN m. When K_{pi} gain is switched in, the amplitude is further reduced to 0.6 kN m. Under the harmonic wind excitations, all controllers are effective in mitigating the resonant in the drive-line. The highest performance is shown by the SDDC with proportional and integral gains. The drive-train speeds for the same test case scenario are represented in Fig. 3.11. The variable component ‘speed’ is represented by the inertias J_1 to J_8 in Fig. 3.11. When the control algorithms are applied the drive-train speeds oscillation amplitude reduced which is visible in Fig. 3.11(a). As the sinusoidal wind excitation is applied at $t = 5$ s, the generator oscillates with a higher amplitude as compared to the rest of the drive-train. There is a 180° phase difference between J_8 and J_7 when control method is in operation. Fig. 3.11(c) shows that when GSF is applied, the speed amplitude of the generator and the remaining turbine become comparable, but there exists a phase difference of about 100° between them. Fig. 3.11(d) shows that under SDC, the amplitude of both inertias are almost the same but a phase difference of 180° exists in the drive-line. With VIDC shown in Fig.3.11(e), a phase shift of 45° is observed and an amplitude difference of 1rpm still exists. With proposed SDDC- K_p gain as shown in Fig. 3.11(f), the phase difference goes down drastically to nearly zero, but a slight amplitude difference between inertias exist. For SDDC with K_p and K_i gain all the amplitudes of all inertias are about the same and the phase difference is almost zero. The twist in the shaft of the drive-train is small, and this correlates with the low torque of SDDC in Fig. 3.10(a) and (g). The speed difference in the drive-line is shown in Fig. 3.11(h). The highest amplitude of speed difference is shown by the turbine and generator. The pitch controller is activated to bring the speed to the original operating point. Fig. 3.11(i) displays the pitch angle variation with the different active vibrational damping control. Comparing with all other active protection methods, the proposed SDDC with K_p and K_i gain have resulted in a slight change in the operating characteristics of the wind turbine though some overshoot is observed in drive train speed and pitch-angle variation.

Scenario II: Impulse Wind Input and Grid-dynamics

In this test case, impulse wind input and grid-side dynamics are investigated. Both the cases are associated with dynamic variations for small time period. Firstly the impulse response of the detailed drive-train model is analyzed with different control

Figure 3.11: Comparison of drive-train speed under sinusoidal wind excitation with different control schemes: (a) drive-train speed with different control schemes, (b) drive-train speed with resonant wind excitation, (c) without controller and with GSF, (d) with GSF and SDC, (e) with SDC and VIDC, (f) with VIDC and SDDC- K_p , (g) with VIDC and SDDC- K_{pi} , (h) speed difference in the drive-line and (i) pitch angle variation.

Figure 3.12: Impulse disturbance controller response: (a) Impulse wind profile, (b) shaft torque response during impulse wind, (c) grid side voltage variation and (d) shaft torque response for grid-dynamics.

schemes. A wind impulse amplitude 20 m s^{-1} is applied to the drive-train model at 5 s and is shown in Fig. 3.12. The coupling shaft torque T_{sh7} is analyzed for vibration reduction and is shown in Fig. 3.12(b). Without any control, the shaft torque oscillates between 0 N m and -80 kN m with a frequency 7.52 Hz and a duration of 4 s. With the GSF control, the lower peak of amplitude stays constant at -80 kN m while the upper peak is reduced from to -20 kN m. The vibration duration is also reduced from 4 s to 0.6 s. When the SDC control is applied, the lower peak is increased to -90 kN m and the upper peak is reduced as well to a value of -10 kN m.

The vibration is damped with 0.8s which is slightly higher than the GSF control. With the SDC method, though the vibration duration is reduced, an amplification of initial peak torque is observed. This phenomenon can have adverse effect on the drive-line. With the VIDC control, both the lower peak and the upper peak has reduced values of -75 kN m and -20 kN m respectively with vibration duration of 0.4 s only. The SDDC- K_p shows that the lower peak is reduced to -70 kN m and the upper peak is reduced to -30 kN m and the vibration is damped within end of the second cycle. The proposed SDDC- K_{pi} demonstrates the best performance in terms of reduction in amplitude of torque as well as the duration of vibration. The lower peak in the shaft torque reduced to -60 kN m and the upper peak is completely removed. The torsional vibrations are damped within 0.1 s. The impressive performance for

peak torque reduction exhibited by SDDC- K_{pi} precedes SDDC- K_p , VIDC, GSF and. SDC is the only method that created an amplification of initial peak over torque.

The grid side fault results in voltage sags instigating sudden generator torque changes as shown in Fig. 3.12(c). Such torque conditions can excite the wind turbine mechanical system and induce torsional vibrations. The drive shaft responses are shown in Fig. 3.12(d). Without any active protection control, the grid failure event has resulted in 16 cycles of torsional vibration with amplitude 10kN m. With GSF control, the oscillation is damped in 8 cycle and the amplitude is reduced to 8kN m. SDC control also shows similar performance as GSF. The VIDC control projects slightly better performance. For SDDC- K_p , the oscillation is damped at the end of second cycle and the amplitude is limited to 4kN m only. SDDC- K_{pi} gives the best results with oscillation damped within the first cycle and the amplitude is limited 2kN m. Thus for grid events too the proposed SDDC controls show the best performance by eliminating torsional vibrations in the wind turbine driveline.

Scenario III: Real Wind Input

After the extremities are tested, the third test aims to evaluate the performance of the proposed SDDC under real wind conditions. The wind condition is also emulated as extreme wind gusts which are random in nature. Fig. 3.13(a) shows wind velocity profile under the condition of random wind. This wind velocity profile is applied to the detailed wind turbine model and all the controllers are tested. The GSF is activated at 15 s, SDC is activated at 30 s, VIDC is activated at 45 s, SDDC- K_p is activated at 60 s and SDDC- K_{pi} at 75 s.

Without the proposed controls, the shaft torque amplitude is peaky nature with the oscillation amplitude varying in the range -70kN m and -10kN m. The GSF control has resulted in the reduction peak torque and the amplitude of torque stays between -55kN m and -25kN m. With the SDC control the amplitude is between -60kN m and -20kN m. In VIDC control the amplitude of peak torque is between -30kN m and -50kN m. With the SDDC with K_p gain, the torque amplitude is limited between -32kN m and -48kN m. When the proposed SDDC controls are switched in the peaky nature of shaft torque is reduced to -44kN m and -36kN m range. Better torque reduction performance is achieved with SDDC- K_{pi} controller as compared to SDDC- K_p for this test case scenario as well.

Figure 3.13: Simulation results with real wind conditions: (a) wind velocity, (b) shaft torque, (c) shaft torque with GSF, (d) shaft torque with SDC, (e) shaft torque with VIDC, (f) shaft torque with SDDC- K_p and (g) shaft torque with SDDC- K_{pi} .

3.5.1 Comparative Analysis Parametric Uncertainty with Varying Stiffness

The proposed SDDC controller gains in Eq. 3.13 require the speed parameters of the WTS drive-line which will vary continuously over the course of its operation. Aided by the mammoth structure, the inertia of the generator, turbine and gear system are almost constants and the data obtained from the data-sheets or name-plates are usually numerically accurate. On the contrary, the high-speed coupling stiffness

Figure 3.14: Parameter variation effects under impulse wind and resonant wind conditions with various control algorithms applied: (a) shaft torque under impulse wind and (b) shaft torque with the resonant wind.

coefficient may vary over time due to mechanical fatigue and stress. Therefore, it is essential that the SDDC controller is robust to any variation in coupling stiffness. The robustness of the proposed strategy is tested under extreme conditions i.e. under resonant wind condition and impulse wind variation. The SDDC controller gains are kept at the same values as given in Table 3.6. Under resonant wind condition, the sinusoidal disturbance frequency are varied to 6.73 Hz and 8.08 Hz corresponding to 75% K_{sh} and 125% K_{sh} respectively. Fig. 3.14(a) and (b) illustrate the shaft torque response as the coupling stiffness coefficient is deviated by $\pm 25\%$. From the figure, it can be inferred that the controller is robust to variations in coupling stiffness because the shaft dynamics are almost identical despite the deliberate changes.

3.5.2 Behavior of dc-link Voltage during SDDC Operation

The dc-link voltage is controlled by the inverter of the B2B topology. Fig. 3.15 represents the dc-link voltage for conditions of grid side dynamics and impulse wind condition. The sinusoidal wind condition is not represented as there is not much variation for different controllers applied.

Figure 3.15: Variation of dc-link voltage for dynamic conditions: (a) grid side LVRT and (b) impulse wind condition.

The stabilization of the dc-link voltage was not the control objective for this work. But it is observed that with the proposed controller i.e. SDDC- K_{pi} the dc-link voltage has higher ripple at the time of grid side fault. Though the low voltage ride through operation is ensured, the dc-link voltage seems to have higher oscillation. Similar scenario is observed for the impulse wind condition as well. For the proposed controller, before stabilization, the dc-link voltage varies twice compared to any other controller tested. But after the impulse, the dc-link voltage stabilizes and the oscillations are similar compared to the other control algorithms.

3.6 Hardware Implementation

To study the effect of the proposed active protection scheme, a laboratory test set up is made. The image of the test set up is shown in Fig. 3.16. The test set up consists of an induction machine, a dc-machine, flywheels and connecting shafts in the drive-line. The dc-machine mimics the characteristics of the wind turbine and the induction machine represents the electrical machine in the simulation. The connecting shafts have a diameter 0.04 m, 0.01 m and 0.04 m. The lengths of the connecting shaft are 0.4 m, 0.2 m and 0.4 m respectively. The flywheels have a mass of 1 kg and a diameter of 0.15 m. All these parameters are presented in Fig. 3.16. The natural frequency of the test rig is 30.8 Hz.

In the experimental prototype, two-speed encoders are used to measure the speed of the induction machine and dc-machine. The encoders are rated at 5000 pulses per revolution. A torque sensor is used to measure the torque in the driveline. The sampling frequency of the torque sensor selected is 400 Hz. The dc-link with resistive load is provided with rectified dc-power from the induction generator via off-the-shelf

2L-VSC used as the power electronic power conversion interface.

Figure 3.16: Experimental test setup with major components labeling.

The control platform is composed of a computer workstation and DSpace1103. The control block is saved and operated from the Control Desk platform in the workstation. The reference signal to the rectifier is provided via DSpace1103 interface and the rectifier is switched at $15kHz$ switching frequency.

The torque sensor provides an analog signal. This analog signal is fed to the DSpace1103 via an analog to digital converter (ADC) card and defined as an input to the controller. The two encoders provide digital output containing the speed information. The data is processed by the digital to analog converter (DAC) card of the DSpace1103 and the obtained speed information is also provided to the controller.

The experimental platform is used to test the proposed controller's two versions for two scenarios. Firstly the $SDDC-K_p$ and $SDDC-K_{pi}$ are tested for critical speed operation emulating sinusoidal input torque in the drive-line. Secondly, the system analyzes the performance of the controller in the impulse load change scenario.

3.6.1 Critical Speed Operation

Two-speed encoders have a 5000 pulse per revolution installed on the two machines in order to measure their speeds. The torque transmitted through the drive-line is measured by the use of a torque-sensor which is tuned to 400 Hz of sampling frequency.

Figure 3.17: Representation of the experimental setup depicting the translation of the studied system into the experimental prototype.

The induction machine is operated in the vector control mode using a commercially available inverter. The switching frequency of the inverter is 15 kHz. DSpace controller (DS1103) is used to provide the reference torque (T_{ref}) to the inverter. (T_{ref}) is given as an analog input and is represented as electromagnetic torque reference in the experimental results. The testing rig has the dynamic mechanical unbalance induced due to the presence of number couplings. As a result of the mechanical unbalance, sinusoidal torque components which are integral multiples of the operating frequency ($\frac{\text{mechanical speed}}{60}$) will be present in the drive-line. The amount of sinusoidal torque input to the drive-line and the mechanical unbalance are difficult to estimate due to dynamic nature of mechanical unbalance.

The effectiveness of the proposed control algorithm is verified against resonant sinusoidal excitation. For this, the experimental system is operated at the critical speed of 1848 rpm and no load condition. The critical speed corresponds to the natural frequency. Fig.3.18 and Figs.3.19 shows the performance of the test rig under critical speed with SDDC control applied. The test result shows good agreement with simulation results. Fig. 17(a) shows the measured shaft torque measured obtained from the sensor data of the torque sensor.

Figure 3.18: Shaft torque under critical speed operation: (a) drive-line shaft torque, (b) shaft torque with SDDC K_p and (c) shaft torque with SDDC- K_{pi} .

The amplitude of the sinusoidal component in the shaft torque is reduced from 0.9N m to 0.4N m with SDDC- K_p and 0.2N m with SDDC- K_{pi} . The zoomed view of shaft torque at instant application of the controls are shown in Fig 3.18(b) and (c). The speed in the drive-line and zoomed views are shown in Fig. 3.19. From the speed waveform shown in Fig. 3.19(a), it is observed that the SDDC control is trying to increase the speed of the induction machine to match with the dc-machine speed. In order to show the effects with higher clarity, zoomed views of the waveforms are depicted. From the Fig. 3.19(b) it can be seen that there exists an amplitude difference of 10rpm and phase difference of 180° between dc-machine and induction machine. This illustrates a torsional twisting point exists between the dc-machine and induction machine under critical speed, which corresponds to the shaft having the lowest diameter.

When the SDDC with K_p gain is switched in, the phase difference between the dc-machine and induction machine is almost reduced but the amplitude difference of 7 rpm still exists as shown in Fig. 3.19(b). With SDDC control with K_{pi} , the phase difference reduced to zero as shown in Fig. 3.19(c). The amplitude reduces with time due to the integral control action. Thus, torsional twisting in the drive-line is substantially reduced. Speed difference in the drive-line shown in Fig. 3.20(a) shows similar performance as the shaft torque. The electromagnetic torque reference is shown in Fig. 3.20(b).

Figure 3.19: Drive-line speed under critical speed operation (a) drive-line speed (b) drive-line speed with SDDC K_p and (c) drive-line speed with SDDC- K_{pi} .

Figure 3.20: Speed difference in the drive-line under critical speed operation: (a) drive-line shaft speed, (b) electromagnetic torque reference command and (c) FFT comparison of different torsional vibration controls.

Figure 3.21: Hardware validation of impulse response test set up with the proposed SDDC- K_p and SDDC- K_{pi} controls: (a) driveline shaft torque response and (b) driveline speed response

Without the active control, the electromagnetic torque reference for no-load operation was 1.5 N m. For SDDC control, a sinusoidal torque component which is a function of speed difference is superposed over 1.5 N m. For SDDC with K_p gain the sinusoidal torque component is 2 N m and for K_{pi} gain the torque component is 3.5 N m. To compare the performance with different torsional vibration schemes experimental investigations are conducted. From the results, FFT of the speed difference is taken and is shown in Fig.3.20(c). SDDC- K_{pi} exhibits the highest speed difference reduction followed by SDDC- K_p , VIDC, SDC, and GSF. From the FFT of speed difference in Fig. 3.20(c), it is seen that the first natural frequency can be reduced by amount -16 dB illustrating $\frac{1}{6.3}$ times reduction in amplitude. On the other hand, in SDDC with the proportional gain, VIDC, SDC, and GSF the amplitude reduction are -10 dB, -4 dB, -2 dB, and -1.95 dB respectively.

3.6.2 Impulse Load Change

The experimental setup is tested under impulse load change condition and SDDC control is applied to limit the transient over-torque. The test results are illustrated in Fig. 3.21. Without any control, under impulse load change the shaft torque is oscillating between 12 N m and 4 N m and oscillation exists for nine cycles. With the SDDC control using proportional gain the peak torque is limited between 11 N m and 6 N m and the vibration is damped within second cycle itself. The SDDC with proportional and integral control gains shows that the shaft torque amplitude is limited between 10 N m and 7 N m and oscillation is damped within the end of the first cycle itself. Thus, the proposed SDDC control is able to limit the impulse load change effects in the experimental setup. Fig. 3.21 (b) depicts the speed response to the impulse load change at $t = 2.65$ s. With no control activated, the dc-machine

speed and induction machine speed projects torsional twists for about 5 cycles. The amplitude of oscillation is high varying with peaks at 1405 rpm and 1360 rpm. With SDDC- K_p and SDDC- K_{pi} the speed oscillation settles after one cycle only and there is no evidence of twists after that. Though SDDC- K_p and SDDC- K_{pi} both perform similarly, SDDC- K_{pi} happens to have far less oscillation thus better damping performance. The time period to overcome the effect of sudden impulse and achieve back to the steady-state is similar for all the cases.

3.7 Summary

In this chapter, a novel active vibrational damping solution based on speed difference between generator and high-speed gear is proposed for the WTS. Based on two-inertia model of the system, detailed theoretical analysis is carried out and the controller gains are designed thereby. From the theoretical analysis, the SDDC control with proportional gain results in damping ratio improvement and the integral gain results in natural frequency shift. The effectiveness of the proposed control schemes is tested in simulation environment. From the simulation results, it is observed that the proposed SDDC algorithm is able to reduce shaft torque amplification, dynamic speed difference and torsional twisting angle within the drive-line. There is a further possibility of improvement of the SDDC controller in terms of overshoot in pitch angle and drivetrain speed variations. The parametric uncertainty effects are validated by varying the coupling stiffness. In hardware experimentation, the proposed controller operation is verified using a multi-inertia test rig having mechanical unbalance operated under the critical speed condition. Hardware results show that the proposed SDDC is able to reduce the phase and amplitude difference between the drive-line elements, which helps to remove the torsional stress in the drive-line. From all the results it can be concluded that the SDDC- K_{pi} controller gives the best performance.

With high power capability of individual wind turbines the voltage stress in individual switches are increasing to the boundary conditions. The Si-based switches have already reached its operating limits. Advanced multilevel converter topologies are discussed in chapter 2. These multilevel converters are able to withstand higher voltage stress. In order to investigate the effect of wind dynamics and grid disturbances from a power electronic perspective, the next chapter (Chapter4) considers

a three-level neutral point clamped (3L-NPC) topology. The disturbance effects are resolved by the integration of an energy storage system. The study in Chapter 3 can easily be extended to the converter topology considered in Chapter4.

Chapter 4

Integration of ESS in Back-to-Back 3L-NPC Converter based WTS

The chapter investigates a full-scale back to back three level neutral point clamped converter operation for grid connected wind turbine system (WTS). The system is supported by the energy storage system (ESS) connected at the dc-link. The ESS is connected via bidirectional dc-dc converter. The dc-dc converter is controlled for active/reactive power injection to the grid or active power storage during grid and wind speed dynamics. Conventional PI control method and model predictive deadbeat control based techniques are investigated for the dc-dc converter control. Simulation study emulates three different case scenarios and the controller performance are investigated.

4.1 Introduction

Larger wind turbines are enhancing the requirement of high power generator side converters. In the last chapter, two level voltage source converters (VSC) were considered, but multilevel converters are one of the plausible solution to high voltage scenarios of the wind turbine system (WTS). Three-level neutral point clamped (3L-NPC) are able to meet the high voltage standing capability and controllability in high power scenarios. Though there are operational challenges of NPC converters in terms of control and dc-link balancing, detailed research has aided this topology to overcome the challenges [8, 49, 55, 57, 68] . Neutral point clamped (NPC) converters

have made its way in industry for numerous applications [69]. This chapter focuses on implementation of a grid-connected 3L-NPC converter supporting a high power generator based WTS. In Chapter 3, the squirrel cage induction generator (SCIG) was considered for the WTS. In this chapter, a permanent magnet synchronous generator (PMSG) is investigated which adds diversity to the dissertation. The back to back (B2B) topology is provided with an additional energy storage system (ESS) with aim to attain compliance to the grid codes and curtail wind variations.

The control of the bidirectional dc-dc converter is already introduced in Chapter 2. The bidirectional dc-dc converter is controlled with conventional PI controller and a MPC based current controller are analyzed for their performances. The control aims on two main objectives, firstly, the difference the difference value between the extracted power from PMSG and the output power of the grid-tied inverter is tracked to obtain the available active power and charge the ESS. Secondly, inject power into the dc-link for any shortage of active power to be delivered according the grid demand. The 3L-NPC are controlled based on the proportional resonant (PR) current controller and the adaptive space vector modulation (ASVM) method.

Integration of ESS with high power systems is always a challenge. With increasing renewable energy penetration into main grid, ESS are becoming a dominant factor of research in power industry [9, 157]. Large scale ESS can be a viable solution for stochastic renewable sources e.g. wind and solar [205]. Integration of ESS with WTS, reduces power fluctuations and enhances system flexibility. Various topologies like electric double layer capacitor or super-capacitor are being investigated for integration with WTS due to its fast response. [206, 207]. However, the super-capacitor cannot be deployed independently due to the issues of controllability and interoperability in wide voltage range. In this chapter the ESS topologies are not investigated.

For the control of the dc-dc converter a conventional PI controller is implemented based on the plausible operational algorithm. A model predictive control (MPC) based deadbeat controller is also implemented for the dc-dc converter current control. Model predictive control (MPC) techniques are generally associated with higher complexity and demand high computational power. But in recent times the MPC applications in power electronics and renewable energy sector are getting popular and attaining high research attentions [8, 161, 162]. For the generator-side rectifier control and grid-tied inverter control, MPC has been deployed and promising results

are obtained [51, 57, 164]. MPC is also widely investigated in dc-dc power converter applications as well [158, 159]. One of the major challenges for all these sectors have been lengthy predictive horizon which requires higher computational power for processing and implementation. In [164], a simplistic MPC method is implemented for active front end converter application. In this method, the step prediction horizon is designed for only one step. This method has not been investigated for dc-dc power converter application in ESS integration with 3L-NPC based WTS. The system configuration considered for investigation is presented in Fig. 4.1.

The chapter analyses the system in light of the dc-dc converter current controller operation by the two control techniques defined above. The simulation study and implementation of the controllers carried out for the generator side rectifier, grid side inverter and the dc-dc converter integrating the ESS. The major analysis carried out in this chapter can be summarized as,

- Design and operation of a grid connected full scale 3L-NPC converter for PMSG based WTS.
- Application of proportional resonant controller for applied for both rectifier and inverter operations.
- Integration of an ESS at the dc-link via a bidirectional dc-dc converter for mitigation of dynamic scenario aberrations.
- Obtaining fast transient response by the implementation of MPC-based current controller.
- Implement MPC-based control to curtail the wind variation effect on the investigated system.
- Provide FRT and ensure reactive power injection for grid related dynamics, without loss of available active power generated by the generator.
- Comparison of the deadbeat predictive controller with the PI controller for performance in this specific operation.

This study focuses on the investigation of the depicted scenario in Fig. 4.1. The study is analytical and comparative. No new control method has been proposed or claimed in this chapter.

Figure 4.1: A PMSG connected WTS with back to back three-level NPC converter with integrated ESS connected via bidirectional dc-dc converter

4.2 B2B Grid connected 3L-NPC Converter for WTS

For the system studied in this chapter, the WTS is analyzed with B2B connected 3L-NPC as its power electronic interface. Two series capacitor makes up its dc-link. An ESS is integrated at the dc-link. The system configuration is depicted in Fig.4.1.

4.2.1 Configuration of the B2B grid-connected 3L-NPC

The 3L-NPC rectifier is deployed to convert the output ac-power of the PMSG to the dc-power, charging up the dc-link. Another 3L-NPC inverter is implemented on the grid-side to convert the dc-power to ac- power comply to the grid requirements. In Fig.4.1, it can be seen that both rectifier and inverter circuits consist of two pairs of IGBT switches (S_{Ra1} and S_{Ra2} for the rectifier and S_{Ia1} and S_{Ia2} for the inverter) with their complementary switches. In the circuit, other repetitive device annotations follow the similar of nomenclature format with different numerals.

The rectifier and inverter are connected to the series dc-link capacitors (C_1 and C_2). The B2B topology operates with three different switching states to synthesize the

three output pole voltage stepped levels at $-v_{dc}/2$, 0 and $v_{dc.ref}/2$ with respect to the midpoint ‘m’ of dc-link.

4.2.2 Control of the B2B grid-connected 3L-NPC

For the control of the B2B 3L-NPC topology conventional PR controller is selected. Though, the implementation of conventional PI current controller is simple, it suffers from multiple frame transformation and thus computational complexity is higher.

Figure 4.2: Proportional resonant controller used for NPC converter for full scale WTS

The controller rectifier and inverter are kept similar for avoiding complicated instances in this investigation. Conventional phase locked loop (PLL) is implemented for both converters to assure appropriate frequency operation. Voltage oriented control involves the PR controller and generation of switching signal which is done by adaptive space vector modulation method (ASVM) [63, 102]. Fig 4.2 represents the control diagram of the inverter. The PR control and ASVM is implemented similarly for the rectifier unit as well.

The measured dc-link voltage (v_{dc}) is compared to the dc-link reference value ($v_{dc.ref}$) and the difference is used as input to an PI controller. The output of the PI-controller gives the reference d-axis current (i_{d*}). The q-axis reference current (i_{q*}) is set to zero for unity power factor operation in the generator side control.

PR controller is used for controlling the converter currents in stationary coordinate ($\alpha\beta$ -coordinate) [58]. The measured three phase currents of the converter (I_{ga} , I_{gb} and I_{gc} for rectifier and I_a , I_b and I_c for grid-tied inverter) are converted to stationary

Figure 4.3: Space vector representation of the NPC converter

frame through the Clark transformation. The transfer function (G_{PR}) of the PR controller is given below:

Figure 4.4: Circuit diagram and current path for vectors of one vector pair

$$G_{PR} = K_P + \frac{K_i \cdot s}{s^2 + \omega_s^2} \quad (4.1)$$

here, K_P represents the proportional gain term, K_i is the integral gain term, and ω is the resonant frequency. The reference voltages ($V_{\alpha*}$ and $V_{\beta*}$) are obtained

from the PR controller and can be directly used as input to the ASVM without any requirement of inverse Park or Clark transformation. The voltage balancing of the capacitors are found to be better in the ASVM compared to the classical space vector modulation (SVM) method. Thus controller can perform faster with lesser computational complexity. This technique can balance the dc-link capacitor voltages by selecting the appropriate switching state [55, 58, 208].

The space vector representation for the 3L-NPC inverter or rectifier is shown in Fig.4.3. For a 3L-NPC, each switching state is composed of three-phase voltages which can be defined as vectors and represented in a three dimensional planar representation. In order to represent the three-dimensional vector values in two dimension Clarke transformation is required. The aim of space vector modulation technique is to generate a reference voltages in similar two dimensional plane so as the appropriate switching sequence can be assigned. For 3L-NPC, the number of states attainable are 27 (n^3) which can be visualized in Fig. 4.3. The SV representation can be divided into six sectors. Each sector is formed of four triangles. The correct vector is selected based its proximity to the generated voltage reference. It can be observed in Fig. 4.3, that there are six common vector-pairs in each internal voltage state and one triple vector at the origin. The voltage generated by these similar vector states are equal as well. The appropriate selection of vector assures balanced capacitor operation. The SVM uses the pair of vectors during every switching cycle period which increases the switching loss due to the high switching frequency operation. The ASVM technique is applied in combination with the PR to improve the efficiency of the specific converters [58]. The overall switching loss is decreased by reducing the switching frequency since one of the vector pairs is utilized in each switching cycle.

For instance in control of the 3L-NPC inverters, even though both vectors generate the same output voltage level, but there are different effects on the dc-link capacitor voltages. When the state vector is (100), the dc-link capacitors C_1 and C_2 are in charging and discharging states respectively, according to the respective voltage potentials. The ASVM voltage balancing method is independent of the main controller. The capacitor voltages can be balanced in all operating situation including unbalance grid faults. The balancing operation of capacitors with ASVM technique is depicted in the Fig.4.4 and the corresponding to the equations can be written as following,

$$(100) \Rightarrow \begin{cases} V_{C1} \leq V_{C2}, & \text{and } I_a \geq 0 \\ V_{C1} > V_{C2}, & \text{and } I_a < 0 \end{cases} \quad (4.2)$$

$$(211) \Rightarrow \begin{cases} V_{C1} \geq V_{C2}, & \text{and } I_a \geq 0 \\ V_{C1} < V_{C2}, & \text{and } I_a < 0 \end{cases} \quad (4.3)$$

4.3 Bidirectional DC-DC converter

The bidirectional dc-dc converter connects the ESS with the system at the dc-link. several configurations of dc-dc converter with bidirectional feature are available. The operation intended in this study can be achieved by a buck-boost converter which operates buck in one direction and boost in other. But in order to keep the investigation range wider for future investigations, a bidirectional buck boost converter is chosen.

4.3.1 Configuration of the Bidirectional DC-DC converter

The chosen bidirectional dc-dc converter consists of four IGBTs and an inductor (L_{DCDC}). The converter is operated either in buck mode or boost mode based on its mode of charging or discharging the ESS. The direction of power flow is assigned by the control based on the an algorithm discussed later. A dc-source is connected at one-end of the dc-dc converter which emulates the ESS operation. Further, this study can be extended to model the appropriate ESS and integration of super-capacitors for even faster dynamics. The voltage across the ESS is termed annotated as v_{ess} .

4.3.2 Control of the Bidirectional DC-DC converter

The overall system control has three points of control points, which are (i) generator-side converter control, (ii) grid-side converter for inverter control, and (iii) bidirectional dc-dc converter control. Before getting in the dc-dc converter control, the algorithm establishing the operating condition of the dc-dc converter is established. The algorithm is discussed below.

4.3.2.1 Algorithm for DC-DC Converter Control

Connecting the ESS to WTS, the dc-dc converter has to be able to operate in both buck mode and boost mode. Buck-boost capability can be achieved by controlling switches in different combinations. Based on the voltage of dc-link the converter controller performs the buck or boost operation either charging or discharging of the ESS. During normal condition of the grid, the dc-dc converter is inactive. Under the grid fault or wind speed dynamics there are four operating conditions that can be defined. The control algorithm can be shown in a flow diagram as represented in Fig.4.5.

Figure 4.5: Representation of control algorithm for the bidirectional dc-dc converter

When dc-link voltage is greater than the reference dc-link voltage ($v_{dc} > v_{dc.ref}$), we know that the extracted power from the PMSG (P_{gen} or P_{O_PMSG}) is larger than the injected power to the grid (P_{O_Inv} or P_{grid}). Therefore the difference between

these two values has to be injected to the ESS i.e dc-dc converter will operate in ESS charging mode. Direction of the power in dc-dc converter will be from dc-link to the ESS with IGBT4 remaining off. Based on v_{dc} and voltage of ESS (v_{ess}), the converter should perform boost or buck conversion and accordingly the switches will be controlled. Hence four different operation modes can be implemented as follows:

- If the $v_{dc} > v_{dc.ref}$ and $v_{dc} > v_{ess}$, then the IGBT1 is controlled and all other IGBTs are set to 0.
- If $v_{dc} > v_{dc.ref}$ and $v_{dc} < v_{ess}$, IGBT1 is set to 1, IGBT 2 and 3 are set to 0, IGBT 4 is controlled (*DC_Switch*).
- If $v_{dc} < v_{dc.ref}$ and $v_{dc} > v_{ess}$, IGBT 4 and 1 are set to 0, IGBT 3=1 and IGBT 2 is controlled.
- If $v_{dc} < v_{dc.ref}$ and $v_{dc} < v_{ess}$, only IGBT 3 is controlled and all other are set to 0.

As the algorithm is defined, futher, the implementation of the control is discussed.

4.3.2.2 PI-controller implementation for dc-dc converter control

Though PR controller are discussed to be more efficient for three-phase systems, for dc-dc converter or single phase ac systems, PI controller are faster, and the harmonics associated are also lesser. Instantaneous dc-link voltage is compared to its reference value. The error is controlled through a PI controller, while it calculates the reference capacitor current (i_{C*}). The implementation of PI control is depicted in Fig.4.1. The dc-dc inductor reference current (i_{L_DCDC}) can be calculated by the following equations.

$$i_{L_DCDC} = i_{dc_Rec} - i_{dc_Inv} - i_{c*} \quad (4.4)$$

here, i_{DC_Inv} is the instantaneous inverter input current and i_{DC_Rec} is the instantaneous rectifier output current.

The current of dc-dc inductor is controlled through the PI controller which gives the reference inductor voltage (v_{L_DCDC*}). Subsequently, pulse width modulation

Figure 4.6: Bidirectional dc-dc converter control for the ESS integration.

(PWM) generates the switching signal from the obtained $i_{L_DCDC}^*$, and thus switching the IGBTs. The PI control diagram of the dcdc converter is shown in the Fig. 4.6.

4.3.2.3 MPC dynamic reference design for dc-dc current control

As discussed in Section 4.1, the literature [164] implements a simplistic MPC based control system for AFE converter in drive application. Similar strategy is adhered and a control technique is designed, implemented and analyzed for the bidirectional dc-dc converter application. In this controller, the dynamic reference of the inductor current is tracked based on one step prediction horizon of the dc-current and the inductor current. From the available data, the current from the rectifier and the current into the inverter are determined as well. Finally the desired current reference is tracked. For this method, information of inductance of dc-dc converter and capacitance of the dc-link are required which were not mandatory for PI-controller.

Firstly, from the system figure (Fig. 4.1), the voltage equation for the voltages can be written as Eq. 4.5,

$$L_{DCDC} \cdot \frac{d i_{L_dc/dc}}{dt} = v_4 - v_{dc} \quad (4.5)$$

Discretization of Eq. 4.5 gives us the Eq. 4.6 where T_S represents the sampling time,

$$L_{DCDC} \cdot \left\{ \frac{i_L(k+1) - i_L(k)}{T_S} \right\} = v_4 - v_{dc} \quad (4.6)$$

Here, $i_L(k+1)$ denotes the future state which is being predicted. This value can be stated as the actual the reference ($i_{L_DCDC}^*$) for the present state $i_L(k)$. And thus simplifying Eq. 4.6 we can obtain the v_4 . Again,

$$v_4 = D \cdot v_{ess} \quad (4.7)$$

Solving Equation 4.6 and 4.7 we can obtain the duty cycle for controlling the dc-dc converter. For the dc-dc converter, the current equation can be represented as the following equation,

$$C_{dc} \cdot \frac{dv_{dc}}{dt} = i_C \quad (4.8)$$

Discretization of Eq.4.8 provides the equation with the present and the future value of v_{dc} .

$$C_{dc} \cdot \left\{ \frac{v_{dc}(k+1) - v_{dc}(k)}{T_S} \right\} = i_C \quad (4.9)$$

Here, $v_{dc}(k+1)$ assigns the reference value for the v_{dc} i.e. v_{dc}^* and $v_{dc}(k)$ is the present value of the dc-link voltage. Thus we can equate the value of i_C from Eq. 4.9.

$$i_C = \frac{C_{dc} \cdot (v_{dc}^* - v_{dc})}{T_S} \quad (4.10)$$

From the three-phase rectifier system and inverter system, we can derive the following equations,

$$v_{gen-a} \cdot i_{gen_a} + v_{gen-b} \cdot i_{gen_b} + v_{gen-c} \cdot i_{gen_c} = v_{dc} \cdot i_{dc_Rec} \quad (4.11)$$

$$v_{an} \cdot i_a + v_{bn} \cdot i_b + v_{cn} \cdot i_c = v_{dc} \cdot i_{dc_Inv} \quad (4.12)$$

In Eq. 4.11, $v_{gen-a,b,c}$ are all same and known value. Similarly in Eq. 4.12, $v_{a,b,c}$ are known. Thus from these two equations we can equate, i_{dc_Rec} and i_{dc_Inv} .

Based on the current flow direction, the reference tracking for the inductor current can be shown as,

$$i_{L_dcdc}^* = i_{dc_Rec} - i_c - i_{dc_Inv} = i_L(k+1) \quad (4.13)$$

Now from Eq. 4.6, Eq. 4.7, Eq. 4.9 and Eq. 4.13, the duty cycle (D) can be calculated. Thus the deadbeat predictive control is thus implemented for dynamic inductor current reference tracking and thus the current control of the bidirectional dc-dc power converter.

Table 4.1: Simulation Parameters

Parameter	Annotation	Value
Grid Voltage	$V_{PCC_{abc}}(L-L)$	400 V
Grid Frequency	f	50 Hz
Line Inductor	L_f	5mH
dc-dc converter Inductor	L_{dcdc}	1mH
dc-link capacitor	C	2.2 μ F
NPC switching frequency	f_s	10 kHz

4.4 Simulation Analysis of ESS Integrated with the WTS

The simulation of the complex system shown was carried out in Matlab[®]/Simulink environment. For simplicity of application, the bidirectional dc-dc converter is pre-conditioned with IGBT1 is always on and IGBT2 is always off. For further case studies these switches would be operated as suggested in the algorithm. Performance of the system is analyzed for three different case scenarios. The case scenarios can be defined as:

- Case-A: Steady-state operating condition

- Case-B: Grid-side fault
- Case-C: Wind-speed Variations

In order to observe the behavior of the described system the grid voltage is considered to be $400\text{ V}/50\text{ Hz}$. The simulation parameters considered for the analysis are presented in Table. 4.1.

Figure 4.7: Case A: Performance of the WTS under steady-state: (a) grid voltage, (b) grid current, (c) generator voltage, (d) generator current, (e) dc-link voltage and (f) active power, reactive power and power of dc-dc converter connecting the ESS.

4.4.1 Case-A: Steady State Performance

The steady-state condition is characterized by the system operating under nominal wind-speed. The grid-side is stable and not dynamic scenarios are observed. The steady state performance of the system is shown in Fig.4.7. The figures presented in Fig.4.7 (a), (b), (c) and (d) show the sinusoidal grid voltage, in-phase currents, generator voltage and the generated currents respectively. These signify the smooth grid integration operation from the 3L-NPC inverter and smooth operation of back to back 3L-NPC configuration for the analyzed WTS. The PR controller and PLL are thus correctly implemented as well. The system is when operated in steady-state condition, no major variations are observed in the dc-link voltage, as presented in

Fig.4.7(e). The power from the PMSG is transferred to the grid with no apparent requirement of reactive power which can be also seen in Fig.4.7(f). The simulation of steady state performance is similar for PI-controller based and MPC controller based system, this is because the ESS is inactive during this scenario.

The steady-state performance of the system presented in Fig.4.7 signifies the immaculate implementation of the PR-controller with ASVM technique discussed above in Section 4.2.2.

4.4.2 Case-B: Grid side fault/voltage sag

Grid-side dynamic ride through performance is one of the major challenging aspect of the grid-connected WTS of any scale. In high power application the difficulties are further more intense. WTS with higher compliance with grid regulatory instructions are classified as the most reliable one. The grid side aberration investigated here emulates a 50 % voltage sag in the grid-side along side sudden requirement of reactive power. The configurations which operate undisrupted during such fault scenario are termed to comply with the FRT compliance. In order to observe the response of the system, this scenario is emulated at the PCC at time $t = 0.05$ s. Fig. 4.8 (a) and (b), represent the grid side voltage and current waveforms with the respective sags. The performance of the implemented PI controller and MPC based controller are reflected in the dc-link voltage regulation and power scenario observed in Fig. 4.8 (c), (d) and (e).

The 3L-NPC inverter injects reactive power to the grid (Q_{grid}), and consequently active power captured from the wind turbine is underutilized. Due to the difference of P_{gen} and the P_{grid} , the bidirectional dc-dc converter activates. The active power from the generator, which is not injected into the grid i.e. the difference of P_{gen} and P_{grid} , is used to charge the ESS. And thus the generated active power is not lost.

The performance of the PI-controller in controlling the dc-dc converter can be summarized by the dc-link voltage behavior and the power curves depicted in Fig.4.8 (c) and (e). Important things to observe here are the variations which the dc-link go through and the rate at which the dc-dc converter responds to the scenario. However, the dc-link variation is within 3% which is acceptable.

Figure 4.8: Case B: Performance of the WTS under grid-side fault scenario with reduced active power requirement and increased reactive power requirement alongside charging the ESS through the dc-dc converter: (a) grid voltage, (b) grid current, (c) fall of active power, injection of reactive power and ESS charged via dc dc converter (PI), (d) fall of active power, injection of reactive power and ESS charged via dc dc converter (MPC), and (e) dc-link voltage .

For the implemented MPC based controller, it is observed that due to fast dynamics of the MPC based deadbeat controller, the dc-link voltage does not show case variations as for PI-controller. For the active power transferred to the ESS, the response of dc-dc converter is faster for MPC-based controller. Though, there is no abrupt variation at time of sag, but the dc-link voltage does appear to be distorted all through the sag condition. The performance of the deadbeat predictive controller can be summarized from the simulation results presented in Fig.4.8 (d) and (e). The dc-link voltage signifies the degraded robustness of the controller.

Overall, for both the controller, the dc-link capacitor voltage is fairly constant and balanced. This signifies the performance of the ASVM for the inverter and rectifier. The WTS does not pose any threat to the grid by unbalancing the voltages or currents. Further, the system injects the required reactive power and the active power captured from the wind turbine is not lost as it is used to charge-up the ESS. Thus it can be concluded saying that the system has FRT capability in this regards. Further,

the line-line, line to ground, etc can be investigated for detailed FRT analysis.

Figure 4.9: Case C: Performance of the WTS under generator-side power variation for sudden wind speed fall: (a) generator current, (b) dc-link voltage (PI and MPC), (c) constant grid active power, fall of generator power and ESS discharged via dc dc converter (MPC control), and (d) constant grid active power, fall of generator power and ESS discharged via dc dc converter (PI control).

4.4.3 Case-C: Wind Speed Dynamics

Case-C underpins the wind-speed dynamics which are studied under two sub-cases. The wind speed is considered to have a sudden drastic drop for the first case and the second case is the scenario where the wind speed variation is more drastic represented by a sinusoidal variation after the sudden wind drop. The WTSs suffer such scenarios from mechanical perspective which is discussed to some extent in Chapter 3. From electrical perspective, the sudden power drop from the generator makes the system under-performing since it cannot meet the predefined active power demand from the grid.

In order to emulate the first sub-case scenario, at $t = 0.05$ s the wind speed input is provided with a step changed and as a result the power from the generator decreases. Fig. 4.9(a) represents the current output of the generator in the defined scenario.

For reduced power produced, difference of the P_{gen} and P_{grid} triggers the activation of the dc-dc converter. The required power for constant power injection to the grid is maintained by drawing power from ESS. For the step wind change, the performance of the MPC and PI controllers are depicted in Fig 4.9 (c) and (d) respectively. The

Figure 4.10: Case C: Performance of the WTS under generator-side power variation for sudden wind speed fall followed by sinusoidal variation: (a) generator current, (b) dc-link voltage (PI and MPC), (c) constant grid active power, fall of generator power and ESS discharged via dc dc converter (MPC control), and (d) constant grid active power, fall of generator power and ESS discharged via dc dc converter (PI control).

difference in the PMSG power is compensated by the ESS. The dc-link voltage is again fairly constant as shown in Fig 4.9 (b). The dc-link voltage variation for PI controller is within the acceptable limit. But for MPC controller, no such variation is observed. The performance observed in case of power injection is very similar for both controller application.

For taking the system through further more detail wind dynamic scenario a second case investigated. The wind speed decreases through a step change at $t = 0.05$ s and then varied sinusoidally till $t = 0.10$ s. Fig 4.10(a) represents the generator current scenario for this test case. The dc-link voltage variation is again higher for the PI controller, whereas the dc-link voltage is maintained constant for the fast responding MPC controller. The power curves for MPC and PI controllers are depicted in Fig. 4.10(c) and Fig. 4.10(d) respectively. The sinusoidal variation of wind speed is curtailed by both controllers with acceptable aberrations. But the PI controller projects higher variation and the benefits of the fast dynamics of the MPC controller can be observed in the simulation results. The PI-controller performance is commendable as it complies with the requirements, but it falls slightly short of the performance projected by MPC based dc-dc converter controller in this specific application.

4.5 Summary

With higher influx of stochastic renewable sources, grid connected generation utilities would require improvisations to suffice the grid-codes implications. Integration of ESS make renewable source based generation systems more stable, reliable and sturdy for dynamic conditions. Even for scenarios with micro-grid in islanding conditions, ESS can mitigate renewable-sources' grid integration challenges. This chapter primarily focused on application of multilevel converters in large wind turbine systems. This chapter analyses the control of the bidirectional dc-dc converter connected to the energy storage system to support the dynamics of wind variations and grid faults. A MPC-based controller and a PI controller are implemented for the control of dc-dc converter. The obtained results are analyzed, compared and summarized. The obtained simulation results are promising. Further, this system can be implemented and investigated in hardware for validating the controller performance.

In the previous chapter we focused on the dynamic load variations and torsional stress applied due to wind variations also affect the overall system stability. Factors like resonant wind excitation, hard stop, wind gust, etc causing similar variations at the dc-link were addressed and solved through a proposed SDDC controller scheme. As discussed in Chapter 2, though the topologies of active power converter are promising there are several issues of reliability due to higher number of semiconductor switches involved. Higher component count becomes alarming when offshore establishments are considered. So, for high power offshore WTS applications, literature suggest use of simpler converter topologies with lower switch counts. And in offshore applications the advantages of dc-power collection over ac-power collection are discussed in detail in Chapter 2. For dc-power collection, the rectifier accompanies the generator in the nacelle. Going forward in this dissertation, the grid side inverter or the dc-ac converter is considered same for all rectifier topologies. In Chapter 5 we investigate a novel converter topology with lower semiconductor switch counts for dc-power collection in WTS.

Chapter 5

Operation of Parallel Unity Power Factor Rectifier for offshore WTS

This chapter proposes detailed modeling and analysis of the parallel operation of auxiliary circuit based three-phase diode rectifier. The converter topology is used as the front end converter for synchronous generator based wind turbine system. The control of the converter focuses on input current shaping, current balancing and constant dc-link voltage. The simulation investigates three scenarios which are represented in Section 5.4. The hardware experimental setup validates the simulation study in a 2.5kW laboratory setup. The hardware results are presented in Section 5.5.

5.1 Introduction

For applications associated with low to medium power, two-level pulse width modulated voltage source converters (VSC) are popular in research for their efficiency and controllability [8]. The VSC based wind turbine system (WTS) with squirrel cage induction generator (SCIG) has been studied in the Chapter 3. In the contrary for high power applications, such converter topologies are not encouraged for the physical limitations of semiconductor device material properties. Multilevel converters like neutral point clamped (NPC) converters are thus gaining more attention for high power applications. But the control aspect of such topologies are more complex and demands higher computational load [8, 19, 209]. In Chapter 4, a 3L-NPC based back to back system is investigated for permanent magnet synchronous generator

(PMSG) based WTS. VSC based and 3L-NPC based converters provide bidirectional power flow operation options whereas unidirectional power converters can suffice the requirements in WTS for dc-power collection [6, 210]. From the literature review, we come to know that with high power rating, simple and rugged three-phase diode rectifier is a plausible choice. However, it produces higher input current harmonics, lower power factor and eventually reduces the efficiency of the overall system [79]. Additional circuitry with passive rectifier has been proposed in the literature so as to overcome the above mentioned drawbacks of three-phase diode rectifier application in WTS [89, 90].

Aditya *et.al* in [6], proposed the use of a three-phase diode rectifier with the auxiliary circuit, to be used as a front-end-rectifier for PMSG based stand-alone WTS. Advantage of such topology lies in high power factor of input-current and low input-current harmonics. Lower number of switch count increases the reliability of the system. High-power high-current applications require high rated power electronic switching devices which are expensive and not popular in practice like ANPC, FC, etc [4, 48]. Parallel operation of converters ensures a higher range of output power, flexibility of power control and lower current stress on each converter module [211]. The parallel operation aids the use of switching devices of lower power ratings [47, 212, 213]. Such topologies are apposite for partial operation at times of system reconfiguration or maintenance. Parallel operation also adds advantages of reduced voltage and current ripples [214]. As detailed before, auxiliary circuit based diode rectifier has advantages over VSC and NPC when used as front end topology for WTS and in spite of it there has not been much research in its operation in parallel for higher power applications.

In the next chapter (Chapter 6), the component failure based reliability and feasibility of the parallel unity power factor rectifier (PUPFR) is analyzed in a comparative study with other topologies discussed in this dissertation. In this chapter, the control strategy for the PUPFR as front-end-rectifier is proposed. The main novelties of the proposed system and control algorithm are:

- The parallel operation for the three-phase auxiliary circuit based diode rectifier for the application of dc-power collection in offshore wind power systems.
- The achievement of constant dc-link voltage with balanced capacitor voltages under all operating conditions.

- The unity power factor operation of the parallel converters with balanced current division between the parallel branches, using a hysteresis current control.

The rest part of the chapter is organized as follows: Section 5.2 presents the proposed system architecture with descriptions of wind turbine and generator module. Both hysteresis current control and dc-link voltage control are discussed in Section 5.3. Section 5.4 and Section 5.5 present the research findings in forms of simulation and hardware experimentation respectively. Finally, the chapter is summarized with the discussion in Section 5.7.

5.2 Proposed System Architecture

The proposed system topology is depicted in Fig.5.1. The rotating turbine blades utilize the linear wind speed (v_{wind}) to convert mechanical power to electrical power. Mechanical torque (T_m) obtained from the rotation is input to the PMSG making system a direct-drive WTS. This rotational torque provides electrical torque (T_e) for the machine, which is converted into electrical power. The proposed power electronic interface rectifies the ac to dc power.

Figure 5.1: Converter current control and dc-link voltage control diagram of the PUPFR for PMSG based dc-power collection in WTS

5.2.1 Parallel UPF Rectifier for WTS

The three-phase ac output from the generator is rectified to make it feasible for dc-transmission. For the proposed parallel system, each branch is provided with three bidirectional switching blocks (BSBs). The generator output is divided into branches each having separate inductors for making the current control of individual branches independent of each other. This would yield advantage at times of fault in any specific branch where it can be modularly segregated and the system can still be operative at a lower power rating. The diode rectifiers are rated to withstand high current and voltage stress.

Upper branch rectifier comprises of diodes from D_{11} to D_{16} and lower branch rectifier diodes are D_{21} to D_{26} . The midpoint of diode D_{11} and D_{14} is $X1$; $Y1$ refers to the mid point of D_{13} and D_{16} ; $Z1$ is the midpoint of D_{15} and D_{12} . For the lower branch diode rectifier similar annotations are defined with midpoints $X2$, $Y2$ and $Z2$. Each phase current passes through the BSBs which eventually shapes the input-current to near perfect sinusoids. Each phase BSB comprises of four diodes and one IGBT. For upper branch phase-a, the current i_{a1} is shaped by the BSB with diodes $D_{a11} - D_{a14}$ and has the IGBT S_{a1} . All other phase currents are treated with BSB with likewise annotations as illustrated in Fig.5.1. The outputs of the rectifiers are connected to the dc-link comprising of two capacitors (C_1 and C_2). The two capacitors' mid point (M) is connected to the common output of BSBs of upper and lower branches. For each phase, when the switches are turned ON the corresponding phases exercise a rise of current. Turning OFF of the switch is associated with the current conducted from the upper diode or the lower diode of the front half of the diode bridge. Consequently, the phase current reduces. Referring to the system diagram in Fig.5.1 the following equations can be obtained for currents flowing through inductances L_1 .

$$\begin{aligned} L_1 \frac{di_{a1}}{dt} &= v_{gen-a} - v_{X1M} \\ L_1 \frac{di_{b1}}{dt} &= v_{gen-b} - v_{Y1M} \\ L_1 \frac{di_{c1}}{dt} &= v_{gen-c} - v_{Z1M} \end{aligned} \quad (5.1)$$

Here i_{a1} , i_{b1} and i_{c1} are line currents. PMSG output voltages are denoted by v_{gen-a} , v_{gen-b} and v_{gen-c} . v_{X1M} , v_{Y1M} and v_{Z1M} are voltage between nodes of the rectifier as defined above and midpoint of the dc-link. For lower branch, similar equations

can be derived for currents through L_2 . Following equations (Eq.5.2-11) are obtained expressing the voltage in terms of their corresponding phase-currents of each branch. For upper-branch,

$$\begin{aligned} v_{X1M} &= \text{sign}(i_{a1})(1 - S_{a1}) \frac{v_{dc}}{2} \\ v_{Y1M} &= \text{sign}(i_{b1})(1 - S_{b1}) \frac{v_{dc}}{2} \\ v_{Z1M} &= \text{sign}(i_{c1})(1 - S_{c1}) \frac{v_{dc}}{2} \end{aligned} \quad (5.2)$$

S_{a1}, S_{b1} and S_{c1} signifies the switching states of the BSBs. V_{dc} is the dc-link voltage. And,

$$\text{sign}(i_x) = \begin{cases} 1, & \text{if } i_x \geq 0 \\ -1, & \text{if } i_x < 0 \end{cases} \quad (5.3)$$

Here, x refers to $a1$, $b1$ or $c1$. Similarly, the equations of v_{X2M} , v_{Y2M} and v_{Z2M} can be derived for the second branch. On the basis of the switch-on and off time, the r.m.s. and the average value current flowing through the switch can be obtained. The values depend on the reference values for each phase. The references are generated from the r.m.s. current values of the generator output current divided in each branch ($\tilde{i} = i_{gen.rms}$).

5.3 Proposed Converter Control

Proposed converter control algorithm has two main factors of consideration. Firstly, the input current is to be maintained near UPF and low-THD with each of the parallel branches having the same magnitude of the current. Secondly, the dc-link voltage is to be kept constant for input variations due to wind or load side dynamics. The overall control diagram is represented in Fig.5.2.

Figure 5.2: Converter current control and dc-link voltage control diagram of the PUPFR for PMSG based dc-power collection in WTS

5.3.1 Input Current Control of the PUPFR

As observed from the converter topology, three-phase diode-rectifiers in both branches are uncontrolled. Control of this converter topology is associated with switches in the BSB. When switches in BSB are off or non-operating, during a positive half cycle of each phase the diodes of the upper leg of both branches conduct i.e. D11, D13, D15, D21, D23, and D25. During the negative half cycle the remaining diodes i.e. the diodes from lower-branch conducts. Input voltage from the generator is considered to be balanced and can be expressed as

$$\begin{aligned}
 v_{gen-a} &= \sqrt{2} \tilde{v} \sin(\omega * t) \\
 v_{gen-b} &= \sqrt{2} \tilde{v} \sin\left(\omega t - \frac{2\pi}{3}\right) \\
 v_{gen-c} &= \sqrt{2} \tilde{v} \sin\left(\omega t + \frac{2\pi}{3}\right)
 \end{aligned} \tag{5.4}$$

Here, $\tilde{v}$ represents generator voltage amplitude ($\tilde{v} = v_{gen-amp}$)

$$\begin{aligned}
i_{a1} &= \sqrt{2} \tilde{i} \sin(\omega * t) \\
i_{b1} &= \sqrt{2} \tilde{i} \sin\left(\omega t - \frac{2\pi}{3}\right) \\
i_{c1} &= \sqrt{2} \tilde{i} \sin\left(\omega t + \frac{2\pi}{3}\right)
\end{aligned} \tag{5.5}$$

Here, $\tilde{i}$ represent the r.m.s. components of the generator current divided in the upper and lower branches. A similar equation is valid for lower branch currents as well. The switching sequence is generated via hysteresis current comparator based on the input phase current and the generated reference current from the dc-link voltage control. Using the hysteresis current control technique each phase currents of upper and lower branches are controlled to track the reference current within the band limit (B). The parameter B setting is discussed later. The switching signals of the BSB can be represented by the equation given below.

$$S_x = \begin{cases} 1, & \text{if}(e_x > 0 \quad \text{and} \quad e_x > e_x^* - B) \\ & \text{or}(e_x < 0 \quad \text{and} \quad e_x > e_x^* + B) \\ 0, & \text{if}(e_x > 0 \quad \text{and} \quad i_x > e_x^* + B) \\ & \text{if}(e_x < 0 \quad \text{and} \quad e_x < e_x^* - B) \end{cases} \tag{5.6}$$

Here, x refers to i_{a1} , i_{a2} , i_{b1} , i_{a2} , i_{c1} or i_{c2} .

5.3.2 DC-link Voltage Control of the PUPFR

The dc-link voltage is expected to be controlled to a fixed value irrespective of input variations. The reference of dc-link voltage ($v_{dc.ref}$) is obtained from dc-power reference. The two dc-link capacitors ($C1$ and $C2$) demonstrated tendencies of asymmetry by charging and discharging to different voltage levels. This variation eventually causes different voltage stresses for the semiconductor devices causing system unbalance. The voltage balance is obtained by inserting a dc-current component based on the voltage difference of the dc-link capacitor voltages.

$$i_{dc.balance} = \tilde{k}_C (v_{C1} - v_{C2}) \tag{5.7}$$

The difference of the $v_{dc.ref}$ and the measured dc-link voltage (v_{dc}) is taken through a compensator. The component $i_{dc-balance}$ is added to the compensated value i_{dc0} . The magnitude of the generator current added to i_{dc0} to obtain $i_{dc.ref}$ for the hysteresis current controller. This is also represented in Fig. 5.2.

5.3.3 Calculation of the Hysteresis Band

The hysteresis band is estimated for each phase referring to the topology presented in Fig. 5.1. Holmes in [135] and Liu in [93], described the procedure of deriving the equation for hysteresis band setting. For the upper branch and the lower branch of the PUPFR, the hysteresis band for the controller is estimated from the input voltage, input current, switching frequency and input inductance. The equations are derived below.

First, referring to the voltage equation for phase-a presented in Eq. 5.1 which can also be presented as,

$$v_{gen-a} = L_1 \frac{di_{a1}}{dt} - v_{X1M} \quad (5.8)$$

In this equation if i_{a1}^* is the reference of phase-a upper branch current and v_{X1M}^* is the corresponding reference voltage,

$$v_{gen-a} = L_1 \frac{di_{a1}^*}{dt} + v_{X1M}^* \quad (5.9)$$

In the hysteresis current control method, the hysteresis band is used to track the current error which can be defined as (γ) and for phase-a it is (γ_a),

$$\gamma_a = i_{a1}^* - \frac{i_{gen-a}}{2} \quad (5.10)$$

Subtracting Eq. 5.8 from Eq. 5.9 and from Eq. 5.10 we get,

Figure 5.3: Current and voltage waveforms to determine the hysteresis band (B) for current control: (a) when phase-a current is positive, and (b) when phase-a current is negative

$$\begin{aligned}
 L_1 \frac{d\gamma_a}{dt} + (v_{X1M}^* - v_{X1M}) &= 0 \\
 L_1 \frac{d\gamma_a}{dt} &= -(v_{X1M}^* - v_{X1M})
 \end{aligned} \tag{5.11}$$

i_{a1}^* operates both in positive and negative values over a period. Referring to the Fig. 5.3(a), over one switching cycle for the time period ($0 < t < t_1$), Eq. 5.11 can be expressed as,

$$-(V_{X1M}^* - 0) = L_1 \left\{ \frac{\gamma_a(t_1) - \gamma_a(0)}{t_1 - 0} \right\} = L_1 \left(\frac{-B - B}{t_1 - 0} \right) \tag{5.12}$$

Here, B is defined as the hysteresis band value. Now, for the time period ($t_1 < t < T_s$),

$$-\left(V_{X1M}^* - \frac{v_{dc-link}}{2}\right) = L_1 \left\{ \frac{\gamma_a(T_s) - \gamma_a(t_1)}{T_s - t_1} \right\} = L_1 \left(\frac{B + B}{T_s - t_1} \right) \tag{5.13}$$

Thus equating for T_s ,

$$T_s = \frac{(2B) * L_1 * v_{dc-link}}{(v_{dc-link} * V_{X1M}) - 2 * (V_{X1M})^2} \quad (5.14)$$

The T_s is inversely related to the switching frequency. Thus, applying Eq. 5.14 in Eq. 5.9 the equation for the hysteresis band determination can be obtained,

$$B = \frac{\left(v_{gen-a} - L_1 \frac{di_{a1}^*}{dt}\right) * v_{dc-link} - 2 \left(v_{gen-a} - L_1 \frac{di_{a1}^*}{dt}\right)^2}{2 * f_s * L_1 * v_{dc-link}} \quad (5.15)$$

The whole process can be repeated for negative half cycle referring to the Fig. 5.3(b). Finally, the equation derived for the hysteresis band can be represented as,

$$B = \frac{\left(|v_{gen-a}| - L_1 \frac{d|i_{a1}^*|}{dt}\right) * v_{dc-link} - 2 \left(|v_{gen-a}| - L_1 \frac{d|i_{a1}^*|}{dt}\right)^2}{2 * f_s * L_1 * v_{dc-link}} \quad (5.16)$$

The Eq. 5.16 is used to determine the value of the fixed hysteresis band for phase-a of upper branch. Same process can be repeated for all other phase currents as well. In this application, for a certain range of values of switching frequency, the hysteresis band values were obtained. The band value which rendered lowest input current THD, has been selected as the value of B . This equation can also be used to implement the variable hysteresis band fixed switching frequency operation of the PUPFR system.

5.4 Simulation Analysis

A PUPFR implemented as generator side rectifier is designed and developed using MATLAB[®]/Simulink. The PMSG providing ac-power has rated power of 3MW which is coherent to the rating of a medium to large offshore wind generator. The base wind speed is considered to be 12 m s^{-1} and the rated dc-link voltage is 2.2kV. The dc-link capacitor is sized based on the reference dc-link voltage. The detailed parameters of the simulation are presented in Table 5.1. In order to validate the performance

of the proposed converter topology with the controller under varying wind speed conditions and dc-grid side dynamics, four scenarios are emulated. Firstly, the system is analyzed in light of the effect of the operation of BSB ensuring unity power factor operation. Subsequently, the three above mentioned scenarios are simulated.

Table 5.1: Simulation Parameters

Parameter	Annotation	Value
Base Wind Speed	v_{wind}	12 m s ⁻¹
Power PMSG	P_{gen}	3 MW
Rated Voltage	V_{rated}	1 kV
Rated dc-link Voltage	$V_{dc-rated}$	2.2 kV
Rated Frequency	f_r	50 Hz
dc-capacitors	$C1, C2$	300 μF
Line Inductors	$L1, L2$	3 mH
Sampling Time	T_s	2×10^{-6}

5.4.1 Steady State Performance of PUPFR

When the BSBs are turned off, the system operates like two three-phase diode rectifiers operated in parallel. The input voltage remains sinusoidal as depicted in Fig.5.4(a) but the input current is distorted and has high harmonic components as shown in Fig.5.4(b). This will eventually cause higher torque ripples in the generator reducing the efficiency and lifetime. THD of input current during this operation is very high. The dc-link voltage is not a pure dc but a rectified dc. Once the BSB switches are turned on at time $t = 0.1s$, the input current is shaped to sinusoidal. It takes one full cycle to reach the rated value. The dc-link voltage is now controlled and it reaches the rated value of $1p.u.$ in $0.04s$. Due to the operation of the dc-capacitor balancing, the capacitor voltages are balanced as shown in Fig.5.4(c). In Fig.5.4(d), the phase-a current (i_{gen-a}) from the generator is illustrated along with the upper branch phase-a current (i_{a1}) and the upper branch BSB phase-a switching current (i_{swa1}). The branch currents are half of the generator current. This emphasizes the fact that in parallel operation, devices with reduced power ratings can be used to accommodate higher generator output current. The switch S_{a1} is operated to shape

Figure 5.4: System performance while switching between modes of operation from parallel diode rectifiers to PUPFR, at time $t=0.1$ s: (a) generator output voltages ($v_{gen-a,b,c}$), (b) generator output currents ($i_{gen-a,b,c}$) (c) dc-link voltages (v_{dc} , v_{C1} and v_{C2}), (d) generator phase-a current (i_{gen-a}), upper branch current of PUPFR (i_{a1}) and current through the BSB corresponding to phase-a (i_{swa1}) and (e) power factor (PF).

phase-a current. The switching with similar logic is true for the other two phases and the lower branch as well. It is observed that the power factor of the system improves by 28% from 0.72 to nearly 1 as shown in Fig.5.4(e).

5.4.2 DC-link Capacitor Voltage Unbalance

After the steady-state operation, the first unbalance condition tested is the capacitor voltage imbalance. For the test the capacitors are pre-charged with different voltages at the beginning of the simulation. With no control implemented, the voltages v_{C1} and v_{C2} are not equal as observed in the Fig. 5.5. C1 is pre-charged at $0.25pu$ and C2 is biased at $0.15pu$.

Figure 5.5: Performance of control of PUPFR with C1 and C2 pre-charged at different voltages

At time $t=0.05s$, the dc-link voltage control is turned on. As the controllers are activated, the capacitors are balanced at $t=0.15s$. The nominal dc-link voltage is attained and $1pu$ is equally divided between the two capacitors.

5.4.3 Current Balance Control in the Parallel Branches

The balance of currents between the parallel branches is a compulsion. When the impedance of the branches are equal, the current ($i_{gen-a,b,c}$) is divided equally between the branches. When the impedances are unequal, the current division is unequal as well. This scenario will cause power imbalance and thus one branch would be overstressed. In order to avoid such scenario current balance control is imperative for ensuring power balance. Considering practicality and factor of aging, impedance mismatch is inevitable for parallel power converters.

For ensuring the equal division of current in the parallel branches, the current controller is updated compared to the conventional controllers available in the literature.

Figure 5.6: Converter input currents: (a) input current with currents balancing control and (b) input currents without current balancing control

For UPFR, the reference of current control is taken from the output of the generator i.e. ($i_{gen-a,b,c}$). For the implementation of current balance control, the converter current control references are compared with individual branch inputs and compared with a common reference current i.e. for each branch the controller is segregated or decoupled. This also ensures uninterrupted current control operation for failure of any one branch, if the converter is to be operated partially.

Figure 5.7: Switch between the converter input current control. Current balancing control implemented from time $t = 0s$ to $t = 0.1s$ and then switched to conventional input currents control from $t = 0.1s$

As discussed above, the impedance mismatch creates an imbalance of current. This scenario is observed in the simulation study. The results are presented in Fig. 5.6 where the behavior of the phase-a current is shown. In Fig. 5.6(a) we can see that when the current imbalance control is turned-on, the input currents to the rectifier are balanced and maintained at the same value. Whereas, if there is an impedance

mismatch and the current balance controller is not implemented, the currents of the branches are unequal as depicted in Fig. 5.6(b). The transition of control is shown in Fig. 5.7. For this investigation, first the system was simulated with the decoupled reference current controller till $t = 0.1s$. Then the conventional current controller with single reference is activated. It is observed that due to the impedance mismatch the current values of i_{a1} and i_{a2} parts away.

Figure 5.8: Power consumption in individual branches of the PUPFR: (a) with current imbalance controller in operation and (b) without current imbalance control in operation

Fig. 5.8 (a) and Fig. 5.8 (b) presents the corresponding power scenario for the imbalance current control operation. Even though there is a presence of impedance mismatch, the controller ensures equal power-sharing between UPFR1 and UPFR2. From Fig. 5.8 (b) we can conclude that if the controller is not implemented, one branch would operate below the rated power and the other branch would be overstressed. Thus the current imbalance control is also contributing to longer life of the PUPFR power converters increasing the reliability for application.

5.4.4 Dynamic System Response

PUPFR is further investigated for dynamic scenarios. The system being direct drive, wind variations directly affect the output voltage and frequency. 12 m s^{-1} is considered as the nominal wind speed for the design of the wind turbine model. The rated frequency of the generator is 50 Hz. To validate the applicability of the proposed PUPFR, the operation is examined under three different scenarios presented

in subsections below.

5.4.4.1 Case A: Wind Decrease

For Case-A, a sudden wind speed to decrease at the input to the generator is simulated. The incident wind speed is reduced from 12 m s^{-1} to 10 m s^{-1} at the time instant of 0.1s. Eventually, the voltage output of the PMSG decreases by 10.2 % and the frequency decrease to 45 Hz from 50 Hz. The simulation results of this case study

Figure 5.9: PUPFR operated in the event of decrease of wind speed from 12 m s^{-1} to 10 m s^{-1} at $t = 0.1 \text{ s}$.

are depicted in Fig.5.9. The wind speed decrease at $t=0.1\text{s}$ and cause the voltage to fall and frequency drops to 45Hz as well. The current is maintained to be sinusoidal for the hysteresis current control with no aberrations as shown in Fig. 5.9(a2). At the time of the dynamic transition, the power factor falls but minimally to a level of

0.98 and is retained to 1 again within one cycle. The unity power factor is maintained for decreasing wind speed dynamics. The dc-link voltage is depicted in Fig. 5.9(a4). A constant dc-link is maintained with a slight dip at the time of speed drop. The PI control maintains the dc-link voltage to the nominal value within one cycle of operation. This must be observed that the dc-link capacitor voltages V_{C1} and V_{C2} are more or less balanced all through the operation which marks the stability of the system.

Figure 5.10: PUPFR operated the case of increase of wind speed at $t=0.1s$: (a) 20% step increase in wind speed from $12m/s$ and (b) 33% step increase in wind speed from $12m/s$

5.4.4.2 Case B: Wind Increase

In Case B two events of wind speed increase scenario are investigated. In order to emulate the condition, first the input to the wind turbine model is increased at a

step from 12 m s^{-1} to 14 m s^{-1} and the results obtained are depicted in Fig. 5.10(a). In the second case to investigate higher wind variation, wind speed is considered to increase from 12 m s^{-1} to 16 m s^{-1} and the results are presented in Fig. 5.10(b). For both the cases the voltage and frequency increase instantly. For the first incremental set, the voltage output of the PMSG increases by 10 % and the frequency increases from 50 Hz to around 55 Hz. For the second test, the voltage increases by 20% and the frequency increases to 60 Hz.

The current at generator output decreases to maintain constant power for both scenarios. The current is maintained at non-distorted sinusoids condition by the virtue of the current controller. The power factor behavior is similar for both tests but for higher wind gust it takes a dip to 0.9 eventually controlled to unity within one cycle. The dc-link voltage control ensures constant v_{dc} and the balance between the capacitor voltages are also maintained for both variations. Based on the simulation results for wind speed variation, Case A and Case B provides evidence of commendable performance achievement for the controller and the topology.

5.4.4.3 Case C: Grid Side Load Variations

The grid side variation is emulated by step change of load resistance. This test case is also done for two events in which one presents higher grid side excursion than the other. The Case C simulation investigation results are depicted in Fig. 5.11(a) and (b). In Fig. 5.11(a) it's observed that the generator output voltage is constant but generator output current had increased after the power demand increase from the load-side. For higher load side excursion the current increases further to $1.58pu$. For both the cases the power factor remains at unity with slight dip at the time of step change. The power factor is maintained within one cycle of operation. All through the system operation the dc-link voltages are maintained within their nominal range of variations. For higher excursion in Fig. 5.11(b), the balance of the v_{C1} and v_{C2} disrupts slightly more than Fig. 5.11(a) but still the variations are within permissible limits.

For all the cases studies i.e. Case A, Case B, and Case C; the PUPFR converter maintains its input current shape and input side unity power factor is also retained. But it is to be noted that at the time of step variations power factor slightly fall down but it is retained for all the cases. The applicability of PUPFR for high power

Figure 5.11: PUPFR operated for grid side dynamics with sudden variation in power demand at $t = 0.1$ s (a) 20% increase in grid side current demand and (b) 50% increase in grid side current demand

dc-power collection based WTS mostly banked on its ability to maintain a constant dc-link voltage and ride-through to large dynamic excursions. The simulation results portray the dc-link voltage (v_{dc}) is maintained at the v_{dc-ref} . The capacitor voltages (v_{C1} and v_{C2}) were balanced within acceptable limits of variation.

5.4.5 Harmonic Analysis of the proposed system

Analyzing the proposed rectifier, THD of the input current i.e. the output of generator has been investigated. The fast fourier transform (FFT) analysis results are presented in Fig.5.12. When the parallel rectifiers are in operation, the THD of the input phase-a current is 1.05 % (Fig.5.12(a)) which is lower than the single branch

Figure 5.12: FFT analysis of input current (i_{gen-a}) of the PUPFR: (a) during steady-state UPF operating mode, (b) during increased wind speed and (c) during decreased wind speed.

operation [6]. For the dynamic case of wind speed increase, the fundamental frequency changes to 55 Hz from the nominal frequency of 50 Hz. THD of the reduced phase-a current increases slightly to 1.37 %. For wind speed fall the fundamental current component increases with the increase of generator output current. THD performance improves to 0.81 % in comparison to the former dynamic condition.

Table 5.2: THD of i_{gen-a} in three different wind conditions

v_{wind}	10m s ⁻¹	12m s ⁻¹	14m s ⁻¹
THD%	0.81%	1.05%	1.37%

Thus the system demonstrates very low THD within acceptable limits for both steady-state conditions and dynamic wind speed variations. The THD in different wind speed is tabulated in Table 5.2.

5.5 Hardware Implementation

The system is implemented in a down-scaled hardware prototype of 2.5kW. The built prototype is shown in Fig.5.13 and the components used for experimentation are listed in the Table 5.3. The generator output in hardware is emulated by programmable ac-source.

Figure 5.13: Hardware prototype setup of PUPFR for experimental validation. Legend: (1) current and voltage sensors, (2) PC and DSpace interface, (3) auxiliary circuit (BSBs), (4) dc-link capacitors (5) three-phase diode rectifiers of upper and lower branches, (6) line inductances and circuit breaker, (7) capacitor pre-charging circuit, (8) variable resistance, (9) programmable ac-source and (10) oscilloscope.

As investigated in the simulation study, four case scenarios are validated in prototype experimentation as well. The input voltages to the converter and the phase-a current, during unity power factor operation, is shown in Fig.5.14(a). Fig.5.14(b) represents the in-phase phase-a current and voltage. The input voltage is set to 110V(r.m.s.)/50Hz and this condition is referred to as arbitrary nominal with respect to the wind speed of 12 ms^{-1} .

Firstly, the switching between uncontrolled 3-phase diode rectifier mode and the 3-phase parallel unity power factor is observed in Fig.5.15. In Fig.5.15(a) phase-a

Table 5.3: Hardware Components

Component	Model	Value
Diode	OIXYS MDD 26	800V
Switches (IGBT)	2MBI100TA-060-50	100A, 600V
dc-capacitor	BHC	+ - 2200 μ F, 500V
Inductor	Local	2mH, 10A
Voltage Sensor	LEM VL 25P	N/A
Current Sensor	LEM LA 100P	N/A
Programmable ac-source	Chroma 61511	N/A

current is observed to alter from typical 3-phase diode rectifier input current to pure sinusoidal in phase with the phase-a voltage. The dc-link reference was set as 280V in the Control Desk software interface. Though set at 280V the measured dc-link voltage obtained was 279.2V due to the line drops.

The converter input current is sinusoidal and it is divided in the two branches. Each branch is controlled with current sensed separately before the inductances. Fig.5.16(a) depicts the input phase-a current (i_{gen-a}) measured 11A and Fig.5.16(b) is the measure of phase-a current flowing through the upper branch (i_{a1}) which is around 5.5A.

The dynamic behavior of the system for input variations and load variation validates the overall control experimentally. As mentioned earlier, nominal condition is considered as 110V(r.m.s.)/ 50Hz balanced three-phase input. In simulation the wind increase and decrease of 2m s^{-1} were associated with generator output voltage variation of 1p.u. and frequency variation of 5Hz. So, wind speed increase to 14m s^{-1} is represented by the increase in voltage to 121V(r.m.s.)/ 55Hz. The decrease in wind speed of 10m s^{-1} is similarly referenced at 99V(r.m.s.)/ 45Hz.

All the outputs for dynamic scenarios are represented in Fig.5.17. Fig.5.17(a) depicts the first case where the wind speed decreases from the nominal in a step change to 99V(r.m.s.)/ 45Hz. The input current of phase-a increases but dc-link voltage is maintained at about its reference value. A transient state is observed in the dc-link, due to the time constant of the PI controller. Power factor is observed to be near unity at 0.996.

Figure 5.14: Operation of PUPFR: (a) balanced three-phase input voltages ($v_{gen-a,b,c}$) and phase-a current (i_{gen-a}) and (b) input voltage (v_{gen-a}) with in-phase input current (i_{gen-a}).

Table 5.4: Translation of values from simulation to hardware prototype

Parameters	Simulation			Hardware		
	Nominal	Wind Increase	Wind Decrease	Nominal	Wind Increase	Wind Decrease
Wind Speed	12 m s ⁻¹	14 m s ⁻¹	10 m s ⁻¹	12 m s ⁻¹	14 m s ⁻¹	10 m s ⁻¹
v_{gen}	1 kV (1pu)	1.2 kV (1.2pu)	0.8 kV (0.8pu)	110 V (1pu)	121 V (1.21pu)	99 V (1pu)
v_{dc}	2.2 kV (1p.u)	2.2 kV (1p.u)	2.2 kV (1p.u)	279.2 V (1pu)	279.2 V (1pu)	279.2 V (1pu)
Frequency	50 Hz (1pu)	55 Hz (1.1pu)	45 Hz (0.9pu)	50 Hz (1pu)	55 Hz (1.1pu)	45 Hz (0.9pu)

With the wind speed increase, the step change is from nominal to 121V(r.m.s.)/55Hz. The dc-link voltage is controlled and maintained to the dc-link reference for this case as well. The input current decreases retaining its sinusoidal shape. The power factor is also maintained to near unity (0.995). This scenario is depicted in Fig.5.17(b).

Dynamics of load variation is observed with a gradual increment of load resistance.

Figure 5.15: Switching from uncontrolled to HCC controlled operation of PUPFR:(a) phase-a input voltage (v_{gen-a}) with in-phase input current (i_{gen-a}) and (b) dc-link voltage (v_{dc}) with input current of phase-a (i_{gen-a}).

Figure 5.16: HCC input currents to the parallel rectifiers from the programmable ac-source: (a) input line current of phase-a (i_{gen-a}) and (b) input line current of the upper branch of the parallel converter (i_{a1}).

Figure 5.17: Hardware validation of PUPFR operation in various dynamic scenarios: (a) decrease in wind speed, (b) increase in wind speed and (c) gradual variation of load resistance

The dc-link voltage and input phase-a current is represented in Fig.5.17(c). Load has been gradually increased from 35.15 Ω to 42.2 Ω . With an increase in the load, input current decreases. The dc-link voltage has been maintained constant all through by the virtue of the converter dc-link voltage control.

Thus dynamic behaviors of the system in three scenarios observed in the simulation are all tested in hardware experimentation. The hardware prototype results justify the claims and thus the simulation results are authenticated.

5.5.1 Discussion of Hardware Results

In the hardware experimentation results presented above, high distortion can be observed for voltage and current outputs. The noisy output is the result of high-

frequency noise components generated due to non-optimal selection of the prototype components. The prototype had been reconstructed by dismantling some prevailing prototypes constraining the optimal selection of all components.

Figure 5.18: Input voltage (v_{gen}) to PUPFR with and without first order butter-worth filtering.

The data of phase-a,b,c (v_{gen-a} , v_{gen-b} and v_{gen-c}) are logged to Simulink from workspace. The data set is fed through a low-pass first order butter-worth filter. It is observed that the filtered output is a pure sine wave as expected. The filtered output along with the prototype data are plotted in Fig 5.18. Thus it can be concluded that as presumed, the high-frequency components in the system are the main factors causing distortion and high current notching in the current waveform signals of the hardware prototype. This is also because of a known shortcoming of hysteresis current control, which is termed as double band transition. This has been widely discussed in literature as well [133–135]. Due to interaction of three phase supply current and hysteresis current control the instantaneous error is not maintained within the hysteresis band. The error current can reach up to twice the hysteresis band and thus the notches are created.

In Fig 5.14 current signal (i_{gen-a}), a zero order hold is observed. Primarily the cause of the hold was supposed to be the variable hysteresis switching frequency and interactions of the controller with the input current. But it is observed in literature [82,92] that in hardware results this behavior is always present where as in simulation it is not. This has been the same case for the PUPFR investigation presented above.

In Fig 5.15, v_{dc} seems to have a high overshoot. The values of the PI-controller were used from the simulation study. With further tuning the simulation overshoot diminished. The reason for the overshoot in the hardware is due to the use of same PI value from the simulation. In this experimentation, more emphasis was given

In absence of permanent magnet in the WRSG, the flux is created from current passing through the field winding of WRSG for which there are numerous excitation schemes standardized and described in IEEE Std 421 [216]. For investigated system architecture Type-AC 5a - brushless excitation topology is optimum [217]. The AC-5a brushless excitation is represented in Fig. 5.20.

Figure 5.20: Representation of Type AC 5a: Simplified rotating rectifier excitation system

Brushless excitation provides increased reliability with less maintenance. It does not require any carbon brushes, commutators nor any collector rings and thus its free from periodical maintenance. It does not have carbon dust issues. The exciter and generator are arranged in the same enclosure which is more suitable to accommodate them in the nacelle. The PM pilot exciter provides an exciter field power and it eliminates hefty power transformer. The PMG of the exciter is about 0.5% in power rating of the main generator. Thus the dependence on PM is reduced by manifolds.

5.6.1 WRSG Field Control

The PM generator (PMG) of the brushless excitation shown in Fig. 5.19 supplies high AC power to an automatic voltage regulator (AVR). AVR compares the PMG voltage, feedback from the potential and current transformers to set-point a reference. AVR provides controlled dc current to rotating exciter. Exciter generates three-phase AC output which is rectified by rotating rectifiers. This rotating rectifier is a three-phase diode bridge. The dc output current is fed rotor shaft and applied to the main generator field winding. The standards of synchronous generator field control

is described in IEEE Std 421 [216]. The transfer function referring to the AC5A brushless exciter is shown in Fig. 5.20. V_S refers to the measured terminal voltage output of the generator, V_C is the load component for stabilization. It is generally considered 0 for simulation simplicity. V_{REF} is the reference generator output *p.u.* to be maintained by the field.

5.6.2 Operation of WRSG with UPFR

In this chapter preceding to Section 5.6, PUPFR with PMSG has been discussed in details. Investigating WRSG, the converter topology considered is kept simpler for less complication. Further the study would be extended to PUPFR and WRSG operations. The applicability of UPFR topology for the system is investigated for similar wind speed scenarios. It is observed that with UPF the power-factor of generator voltage and current is maintained at near unity. THD of the input current (i_{gen}) is 6.08% which is higher than the PMSG and PUPFR system.

- *Wind Speed Increase:* The wind speed is increased from 12 ms^{-1} to 13 ms^{-1} in period $t = 1\text{s}$ to 2s . The generator respond is similar as frequency and voltage increases. The field voltage increases with the increase in generator rotational speed (ω_r) and settles down for the value of 0.6 *p.u.* The v_{gen} varies but by the virtue of control of the AC-5a, its the voltage is maintained at 1 *p.u.* The scenario is represented in Fig.5.21(a). The dc-link voltage (v_{dc}) does not vary during all these dynamics. It is maintained constant at the defined reference dc-link voltage (v_{dc-ref}). The power factor varies to 0.99 with the variation of the wind speed.
- *Wind Speed Decrease:* Simulation results for the dynamic behavior in case of wind speed decrease is illustrated in Fig.5.21(b). As the wind speed decreases from 13 ms^{-1} to 12 ms^{-1} , frequency generator output voltage and current decreases. The field control responds to regulate the generator output to 1 *p.u.* As the wind speed comes back to the nominal value, the power factor is again retained at unity. For this scenario, dc-link voltage is again maintained constant and the voltage across the capacitors (v_{C1} and v_{C2}) are maintained in a balanced condition.

Figure 5.21: Operational performance of UPF connected AC 5a exciter based WRSG for dc wind power collections:(a) variation of wind speed from 12 m/s to 13 m/s , (b) variation of wind speed from 13 m/s to 12 m/s .

5.6.3 Discussion

Section 5.6 is a primary work to investigate and understand the operational dynamics of the WRSG based systems. The converter control and the generator field control are completely decoupled in this experiment. It is observed that similar to the PUPFR the UPFR projected promising results but the advantage of PUPFR lies mainly with high power applications. The THD of the input current was higher for WRSG-UPFR model compared to PMSG-PUPFR.

5.7 Summary

In this study, a parallel unity power factor rectifier has been designed and implemented as a generator side converter for wind power application. Due to advantages of HVDC transmission over HVAC, this study focuses on topology for dc-power collection. The proposed converter topology has advantages of using lower switch count compared to other topologies in high power applications. Hysteresis current control has been implemented for converter control and unity power factor operation has been maintained at the generator output.

First, in Chapter 3 a B2B VSC based SCIG WTS and in Chapter 4 a B2B 3L-NPC based PMSG WTS has been investigated addressing different problems. For offshore dc-power collection the generator side converter has been investigated in this chapter for dynamic conditions. As discussed in Chapter 2, for the application of dc-power collection, constant dc-link voltage and the capacitor voltage balancing was imperative for PUPFR to be a viable topology. The dc-link voltage control ensured constant voltage operation not only for steady-state but also for dynamic transitions. Maximum power point tracking has not been investigated as the focus was to obtain constant dc-link voltage. Simulation of various dynamic scenarios demonstrated the success of converter control in maintaining constant dc-link voltage and unity power factor. The THD of the input current is lower than 5% for dynamic scenarios. Simulated scenarios have been re-examined in hardware experimentation obtaining satisfying conclusions and validating the claims. Further, in order to investigate the promising WRSG based system, a WRSG-UPFR model has been investigated. The study is a partial accomplishment of applying PUPFR for WRSG based WTS with co-ordinated field and converter control.

Till this point in the dissertation VSC, PVSC, 3L-NPC, UPFR and PUPFR are investigated or considered in different scenarios. All the topologies are promising front end converter topologies for WTS. In order to conclude the most reliable and economically feasible converter topology, a detailed study is proposed and represented in the next chapter.

Chapter 6

Component Failure based Reliability-estimation for Rectifiers

This chapter focuses on the comparative reliability estimation of the front end converter topologies for WTS, which are investigated in this dissertation. The rectifiers i.e. VSC, PVSC, 3L-NPC, UPFR, and PUPFR are analyzed for their component failure probabilities based on an available handbook tool. The obtained results are compared and presented. The passive rectifier based topologies, i.e. UPFR and PUPFR, are further investigated based on the economic feasibility of the converters and power loss calculations. The summary and discussion of this chapter is drawn in Section 6.8 .

6.1 Introduction

For offshore wind power, dc power collection has several advantages over the ac-power collection. This aspect is detailed in Chapter 2. Considering the dc-power transmission, the onshore inverter module can be same for different generator-side rectifiers for the WTSs. Based on the some specific applications there may arise requirement of dc-dc converters, but that would be common for all converter topologies, irrespective of it being unidirectional or bidirectional.

Recalling the literature review, for the rectifier topology, the preference would be converter topologies with a higher reliability, lower fault recurrence, and faster re-

pair time. With lesser number of switches involved the power electronic converter interface are tendentious of projecting higher reliability. Three-phase diode rectifiers are rugged and simple but they inherently produce unwanted harmonics resulting in generator torque ripples [79]. For this type of topology, with the variation of input wind speed and for any grid-side dynamics the dc-link voltage would vary by far. For a specific power level, 2L-VSC are very popular due to its simplicity and controllability [48]. For high power the paralleling of 2L-VSC is investigated in the literature as well [2, 47, 212]. Unity power factor rectifiers (UPFR) have promising results in WTS application but needs further investigation. They are operable in similar power range as 2L-VSC. Similar to PVSC, parallel operation of the UPF rectifier (PUPFR) higher power with lower rated switches. But PUPFR associates only half the number of switches as compared to PVSC and far lower than three level neutral point clamped rectifiers (3L-NPC)

This chapter assesses the reliability analysis of the auxiliary circuit based three-phase diode rectifier module and its parallel operation (UPFR and PUPFR). Other topologies of active rectifiers discussed in Chapter 3 and Chapter 4 are assessed for their failure contingency based on the individual component failure estimations. Several reliability studies are carried out for the VSC, PVSC and 3L-NPC based WTS [189, 191–193]. However, investigations regarding UPFR and PUPFR are lacking by far. The main objective of the study in this chapter is to investigate UPFR and PUPFR in detail and summarize whether PUPFR would be reliable and economically feasible topology for WTS applications.

For all the discussed rectifier topologies, the reliability estimation analysis is done based on the data obtained from the Military Handbook, Reliability Prediction of Electronic Equipment, MIL-HDBK-217 [196]. This handbook is widely known and has been in use for long as a tool for performing reliability predictions on power electronic equipments [197].

For initiations of offshore wind projects, reliability and feasibility remain as the major concerns. The down-time rate and failure rate of a WTS are represented in Fig. 6.1 [5] which illustrates the failure of WTS as a whole. The down-time rate is higher for generator and gear-box which emphasizes the selection of PMSG for offshore applications with options of lesser maintenance. The electrical components have a higher annual failure rate compared to all other factors. The study in Chapter 3 investi-

Figure 6.1: Bar diagram representation of contribution of WTS subsystems to the overall failure rate of wind turbines overall downtime rate of wind turbines [5].

gates factors affecting the reliability WTS from an electromechanical perspective and from Fig. 6.1 the importance of reliability assessment for the power electronic interfaces for WTS becomes evident [38, 182, 186, 218, 219]. In accordance to this scenario several studies have been carried out to estimate the reliability of power electronic interface in WTS [183, 188, 195, 220, 221]. The component failure based reliability estimation of the systems proposed in [6, 222], has not carried out till date. One of the reliability factor in offshore and onshore WTS is associated with the number of power semiconductor switches used, as they are prone to faults [190, 223–225].

This chapter analyses the reliability and economic feasibility of PUPFR in comparative forum with the available topology of UPFR. All other topologies are compared based on their component failure contingencies 3L-NPC, 2L-VSC, and parallel 2L-VSC (PVSC). The main contributions in this chapter can be summarized in the following points:

- Calculation of individual component failure rate of PUPFR, and UPFR, in order to quantify the overall converter failure rate, mean time between failure, and availability.
- Calculation of component failure based reliability estimation of 3L-NPC, VSC, and PVSC rectifiers adopting the similar methodology of analysis.
- Component selection of UPFR and PUPFR topologies, for a predefined power

level in order to analyze the economic aspects like the initial cost, operational cost and capacity factor.

- Calculation of power loss of UPFR and PUPFR, based on the component datasheet.

This chapter first introduces the method used for converter failure detection in Section 6.2. The reliability analysis of the PUPFR and UPFR is designed and equated in 6.3 and the active rectifiers are analyzed in 6.4. Based on the discussion of reliability analysis, two most reliable rectifier topologies are equated for the power loss in Section 6.5. The feasibility analysis of the PUPFR system is analyzed in Section 6.6. Finally, the discussion and summary of the chapter are drawn in Section 6.7 and 6.8.

6.2 Component Failure based Reliability Analysis

MIL217 Handbook provides formulas to assess the failure rate of electronic components making up a device. Each of the failure rate index is calculated by multiplying a base failure rate index with other influential factors like voltage stress, temperature factor, etc. The method of MIL-HDBK-217 does not consider the operational context, e.g. temperature cycling loading. The steps followed for converter failure estimation and partial reliability assessment can be summarized as follows:

- Obtain the equation of failure rate for IGBTs, diodes and other components from the handbook.
- Determine the quality factor parameters and equate the failure rates for the switching devices.
- Determine the overall converter failure equation taking individual components into consideration.
- Empirically determine the mean time to failure (MTTF) and mean time between failure (MTBF).
- MTBF and the converter repair rate aids to the calculation of the tentative availability index.

Reliability prediction of electronic equipment using MIL-HDBK-217 do adhere to

the traditional reliability prediction methods. The method relies on the failure data and various modifiable operators. The reliability is equated and quantified based on voltage/current stress. Overall parts count is one of the influencing factors in this method. This method provides an initial outline of the system structure and its components.

6.3 Reliability Analysis of UPFR and PUPFR

UPFR system and PUPFR system are shown in Fig 6.2 and Fig. 6.3. Reliability analysis of power electronic interface for WTS provides an overview of the system response over the product lifetime and gives the edge for different quantitative economic analysis. PUPFR and UPFR will include IGBTs, snubbers, gate drivers, IGBT-diodes, power rectifier diodes, general purpose diodes, voltage sensors and current sensors, dc-link capacitors, circuit breaker and a thermal cooling system.

Figure 6.2: System diagram of WTS with UPFR proposed in [6]

Based on the failure index in Military Handbook, Table 1,2 and 3 is arranged for IGBT, diodes in rectifier and diodes in BSB respectively. The IGBTs in both PUPFR and UPFR topologies, withstand half the rated voltage value of the dc-link due to its topology. The voltage stress factor is considered to be half of the value of the rated dc-link voltage stress factor. The failure rate of IGBTs (λ_{igbt}) is calculated from the following Equation 6.1,

$$\lambda_{igbt} = \lambda'_b \cdot \pi_E \cdot \pi_Q \cdot \pi_A \cdot \pi_S \cdot \pi_R \cdot \pi_C \cdot \pi_T \quad (6.1)$$

Figure 6.3: System architecture of PUPFR for dc-power collection in WTS.

The failure rate of diode for both rectifier ($\lambda_{p_d_rec}$) and BSB ($\lambda_{p_d_bsb}$) are calculated from the following Eq. 6.2,

$$\lambda_{p_d} = \lambda_b \cdot \pi_T \cdot \pi_S \cdot \pi_C \cdot \pi_Q \cdot \pi_E \quad (6.2)$$

For the given topology of the rectifier, IGBTs carry out hard switching scenarios only so no soft-switching sequence is considered. Based on the values obtained from Table. 6.3, 6.2 and 6.3; and using them in Eq. 6.1 and Eq. 6.2, the calculated failure rates are given below,

$$\begin{aligned} \lambda_{igbt} &= 0.531 \text{ FITS} \\ \lambda_{p_d_rec} &= 7.7e - 3 \text{ FITS} \\ \lambda_{p_d_bsb} &= 2.01e - 3 \text{ FITS} \end{aligned}$$

UPFR is considered for the comparative reliability analysis with the PUPFR. The peripheral circuit components are considered in order to have a realistic evaluation. The values of failure rate of each of the circuit components are tabulated in Table 6.4. The failure rate for a UPFR is calculated taking each component in consideration and can be represented in the equation as,

Table 6.1: Quality Index Parameters for IGBT

Factor	Parameter	Index
Basic Failure Rate	λ'_b	0.0022
Quality Factor	π_Q	2.4
Environmental Factor	π_E	3.0
Circuit Factor	π_A	1.0
Voltage Stress Factor	π_S	0.41
Temperature Factor	π_T	21
Rating Factor	π_R	3.9
Construction Factor	π_C	1.0

Table 6.2: Quality Index Parameters for Diodes in Rectifier

Factor	Parameter	Index
Basic Failure Rate	λ_b	0.005
Quality Factor	π_Q	1.0
Environmental Factor	π_E	1.0
Voltage Stress Factor	π_S	0.11
Temperature Factor	π_T	14
Construction Factor	π_C	1.0

$$\lambda_{UPFR} = 2\lambda_4 + 3(\lambda_{igbt} + \sum_{i=1}^3 \lambda_i) + 6(\lambda_{p.d.rec}) + 12(\lambda_{p.d.bsb}) + \sum_{j=5}^8 \lambda_j \quad (6.3)$$

$$\lambda_{UPFR} = 18.543 \text{ failure}/10^6 \text{ hours} = 0.1602 \text{ failure/year}$$

The proposed topology for front end rectifier use, is the parallel operation of the UPFR. The second branch in parallel is a redundant block. The reliability analysis of parallel converter with redundant branches are explained in [226, 227]. In the parallel power conversion architecture with a total of $N + X$ converters, the required performance is obtained when ‘N’ converters operate and ‘X’ converters are considered redundant. In the case of the proposed PUPFR, $N = X = 1$ as two branches are considered to be operating in parallel. The system reliability function for a parallel configuration “ R_{N+X} ” can be represented in the equation form given below,

Table 6.3: Quality Index Parameters for Diodes in BSB

Factor	Parameter	Index
Basic Failure Rate	λ_b	0.0038
Quality Factor	π_Q	0.7
Environmental Factor	π_E	1.0
Voltage Stress Factor	π_S	0.054
Temperature Factor	π_T	14
Construction Factor	π_C	1.0

Table 6.4: Failure Rates of Individual Circuit Components

Factor	Parameter	Index
IGBT	λ_{igbt}	0.531
Diode (Rectifier)	$\lambda_{\text{p.d.rec}}$	7.7e-3
Diode (General Purpose)	$\lambda_{\text{p.d.bsb}}$	2.01e-3
IGBT-diode	λ_1	0.7
Snubber	λ_2	0.0001
Gate Driver	λ_3	1.0
dc-link Capacitor	λ_4	3.03
Voltage Sensor	λ_5	0.56
Current Sensor	λ_6	0.50
Cooling System	λ_7	1.36
Circuit Breaker	λ_8	3.3

$$R_{N+X} = \sum_{i=N}^{N+X} \binom{N+X}{X} R^i (1-R)^{N+X-i} \quad (6.4)$$

With respect to the single branch result from Eq. 6.3 , the failure rate of the PUPFR system is equated in the following equation,

$$\lambda_{N+X} = \frac{1}{\frac{1}{\lambda_{\text{UPFR}}} \sum_{i=N}^{N+X} \binom{N+X}{i}} \quad (6.5)$$

As mentioned above, for PUPFR $N=X=1$, and putting values in equation below the failure rate is calculated as

$$\lambda_{N+X} = \frac{1}{\frac{1}{0.1602} \left(1 + \frac{1}{2}\right)} = 0.1068 \text{ failure/year}$$

$$\lambda_{N+X} = \lambda_{\text{PUPFR}} = 0.1068 \text{ failure/year}$$

The parameter mean time to failure (MTTF) is considered for ir-repairable items only. But for repairable items, the time between subsequent failures i.e. mean time between failures (MTBF) is defined as the measure of failure rate. The MTBF for the UPFR and PUPFR are given by the equations

$$\text{MTBF}_{\text{UPFR}} = 1/\lambda_{\text{UPFR}} = 6.24 \text{ years} \quad (6.6)$$

$$\text{MTBF}_{\text{PUPFR}} = 1/\lambda_{\text{PUPFR}} = 9.36 \text{ years}$$

For converter faults in offshore WTS, additional installation time plays an important role. Generally, the repair rate of the IGBT based converter system is assumed to be 20 days and 10 days for installation in offshore WTS scenario; thus the overall expression for a repair rate can be given as

$$\mu_u = 365/30 = 12.16/ \text{ year} \quad (6.7)$$

The overall availability is an important factor as it characterizes the down-time. The availability for the single branch UPFR system can be calculated using the following equation

$$A_{\text{UPFR}} = \frac{\mu_u}{\mu_u + \lambda_{\text{UPFR}}} = 0.9862 \quad (6.8)$$

The overall availability of a PUPFR system is given as [226],

$$A_{\text{PUPFR}} = \sum_{i=N}^{N+X} \binom{N+X}{X} A^i (1-A)^{N+X-i} \quad (6.9)$$

For $N = X = 1$, the calculated probability of availability for the parallel UPF ie PUPFR is given as,

$$A_{\text{PUPFR}} = \sum_{i=1}^{1+1} \binom{1+1}{1} A^1 (1-A)^{1+1-1} = 0.9983$$

From the analysis made above it is seen that the in percentage, the failure rate of PUPFR is about 33.35% lower with respect to UPFR. From A_{PUPFR} and A_{UPFR} , it is observed that the probability of availability of PUPFR system is higher than the UPFR under the similar operating conditions. Thus it can be concluded that the PUPFR is a more reliable front end converter in comparison to UPFR for offshore wind power scenarios.

6.4 Component Failure based Reliability-estimation of Active Rectifiers

In the sections above, the failure contingencies and MTBF of UPFR and PUPFR have been calculated. Looking back the UPFR and PUPFR have been chosen due to its simplicity and lower switch count but in order to select PUPFR as the most plausible topology the failure rate of the active converters discussed in Chapter 3 and Chapter 4 must be compared. In Chapter 4, 3L-NPC in back to back topology was investigated. As mentioned earlier, for dc-power collection the inverter section is not considered in the analysis. The VSC are popular and available off-the-shelf. To match the power rating to VSC to NPC the reliability for the parallel operation of the VSC is also investigated.

6.4.1 Voltage Source Converter and Parallel Voltage Source Converter

Voltage source converters are one of the most popular converter topologies in research and industry. It comprises of six IGBTs. The IGBTs in VSC and PVSC are exposed to full dc-link voltage. As a result, the factor of voltage stress would be double to

the UPFR and PUPFR. Thus,

$$\lambda_{\text{igbt_VSC}} = \lambda'_b \cdot \pi_E \cdot \pi_Q \cdot \pi_A \cdot (2 \cdot \pi_S) \cdot \pi_R \cdot \pi_C \cdot \pi_T = 2.7621 \quad (6.10)$$

Thus similar to the 6.3, the equation of the VSC can be derived as,

Figure 6.4: Use of VSC in dc-power collection in offshore WTS.

Figure 6.5: PVSC used as front end converter in offshore WTS.

$$\lambda_{\text{VSC}} = 2\lambda_4 + 3(\lambda_{\text{igbt_VSC}} + \sum_{i=1}^3 \lambda_i) + \sum_{j=5}^8 \lambda_j \quad (6.11)$$

Based on the values defined from the handbook, presented in Table 6.4 and the value of $\lambda_{\text{igbt_VSC}}$, the failure rate of the VSC is calculated as,

$$\lambda_{\text{VSC}} = 28.353 \text{ failure}/10^6 \text{ hours} = 0.2449 \text{ failure/year}$$

As mentioned earlier, for higher power operations the use of VSC in parallel is highly common practice. Thus the failure rate for Parallel VSC (PVSC) is calculated with respect to single branch use and it is given below:

$$\lambda_{N+X} = \frac{1}{\frac{1}{\lambda_{\text{VSC}}} \sum_{i=N}^{N+X} \left(\frac{1}{i}\right)} \quad (6.12)$$

Similar PUPFR, for PVSC $N=X=1$, and putting values in Eq 6.12 the failure rate is calculated as

$$\lambda_{\text{PVSC}} = \frac{1}{\frac{1}{0.2449} \left(1 + \frac{1}{2}\right)} = 0.1633 \text{ failure/year}$$

Calculating the MTBF for the VSC and PVSC,

$$\text{MTBF}_{\text{VSC}} = 1/\lambda_{\text{VSC}} = 4.083 \text{ years} \quad (6.13)$$

$$\text{MTBF}_{\text{PVSC}} = 1/\lambda_{\text{PVSC}} = 6.123 \text{ years}$$

6.4.2 Three Level Neutral Point Clamped Converter

A three-phase three-level NPC (3L-NPC) operated as rectifier has twelve IGBTs, and 6 diodes. The diodes are similar in operation to the diodes in the bidirectional switches. Thus $\lambda_{\text{p.d.npc}} = \lambda_{\text{p.d.npc}}$. For 3L-NPC, the voltage stress of the IGBTs are half of that exercised by IGBTs in PUPFR or UPFR. Thus,

$$\lambda_{\text{igbt_NPC}} = \lambda'_b \cdot \pi_E \cdot \pi_Q \cdot \pi_A \cdot \left(\frac{\pi_S}{2}\right) \cdot \pi_R \cdot \pi_C \cdot \pi_T = 1.9656 \quad (6.14)$$

Based on the components of the 3L-NPC, the equation for failure rate detection can

Figure 6.6: System architecture of PUPFR for dc-power collection in WTS.

be deduced as 6.15 and the value is calculated based on Table 6.4 and the equation above.

$$\lambda_{NPC} = 2\lambda_4 + 12(\lambda_{igbt_NPC} + \sum_{i=1}^3 \lambda_i) + 6(\lambda_{p_d_npc}) + \sum_{j=5}^8 \lambda_j \quad (6.15)$$

$$\lambda_{NPC} = 35.379 \text{ failure}/10^6 \text{ hours} = 0.3056 \text{ failure/year}$$

Calculating the MTBF for NPC converters,

$$MTBF_{NPC} = 1/\lambda_{NPC} = 3.27 \text{ years} \quad (6.16)$$

This must be noted that though the failure rate of 3L-NPC is very high, this is not conclusive of the fact that the filter failures was not considered. 3L-NPC has added advantage of smaller filter sizing and lesser prone to the faults.

Discussion

From the component failure estimation analysis it is observed that in comparison of the two active rectifier topologies, VSC operated in parallel proves to be lesser

prone to failures. The VSC and PVSC both have higher failure rates compared to UPFR. It is observed that the failure rates are highly influenced by the number of active switches present in the topology. But it does not conclude that higher number of active switches project higher failure rate. Compared to three active switch containing VSC, PVSC with six-switches has higher MTBF and lower failure rate. Similar results are reflected when UPFR and PUPFR are compared.

Table 6.5: Comparison of front end converter failure rates

Sr. No.	Converter type	Number of Active Switches	Number of Diodes	Converter failure rate (per year)	MTBF
1	3L-NPC	12	6	0.3056	3.27
2	VSC	6	0	0.2449	4.083
3	PVSC	6	0	0.1633	6.123
4	UPFR	3	18	0.1602	6.24
5	PUPFR	6	36	0.1068	9.36

The values are tabulated in Table 6.5 for a numerical overview of the statements made above. It was interesting to observe that the 3L-NPC had the highest failure rate and shortest MTBF. But this must be noted that the operational context has not been taken into account. This study can be further enhanced with detailed thermal analysis and loss modeling which includes heat-sink, control aspects, etc. The values represented in Table 6.5 concludes the failure estimation based on component failure contingencies. Based on the analysis, PUPFR shows promise as a rectifier for offshore WTS for dc-power collection.

The reliability of UPFR and PUPFR has not been analyzed in details in literature. With the component failure estimation assessed, the PUPFR is now compared to the UPFR in respect to power loss and economic aspects which are carried out in the following sections.

6.5 Power Loss Estimation for UPFR and PUPFR

Power loss calculation for power electronic devices are characterized by conduction loss and switching losses. Thus in equation it can be represented as:

$$P_{loss} = P_{cond} + P_{sw} \quad (6.17)$$

Based on the input current variations between the UPFR and PUPFR, some basic devices are selected from SEMIKRON in order to design a system of similar power rating. The selected devices are represented in the Table 6.6. The UPFR device is selected for the line current ($I_{a,b,c}$) of 300A and V_{dc} is 1200V. The PUPFR devices are selected based on half current rating but the same voltage rating. Based on these devices data and SEMIKRON guide [228] the power loss calculations and economic aspects are analyzed.

Table 6.6: Comparative selection of components for UPFR and PUPFR

Component, Unit & Quantity	UPFR	PUPFR
IGBT	SKM600GA12E4	SKM600GA12E4
Unit Price	€140.26	€93.85
Quantity	3	6
IGBT Drivers	SKYPER42R	SKYPER32R
Unit Price	€97.71	€58.87
Quantity	3	6
BSB Diodes	SKKD 170F	SKKD 105F
Unit Price	€82.51	€50.38
Quantity	12	24
Rectifier	SEMiX50D17Fs	SEMiX29D16Fs
Unit Price	€97.38	€57.21
Quantity	1	2

In the UPFR and PUPFR, IGBTs and diodes are the switches involved. Each of these devices goes through static and dynamic states during its operation and each state is associated with power dissipation. Firstly the diode rectifier has six diodes for

continuous conduction and the average power dissipation (P_D) is expressed as [228]:

$$P_D = V_f(T_{junc}) \cdot I_f + r_f(T_{junc}) \cdot F_f^2 \cdot I_f^2 \quad (6.18)$$

The power dissipation for the rated operation of the diode rectifier selected for the two topologies are obtained from the manufacturer datasheet. The value of the average power dissipation depends on I_f as all other conditions are considered identical for both the converters.

Table 6.7: Power dissipation of UPFR and PUPFR

Power Dissipation	UPFR	PUPFR
Diode Rectifier	$1 \times 1150\text{W}$	$2 \times 450\text{ W}$
Bidirectional Diode Modules	$3 \times 708\text{ W}$	$6 \times 318\text{ W}$
IGBT Conduction Loss	$3 \times 41.18\text{ W}$	$6 \times 20.55\text{ W}$
IGBT Switching Loss	$3 \times 53.9\text{ W}$	$6 \times 19.9\text{ W}$
IGBT Drivers Loss	$3 \times 5\text{ W}$	$6 \times 5\text{ W}$
Total	3574.24 W	3080.7 W

The IGBTs in both the UPFR and PUPFR topologies are have half load of the dc-link voltage. For IGBTs, the conduction and switching losses both are major contributors to the power dissipation. The basic equations for calculating the IGBT losses are is represented as,

$$P_{cond}(T) = \left(\frac{1}{2\pi} + \frac{m \cdot \cos(\psi)}{8} \right) \cdot V_{CEO}(T_{junc}) \cdot \hat{I}_1 + \left(\frac{1}{8} + \frac{m \cdot \cos(\psi)}{3\pi} \right) \cdot r_{CE}(T_{junc}) \cdot \hat{I}_1^2 \quad (6.19)$$

$$P_{sw}(T) = f_{sw} \cdot E_{ON+OFF} \cdot \frac{\sqrt{2}}{\pi} \cdot \frac{I_{out}}{I_{ref}} \cdot \left(\frac{V_{cc}}{V_{ref}} \right)^{K_v} \cdot (1 + TC_{Esw} \cdot (T_j - T_{ref})) \quad (6.20)$$

The switching losses have been considered according to the manufacturer's datasheet. The obtained power loss values are tabulated in Table 6.7. It is observed that with standing the same power input, the power loss for devices with the higher current is higher compared to multiple lower current rated devices connected in parallel.

6.6 Feasibility Analysis of PUPFR

The cost-effectiveness of power electronic converters is of preeminent importance in the offshore wind power industry due to market competitiveness and economic concerns regarding renewable power source integration. In this section, the unit price of the selected components from Table 6.6 is computed for initial cost calculation. The MTBF is taken into consideration to evaluate the operational cost. The economic projection of the WTS is then analyzed by analyzing the variation of the capacity factor for UPFR based and PUPFR based systems.

6.6.1 Comparative Economic Aspect

In reality, an individual WTS can be in service for about 20-25 years. Engineers are striving for an extended life-time as replacing a WTS in the offshore scenario is a challenge as well. From the reliability analysis done in the section above, the mean time between failures were calculated from Eq. 6.6 for both UPFR and PUPFR. From the calculations, it can be concluded that during the life-span of the WTS (25 years), a PUPFR system has to be repaired for two times whereas the UPFR system has to be repaired for four times. In addition to this, for a single branch failure, the PUPFR will still be operating at half the rated power for the estimated 30 days time of repair. This factor emphasizes greater monetary profits when translated into repair time and associated costs.

From the Table 6.6, the initial cost for a UPFR is €1801.41 compared to the PUPFR's €2240.46. Taking the failure rate in consideration the cost of repair for power converters can be 10% of initial cost and thus the operational cost of UPFR and PUPFR for the lifespan becomes is €2521.974 and €2688.54 respectively. Even if the downtime is ignored the UPFR is cheaper by mere €160. Thus concludes that with 8% higher initial investment to obtain a PUPFR is economically plausible.

6.6.2 Capacity Factor

The power output of a WT depends both on the design and characteristics of the system designed and the wind quality. Capacity factor (C_F) is the ratio of actual

energy output to the maximum possible energy output over a given time period. Capacity factor is a measure for more of economic evaluations and decision [229]. Hence, the capacity factor can be defined by the equation

$$C_F = \frac{E_C}{E_R} \quad (6.21)$$

In the Eq. 6.21, E_R ($E_R = T \cdot P_R$; where T is the time period and P_R is the rated generator power) is the arbitrary measure of energy produced at full capacity for a certain time and E_C is the actual output energy in the same time period. The power output of WTS and the wind speed are characterized by the operational wind speed parameters. Cut-in speed (v_{cut-in}), rated speed (v_{rated}) and cut-off ($v_{cut-off}$) wind speeds mark the three operating region of any WT.

$$P(v_{wind}) = P_r \begin{cases} 0, & \text{if } v_{wind} < v_{cut-in} \\ & \text{or } v_{wind} \geq v_{cut-in} \\ P_n, & \text{if } v_{cut-in} \leq v_{wind} < v_{rated} \\ 1, & \text{if } v_{rated} \leq v_{wind} < v_{cut-off} \end{cases} \quad (6.22)$$

When the v_{wind} is either lower than the v_{cut-in} or higher than $v_{cut-off}$, the output power will be zero. If v_{wind} is in between the v_{cut-in} and v_{rated} the power generated would follow the converter control which might be constant dc-link voltage control, MPPT or something else. In the third scenario when v_{wind} is in between the v_{rated} and $v_{cut-off}$ then the rated power will be generated. Considering the fault scenario and down-time scenario to the power output WTS can be further modified and represented as

$$P(f) = \begin{cases} 0, \\ P(v_{wind}) \end{cases} \quad (6.23)$$

For PUPFR, for fault at any specific branch; the faulty branch can be segregated and the system can operate at half of its rating. The system would be at zero when

both the branches are at fault. Thus the Eq.6.23 can be further modified to

$$P(f_{\text{PUPFR}}) = \begin{cases} 0, \\ P(v_{\text{wind}}), \\ 0.5 * P(v_{\text{wind}}) \end{cases} \quad (6.24)$$

The actual energy produced for a given time can be obtained by the following Eq. 6.25. Eq. 6.25 utilizes the PUPFR power equation from Eq. 6.24.

$$E_C = \sum_{i=1}^N P_i(f) \Delta t_i \quad (6.25)$$

$$E_{C_{\text{PUPFR}}} = \sum_{i=1}^N P_i(f_{\text{PUPFR}}) \Delta t_i \quad (6.26)$$

It is evident that for any scenario $E_{C_{\text{PUPFR}}}$ is greater than E_C for a given rated power for a WTS.

Thus the capacity factor from the Eq.6.21 will be larger for a PUPFR system and thus the economic viability is also higher. For the lifetime of 25 years, the E_R would be 27.5 GW h. With consideration of wind variation, failure, and repair time the $E_{C_{\text{UPFR}}}$ would be 82782MW h. For PUPFR there can be two scenarios where once both the converter fails and secondly only one branch failure when partial operation is maintained. For a 2MW system, if a UPFR gives a CF of 35% for its lifetime, the PUPFR would yield a higher CF due to lower converter losses. PUPFR would also have an added advantage of partial operation which would add 120 or operation at half of rated power and thus escalating the CF to 40%.

Table 6.8: Calculated Capacity Factor

Converter	Down-time	E_C	C_F
UPFR	Complete shut down	82782 MW h	35%
PUPFR	Complete shut down	82782 MW h	37%
PUPFR	Partial Shut down	96342 MW h	40%

The PUPFR projects higher economic reliability for the system and can result in higher confidence in utilities based on the calculations of the capacity factor.

6.7 Discussion of UPFR and PUPFR Analysis

Failure rate estimation, MTBF, availability, estimated power loss, initial cost, operational cost, and capacity factor are analyzed in comparative forum for UPFR and PUPFR. The hardware efficiency is calculated based on the hardware presented in Chapter 5. The obtained results are accumulated and presented in a normalized bar diagram illustrated in Fig. 6.7. The subjects with ‘green’ color emphasizes the performance of PUPFR being better and the subjects with ‘red’ color represent the sectors in which UPFR performed better. In this study, eight factors are evaluated quantitatively and qualitatively. The UPFR has an advantage in terms of initial investment and conditional operational cost. All other analyzed parameters suggest

Figure 6.7: Normalized comparative projection of eight analyzed parameters for PUPFR and UPFR

PUPFR to be advantageous. The failure rate, MTBF and power loss are of high difference in favor of the PUPFR suggesting the more reliable rectifier of the two.

6.8 Summary

Reliability and feasibility analysis are imperative for electrical power converters in WTS. And these analysis becomes much more important when the context of offshore application is taken into account. Reliability and feasibility analysis give the utility confidence in investments and security of calculated risk. Various power converters are proposed across the research world, and such analysis validates the applicability of the converters. In this chapter, the reliability of the UPFR and PUPFR systems have been analyzed based on several factors, like: the individual component failure, availability, power loss, economic feasibility, etc. The proposed PUPFR topology has advantages of using lower switch count compared to other topologies in higher power scenarios. UPFR, 3L-NPC, VSC and PVSC are all analyzed for their component failure contingencies which underpins the base of further reliability investigations to be built on. Based on the analysis PUPFR was found to be lesser prone to component failure. But it must be noted that the study did not take the operational context in consideration. Literature lacked investigations related to UPFR and PUPFR and so, further analysis is done considering economic feasibility investigation, power loss calculation, operational cost, and capacity factor estimation. The result of the reliability analysis concluded with findings that support PUPFR to be more reliable than UPFR based on its components failure rate. The feasibility of the converter module was also analyzed for WTS in terms of its economic aspect. In respect to the economic parameter of capacity factor the PUPFR provided higher value than a single branch operated system. The wind power industries are continuously striving for ways to increase the efficiency, life-span and particularly the reliability. The analysis done in this chapter concludes the proposed PUPFR as a promising topology for offshore dc-power collection.

Chapter 7

Conclusion and Future Work

This chapter summarizes the overall work done for this dissertation. The contributions are summarized as well. The research gaps obtained from the detailed literature review, and the addressed topics in this thesis, can be extended for further refinement; thus further research directions and recommendations are comprehensively described in this chapter leading to the end of this dissertation.

7.1 Conclusions

Global warming concerns, fossil fuel economy and the urgency of sustainable energy for the future, together with lead to the accelerated technological development in the sector of renewable energy. Wind turbine systems have several challenges to address but is one of the gateways of freedom from fossil fuel. This dissertation has addressed aspects of electromechanical and power electronic challenges with proven contributions made to improve the overall system.

The control challenges in WTS begin from the rotating turbines continues until the grid integration. Addressing the electromechanical challenges specifically torsional vibrations a control algorithm called speed difference damping controller is proposed in Chapter 3. SDDC reduced torsional variation effect due to load dynamics and wind dynamics. The controller operation is validated in simulation for various case scenarios. Experimental hardware setup is developed to verify the practical authenticity of the proposed controller's simulation outcomes.

The dynamics of the wind turbine system can also be dealt with power electronic control and addition of supplementary circuitry. Utilities are increasingly incorporating battery storage i.e. the energy storage system into wind energy projects onshore and offshore. ESS provides individual wind turbines the added degree of freedom, making it able to utilize the ESS in order to curtail the effects of stochastic wind speed. Chapter 4 analytically discusses a full-scale back to back three-level neutral point clamped converter (3L-NPC) operation with integrated ESS, for grid-connected wind turbine system (WTS). The ESS is connected at the dc-link via a bidirectional dc-dc converter. The bidirectional dc-dc converter control has been investigated in details and comparatively assessed. The dc-dc converter is controlled for active/reactive power injection to the grid or active power storage during grid and wind speed variations. Simulation results of the controller performance in different case scenarios are illustrated and discussed.

Onshore wind power still continues to be major contributors in terms of global installed capacity. But offshore wind capacity is being explored in high percentage and it has the promise for future expansion in large scale. Offshore WTS utilities are installing larger wind turbines as soon as the technology is made available. The bigger size of turbines reduce the repetitive cost and challenges of multiple tower installation for same range of power. Simplistic generator-side converters with lower switch count and with lower voltage stress on switches would result in longer lifetime for converters. This can be highly valuable for offshore wind farm scenarios. Chapter 5 investigates a detailed analysis of a auxiliary circuit based three-phase diode rectifier operated in parallel for front end converters in offshore WTS. The control of the converters are done based on hysteresis current control, current balancing and dc-link voltage control. In the simulation studies, dynamic scenarios which could disrupt the converter operation are investigated. A scaled down hardware experimentation is carried out to validate the simulation study for the proposed topology.

Wind turbine systems require high investment just to begin with. This is one of the major factors affecting the popularity of the energy source. But with research on the economic feasibility and reliability of the system utilities can build confidence before investment. Chapter 6 in this dissertation focuses on the reliability analysis of the converter topologies in a comparative forum. The reliability of front end converter topologies discussed in this dissertation is equated and analyzed comparatively. The reliability and economic feasibility of proposed PUPFR is assessed in details. From

the obtained results and discussions it can be concluded that the PUPFR are the most reliable front end converter topology for WTS.

7.2 Summary of the Contributions

The research conducted focused on different types of power collection for WTS. The power converter topologies investigated focused more on the front end converters for WTS. The grid connected inverter has also been investigated for two instances. Furthermore, addressing the reliability of WTSs, the electromechanical interactions has been investigated alongside the power electronic component failure assessment. The major contributions of the dissertation are concluded below in bullet points:

⇒ A state of the art review of the types of WTS, ESS integration, vibration damping control strategies, converter topologies are carried out.

- Survey on the types of power collection schemes for onshore and offshore WTS.
- A review of different vibration damping techniques available in literature and realization of the current research gap.
- Review of active and passive converters for WTS.
- Overview of the reliability studies carried out for WTS and assess the importance of component failure based reliability prediction.

⇒ A novel control for Torsional vibration damping in WTS.

- The reduction of load dynamics and transient torsional oscillations effects in WTS utilizing the SDDC.
- Detailed theoretical analysis, designing the control gains with a derived two-inertia model.
- Simulation and hardware experimentation of the controller is carried out testing different dynamic conditions.
- Comparative analysis and parametric variation uncertainty analysis is presented for the VIDC, SDC, GSF, and proposed SDDC control.

⇒ **Study of control of dc-dc converter integrating an ESS with a 3L-NPC converter based B2B WTS.**

- Integration of an ESS connected to the dc-link through a bidirectional dc-dc converter to curtail the effect of dynamic of wind speed and grid for a grid-connected WTS.
- Control of the dc-dc converter with the objective of control the power flow in and out of the ESS to stabilize the system in transient conditions.
- Proposed and designed the implementation of MPC based dynamic reference tracking technique for dc-dc converter current control.
- Comparison of the performance of PI-controller and proposed MPC-based controller performances.

⇒ **PUPFR operation as a front end WTS for dc-power collection**

- Proposed configuration of parallel unity power factor rectifier to be utilized as efficient, low THD front end converter for offshore WTS.
- Constant dc-link voltage with balanced capacitor voltages under all operating conditions is achieved via dc-link voltage control.
- Unity power factor operation of the generator output current and voltage, and balanced current division between the parallel branches is assured using a hysteresis current control.

⇒ **Component failure based detail reliability estimation for front end converters in WTS.**

- Equating the failure rates of front end converters based on individual components' failure parameter index.
- Reliability assessment of the generator-side power converter topologies based on the obtained failure rate, MTBF and converter availability.
- Analysis of the viability of PUPFR for offshore WTS applications in a comparative analysis with UPFR on factors of economic sector, power loss and capacity factor estimation.

The research has been conducted in various boundaries and limitations. There are promising results, but there are some potential problem which could not be investigated in detail. These promising problems and plausible new investigations can be potential future work in this sector. These probable future research are thus recommended in the following section.

7.3 Recommendations for Future Research

Future research works, suggested as an extension to the presented findings in this thesis are listed below:

1. Coordinated control of the back to back converter topology and the proposed SDDC.
 - The study discussed in Chapter 3 can further be extended in terms of control of the converters. The dynamics of wind speed and grid variations disrupt the dc-link voltage as presented in Fig. 3.15. This can partially be mitigated by specific control strategy of the inverter. Again similar disruption is caused at the mechanical components causing torsional vibration which can be mitigated by the proposed SDDC. A detailed study of the co-ordinated control of the front end converter and the grid connecting converter can be a promising research direction with opportunities of valuable contribution.
2. Overshoot damping of the pitch angle and limiting the drive train speed variations
 - Fig. 3.11 in Chapter 3, compares the drive-train speed under sinusoidal wind excitation with different control schemes. Overshoot is observed in the speed response in as observed in Fig 3.11(a). But in Fig. 3.10(a) there is no overshoot for torque response. Thus the overshoot in speed is not reflected in drive train torque. Though torsional vibration is mitigated the speed overshoot is an interesting scenario to be further investigated and if possible it's mitigation can lead to a true contribution.
3. Optimization of gain selections through AI meta heuristic optimized controllers.

-
- The “AI meta heuristic optimized controllers” (AI-MHO) are promising for renewable energy applications. In system level, the optimization technique can be used for optimal selection of power converter topologies, component level circuitry analysis, control parameters, magnetic components and filter sizing. The selection of K_p and K_i values in Chapter 3, can be optimized using AI-MHO.
4. Investigating integration of hybrid ESS considering details of state of charge (SOC) for the grid-connected B2B WTS.
 - In Chapter 4, a 3L-NPC based B2B WTS is investigated. The grid-side and generator side dynamics are curtailed by support of an ESS connected through the bidirectional dc-dc converter. The ESS SOA has not been taken into consideration. The detail modeling of ESS for the operation specified is a plausible future work. The MPC based controller showed commendable improvement compared to PI-controller in terms of faster response. Modeling ESS with hybrid configuration of super capacitor and battery might improve the system performance furthermore.
 5. Investigation of torsional vibration damping control with PUPFR and UPFR
 - The torsional vibration damping control proposed in Chapter 3, alleviates issues for B2B VSC based system. Chapter 5 and 6 concludes PUPFR to be one of the promising front end converter topology for dc-power collection. Thus a similar study of torsional control can be extended for PUPFR. Challenges of addressing dc-link voltage variation alongside mechanical torsional aspects will result in substantial contribution.
 6. Investigation of zero voltage current hold problem observed for PUPFR
 - In Chapter 5, the hardware prototype current waveforms showed a tendency of zero-order hold. This problem was initially thought to be caused by the interaction of the hysteresis current control and the input currents itself. But, after reviewing further, it is observed that the zero order-current holdup has been a common problem in most of the journals and transactions discussing the basic topology of UPFR. Thus this can be an interesting future work addressing a basic problem of the UPFR topology.

7. Investigation of the system configuration of WRSG and PUPFR for dc-power collection
 - PMSG, though the most popular choice of the generator, they are getting expensive day by day for the unavailability of rare earth permanent magnets [144, 145]. WRSG with brushless excitation is a probable alternative and it brings added advantage of field and flux control [230, 231]. UPFR and WRSG have been investigated and initial results are presented in Chapter 5. PUPFR has been analyzed to be highly reliable and economically feasible. PUPFR and WRSG can be a promising duo for offshore dc-power collection with appropriate coordination between converter control and the field control of the WRSG.
8. Investigation of modular operation of PUPFR
 - Parallel and multilevel operation of power converter brings in advantages of redundancy and ease at fault tolerant operations. PUPFR proposed in Chapter 5, can be explored for the further higher number of branches and investigated for modular operation.

List of Publications

Journals

Accepted for publication

- [1] **M. S. U. Khan**, A. I. Maswood, M. Tariq, H. D. Tafti and A. Tripathi, “Parallel Operation of Unity Power Factor Rectifier for PMSG Wind Turbine System,” in *IEEE Transactions on Industry Applications*, vol. 55, no. 1, pp. 721-731, Jan.-Feb. 2019.

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Accepted Publication

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