RELIABILITY IMPROVEMENT OF DFIG-BASED WIND ENERGY CONVERSION SYSTEMS BY REAL TIME CONTROL

By

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A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

Electrical Engineering - Doctor of Philosophy

2015

ABSTRACT

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Reliability is the probability that a system or component will satisfactorily perform its intended function under given operating conditions. The average time of satisfactory operation of a system is called the mean time between failures (MTBF) and, the higher value of MTBF indicates higher reliability and vice versa. Nowadays, reliability is of greater concern than in the past especially for offshore wind turbines since the access to these installations in case of failures is both costly and difficult. Power semiconductor devices are often ranked as the most vulnerable components from reliability perspective in a power conversion system. The lifetime prediction of power modules based on mission profile is an important issue. Furthermore, lifetime modeling of future large wind turbines is needed in order to make reliability predictions in the early design phase. By conducting reliability prediction in the design phase a manufacture can ensure that the new wind turbines will operate within designed reliability metrics such as lifetime.

This work presents reliability analysis of power electronic converters for wind energy conversion systems (WECS) based on semiconductor power losses. A real time control scheme is proposed to maximize the system's lifetime and the accumulated energy produced over the lifetime. It has been verified through the reliability model that a low-pass-filter-based control can effectively increase the MTBF and lifetime of the power modules. The fundamental cause to achieve higher MTBF lies in the reduction of the number of thermal cycles.

The key element in a power conversion system is the power semiconductor device, which operates as a power switch. The improvement in power semiconductor devices is the critical driving force behind the improved performance, efficiency, reduced size and weight of power conversion systems. As the power density and switching frequency increase, thermal analysis of power electronic system becomes imperative. The analysis provides information on semiconductor device rating, reliability, and lifetime calculation.

The power throughput of the state-of-the-art WECS that is equipped with maximum power point control algorithms is subjected to wind speed fluctuations, which may cause significant thermal cycling of the IGBT in power converter and in turn lead to reduction in lifetime. To address this reliability issue, a real-time control scheme based on the reliability model of the system is proposed. In this work a doubly fed induction generator is utilized as a demonstration system to prove the effectiveness of the proposed method. Average model of three-phase converter has been adopted for thermal modeling and lifetime estimation. A low-pass-filter based control law is utilized to modify the power command from conventional WECS control output. The resultant reliability performance of the system has been significantly improved as evidenced by the simulation results.

ACKNOWLEDGMENTS

My Lord, increase me in knowledge. Quran (20:114)

"O Allah, I ask you for knowledge which is beneficial and sustenance which is good, and deeds which are acceptable." hadith - The greatest prophet Muhammad

Alhamdulilah. This thesis has been completed with the blessing of the Merciful and Almight, Allah S.W.T. I praise him for providing me opportunity and granting me the capability to proceed successfully.

At this moment of accomplishment, first of all I pay homage to my supervisor Prof. Bingsen Wang, who gives me hope when I thought hope was gone. My supervisor has constantly forced me to remain focused on achieving my goals. His observation, comments, immense knowledge, invaluable ideas helped me to establish the overall direction of the research and to move forward with investigation in depth. I have learned a great deal from his unique perspective on research and his expectations of excellence. This work would not have been possible without him. It is a great honor to work under his supervision. I owe him so much.

I express my sincere gratitude to my PhD committee members, especially prof. Hassan Khalil, for his kind help, generous advice and support. My sincere appreciation is to Prof. Guoming Zho and Prof. Elias Strangas for their helpful comments and suggestions during my progress thesis presentation.

Life would not have been as colorful without many good people who have helped me during my study in MSU, especially, Family Resource Center (FRC), Office for International Students and Scholars (OISS) and Electrical and Computer Engineering Department Staff. My sincere thanks to all my friends who I can not mention their names in this limited space.

Words fail me to express my appreciation to my beloved family for their encouragement, unconditionally support, and generous care. They are always beside me during the happy and hard moments to push me, motivate me and lifting me uphill this phase of life.

To all of these, I gratefully acknowledge my deep indebtedness.

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Abbreviations

v_s, v_r	RMS voltages for stator and rotor
i_s, i_r	RMS currents for stator and rotor
s	Slip
λ_s, λ_r	Flux linkages of stator and rotor
m_1, m_2	Modulation functions of stator- and rotor- side converters
v_a, v_b, v_c	3-phase supply voltages
v_d, v_q, v_α, v_β	Supply voltage components in dq- and $\alpha\beta$-reference frames
ω_e, ω_r, ω_{slip}	Supply, rotor, and slip angular frequencies
P, Q	Active and reactive powers
θ_e, θ_s	Phase angles of supply voltage vector and stator flux vector
C	DC link capacitance
V_{dc}	DC link voltage
L_s, L_r	Per-phase inductances of stator and rotor windings
L_{ls}, L_{lr}	Per-phase leakage inductances of stator and rotor windings
L_m	Magnetizing inductance
R_s, R_r	Per-phase resistances of stator and rotor windings
L, R	Inductance and resistance of supply
p	Number of pole pairs
J	Inertia of machine wind turbine rotors
T_e	Electromagnetic torque

Chapter 1

Introduction

1.1 Background

1.1.1 Why wind is chosen for study?

Wind generation is one of the most successful forms of energy production from renewable sources in terms of accumulative installed capacity. As the number of grid connected installations grow rapidly worldwide, there is a need to study the reliability of these energy conversion systems and further to assess their impact on the overall system.

The impact can potentially embody in multiple aspects.

- Environmental issues and regulations:

  Wind energy generation systems, in contrast to fossil-fuel-based systems, do not produce green house gas (GHG) emissions that adversely affect climate change. Furthermore, UN Secretary General of Sustainable Energy states that the world recently passed 400 parts per million of atmospheric CO_2, which is adequate to potentially stimulate warming of 2°C compared with pre-industrial era [6]. Thus, environmental friendly wind generation systems squarely address the regulatory and practical environmental concerns.

- Economic aspects:

  Investment in renewable energy production will lead to job creation in this relatively new industry [6]. In addition, electrical energy is the key to development of a modern economy. It is has acceptable range of ?levelized cost of production?, which depends on capital cost, operating costs and fuel costs. Remote areas that are not connected to electricity power grid can use stand-alone turbines to avoid high cost associated with the infrastructure of transmission lines.

- Technical maturity:

  Wind energy is widely available and accessible. The wind energy has been proven an economically viable alternative to fossil-fuel based energy.

- Small footprint:

  Wind system produces low-level noises and no waste product. The small footprint of wind system is compatible with many land uses or small plot of land, which means the land below can still be utilized. This is especially in case of agriculture area as farming can still continue. Nowadays more attention towards marine wind farms.

- Energy safety and security:

  Renewable electricity generation makes the overall electricity generation system less reliant on coal and natural gas and thus less vulnerable to volatility in domestic and global fuel markets.

- Deferring of fossil fuel production:

  The more developed skills in finding alternative energy resources such as wind energy decreased the level of interest of super powers in the oil-producing countries.

- Industrial pollution:

  Wind plant has less industrial mishaps that have to be brought under control, unlike conventional generation plant produce multiple forms of industrial pollution that include contamination of drinking water, air and soil.

For the aforementioned reasons, wind generation system technology is one of the most promising renewable energy technologies. Nonetheless, the fast expansion of the wind power faces some challenges that require focused research attention. The research areas that address these challenges include wind farm modeling for reliability studies and application of the reliability assessment techniques with mission profile and dynamic model brought into consideration. Wind plants, which are unlike coal or natural gas power plants, cannot be deterministically scheduled to deliver specified amounts of power at specified times dues to the stochastic nature of available wind power. Wind power plants generate electricity when energy resource is available. Many electricity system operators see this variability as bluster to system stability and reliability. There are three fundamental solutions to the variability challenge [7] .

- Increasing the flexibility of electricity supply options:

  This solution involves constructing wind farms that can rapidly adjust their output by increasing installed capacity. For instance, Germany affectively increases its installed capacity through contractual trading of electricity with the neighboring country Denmark.

- Demand side management:

  Demand side management employs pricing and other incentive tools to influence or control the demand for electricity. Increased demand flexibility can lead to reduced peak load and improved capacity factor of the system.

- Energy storage:

  Using physical storage of electricity to ?smooth? the output of variable electricity sources. There are several physical storage technologies under development. Energy storage technologies that can quickly deliver energy include flywheel energy storage, batteries, and super-capacitors.

The most serious implementation barriers for increasing wind generation are high costs associated with constructing new transmission lines that typically cost two to four million dollars per mile [7], and the difficulty associated with siting and permitting processes. Moreover, the main environmental disadvantages are erosion, moving shadows, interference with electromagnetic communications, impacts on birds, unsightly structures and some pollution produced during the manufacturing process.

1.1.2 Why Reliability?

Since it first appeared in 1800s, reliability has been a fundamental attribute to the safe operation of any modern technological system. The term reliability was first coined by the English poet Samuel T. Coleridge, who along with William Wordsworth started the English Romantic Movement [8]. Reliability of a system is the probability that the system will perform its intended tasks. This probability is usually determined as a percentage of time [9]. A principal objective of reliability analysis is to gain feedback for improving design. Reliability study of systems allows for optimizing the maintenance strategy in order to reduce cost.

1.1.3 Why Wind Reliability?

Development of wind power generation is beneficial to adjust the structure of energy, reduce the environmental pollution and pressure of energy import and export and promote the economic development [10]. That leads us to shed strong light on one of the most important aspects in wind energy, reliability. The reliability can be improved by choosing proper design specifications and exercising strict control on the manufacturing process or by using good quality materials. In addition, preventive maintenance techniques also play an important role in reliability improvement. The literature survey suggests that wind reliability is to increase the wind energy growth and correspondingly to decrease the cost of wind energy. Moreover, improvement of wind system reliability can further extend penetration limits and enhance the reliability of the overall power system.

Reliability is considered as the science of failures [10] or ?probability of success? [11]. Reliability evaluation and enhancement is an important factor in wind energy. Consequently, the reliability methods and procedures of wind systems are of great importance and will receive focused attention in the future with increasing generation from wind resources. Reliability analysis of wind turbines would allow to identify weaknesses in parts and subassemblies. Sensitivity analysis based on reliability evaluation could indicate the spread of unreliability among parts and subassemblies in the wind turbine and a ranking of critical subassemblies could be achieved. There is great potential for more wind turbines to be erected in remote and offshore locations where a greater wind energy harvest can be achieved. Nonetheless, the access to these remotely located turbines for maintenance will be limited, which necessitates accurate reliability predictions. Reliability predictions for wind turbines will have an important bearing on the future development of wind power resources.

1.1.4 Why Wind Plant Reliability Modeling?

The key issue in developing any system in general, and wind energy system in particular, is to realize and understand the requirements and purpose. In wind energy system, the requirements should be considered in two aspects: components availability and wind speed's randomness and variability. The objectives are to maximize wind energy production while minimize maintenance and reduce cost without compromising reliability. In essence, the inquiry amounts to what is important for wind model to perform and what is not.

Wind energy systems can be modelled at two different levels: wind farm level and wind energy generation system level. At wind farm level, the overall system reliability is focused. Thus, the relation between wind farm reliability and power system reliability is studied. Power system reliability is to assess the ability of power system providing energy to customers with the acceptable quality and quantity without interruptions. Power system reliability can be divided into two basic categories: system adequacy and system security.

- **System Adequacy** relates to existence of sufficient facilities within the system to satisfy the load demand or system operational constraints, considering system components scheduled or unscheduled outage. Adequacy is also named static reliability since it categorizes the ability of system providing enough power to customers under static conditions. This concept of adequacy considers a state in complete isolation without taking the actual entry or departure transitions as cause of problems.

- **System Security** means the ability of power system responding to disturbances, such as short circuit faults, or generator outages, arising within that system. Security is also referred as dynamic reliability, which represents the ability of system to supply power to customers under dynamic conditions without interruptions.

1.2 Literature Review

A thorough literature review suggests that significant research efforts have been focused on improving the reliability of wind energy systems. These efforts can be categorized into two levels: wind farm (WF) level and wind energy conversion system (WECS) level. The combination of these two levels will be the building blocks for future wind energy system. A wind turbine system is composed of many subsystems which cover the topics of electrical and electronic engineering, software engineering and mechanical engineering. Although there are a number of studies considering the impact of wind power on the reliability of a large power system [12], [13], there have been few articles that consider wind turbine [14]. A number of methods are now available for the reliability prediction of electronic systems and equipment?s [15, 16, 17]. They include physics of failure method [18], [19], empirical methods [20], similar item data based method [17] , test or field data based method [17], and system reliability prediction [21], [22]. Concerning power system reliability techniques, the models proposed in the literature are either simulative based on Monte Carlo technique [23], or analytical based on Markov method [24], [25]. These methods have advantages and drawbacks and can be very powerful with the proper application. Furthermore modeling wind farm reliability [26, 27, 28, 29], in addition to the modeling of wind turbine reliability [30, 31, 32], studies focus on economic benefits of reliable system [33], [34]. Moreover, wind farm reliability issues are discussed in [35], [36],[37],[38]. Commonly adopted reliability indices are introduced [39, 40, 41]. Attentions have also been devoted to improved power electronic systems in terms of reliability [42, 43, 44, 45].

The research on lifetime prediction has been mainly focused at either device level [46] [47], [48], or system level [49], [50], [3]. Reliability of power electronic components is a key concern nowadays. It is strongly influenced by the operating temperature of these components [51], [52]. Switching frequency has been modified through the control to decrease thermal cycles [53]. The converter topology has been discussed widely. Hence multilevel topologies tend to share the stress among devices and the stress on each single device depends on the total number of devices in the converter [54][55]. Furthermore, fault tolerant architectures have been proposed to increase the lifetime significantly [56], [57], [58]. The cooling system design has played a significant role in lifetime optimization [59], [60], [61]. In addition condition monitoring has been proven to be a cost effective means of enhancing reliability and improving customer service in power equipment [62] [63],[64]. The thermal performance can be improved by injecting proper reactive power circulation within the wind turbine system, thereby the thermal cycling can be reduced and the reliability of the power convert can be enhanced [65], [66]. Besides, advanced power electronic converters can provide the means to control power flow and ensure proper and secure operation of future networks space here [67]. Aging has been investigated by focus on the aging of thermal interface materials that are subjected to thermal cycling conditions [68],[69]. The use of discontinuous pulse width modulation (DPWM) is can minimize losses due to the effectively reduced switching frequency and consequently can enhance system reliability [70], [71]. Improved packaging technology is needed to improve reliability [72]. Therefore lifetime schemes can be classified as active thermal control and passive thermal control.

1.3 Motivation of the Work

An important observation about the research of the wind energy reliability is that it lags the research progress of reliability in many other industries. The intention of this work is to provide an introduction on the reliability of wind energy systems at both wind farm level and wind energy generation system level and review the related research efforts. Although it surely can not cover all the concepts, this thesis tries to reach this laudable goal. Some important questions that are to be answered include: Why do we do the research on wind? Why do we do research on reliability of wind? Why do we need prediction models? What are the available reliability methods and procedure are used in wind turbine? Why offshore wind energy? A detailed literature survey is conducted to investigate the various available reliability methods. State of the art of wind farm reliability is provided. An overview of reliability of power electronics in wind energy publications is discussed. A key message is that there exists great space for improvement although a lot of progress has already been achieved. The pace of active research from academic institutions and wind industries will increase over time.

Reliability has a great role in wind energy. Many ideas and proposals that are on the researchers tables will provide important context for the proposed work in this thesis. Some important issues have been investigated. The survey is to explain why wind reliability is studied. Also the survey has attempted to show that more effort must be invested as the prediction process becomes more credible and less imprecise. The survey has also described the attempts which have been made to improving wind farm and wind energy generation systems reliability. The survey still left with many open problems viz. grid requirements, vibration sensors collecting data of generator health, wind turbine condition monitoring and fault diagnosis techniques. Despite that wind turbine is one of marvels among generation plant, it is actually falling far short in terms of real time research.

Reliability evaluation and enhancement is an important factor in wind energy. Consequently, the reliability methods and procedures of wind systems are of great importance and will receive more attention in the future with increasing generation from wind energy. Each reliability method has its own advantages and drawbacks. All methods contain certain assumptions that may or may not be fulfilled. The specified approach should be made available sufficiently early to influence the reliability design and selection of the design parameters for the wind system. The influence of large wind farms in power system operation and planning must be highlighted. In a large wind power plant, an over simplified model of the plant as a single turbine is generally inadequate. A very large wind power plant should be represented by groups of wind turbines represented by their unique characteristics with respect to the location, the type of turbines, the control setting, and the line impedance. It is preferred to use wind energy in harmony with other forms of energy. Power electronics for modern wind turbines has captured the attention of researchers all over the world. It plays a very important role in the integration of wind energy sources. Finally, almost all of the aspects related to the wind energy technology are still under active research and development since there are many problems still afloat.

Further effort is required to improve reliability of wind energy systems, additional information should be supplied for selecting high risk components that need both research and industry developments. Upgrade science and innovative techniques should be implemented in wind energy generation systems. In addition maintenance techniques that have been proven and improved in other industries should be established in wind energy industry. The question that still needs to be investigated is the exact reliability mechanism behind such observed behavior in wind turbine failures. Wind turbine materials and manufacturing techniques, processes for repair operations, collecting monitoring data must be proved and improved based on lessons learned from the field and on a long successful history in industrial and commercial applications.

1.4 Problem Statement

Reliability is the probability that a component will satisfactorily perform its intended function under given operating conditions. The average time of satisfactorily operation of a system is called the mean time between failures (MTBF) and the higher value of MTBF indicates higher reliability and vice versa. Nowadays, reliability is of greater of concern than in the past especially for offshore wind turbines since the access to offshore wind turbines in case of failures is both costly and difficult. Power semiconductor devices are often ranked as the most vulnerable components in a power conversion system in terms of reliability. The lifetime prediction of power IGBT modules based on mission profile is an important issue. Furthermore, lifetime modeling of future large wind turbines is needed in order to make reliability predictions about these new wind turbines in the early design phase. By conducting reliability prediction in the design phase a manufacture can ensure that the new wind turbines will operate within designed reliability metrics such as lifetime.

This work presents reliability analysis of power electronic converters for wind energy generation systems based on semiconductor power losses as well as aims to maximize semiconductor lifetime using low-pass-filter (LPF) based control scheme since MTBF will be higher than without filter. The fundamental cause to achieve higher MTBF lies in the reduction of the number of thermal cycles.

The key element in a power conversion system is the power semiconductor device, which operates as a power switch. The improvement in power semiconductor device is a critical driving force behind the improved performance, efficiency, size and weight of power conversion systems. As the power density and switching frequency increase, thermal analysis of power electronic system becomes imperative. The analysis provides information on semi conductor rating, reliability, and lifetime calculation.

1.5 Scope of the Work

- The first goal is to discuss an overall survey about reliability in wind energy applications.
- The second goal is to calculate lifetime and design the reliability for high power IGBT's in wind power applications.
- The third goal is to optimize the dynamic system lifetime for IGBT module in wind energy applications.

1.6 Organization of The Thesis

This thesis is organized in the following chapters.

- In Chapter 2, some methods and techniques are discussed such as reliability prediction, which involves physics of failure prediction techniques, test/ field data, system reliability assessment prediction, similar item/circuit prediction and prediction by operational translation. These methods also include free tree analysis, reliability block diagram, failure modes and effect analysis, the analytical methods and simulation methods.
- In Chapter 3, issues related to reliability analysis on wind energy generation system level are presented. Moreover, modeling of wind turbine reliability, life curve are presented. Reliability design of wind energy generation system includes design for electrical, mechanical, and power electronic subsystems.

- In Chapter 4, wind farm reliability is studied and the issues are introduced. The topics include reliability modeling of wind turbines, reliability indices and characteristics of wind farm, factors influencing reliability assessment for wind farm, significance of offshore wind, technical aspects of integrating wind farm into power system, wind farm topologies, wind farm losses, challenges and operation and maintenance planning.

- In Chapter 5, concepts, mathematical equations, implementation of wind turbine characteristics, doubly fed induction generator (DFIG) and the average model for the converter and the physical system are presented. Semiconductor power losses, junction temperature and its variation that directly affect the lifetime of the converter are discussed. Furthermore, lifetime calculations and reliability estimation are presented. Issues related to an adequate control for smoothing the power command of DFIG is introduced.

- In Chapter 6, a summary of the main contributions of the work and topics of future work are presented.

Chapter 2

Analysis and Methods in Wind Reliability

2.1 Introduction

For the analysis of the reliability of wind energy systems, many methods and techniques either qualitative or quantitative, numerical or analytical have been developed. The qualitative techniques lead to identification of weaknesses in the design prior to quantitative approaches, which are executed by using several system level failure mode and effect analysis (FMEAs). Further, quantitative approaches are used during the design stage. Some of these methods employ reliability prediction tools of fault tree (FT), reliability block diagram (RBD), reliability graph (RG). Analytical methods are based on Markov and simulation methods are based on Monte Carlo.

2.2 Reliability Prediction

As the first step of reliability prediction, a set of factually possible conditions and their related consequences must be considered by which the system can be designated as being failed. Then, converting the qualitative approach into a quantitative approach is a second stage. This is obtained by probability theory, and the assignment of probabilities to each of the states that lead the system to failure. Sometimes this rather complicated procedure can be partially circumvented by a statistical analysis of previous failure data, from which direct estimation of failure probability can be made. Thus, the prediction problem is not merely to characterize the system in some way. It also has to take into consideration further factors such as the experience of the design team, the conditions under which the design was achieved.

Reliability predictions for wind turbines will have an important bearing on the future development of wind power resources. This section is concerned with understanding the reliability prediction of modern wind turbines and power electronic subsystems. This method is not only applicable to wind turbines but also applicable to any repairable system. The main purpose is to discuss the practical methods of predicting large-wind-turbine reliability. More research efforts will provide both new insights and specifics for wind turbine generation model development and application. Reliability prediction is considered as a quantitative reliability analysis technique. It is used to predict the failure rate of a system based on its components and operating conditions. This technique is also used to verify progress in reliability engineering.

The reliability prediction calls for building a mathematical model for the system under study and defining some reliability measures such as expected energy not supplied (EENS), annual interruption frequency, annual interruption duration, mean time to failure (MTTF). Then it is followed by developing a technique for evaluating the reliability measures, and comparing predicted data against experimental results. The comparisons of different methodologies are tabulated in Table 2.1.

The reliability prediction of electronic systems and equipment requires adequate knowledge and realization about the components, besides deep understanding about the design,

Table 2.1: Comparison of different reliability prediction methodologies for electronics.

Methods	**Advantages**	**Disadvantages**
Empirical	Implementation is very simple since models are already available.	Historical records can result in inaccurate estimate for new components.
Physics of Failure	High level of prediction using known failure mechanism is performed to determine the wear-out function.	High level of knowledge of component materials and process and design science is required. Hence, it is challenging to apply since too many data and parameters are needed , hard to calculate as too many data are required.
Similar Item Data	Fastest way to estimate a new product?s reliability and it takes place when limited design information is known.	The similar product for evaluation may be substantially different from the one under consideration.
Test/Field Data	Results can be accurately determined as tests include associated uncertainty.	The test/field data are difficult to obtain and assess.
Operational Translation	Handy and application of environmental factors for tough conditions.	Shortage of up-to-date and limited number of translation scenarios present the challenge.
System Reliability Assessment	Combine the field and test data with empirical prediction through statistical analysis.	It demands augmented computation.

the manufacturing process and the expected operating conditions. The prediction models should be relatively simple and easy to maintain, fully defined in terms of their jobs and requirements with identified constraints on their application. The choice of reliability prediction method is based on experience and the number of modes or periods of operation time that each method is effective, which is indicated by check marks as shown in Table 2.2.

Table 2.2: Time operation period for reliability prediction methodologies.

	Methods	$\beta < 1$	$\beta = 1$	$\beta > 1$
1	Test or field data	✓	✓	✓
2	System reliability assessment	✓	✓	✓
3	System item data	✓	✓	–
4	Translation	✓	✓	–
5	Empirical	✓	✓	–
6	Physics of failure	–	–	✓

The prediction models in different categories have been classified based on their usage, characteristics, and conditions for applications. Each model is dependent on widely different sets of physical parameters such as electrical stress, environment, quality, and temperature. It is based on the assumption that systems fail as a result of failures of component parts, which fail partly as a result of exposure to application stress. Again, the selection of the method is a fundamental choice made by the design engineers and direct company policies based on the application in consideration. It also varies according to the product life cycle and related reliability metrics. It is driven by the critical parts in the system to be modeled and by the system requirements. The fitness of a reliability prediction depends on how well it is designed, developed, and applied. It can also be assessed based on how well it matches the system?s specification as well as the field observed behavior. Depending on the assumptions and methods used, reliability numbers can vary dramatically and possibly lead to misapplication of the system being considered.

Reliability prediction is effective due to the following aspects [73]:

- Supply reliability with a quantitative forecast.
- Improve design and manufacturing process.
- Result in process that meets end-user reliability.
- Create competitive among designs.
- Highlight problems associated with reliability such as design imbalance, source of unreliability.
- Help in feasibility evaluation to achieve design reliability laudable goals.
- Predict warranty cost and maintenance support requirements.
- Assess risks and providing inputs to analysis.

Reliability prediction approaches are widely adopted throughout the electronics industry. These approaches are considered as a yardstick and a criterion for the comparison of different types of equipment. Some of these approaches have narrow scope, and some have been replaced by newer approaches or have been modified, but most of them have wide spread adoption. Here an overview of the commonly used reliability predictions methodologies is presented.

2.2.1 Empirical Prediction Approach

Empirical prediction approach is based on modeling past-experience data and present good estimations data for the same products. Thus empirical models have been developed from historical reliability records, which are obtained from different sources and environments, either from active field or laboratory tests. Therefore, the reliability prediction will vary as a function of the specific empirical prediction approach. Some of the frequently utilized empirical prediction techniques were initially developed for military or telecommunications, but now they have also been widely applied in many other industries.

- MIL-HDBK-217: the military handbook for the reliability prediction of electronic equipment.
- Telcordia (Bellcore): reliability prediction procedure (RPP) for electronic equipment TR-332.
- HRD-5: British Telecom handbook of reliability data for components used in telecommunication systems.
- NTT Procedure: Nippon Telegraph and Telephone Corporation standard reliability table for semiconductor devices.
- CNET-93: French National Center for Telecommunications studies;
- RDF 2000: French Telecommunications.
- IEC 61709: reference conditions for failure rates and stress models for conversion.
- IEC 62380: reliability prediction program based on the French Telecommunications standard RDF 2000.
- 229B: Chinese Military Standard.
- Siemens Procedure: Siemens reliability and quality specifications failure rates of components.

- PRISM: system reliability assessment methodology developed by RAC.

The main advantages of empirical approach is that it serves as good performance indicators or yardstick of field reliability, simple to use if the models are available, and it provides a reflection of actual field failure rates. On the other side it is hard to keep support data, difficult to collect data from their sources either field application or laboratory test since failure rates can depend on the diversity of the sources of data [73].

2.2.2 Physics of Failure Prediction Techniques

The technique based on physics of failure models each failure mechanism for each component. This method has been used in design stage prior to device life. Bottom up physics of failure method requires comprehensive knowledge of the thermal, mechanical, electrical and chemical life cycle environment as well as processes leading to failures in the field in order to apply appropriate failure models. The ultimate goal is to predict for a certain component when end of life mechanism will take place. The component failure rate is the sum of all the failure rates due to various factors such as thermal, humidity, voltage, and thermal cycling. The system failure rate is the sum of all the failure rate of the components. Examples of such failure modes include the thermal aging of electrical components, the onset of high cycle fatigue cracks in structures subject to cyclic loads or the deterioration of seals leading to lubricant leakage and contamination.

Physics of failure has prosperous long history in electronic reliability field. Typical advantages of the physics-of-failure are modeling of potential failure mechanisms, estimating of end-of-life, determining the variability of each design parameter. Moreover, common failure models that are effective for existing designs can be effectively applied to new materials and structures. On the contrary it cannot be used to estimate the field reliability. Furthermore, proper applications of this method requires deep understanding of failure mechanism and design process and it is not applicable for assessing a whole system.

2.2.3 Test/Field Data

The method based on test/field data works in the three modes of operations. The reliability outcome can be precisely determined including the associated uncertainty of the estimate, but it is a difficult method since the data are not easy to collect and organize. It is used to evaluate reliability of electronic equipment based on both failure and time.

2.2.4 System Reliability Assessment Prediction

This approach to reliability analysis allows system architects to analyze reliability of the system before it is built. This approach involves two successive stages: pre-build phase and post-build phase. The first phase is based on using consolidated reliability assessment method, which takes into account the process grading factors, requirements definition, part quality, design and manufacturing in addition to initial prediction, operational profile, software . The second stage consolidates the best estimates with system test data and process defect data using Bayesian combination. The Bayesian technique is a statistical theory for combining the results of separate statistical data. The technique has been proposed as a method for combining test results with previous data or with subjective judgment in order to derive better or more economical reliability predictions based on limited data.

2.2.5 Similar Item/Circuit Prediction

This method has been used to collect data of the past experience on the similar products. If the new product shows a good performance, then the data provide good record for comparison for the new item. During the translation process environment and operating conditions must be considered. The main feature of this technique is that it is very quick to estimate the new product reliability and it is a valuable approach when there is shortcut in design information. Nonetheless, the possibility that the new product is different from the similar one could cause inaccurate prediction, which constitute a main deficiency.

2.2.6 Prediction by Operational Translation

The operational translation method is based on empirical approach to estimating field reliability value. It depends on factors affecting field reliability, which include all failure causes viz. induced failures resulted from incompetent system design, imperfection manufacturing. Although it is a straightforward process to apply this method, there could be limited availability of both translation scenarios and up to date empirical data [74].

It is worth mentioning that according to [75], the best reliability prediction could only be achieved by a combined use of different methods, depending on the design, development or manufacturing phase, provided that these methodologies are not interchangeable approaches. The reliability predictions are essential techniques, which improve reliability, and are mathematically simple but not accurate. Historical data play a major role. They take into account the design tradeoff between using a large number of low failure rate components versus using a lower number of high failure rate components.

Furthermore, through competitive analysis, a first-step approximation of the product's inherent reliability is obtained by comparing MTBFs of competing products against the ones predicted by models. The higher complexity of the product typically correlates to the higher probability of imperfection in the field. In summary, reliability prediction methods are coherent and mathematically sophisticated, but on the other hand they have some limitations and they are inaccurate. The limitations it can be overcome with the use of historical data and records and appropriate correction factors. Reliability predictions can achieve adequate accuracy on a practical level. The value of these methods is very high at the early phase, but the value decreases rapidly as prototypes become available for testing. Employing these methods can increase the baseline reliability of a product. Since product reliability depends mainly on design and operation conditions, other methods and techniques should be used to prove and improve reliability [76].

2.3 Fault Tree Analysis (FTA)

Fault trees analysis is analytical logic technique that can be applied to analyzing system reliability. The diagram follows a top-down structure and represents a graphical model of the pathways within a system that can lead to a failure. Based on a set of rules and logic symbols from probability theory and Boolean algebra, the pathways interconnect contributory events and conditions using standard logic symbols. For the connected system in this study, the resulting fault tree diagram is a graphical representation of chain of events in wind system. The probability of the top-level event can then be determined by using mathematical techniques that are widely used in system reliability and safety studies. Fault tree analysis offers the ability to focus on an event of importance, such as a highly critical safety issue, and subsequently to avoid its occurrence or minimize the consequence.

2.4 Reliability Block Diagram (RBD)

In this graphical analysis technique, the subsystems or components are connected according to their function or reliability relationship. The main advantage of the RBD method is that it is easy to read. In a RBD, the logic diagram is arranged to indicate which combinations of component failures result in the failure of the system, or which combinations of properly working components will keep the system operational. A block in RBD represents the working physical component, and the failure of this component is indicated by the removal of the corresponding block. If enough blocks are removed in an RBD to interrupt the connection between the input and output points, the system fails. In other words, if there is at least one path connecting input and output points, the system is still operating properly. Generally two main types of connection, series and parallel, can be established between two or more components [77]. Series connections represent logic AND of components, and parallel connections represent logic OR. The parallel units in the system means redundancy. A system keeps operating successfully until no valid path from leftmost node to rightmost node can be formed from available connections. Typically, the one-line diagram is preferred since it is easy to understand by engineers with minimal experience with reliability engineering. This makes RBD an easy tool to use for determining the reliability of specific designs and for comparing multiple design variations to determine the point of diminishing returns. Using RBD one can handle most of reliability situations even though it has some limitations. For example it supports only standard configurations besides its inability to represent sequence dependent failures. In addition, it is not intuitive to represent failures caused by human operators, external events, and the like [78].

2.5 Failure Modes and Effects Analysis (FMEA)

FMEA is a subjective analysis tool, using a qualitative approach to identifying potential failure modes and their initiating risk to either the system design or manufacture or operational phase. Hence, the FMEA drives designs towards higher reliability, quality, and enhanced safety. It can also be used to assess and optimize maintenance plans. In brief it is a method to improve reliability during design stage [79]. From the FMEA, a numerical value is assigned to individual failure modes in order to highlight particular areas of risk. The main goal is to identify and limit or avoid risk within a design. FMEA is usually carried out by a team consisting of design and maintenance personnel whose experience includes all the factors to be considered in the analysis. The factors include severity S, how the failure affects the capital operation of the system, occurrence O, how the failure mode is to initiate, and detection D, how likely failure is to be detected using current condition monitoring and inspection techniques. These three main factors are individually rated using a numerical scale, typically ranging from 1 to 10. These scales, however, can vary in range depending on the FMEA standard being applied. The risk priority number (RPN) is then calculated as follows:

$$RPN = S \times O \times D \tag{2.1}$$

with final values being

$$S \times O \times D = \sum (W_i \times x_i) \sum W_i. \tag{2.2}$$

where W is weight value of the experts, x is rank and i is number of experts [80].

2.6 The Analytical Methods

Markov models that are also known as state space diagrams or state graphs provide various measures of a system including availability, MTTR. Markov model may become excessively complex depending on the dimensions of the state space. This method considers wind speed, failure and repair rates of wind turbines as well as load demands for short-term and long-term reliability calculation and comparison. Effect of change in initial number of working wind turbines and repair crew can be investigated. So the analytical methods represent the system by enumerating potential incidents. The complexity of calculation increases significantly with expansion in size of power system [23]. When a wind farm is composed of hundreds of wind turbines that are grid-connected, the calculation will be confronted with great difficulties. It has to be determined when the system is represented by mathematical models and when direct analytical solutions are used to evaluate reliability indices. These techniques require some degree of approximations even if they represent the fastest solution in almost any kind of analysis. They might act as a black box and some internal aspect of the model might not be completely evaluated.

In analytical methods the system is represented by mathematical models, from which direct analytical solutions are obtained to evaluate priori reliability indices. The Markovian approach is suitable for modeling the energy production and power availability of a wind turbine. In this approach, the wind speeds̀ time variability is taken into account by means of wind speed classification in a discrete number of contiguous classes with each corresponding to a range of values. The duration of each class is statistically treated to preserve information about its duration and the transition rates into all the other classes. The major disadvantage of the analytical approach is that it does not consider the chronological variation of wind speed. Moreover, the Markov model has a new technique called voter based state reduction (VBSR) technique for reducing the number of states in FMEA. The VBSR technique makes reliability analysis and assessment of power electronic systems more simple and meaningful [25].

2.7 Simulation Methods

Simulation methods based on Monte Carlo technique requires unfortunately large computational burden due to the amount of data processing. Although the main drawback of a Monte Carlo simulation is usually its long computation time, computation time may not be an issue if the studied system is not large. The simulation method has advantage of including all variables of the system and featuring more flexibility in the analysis. A Monte Carlo simulation approach is based on hourly random simulation to mimic the operation of a generation system, taking into account the fluctuating nature of wind speed, the random failures of the system. The Monte Carlo simulation must be optimized to reduce required time and sample numbers.

This method estimates reliability indices by repeatedly simulating large number of trials to replicate the operation of a power system and random behaviors in the system. This method treats the problem as a series of real experiments. One of its advantages is that the multi-state components can be incorporated in the analysis without significant increase in the computing time [81]. There are two basic techniques used when Monte Carlo methods are applied to power system reliability evaluation, which are known as the sequential and non-sequential techniques.

- Monte Carlo sequential simulation is suitable for the analysis of choppy wind generating sources. The main feature is the reliability evaluation combines the chronological characteristics of wind such as diurnal and season wind speeds, load profiles and the chronological transition states of all the components within a system. Sequential simulation can provide realistic and accurate results related to wind power [82].

- A non-sequential Monte Carlo method has been developed to evaluate the reliability indices of interest. This Monte Carlo simulation theoretically could incorporate any number of system parameters and states. Nonetheless, in the established non-sequential simulation, only hourly uncorrelated states are considered.

In component modeling for reliability assessment, Monte Carlo simulation can include multi-state component reliability models defined by any kind of probability distribution, not only the exponential one as in other methods [83].

Monte Carlo simulation may be preferable for [83]:

- Models with non-exponential time distributions;
- Characterization of peaking units;
- Definition of distributions function of output indices;
- Use of time dependent on chronological issues.

So we can summarize Monte Carlo as [83]:

- Among reliability assessment methods, it is a robust method because the detailed models of primary generating resources availability, internal/external generating dispatch and customer demand are simulated. Also it can be easily integrated into operative actions such as load shedding, re-dispatch, reactive power management and planning tools like optimization.

- Any kind of probability distribution such as exponential one is allowed in Monte Carlo for modeling times to outage and times to restoration of the components. Thus, with this method, aged components, failure rate, and restoration times, can be easily modeled.

- The high correlation between detailed modeling and reliability assessment of energy limited systems leads to more factual studies with low risk of using the results when decision making is required.

- In the cases of energy limited systems, if the operators work on maximum capacity and exceed the components useful life, the need for the system upgrading is very essential, in order to have a detailed model in this severe mode of operation.

Chapter 3

Reliability at Wind Energy Conversion Level

3.1 Modeling Wind Turbine Reliability

Because of economic importance, reliability theory categorizes the systems into repairable and non-repairable systems. The major reliability index of a system is failure rate, or to be more precise, instantaneous failure rate. In reliability, “rate”is always a conditional rate, For the case of non-repairable system components have not failed or failed only in which case the “hazard rate”is the suitable term to reflect reliability measurement. Otherwise, for repairable systems, it is commonly assumed that the condition of the components can be restored to full functional performance, in which case the term “failure rate”will be used to avoid confusion. The subject of reliability can then be treated by the theories of probability and statistics.

Repairable wind turbine system modeling has shed light on reliability aspect. Earlier studies and results in this field usually consider that a system after each repair is as same as new for perfect repair or as same as old for minimal repair. These two assumptions are found very limited uses in practical wind turbine applications since most repair activities may realistically result in a complicated one that is in between. Nowadays, researchers start to focus more on this type of repairable systems where repair actions do not bring the system to an as-same-as-new situation but rather bring the state of a failed system to a level that is somewhere between new and the status prior to failure.

Most important models of wind turbines are based on either homogeneous poisson process (HPP) or power law process (PLP). From this point different mathematical models rises such as point process, Poisson processes, homogeneous Poisson process (HPP) and non-homogeneous Poisson process (NHPP) [30] [31] [32].

- Point process is a stochastic process describing the occurrence of events in time. In studying wind turbine reliability the events are failures and the index is a set of times or a set of variables expressing the life of objects. The time between failures are not independent and identically distributed (IID).
- Poisson processes is a point process that satisfies the following:
  - Set the observation beginning period at $t = 0$, the number of failures is $N(0) = 0$.
  - The number of periods are independent,

$$\forall a < b \leq c < d \Longrightarrow N(a, b] and N(c, d] \tag{3.1}$$

  - The intensity function if exists

$$\exists \lambda(t) : \lambda(t) = \lim_{\Delta t \to +0} \frac{P[N(t, t + \Delta t) = 1]}{\Delta t} \tag{3.2}$$

  - The possibility of simultaneous failures

$$\forall t : \lim_{\Delta t \to +0} \frac{P[N(t, t + \Delta t) \geq 2]}{\Delta t} \tag{3.3}$$

For Poisson process, the number of failures in an interval (a,b) is a random variable having a

$$\bigwedge(a,b] = E[N(a,b]] = \int_a^b \lambda(u)du \tag{3.4}$$

distribution mean

$$P\left(N\left(t\right)=n\right)=\frac{1}{n!}\left(\int_0^t \lambda(u)du\right)^n \exp\left(-\int_0^t \lambda(t)du\right) \tag{3.5}$$

- Homogenous Poisson process (HPP) [41]
  - Poisson process is considered a HPP with constant intensity function $\lambda(t) = \lambda$
  - Point process is considered HPP with intensity if and only if the TBF are IID exponential random variables with the exponential distribution having probability density function (pdf) $f(t) = \lambda \exp(-\lambda t)$.
    1. Group certain number of turbines in certain period (month/quarter) and treat it as an independent variable population.
    2. Consider the time between failures (TBFs) as independent identically distributed (IID) exponentially random variables.
    3. The probability P(t) of having n failures through time t as:

       $$P\left(N(t)=n\right)=\frac{1}{n!}\left(\lambda t\right)^n \exp^{\lambda i}, n=0,1,2,... \tag{3.6}$$

       where $\lambda = \frac{1}{\theta}$ with θ being the MTBF.

- Non homogenous Poisson process is the Poisson process that has non-constant intensity functions.

- Power law process

  1. The PLP model is used as a trajectory to measure the reliability improvement of a system.
  2. The PLP model can foretell the effectiveness of further design developments.
  3. Necessary to apply fit test.
  4. The PLP is a special case of a Poisson process with the failure intensity function

     $\lambda(t) = \rho \;\, \beta \;\, t^{(\beta-1)}$

     where β is obtained by numerically solving the nonlinear equation

$$\sum_{i=1}^{l} n! \left(\frac{t_i^{\beta} \ln t_i - t_{i-1}^{\beta} \ln t_{i-1}}{t_i^{\beta} - t_{i-1}^{\beta}} - \ln t_i \right) = 0 \tag{3.7}$$

Here the failure intensity function of wind turbines λ is focused on rather than other wind turbine parameters such as availability and capacity factor wind conditions and the consequences of faults. Thus the failure intensity function λ depends foremost on WTCS construction and is intrinsically predictable. It has been shown that wind turbine gearboxes seem to be achieving reliabilities comparable to gearboxes outside the wind industry [84]. However, wind turbine generators and converters are both achieving reliabilities considerably below that of other industries although the reliability of these subassemblies improves with time. For clarity of understanding the wind turbine reliability, the following terminology will be used [84]:

- System: for the entire wind turbine and the connection infrastructures.
- Subsystem: to generically indicate part of the wind turbine that deals with the same form of energy. For example the entire drive train consisting of rotor hub, shaft,

bearing, gearbox, couplings and generator is considered as a subsystem.

- Subassembly: to indicate devices performing more specific functions for which the failure data are recorded separately. For example the gearbox is a subassembly.
- Component: to indicate small devices typically non repairable constituting the subassemblies. For example, the gearbox/generator coupling is a component.

The subassemblies with the highest failure rates are, in descending order, electrical system, rotor (i.e. blades and hub), converter (i.e. electrical control, electronics and inverter), generator, hydraulics, and gearbox [84]. It is found that the power electronic converters of direct-drive and geared WTs exhibit higher failure intensities throughout their operation than converters in other industries. It is worth noting that direct drive wind turbines do not necessarily have better reliability than geared one [85]. It is also found that during starting phase, direct drive and geared generators have higher failure frequencies than generators in other industries, and smaller WTs have a higher reliability than larger WTs.

The procedure of WTG design of reliability can be performed on both the overall system level as well as the sub-system levels. The overall system level reliability analysis is to integrate the whole system reliability model using common reliability analysis methods and procedures as discussed in the prior section. The sub-system level reliability analysis builds an individual reliability model for each subsystem in order to:

1. Study the interaction of the sub-system models within the whole system;
2. Promote a design procedure created by a skilled and experienced design for sub-system;
3. Optimize the location of sensor and observers devices for characterizing sub-system failures.

3.2 Life Curve

A typical life curve of machinery [31] is illustrated in Figure 3.1. The failure rate of wind turbine is [32]:

$$\lambda(t) = \frac{\beta}{\theta}\left(\frac{t}{\theta}\right)^{\beta-1} \tag{3.8}$$

where β is a dimensionless shape parameter that determines the shape of intensity function. θ is a scale parameter has dimension of time. Three fractions of time with occurrence of the main failure types:

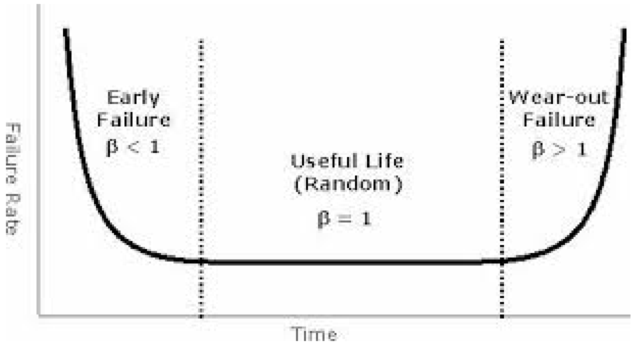


Figure 3.1 Bath tube Curve.

1. The infancy period is characterized by a decreasing failure rate that starts with a relatively high initial value.

2. In the useful life period there is an ideally constant failure rate. This is due to extrinsic failures which appear spontaneously and are independent from operation time and thus can also occur in the infancy period and in the wear-out period. They are a consequence of overstress such as overvoltage or over current in an electronic device.

3. The wear-out period is the final period in service life. Due to intrinsic causes such as deterioration and fatigue in electronic components, intrinsic failures arise predominantly.

3.2.1 The Shape Parameter β

3.2.1.1 Early failure $\beta < 1$

The failure intensity in (3.8) decreases with time. Hence PLP describes reliability improvement. The major causes of early failures are the following [86]:

- Poor manufacturing techniques including processing, handling and assembly practices;
- Poor quality control;
- Poor workmanship;
- Insufficient burning in or debugging;
- Substandard parts or materials;
- Replacing failed components with non screened ones;
- Parts failed during storage or transportation due to improper PHST practices;
- Improper installation;
- Improper start up.

3.2.1.2 Constant failure rate $\beta = 1$

With the intensity function of the PLP equal to ρ, the process represents the bottom of the bathtub curve, which is called the intrinsic failures phase. During the intrinsic failures phase, the constant failure rate λ is described as the average failure rate. The failure rate in 3.9 becomes to a constant and the process becomes a HPP. θ becomes the mean time between failures (MTBF) of the turbine, and the maximum likelihood estimates (MLE) of θ is [32]:

$$\theta = \frac{1}{\lambda} = \frac{\sum\limits_{i=1}^{l} T_i}{\sum\limits_{i=1}^{l} n_i} \tag{3.9}$$

i : length of interval (month or quarter).

I : Number of intervals for which data were collected.

$N_{i,k}$: Number of failures per interval i per subassembly k,

The major causes of chance failures are the following [86]:

- Stress strength interference during operation;
- Occurrence of random loads higher than expected;
- Occurrence of random strengths lower than expected;
- Insufficient safety margins;
- Human errors in usage;
- Unexplainable causes.

3.2.1.3 Deterioration $\beta > 1$

For $\beta > 1$, the intensity function increases with time and PLP describes reliability deterioration or wear out. Practically, it has not yet been encountered in wind turbines, probably owing to their relatively young age. Furthermore, if the reliability of a wind turbine reduces dramatically, it will be taken out of service before the deterioration phase can be detected. The major wear-out failure causes are the following:

- Aging;
- Wear;
- Degradation in strength;
- Fatigue;
- Creep;
- Corrosion;
- Mechanical, electrical and chemical deterioration;
- Replacement of failed parts by partially aged ones;
- Short designed in life.

The failure rate is obtained by the number of failures per turbine per year, which is calculated by [32]

$$\lambda = \frac{\sum\limits_{k=1}^{K} n_{i,k}}{\frac{N_i T_i}{8760}} \tag{3.10}$$

where

N_i is the failure rate and obtained as the number of failures per turbine per year.

$n_{i,k}$ is the number of failures in subassembly k during interval i.

T_i is the number of turbines in population at interval i.

3.3 Electrical and Electronic Components Reliability

Due to low accessibility, the electrical and electronic components of offshore wind turbines require high reliability to make the WTG meet availability. It is worth mentioning that the electrical and electronic failures are more difficult to identify before failure takes place. And the working conditions for wind power plant electrical and electronic equipment?s are different from those working in other industrial conditions. Evaluation of electrical and electronic components reliability must consider operation conditions, maintenance records, and failure records.

3.3.1 Electrical Components

Inside the nacelle, a WECS is composed of a suggested machine type connected to a high-frequency step up voltage three-phase transformer satisfy that transformers operating at high frequency can reduce its volume and weight that can be easily able to fit into the nacelle of wind turbine [87]. In addition, the transformer with high frequency provides a galvanic isolation between grid and the generator. A complete power electronic WECS is necessary. Reliability assessment of wind turbines` electrical components should consider both physical model and measurement uncertainties. The deterioration criteria for electrical components must be proposed due to operational temperature fluctuations within wind turbines. In addition to environment factors, temperature, humidity, turbulence stress directly influence reliability assessment. The main root cause of electrical failures is the typical voltage irregularities and electrical stress. The mechanical stresses of wind turbine machine also play a significant role. Sometimes they are also affected by poor power quality from IGBT convertors in wind turbines. Among all types of failures, the electrical ones are the most difficult to identify before failures. Appropriate maintenance and other predictive techniques are considered as a key for increasing machine life and can drive the major improvements toward zero maintenance and reducing cost. Here are some of electrical windings failures in wind turbine generators [88]:

- Rotor banding;
- Conductive wedges;
- Cooling system failures;
- Rotor lead damage;
- Under-designed materials and systems;
- Catastrophic failure due to surges;
- Contamination issues.

Turbine electrical and electronic components require monitoring, control, reporting, routine maintenance and testing to manage their failure and increase their reliability. The failure rates of electrical and electronic subassemblies are higher than the mechanical subassemblies, but their downtime are lower than the mechanical ones. This is due that the electrical and electronic ones have high exchangeability. Thus there is a need to achieve higher MTBF of the power electronic components for a reliable design of the power electronic systems in WECS.

3.3.2 Electronic Components

Power semiconductor devices such as IGBTs are widely used in electronic applications as well as WECS electronic modules. WECS component suppliers and producers offer IGBT as a solution to handle the increased voltage peaks within the generator that might harm the components. Further, IGBTs are used in WECS control systems as well. The IGBTs work in a harsh environment, where temperature fluctuates drastically. The mission profiles for IGBTs can be categorized as operational, mechanical and environmental temperature loadings. The voltages stress is created by power electronic converters in the same unit or the neighboring units within the same wind farm or other wind farms in power system plant. In general defining root causes is not an easy task. Power electronic is able to change the basic characteristic of wind turbine from being an energy source to be an active electrical power source [89]. The reliability design of power electronic converters in wind systems must consider the requirements of minimum power loss for converter, maximum operation reliability and minimum capital cost of the system [33]. The three most important causes of failure of semiconductor devices are voltage stress, cosmic rays, and thermal cycling [90].

Although there are some problems raised with converters in wind turbines such as [91]:

- Converters has a considerable failure rate, hence loss of power production.
- At low power levels, converters have low efficiency.
- Due to PWM, converters cause harmonic voltage on the grid.

Power electronic converter of various topologies such as matrix, modular and multilevel converters play a significant role in wind turbines. They enable improved output waveform, reduced harmonic content compared to standard two-level converters, higher power rating, and lower stress across the switches. Nonetheless, a multilevel topology has not been widely adopted in wind turbines due to complexity feature and negative reliability impact. Furthermore, redundant multilevel converters will be more expensive [91]. Related to matrix converters it has several features in wind turbines viz. all-silicon based converter, no DC-link, high power density and compact design. The disadvantage of matrix converters is the high cost due to high number of switches [91]. Modular converters typically comprise a number of converter modules connected in series or parallel. For the topology of modular converters, the main advantage is that the basic modules are interchangeable and reconfigurable, thereby providing a flexible, redundant and reliable converter system [91].

Increasing availability of power electronic converters typically involves [79]:

- Improvement of the reliability of a component;
- Condition monitoring applied to the system;
- Condition monitoring applied to the components;
- Prognosis applied to the components;
- Redundancy and fault tolerance.

When the system is equipped with redundancy, the affected component will be isolated and the redundant component takes over the operation in case of failure. Redundant strategy tries to keep up operation when the failure takes place. Prognosis applied to the components enables the prediction of the remaining useful life for the components until reaching the wear-out period. Although the component lives in the period of a higher failure probability due to the deterioration mode, an exact time for the failure point cannot be predicted.

Condition monitoring (CM) is a real-time measurement of the condition of a component. If it drifts away from the healthy condition, an appropriate action will be taken [92]. This technique monitors the operating characteristic of power electronic components in wind turbines. It is considered as one of the cost effective means of improving reliability and customer service in power equipment?s [92]. It is applied to the components that are closely related to the deterioration failures in the wear-out period of the components. It enables to decrease the number of extrinsic failures in the components. The main feature is that change of the monitored characteristic can be used to schedule maintenance before failure occurs. Condition monitoring techniques are utilized in some aspects such as vibration analysis, oil analysis, thermography, strain measurements, acoustic monitoring, electrical effects, process parameters, visual inspection, performance monitoring and self-diagnostic sensors. The main problem is associated with condition monitoring techniques is the requirement of large number of sensors among the fleet of wind turbines, which makes this technique complex and expensive to implement. Nonetheless, the application of condition monitoring to power electronic systems is very important because [92]:

- In unpredictable failure such as catastrophic accident or unscheduled maintenance, the use of CM in power electronic becomes more essential.
- Comprehensive knowledge about the failure in wind turbines in addition to improvement in sensors and signal processing leads to effective power electronic converter CM systems. Applying the concept of condition monitoring to power electronics is challenging issue, and must be addressed in a survey paper [92]. Structure health monitoring (SHM) techniques are unclear. Particularly the vibration monitoring on the wind turbine tower has not been overcome yet [93]. Some of the components of wind turbine that need to be monitored are faults due to imbalance, wear, fatigue and impending cracks in rotor blades, bearings, shafts, gearbox, generator, yaw and the pitch angle mechanism [93].

Diagnosis is to identify the root cause of that fault if it has occurred [92]. Diagnosis encompasses detecting, isolating, classifying, and analyzing faults [94]. Prognosis assesses the current health level of a component, and predicts the health of the component at some point in the future [92]. The most important aspect for connecting a WECS with the electric grid requires a power electronic converter that allows variable speed operation, reduces mechanical stress, and increases reliability. Zhu et al. clarified base on available statistics that around 40% of system failures is related to wind turbines converters reliability caused by indelicate design or indecorous operation or improper control [95].

3.4 Reliability Design in WECS

Nowadays, presenting favorable circumstances likely results in or shows signs of success in power electronic of wind turbines. Power semiconductors are normally used in applications where high reliability is a must. Long life cycle of power electronic, warranty costs reduction, and miniaturization electronic component, in addition to accurate, inexpensive, sufficient and less time consuming reliability test methods, are needed for power electronic components among fleet of offshore wind turbines. Some methods or testing protocols have been tried to be integrated to help wind farm engineers and operators reveal and predict reliability issue in speedy and efficient way, such as:

- Highly accelerated life test (HALT) reveals weak points and possible failure modes in short testing time, say 2-5 days and provides information about product operation in a harsh offshore environment. This test can rapidly find weaknesses under accelerated stress conditions. The main features of HALT include saving time and money due to easy applications. This test technique is best suitable for application during early engineering development.
- Accelerated life testing (ALT) is a process of determining the reliability of an electronic

components over a fleet of wind turbines in a short period of time by accelerating the use environment. ALT is also suitable for finding dominant failure mechanisms. It is usually performed on individual assembly level rather than subsystem level or system level. It is preferred to use when there is wear-out mechanism involved. It also predicts the life of the power electronic and electrical components in the offshore wind turbines and allows the operators to prioritize component improvements. The failures for ALT are time-dependent. Life models are utilized to correlate the product test and application load conditions to the failure sites and local stress conditions and then to relate these local stress conditions to damage based on the identified failure mechanisms and material properties. The main disadvantage is that is needs significantly more test time and samples although it provides information about the life expectations in the test conditions. This life information is useful to evaluate design changes, warranty issues, and life cycle costs. This test technique is best suitable for application before production release [95].

- Environmental and functional testing is to guarantee top performance in climatic conditions. Power electronic converters in wind farm must have high quality to work perfectly wherever and whenever. Extreme environmental conditions can have an extreme effect on overall functions. Converterś lifecycle and qualification tests prove its reliability and to identify weaknesses and initiate its improvements at an early stage. This test verifies that a component is capable of operating under the test conditions for a certain period of time. It cannot be used to quantify reliability parameters, such as failure rate, MTBF, failure distributions, performance degradation, etc.

Root cause analysis related to electrical and electronic subassemblies in wind turbines have been conducted in [96]. The analyses include component thermal aging, thermal mechanical cycling fatigue mechanisms in the conduction and insulation materials of electromechanical components, and thermal mechanical fatigue stress experienced by packaging materials of the integrated power modules (IPM) in the power electronic. In addition to root causes presented in [97], viz. stress strength interference during operation, occurrence of random loads higher than expected, occurrence of random strengths lower than expected, insufficient safety margins, human errors in usage, this survey suggested some protocols of reducing the effect of these failure causes such as equipment failure begin with a complete understanding of the equipment. It has been found that the most important factor affect component reliability is the degree to which the manufacturer is able to fabricate defect-free components [97]. The in-depth knowledge of operation and maintenance practice and references to equipment design and engineering practices make it possible to develop an overall understanding of the root cause and to efficiently direct the investigation of an electrical and electronic system.

Reliability strategies involve a structured approach to identifying critical equipment and systems. This could include a FMEA to identify the critical component or system failure modes. A MTTF or MTBF model can also be used to derive a probabilistic reliability model. Defining the appropriate maintenance regimen and replacement strategies based on that criticality determination is also part of a well-designed reliability mechanism. When done properly, wind turbines leads to laudable target, optimal reliability. At various levels, root causes analysis can assist design, operation, feasibility studies, scheduling, budgeting, and revenue allocation.

Properly integrated analysis can be modularized at any desired level, resulting in useful information to aid decision making about failure in electrical and electronic components. Factors affecting operations reliability are analyzed to evaluate the cause of breakdown and energy production stoppage or reduction. Such factors include reliability, performance, and adequacy of structures, equipment, control systems, and operating and maintenance procedures. Detailed analysis of critical structural systems and process equipment must be performed. In addition, factors affecting product quality are analyzed to reduce the potential of electrical and electronic components being manufactured outside specification. These include process control ranges, statistical sampling, and quality assurance testing and reliability testing methods. Work execution includes the identification of work to be performed, as well as the planning, scheduling, and performance of that work. This is part of quality control scenario. Continuous improvement is the process by which an organization learns from the performance of each in the process and applies that knowledge to improve effectiveness and efficiency through each process cycle. It includes proper work closeout procedure, as well as a comprehensive corrective action program in reliability community.

3.4.1 Design for Electrical Reliability

Wind turbines are subjected to different types of failures. Thus it is necessary to identify which kind of failures can be found in the real world of wind plant. Each component in the wind farm will eventually fail assuming that it has been in service for a long time. Deep understanding of the types of failures and their occurrence frequency in a fleet of turbines is important issue in reliability community. Wind turbine lifetime has been related to many factors viz. electrical equipment failure incorrect installation, inaccurate connection between systems, subsystems, components in wind turbine, faults, erroneous grounding system etc..

Moreover, human errors can take place at any instant in life cycle of wind turbine beginning with the first steps of design. Human errors can be classified into various categories viz. design, installation, assembly, inspection, operating and maintenance [98]. The failure rate is a function of thermal stress, electrical stress, device geometry, construction stress, corrosion cracking, dielectric breakdown, defective conductor tracks, all of which can lead to failures. The emphasis has been put on reliability design procedure with more attention to failure rates, failure mode, and failure data for manufacturers and suppliers to identify weak design points and failure common effects within the system and also to identify fault stages generation, discovery and correction. As mentioned earlier, since wind turbine is complex electromechanical system, several techniques viz. condition monitoring and fault diagnosis and prognosis techniques, in addition to redundancy mechanism and fault tolerant, have been attempted to increase wind farm reliability, increasing energy availability and life time service of the wind farms while reduce downtime and maintenance cost.

From reliability point of view, it is preferred to handle any fault of wind turbines without mechanical vibration sensors, which is very attractive for condition monitoring systems to collect data about healthy situation of wind turbines. Furthermore, it is difficult to install sensors especially in wind regime in addition to the reliability issues of the sensors. On the other hand, electrical signature analysis is more reliable, less expensive and speedy to detect wind turbines faults. Consequently state observers must be resorted to obtain the required information using only measured voltages and currents at WECS terminals. Condition monitoring techniques are defined around vibration analysis, oil analysis, thermography, strain measurements, acoustic monitoring, electrical effects, process parameters, visual inspection, performance monitoring and self-diagnostic sensors [99].

With regard to reliability WECS converters issues, fault diagnosis and fault tolerant operation capability have been studied in [95]. In addition, grid event/grid fault ride though, and single thread versus multithread needs comprehensive investigation. Shafiee et al. present an efficient method to improve the reliability and availability of the converter system by having at least one independent redundant converter which guarantees the system operation in case of a converter failure [100]. Although the redundant converters will increase the system?s cost, volume, and weight, the proposed cost-rate minimization model aims to simultaneously determine the optimal allocation of redundant converters and the optimal number of the converters that are allowed to fail before sending a maintenance staff to the offshore platform. Briefly the total downtime is highly influenced by all electrical components. such as transformers, cables, generators.

3.4.2 Design for Mechanical Reliability

The generator bearings and gearbox in wind turbines drive train are considered the most fragile components. One of the most important wind turbine failures is attributed to gearbox related issues. Gearbox is a mechanical device capable of transferring torque loads from a primary mover to a rotary output, typically in different relationships of angular velocity and torque. In wind turbines, the gearbox connects the low-speed shaft and the generator. Therefore, its gear ratio is generally dictated by the requirement of the generator and the angular velocity of the turbine rotor [101]. Gearbox failure rate is still high, which is around 20% of downtime of wind turbine [101]. Even if the failure of gearbox is a nuisance one, it needs a crane to handle, replacement, greasing. Crane rental, labor, economic losses will lead to expensive operations. The gearbox have to work in random loading conditions. Many factors such as friction lead to over temperature. The mechanical stresses cause shaft crack, tooth breakage, shattering and in worst cases damage the tower. Wind turbine condition monitoring is a witness that gearbox fault diagnosis is not easy task and it is important to enhance wind turbine system?s reliability. Each component in gearbox can generate vibration signals that are weak and hard to detect during early stages.

The vibration analysis is the most known technology applied for condition monitoring, especially for rotating equipment in wind turbine such as gearbox. The vibration measurement is conducted to identify the healthy situation of wind turbines using sensor or observers that are spread over the wind turbine. Operators can measure acceleration. In-depth understanding of the vibration can be achieved by analyzing the data from sensors. Frequency spectrum is evaluated using spectral analysis algorithms based on fast Fourier transform (FFT), which can provide us with critical information regarding the vibration being healthy or not.

Another one of the main failures in wind turbines is transformers, which cause long downtime. The replacement in such failure case is very expensive, hard and consumes time especially in harsh weather. Thus in some case it is preferable to be eliminated. Nonetheless, the limits of cost and voltage rating of the power electronic converter and increased losses in cables and transmission leave solid-state transformers great space for improvement before widely spread adoption. Three level converters have been recommended to connect to a network without a transformer [102].

Due to the long distance between the fleet of wind turbines and the large area of wind farms, the reliability of the entire wind farm is strongly impacted by the reliability of the cables. Cable life can be divided into stages; manufacture, storage, installation, services, and recovery. To maintain cables in service, it is clear that troubleshooting and repair procedures have to be established with reactive repair and replacement and proactive replacement. It is important to insure that these cables use quality compounds and consistently meet the specification and qualification requirements. Failures could occur while the cable is handled, installed, and operated within specifications. The effective and reliable operation of infrastructure cables and redundancies support the availability of power during failure case. There is essential need for a reliable way to terminate a cable such that it can withstand the long life service in the marine environment where the mechanical and environmental conditions are unfriendly. It is worth noting that the repair strategies play an important role in identifying overall availability [103]. In addition, low-frequency electrical noise is recognized as a very sensitive measure of the quality and reliability of electrical and electronic components [104].

How to design against failure [102]?

- Condition monitoring;
- Diagnosis and prognosis;
- Redundancy and fault tolerant;
- Collecting field data;
- Wind farm topology and architecture;
- Field experience;
- Operating environment conditions;
- Choosing components.

The decision of component choice is more complicated and is driven by a number of varied factors. Proper decision will provide excellent support and flexible solutions to meet wind farm needs, take advantage of lower costs, increases flexibility, high quality. Choosing components appear to be a daunting task with many different models and features available.

The overall purpose for the reliability analysis is to:

- Complete description about failure and its impact on components, subsystems and systems levels and revoke and prevent unacceptable impacts;
- Build a rigid safe and reliable system;
- Provide information in order to develop systems and subsystem architecture and validation design;
- Fault-tolerance or graceful degradation mechanisms viz. redundancy or backup systems at various levels of wind turbine generator to enable it to continue operating properly in the event of the failure. If its operating quality decreases at all, the decrease is proportional to the severity of the failure. Fault-tolerance is particularly sought-after in high availability of wind turbines.

3.4.3 Design for Power Electronic Reliability

The main task of power electronics is to handle energy flow between players. For example power converter provides flexible and high efficient interconnection between players on smart grid, generation, energy storage systems, transmission, distributions and loads. All these players must give grid security and safety the highest level of priority. Three important issues of concern in using a power electronic system are reliability, efficiency, and cost [105]. Power electronics for modern wind turbines has experienced a dramatic evolution in wind industry. This section focuses on state of the art main issues of introducing power electronics in modern wind generation systems. The applications of power electronics in wind turbine generation systems are greatly improving wind turbine behavior and performance.

Nowadays the reliability of power electronics is an important topic for researchers. Reliability is especially important for offshore wind turbines as the size and the number of installed WTs increases. The cost of repairing and the value of the lost energy when failure occurs can be high and sometimes disastrous for wind farm owners. The availability of modern onshore WTs is around 95% to 99% [106]. As mentioned earlier, the goal of WECS industry is to achieve extremely high reliability with zero maintenance. Very high reliability is also the main priority for offshore WTs because it consumes time, money, effort to repair them. WECS manufacturers need to consider the reliability issue when they design new power converters for turbines. By designing the power converter taking into account reliability, they can guarantee that the power converters will last long enough [107] [108], [44], [109], [110], [106], [111].

Wind farms that can produce large amounts of power are established by installing and utilizing many wind turbines. It becomes increasingly important to develop techniques that are practically useful for power electronic industries. The reliability of the wind farm whose variable speed capabilities are achieved through the use of an advanced power electronic converter. Grid power quality with variable speed wind turbines modeling and simulation techniques were presented [112], [113]. An analytical review of different stand-alone wind energy conversion systems based on possible generator types available in wind market has been reported in the literature [114]. The overview is concentrated on the variable-speed turbines. Geared-drive turbines using induction generators and gearless-drive turbines using synchronous generators were considered. The more studies now are on developing real time electronic controllers such as a DSP- and FPGA with high-speed communication interfaces.

Thus, it is possible to monitor, store, and transfer a large number of internal variables that can be sent online to local or remote hosts in order to take new set points of different generation units [115], [116]. Power electronic devices and converters topologies such as back-to-back (BTB) connected two- and multi-level voltage source converters (VSCs), BTB current source converters (CSCs) and, matrix converters [44] [117]. State of art regarding power electronic topologies and wind energy conversion systems such as PMSG, DFIG, IG and SG are discussed and some of the possible control strategies are touched upon in order to capture maximum energy transfer from the wind turbine to the grid [107]. Control techniques for wind turbines include basic control targets, active damping control and sensorless control [118], [119].

3.5 Severity Classifications

The reliability community rates the impact of security issues found wind energy generation systems using a four-point scale: minor, marginal, critical, and catastrophic. This severity scale provides a prioritized risk assessment to help understand and schedule upgrades to wind turbine systems. The scale takes into account the potential risk based on a technical analysis of the failure on system and subsystem levels.

Table 3.1: Severity of Failures Modes.

Description	**Category**	**Definition**
Catastrophic	*i*	A failure mode that causes death, WTG loss or severe environmental damage.
Critical	*ii*	A failure mode that causes severe injury, severe occupational illness, major WTG or environmental damage.
Marginal	*iii*	A failure mode that causes minor injury, occupational illness, minor WTG and environment damage, or mission degradation.
Minor	*iv*	Less than minor injury, occupational illness or less than minor WTG or environmental damage

Chapter 4

Reliability at Wind Farm Level

4.1 Introduction

Wind generation system technology is still the most promising one among the renewable energy technologies. The fast expansion of the wind power faces some problems that require focused reliability studies. The profitability and revenue of wind farms is adversely affected by poor system reliability, and hence, high maintenance costs. The effect of low reliability on turbine downtime has been seen most acute during the move to offshore wind farms. The wind energy expansion and its penetration into the power system is an important driver necessitating the consideration of wind farm reliability where wind farm is consider as a power source. For example in Denmark it is no longer possible to ignore wind farm reliability in overall system reliability studies. The approaches evaluating WF affects both planning and operation of the power system as a whole. The potential of wind farm is tremendous.

Wind system researcher?s seek and investigate solutions while considering the new technologies available for reliability in wind farm. The main reason is that the number of random variables and system complexities greatly increase when renewable energy sources are added to the system. Moreover, detailed hourly load models considering different areas and zones of the system are becoming a concern to many planners. New computational models and tools have to be developed to deal with these new time-dependent variables. To identify the critical failure modes at the component, subsystem and system scale within wind energy based on the analysis of available long term operational data and fault records logged by supervisory control data acquisition (SCADA) and condition monitoring, large data recorded from wind farms operating in different locations around the world. A typical wind farm consists of a few to hundreds of turbines installed in arrays perpendicular to the prevailing wind direction. The turbines sit on towers up to 300 feet or more to take advantage of less turbulence of air flow. The separation distance between each wind turbine unit and the other is typically around eight times the rotor diameter to minimize the wake effects. Large- wind farms is typically connected to the grid at transmission level.

The transmission system operator has to focus on the impact of wind farm on power system in terms of stability and quality. understanding of wind farm control capabilities will leads to the important knowledge of strategy that can be used to simulate the dynamic interactions between a wind farm and a power system. The power collection system in the wind farm include the electric machines, wind model and aerodynamic models for the wind turbine, transformers, transmission lines and finally, the grid. Offshore wind farms are more expensive than onshore wind farms in both installation and maintenance.

The power output of each wind turbine generator (WTG) depends on the wind with inherent variability and on the non-linear control characteristic relating the power output to the wind speed. The output power of wind farm also depends on the availability of the energy conversion devices or power electronic devices. Reliability assessment is used to account for the effects of the failure and repair processes of wind turbine generators and to evaluate the performance of the in terms of available power output.

It is well known that many large wind farms are being installed around the world for bulk power generation. Large wind farms are usually installed in locations with good wind resources, and connected to a power system through transmission lines. It is increasingly important to assess the adequacy of the transmission facility required to deliver wind power from wind farms to the loads. The wind farm power generation model can be further modified to incorporate the effect of the transmission line connecting the wind farm to the bulk electric system through transformers. The reliability of power system decreases with increasing system load. The effect of tie line unavailability on the reliability level of wind power delivery system is relatively small compared with the wind speed effect on wind turbine generators.

Integration of WFs with distribution and transmission networks raises questions regarding the reliability of the overall system and how the system reliability is influenced by factors such as the wind regime, level of penetration, load model. The wind farm reliability model should account for the variable and uncertain nature of supply and failure and repair characteristics of wind energy conversion systems, in addition to the correlation of WECS output with load requirements. It is preferred to include the load modification approach for both the peak load and base load in order to compute the system risk. The coincidence of load profile and wind speed pattern highly affects the reliability of the system [120]. Hence, appropriate policies should be considered to enhance the reliability. Translating this general insight into practical policies is very difficult. Researchers could outline reliability assuring measures from the technical aspects to facilitate policy making.

A wind farm may be modeled as a block diagram as shown in Figure 4.1. The model consists of four main parts:

- **Block a**: The model input is speed records data, which can be obtained either from wind speed measurements or from the results of simulation. In case of sequential analysis, a Monte Carlo simulation requires a wind speed time series for each sample,

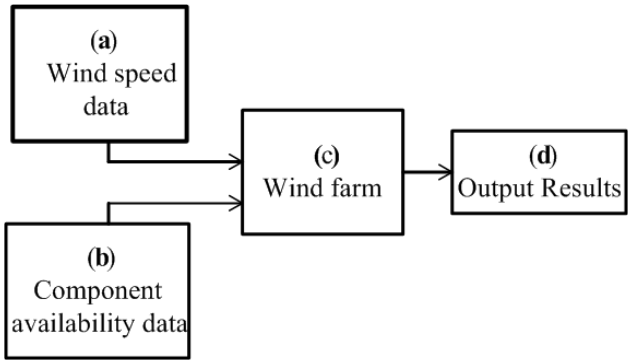


Figure 4.1 Wind Farm Block Diagram.

whereas the analytical model needs a set of statistical information.

- **Block b**: the term availability is the probability that the system is operating appropriately [121]. It is worth mentioning that the operation and maintenance strategy of the system is the main variance between reliability and availability. The system is considered highly reliable if its failure frequency is excessively low. When a failure, the termination of the ability to perform a required function of a system [121], takes place, then availability becomes very low if there is no maintenance or repair action is performed. The main three parts of this block are wind turbine, internal transmission cables and connectors to shore [37]. Each component can be up or down.

- **Block c**: lumped both (a) and (b) blocks to have the output power of the wind farm.

- **Block d**: depending on the generated output power, some indices reflect the term reliability. Examples of meaningful indices are capacity factor (CF), loss of load expectation (LOLE), loss of energy expectation (LOEE), and expected load not supplied (ELNS).

The generating units are divided into two main groups: the conventional and the unconventional unit, the conventional can be controlled, scheduled and represented by a two-state model *upanddown* or by a multistate model that includes derated states. While the unscheduled nonconventional units, i.e. WECS can be represented by several partial-output states, while the number of states depend on the type of wind data available, the nature of the wind regime, the characteristics of the wind turbine, availability of computational time and the desired accuracy [122]. The generation system consists of components viz. aerodynamic components of blade angle and mechanical coupling through shaft, generator component of generator excitation system, generator winding, circuit breaker components of switchgear and relay protection and step up transformer. It is therefore the reliability of generation system that will be affected even when any one of the component?s reliability is at risk. Thus, reliability is based on the incremental reliability of its parts. The reliability of the distribution system depends on the reliability of individual and collectively components, which follows a Poisson distribution that is a function of the failure rate and the interruption time. WECS reliability affects wind farm reliability, consequently affects distribution system reliability.

4.2 Reliability Modeling of Wind Turbine

4.2.1 Wind Source

Wind is undoubtedly the most popular source of electricity around the world. Wind energy is fluctuant, random, intermittent and non-scheduling. Wind has instantaneous, minute by minute, hourly, diurnal and seasonal variations. Reliability and cost of WECS requires simulation of long term chronological wind speed data for geographical wind farm locations. Many studies have reported statistical tests on wind speeds using different distributions, such as Weibull, Rayleigh, r_2 and so on. Weibull distribution is most commonly used to model wind speeds. It is versatile and involves a scale parameter and a shape parameter which can be adjusted to suite the wind regime under study. Using this model, the probability of wind being between any two values can be easily calculated. Weibull model for wind speeds and IEEE RTS-79 test system was employed with Power World Simulator 8.0. The Weibull probability density and the cumulative distribution functions are given as follows:

$$f_w(\nu) = \frac{\beta}{\alpha}\left[\frac{\nu}{\alpha}\right]^{\beta-1} \exp\left[-\left(\frac{\nu}{\alpha}\right)^{\beta}\right] \tag{4.1}$$

$$F_W(\nu) = 1 - \exp\left[-\left(\frac{\nu}{\alpha}\right)^{\beta}\right] \tag{4.2}$$

where α is the scale parameter provides information about the average of the wind speed profile, and β is the shape parameter of the Weibull distribution and it provides information about the deviation of the wind speed values from the mean as well as the feature of probability density function. These two values can be obtained by using analytical methods such as maximum likelihood estimator (MLE), method of moments (MOM) and least squares method (LSM). There are a number of different models that can be used to represent wind speeds in power system reliability studies. For example, observed wind speed, mean observed wind speed, ARMA, MA, normal distribution, and Markov chain models to simulate wind speeds in a generating capacity reliability study. The different wind speed models result in different wind speed probability distributions. Other wind parameters such as wind frequency, site air density, power law index, environmental, land laws and social aspects should also be taken into account in a reliability study. Wind speed profile can affect system reliability significantly.

It is well understood that wind power generation is an inconsistent and intermittent energy source. The fluctuation of wind speed depends on the location of wind farms. The power output from the wind turbine also fluctuates, which makes it necessary to study the influences of wind energy on electric network. Wind power potential is assessed by wind monitoring, wind mapping and complex terrain studies.

4.2.2 Wind Turbine Characteristics

There is a nonlinear relationship between the power output of the WECS and the wind speed. The relationship can be described by the operational parameters of the WECS. The commonly used parameters are the cut in, rated, and cut out wind speeds. The hourly power output can be obtained from the simulated hourly wind speed using:

$$P_t = \begin{cases} 0 & 0 \leq SW_t \leq V_{ci} \\ \left(A + B \times SW_t + C \times SW_t^2\right) P_r & V_{ci} \leq SW_t \leq V_r \\ P_r & V_r \leq SW_t \leq V_{co} \\ 0 & V_{co} \leq SW_t \end{cases}$$

where V_{ci}, V_r , V_{co} and P_r are the cut in speed, the rated speed, the cut out speed, and the rated power of a WTG unit, respectively [123]. A WTG produce no power if there is not enough wind energy to supply the grid. The constants A, B, C may be found as functions of V_{ci} and V_r with the following equations [124]:

$$A = \frac{1}{(V_{ci} - V_r)^2} \left[V_{ci}(V_{ci} + V_r) - 4V_{ci}V_r \frac{(V_{ci} - V_r)^3}{2V_r} \right] \tag{4.3}$$

$$B = \frac{1}{(V_{ci} - V_r)^2} \left[4(V_{ci} + V_r) \frac{(V_{ci} - V_r)^3}{2V_r} - (3V_{ci} + V_r) \right] \tag{4.4}$$

$$C = \frac{1}{(V_{ci} - V_r)^2} \left[2 - 4 \frac{(V_{ci} - V_r)^3}{2V_r} \right] \tag{4.5}$$

Thus, the power output of wind turbine can be calculated from its ?speed-power? curve. This relation is usually given by the turbine manufacturer, designated as power curve of the turbine. The individual WECS output power depends on the same primary energy source, the wind. Generally, is not necessary to assume that all the turbines in a wind farm have similar characteristics. Wind turbine power output is a function of some neglected variables such as air density, pressure, temperature [35].

4.3 Reliability Characteristics

As mentioned in [97][125], the key reliability metrics include:

- Mean availability: the average availability over time
- Failure frequency: expected number of failures per unit time at a specified time.
- Total down time: the total downtime between the indicated start and end time (t_1 to t_2).

$$TDT(t_1, t_2) = \int_{t_1}^{t_2} U(t)d(t) \tag{4.6}$$

- Expected number of failures: the total number of failures expected between the indicated start and end times (t_1 to t_2)

$$n_f(t_1, t_2) = \int_{t_1}^{t_2} v(t)d(t) \tag{4.7}$$

Some useful definitions related to reliability characteristics include:

- Availability is the probability of finding a system in the operating state at some time into the future;
- Mean time to failure;
- Mean time to repair or down time MTTR: the average time for a sub assembly to be recovered for any failure;
- Mean downtime MDT: total number of hours during which the turbine was not operational i.e includes all the time needed to restore the WECS to an operating condition;
- Time to repair TTR: actual number of hours completing the repair, excluding logistics associated with repair action such as having the component delivered to site or arranging the technicians? time;
- Mean time between failures or reliability.

$$MTBF = MTTF + MTTR = \frac{1}{\lambda} + \frac{1}{\mu} \tag{4.8}$$

The average period between unplanned stoppages of a subassembly, in the event that a failure can not be repaired immediately, there may be a logistic delay time (LDT) to carry out the repair. Then the MTBF:

$$MTBF = MTTF + MTTR + LDT = \frac{1}{\lambda} + \frac{1}{\mu} + LDT \tag{4.9}$$

where:

$$FailureRate, \lambda = \frac{1}{MTBF} \tag{4.10}$$

$$RepairRate, \mu = \frac{1}{MTTR} \tag{4.11}$$

$$A = \frac{MTBF - MTTR}{MTBF} = \frac{1 - \lambda}{\mu} \tag{4.12}$$

The power output of WF can be determined from the wind speed and wind turbine availability. It is well known that when the wind speed is either lower than the cut-in speed or higher than the cut-out speed, the output power of the turbine will be zero. for example, most WTGs are taken out of service whenever the wind speed overpasses or drops below certain values. If the wind speed is in between, rated power will be generated. The generated power can be split finite states, the number of which is arbitrary and depends on the required accuracy of the model. Then the time series of the output power is obtained.

Different types of wind turbines with different rated capacities and parameters are used in wind farms. Not all of wind turbines in a wind farm are under the influence of the same wind speed magnitude and direction at the same time. Wind energy produced can be classified into three categories: energy produced by each wind turbine units during lifetime operation, energy dispatched to the power system grid also during lifetime operation, and energy losses due to both normal operation and failures. Indeed, power production of wind turbines may be interrupted because of failure, the availability status of wind turbine should be considered when WF output is determined. In reliability analysis of a wind farm system is that each individual unit depends on the same energy source, the wind. WECS forced outage rate (FOR) is defined as the unit unavailability, that is a factor indicates in a probabilistic fashion, the degree to which mechanical or electrical failures will modify the machine's power output [126][124]. The turbine FOR has slight effect on reliability indexes, such as LOLE and LOLF indices [120]. For this aim, WECS fluctuating output power is presented by different approaches. Thereafter, the mean time to fail MTTF and the mean time to repair MTTR are evaluated. Afterward, several approaches used either analytical or simulation methods used to estimate the reliability indices of the WECS system. By measuring the availability of each wind turbines component and by recording the failure history of a unit similar to the one under study From these life history records, some statistical information are usually extrapolated. However, if first priority is accuracy then it becomes necessary to measure this failure history for a period that is long enough in order to have a significant number of samples. Then we have [127]:

$$Unavailability(FOR) = \frac{\lambda}{\lambda + \mu} \tag{4.13}$$

$$Availability = \frac{\mu}{\lambda + \mu} \tag{4.14}$$

This model is directly applicable to a generating unit which is either operating or forced out of service. Also we have [127]:

$$MTTF = \frac{1}{\lambda} \tag{4.15}$$

$$MTTR = \frac{1}{\mu} \tag{4.16}$$

$$MTBF = MTTF + MTTR \tag{4.17}$$

where:

μ : Repair rate in $repair/year$

FOR : Forced outage rate.

$MTTF$: Mean time to failure.

$MTTR$: Mean time to repair.

MTBF: Mean time between failures.

It observed that much of the sophisticated calculations for both wind variations and forced outages are important for small number of wind. The effect of forced outages will diminish as the number of turbines increases. At some point it may be possible to ignore it completely with only a small resultant error. In wind farm it will be assumed that capacity variations are only due to wind speed variations.

4.4 Reliability Indices

Optimum selection of WTG type is focused on some indices. The grid operators mostly sacrifice reliability during peak load hours or high price hours since injection wind power into the grid in peak period brings more profit to the WF owners although it compromises system security. There must be coincidence between system load pattern and wind power regime [128]. System security issues associated to the integration of wind power have been mostly important for the transmission system pperator?s (TSO). Researches must develop requirements and methods that enable wind turbines to withstand critical system events. The capacity model of the power system lumped together both WF and conventional generation.

Studying reliability evaluation is raising some numerical reliability indices. The reliability test system (RBTS) is used to examine the effects of different types of wind turbines on these indices. wind profile plays a significant role when studying WF by seasonal RBTS. For example in seasons which wind speed is quite good, the load demand is low, and on the other hand in seasons when load demand is high, wind speed is low. Thus, unfortunately annual peak load takes place in seasons when wind speed is low. Reliability analysis must shed light for RBTS that considers seasonal-hourly pattern of wind speed. The RBTS can be used in different models because it improves assessment of wind farm reliability evaluation [40]. Some of the basic indices in generating system adequacy assessment are:

- Loss of load expectation (LOLE): is the expected number of days or hours in a specified period [40].
- Loss of energy expectation (LOEE); is the expected unsupplied energy due to generating inadequacy more complex index and is a composite of the frequency, duration and magnitude of load loss [40].
- Expected load not supplied (ELNS): expected value of the load (power demand) not supplied. Hence, it is a power from the dimensional viewpoint [41].
- Expected energy not supplied (EENS): expected value of the energy not supplied by the power generation system with respect to that demanded by the loads [41].
- Loss of load probability (LOLP): probability that the loads are not supplied [41].

The performance of the wind farm was measured by the reliability indices [39]

- Installed wind power (IWP): the sum of the nominal power of all turbines of the wind farm.
- Installed wind energy (IWE): represents the energy that can be extracted in one year from the wind farm.

$$IWE = IWE * 8760 \tag{4.18}$$

- Expected available wind energy (EAWE): amount of energy that can be generated in one year without considering failure of wind turbines.

- Expected generated wind energy (EGWE): amount of energy that can be generated in one year, considering the failure of wind turbines.
- Wind generation availability factor (WGAF): similar to the load factor of conventional plants but considering the effect of the failure of wind turbines.

$$WGAF = \frac{EGWE}{IWE} \tag{4.19}$$

Besides, the capacity factor of the wind farm can be calculated without considering the effect of the failure of wind turbines, just the wind availability.

$$FC = \frac{EAWE}{IWE} \tag{4.20}$$

Generation ratio availability (GRA): an availability index, it is proposed to evaluate the electrical system of offshore wind farms (OWF). The GRA is the probability that at least a certain percent of wind power could be transferred to the grid system through the concerned electrical system. The GRA does not depend on the load demand and has weaker correlation with the wind speed in comparison with other reliability indices, such as LOLP and EENS [129].

4.5 Factors for Wind Farm Reliability Assessment

factors that influence reliability assessment of wind farm include [23]:

Wind speed randomness and variability;

Wind turbine technology and topology;

Power collection grid;

Grid connection configuration;

Offshore environment;

Different wind speeds within the installation site;

Hub height variations;

Wake effects and power losses;

Correlation of output power for different wind farms;

Effect of penetration.

4.6 Offshore Wind Farm

Nowadays, many coastal states are developing plans to build wind farms in favor of going offshore where winds are strong and land use is relatively insignificant. It can be estimated that the cost for offshore operation is ten times the cost of the same operation for on-shore wind turbine fleet [32]. In order to site an offshore wind farm, various issues need to be considered, which include: wind speeds and direction, wave heights, correlation of wind and wave data, tidal data, water depths, cable connections, closeness to load, seabed geology, adjacent shoreline use, dumping, existing shipping movements, and perdition from national and local planning authorities, again, availability of wind recourses, high speed and more uniform, homogeneous and systematic waves. Wind conditions tend to improve as the distance from shore increases. Offshore wind farms have many advantages. Minimal turbulence effect leads to increased lifetime of turbines components. The existence of an offshore substation, where the voltage level is stepped up before being transmitted to shore, depends on the size of the farm and the voltage level at the point of common coupling (PCC) which is considered as the gate between wind farm world and power system world ,that is located on land. In addition to cables between wind turbines are easily identified by fishing/traffic and have no negative impacts on wildlife. The marine environment can influence the failure rate and (MTTR) which largely increases due to tough weather conditions. In addition, noise level is not as big issue offshore WF as on land.

On the other hand, wind farms require more area per MWh than many other electricity generation technologies. High cost is associated with construction and maintenance. Sometimes the seabed is far away from the center of loads. Influence of repair time increases access time required for transport, inspection, and repair due to transport vehicle and weather conditions. Thus It is costly to send crews by helicopter or a boat to repair failures and perform scheduled maintenances in the nacelle, This work find out there are shortage in studies regarding offshore wind farm technology, suitable topology, conventional wind generator type, developed power electronic reliability design, optimization electrical component, protection and earthing systems, foundation design, marine cables, insulations, fulfillment of the requirements of the TSO?s related to system security. All of these issues must be taken into account along marine environments such as: humidity, corrosion, weather, waves, tide, sea surface, water intrusion, which are more complicated than onshore environment but no doubt it has brilliant future.

4.7 Technical Aspects of Integrating Wind Farms into Power Systems

large-scale wind farm will have significant impact on traditional power grid. So there is a need to explore power grid and wind turbine power efficiency, security and stability issues. The main aim of this section is to find the effect of the WECS penetration level. The designer decision is to match WTG and wind farm from one side with power system from another side. The decision is not only depend on reliability level but also depends on the economic parameters of the system. As a result, the total life-cycle costs installation costs, the operational and maintenance costs, plays important role to achieve high level of reliability. Due to the burgeoning and high penetration level of the wind power technology, wind farms are asked to meet grid requirements. Consequently, some grid codes have been defined or modified.

Large wind farms may contribute significant power to the grids and play an important role in power system operation and control. The term wind energy “penetration”refers to the fraction of energy produced by wind generation units compared with the total available generation capacity. In reality there is no generally accepted “maximum”level of wind penetration. The limit depends on many factors such as: the existing generating plants in service, pricing policy, capacity for storage units, system planning, load forecasting, power electronic equipments and demand management, etc. Integrating wind energy into power system grid can be challenging due to a few main issues of grid requirements that wind turbines have to meet.

4.7.1 Active Power Control

Active power control is required in order to limit overproduction of wind power that can cause grid instabilities. Since electric power varies as cube of wind speed, rate variation control requires operation at reduced output power levels during conditions when wind speed varies. The wind farms can be controlled to provide frequency response, within the limitations of the available wind power. Active power control is used to control the system frequency by changing the power injected into the grid. The reliable operation and balance on the transmission system is maintained by use of the system frequency. Frequency in the power system is an indicator of the balance between production and consumption or between supply and demand. For the normal power system operation, the frequency is close to its nominal value. Wind turbine technologies allow its participation in frequency regulation. For both cases, controls for providing response against high frequency are effective and are enhanced by the intermittency of the wind. On the contrary, controls for providing low frequency reserves may be negatively impacted by wind variations. One of the best ways to improve the situation is to effectively utilize the speed of response of energy storage technology such as batteries, pump storage, fuel cells and fly wheel. Fast frequency response services can stabilize the grid and can provide more reliable reserves to low frequency events. In conventional generating units, the reliable operation of frequency control is normally provided by fast autonomous control of individual turbine generators through governor control, automatic generation control (AGC).

4.7.2 Reactive Power Control

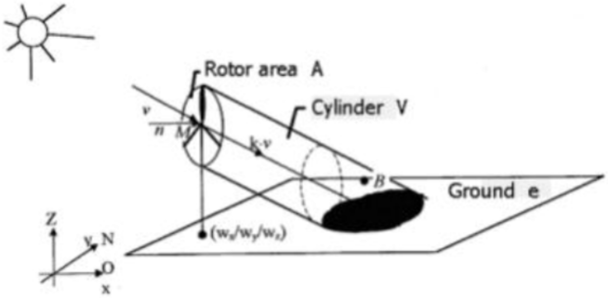
As mentioned earlier, when wind speeds go below or exceed certain values or systems go under certain severe disturbances, wind farm could lose grid synchronism. Consequently both real power and reactive power are lost. Reactive power is used in order to keep the voltage within the required limits and avoid voltage collapse. Wind generation should also contribute to voltage regulation in the system. One of the big challenges is that due to high penetration level of wind farm in power system the disconnecting of wind farm during short circuits faults or grid instability presents, a big risk for the system stability. Therefore,the provision and planning of reactive power become extremely important. New regulations require that wind farms remain connected during a line voltage fault and participate in recovery from the fault. Since wind turbines are responsible to improve load performance, they must be able to supply reactive power. Traditional approaches to managing reactive power are no longer acceptable[105]. The reactive power can be controlled in wind turbines with PWM converters. Various dynamic reactive devices such as static var compensator or synchronous condenser, are used for grid consolidation where dynamic voltage support is required.

4.7.3 Voltage Flickers

In wind power plants voltage fluctuation is highly expected [29] [130]. Lack of power quality causes a consumer inconvenience and complaints. Wind farms connected to weak power system grid have pronounced voltage flicker, which is embodied by the fluctuation of voltage amplitude due to wind gusting nature and tower shadow is a source of power fluctuation at the frequency at which the rotor blades pass the tower. Also variation of active power and reactive power at the PCC with the grid gives rise to flicker. The wind turbine operating point and the Q-P characteristic of the generator determine the point of minimum flicker emission.

The flicker phenomenon is evaluated by the flickermeter, described in IEC $61000-4-15$ [131]. High capacity wind turbines cause serious flicker problem, which leads to short the life span of wind farm electrical and electronic equipments. The flicker is influenced by the grid strength and X/R ratio of grid internal impedance. The rotating wind turbine blades through constrained can cast shadows to the windows of neighbouring properties, a phenomenon known as shadow flicker, which has been used by some wind farm opponent groups as a reason for impeding new developments as shown in Figure 4.2 [132].

Where Shadow Flicker Falls



(from *Update of UK Shadow Flicker Evidence Base*)

Figure 4.2 Shadow flicker evidence base.

4.7.4 Harmonics

Harmonics is one of the power quality issues of wind farms. Knowledge of the wind farm harmonic pollution behavior is fundamental to study the influence of these farms on network harmonic distortion. The assessment of the wind farm harmonic spectrum and the analysis of the influence of operating point in WECS are very important. The combination of wind turbines and power electronics excite voltage distortion in networks [133] due to the low switching frequency of high power converters, control system imperfection, generators and transformers nonlinearities [134]. Harmonics measurement procedure for individual WECS is described in IEC 61400−21 [135]. The harmonic currents summation of individual wind farm units are used for harmonic emission evaluation in wind farms [135]. It is worth mentioning that there are few studies that apply both probabilistic and deterministic techniques to actual wind measurements.

4.8 Wind Farm Topologies

The wind farm is characterized by a specific number of turbines simultaneously connected the power system without sacrificing. Turbines interconnection within a wind farm is based on AC or DC topologies. A suitable topology and voltage level of the offshore network should be chosen for optimal efficiency, reliability, maintainability and cost effectiveness. The total power produced by wind farm as a whole, the power produced by each individual wind turbine, and the distance to shore and the individual distance between each wind turbine are the main factors that are considered in designing wind farm topology.

4.8.1 AC Topologies

1. AC radial connection: The radial connection system is widely spread and it is considered as the simplest way of connection where a number of turbines are connected to the same feeder. Subsequently, many different feeders are connected together at a substation that collects power from the entire farm. The system voltage is stepped up and transmitted to the grid. The main features are low cost and simple control.

On the other hand, high losses and lack of redundancy, poor reliability are the main disadvantages.

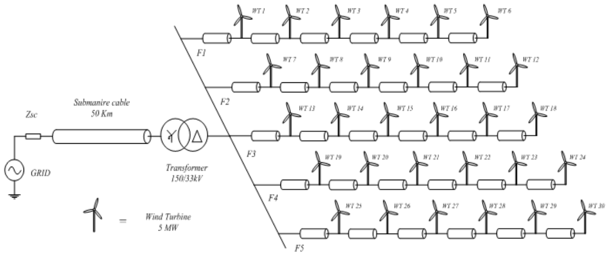


Figure 4.3 AC redial system. [1]

2. AC single-sided ring: A number of turbines are connected to the same feeder from the both ends, which means one more cable is connected from the last turbine in a row. This cable should be able to carry the cumulative power. Although it is more expensive, the single-sided ring topology will have less losses and be more reliable.
3. AC radial loop connection: In this connection, the power generated in a faulted feeder may be supplied by the rest of feeders. The main features are high degree of reliability and low losses, although it is considered having high cost. The control system could be complicated depending on number of switches and their locations.

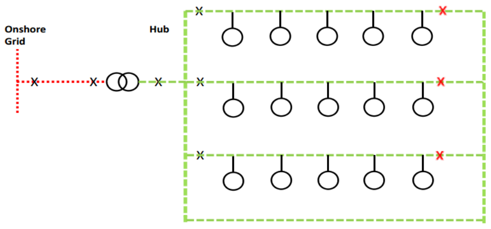


Figure 4.4 AC redial loop system. [2]

4. AC star/cluster connection: Each turbine is connected to the point of interconnection

of star point in this topology. The advantages is cable rating is equal to turbine current rating connected to it. The main pros are high level of security due to complex control and protection for each arm. Each wind turbine has its own connection to the platform. Conclusion around cost can not be drawn unless each case is studied separately. In some cases of star connections multiple clusters are required in order to reduce cabling construction cost.

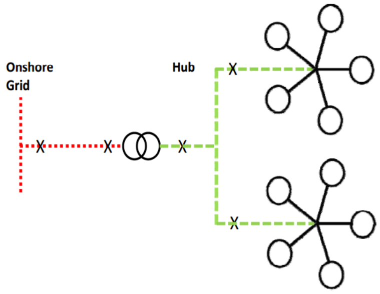


Figure 4.5 AC star system. [2]

4.8.2 DC Topologies

The core idea of DC topology wind farms is to raise the voltage to connect directly to transmission lines without converter station by series connection of WECS. The reason behind sizing the ratings of DC wind turbines is to gain features in terms of efficiency of DC and reduce losses through eliminating large converter stations offshore. Because it is attainable for maintenance and repairs and it has highly secure connection [102]. The common DC topologies include the following:

1. DC radial connection: This topology satisfies that, the turbine output power is either MVDC or AC and is transmitted as HVDC.

2. DC series/daisy chain connection: In this wind farm connection, the accumulative

DC is obtained by series connection of turbine outputs in order to increase voltage to transmission level.

3. DC series-parallel connection: In this topology, wind turbines are first connected in daisy chain connection. In addition, a certain number of series connections are connected in parallel in order to increase wind farm capacity power.

Based on field experience, the radial system connection is the best among the others and most popular due to relative low losses and cost without sacrificing reliability [37]. If the first priority is cost, then the wind farm owner may choose dc series topology. AC redial topology outperforms others in terms of is better [136]. As a general comparison between dc and ac options, more advantages are gained by selecting a dc series topology, which is based on both reliability and cost. The cost calculation includes both equipments and installation and neglected other factors such as taxes, interest rates and so on.

4.9 Wind Farm Losses

Losses in general depend on load flow calculation. in wind farms, the losses will vary with wind speed [137] and can be divided into two main groups; turbine losses, and collection and transmission system losses. The turbine losses in turn can be divided into generator, converter and transformer losses while the collection system losses consists of ohmic losses. The transmission losses include the offshore converter and transformer losses along with the transmission cable losses. Electrical and control system losses play a relevant role in the assessment of output power, depending on size and design of the wind farm. These two elements reduce the total output of the wind farm and they might be included in a complete model. The simplest solution uses an efficiency coefficient which depends on wind direction, number of wind turbines, their spatial arrangement and power collection grid design. If planners of energy limited systems want to exploit current systems to their maximum capacity and extend the use of system components beyond their useful life, they must be aware of losses calculations since cables insulations which affect reliability. Thus a detailed modeling is required because the results obtained using a simplified one are more conservative and could indicate the need of system up grading before necessary.

Factors affecting the choice of voltage level are:

1. Operational costs;
2. Capital costs;
3. Voltage insulation;
4. Converters;
5. Networking factors and cable lengths.

4.10 Challenges

The integration of wind power farm into the grid faces some challenges from both operation and security aspects such that:

1. Tripping in transmission lines because of faults single phase and three phases;
2. Varying wind speed cause output voltage fluctuations;
3. Lack of control voltage regulation;
4. Inability to control active power production;

5. Shortage of reactive power control;
6. Maximum power transfer where power electronics that play important role may limit the power extraction. At the same time, the power electronics helps protect the source from sudden load changes;
7. Power quality
8. Harmonic distortion must be remedied by control algorithm such as resonant filter;
9. Lack of historical records data for wind resources.

4.11 Operation and Maintenance Planning

In MIL-STD-721 maintainability is defined as the measure of the ability of an item to be retained in or restored to specified condition when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources, at each prescribed level of maintenance and repair. Recently many studies are devoted to identify the optimal OM strategies that will overcome the high cost of unexpected failures. The maintenance costs amount to around 30% of the total energy generation cost [136]. Therefore, researchers must shed more light on maintenance definitions, procedures and developments. Generally, OM planning might be classified into four categories: corrective maintenance, preventive maintenance, predictive maintenance, and proactive maintenance.

- Corrective OM (COM) is performed after the failure event has been observed. It is referred as reactive, breakdown, repair, fix-when-fail, or run-to-failure (RTF) maintenance. It may include one or some or all of this group localization, isolation, disassembly, exchange, reassembly, alignment, checkout. The main pros are low maintenance cost during operation and maximum life use of components while the main cons are consequential damges cause extensive downtimes.

- Preventive OM (POM) is implemented while the failure event is not observed. It may include one or some or all of this group regularly scheduled inspection, adjustments, cleaning, lubrication, parts replacement, calibration, and repair of components and equipment. The main pros are downtime is not long, scheduled process, while the main cons are expensive.
- Predictive maintenance or condition-based, maintenance activities comprise equipment tests based on the use of on-line and off-line sensors and tests. It uses primarily non-intrusive testing techniques, visual inspection, and performance data to assess machinery condition. Data collected are used in one of following ways to determine the condition of the equipment and identify the precursors of failure. The methods of analysis include trend analysis, pattern recognition, data comparison, tests against limits and ranges, correlation of multiple technologies, statistical process analysis.
- Proactive Maintenance is designed to extend the life of machinery as supposed to:
  - Doing repairs when often nothing is broken;
  - Accommodating failure as routine and normal;
  - Preempting crisis failure maintenance.

Further, POM might be performed based on usage age, periodically scheduled, condition based and risk based maintenance strategies. To determine an optimal OM strategy, the objective functions should be determined by minimization or maximization during the service life or infinite time horizon, subject to the model limitations. Objective functions to be minimized might be defined based on costs or downtimes, whereas objective functions to be maximized could be defined based on profits (benefits) or availabilities.

Chapter 5

Real-Time Optimization of Thermal Cycling Capability of Rotor Side Converter in DFIG-Based WECS

5.1 Introduction

Reliability is the probability that a component will satisfactorily perform its intended function under given operating conditions [138]. The average time of satisfactorily operation of a system is called the mean time between failures (MTBF) [138] and the higher value of MTBF indicates higher reliability and vice a versa. Nowadays, reliability is more of concern than in the past especially for offshore wind turbines since the access to offshore wind turbines in case of failures is both costly and difficult [3]. Power semiconductor devices are often ranked as the most fragile components in a power conversion system [139]. The lifetime prediction of power IGBT modules based on mission profile is an important issue. Furthermore, lifetime modeling of future large wind turbines is needed in order to make reliability predictions about these new wind turbines in the early design phase. By conducting reliability prediction in the design phase a manufacture can ensure that the new wind turbines will operate within designed reliability metrics such as lifetime.

This work presents reliability analysis of power electronic converters for wind energy generation systems based on semiconductor power losses as well as aims to maximize semiconductor lifetime using low-pass-filter (LPF) based control scheme since MTBF will be higher than with filter. The fundamental cause to achieve higher MTBF lies in the reduction of to reduce the number of thermal cycles.

The key element in a power conversion system is the power semiconductor device, which operates as a power switch. The improvement in power semiconductor device is driving a critical force behind the improved performance, efficiency, size and weight of power conversion systems. As the power density and switching frequency increase, thermal analysis of power electronic system becomes imperative. The analysis provides information on semi conductor rating, reliability, and lifetime calculation. A comprehensive thermal model for power IGBT is developed in three steps [140]: *i*) the power losses are calculated [141],[142]; *ii*) the junction temperatures are evaluated [143], [51]; [144], [145], [52], and *iii*) the lifetime is estimated [49], [50].

5.2 Physical System Modeling

5.2.1 Wind Turbine Characteristics

Mapping a mission profile in wind power applications involves multiple time constants. The time constant range from short term in electrical components, to medium term in mechanical components, to long term in wind speed and much longer term in system reliability. Wind turbines capture power from the wind by means of aerodynamically designed blades and convert it to rotating mechanical power. The number of blades is typically three in a modern wind turbine. For multi-MW wind turbines, the rotational speed is typically $10-15\,rpm$

. The most weight efficient way to convert the low speed, high torque mechanical power to electrical power is to use a gear box and a standard generator with a power electronic interface. The energy produced from the wind turbines converting and depends on wind speeds. At low wind speeds around $1 - 3\,m/s$ the wind turbine will not function. At "cut in wind speed"$2.5 - 5\,m/s$ the wind turbines will start. The wind speed range of about $12 - 15\,m/s$ is called the "nominal or rated wind speed", with wind turbines working on their full range. At high wind speeds over the cut out speed $25\,m/s$, the wind turbine will be stopped due to potential damage to the wind turbines blades and tower structure. The output power P_m is dependent on the power coefficient C_p . It is given by [146]:

$$P_m = \frac{1}{2}\rho R^2 \upsilon^3 C_p(\lambda, \beta) \tag{5.1}$$

and the tip speed ratio is defined as:

$$\lambda = \frac{\omega_t R}{\upsilon} \tag{5.2}$$

where ρ is specific air density; R is radius of the turbine blade, υ is the wind speed. ω_t is turbine rotational angular; C_p is the coefficient of power conversion and β is the pitch angle. The power coefficient $C_p(\lambda, \beta)$ is further expressed as [146]:

$$C_p(\lambda, \beta) = c_1 \left(\frac{c_2}{\lambda_1} - c_3\beta - c_4 \right) e^{\frac{-c_5}{\lambda_1}} + c_6\lambda \tag{5.3}$$

where the coefficients c_1 through c_6 depend on the shape of the blades and its aerodynamic performance of wind turbine. And λ_1 is defined as:

$$\frac{1}{\lambda_1} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{5.4}$$

5.2.2 Doubly-Fed Induction Generator

The DFIG is considered as one of the most popular topologies applied in WECS. Its main advantage is to adjust the speed of large system with power converters of a third of full rating. This is because its RSC operates under slip frequency. Only needs to support slip power to the overall system. The semiconductor power devices such as insulated gate bipolar transistors (IGBTs) in the RSC and grid side control (GSC) are susceptible to power cycling caused. DFIG configuration allows for controls from rotor side as well as stator side.

The wind turbine rotor is connected to the generator via gearbox. The rotor of the DFIG is fed by back-to-back voltage source converter (VSC). The generator speed corresponding to rated wind speed can be set at any point by the choice of gear box ratio. The back to back configuration allows for independent control of the RSC and the GSC due to the decoupling provided by the dc-link capacitor. The RSC operates the speed and torque of the generator while the GSC controls the active and reactive power injected to the grid. An offshore wind farm equipped with power electronic converters can perform both active and reactive power control. It operates the wind turbines in variable speed to maximize the energy captured. Besides it reduce the mechanical stress and acoustical noise.

The overall control structure of a DFIG consist of cascaded control loops: inner control loop and outer control loop as shown in Fig. 5.1. The inner loop provides adequate decoupling between active and reactive powers. The designed control laws are to track the power command of in the wind generator. The outer loop, the error signals feeding its PI controllers

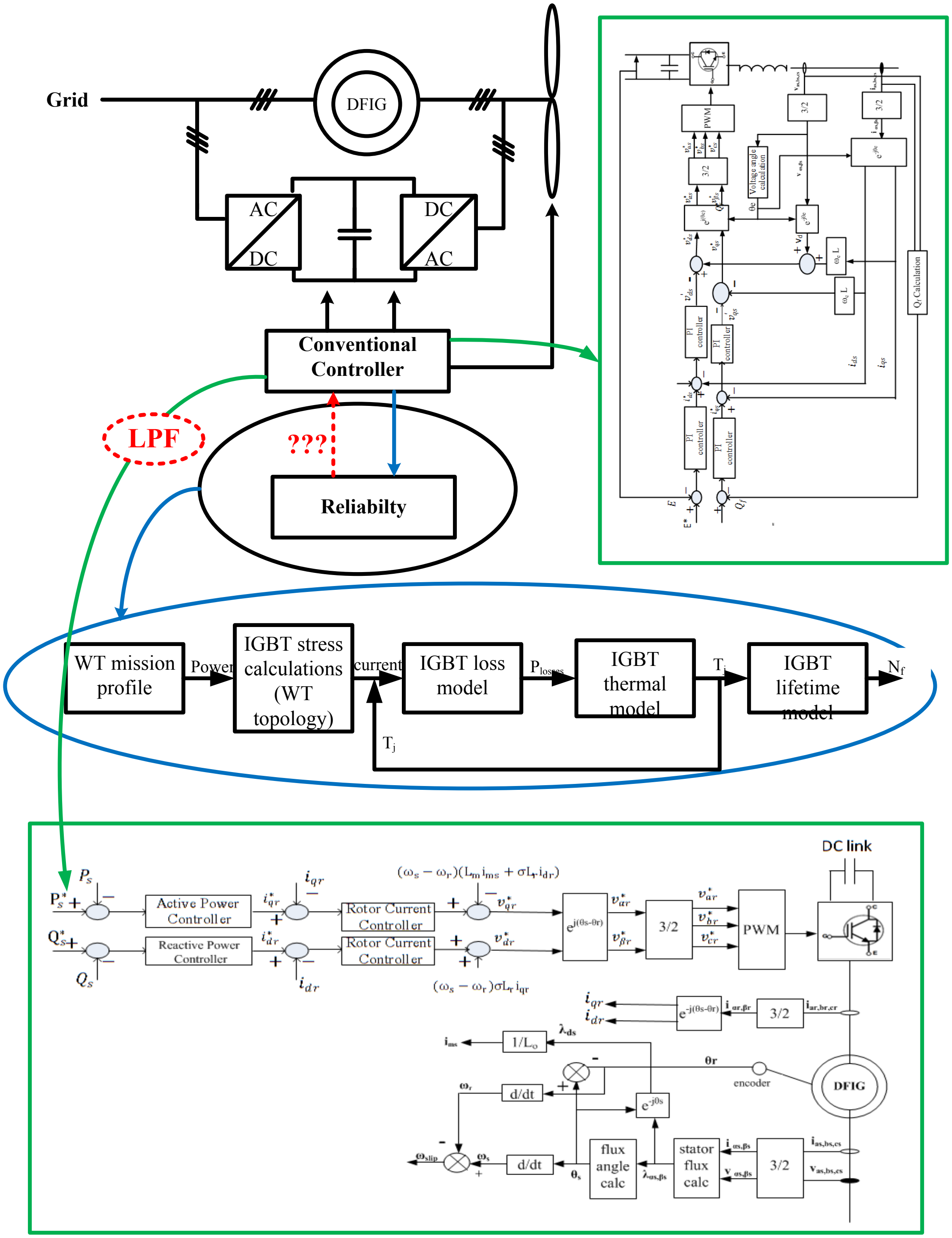


Figure 5.1 System under study. [3][4]

are obtained by subtracting the reference powers $P_{s_{ref}}$ or $Q_{s_{ref}}$ from their actual values P_s or Q_s. The following equations describe the dynamic model of DFIG [147]:

$$v_{ds} = r_s i_{ds} + \frac{d\lambda_{ds}}{dt} - \omega\lambda_{qs} \tag{5.5}$$

$$v_{qs} = r_s i_{qs} + \frac{d\lambda_{qs}}{dt} + \omega\lambda_{ds} \tag{5.6}$$

$$v_{dr} = r_r i_{dr} + \frac{d\lambda_{dr}}{dt} - (\omega - \omega_r)\lambda_{qr} \tag{5.7}$$

$$v_{qr} = r_r i_{qr} + \frac{d\lambda_{qr}}{dt} + (\omega - \omega_r)\lambda_{dr} \tag{5.8}$$

$$\lambda_{ds} = L_s i_{ds} + L_m i_{dr} \tag{5.9}$$

$$\lambda_{qs} = L_s i_{qs} + L_m i_{qr} \tag{5.10}$$

$$\lambda_{dr} = L_m i_{ds} + L_r i_{dr} \tag{5.11}$$

$$\lambda_{qr} = L_m i_{qs} + L_r i_{qr} \tag{5.12}$$

$$T_e = \frac{3}{2} p L_m (i_{qs}\, i_{dr} - i_{ds}\, i_{qr}) \tag{5.13}$$

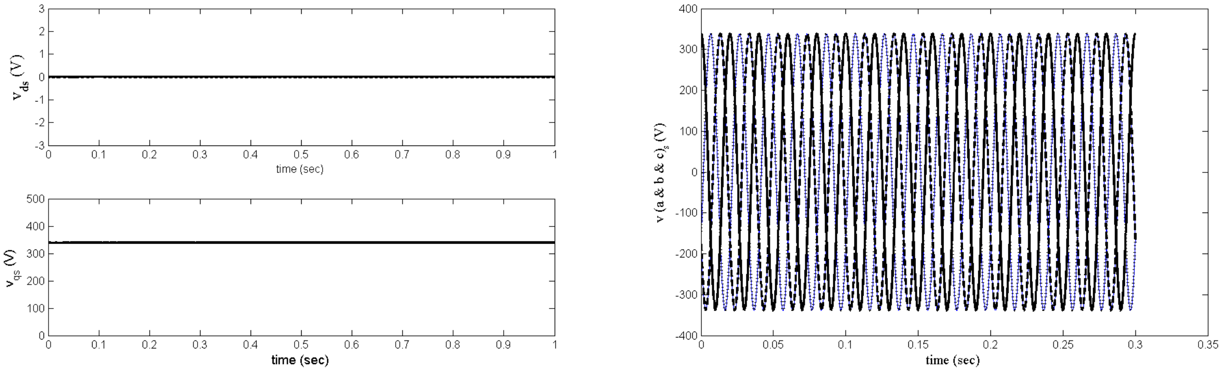
where:

$$L_s = L_{ls} + L_m \tag{5.14}$$

$$L_r = L_{lr} + L_m \tag{5.15}$$

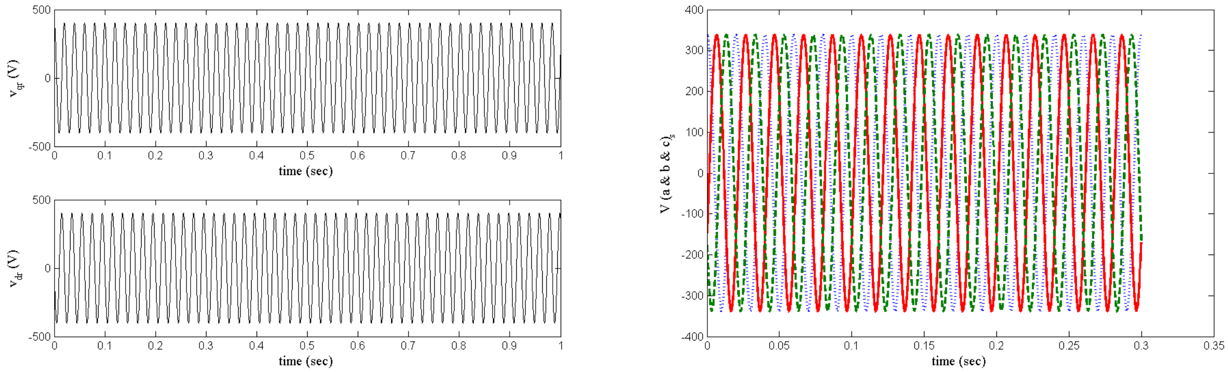
The parameters of the system under analysis are listed in Table 5.1.

The model of DFIG has been built from scratch. Figure 5.2, show the *DFIG* performance in stationary, synchronous and rotor reference frames.



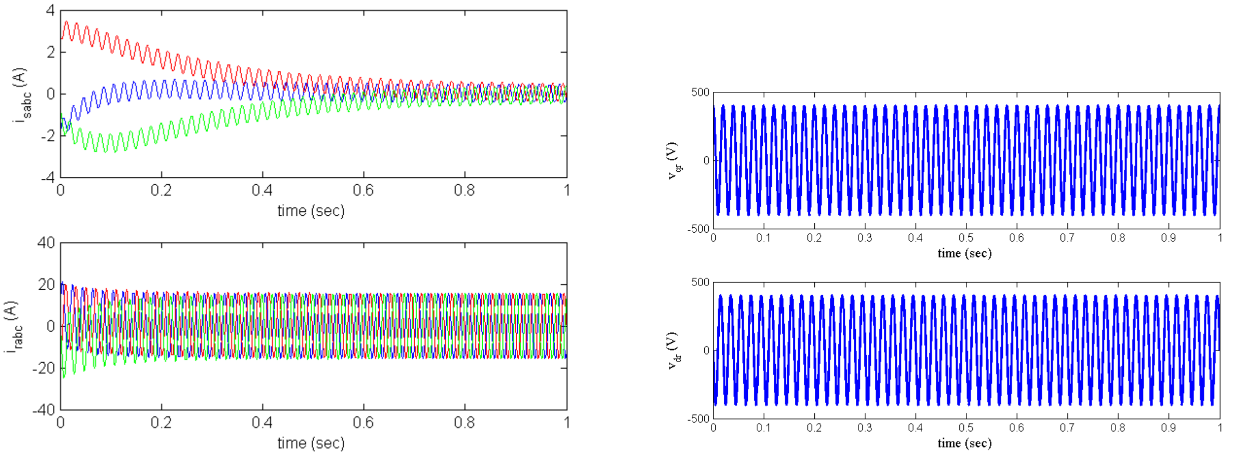
(a) V_{ds} & V_{qs} in synchronous reference frame.

(b) $Vabc_s$ in synchronous reference frame.



(c) Vqr & Vdr in rotor reference frame.

(d) $Vabc_s$ in rotor reference frame.



(e) $I(abc)_s$ & $I(abc)_r$ in rotor reference frame.

(f) V_{qr} & V_{dr} in stationary reference frame.

Figure 5.2 Variables of three phase DFIG in stationary, synchronous and rotor reference frames.

Table 5.1: DFIG Electrical Parameters

Power, P_n	7.5 KW
Stator Voltage, V_n	415 V
Frequency, f_n	50 Hz
Stator winding resistance R_s	1.06 Ω
Stator winding inductance L_s	0.2065 H
Rotor winding resistance R_r	0.8 Ω
Rotor winding inductance L_r	0.081 H
Magnetizing inductance L_m	0.0644 H
Inertia J	7.5 kgm^2
Pole pairs	3
Rated speed	970 rpm

5.2.3 Averaged Model of *(PWM) converter*

The averaged model of three-phase back-to-back PWM converter is widely adopted in practical engineering because it is suitable and efficient for simulation of control system. It is mainly used to replace the switching circuits in simulation environment to reduce the computational complexity. The small signal model for controller design are conventionally derived from the average model. In the meantime, the averaged model is suitable for evaluation of power losses of a converter.

One of the commonly adopted approach to formulating the average model of the system is to replace the instantaneously switched regions within average models. The average model of the switches is typically represented by the controlled current and voltage source with the duty ratio or modulation function as a control input. In averaged circuit model, the complexity is reduced and leads to faster time-domain simulation while adequate accuracy of the system dynamics is still maintained. Furthermore, over-modulation, saturation effects amongst other non-linearities can also be properly modeled. Although the average model is not suited for analysis of switching frequency ripple, It is suitable for evaluation of the power losses of the system under various loading conditions.

5.3 Electrothermal Modeling and Lifetime Estimation of the Voltage Source Converter for Wind Turbine

The power loss model [148] has been successfully built to perform the thermal analysis. The model is based on look up table that includes both the switching and conduction losses. The model parameters of the thermal network are extracted from the data sheet ABB HiPack IGBT Module 5SNE 0800M170100. The exact modeling approach describes a converters as a time varying system. It is typically not applicable for control design purpose, because they are difficult to analyze and impractical for the simulation of the relatively large systems. In addition, simulation time steps have to be much smaller than switching period, which leads to a very computationally expensive simulation. Thus, an averaged model is more suitable for electro thermal simulation. It can be used to calculate the semiconductor losses at any output current waveform. In addition, it can be parameterized with conventional data sheet information. For calculating the instantaneous junction temperature of the semiconductor device under junctions at different load conditions a thermal model of the inverter sub-system is necessary. A straightforward approach is to use a network of thermal capacitance C_{th} and thermal resistance R_{th}. Such networks are readily implemented in various programming or simulation environments.

The procedure for calculating the estimated lifetime for semiconductors devices in WECS is illustrated in Fig. 5.3. Lifetime estimation starts from power losses calculation which is based on the lookup table method. An equivalent RC network model has been built to perform the thermal analysis. The junction temperatures and thermal cycle counts can be accordingly determined. The lifetime is subsequently predicted according to Miner's rule [149]. The real time simulation environment dictates the requirements for the models. Easy implementation on the software platform Simulink/Matlab and fast calculation time.

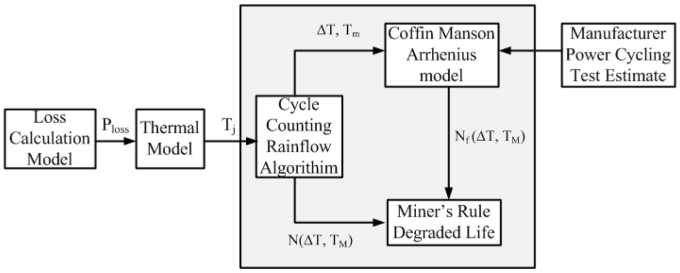


Figure 5.3 Lifetime estimation model for power semiconductor devices. [5]

5.3.1 Power Losses of IGBT in the RSC

There are three types of losses in power devices: conduction losses, switching losses, and gate losses. Increasing the switching frequency will increase switching losses. Switching losses typically dominate total power losses in high switching-frequency PWM converters. The gate losses is left out as it is insignificant as compared to the switching and conduction losses of the main power circuit. The current and voltage transient waveforms are not always available, which are necessary is a prerequisite for computing the power losses. Therefore, simulation and analytically solutions become important.

Different approaches for the calculation of switching losses have been published in literature. If the necessary parameters with temperature dependencies are known. the switching losses can be estimated by piecewise approximation of the transient current and voltage waveform in the semiconductors [142],[148]. There are numerous other methods used to estimate the switching losses, such as exponential or polynomial approximation functions with parameters empirically obtained or extracted from data sheet.

The method used in this study is based on lookup tables usually the manufacturer of power semiconductor devices provide the transient thermal impedance curve or table for the IGBT and diode inside a module.

$$P_{IGBT} = P_{cond} + P_{sw} \tag{5.16}$$

In power converters IGBT, the conduction losses depends on three parameters: the current through the device I_c, the on-stage voltage across it V_{CE}, and the junction temperature T_j. Using the DC characteristics extracted from experiment or simulation, the on-stage voltage V_{CE} can be expressed as a function of the current through the device I_c, which leads to the conduction losses expressed as:

$$P_{cond} = f(I_c, T_j) \tag{5.17}$$

For switching losses, it is assumed and verified that the switching energy losses linearly depends on the switched current. The dependency of the switching losses on the DC link voltage V_{DC} and the junction temperature T_j, can be extracted from experimental data or simulation results. In general, the empirical relation between the switching losses and three parameters can be found by curve fitting methods [51],[52].

$$P_{sw} = f(I, V_{DC}, T_j) \tag{5.18}$$

A fast simulation model for estimating power losses of a three phase converter has been proposed in this paper based on average model. Larger simulation time steps allow for power losses and thermal performance of an converter to be predicted over long periods time. This simulation methodology brings together accurate models of the electrical systems performance. The speed up is obtained by simplifying the representation of three phase converter at the system modeling stage using large time step of 100 s.

Losses in IGBTs:

Turn on loss:

> Pre-switching value of the voltage across the device, post switching value of the current flowing into the device, and the junction temperature are used to determine the energy loss with the help of 3D lookup table,this energy is converted into a power pulse which is injected into a thermal network.

Turn off loss:

> Pre-switching value of current flowing into the device, post switching value of the voltage across the device, and the junction temperature are used to determine the energy loss with the help of a 3-D lokup table. This energy is converted into a power pulse which is injected into the thermal network.

Conduction loss:

> Value of the current (I_c) flowing in the device and its junction temperature determine what would be the saturation voltage (V_{ce}) across the IGBT using a 2-D look-up table. The V_{ce} is then multiplied by I_c to obtain the losses which are injected into the thermal network.

5.3.2 Thermal Modeling Technique

In literature review, different approaches have been used to perform thermal analysis. They include analytical, numerical and behavioral models. In particular applications, the IGBT modules in power converter are mounted to heat sinks that are air or liquid cooled. Conduction among different layers of materials is the main mechanism of heat transfer although the heat generated inside the IGBT module can also dissipated by convection or radiation.

Analytical methods have long been used in thermal analysis to predict the operating temperature of semiconductor devices. These methods provide better physical insight by use of physical model. Various assumptions for the boundary and initial conditions are made in order to solve the heat conduction equation [145]. Numerical methods are alternatively employed for thermal analysis. Finite element method (FEM), or finite difference method (FDM) are used for discretization of the differential equation for heat conduction. Computational fluid dynamic (CFD) is used to solve the equations governing the conservative of mass, momentum and energy [144]. RC ladder networks are commonly adopted for thermal analysis, since they are readily to be integrated into existing circuit simulator and are capable of simulating both electrical and thermal characteristics circuits. RC thermal model is selected in this study for real time simulation due to its easy implementation and reduced computational complexity [143]. An RC thermal network for IGBT is built as shown in Fig. 5.4 and Table 5.2.

Table 5.2: IGBT thermal characteristic values.

i	1	2	3	4
$R_i(K/kW)$	15.2	3.6	1.49	0.74
$\tau_i(ms)$	202	20.3	2.01	0.52

Once the power dissipated in IGBT power converter has been obtained, this power is used as the exciter current source in a thermal model built to estimate the junction temperature of operational IGBTs. The thermal model will be incorporated in a real time simulator. The values of the thermal impedance would be extracted from the dynamical thermal impedance curve from experiment, simulation, manufacturers' data sheet. The model adopted in this paper co-simulates the thermal and electrical performance of the system. The temperature of the device varies according to real-time operating. The electro-thermal model has been built in three steps: *i*) the electronic model of the device is developed; *ii*) the thermal model is built; and *iii*) a coupling between the two models is established. The coupling can be implemented by setting the temperature in the electrical models as the state variable. The device's temperature is determined by integration in each simulation step. Self heating effect is taken into account through temperature dependent parameters that are modified by the device's operating temperature. The Foster network is usually referenced in data-sheets.

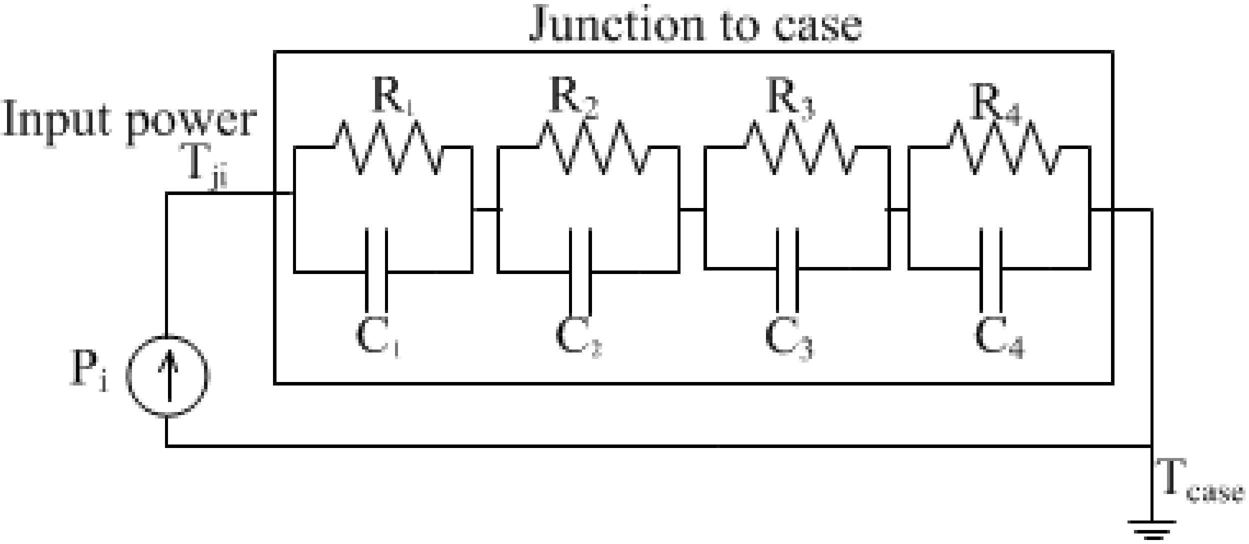


Figure 5.4 Foster Thermal Impedance Between the Junction Temperature and Case Layer.

The operating temperature plays a major role for performance and reliability of semiconductors devices. As a consequence It is not surprising that the safety margin or reliability of a semiconductor devices decreases as the temperature increases. By use of the power losses as current source value in the circuit, the junction and case temperature can be determined from the corresponding node voltages. In frequency domain, the power losses and the temperatures are related by the thermal impedance expressed as transfer function as in (5.19).

$$Z_{thermal} = \frac{\Delta T(s)}{P(s)} \tag{5.19}$$

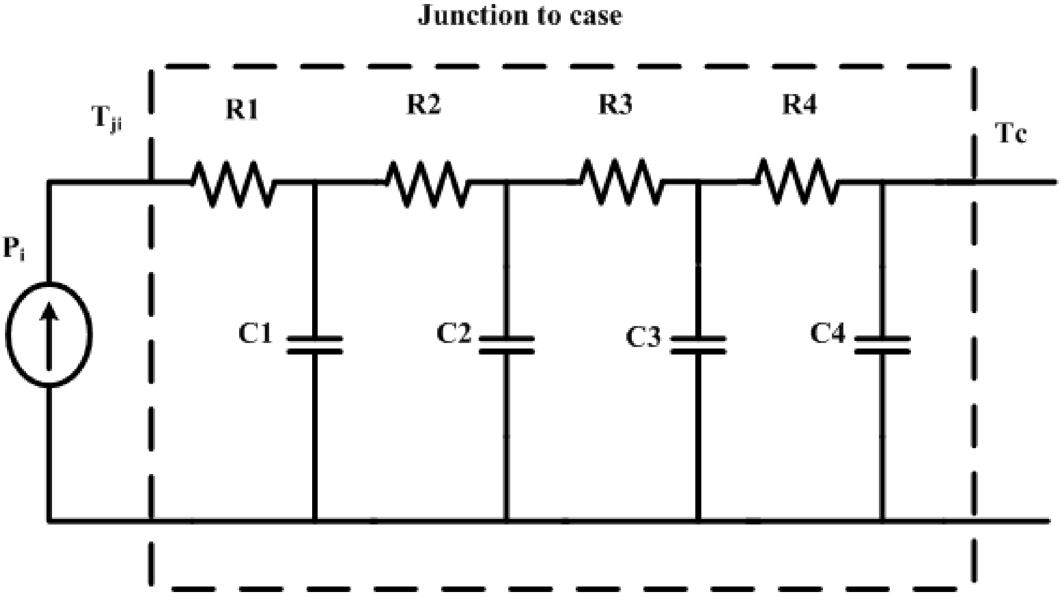


Figure 5.5 Cauer Thermal Impedance Between the Junction Temperature and Case Layer.

Table 5.3: Thermal Electrical Analogous Quantities

Analogous Quantities	**Thermal**	**Electrical**
Through Variable	Heat transfer rate, P, watts	Current, i, amps
Across Variable	Temperature, T, K or C	Voltage, V, volts
Dissipation Element	Resistance, R_{th}, $k/watt$	Resistance, R, ohms
Storage Element	Capacitance, C_{th}, $sec.watt/k$	Capacitance, C, farads

The thermal RC circuits for IGBT and diode are built, using the power losses as current source value in the circuit, the junction and case temperature can be determined for corresponding node voltages. In the frequency domain, the power losses and the temperatures are related by the thermal impedance expresses as transfer function as in equation **??**

$$Z_{th(j-c)}(t) = \sum R_i(1 - e^{-t/\tau_i}) \tag{5.20}$$

$$\tau_i = R_i.C_i \tag{5.21}$$

where P is the power losses and T is the temperature. In the simulink, if the input signal and output signal can be expressed as transfer function as the form shown in equation 5.23, the output can be obtained by connecting input signal to the transfer function block:

$$H(s) = \frac{y(s)}{u(s)} \tag{5.22}$$

$$= \frac{num(s)}{den(s)} = \frac{num(1)S^{nn-1} + num(2)S^{nn-2} + ... + num(nn)}{den(1)S^{nd-1} + den(2)S^{nd-2} + ... + den(nd)} \tag{5.23}$$

where nn and nd are the number of numerator and denominator coefficients, respectively, num and den contains the coefficients of the numerator and denominator in descending powers of (s), our goal is to find the coefficients in equation 5.23 based on RC thermal circuits for IGBT and diode. Thermal resistor (RC) networks widely used for thermal analysis, the transient thermal impedance is defined as time t as:

$$Z_{jc}(t) = \frac{T_j(t) - T_c(t)}{P} = \frac{\Delta T_{jc}}{P} \tag{5.24}$$

$$Z_{jc}(t) = \sum_{i=1}^{n} \gamma_i. \left(1 - exp\left(\frac{-t}{\tau_i}\right)\right) \tag{5.25}$$

The transient thermal impedance curve is a step response curve with zero initial conditions. It is well known that the step response of a linear system contains the full description of the system. Before extracting of thermal RC networks's, the curve fitting method is applied to the experimental transient thermal impedance data which resulting in finite series of exponential terms that are provided by manufacturer as in equation 5.25. The transfer function (input impedance) of the thermal RC network is founded by applying laplace transform to 5.27.

$$Z_{jc}(C) = \sum_{i=1}^{n} \frac{\frac{\gamma_i}{\tau_i}}{s + \frac{1}{\tau_i}} \tag{5.26}$$

In order to derive the thermal RC network parameters value, we need to transfer 5.27 in the following form:

$$Z_{jc}(s) = \frac{1}{sC_{th1} + \frac{1}{R_{th2} + \frac{1}{sC_{th2} + \ldots + \frac{1}{R_{thn}}}}} \tag{5.27}$$

5.4 Lifetime Prediction and Design of Reliability

When designing a control strategy for wind energy applications, the main control objective can be summarized as:

- Maximize energy production.
- Maximize lifetime operation.
- Minimize maintenance costs.
- Guarantee safe turbine operation.

The safe turbine operation is mainly due to wind speed and ensured by limiting the angular speed of the rotor shaft and by coerce the operation the operating range of the turbine to safe limit within the maximum wind speed $25m/s$. This maximum is determined by the noise level produced by rotating blades, which is related $\lambda = \frac{\omega_t R}{\upsilon}$ and the forces acting on the blades, tower, etc. Maximizing the energy production can be achieved by obtaining the optimal tip speed ratio for each wind speed. Operation and maintenance costs can be minimized by limiting the dynamics loads acting on the mechanical components, this can be done by, for example, capturing wind gusts in the inertia of the rotoor. The importance of each objective depend on the operating point of the wind turbine, ranges from cut in speed to rated wind speed to cut out wind speed. All are beyond the scope of this thesis except our main goal, maximize lifetime operation.

The lifetime estimation of high IGBT is estimation the life expectancy of the devices under certain operating conditions (stresses). For the IGBTs the stresses can be temperature, voltage, current, vibration, humidity, cosmic radiation level [106]. The accurate assessment of the reliability issue of wind power converter is critical for lifetime estimation and cost reduction for wind power applications [150]. The converter is one of the most unreliable subsystems of an electrical system operating in a harsh environment [151]. The cost associated with converter failure and corresponding unscheduled maintenance is high in the case of offshore application due to limited accessibility of the system. The system reliability can be greatly improved by replacing devices before they fail. Therefore, lifetime prediction of an converter and its components becomes a critical issue.

A design focused on quality performance and reliability is essential in order to satisfy the expected customer requirements. In recent years there are various models and counting algorithms to estimate the lifetime of an IGBT power converter. They differ in the number of parameters used to specify a temperature cycle. Basically, the lifetime estimation of power converter establishes the linkage between an application's typical loading profile with

IGBTs' specific lifetime model. Several cycle counting methods have been developed, which include . For example, the level crossing counting method, the peak counting method, and the simple range/mean counting method. However, these methods cannot capture all the characteristics needed for accurate fatigue analysis.

5.4.1 Rainflow Cycle Counting

Counting methods have initially been developed for the study of fatique damage generated in aeronautical structures. since different results have been obtained from different methods, errors could be taken in calculations for some of them. Level crossing counting, peak counting, simple range counting and rainflow counting are the methods which are using stress or deformation ranges. One of the preferred methods is the rain flow counting method. The signal measured, in general, a random stress $S(t)$ is not only made up of a peak alone between two passages by zero, but also several peaks appear, which makes difficult the determination of the number of cycles absorbed by the structure.

The Rainflow cycle counting method, which was developed in 1968 by Endo and Matsuishi, is one of the most popular cycle counting techniques used in fatigue analysis [152]. The Rainflow counting method was originally terms as is called "Pagoda Roof Method". It can be explained as a random stress S(t) representing a series of roofs onto which water fall with time being the vertical axis. This algorithm was originally developed for mechanical fatigue analysis. Herein, it is used to extract the number and amplitude of thermal cycles captured from real time simulation of the temperature profile. Repetitive thermal stresses caused by power cycling induce fatigue in WECS and reduce the expected lifetime of the converters. Although there are various approaches for lifetime modelling of power semiconductor devices, the lifetime models provided by device manufacturers are frequently used

[153, 154, 155, 156].

This analogy is concluded from the comparison of rain falling on the pagoda and running down the edges of the roof. it can be summarized as follows [157]:

1. Rotate the loading history 90^o, that is vertical time axis downward and the load time history resembles a pagoda roof.
2. imagine a flow of rain starting at each successive extremum point.
3. Define a loading reversal (half cycle) by allowing each rainflow to continue to drip down these roofs until:
   - It falls opposite a large maximum or smaller minimum point.
   - It meets a previous flow falling from above.
   - It falls below the roof.
4. Identify each hystersis loop (cycle) by pairing up the same counted reversal.

The signal measured, in general, a random stress $S(t)$ is not only made up of a peak alone between two passages by zero, but also several peaks appear. which make difficult the determination of the number of cycles absorbed by the structure, an example of random stress data is shown in fig. 5.6. The counting of peaks makes it possible to constitute a histogram of the peaks of random stress which can be transformed into a stress spectrum giving the number of events for lower than a given stress value. The stress spectrum is thus a representation of the statistical distribution of the characteristic amplitudes of the random stress as a function of time.

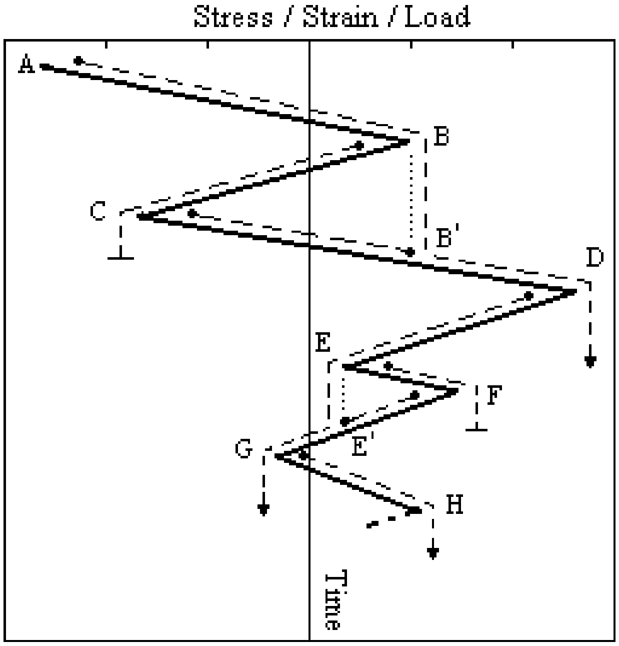


Figure 5.6 Stress Strain cycles.

5.4.2 Lifetime Modeling

The IGBT lifetime prediction models can be categorized into analytical and physical models. Physical modelling requires failure and deformation mechanisms to be priorly known. It is based on the knowledge of stress/strain deformations within devices that can be gained either by experiments or simulations [158]. Analytical models describe the dependence of the number of cycles to failure N_f on the parameters of temperature cycles such as amplitude, duration, frequency, mean value and maximum and minimum temperatures. Coffin-Manson model is considered one of the analytical models have been published in literature. The model is used in this paper, takes into consideration only the temperature swing $\triangle T$ which has been extracted from the Rainflow counting algorithm [159]. The number N of cycles until a certain percentage of the module fail can be calculated as shown in (5.28) [160]:

$$N = k_1.\Delta T^{-k_2} \tag{5.28}$$

The two parameters k_1, k_2 respectively are scale parameter and the exponent parameter or the shape parameter that controls how strong the temperature dependence is. Both of them are device dependent, and have to be determined based on measurements. Where $k_1 = 8.2 \times 10^{14}$ and $k_2 = 5.28$ [160].

Furthermore, it is not possible to calculate the exact lifetime of individual modules. Instead the lifetime must be expressed in terms of the B_{10} lifetime, that is the number of cycles during which 10% of the total number of modules fails. The analytical life is performed by means of using Miner's Rule for damage accomulation [161],[162]. The correlation between temperature changes and the damaged produced within the IGBT has to be defined and then lifetime is presented as inverse of the total damage accumulated within a power module until the suspension of its normal working. Therefore, mission profile transformation into a sequence of non-uniform temperature cycles is the main issue of the analytical approach. The main assumption is that every temperature cycle consumes a certain fraction of the IGBT's lifetime. The total damage can be defined as the sum of all the fractional damages over a total of k blocks as shown in 5.29.

$$\left[\frac{n_{at\Delta T_1}}{N_{10\%,\Delta T=\Delta T_1}}\right] + \left[\frac{n_{at\Delta T_2}}{N_{10\%,\Delta T=\Delta T_2}}\right] + ... + \left[\frac{n_{at\Delta T_k}}{N_{10\%,\Delta T=\Delta T_k}}\right] < 100\%. \tag{5.29}$$

The lifetime of the IGBT is predicted to be 4818.5 hours if running at these load conditions during 30 s interval.

The limitations of the Palmgren Miner rule can be summarized as the following:

- Linear it assumes that all cycles of a given magnitude do the same amount of damage, weather they occur early or late in the life.
- Non interactive(sequence effects) it assumes that the presence of S_2 etc. does not

affected the damage caused by S_1.

- Stress Independent it assumes that the rule governing the damage caused by S_1 is the same as that governing the damaged caused by S_2. The assumptions are known to be faulty, however, Palmgren-Miner rule is still used widely in the application of the fatique life estimates.

5.5 Principles of Filtering Wind Turbine Power Command Fluctuations

In WECS based on variable speed drives, the modern power electronic converter normally operate under maximum power point tracking (MPPT) algorithms and capture the maximally available wind power that is subject to fluctuations at multiple time scales. One of the pivotal parameters for lifetime estimation of IGBT is the thermal environment and the number of thermal cycles that the devices undergo. Although WECS power converters have few moving parts involved that may mechanically wear out, they are vulnerable to excessive voltage and currents and their variations. Damages could result from even by very-short duration shocks above maximum ratings. In a well designed system, the power converter devices are well protected from such events.

Studies have shown that the power cycling of the IGBT is one of the dominant failure mechanism in power converters [49]. A LPF has been proved an effective approach to minimizing number of thermal cycles. The control strategy is mostly focused on wind turbine side active power control but not the power grid side. However, the wind turbine's output power fluctuates due to wind speed variations. Therefore, a LPF is used to smoothing these fluctuations.

This paper proposes a new real power control method, in which the smoothing performance is examined. The simulation results show that a WECS with the proposed control method has superior performance for output power wind turbines with reduced thermal cycle count. A low pass filter is used to remove tidal and higher frequency fluctuations from the time series data. It sometimes suppresses smaller fluctuations in the time series plots that are driven by wind and density fields. This filter parameters are determined by the new term "missing energy"or "dead energy"and the number of thermal cycles. Simulation results show that the proposed method can ensure the effects of smoothing wind power fluctuation. This control strategy can modify the number of thermal cycles. Besides, it extend the service life of the semiconductor devices. The LPF design is strongly application dependent.

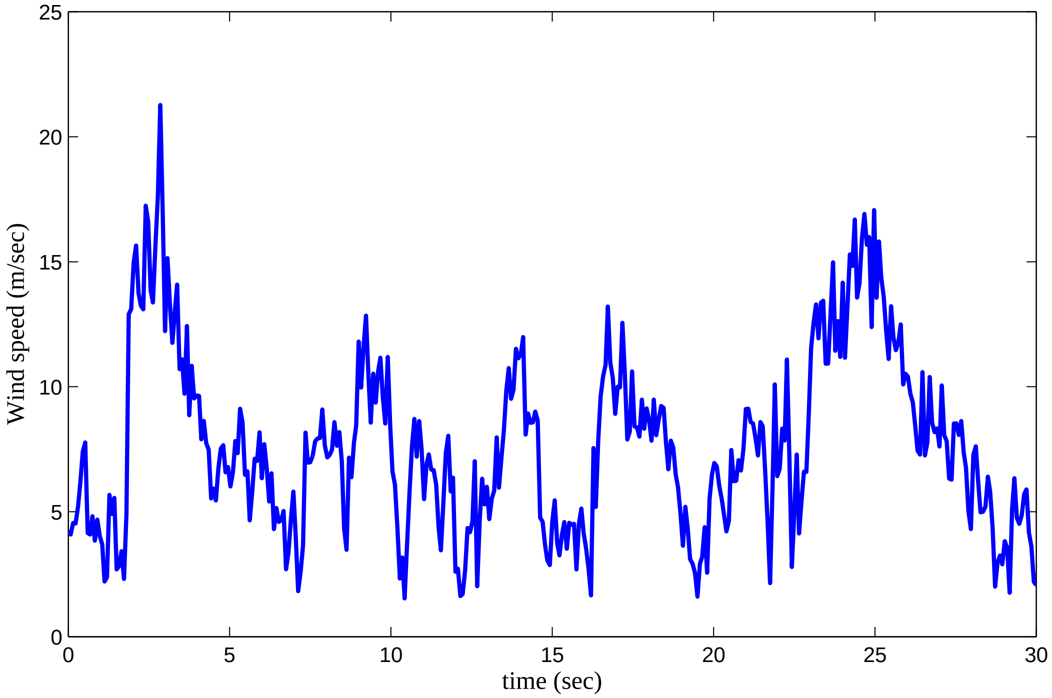


Figure 5.7 Profile of the wind speed used in this simulation.

This paper presents a comparative study between conventional controller and proposed controllers. It has been shown that the number of thermal cycles in IGBT power converters can be significantly reduced by applying LPF to variable speed DFIG. The number of thermal-cycles of the converter reduces by approximately 7 times with the proposed LPF control method. In addition, the lifetime increases by approximate around 22.25%. The thermal stresses of the IGBT junction temperature are much reduced when the control method is enabled. Furthermore, the wind speed signals used is a real world signals, which make simulation close to reality as shown in Fig. 5.7. Data on the wind profile are assumed as a prerequisite. These wind data can be processed with a model of the WECS to derive the electrical operating conditions of the converter. Thus the power dissipation for each semiconductor device can be determined and used to calculate the related junction temperatures.

In designing the LPF, more attention should be paid to the kinetic energy stored in the rotating mass of the WECS. which is given by:

$$E = \frac{1}{2} J \omega_t^2 \tag{5.30}$$

The inertia is the congregational inertia of the wind turbine blades that capture energy, and a rotor hub, that connects the blades to the shaft, along with pitch mechanism that assists in efficient capture of energy. When the filtered power command becomes higher than the available power, problem arises. The LPF time constant is determined based on the amount of energy available to be drawn from the rotating assembly. To optimize the value of the LPF time constant a detectable amount of missing energy or dead energy has been considered. This missing energy has been estimated by the difference between two areas under the two curves in Fig. 5.8. This energy has been decreased the rotor speed of rotating group. That means, the value of time constant is examined. Where high time

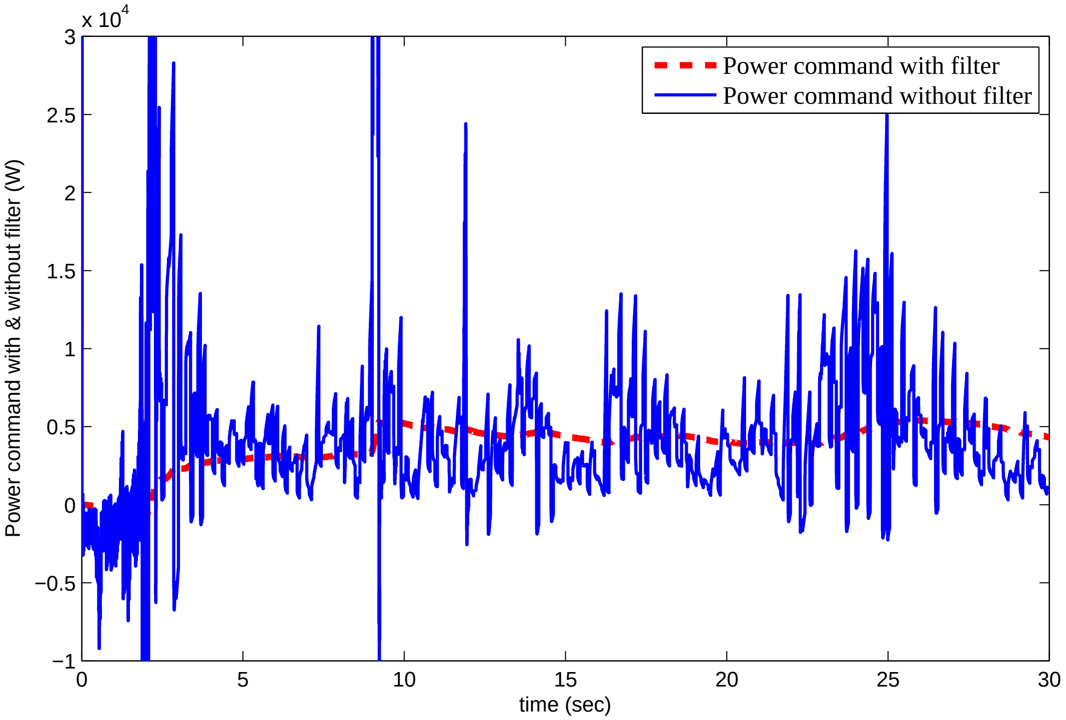


Figure 5.8 Plots of the power commands with and without the LPF.

constant leads to narrow band pass filter. Subsequently missing energy will be increased. On the other hand, the low time constant means the band pass frequency will be high, and the missing energy will be decreased. In other words, come back to the actual power command which means do nothing to suppress the thermal cycles. The tradeoffs of deloading the wind turbine to overcome the shortage of kinetic energy are evaluated. Large contributions to inertial response are possible, but vary with operating point. Contributions are limited to above a certain wind speed due to rotor under-speed. De-loading can be used to maximize the contribution over the viable range. Wind variations reduce the magnitude of the contribution, and make rotor speed instability possible for some control references. Reducing rotor speed is considered as the most route for lowering noise emission in wind turbines. In addition, variable speed operation is also effective, enabling designers to program operation for lower speeds at night, when noise sensitivity is greatest.

Table 5.4: The effectiveness of the new strategy.

	Without LPF	With LPF
The total kinetic energy captured (J)	139907	114538
The revolving group low side speed (rpm)	193	175
The revolving group high side speed (rpm)	976	884
Lifetime calculated (years)	0.55	12.79
Number of thermal cycles	1679.5	229

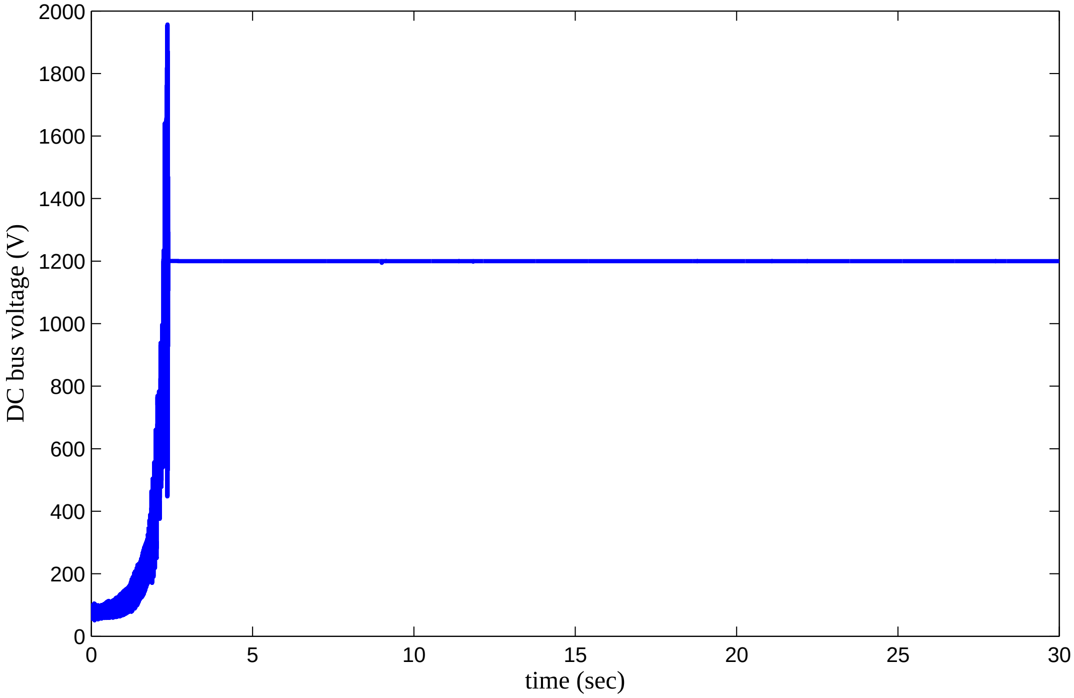


Figure 5.9 Plot of the dc bus voltage that stays the same with or without LPF.

As a matter of fact, semiconductor devices are subjected to a variety of temperature changes due to many factors; some of these are caused by the devices themselves, e.g. by switching or conduction losses, converter power variation, and some of the temperature changes are caused by external factors, e.g. change of seasons or reduced cooling The magnitude of a temperature change can range from fractions of degrees to more than 100 Kas shown in figure 5.12.

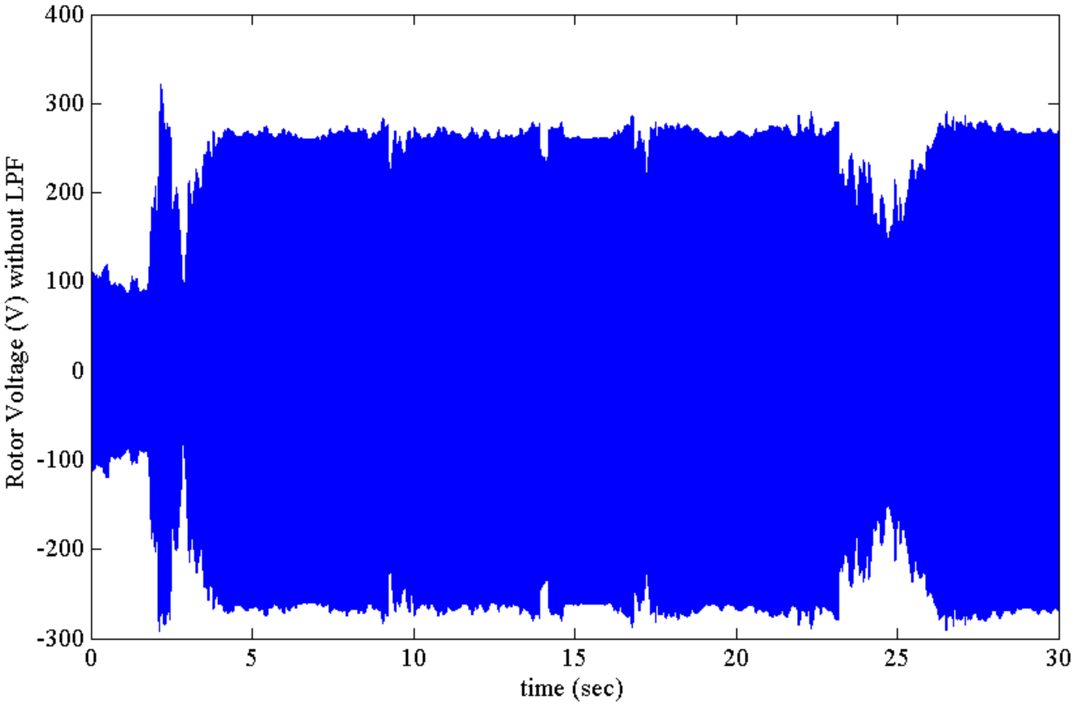


Figure 5.10 Rotor winding terminal voltage without LPF.

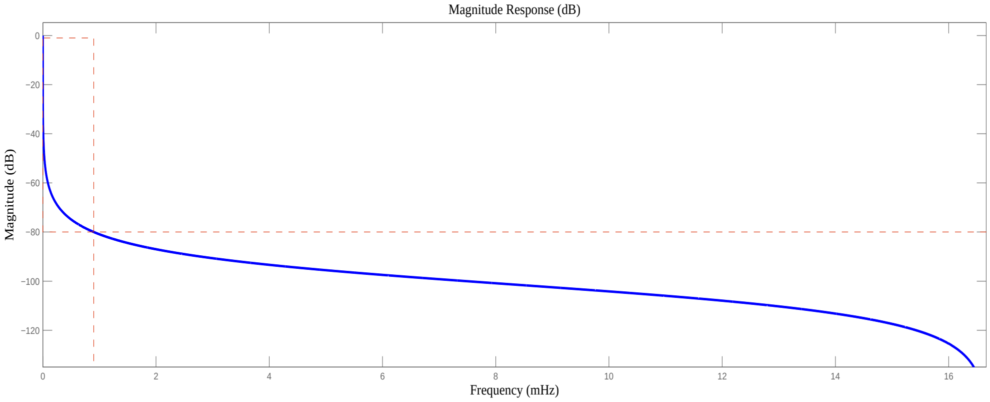


Figure 5.11 LPF response characteristic using IIR impulse response, minimum order mode, single rate type, Butterworth algorithm.

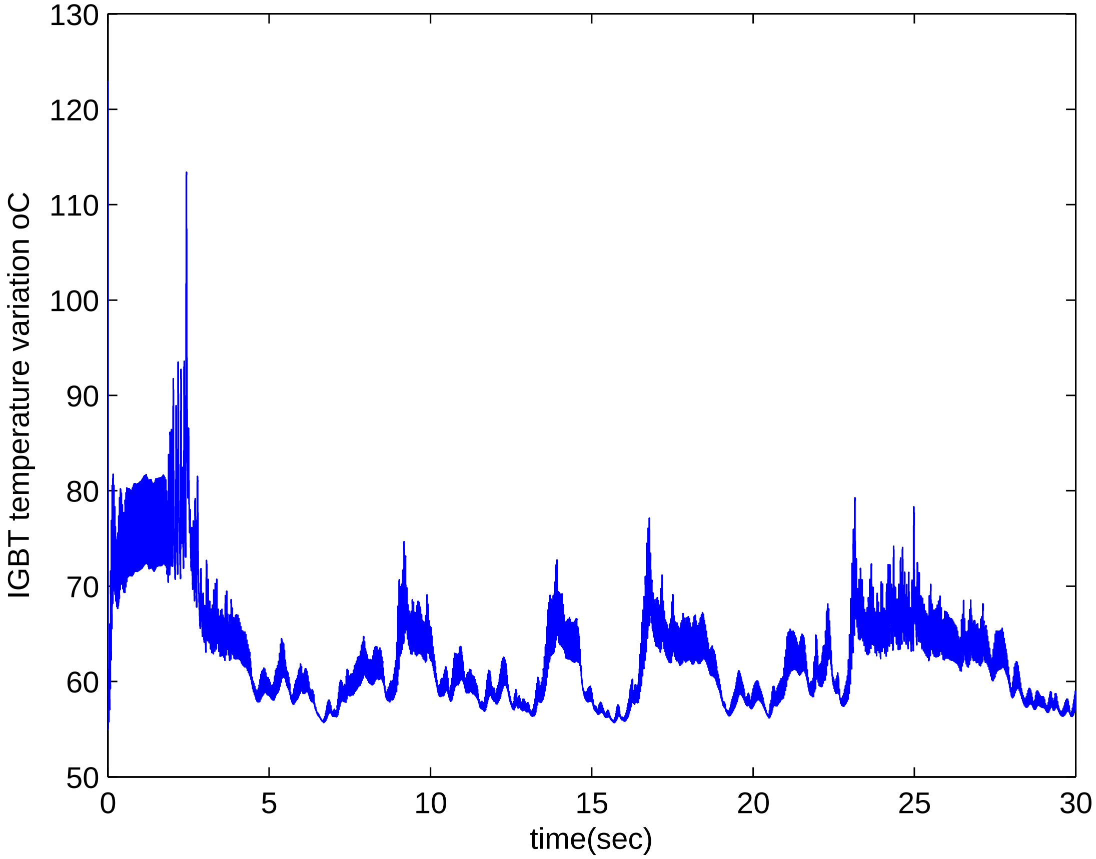


Figure 5.12 IGBT junction temperature variations without LPF.

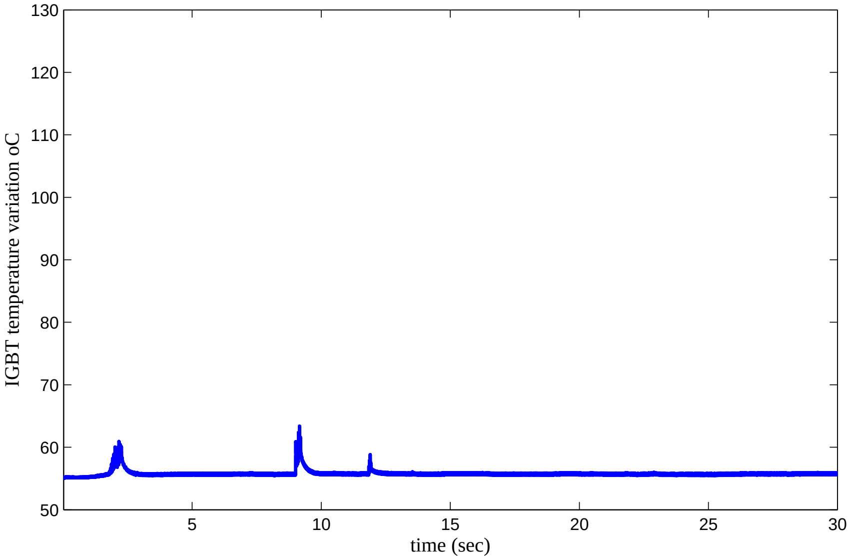


Figure 5.13 IGBT junction temperature variations with LPF.

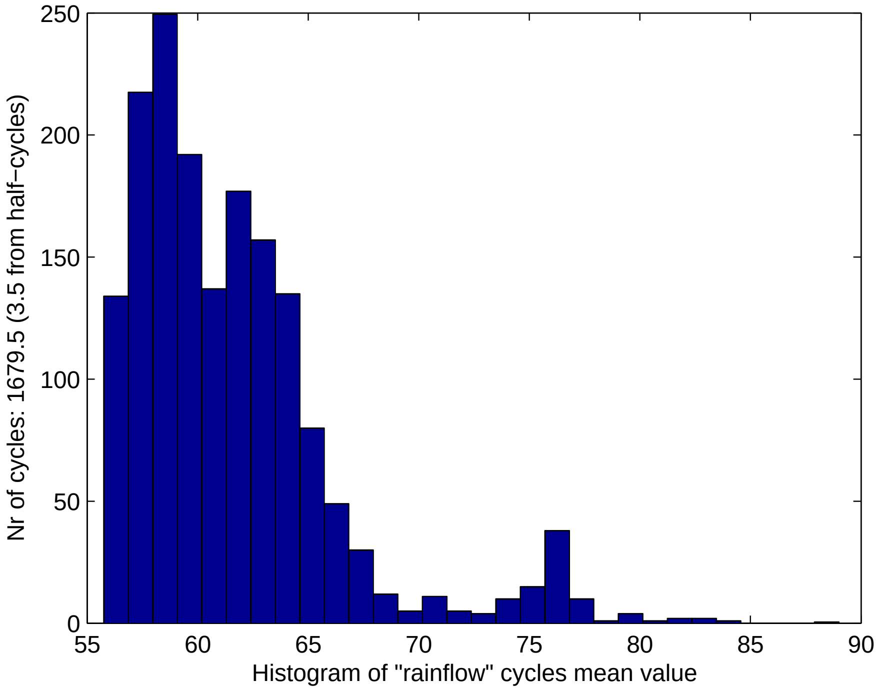


Figure 5.14 Temperature mean value T_m extracted from rainflow counting algorithm without LPF.

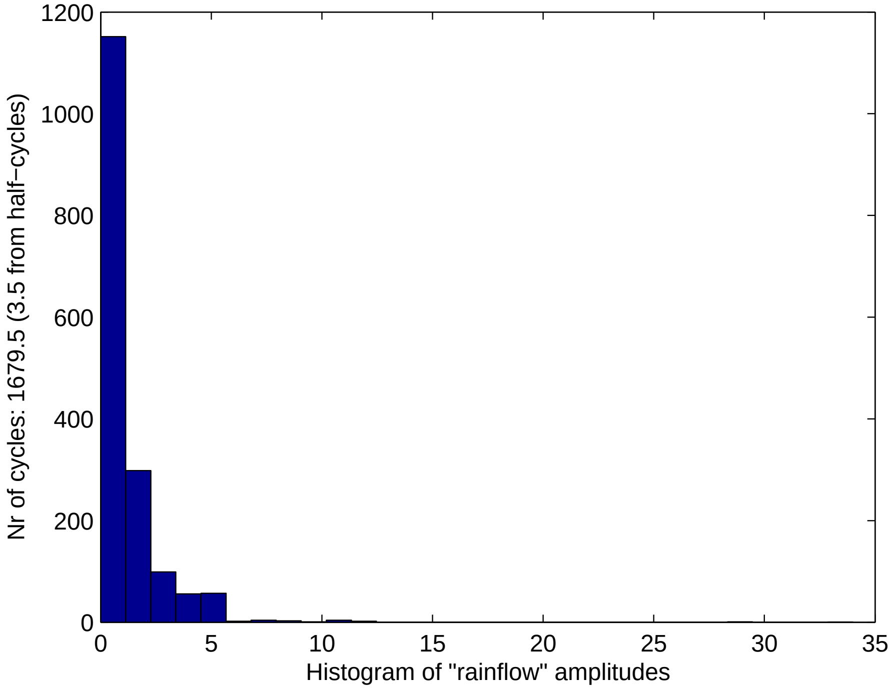


Figure 5.15 Amplitude, ΔT extracted from rainflow counting algorithm without LPF.

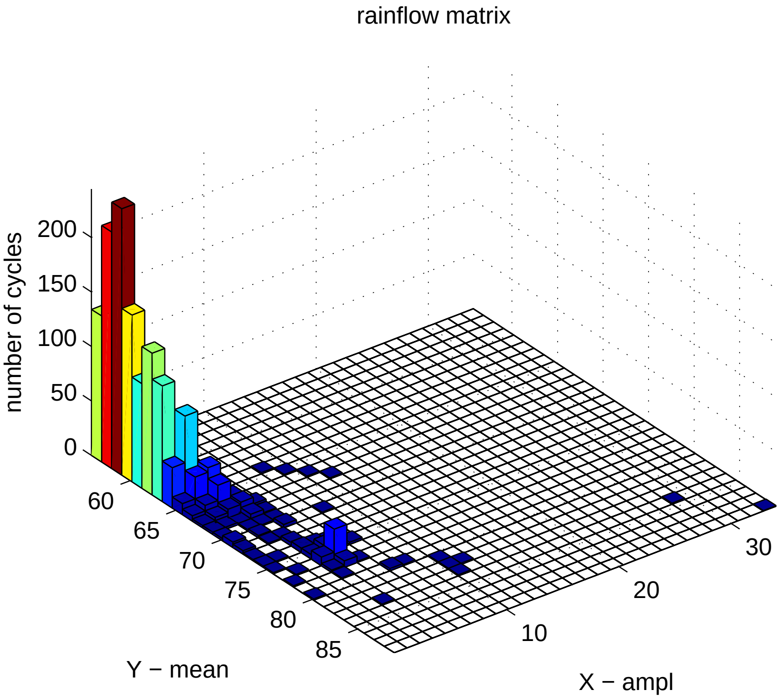


Figure 5.16 Frequency distribution of temperature cycles defined by their amplitude ΔT and temperature mean value T_m extracted from rainflow counting algorithm without LPF.

Chapter 6

Conclusions and Future works

6.1 Conclusions

The prediction of power cycling lifetime for a power electronic converter in rotor side control in DFIG is examined. A comprehensive thermal model for the power IGBT modules used in three-phase converter has been built to predict the dynamic junction temperature rise under real operating conditions. The power loss model, which is based on the look-up table method for calculating the conduction and switching losses has been successfully verified with simulation. An equivalent RC network model is built to perform the thermal analysis. Lifetime is estimated.

The analysis shows that the lifetime is heavily influenced by thermal cycling, and the behavior of the semiconductor devices and their mission profile which directly affects the lifetime. Hence, an active real-time control method is used to minimized the power fluctuations experienced by the DFIG system and subsequently to reduce the number of thermal cycles. By using the proposed LPF method, the stress on the power converter due to thermal cycling has been significantly reduced and the estimated lifetime of the system has substantially increased.

Contributions of the thesis are:

- To the best of my knowledge this is the first work on real time control scheme based on wind reliability model.

- The overall methodology applied to wind energy applications is origional.
- A LPF has been proved an effective approach to minimize number of thermal cycles and maximize lifetime.
- To the best of my knowledge this is the first work using average model to reduce complexity and leads to faster time simulation to prove reliability in WECS.
- To the best of my knowledge, this is the first work review reliability methods for WECS and WF together.
- To the best of my knowledge, this is the first work classifying reliability on wind energy into WECS and WF.
- To best of my knowledge, this is the first work discussing reliability over WECS and WF.

6.2 Future Work

- Continue to stay close to industry.
- Include end users in future work.
- More attention on GSC reliability.
- More work on missing energy and the effectiveness of maximum wind energy.
- Wind energy generation systems reliability is an open problematic issue. Where is the determination of the most thermo- electrically stressed devices of a power con-

verter is very important. The voltage and current of IGBT modules must remain within the limits given by their manufactureer under operating conditions. And the working temperature and its variations (temperature swing) does not exceed certain maximum values. Several efforts should have been addressed to improve the power devices ruggedness under overloading conditions.

- With an increasing IGBT operating temperature, we have to choices either raising of the output current, or decreasing of cooling costs. the impact of the interaction between the power module and its cooling system on the inverter reliability need more attention
- Conducting more research on a good thermal management and take into account the surrounding area.
- Enable smaller and more cost efficient inverter designs. designing a low losses, reliable operation at high temperature power electronic modules.
- Working on power electronic modules that enable reliable operation at high temperature and high currents.
- Studying the switching speed of an IGBT module design by focusing on electro magnetic simulations. Find new simulations methods that enables fine tuning to meet the requirements of low loss and good short circuit behavior.

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