Different Control Strategies for PMSG Connected Wind Turbine System

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THÈSE DE DOCTORAT

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Ahmed Omar Ahmed Mohamed Elgharib

Différentes stratégies de contrôle pour le système d'éolienne connecté PMSG

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Je soussigné, [Ahmed Elgharib], déclare par la présente que le travail présenté dans ce manuscrit est mon propre travail, réalisé sous la direction scientifique de [Aziz Naamane], dans le respect des principes d'honnêteté, d'intégrité et de responsabilité inhérents à la mission de recherche. Les travaux de recherche et la rédaction de ce manuscrit ont été réalisés dans le respect à la fois de la charte nationale de déontologie des métiers de la recherche et de la charte d'Aix-Marseille Université relative à la lutte contre le plagiat.

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List of publications and participation in conferences

List of publications produced as part of the thesis project:

2022	**A.O. Elgharib**, S. Benzaouia, Abdelhamid Rabhi and A. Naamane. **Experimental Validation for Different Configurations based on Wind Tubrine Stand Alone PMSG Connected System**. To be submitted
2022	**A.O. Elgharib**, S. Benzaouia, Abdelhamid Rabhi and A. Naamane. **Experimental Validation based on Variety of Tests for DFIG Wind Turbine Grid Connected System**. To be submitted
2022	**A.O. Elgharib**, S. Benzaouia, and A. Naamane. **Linear and Nonlinear Control Techniques Assessment for Variable Speed Wind Turbine Systems**. In *International Journal of Control, Automation and Systems*
2022	**A.O. Elgharib**,S. Benzaouia, and A. Naamane. **Enhancement of Standalone PMSG Wind Turbine System Utilizing Non Linear Proportional Integral Control Technique**. In *3rd International Conference on Electronic Engineering and Renewable Energy]. 2022 by Springer*
2022	**A.O. Elgharib**, M. Alhasheem, R.A. Swief, and A. Naamane. **An Efficient Finite Control Set Model Predictive Control Scheme for a Stand-alone Wind Turbine System**. In *8th International Conference on Control Decision and Information Technologies[CODiT]. Page(s):[537 - 542], 2022 by IEEE and IFAC*
2022	**A.O. Elgharib**,S. Benzaouia, and A. Naamane. **Sensorless Control of Direct-Driven PMSG Wind Turbines using NPIC & MRAS Observer**. In *International Journal of Simulation and Process Modelling. 2022*
2021	**A.O. Elgharib**, M. Alhasheem, R.A.Swief and A. Naamane. **LOSSES Evaluation of Boost Converter Using Different Control Strategies for Vertical Axis Wind Turbines Utilizing PLECS Software**. In *International Telecommunications Conference (ITC-Egypt)*. Page(s):[1 - 5], 2021 by IEEE
2021	**A.O. Elgharib**, M. Alhasheem, R.A. Swief and A. Naamane. **Wind Turbine Performance Assessment Boost Converter Based Applying PI Controller Integrating Genetic Algorithm**. In *33th International Conference on Microelectronics (ICM)*. Page(s):[236 - 241], 2021 by IEEE

List of acronyms

- PMSG: Permanent magnet synchronous generator
- WT: Wind turbine
- WESET: Wind engineering skills in Egypt and Tunisia
- NSSFC: Nonlinear static state feedback controller
- NDSFC: Nonlinear dynamic state feedback controller
- NPIC: Nonlinear proportional integral controller
- MRAS: Model reference adaptive system
- PI controller: Proportional integral controller
- PID controller: Proportional integral-derivative controller
- GA : Genetic algorithm
- MPC: Model predictive controller
- CTF: Clean technology fund
- IBRD: International bank of construction and development
- BOO: Own built operate
- GHG: Green house gases
- EETC: Egyptian electricity transmission company
- TWh: Terrawatt-hours
- HAWT: Horizontal axis wind turbine
- VAWT: Vertical axis wind turbine
- SG: Synchronous generator
- SCIG: Squirrel cage induction generator
- DFIG: Doubly fed induction generator

- WECS: Wind energy conversion system
- GWEC: Global wind energy council
- WRIG: Wound rotor induction generator
- EESG: Electrically excited synchronous generator
- RFPM: Radial flux permanent machine
- AFPM: Axial flux permanent machine
- SMC: Soft magnetic composite
- GE: General electric
- TFPM: Transverse flux permanent magnet machine
- EVT: Electrical variable transmission
- HCS: Hill climb searching control
- TSR: Tip speed ratio
- MPPT: Maximum power point tracking
- P and O: Perturbation and observation
- FL: Fuzzy logic
- NN: Neural network
- SCR: Silicon controlled rectifier
- EMPC: Explicit model predictive controller
- GPC: Generalized predictive controller
- OSV-MPC: Optimal switching vector model predictive controller
- OSS-MPC: Optimal switching sequence model predictive controller
- CCS-MPC: Continous control set model predictive controller
- FCS-MPC: Finite control set model predictive controller

Résumé

Les énergies renouvelables sont considérées comme une alternative viable aux générateurs de combustibles fossiles conventionnels globalement. Il s'agit d'une solution fiable au problème de diminution de l'approvisionnement en combustibles fossiles et de son impact sur l'environnement. L'énergie éolienne est l'une des sources d'énergie renouvelables les plus attrayantes et prometteuses. Celle-ci offre un excellent substitut à la production d'énergie électrique traditionnelle. Les éoliennes basées sur un générateur synchrone à aimant permanent (PMSG) sont les mieux adaptées aux applications autonomes en raison de leur fiabilité et de leur haute efficacité. L'énergie éolienne a continué à jouer un rôle important et peut être considérée comme la source d'énergie renouvelable la plus déployée. Cependant, le niveau d'efficacité et la rentabilité d'un système d'éolienne, en ce qui concerne l'application du vent, dépend énormément de son contrôle.

Ce travail de recherche propose quelques méthodes de contrôle efficaces associées au contrôle de l'énergie éolienne. Il porte principalement sur le réajustement de certaines approches de contrôle disponibles, comme l'amélioration du NSSFC (contrôleur de retour d'état statique non linéaire) et du NDSFC (contrôleur de retour d'état dynamique non linéaire), afin d'augmenter les performances du contrôleur pour un tel système. En parallèle, ce travail traite le contrôleur NPIC qui a été ajouté au système en présentant une technique de contrôle sans capteur d'une éolienne PMSG à entraînement direct, afin d'étudier le système d'une dimension électrique après avoir considéré la partie mécanique utilisée par les deux contrôleurs (NSSFC) et (NDSFC). Cette approche utilise un observateur, appelé MRAS, pour générer une estimation de la vitesse de rotation. Ensuite, le contrôleur PI est étudié dans ce travail en intégrant un algorithme génétique qui a un impact significatif sur l'efficacité des applications éoliennes et de leur système entier. Le contrôleur prédictif de modèle (MPC) est le dernier contrôleur qui a été exploré avec ses résultats de simulation pour le système. Tous ces contrôleurs utilisent PMSG, discutés sous différentes modes opératoires de la vitesse du vent. Plusieurs tests expérimentaux ont été appliqués à une grande variété de configurations telles que la boucle ouverte, la boucle fermée, en cascade (contrôleur PI basé sur le contrôle de la boucle externe, contrôleur PI basé sur le contrôle de la boucle interne) et la loi de contrôle basée sur le contrôleur sans modèle, afin de valider les résultats de simulation obtenus. Cette thèse de recherche servira comme référence pour les études futures sur le contrôle des systèmes d'éoliennes.

Mots clés : Générateur synchrone à aimant permanent(PMSG), Contrôleur prédictif de modèle(MPC), Système adaptatif de référence de modèle(MRAS), Contrôleur de rétroaction d'état statique non linéaire(NSSFC), Contrôleur de rétroaction d'état dynamique non linéaire(NDSFC).

Abstract

Renewable energy is considered as a viable alternative to conventional fossil fuel generators globally. This is a direct reaction to the problem of diminishing fossil fuel supplies and its impact on environmental pollution. One of the appealing and promising renewable energy sources is wind energy. This renewable energy source offers an excellent substitute for the generation of traditional electricity. Wind turbines based on permanent magnet synchronous generator (PMSG) are best suited for stand-alone applications due to their reliability and their high efficiency. Comparisons of various wind generator systems are required in order to guarantee that the most appropriate generator that can be utilized in our wind turbine system is PMSG.

Wind energy has continued to play a significant role and can be regarded as the most deployed renewable energy source, however the efficiency level and cost effectiveness of a wind turbine (WT) system with regards to wind application is very much dependent on its control. This research work proposes some efficient control methods associated with wind energy control. It is focused more on the readjustment of some available control approaches as the improvement of NSSFC (nonlinear static state feedback controller) and NDSFC (nonlinear dynamic state feedback controller) to increase the controller performance for such a system. In sequence with that, this work moves forward to another controller(NPIC) which has been added to this system by presenting a sensor-less control technique of direct driven PMSG wind turbine, in order to study the system from the electrical point of view after considering the mechanical part utilized by the two controllers (NSSFC and NDSFC).

This approach uses observer which is called MRAS observer for generating rotational speed estimation. Afterwards, PI Controller is studied in this work by integrating genetic algorithm that has significant impact on the efficiency and execution of wind turbine applications and their whole system. Model Predictive Control (MPC) is the last controller that has been explored with its simulation results for the system. All of these controllers are using PMSG, discussed under different operating ranges of wind speed. Several experimental tests were applied to wide variety of configurations such as the open loop, closed loop, cascaded (outer loop control-based PI controller, inner loop control-based PI controller) and the control law based on model free controller in order to validate the simulation results produced. This research aims to serve as a detailed reference for future studies on the control of wind turbine systems.

Keywords: Permanent magnet synchronous generator(PMSG), Model predictive controller(MPC), Model Reference Adaptive System(MRAS). Nonlinear Static State Feedback Controller(NSSFC), Nonlinear Dynamic State Feedback Controller(NDSFC).

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General introduction

0.1 General introduction

The project goal of wind power expansion is to provide commercial plans and infrastructure for expanding wind power generally worldwide and especially in Egypt.

Egypt has a fantastic wind pattern, especially in the Suez Gulf At an average capacity factor of 40.6%, that Zafarana farm can produce for power annually. The demand for other forms of energy was also expanding quickly, which contributed to a substantial rise in carbon dioxide emissions, which had been growing at a pace of 7% annually and were predicted to keep doing so. Egypt was listed as one of the 11 emitters of greenhouse gases (GHG) with the quickest rate of growth as a result.

The government had implemented new laws and regulations to help private wind developers, including:

- Special policy for access to land
- Zero customs duties on wind equipment
- The usage of own built operate (BOO) model for developers
- power purchase agreements
- assistance with obtaining necessary environmental, social, and defense clearances

Egypt has excellent solar resources while wind capacity is also quite good and commercially available in the Gulf of Suez Area. As a result of these factors, one of the key pillars of the Government of Egypt's Energy Strategy has greater reliance on renewable energy sources. Interest in the Egyptian wind business has increased as a result of the developed contractual framework. Future of Egypt's energy strategy and market structure: Clarity of the project pipeline and plans, as well as the power market structure (auctioning, storage models, etc.), are essential to sustaining and pursuading investments in this area. Clarity would secure the best value for the national utility and would also encourage competition and transparency. By talking about future of wind energy in Egypt, there is a large project has been started in Egypt with the co-operation of Tunisia is called WESET project that will be discussed briefly in the next section.

0.1.1 WESET project

Such a project intends to transfer expertise and technology in the field of wind engineering across universities in Europe, Egypt, and Tunisia. helps the partner Egyptian and Tunisian institutions with modernization, development, and internationalisation strategies by tying master's degrees to the demands of business and society and establishing connections with European institutions. The program will help to address the shortage of wind engineering professionals in Egypt and Tunisia, which is impeding the adoption of wind as a dependable, affordable, and pollution-free source of electricity. On 08/09/2021, WESET partners in Egypt held a successful conference in Cairo. In order to conclude such a conference, it can be summarized as follows:

- Future of Egypt's energy strategy and market structure: Clarity of the project pipeline and plans, as well as the power market structure (auctioning, FIT, storage models, etc.), are essential for keeping and encouraging investments in this area. Clarity would secure the best value for the national utility and would also encourage competition and fairness.

- Legislation I: It is necessary to enhance and simplify the land use, authorization, and wheeling processes in order to encourage more FD and local investments. The growth of renewable energy projects and the reduction of carbon emissions is important target in industries would be aided by a defined structure for BOO initiatives in a confidential manner.

- Legislation II: Small-scale Wind creates fantastic opportunities for the growth of the local value chain (design, manufacture, jobs, etc.) as well as for a greater use of wind power. However, a grid-code, laws governing their authorization, and grid integration are required to facilitate their use. The Electricity regulatory authority of Egypt has to address and support concerns regarding the certification and dependability of small-scale wind.

- While Egypt's wind potential is encouraging, it is known that the most desirable locations for wind power production are now concentrated in a few selected locations. Increased wind power output on the grid in a few concentrated places will increase the cost of the transmission infrastructure and place additional technical demands on the grid operator. Off-grid applications or a nearby storage facility will undoubtedly aid in increasing the amount of money invested in Egypt's onshore wind generation. A more sector-specific education would boost people's faith in renewable energy and support the development of high-value jobs in Egypt's wind power industry.

- Improve the stakeholders' understanding of wind energy and its development in Egypt.

- Understand the theoretical and practical sides of wind turbine components, control and operation.

0.1.2 Wind Turbines

The wind turbines have experienced momentous progression and improvisation in their structure for perfect execution, and the wind curves can change according to the wind speed. In expansion to few natural issues caused by wind turbines in disfavour show towards the wind energy that is named by the clean energy and a neighborly environment, these issues can be classified into two variables: Negative effect on the environment, and noise issue.

0.1.2.1 Power electronics for wind turbines

For the past 35 years, the advancement of wind turbine technology has remained consistent. The designs of wind turbines can generally be divided into a number of categories, depending on the generator types, power electronics, speed controllability, and the manner in which the aerodynamic power is limited. These wind turbine models use power electronics, which have a variety of power rating coverage and serve fairly varied functions in the WTs. Actually, in the most popular wind turbine power ranges, full-scale power converter systems are emerging as the top technical options for wind turbine models Blaabjerg and K. Ma 2013.

0.1.2.2 Emerging technology challenges for the power electronics

The concentration nowadays is on the technology issues of power electronics in terms of the cost, new power electronic devices, circuits and reliability.

- How to reduce the energy cost and can reach to the lowest value, as the cost problems are the most significant factor for the technology.
- How to implement higher reliability to the system.
- Future wind power conversion technologies: Nowadays, the majority of installed wind turbines are powered by induction, permanent magnet, or wound rotor synchronous generators at low voltage levels (690 V).

0.1.2.3 Wind turbine control strategies

The great efficiency and cost-effectiveness of wind energy applications are ensured by the control of wind turbines (WTs). This topic has undergone much investigation, and its advancements are essential for creating wind turbines that are even better and more effective. However, there are currently very few studies that discuss, list, and synthesise wind turbine control principles. This report discusses in details different control strategies applied on a wind turbine system.

0.1.3 Short summary on chapters of the report

- First chapter gives several ideas for the probable generator types for wind turbines, a complete analysis has been conducted based on a survey of quantitative comparison of different wind generating technologies. Different forms of wind turbine control strategies have been presented also in this chapter.

- Second chapter is going through modelling of the system and its characterization, as there are models, designs for wind turbines and various converter typologies are illustrated along with the control systems.

- Third chapter discusses the behaviour and improvement of two controllers which are non-linear state static and dynamic feedback controllers and their effectiveness on the wind turbines from the mechanical side point of view then to be in sequence, PMSG is controlled by nonlinear proportional integral controller to discuss the system from the electrical part point of view.

- Fourth chapter determines the genetic algorithm and its usage in the system by involving the PI controller to see whether there is an improvement in the assessment of the studied system or not, and the same system is tested by utilizing another controller which is the model predictive one to accelerate the system's time response especially at various wind speeds.

- Fifth chapter determines validation of the system with the experimental results according to the test bench available in the laboratory.

- Finally, a general conclusion for the different control techniques that are applied to the wind turbine system is determined clearly.

Objectives and Contributions of Thesis

The main objective and contribution for this thesis is finding the best control strategy that can be applied to wind turbine PMSG connected system by running different control strategies for the system. The control strategies can be categorized into six different control techniques which are nonlinear static state feedback controller, nonlinear dynamic feedback controller, they are presented as efficient controllers for wind turbine control and in this situation, we are concentrating on mechanical part of the system which is considered to be the inner loop, as the electrical part is faster in response and efficiency, so we can depend mainly on the mechanical part to get the torque needed as an output from the mechanical part in order to act as an input to the electrical one as presented in paper **A.O. Elgharib**, S. Benzaouia, and A. Naamane. **Linear and Nonlinear Control Techniques Assessment for Variable Speed Wind Turbine Systems**. In *International Journal of Control, Automation and Systems* This part presents a comparison between the perturbation and observation technique and the tip speed ratio one according to difference between rotational speed reference and the measured one to eliminate the error as much as possible. Nonlinear Dynamic State Feedback Controller has greater performance and robustness through the wind turbine model. The main goal of this consideration is to keep following MPP. According to this, tip speed ratio technique has shown much better performance than perturbation and observation one because it follows the reference more efficiently than P&O technique. Nonlinear static state feedback controllers can be affected by perturbation or error, which leads to a reduction in following reference, whereas NDSFC have a robust control on such a system, cannot be affected by errors unlike NSSFC, and follows the reference more efficiently than any other technique mentioned.

Furthermore, after discussing such a system from the mechanical part point of view, a validation of the electrical point of view (outer loop of the system) is going to be discussed through adding updated controller which is: Nonlinear Proportional Integral controller(NPIC) using the model reference adaptive system (MRAS), PMSG is controlled by NPIC controller, it assigns a very well dynamic performance according to the variability of wind speed. Such a control method can take advantage of high efficiency, particularly by using PMSG, such a system has been validated by simulation results using Matlab Simulink as presented in paper **A.O. Elgharib**,S. Benzaouia, and A. Naamane. **Sensorless Control of Direct-Driven PMSG Wind Turbines using NPIC & MRAS Observer**. In **International Journal of Simulation and Process Modelling. 2022**, and textbfA.O. Elgharib,S. Benzaouia, and A. Naamane. **Enhancement of**

Standalone PMSG Wind Turbine System Utilizing Non Linear Proportional Integral Control Technique. In **3rd International Conference on Electronic Engineering and Renewable Energy]. 2022 by Springer**. Continuing to discuss different control strategies, the traditional PI controller integrating the genetic algorithm is the next controller studied, this technique leads to an improvement for the studied system by applying many iterations in order to decrease the transient state for such a system as presented in paper **A.O. Elgharib**, M. Alhasheem, R.A. Swief and A. Naamane. **Wind Turbine Performance Assessment Boost Converter Based Appyling PI Controller Integrating Genetic Algorithm**. In *33th International Conference on Microelectronics (ICM)*. Page(s):[236 - 241], 2021 by IEEE. Finally, Model Predictive Control (MPC) technique is utilized in such a system in order to enhance the voltage tracking behavior and provide high power quality as presented in paper**A.O. Elgharib**, M. Alhasheem, R.A. Swief, and A. Naamane. **An Efficient Finite Control Set Model Predictive Control Scheme for a Stand-alone Wind Turbine System**. In *8th International Conference on Control Decision and Information Technologies[CODiT]. Page(s):[537 - 542], 2022 by IEEE and IFAC*. A validation for the simulation results with experimental work according to the available test bench found in the laboratory has been added in order to validate these results.

organization of the manuscript

0.2 Chapter 1

This chapter provides an overview of several ideas and probable generator types for wind turbines. Based on modern wind turbine principles, the fundamental setups and traits of various wind generator systems are discussed, along with benefits and drawbacks. Surveys have been done on AFPM, RFPM, and TFPM machines, three potential direct-drive PM machines. A complete analysis has been conducted based on a survey of quantitative comparison of different wind generating technologies and their market penetration. It has been looked into how wind generator systems are developing and certain benchmarks have been provided. Recent advancements in PM efficiency and cost have made variable speed direct-drive PM machines with full-scale power converters increasingly desirable for offshore wind power generations.

Different forms of wind turbine control strategies have been categorised, presented, and investigated in the second part of the chapter. The bases for each subsystem are covered by the state of art described in this chapter, which will then be used to propose our system at a reasonable cost and with great service reliability.

0.3 Chapter 2

Due to recent advancements in power electronics and control systems, wind turbine manufacturers have begun to pay more attention to PMSG. In terms of renewable energy production, PMSG's wind energy conversion technology is particularly promising. However, the performance of grid-connected PMSGs is greatly affected by grid disturbances because their stator windings are interfaced with the grid directly. PMSG wind turbine effectiveness, which is integrated with various controllers, is also shown in this chapter. Additionally, the operating ranges of wind turbines and various types of converters are described in details, along with their benefits, drawbacks, and applications for both controlled and uncontrolled rectifiers. In this chapter, models and designs for wind turbines and various converter typologies are examined along with control systems.

0.4 chapter 3

Both nonlinear static and dynamic state feedback controllers are discussed in this chapter as effective controllers for controlling wind turbines, with the wind turbine model demonstrating the nonlinear dynamic state feedback controller's superior performance and robustness. MPP tracking is the main objective of this consideration. This objective claims that TSR improves P&O technique because it follows the reference more effectively than P&O. This chapter also studies the difference between NDSFC and NSSFC according to reference tracking in order to determine which has the robust control on the system and which one can withstand the perturbations. This is happened using Simulink/Matlab environment based on several system parameters, including the power coefficient, rotational speed, and theoretical power for this system, the efficiency and robustness of each controller are confirmed and illustrated.

A wind turbine stand alone system based on PMSG is also presented in this chapter by another controller technique, the wind turbine is utilized by adding updated online controller technique that assigns very well results by using MPPT method. In order to deliver sinusoidal currents, The rectifier is selected and planned, this enhances PMSG efficiency. Moreover, MPPT control technique is utilized for increasing power for wind turbine, the maximum is extracted without using mechanical speed sensor. It is common and well control method with favorable dynamic performance. PMSG is controlled by NPIC controller. Furthermore, the utilized control methods can take advantage of high efficiency, particularly by using PMSG. The stand-alone wind turbine system has been validated by using Matlab/Simulink environment. The proposed sensorless approach is utilized by a model reference adaptive system for generator rotational speed estimation as will be discussed in details in this chapter. This latter needs only three phase voltage and current measurements provided by cheapest electrical sensors. The wind turbine simulation has been developed in an online control program in order to improve the influence and validation of research methods on wind turbine systems and effectiveness of MPPT control method using variable wind profiles.

0.5 Chapter 4

This chapter discusses the effect of utilizing genetic algorithm integrating the PI controller that is already applied on PMSG wind turbine system in order to show that there is an improvement for the assessment of the studied system or not by running the system at different operating ranges of wind speed to know the best one for all the power output results, so a lookup table has been made for that instead of utilizing the transfer function for each operating range, we have discussed this process in order to improve the transient operation of DC link voltage just before the three phase voltage. The experimental test bench that has been tested and validated as it includes the load, DC motor, Permanent Magnet Synchronous Motor (PMSM), uncontrolled rectifier, Digital Signal Processor(DSP), and oscilloscope, these are the main tools that are connected to validate the genetic technique applied in the main system by applying the same cases already utilized in the simulation process.

An improvement of standalone wind turbine system employing the FCS-MPC methodology is also shown in this chapter. The improvement is based on the boost and inverter power circuits employing predictive control. The control system receives two voltage references: One to manage the dc-link voltage and the other to provide the desired output AC voltage. Therefore, by using such a control strategy, the system's time response can be accelerated, especially at various wind speeds. Additionally, the effectiveness of stated control mechanism is confirmed when the load changes unexpectedly. Tests are done on the suggested control strategy, and verified in a MATLAB/Simulink framework.

0.6 Chapter 5

This chapter includes validation of the system with experimental results according to the test bench utilized in the experimental work. The experimental test is applied to wide variety of configurations as the open loop, closed loop, cascaded (outer loop control-based PI controller, inner loop control-based PI controller) and the control law based on model free controller. There is another experimental test is applied according to the whole system connected to the grid. All these tests have been made in order to validate the simulation results that were produced before in this work.
Finally, a general conclusion for the different control techniques that are applied to the wind turbine system is determined.

1 State of art

Summary

1.1 State of Art

1.2 Overview of different wind generator systems and their comparisons

Different wind turbine models have been developed as a result of wind power technology quick development and large increase in installed wind power capability globally. Various wind generator systems comparisons are required because much more cost-competitive wind energy conversion technology is desired. There is a comparison of various wind generating systems and an overview of them. First, the control features and drive train types of modern wind turbines are categorized, and their advantages and disadvantages are discussed. Investigations are also conducted on the prospective permanent magnet generator types. The market breakthrough and quantitative comparison of several wind generator systems have taken place.

Finally, evolving trends of wind generator systems are reviewed along with suitable comparison standards. It has been demonstrated that power electronics and variable speed concepts will be the most effective and promising wind farm technology. Future wind turbine models' commercial viability may be significantly impacted by their capacity to satisfy both market demands and grid utility company standards.

Technology for converting wind energy has improved over time since the 1970s, but it really began to pick up speed in the 1990s. Numerous wind generator designs are produced, and different wind turbine concepts are being devised. There are now three different types of conventional generating systems for large wind turbines A. D. Hansen and Lars H Hansen 2007, Zhe Chen and Blaabjerg 2004, Blaabjerg, Zhe Chen, and Kjaer 2004, Harrison, Hau, and Snel 2000. The first kind is a fixed-speed wind turbine system that is directly connected to the grid and uses a multi-stage gearbox and a typical squirrel-cage induction generator (SCIG), and doubly fed induction generator (DFIG) with a multi-stage gearbox and variable speed wind turbine system is the other one, where stator winding of DFIG is directly connected to the grid and power electronic converter feeding rotor winding has a power rating of 30% of generator capacity. The third type of wind turbine is likewise variable speed, but it has a direct-drive generator instead of gears. Typically, a low-speed, high-torque synchronous generator and a full-scale power electronic converter are employed. Furthermore, a number of novel wind turbine concepts are emerging. One fascinating option would be a combined system that combines a gearbox with a minimal, low-speed permanent magnet synchronous generator (PMSG) Harrison, Hau, and Snel 2000, Siegfriedsen and Böhmeke 1998, Polinder, Van der Pijl, De Vilder, et al. 2006, owing to massive power levels and eliminating rotor speeds, direct-drive wind generators are growing larger and even more expensive. This chapter's primary goal is to offer a comprehensive overview of many types of wind generator systems that are already in use, potential generator configurations, and some comparisons of various systems for wind generator found in literature and on market. In this manner, the chapter is structured as follows: Initially, it provides analysis of several wind turbine designs, including potential direct-drive permanent magnet (PM) machine types, in terms of both their control capability and drive train kinds. Then, based on certain technical data from literature that is currently available, quantitative comparisons of various wind generator technologies are proposed, including their market penetration and share. After discussing appropriate comparison criteria for various wind generator systems, trends and advances of wind generator systems are provided. By moving on after that to analyse various control mechanisms for variable speed WECS and their classification.

Since 1973 oil crisis, which was brought on by a shortage of gasoline, development of renewable energy sources like wind energy has steadily accelerated. Kinetic energy of wind is converted into mechanical one by wind turbines.

Wind energy development gained widespread attention because of oil crisis. Distinctive mechanical utilization have been credited with its ongoing progress. This machine called a windmillHills 1996. The most reliable windmills were created in seventh century in Sistan, Iran Akhgari 2011. Dutch windmill was the primary one used in Europe during Middle Ages D'Ambrosio and Medaglia 2010. The first attempt to use a HAWT is to convert wind energy from mechanical to electrical power was made in Scotland in 1887. Charles Brush made an even larger attempt in Cleveland, Ohio, the following year Sine and B. H. Lee 2009.

Government and electrical industry regulations play a significant role in determining how quickly wind force will be embraced given the presence of significant wind resources. Denmark is attempting to generate 40% of its energy from wind turbines. The largest wind energy asset is in the UK, and it will soon undergo a significant extension to lower wind energy costs. Worldwide wind report was released by Global Wind Energy Council (GWEC). In 2016, more than 54 GW of wind energy were introduced to the market globally. According to GWEC's five-year gauge, there will be around 60 GW of new wind establishments by 2017, leading to an annual market of approximately 75 GW by 2021, resulting in the installation of more than 800 GW of installed capacity by the end of 2021. Chudnovsky 2019.

It is a well-established industry to harness wind power using contemporary turbines and energy conversion technologies. It is possible to create machines with ten watts to several megawatts of power and widths from a few centimetres to several hundred metres. Conventional mechanical-only equipment have been developed for water pumping, however generating electricity now prevails the market. Numerous countries of wind power potential, including those of Europe, United States, and parts of India and China, have embraced "wind turbine generators" as "mainstream generation" for utility grid networks; another countries are steadily improving their wind power output. Smaller wind turbine generators are frequently used for remote and independent power generation. Fast expansion of global power generation capacity from (2008-2018) is shown in Fig. 1.1 and fig1.2 Twidell 2006.

Wind turbines generate electricity by using the wind force to empower a generator Vickers 2017. The generator creates power and moves from the peak to an accessible transformer and changes from output voltage (generally around 700 V) to almost the nationwide grid (33000 V) or individual use (around 240 V) Saad and Asmuin 2014.

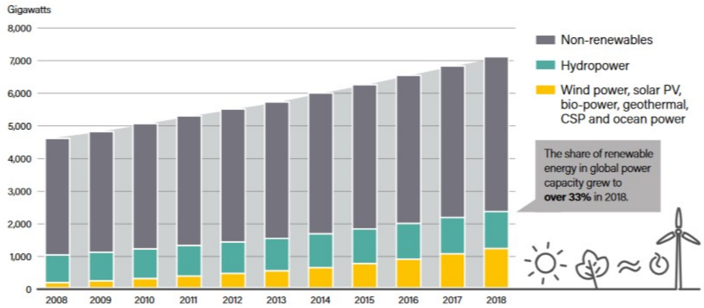

Figure 1.1: global capacity to generate electricity/MW Twidell 2006

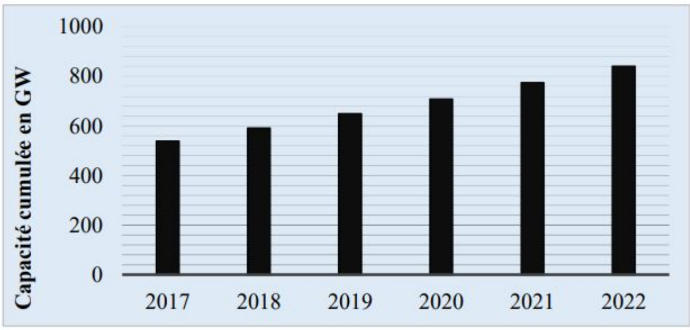

Figure 1.2: Projection of worldwide cumulative wind capacity installed from 2017 to 2022 Musial, Spitsen, Duffy, et al. 2022

Wind power is an appealing and elective force hot spot for all size forms of wind and convenient power age applications. one of the most significant focal points of wind energy is being modular and adaptable. Using wind has many symptoms like the dependence on petroleum derivative additionally is decreased. People pushing ahead into the 21st century with a forceful activity to quicken the advancement of wind innovation and further diminish its expenses, in order to make new openings, and improve natural quality. Onshore wind farms, that are considered to be the substantial installations of wind turbines situated on ground as shown in Fig.1.3, and there are establishments situated in bodies of water that indicates the offshore wind farms as shown in Fig.1.4. The wind farms (offshore and onshore) give two choices for producing a lot of energy. Onshore wind farms are now the most common worldwide, but offshore wind farm building is progressing in industrialised nations Zheng, C. Y. Li, J. Pan, et al. 2016. Wind forces, which can vary greatly across different geographic areas, have a significant impact on the capacity and efficiency of wind farms. Possner and Caldeira 2017. The consistency of the ability to generate energy is the key difference between offshore and onshore wind farms. Offshore wind farms have capability of producing electricity more steadily compared to their onshore counterparts Kaldellis and Kapsali 2013. In the other hand onshore farms need careful examination when choosing an area for development to make sure of wind speed sufficiency. One of the merits of onshore farms is that they have accessibility more than those placed in offshore environments, they are connected easily to local power grids Zheng, C. Y. Li, J. Pan, et al. 2016. The presence of established onshore farms also offers a number of resources for enhancing the effectiveness of wind farms and producing simulations that are as accurate as possible Zheng, C. Y. Li, J. Pan, et al. 2016. One of the major issues associated with the growth of onshore farms is noise pollution and its impact on people Nissenbaum, Aramini, Hanning, et al. 2012. Onshore wind turbines impact on health are not supported by sufficient data Rubin, Burns, Wessely, et al. 2014. One of the most important factors in cost comparisons between offshore and onshore farms is their location. For the time being, onshore farms are far less expensive to build and maintain than offshore farms Clancy, Gaffney, Deane, et al. 2015. Onshore farm is an affordable wellspring of electric power, serious than coal or gas plants Neslen 2014, Walwyn and Brent 2015, Gasch and Twele 2010. Offshore farm is more steady and solid than onshore, they have less visual effect, development and maintenance costs are much higher than onshore development and maintenanceGipe 1993. Therefore, offshore farms are at present falling behind onshore farms Clancy, Gaffney, Deane, et al. 2015.

Figure 1.3: Onshore wind farm Musial, Spitsen, Duffy, et al. 2022

1.3 Wind turbine control: Trends and Challenges

In order to meet goals of getting 100% renewable energy by 2050, various nations have defined their targets to get their energy from renewable sources. For instance, Denmark has committed to getting its energy from renewable sources by 2050. Various types of renewable energy sources such as wind, waves, and geothermal heat are expected to contribute significantly to the energy supply of nations in the future. For instance, Denmark has committed to getting its energy from renewable sources by 2050. Mathiesen, Lund, Connolly, et al. 2015. Among these renewable power sources around the world. The usage of wind power generation is extending rapidly.

Figure 1.4: Offshore wind farm Musial, Spitsen, Duffy, et al. 2022

1.3.1 Generator types and concepts for wind energy

Wind turbine concepts can be divided into fixed speed, limited variable speed, and variable speed according to the rotational speed. Variable speed wind turbines can be further divided into wind generator systems with a partial scale and a full scale power electronic converter based on the rating of power converter related to generator capacity. Concepts of wind turbines can also be divided into geared drive and direct-drive wind turbines based on the parts of drive train. In geared-drive wind turbines, there are two common configurations: one has a single stage gear and a low-speed generator; the other one has a multiple-stage gear and a high-speed generator. Siegfriedsen and Böhmeke 1998. This section describes the fundamental setups and features of various wind generation systems in accordance with modern wind turbine principles.

1.3.1.1 Fixed speed concept

A multiple-stage gearbox and SCIG that is directly connected to grid via transformer have been employed with fixed speed wind generator systems. As illustrated in Fig.1.5. A wind turbine which is fitted with this kind of generator can be referred by fixed-speed wind generator system since SCIG only operates in a constrained range around the synchronous speed. During the 1980s and 1990s, several Danish wind turbine manufacturers used this standard concept: an upwind, stall-regulated, three-bladed wind turbine employing a SCIG Lars Henrik Hansen, Helle, Blaabjerg, et al. 2001, A. D. Hansen and Lars H Hansen 2007. Consequently, it is usually known as "Danish notion." This idea was expanded with a capacitor bank for reactive power compensation in the 1980s because SCIG always draws reactive power from the grid. A soft-starter was used to achieve a smoother grid connection. A pole-changeable SCIG has been employed also, leading two different rotational rates. This idea has been used in products from some manufacturers, including Micon (now incorporated into Vestas), Bonus (today Siemens), Made, and Nordex.

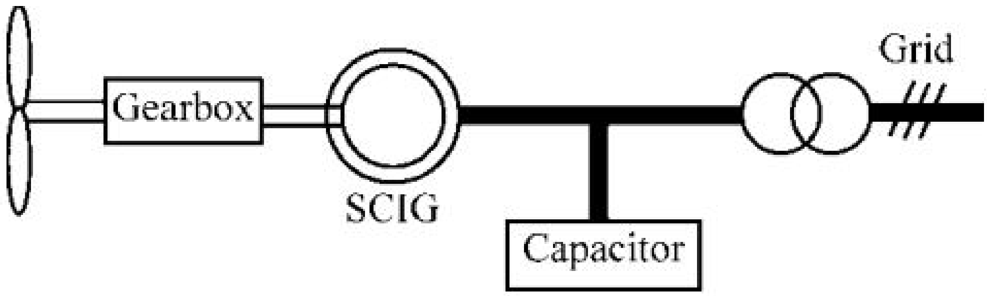

Figure 1.5: Fixed speed concept with SCIG system scheme M. Cheng and Zhu 2014

The robustness, simplicity, and affordability of SCIG are well-known benefits for mass production. Additionally, when it is coupled to a big grid, which offers a consistent control frequency, it allows stall-regulated machines to run at a constant pace. Although the active stall control or pitch control have been employed, the stall control approach is typically used with the fixed speed SCIG for power control. The following references are some drawbacks of SCIG for fixed speed wind turbine idea Soens 2005, Lars Henrik Hansen, Helle, Blaabjerg, et al. 2001, A. D. Hansen and Lars H Hansen 2007. Only speeds higher than the synchronous speed are feasible for generator operation within the relatively small range in which the speed is neither regulated nor variable. The slip is often not higher than 1 percent for 1 MW wind turbines because a higher slip indicates a higher dissipation of electrical energy, like what happened in rotor bars Polinder and Morren 2005. Furthermore, fixed speed concept causes high mechanical and fatigue stresses on the system (turbine blades, gearbox, and generator) and may lead to swing oscillations between the turbine and generator shaft. As a result, wind speed variations are directly translated into electromechanical torque variations. Additionally, speed fluctuations do not dampen the periodic torque dips caused by tower shadow and shear effect, which increases flicker. Additionally, in order to maximise aerodynamic efficiency, the turbine speed cannot be changed in response to wind speed. Despite being employed in some commercial wind turbines, a pole-changeable SCIG does not offer constant speed variations. For this wind turbine idea, the drive train needs a three-stage gearbox. The nacelle's gearboxes account for a sizable portion of investment expenses as well as its mass. Excitation current must be obtained from SCIG stator terminal. Therefore grid voltage control is not practicable. In order to account reactive power consumption, capacitors are typically linked in parallel with the generator.

1.3.1.2 Limited variable speed concept

The Opti-slip concept, also known as the limited variable speed concept with a multiple-stage gearbox, has been utilized by Danish manufacturer Vestas since mid-1990s Polinder and Morren 2005, Lars Henrik Hansen, Helle, Blaabjerg, et al. 2001.

This wind turbine design makes use of a power electronic converter and pitch control method to operate wound rotor induction generator (WRIG) with variable rotor resistance, as shown in Fig.1.6. Manufacturers of Vestas and Suzlon currently have products built around this idea.

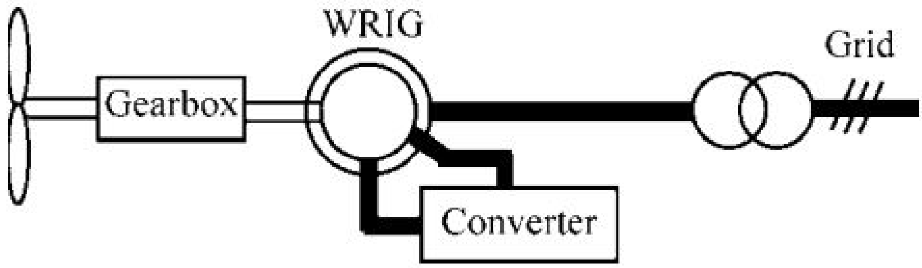

Figure 1.6: Limited variable speed concept(Optislip) with WRIG system scheme M. Cheng and Zhu 2014

While rotor winding of WRIG is connected in series with regulated resistor, the stator is connected directly to grid. Controlling energy collected from the WRIG rotor can result in variable-speed operation, but this power needs to be lost in the external resistor. A larger slip indicates a higher power drawn by the rotor and a lower generator efficiency as the variable speed range expands, necessitating an increase in resistor rating. Therefore, the size of variable rotor resistance determines the dynamic speed control range, and energy removed from the external resistor is also lost as heat in controllable rotor resistance. Typically, a limited variable speed range is just 10% faster than synchronous speed Soens 2005, Lars Henrik Hansen, Helle, Blaabjerg, et al. 2001, Li and Chen 2008. Additionally, slip rings may be avoided; for instance, the power converter and resistor were incorporated inside the rotor of wind turbine manufactured by Vestas, and control signals were sent to revolving electronics via an optical link. For this idea, a soft-starter and reactive power correction are also necessary.

1.3.2 Speed-variable partial-scale power converter design

WRIG and partial-scale power converter on the rotor circuit are part of this arrangement, which is also referred to DFIG concept, as illustrated in Fig.1.7. While the rotor is connected to grid via power electronic converter, the stator is connected directly to grid. Rotor frequency and rotor speed are both managed by power converter. Depending on the size of frequency converter, this concept can operate at a variety of speeds. The variable speed range is typically +30% of synchronous speed. Svensson 1998, Li and Chen 2008, Lars Henrik Hansen, Helle, Blaabjerg, et al. 2001, Soens 2005, Lars Henrik Hansen, Helle, Blaabjerg, et al. 2001. Power electronic converter's rating is only 25 to 30 percent of the generator's capacity, which makes this idea appealing and well-liked from an economic standpoint. This idea is used in the market by numerous firms, including Vestas, Gamesa, Repower, and Nordex. Re-commercial power's wind turbine product with DFIG has a maximum capacity of up to 5 MW. Unlike Optislip concept, the power electronic converter allows rotor energy to be fed into grid rather than of being wasted. As an example, the grid-side converter can adjust its reactive power independently of generator operation, enabling execution of voltage support towards the grid. In addition, the power converter system can perform reactive power compensation and smooth grid connection. However, DFIG system has the drawbacks described obviously in the following references Lars Henrik Hansen, Helle, Blaabjerg, et al. 2001, Soens 2005, Lars Henrik Hansen, Helle, Blaabjerg, et al. 2001, Soens 2005. As a result of the speed range for DFIG is much greater than the typical turbine speed range of 10 to 25 rpm, a multi-stage gearbox is still required in the drive train. It goes without saying that a gearbox will have some downsides, like heat generation from friction, ongoing maintenance, and loud noise. Through employment of a partial-scale converter, which requires routine maintenance and could lead to equipment failures and electrical losses, slip ring is utilised to transfer the rotor power. As an example, during grid fault conditions, big stator currents lead to huge rotor currents, necessitating protection of power electronic converter; while on the other hand, large stator peak currents may result in high torque loads on the wind turbine drive train. Due to grid connection requirements for wind turbines, the accompanying control techniques may be challenging because during grid disturbances, a ride-through capability of DFIG is also required.

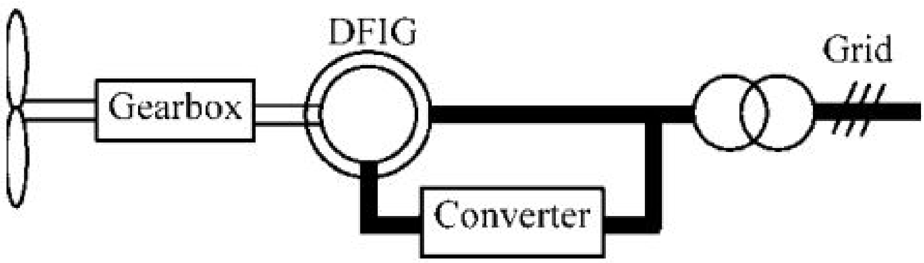

Figure 1.7: Variable speed concept with DFIG system Scheme M. Cheng and Zhu 2014

1.3.2.1 Variable speed direct-drive concept with full-scale power converter

This arrangement might be comparable to a wind turbine with variable speed and a direct-drive generator linked to grid via a full-scale power converter. Generator rotor speed is the primary distinction between geared drive wind turbines and direct-drive models. As the generator rotor is directly mounted on the hub of turbine rotor, the direct-drive generator revolves at a low speed. Due to the reduced speed, a higher torque must be generated in order to give a certain amount of power. Larger generator is required for a higher torque. A higher torque necessitates a larger machine's space for a larger direct-drive generator, and given the current loading and gap flux density constraints, the torque density could not be further significantly increased. Direct-drive generators are typically built with a large diameter and small pole pitch to improve efficiency, reduce the weight of active parts, and minimise end winding losses M. R. J. Dubois 2004,Grauers 1996. Direct-drive wind turbines also have the benefit of a streamlined drive train, high overall efficiency, high dependability, and availability due to absence of the gearbox. Full-scale power converter can execute seamless grid connection over complete speed range, in contrast to variable speed approach with a partial-scale power converter. Since the power converter must handle all of generated power, it is more expensive and results in larger power losses in power electronics. Electrically excited synchronous generator (EESG) and permanent magnet synchronous generator (PMSG) are the two main categories of direct-drive generators found in market. The following section provides an overview of EESG's key characteristics. After the key features of EESG that are discussed in the preceding section, the features of several PMSG topologies are offered.

1.3.2.2 Electrically excited synchronous generator

The field system carrying rotor for EESG is often equipped with a DC excitation. Three-phase winding in the stator is quite similar to that in the induction motor. The rotor could be cylindrical or feature prominent poles. Salient poles may be the most practical version for usage with direct-drive wind turbines because they are more common in low-speed machines. An EESG grid connection plan for wind turbines with direct drives is shown in Fig.1.8. The power electronics at the generator side can fully adjust the voltage's amplitude and frequency, making generator speed entirely controllable over a large range, even at extremely low rates. Additionally, excitation current can be regulated by utilizing power converter on the rotor side, EESG has the ability to manage flux for a minimised loss in various power ranges. Furthermore, it is not necessary to use PMs, which would substantially increase generator costs and risk performance degradation under adverse air conditions. Consequently, it is the most popular form of direct-drive generator that is currently available Bywaters, John, Lynch, et al. 2004. The typical manufacturer is Enercon, and the direct-drive EESG's maximum capacity has reached 4.5 MW. Some drawbacks of direct-drive EESG systems, including those of direct-drive wind turbines as opposed to geared-drive wind turbines, can be summed up in the following references M. R. J. Dubois 2004,Grauers 1996. Higher number of parts and windings undoubtedly make a heavy weight and expensive option as the pole pitch needs to be large enough to accommodate excitation windings and pole shoes for the large diameter-specific design. Rotor winding must be excited with DC, either using slip rings, brushes or revolving rectifier as a brushless exciter, and as well as field losses are required.

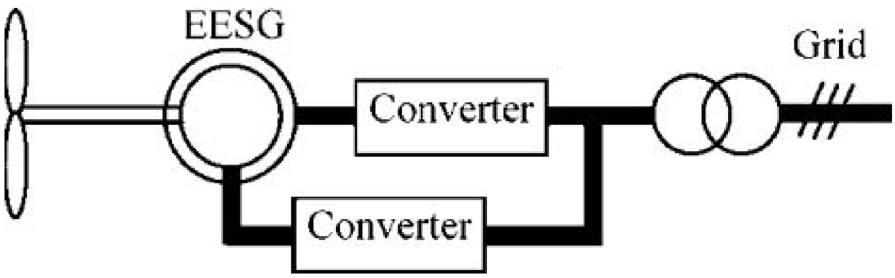

Figure 1.8: Direct-drive EESG system scheme M. Cheng and Zhu 2014

1.3.2.3 PM synchronous generator

Grid-connected PMSG for direct-drive wind turbines is illustrated in Fig.1.10. According to literature, the benefits of PM machines versus electrically excited machines can be summed up as follows: [M. R. J. Dubois 2004,Grauers 1996, Hanitsch and Korouji 2003, Versteegh 2004, Yicheng Chen, Pillay, and Khan 2005, J. Chen, Nayar, and Longya Xu 2000, Aydin, Huang, and Lipo 2004, M. R. Dubois 2000]. Improved thermal properties of PM machine due to absence of field losses, improved durability due to absence of mechanical components like slip rings, higher power to weight ratio, higher efficiency and energy yield, and no additional power source for magnet field excitation. However, there are several drawbacks for using PM machines, which can be summed up as follows: expensive PM material, manufacturing challenges, and demagnetization of PM at high temperatures. Fig. 1.9 depicts a WECS with an outer rotor PMSG that is driven directly.

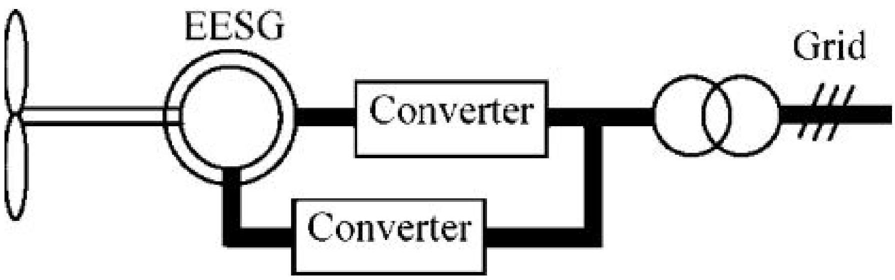

Figure 1.9: Direct-drive WECS with outer rotor PMSG M. Cheng and Zhu 2014

Because of improved performance and declining costs, PMs utilization has been more appealing recently than it was in the past. The patterns increase the appeal of PM machines with a full-scale power converter for direct-drive wind turbines. Currently, 2

MW wind turbines on the market from Zephyros (formerly Harakosan) and Mitsubishi use this idea. In order to accommodate different typologies, PM machines, which are not your typical off-the-shelf machines, offer a considerable flexibility in their shape. Based on the direction of flux penetration, PM machines can be categorised into three different types: radial flux, axial flux, and transversal flux. Several fundamental literary motifs and structures [M. R. J. Dubois 2004,Grauers 1996, Hanitsch and Korouji 2003, Versteegh 2004, Yicheng Chen, Pillay, and Khan 2005, J. Chen, Nayar, and Longya Xu 2000, Aydin, Huang, and Lipo 2004, M. R. Dubois 2000, Widyan 2006, Parviainen et al. 2005, Lampola et al. 2000, Böhmeke, Boldt, and Beneke 1997] are simply summarised and described as follows: PMs of radial-flux devices. The wind generator system can function well across a wide speed range when radial-flux PM (RFPM) machines are used for direct-drive wind turbines. Gluing PMs to the rotor surface is the easiest approach to build a machine with a lot of poles when it is being manufactured. Both machine length and air-gap diameter can be selected individually in RFPM machines. If required, a long machine can be used to create a radial-flux machine with a tiny diameter. Since RFPM machines have advantage over EESGs in terms of torque density, several literatures have studied various RFPM machine types. References have largely explored two types of RFPM machines: slotted flux concentrating PM machine and slotted surface mounted PM machine [M. R. J. Dubois 2004,Grauers 1996,Hanitsch and Korouji 2003, Versteegh 2004,Yicheng Chen, Pillay, and Khan 2005,J. Chen, Nayar, and Longya Xu 2000,Aydin, Huang, and Lipo 2004, M. R. Dubois 2000]. Two rotor designs: one with flux concentration and one with surface-mounted magnets. Due to requirement of magnets on rotor surface that have permanent flux density greater than the necessary air-gap flux density, the rotor design is fairly straightforward and light in weight. M. R. J. Dubois 2004,Grauers 1996,Lampola et al. 2000,J. Chen, Nayar, and Longya Xu 2000 have discussed RFPM machines with surface-mounted magnet, This appears to be sensible option for the design of big direct-drive wind turbinesM. R. J. Dubois 2004,Grauers 1996. Flux concentration RFPM devices have been discussed and contrasted with surface-mounted RFPM devices in J. Chen, Nayar, and Longya Xu 2000,Aydin, Huang, and Lipo 2004,M. R. Dubois 2000,Spooner and Williamson 1996. A stand-alone outer rotor design for this type of generator has also been described by Chen et al.J. Chen, Nayar, and Longya Xu 2000. According to this source, the outer-rotor RFPM machine has a number of benefits. For instance, as compared to inner-rotor construction, the multi-pole structure can be readily accommodated thanks to the larger outer-rotor drum perimeter, which shortens the overall length of magnetic path. Due to the rotor's direct exposure to wind, the magnets' cooling conditions can be increased, increasing their resistance to demagnetization due to temperature. Additionally, Chen et al. Yicheng Chen, Pillay, and Khan 2005 have contrasted various PM wind generating architectures. Additionally, Hanitsch and Korouji Hanitsch and Korouji 2003 have developed rare-earth RFPM wind-energy generator with novel topology that consists of two rotors and one stator with short end windings. This generator is described in Hanitsch and Korouji 2003. By lowering the weight, raising efficiency, and lowering price of the active materials, it can enhance machine's performance. Axial-flux PM apparatuses A machine that produces magnetic flux in axial direction as opposed to the radial direction is known as axial-flux PM (AFPM) machine. The slot-less and slotted surface-mounted PM are the two AFPM machine types that have received the greatest attention in the literature.

The benefits of AFPM machines can be summed up as follows as compared to RFPM machines: simple winding, minimal cogging torque and noise (in slotless machines), short axial length, higher torque/volume ratio. However, AFPM machines have the following drawbacks as compared to RFPM machines: Bianchi and Lorenzoni 1996,M. R. Dubois 2000,Widyan 2006,Parviainen et al. 2005,Lampola et al. 2000: The slotless machine has lower torque/mass ratio, larger outer diameter, a lot of PM, and structural instability. The slotted machine has harder time keeping air gap with larger diameter, and it has harder time producing stator core. In certain references, various AFPM machine structures with surface-mounted PM have also been shown, along with discussions on viability and potential of AFPM machines for large-scale direct-drive wind turbines. Parviainen et al. 2005,Aydin, Huang, and Lipo 2004,Yicheng Chen, Pillay, and Khan 2005. Spooner and Chalmers Bang, Polinder, Shrestha, et al. 2008 and Wu et al. Wu, Spooner, and Chalmers 1995,Wei Wu, Spooner, and Chalmers 1995 have also studied slotless, toroidal-stator AFPM generator, which offers a number of benefits including lightness, compactness, short axial length, appropriate integration with engine, and others. The machine often has good power to weight ratio due to its short axial length. Additionally, five different AFPM machine typologies, including slot-less single-stator double-rotor (Torus machine), single-sided AFPM with stator balance, single-sided AFPM with rotor balance, double-stator slotted type, and double-rotor slotted type, have been researched and compared with RFPM machines by Chen et al. Yicheng Chen, Pillay, and Khan 2005. According to Yicheng Chen, Pillay, and Khan 2005, one-sided constructions consume less copper and have smaller conduction loss, so the two-sided AFPM machine is preferable to the one-sided AFPM machine. The Torus is built simply, but because there is greater air gap to accommodate stator windings, it requires a heavier magnet. The air gap and air gap reluctance grow higher as the power rating rises, making this architecture more appropriate for wind turbines with lower power ratings. Additionally, the low speed, direct-drive axial flux PM wind generator's potential use of soft magnetic composite (SMC) material was also examined. by Chen et al.Yicheng Chen and Pillay 2005. On numerous configurations of PM generators having both lamination core and SMC core, comparative design studies have been done.

1.3.2.4 Concept for full-scale power converter and single-stage geared motor with variable speed

A low-speed permanent-magnet generator and single-stage planetary gearbox that boosts speed by a factor of about 10 are both coupled to wind turbine with variable speed pitch control in this system. The concept's grid connecting scheme is shown in Fig.1.11. With the advantages of greater speed than the direct-drive concept and smaller mechanical component than the multiple-stage gearbox concept, this idea, which was first presented as the Multibrid, has drawn interest. This idea has in-

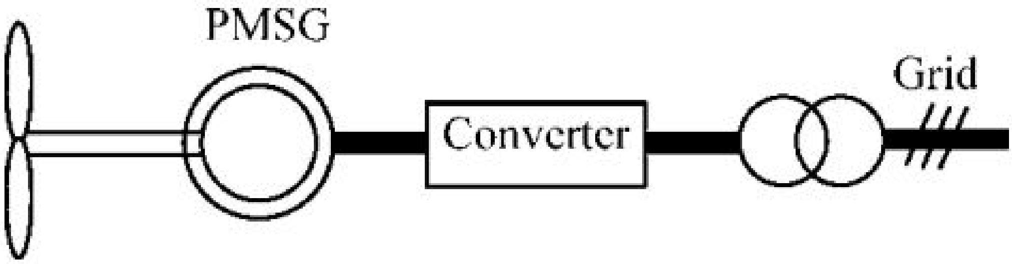

Figure 1.10: Direct-drive PMSG system scheme M. Cheng and Zhu 2014

spired devices from wind turbine manufacturers like Multibrid and WinWind that are currently on the market. The Clipper system has also been introduced; it is a single-stage gearbox with numerous output shafts that drives a number of medium-speed, medium-torque PMSGs. A specific power electronic converter is attached to each of the generator outputs. With a rated power of 2.5 MW, the Clipper system concept is currently employed in the market (four 660 kW PMSGs). Dismukes, Miller, Jagani, et al. 2007.

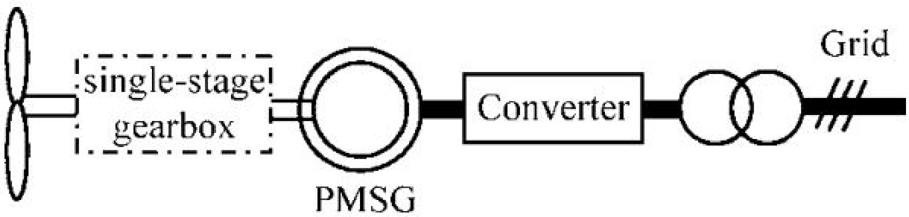

Figure 1.11: Single-stage drive PMSG system with a full-scale converter scheme M. Cheng and Zhu 2014

1.3.2.5 Full-scale power converter with numerous stages of variable speed gearing concept

In variable speed wind turbine ideas with full-scale power converter, the generator's volume is reduced and its efficiency is increased by using a PMSG system with multiple gearboxes. Fig.1.12 demonstrates this concept's grid connecting technique. The advantages of this wind generator technology over the DFIG system are as follows: The generator is more effective. The generator might not have brushes. The ability to ride through a grid fault is less complicated. Moreover, the following drawbacks: All powers are processed by the power electronic converter, the converter is bigger, more expensive, and has higher losses (100 percent of rated power as opposed to 30 percent). This arrangement has been employed in GE's multi-megawatt series on the market.

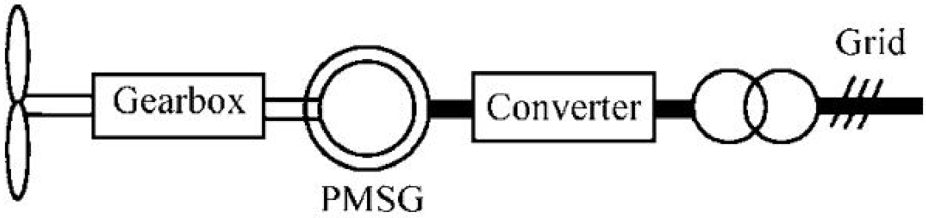

Figure 1.12: Scheme of multiple-stage geared PMSG system with full-scale converter M. Cheng and Zhu 2014

1.3.2.6 SCIG system

A variable speed multiple-stage geared SCIG with full-scale converter might be utilized instead of the capacitor bank and soft-starter of "Danish concept" in order to complete the variable speed operation with SCIG as shown in Fig.1.13.

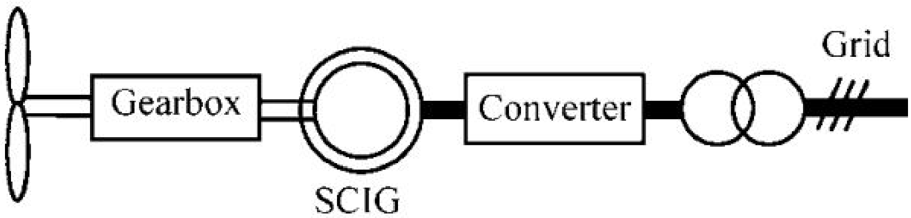

Figure 1.13: Scheme of multiple-stage geared SCIG system with full-scale converter M. Cheng and Zhu 2014

As previously indicated, this approach provides advantages over the "Danish model" in terms of flexible control with full-scale power, including variable speed operation, improved reactive power adjustment capabilities, and smooth grid connection. The gearbox induction generator and converter's combined efficiency may be low due to high cost and losses of full scale converter. The market is now being utilized by Siemens with rated power of 3.6 MW and generator speed range of 595-1547 rpm. Variable speed multiple-stage geared designs (both PMSG and SCIG, as noted above) may be more appealing due to the falling cost of power electronics (approximately a factor of 10 over the previous 10 years) and the absence of brushes.

1.3.2.7 Comparison of various wind power systems

Some academics have made some comparisons between various wind generator systems Siegfriedsen and Böhmeke 1998,Polinder, Van der Pijl, De Vilder, et al. 2006,Lars Henrik Hansen, Helle, Blaabjerg, et al. 2001,Polinder and Morren 2005,Li and Chen 2008,Svensson 1998,Grauers 1996,Yicheng Chen, Pillay, and Khan 2005,Bianchi and Lorenzoni 1996,Parviainen et al. 2005,Price, Bunn, Probert, et al. 1996,Böhmeke, Boldt, and Beneke 1997,Poore and Lettenmaier 2003. Grauers Grauers 1996 has offered a quantitative comparison between the fixed-speed approach with SCIG and the variable speed direct-drive concept of RFPM generator system with forced-commutated rectifier. For two rated power levels of 500 kW and 3 MW, some key parameter comparisons are correspondingly, shown in Table 1.1. According to Grauers 1996, The direct drive PMSG's outer diameter is almost twice that of the traditional geared-drive SCIG, but the system's overall length—including length of high-speed shaft—is two to three times shorter. Additionally, at 500 kW and 3 MW rated power respectively, the direct-drive PMSG system's average efficiency is 2.3 percent and 1.6 percent greater than the fixed speed SCIG system. Direct-drive PMSG system may generate 5 to 10 percent more energy than the fixed two-speed idea or 10-15 percent more than the fixed single-speed concept thanks to its variable speed operation. Annon Price, Bunn, Probert, et al. 1996 has made several comparisons between the standard geared-drive SCIG and the direct-drive PMSG of commercial 500 kW wind turbines. Direct-drive PMSG and EESG comparison reveals that the active material cost of PMSG is lower. This is mostly because PMSG has smaller pole pitch and allows for setting a greater number of poles for a given diameterM. R. J. Dubois 2004,Grauers 1996,M. R. Dubois 2000.

1.3.2.8 Market share of various wind turbine ideas

There are numerous varieties of wind turbines available, each with a distinct level of power. Some wind turbines with rated powers over 2 MW from various manufacturers, including Vestas, Gamesa, GE Wind, Repower, Nordex, and others, are used to demonstrate market trends for various wind generator systems. Information about the wind turbine concept, generator type, rated power, and turbine rotor speed was gathered from websites of the manufacturers Gaur, Choudhary, and Sharma 2014,Gaur, Choudhary, and Sharma 2014,Li and Chen 2008,Li and Chen 2008,Dismukes, Miller, Jagani, et al. 2007,Dismukes, Miller, Solocha, et al. 2008,M. Cheng and Zhu 2014,S. Li and Haskew 2008. Future trends in wind turbine industry will likely focus on the steady advancement of currently known technologies due to rapid growth of wind turbine technology. These trends can be summed up as shown in the following references Zhe Chen 2005,Sø rensen, Bak-Jensen, Kristiansen, et al. 2001,A. D. Hansen and Lars H Hansen 2007,Soens 2005. As a result of that, the cost of putting wind turbines will become lower, especially for offshore wind farms and the power output of a single wind turbine will continue to rise. Since there is more space and stronger winds offshore than onshore, it is more appealing. Dispersed single wind turbines are increasingly being replaced by concentrated wind turbines in sizable wind farms.

1.3.2.9 Conclusion on these generator types

This chapter offers a summary of several wind turbine theories and potential generator kinds. Based on modern wind turbine principles, the fundamental setups and traits of various wind generator systems are discussed, along with benefits and drawbacks. Surveys have been conducted on the promising direct-drive PM machines, including the AFPM, RFPM, and TFPM machines. Based on a survey of quantitative comparison for various wind generator systems as well as their market penetration, a thorough analysis has been carried out. It has been examined how wind generator systems are evolving and offered some comparative criteria. In recent years, PM performance and cost has improved, increasing the appeal of variable speed direct-drive PM machines with a full-scale power converter more attractive for offshore wind power generations.

1.3.3 Overview of several control techniques for WECS with variable speed

1.3.3.1 Introduction and context

An extensive analysis of the most recent developments in wind energy conversion systems (WECS) and technologies is presented here, with a focus on wind power generation and control. First, many typical WECS kinds are categorised in accordance with their features and drive train types. Volume, weight, cost, efficiency, system dependability, and fault ride through capability of WECSs are compared. In variable speed WECSs, maximum power point tracking (MPPT) control, which attempts to make generator speed meet an ideal value to assure the greatest energy yield, is crucial. The four most widely used MPPT control methods are thoroughly examined, compared, and improvements for each method are offered. The most recent advances in wind energy conversion technology are also covered, including brushless doubly fed induction generator (BDFIG), stator permanent magnet synchronous generators, magnetic-geared generators, dual power flow WECS with the electrical variable transmission (EVT) machine, and direct grid-connected WECS. Discussion of future technological trends is concluded.

Traditional WECSs can be divided into the following categories based on rotational speed and drive train types: constant speed WECS with multiple stages of gearing; limited variable speed WECS with multiple stages of gearing; variable speed WECS with multiple stages of gearing; variable speed direct-drive WECS; and variable speed WECS with a single stage of gearing.

1.3.3.2 MPPT control strategies in variable speed WECSs

In order to make the most out of wind power. When the wind speed is less than the rated speed, MPPT control for variable speed WECs becomes essential. The produced wind turbine mechanical power can be given Dahbi, Hachemi, Nait-Said, et al. 2014 as shown in the following :

$P = \rho \pi R^2 C_p(\lambda, \beta) v^3 / 2(1)$

where ρ refers to air density, R is the radius of turbine blades, v is identified by wind velocity, and C_p is the power coefficient which is nonlinear function of tip speed ratio k and blade pitch angle b. K is defined as:

$\lambda = \omega * R / v(2)$

Fig.1.14 shows the curve of C_p versus λ. It is clear that there is a value of λ, for which C_p is maximized, thus maximizing the power for given wind speed Zhu, M. Cheng, W. Hua, et al. 2012. Then the variable speed WECS follows the maximum C_p to capture the maximum power by varying rotor speed to keep the system at the optimum TSR $\lambda_o pt$. To keep the wind turbine at the optimum TSR, By altering the generator's torque, wind turbine's speed can be managed. As a result, several MPPT algorithms have been created and can be divided into four categories: Hill climb searching (HCS) control, optimal TSR control, power feedback control and fuzzy-logic based controlZhu, M. Cheng, W. Hua, et al. 2012,Shirazi, Viki, and Babayi 2009,Musunuri and Ginn 2011. Since each method has merits and demerits of its own, numerous modifications of these systems have been suggested throughout the years to address the pertinent deficiencies in various ways.

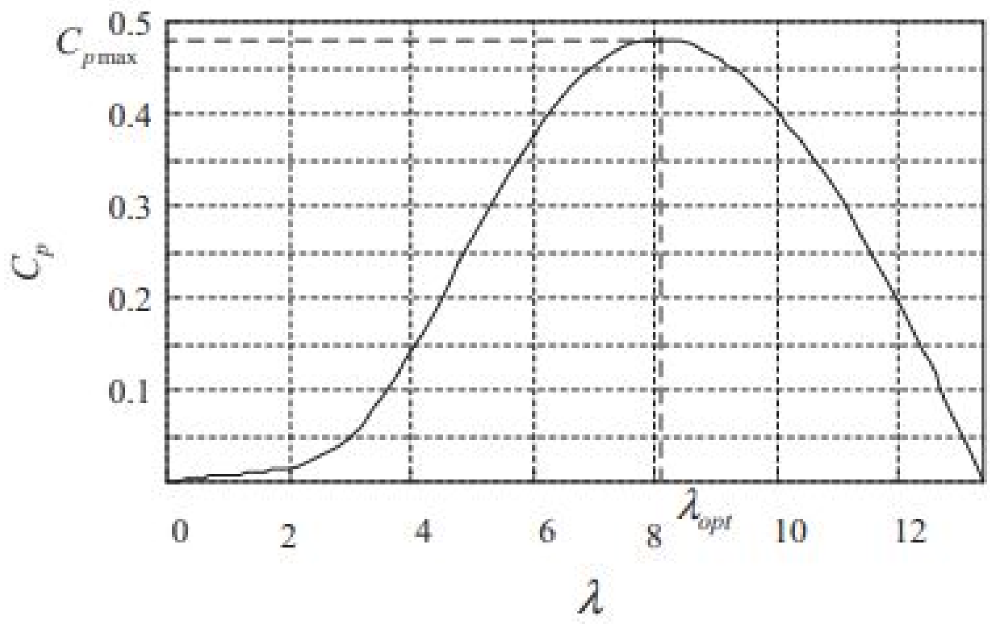

Figure 1.14: Power coefficient curve versus TSR λ M. Cheng and Zhu 2014

1.3.3.3 Optimum TSR control

In order to maintain an ideal TSR, the optimal TSR control modifies the wind turbine rotor speed, as shown in Fig.1.15. The wind speed and turbine speed must both be measured when using the MPPT approach. An anemometer is typically used to measure wind speed, which raises system costs and makes it nearly impossible to really get an accurate reading. Additionally, the characteristic of the wind turbine, which varies from system to system, is also crucial. Therefore, despite the fact that the control strategy is very straight-forwarded, the optimum TSR MPPT method is rarely used in the actual WECSs.

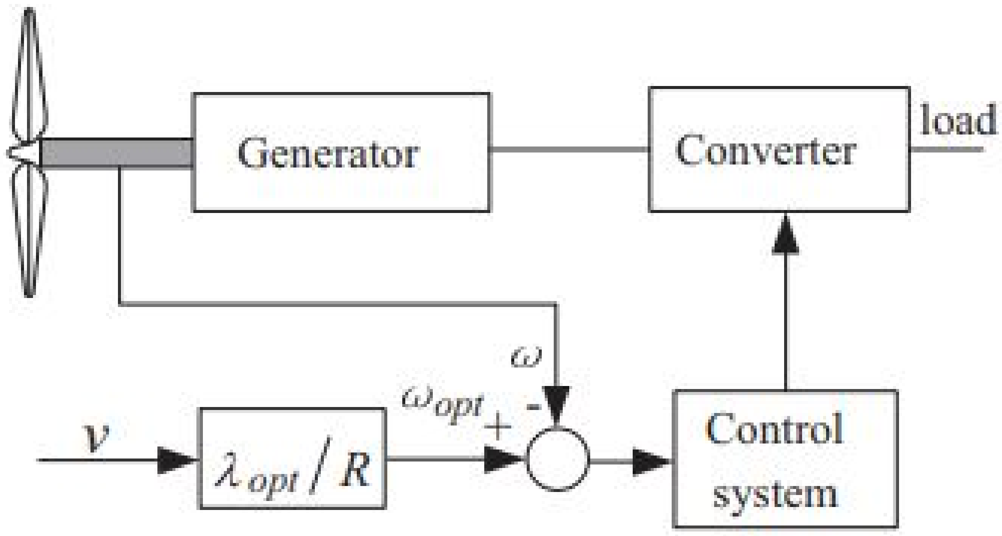

Figure 1.15: Control diagram of optimum TSR MPPT method M. Cheng and Zhu 2014

1.3.4 Power feedback control

Without the requirement for wind speed, the power feedback MPPT control is accomplished based on calculations of the generator speed; nonetheless, the parameters of wind turbine and generator speed are essential. The two categories of this method are the best torque feedback control and the best power feedback control. However, both control strategies are fundamentally the same. The results of equations (1) and (2), the optimum power and torque output by the wind turbine are given by Dahbi, Hachemi, Nait-Said, et al. 2014.

$$P_{\text{opt}} = \rho\pi R^5 C_{p\max}\omega_{\text{opt}}^3 / 2\lambda_{\text{opt}}^3 = k_{\text{opt}}\,\omega_{\text{opt}}^3 \ldots.(3)$$
$$T_{\text{opt}} = \rho\pi R^5 C_{p\max}\omega_{opt}^2 / 2\lambda_{\text{opt}}^3 = k_{\text{opt}}\,\omega_{opt}^2 \ldots.(4)$$

where k_{opt} is the factor determined by wind turbine characteristics. Equations (3) and (4) have relationship that shows that the ideal power and torque corresponding to the ideal generator speed that can be shown in Fig.1.16. intuitively Dahbi, Hachemi, Nait-Said, et al. 2014. In other words, the wind turbine can produce its greatest amount of power and torque when the generator speed is at its ideal level. The control diagram of conventional MPPT control techniques for optimum power feedback and optimum torque feedback is shown in fig.1.17 respectively. The classic power feedback control method has two main flaws: (1) There is no precise way to calculate the factor k_{opt} since blade aerodynamics can change dramatically over time. (2) Wind speed fluctuations make it impossible to estimate the generator speed precisely and force the wind turbine to operate off the peak of its Cp curve for the majority of time, even when the k_{opt} can be precisely calculated by simulation or tests. Due to the drawbacks of conventional power feedback control, experts have suggested a number of efficient ways to make improvements. It was suggested to utilize sliding mode power feedback MPPT approachBeltran, Ahmed-Ali, and Benbouzid 2008, as it can minimize the detrimental effects of both the unknown k_{opt} and the altered optimal operating point brought on by turbulence in wind speed. In S Masoud Barakati, Kazerani, and Aplevich 2009, It was suggested to replace the need for a shaft speed sensor with a mechanical speed-sensorless power feedback control using a matrix converter (MC). It was suggested to use unique MPPT control with adaptive compensating control C.-T. Pan and Juan 2009, according to the best torque feedback management. Based on adaptive control, it is possible to enhance dynamic response and increase wind energy capture during wind speed variations. The most effective current MPPT technique based on Dahbi, Hachemi, Nait-Said, et al. 2014 was proposed with considering system torque losses, consequently the efficiency of wind energy conversion is increased.

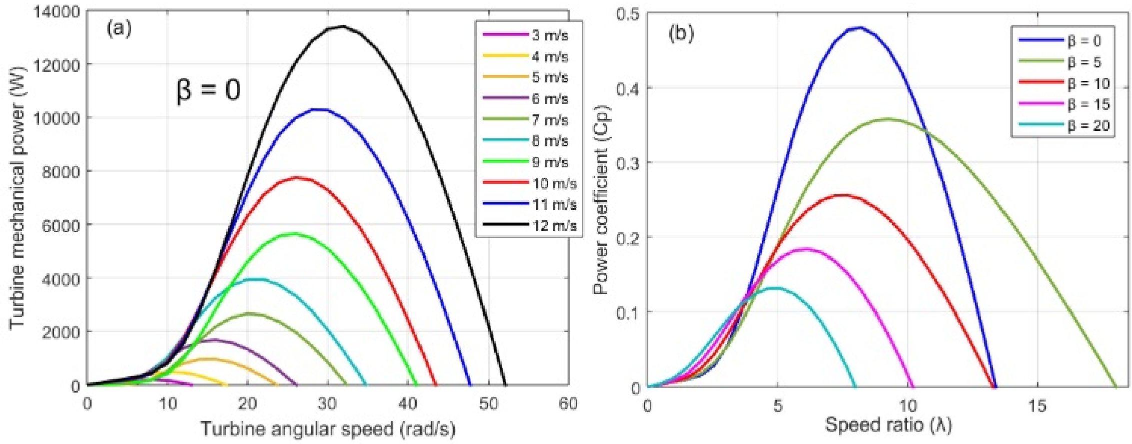

Figure 1.16: Wind Turbine Characteristics

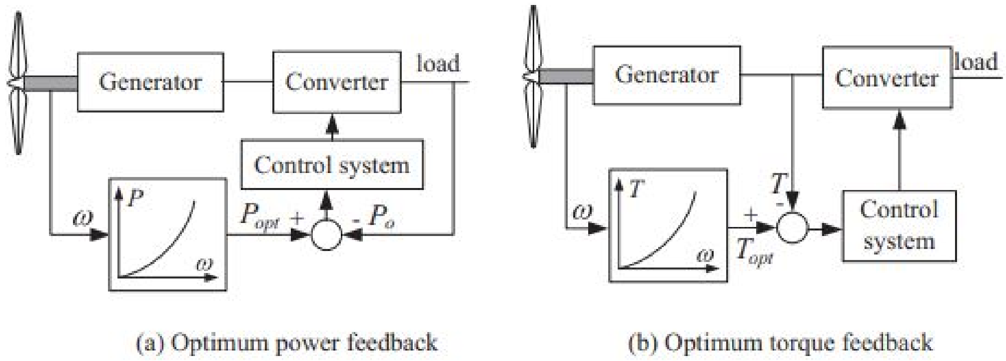

Figure 1.17: Control diagram of power feedback MPPT method M. Cheng and Zhu 2014

1.3.4.1 Hill climb searching control

The perturb and observe (P and O) method, also known as the hill climb searching (HCS) control, involves changing control variable and then observing whether power increases or decreases as shown in Fig.1.18. The same perturbation is then utilized for the following control instance if it causes rise in power. Alternatively, to track in the direction of rising power, the perturbation's sign is reversed Datta and Ranganathan 2003. HCS control has the benefit of not requiring the measurement of generator or wind speed, as well as being independent of system parameters. Due to these capabilities, the HCS appears to be the best option for MPPT control in WECSs. However, severe problems exist in HCS approach. As shown in Fig.1.18(a), Large perturbation step sizes accelerate convergence but reduce MPPT's effectiveness by enhancing oscillations at the maximum power point (MPP) $P_m ax$. The smaller step size as shown in Fig.1.18(b) boosts the efficiency but reduces the MPPT control speed which may result in incapability of tracking the exact MPP under rapidly varying wind speed. Furthermore, when wind speed changes quickly, it may be difficult to determine the next perturbation's sign, which is determined by the prior perturbation's power rise or drop. The MPPT control as a whole could fail if the wrong choice is made at that point. Because of that, standard HCS control only functions effectively when the inertia of wind turbine is low and turbine speed responds to wind speed virtually instantly. The system output power for wind turbines with significant inertia is interlaced with turbine mechanical power and the rate of change in the mechanically stored energy, which can always result in failure of HCS MPPT control, particularly under quickly varying wind conditions. So, based on this methodology, certain enhanced measurements have been suggested. In L. González, Figueres, G. Garcerá, et al. 2010, It was suggested to employ an improved intelligent HCS control method to get around the problems with the earlier standard HCS systems brought on by the inertia of wind turbines. The algorithm can save the ideal system operating settings by recording outcomes of HCS searching through an online training process in an intelligent memory, and then use direct current demand to quickly and accurately discover the maximum power points. In comparison to traditional methods, a different enhanced MPPT method in Agarwal, Aggarwal, Patidar, et al. 2009 can lessen the mechanical stress on turbine, which is projected to improve both maintenance requirements and average time between failures. The proposed approach is similar to the classic HCS method, except the change of generator's reference speed, a ramp signal rather than a stepped signal is employed. This results in a softer response of mechanical variables than is typically obtained by conventional HCS methods. The authors of this reference developed a fast HCS control method that does not require any additional hardware and is far faster than the majority of HCS MPPT systems now in use. There are two steps to the algorithm: Large iterative steps are employed in the initial stage to approach MPP closely. In the second stage, the precise MPP matching to the present wind speed is tracked utilizing the conventional HCS approach.

1.3.4.2 Fuzzy-logic and neural network based control

The advantages of fuzzy-logic-based MPPT control systems are quick convergence, parameter agnosticism, and acceptance of noisy and erroneous signals Hilloowala and Sharaf 1996. Three fuzzy-logic (FL) steps are adopted in M. G. Simoes, Bose, and Spiegel 1997. In order to extract the most power, the first FL phase, which is based on the HCS, changes the generator speed, monitors power production, and then tracks the generator speed. In order to maximise the effectiveness of machine-converter system, the second FL phase programmed the machine flux utilizng online search. To effectively manage speed in the face of turbine oscillatory torque and wind vortex, the third FL step is employed. A data-driven design process is presented in the publications Vincenzo Galdi, Antonio Piccolo, and Pierluigi Siano 2008 and Galdi, Piccolo, and Siano 2009 that can provide Takagi-Sugeno-Kang (TSK) fuzzy model for MPPT control. Fuzzy clustering techniques for dividing the input-output space, along with genetic algorithms and recursive the least-squares optimization techniques for model parameter adaption, are used to create the TSK model. Because of TSK fuzzy system's adaptability and capacity for learning, wind turbine manufacturers may find it useful. In order to give quick and precise velocity information without utilising anemometers, the neural network (NN) based wind velocity estimator was created in Ro and Choi 2005, Hui Li, Shi, and McLaren 2005. Additionally, a NN-based approach was put forth to correct for potential wind turbine power coefficient drift without the use of additional sensors. In Meharrar, Tioursi, Hatti, et al. 2011, the MPPT approach based on adaptive neuro-fuzzy inference system that was created as mix of Sugeno fuzzy model and neural network was introduced.

1.3.4.3 Comparison

The comparisons of four MPPT approaches are shown in Table 4.1 based on the preceding description. by considering the important criteria—tracking speed, complexity and performance under varying wind, where "+" denotes strong, "-" denotes weak,

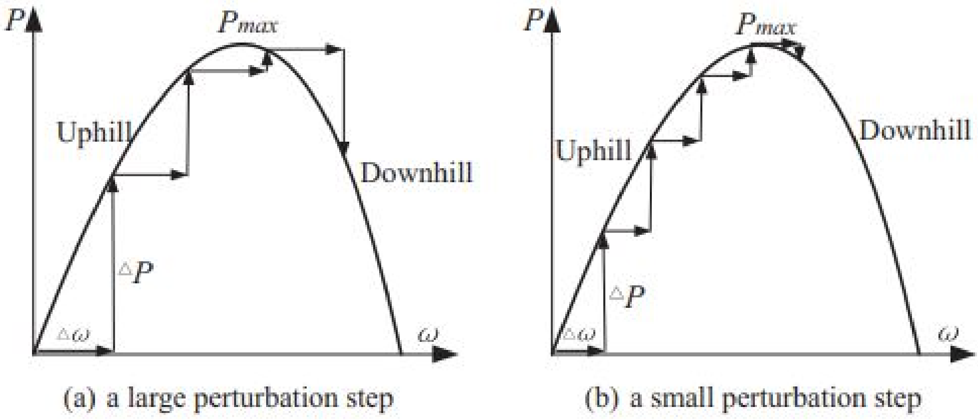

Figure 1.18: Control diagram of power feedback MPPT method M. Cheng and Zhu 2014

and “+/-” denotes medium. The best TSR MPPT method has the greatest number of system requirements, making it impractical for use even if it has several benefits like quick tracking speed, easy installation, and little impact from changing wind. The most commonly used method in practice is:

The power feedback control is effective since it doesn't depend on wind speed and is easy to install. Numerous research publications, have tested and verified HCS MPPT control methods in small wind turbines by many research papers such as Dalala, Zahid, W. Yu, et al. 2013. Nevertheless due to the weak dynamic response under wind turbulence, it has not been shown yet to be used in large-scale wind turbines. Due to complexity of the fuzzy-logic and neutral network based MPPT approaches, a lot of time is required to compute the algorithms, which will have an impact on the tracking speed and performance in different wind conditions. As a result, it is still challenging for them to be implemented in operation at this time. The applicable range of each way is currently being expanded as more and more improvement measures are suggested based on these control methods; therefore, they will likely be accessible in the future.

Table 1.1: Comparison of the typical four MPPT methods

Parameter	**Optimum TSR**	**Power feedback**	**HCS**	**FL, NN based**
Wind speed	Need	No	No	No
Rotor speed	Need	Need	Need	Need
Wind turbine characteristics	Need	Need	No	No
Tracking speed	+	+/-	-	-
Complexity	+	+	+	-
Performance under varying wind	+	+/-	-	+/-

1.3.5 Other methods

Artificial intelligence control and hybrid techniques have been used to address many of the issues with the aforementioned methodologies. based on one study M. Simoes, Bose, and Spiegel 1997, The fuzzy logic control approach is advantageous in that as it quickly converges, is parameter insensitive, and accepts imperfect and noisy signals. This technique can also be used to determine the ideal step size for the traditional HCS method Hui, Bakhshai, and Jain 2011,Trinh and H.-H. Lee 2010. In order to estimate the wind speed based on real machine torque and speed, wind speed measurement and its associated limitations have been overcome Pucci and Cirrincione 2010,C.-Y. Lee, Shen, J.-C. Cheng, et al. 2009. HCS technique performance is improved by the control structure, Wilcoxon radial basis function network (WRBFN)-based with HCS MPPT strategy and modified particle swarm optimization (MPSO) algorithm, published in W.-M. Lin and C.-M. Hong 2010. A hybrid approach combines two techniques and takes advantage of one technique's strengths to compensate for the weaknesses of the other. In Kazmi's demonstration Kazmi, Goto, Guo, et al. 2010a of these techniques, the OTC method was combined with HCS to address the two issues with standard HCS: speed efficiency trade-off and incorrect direction under rapid wind change. Another illustration is the way Quincy and Liuchen Q. Wang and Chang 2004 used PSF control and HCS to create a sensorless, adaptable approach that can be used at all wind turbine levels.

1.3.6 Future trends

Since wind speed is stochastic, the wind power produced by WECSs is subjected to sharp fluctuations. The power variations will result in a number of major issues, including grid frequency fluctuations, active power fluctuations, and voltage flicker at the power grid's buses. The electricity system will then have challenges due to poor quality and volatility Howlader, Urasaki, Yona, et al. 2013. To address these issues, a number of power smoothing techniques have been developed. The majority of techniques rely on energy storage devices like batteries and flywheels Jiang and H. Hong 2012. The energy storage method is expensive. Therefore, the low-cost power smoothing techniques without energy storage system will be in demand in the future. Currently, a double objective control strategy based on the frequency separation principle has been presented in F. Xu, M. Cheng, J. Zhang, et al. 2010 to reduce the torque variations of turbine shafts. The active current control method in Y. Zhang, W. Hu, Zhe Chen, and M. Cheng 2013, the generator torque control strategy in Y. Zhang, W. Hu, Zhe Chen, M. Cheng, and Y. Hu 2014 and individual pitch control in Y. Zhang, W. Hu, Zhe Chen, M. Cheng, and Y. Hu 2014 were proposed to smooth the generator output power oscillations. Wind turbines are frequently installed in isolated locations and are subjected to harsh weather conditions. Due to WECS outages, these variables not only raise operation and maintenance (O and M) costs but also decrease the availability of wind power Hameed, Y. Hong, Cho, et al. 2009, Márquez, Tobias, Pérez, et al. 2012. Focusing on lowering O and M costs and increasing WECS availability are crucial if wind power is to be competitive with conventional power technologies. Applying fault diagnosis, which is a prerequisite for fault tolerant control, is an efficient technique to achieve this improvement. In recent years, a number of general approaches have been proposed in the area of WECS defect diagnosticsFreire, Estima, and Cardoso 2012, Gong and Qiao 2013, Gong and Qiao 2011,Hang, J. Zhang, and M. Cheng 2014. Fault detection for WECS will become more and more crucial in the future with growing share of wind power generation in power grid and offshore wind power generation. One of the most promising sources of renewable energy is offshore wind. When compared to conventional onshore WECSs, harvesting offshore WECSs is more expensive. The weight of the nacelle will there after increment as the transformer is installed in nacelle, Chong H Ng, Max A Parker, Li Ran, et al. 2008. Therefore, in the case of large offshore WECSs, the transformer-less generator or converter is advantageous. Several ideas have been put up in recent years to raise the WECS' output voltage without using a distribution transformer M. Parker, C. Ng, Ran, et al. 2006, M. Parker, C. Ng, Ran, et al. 2006. Future applications and perceptions of even more effective concepts are possible. The parallel connection of converters is used to boost the wind turbine's current and voltage capacity. This therefore results in an increase in the number of legs, which prompts the adoption of multi-phase generators. Modularity is a benefit of multi-phased constructions, with obvious implications for manufacture, assembly, transportation, and maintenanceVizireanu, Kestelyn, Brisset, et al. 2005. Additionally, multi-phase machines have better fault tolerance than conventional three-phase machines. Multi-phase machines can still function utilising the remaining healthy phases when one or more of the phases experience failures without the need for extra hardware Levi 2008, F. Li, W. Hua, M. Cheng, et al. 2014. As a result, the multi-phase generators have strong chance of being used in WECS in the future.

1.3.7 Conclusion

In this chapter, detailed different types of machines, converters associated, configurations and control strategies are described, and more particularly for wind turbine modelling systems. As the main energy source that is utilized here in such a system is wind energy, the first part of this chapter presents an overview of different types of wind turbines/generators including their advantages and disadvantages, trends and challenges. The appropriate choice should be taken into consideration, cost, reliability, performance and the ability to operate in a completely autonomous manner in areas and isolated sites. In the second part of this chapter, different types of wind turbine control strategies have been classified, presented and studied, as the tip speed ratio, hill climbing method, and the neural network based control. The state of art presented in this chapter encompasses the base on each subsystem and which will subsequently be used for the presented system at low cost and with excellent service reliability.

2 Modeling

Summary

2.1 WECS modelling and system description

2.1.1 Introduction and context

Wind energy is one of the attractive and promising renewable energy sources. This renewable energy source represents a good alternative solution to the production conventional electricity. It reduces and minimizes the pollution effect caused by greenhouse gas emissions and could be used to electrify sites and isolated areas where access to conventional energy is difficult or practically impossible. Wind turbines based on a permanent magnet synchronous generator are best suited for stand-alone applications due to their reliability and their high efficiency. The modeling and characterization of the system is an essential step which precedes the phase optimization and which requires very special attention to achieve a system of quality wind pumping with acceptable autonomy and excellent service reliability. The work presented in this chapter generally concerns: [1]The modeling as well as sizing of the proposed system. [2] characterization of the permanent magnet synchronous generator. [3] The operating ranges of wind turbine. [4] Converter typologies and their mathematical model. [5] The design and production of an emulator allowing reproduction of non-linear behavior for variable-speed wind turbine.

2.1.2 Wind turbine model

The power of wind is defined by Brahmi, Krichen, and Ouali 2009:

$$p_v = \frac{\left(\rho \cdot A \cdot {v_w}^3\right)}{2} (1)$$

Where ρ is the density of air (KG/m^2)), A is the area of blades $(A = \pi * R^2)$, v_w is the speed of wind (m/s) The mechanical (aerodynamic) power produced by the turbine is expressed by:

$$p_m = \frac{1}{2} C_p(\lambda, \beta) \cdot \rho \cdot A \cdot {v_w}^3 (2)$$

$$\lambda = \frac{\Omega_m^G R}{v_w} (3)$$

Where C_p represents the power coefficient which depends on the pitch angle β and the ratio of reduced speed (Specific speed) λ, Ω_m^G is the turbine rotor speed (rad/s) R is the turbine radius (m). The power coefficient indicates the efficiency with which wind turbine that converts energy of wind into electricity. Theoretically, the wind turbine can only recover 59.3% of the total energy provided by wind that is called: Betz limit Dai, Liu, Wen, et al. 2016. For any wind turbine manufactured, there is a specific characteristic of power coefficient C_p Xia, Ahmed, and Williams 2012. According to Aissou, T. Rekioua, D. Rekioua, et al. 2016, the maximum value of the power coefficient C_p of Savonius type wind turbines and of about 0.14 and for Darrieus wind turbine the C_p is about 0.4. Fig.2.1 illustrates the characteristics of aerodynamic power coefficient as a function of the ratio λ for different types of wind turbines.

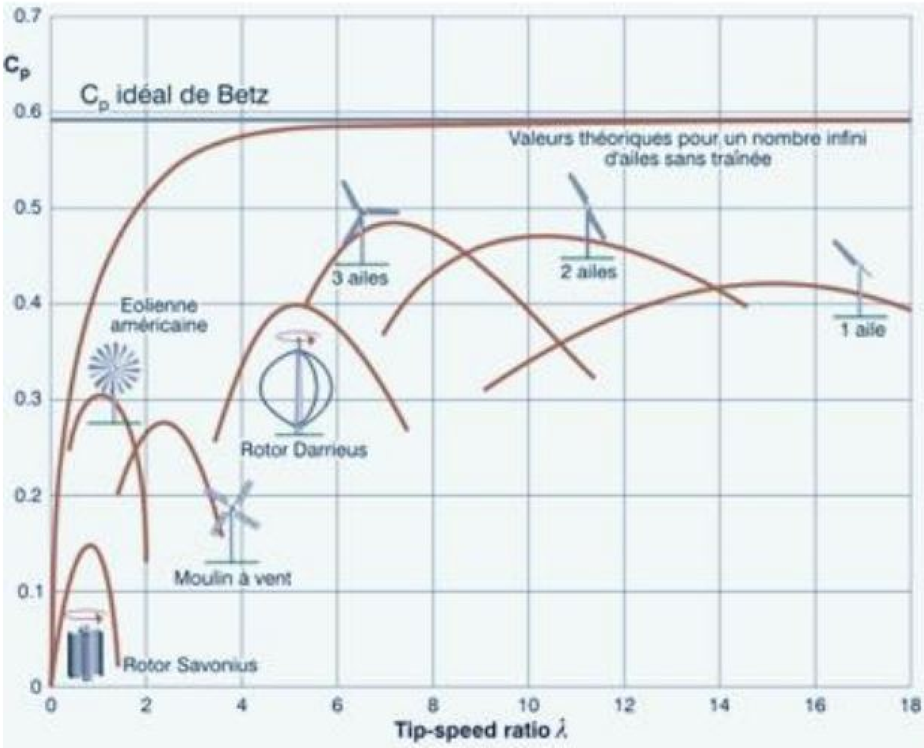

Figure 2.1: Power coefficient as a function of λ for different types of wind turbines Aissou, T. Rekioua, D. Rekioua, et al. 2016

The expressions (4), (5) and (6) represent the main models of power coefficient (C_p)proposed in Xia, Ahmed, and Williams 2012,F. Martinez, Herrero, and Pablo 2014,Daili, Gaubert, Rahmani, et al. 2019 and utilized in the literature.

$$\begin{cases} C_{p1}(\lambda,\beta) = C_1\left(\frac{C_2}{\gamma} - C_3\cdot\beta - C_4\right)e^{\frac{-C_5}{\gamma}} + C_6\cdot\lambda (4) \\ C_1 = 0.5176, C_2 = 116, C_3 = 0.4, C_4 = 5, C_5 = 21, C_6 = 0.0068 \\ C_{p2}(\lambda) = (1.12\lambda - 2.8)e^{-0.38\lambda} (5) \\ C_{p3}(\lambda,\beta) = 0.22\left(\frac{116}{\gamma} - 0.4\beta - 5\right)e^{\frac{-12.5}{\gamma}} (6) \end{cases}$$

With: $\frac{1}{\gamma} = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1}$ Figures 2.2.a, 2.2.b and 2.2.c represent the characteristics of power coefficient C_p as a function of the reduced speed ratio λ for models of equations (4), (5) and (6).

The original model for C_{p1} and C_{p3} presents a model with a variable pitch angle, while in our case the model has been modified to represent a wind turbine with fixed pitch angle. By giving the value zero to βFathabadi 2016, the power coefficient becomes solely as a function of lambda λ. The mechanical torque developed by the turbine is determined by:

$$T_m^G = \frac{p_m}{\Omega_m^G} = \frac{1}{2\cdot\Omega_m^G}C_p(\lambda,\beta)\cdot\rho\cdot A\cdot {v_w}^3 (7)$$

As the wind turbine is directly connected to the permanent magnet synchronous generator Brahmi, Krichen, and Ouali 2009,Qiao, X. Yang, and Gong 2011, the wind energy conversion system tree can be represented by a one-mass model. The dynamic equation of the shaft is then given by Aubrée, Auger, Macé, et al. 2016, Zhe Zhang, Y. Zhao, Qiao, et al. 2014,Aziz, Jamal, Othmane, et al. 2019:

$$\begin{cases} T_m^G = J^G \Omega_m^G + f \cdot \Omega_m^G + T_{em}^G \\ J^G = J_{\text{turbine}}^G + J_g^G (8) \end{cases}$$

Where T_{em}^G represents the electromagnetic torque produced by the generator, f is the coefficient of friction and J^G is the inertia total moment of the rotating parts.

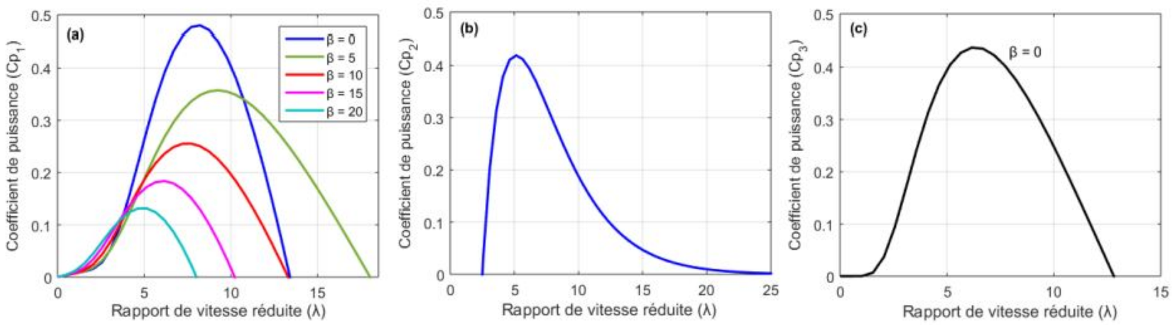

Figure 2.2: Different power coefficient models of wind turbines

2.1.3 Wind turbine operating ranges

To efficiently extract wind energy while maintaining safe operation, the wind turbine must be operated according to the three operating regions as shown in the Fig.2.3 Aubrée 2014Beltran 2010. In region I, when the wind speed vw is less than the start speed $vwcut-in$, the wind turbine is stopped and does not produce electricity because the wind is not strong enough. In region II, when the wind speed vw is between the starting speed $vwcut-in$ and the nominal speed $vwrated$, the goal is to maximize power of the turbine and optimize energy efficiency. This region corresponds to the operation in Partial load of the aero generator. In region III (strong wind region), when the wind speed vw is between the rated nominal speed v and the maximum speed $vwcut-out$, the power is limited in order to protect and avoid damaging the wind turbine. This region corresponds to full load operation.

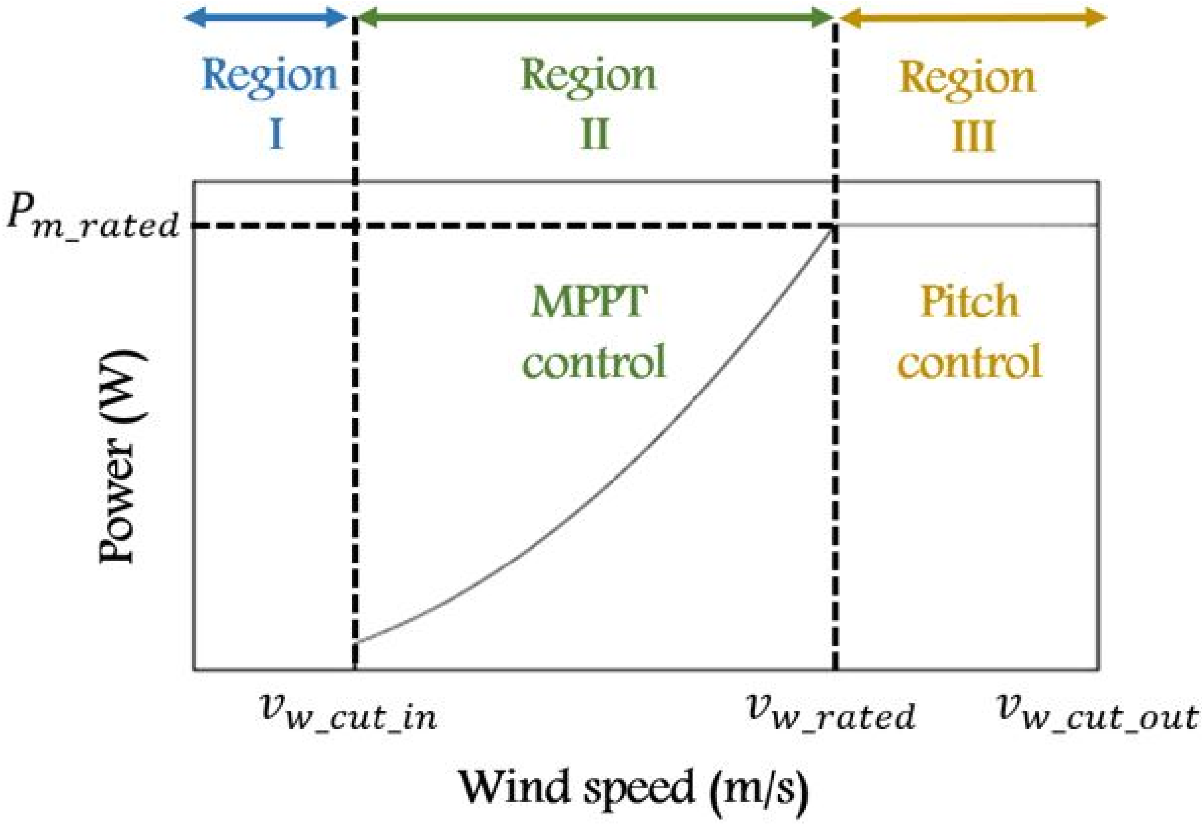

Figure 2.3: Wind speed regions

2.2 PMSG model

2.2.0.1 Permanent magnet synchronous generator mathematical model

A permanent magnet synchronous generator (PMSG) can be modeled using abc phase quantities. Through appropriate coordinate transformations, models of PMSG in the rotating frame d-q Fig.2.4 and the stationary frame $\alpha - \beta$ can be obtained. The relationships between these reference frames are illustrated in Fig.2.5. The dynamic model of generic three-phase PMSG can be written in d-q frame as follows Aziz, Jamal, Othmane, et al. 2019,Qiao, X. Yang, and Gong 2011:

- Tension stator: $\begin{cases} V_{ds} = R_s I_{ds} + L_d \dot{I}_{ds} - \omega_r \psi_{qs} \\ V_{qs} = R_s I_{qs} + L_q \dot{I}_{qs} + \omega_r \psi_{ds} \end{cases}$ -
- Flux stator: $\begin{cases} \psi_{ds} = L_d I_{ds} + \psi_0 \\ \psi_{qs} = L_q I_{qs} \end{cases}$ (9)

PMSG differential equations can be obtained as follows:

$$\begin{cases} L_d \dot{I}_{ds} = V_{ds} - R_s I_{ds} + \omega_r L_q I_{qs} \\ L_q \dot{I}_{qs} = V_{qs} - R_s I_{qs} - \omega_r L_d I_{ds} - \psi_0 \omega_r \end{cases} (10)$$

The electromagnetic torque is represented by:

$$T_{em}^{G} = \frac{3}{2} p \left[\left(L_d - L_q \right) I_{ds} I_{qs} + \psi_0 I_{qs} (11) \right]$$

PMSG is assumed to be smooth poled, i.e. $L_d = L_q$, and expression of electromagnetic torque in the rotor can be described as follows:

$$T_{em}^{G} = \frac{3}{2} p \psi_0 I_{qs} (12)$$

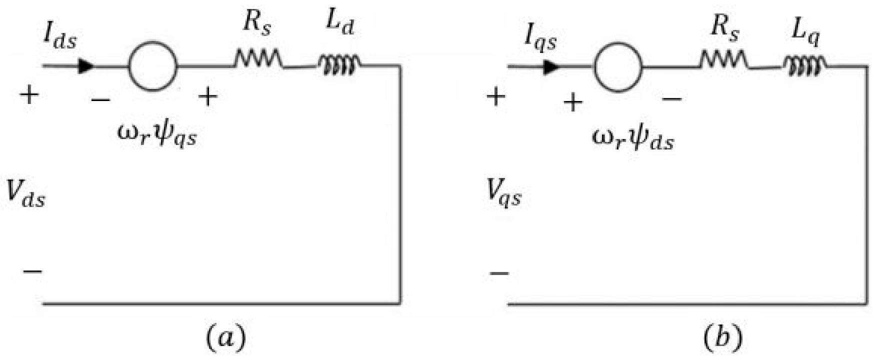

Figure 2.4: Equivalent circuit of the permanent magnet synchronous machine in the d-q frame Benzaouia 2020

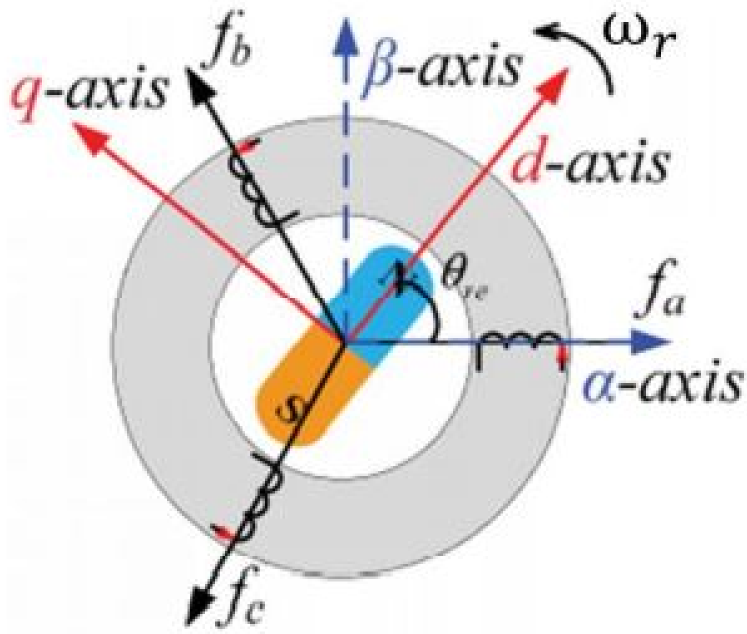

Figure 2.5: Coordinate reference frame definitions for GSAP modeling Benzaouia 2020

2.2.0.2 The conversion AC/DC

The generator provides alternating voltage of variable amplitude and frequency, the realization of an AC/DC conversion is essential, the latter can be carried out either by a diode rectifier followed by a step-up chopper or by a controlled rectifier. As will be seen in the following chapter, the usage of such converters associated with maximization command called MPPT (Maximum Power Point Tracking) will serve also to improve efficiency of wind pumping system.

2.3 Converter typologies

An electrical device called a rectifier changes alternating current (AC), which occasionally flips direction, into direct current (DC), which only flows in one direction. In this thesis, controlled rectifier and uncontrolled rectifier typologies are utilized to compare their performance in the system of wind turbine permanent magnet synchronous generator. Half-wave rectifiers, the most basic type of rectifier, limit the flow of current to one direction by removing one side of the AC. Unlike uncontrolled rectifier, the controlled one requires a triggering circuit while the uncontrolled rectifier does not. In contrast to controlled rectifier, an uncontrolled rectifier does not provide for output control. Appliances are powered by rectifiers. Rectifiers are used in power supplies to convert AC power to DC. Large appliances frequently employ bridge rectifiers because they can convert high AC voltage to low DC voltage. In our work we have studied the two converter typologies: Controlled rectifier for using nonlinear proportional integral controller utilized in PMSG wind turbine connected system and the uncontrolled one for utilizing model predictive controller in wind turbine system, so a detailed brief is given for both of them.

2.3.0.1 Controlled rectifier

First of all, it is known as a controlled rectifier since diodes are uncontrolled rectifiers because they conduct if their anode voltage is higher than their cathode voltage (under forward bias state without any control). For this reason, the thyristor is often referred to a controlled rectifier or a silicon controlled rectifier. A controlled rectifier output occurs when SCR (Silicon Controlled Rectifier) is used to convert AC to DC since the output voltage may be controlled. Diodes begin to conduct as soon as the voltage changes to positive. A controlled rectifier is a circuit that transforms AC power into a unidirectional DC supply and has the ability to regulate the amount of power delivered to the load. Controlled rectification is another name for the process of converting alternating current (AC) to direct current (DC).

2.3.0.2 Uncontrolled rectifier

The circuit in this rectifier that simply uses diodes is known as an unregulated rectifier circuit. SCRs don't immediately start conducting after their voltage changes to positive, unlike diodes. Because the triggering gate pulse is necessary for the SCR's forward conduction.

2.3.0.3 Controlled and uncontrolled rectifier devices

Semiconductor diodes are the most widely used component in uncontrolled rectifier circuits and are arranged to produce either a half-wave or a full-wave rectifier circuit. It is known as an uncontrolled rectifier because rectifier circuits are used to transform alternating current (AC) input power into direct current (DC) output power.

2.3.0.4 Difference between uncontrolled and controlled rectifier

The controlled rectifier uses SCR while the uncontrolled one uses simple diodes. Unlike the uncontrolled rectifier, the controlled one requires a triggering circuit. In contrast to a controlled rectifier, an uncontrolled rectifier does not provide for output control. In a controlled rectifier, the output may be changed by adjusting the firing angle, whereas in an uncontrolled rectifier, there is no such thing as a firing or triggering idea.

When compared to the price of a controlled rectifier, an uncontrolled rectifier is less expensive. In a controlled rectifier, output can be smoothly controlled. In comparison with building uncontrolled rectifier, designing controlled rectifier takes more time. The uncontrolled rectifier has the benefit of not requiring a center-tapped transformer. As a result, the circuit's price and size are decreased. Uncontrolled Rectifiers Give a certain A.C. that feed a fixed D.C. output voltage which only uses diodes. (a) Half-controlled: Permits just rectification of electrical power flowing from A.C. to D.C. (b) Significant control: Enables the power flow in both directions (i.e. rectification and inversion).

2.3.0.5 Different kinds of controlled rectifier

Controlled Rectifier:

- Half Wave Controlled Rectifier.
- Full Wave Controlled Rectifier.
- Controlled Bridge Rectifier.
- Controlled Center-Tap Rectifier.

2.3.0.6 Controlled rectifier function

Another noteworthy use for controlled single-phase rectifiers is the control of low power DC motors. To generate the necessary torque, the controlled rectifier controls motor current by regulating the armature voltage.

2.3.0.7 Controlled rectifier applications

Applications of Phase Controlled Rectifier can be categorized as follows:

- AC fed traction system using a DC traction motor.
- Electro-metallurgical and Electrochemical processes.
- Reactor control.
- Magnet power supply.
- Portable hand instrument drive.
- Flexible speed industrial drive.
- Battery charges.
- High voltage DC transmission.

2.3.0.8 Uncontrolled rectifier Applications

All electronic equipment utilizes rectifiers to create dc supply from available AC supply. In the high voltage direct current transmission system, controlled rectifiers are employed to transform generated AC power into DC power for transmission. Additionally, it is utilised in household inverters, battery charges, etc.

2.3.0.9 Advantages and Disadvantages of controlled rectifier

In order to balance differences for DC line voltage brought on by changes in the medium voltage power network. to maintain constant voltage despite changes in the load to enhance line protection settings and control fault current on faults away from the electrical substation.

Problems with SCR have a single direction of conductivity. As a result, it can only control power for one half of AC cycle. Due to the source voltage's high dv/dt, it may accidentally turn on. Turning off the conductive SCR is not simple. And the controlled rectifier's primary flaw is SCR (silicon controlled rectifier) that can only regulate power in DC during the positive half of AC supply, it can only be utilized to control DC power. Negative gate current is impossible. It must be switched on every cycle in AC circuit.

2.4 Conclusion

This chapter analyzes the wind turbine model, wind turbine operating ranges, models. This chapter also demonstrates the efficiency of PMSG wind turbine which is integrated by different controllers, as recently PMSG has gained attention by wind turbine manufactures due to advance of control system and power electronics. The wind energy conversion technology of PMSG is very promising in renewable power generation. However, the performance of grid-connected PMSGs is greatly affected by grid disturbances because their stator windings are interfaced with grid directly. Such a chapter describes lastly the designs for converter typologies in details with merits, demerits and applications utilized including controlled and uncontrolled rectifiers, functions, applications for the controlled and uncontrolled rectifiers and their advantages and disadvantages.

3 MPPT control strategies

Summary

3.1 Introduction

A wind turbine system with precise and effective maximum power point tracking (MPPT) control that can improve the controller and increase amount of energy produced. Prior to that, a variety of controllers are presented in order to improve their performance. As this work begins with a readjustment of some available control approaches, the most analysis and research has taken place on the classical proportional integral (PI) controller. Furthermore, because the dynamic aspects of wind and aeroturbine are not taken into consideration, their enhancement and performance are powerless. Nonlinear static and dynamic feedback controllers are presented for enhancement; beyond that, the goal is to use the wind turbine dynamics as a quantification tool. Although, due to the wind speed form difficulty and nonlinear model, which might lead to a lack of assurance, its execution and implementation are limited. To address these flaws, this chapter proposes an improved controller including the NSSFC (nonlinear static state feedback controller) and NDSFC (nonlinear dynamic state feedback controller) to increase the controller performance for such a system. The control target below the evaluated wind speed is to attain the optimum for the harvested energy from wind while reducing mechanical loads, and this chapter presents a nonlinear technique based on speed variability of wind turbines control. Nonlinear static and dynamic state feedback controllers with varied wind speed profiles are determined to bring a few changes and to examine the competency of nonlinear controllers. The offered controllers are analyzed in a comparative study. The MATLAB/SIMULINK environment was used to test and evaluate all of these strategies. The results reveal a difference in control between the TSR and P&O methods, as well as the effectiveness of nonlinear static and dynamic state feedback controllers and PI controllers. Latterly, the prominence of clean energies has turned into a wide range with the increment of energy demand and the effect of global climate warming and another energy sources, discovering pure or clean energy has turned into a universal duty. Renewable energy can fix a lot of issues that happened because of the traditional energy sources. Specially, wind energy has catched up a considerable interest from professionals, and researchers predicted that in 2020 the global electricity generation will be raised to 10% of global energy Civelek, Lüy, Çam, et al. 2016, and its already happened. Horizontal WT is more centered on all of WE sorts. The settled speed of WT can be an early platform that employs a transformer to put through the grid. Essential disadvantages of this plan are considered to be the frequency and voltage changes produced by wind speed varieties. After the improvement of electronic gadgets showed up the speed variability of WT, which AC–DC rectifier and DC–AC inverter are utilized for keeping up frequency as well as the voltage at a consistent levels, in spite of wind speed changeY. Yang, P. Chen, S. Ma, et al. 2022. For all intents and purposes, WT control is depending on the run of wind speed estimation. In a low-speed circumstances, WT can produce the most extreme energy utilizing MPPT. In advance, in high wind speed situation or turbulence conditions, it ought to be protecting machine and guarantee the benefit coherence by utilizing pitch point control Majid A Abdullah, Yatim, Chee Wei Tan, et al. 2012. Another controllers within

WT framework which are: current control at the generator level, DC-link voltage and recurrence control. In this investigation, we have centered on comparison between tip speed ratio(TSR) and (P&O) technique Elgendy, Zahawi, and Atkinson 2011, MPPT, PI controller Elgharib, Mohammed Alhasheem, Swief, et al. 2021,Karanam and Shaw 2022, NSSFC controller Milani 2007, and NDSFC controllerSkruch and Długosz 2019. Robust control of WECSs has been introduced and utilized as well inOussama, Abdelghani, and Lakhdar 2022. Taking into consideration that wind turbine is operating in steady state conditions, while unfortunately most of the work that has been valid before being acted on dynamical aspect of the turbine as well as the wind, as the nonlinear characteristics of WECS are strong. The main target for the control of wind turbine, for low wind speeds is to generate optimal power from the wind by rotating rotor of wind turbine at a proportional referred to the impacted wind speed. There are some investigations and assumptions made refer to that the impacted wind speed is measurableBoukhezzar and Siguerdidjane 2010,Lei, Mullane, Lightbody, et al. 2006, that leads to assume that the wind turbine can be extended to steady state region on its maximum efficiency curve. The models that has linearity in their specifications are usually being utilized. The turbulence of high wind speed leads this assumption to be unacceptable leading to weak performance of the integrated controllers, specially in terms of electrical efficiency. In most of the situations, one-mass model of the wind turbine can be utilized for controller design Beltran, Ahmed-Ali, and Benbouzid 2008,Munteanu, Bratcu, CeangĂ, et al. 2008,Vincenzo Galdi, Antonio Piccolo, and Pierluigi Siano 2008. The main objective of this work is to design nonlinear controllers that take into consideration the dynamical aspect of wind turbine and speed, without aid of wind speed measurement. Straight PID controller has been presciently utilized for MPPT. Moreover, their execution is restricted over large extent of non-linearities of wind turbine system. In this respect, various robust/intelligent controller designs have been presented within the writing to affirm their effectiveness.

Improvement in wind turbine technology has forced the energetic control systems to enhance their design. So as to to develop wind turbines conductance, and to be useful and helpful. Variable speed wind turbines have higher characteristics specially in component pressure and power output as well as smaller grid connection power peaks. In order to take a full advantage, variable speed should be controlled in significant path. A lot of actions have been taken in WECS control that can treat extraction of aerodynamic power in partial load area are optimized. Classic controllers, particularly the PI regulator, have been extensively employed for this objective Oussama, Choucha, and Chaib 2019,Maroufi, Choucha, and Chaib 2020,B. Yang, T. Yu, Shu, et al. 2019. WECSs now have more robust control. and utilized in Boubakir, Touil, Labiod, et al. 2021. Because WECS have strong nonlinear characteristics, most of these articles ignore the dynamical aspect of wind turbine by assuming wind turbine operates in steady state conditions. Furthermore, wind speed is considered to be measured in the majority of these experiments. Despite the fact that an anemometer was utilized to measure wind speed, value of resultant differs from the one found in wind turbine model equations since it is a mean value.

The goal of the first part of this chapter is to develop reliable nonlinear controllers that has taken into account the dynamical aspects of wind turbines and their speed.

This chapter also in its second part presents a sensorless control technique of a direct driven PMSG wind turbines. The proposed sensorless approach utilizes an MRAS observer for generator rotational speed estimation. This latter needs only three phase voltage and current measurements provided by cheapest electrical sensors. There are two main objectives in this article: First one is extracting and achieving the maximum power point using a vector control technique based on nonlinear proportional integral controller, while the second one is to avoid the use of mechanical speed sensor by utilizing an MRAS observer for cheaper implementation. Such an article shows performance of the whole system by using the proposed control strategy with and without speed sensor. The obtained results determine the effectiveness of the developed approach.

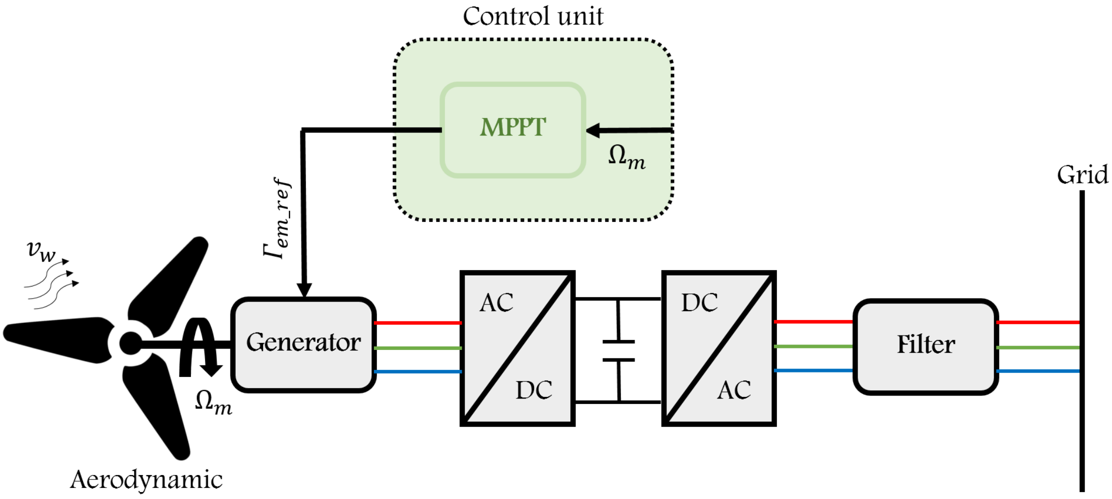

Figure 3.1: Overall wind turbine system

The Proposed wind turbine system within range 10 KW on a horizontal wind turbine plantOussama, Choucha, and Chaib 2019. As proposed in Fig.3.1, the essential components of wind energy conversion systems are the generator, aerodynamics, actuator pitch, and the control part. These elements are discussed in the following sub-sections.

3.2 Aerodynamic

3.2.1 Generator Model

Different kinds of generators are utilized for wind turbine application. Although, PMSG is the favorable one as it has no gearbox, low cost of maintenance and control simplicity. As the wind turbine is linked directly with PMSG, the shaft system of WECS can be clarified by a one-mass model. PMSG mathematical model is given by the following equations:

The d-q stator voltages of generator are introduced by the next equations:

$$V_{ds} = R_s I_{ds} + L_d \frac{dI_{ds}}{dt} - \omega_r \psi_{qs} (9)$$

$$V_{qs} = R_s I_{qs} + L_q \frac{dI_{qs}}{dt} + \omega_r \psi_{ds} (10)$$

$$\psi_{ds} = L_d I_{ds} + \psi_0 (11)$$

$$\psi_{qs} = L_q I_{qs} (12)$$

Where L_d and L_q are considered to be inductance of the generator on d and q axis respectively, R_s is resistance of stator, ω_r is the electrical rotating speed of PMSG that has been introduced by

$$\omega_r = p \cdot \Omega_m (13)$$

, and ψ_0 is the permanent magnetic flux. By substituting Equations (11) and (12) into Equations (9) and (10), the differential equations of PMSG are presented by the following:

$$\begin{cases} L_d \frac{dI_{ds}}{dt} = V_{ds} - R_s I_{ds} + \omega_r L_q I_{qs} (14) \\ L_q \frac{dI_{qs}}{dt} = V_{qs} - R_s I_{qs} - \omega_r L_d I_{ds} - \psi_0 \omega_r (15) \end{cases}$$

The electromagnetic torque is explained by:

$$T_{em} = \frac{3}{2} p \left[\left(L_d - L_q \right) I_{ds} I_{qs} + \psi_0 I_{qs} \right] (16)$$

Where p is the number of pole pairs. PMSG is supposed to be wound-rotor, then L_d=L_q, and the term of electromagnetic torque in rotor is presented as shown below:

$$T_{em} = \frac{3}{2} p \psi_0 I_{qs} (17)$$

3.3 Controller Objectives

In this part, controller aims and objectives are discussed, the target of controller is to track reference of any parameter that is already taken into consideration like theoretical power, power coefficient and rotational speed in order to maximize the extracted power. Wind turbine electric system reaction has much more acceleration than any other part of wind turbine. Such a reaction can lead to the dissociation possibility for the generator and control of aeroturbine (aerodynamic mechanical components) designs, so a consecutive control composition can be formulated from two control loops:

- Outer control loop that concentrates on the mechanical and aerodynamic part in order to feed the inner loop with reference input.

- Inner control loop that concentrates on the electric generator across the power converters of such a system.

A lot of research concentrates on the section of electrical control without utilizing mechanical part. Starting from assumption of saying that the internal or electrical control loop is well designed and controlled, this part of the chapter concentrates on the outer loop that contains mechanical and aerodynamic part. Hence, electric generator is not taken into consideration in such work. The main target of this work is to plan and resolve much more better controllers. In this part of the chapter, the proposed controllers have been compared with main quantities in wind turbine connected system which are: rotational speed, power coefficient and reference theoretical power. Fig.3.4 presents that there are three essential parts that operation of the system works out. Wind Turbine is in Area I and can not generate power or energy before wind speed reaches to $v_{cut-in} = 3m/s$, while Area II that is restricted between v_{cut-in} and v_{rated} and in such case, MPPT dominance is utilized to follow MPP for wind speed rating or estimation, and the third region (Area III) generates a consistent output until cut-off speed is reached. The turbine is switched off after this speed (region 4) to protect its components from severe winds; thus, it generates no electricity in this area.

3.3.1 Maximum power point tracking

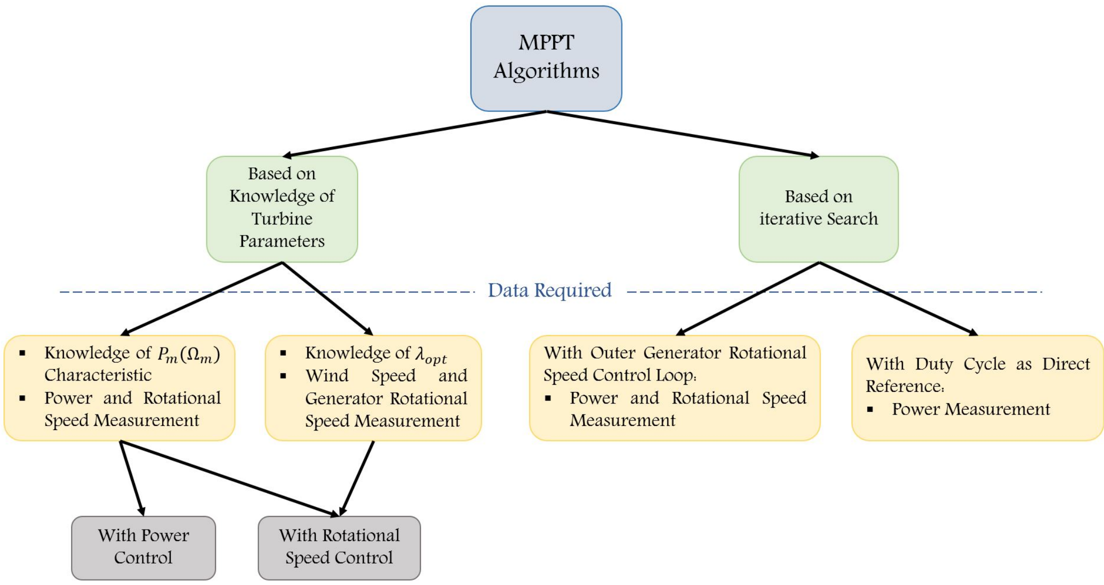

Figure 3.2: MPPT algorithms classification

The generator rotational speed must be managed using MPPT methodology through a controlled AC-DC converter or an uncontrolled AC-DC converter followed by DC-DC converter in order to produce the greatest energy from wind turbineKot, Rolak, and Malinowski 2013. Several MPPT techniques are available nowadays, but all can be classified into two classes. Techniques in the first class need previous information of turbine parameters to figure out the operating point. While the second class depends on repeated study of the maximum taking into account the utilization of reference speed. Fig.3.2 suggests a more detailed segmentation of these techniques, which differ in the kind of sensors required and how they are implemented. Furthermore, the procedure's principle remains the same.

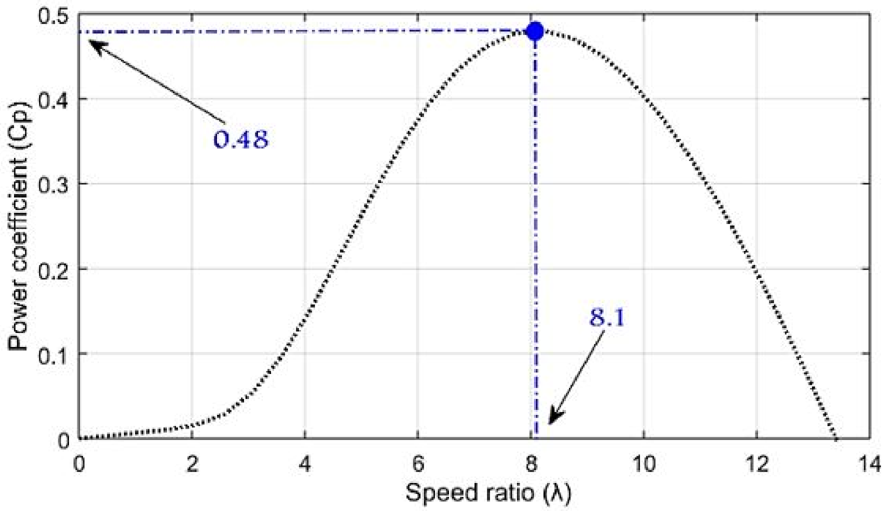

Figure 3.3: Characteristics of C_p and λ

3.3.1.1 Tip speed ratio control

In order to track maximum power point, as described in Fig.3.3, the wind turbine is oriented and controlled to maintain C_P to C_{Pmax}=0.48, in addition to λ to λ_{opt}, in spite of wind speed fluctuations. This can be happened by imposing the wind turbine system to reach its maximum power by emulate the actual generator speed and scope this inaccuracy or error to the controller.

Maximum TSR for any wind turbine available is fixed whatever the value of wind speed. It is ensured that the produced energy will be the maximum needed. Moreover, this technique aims to impose energy conversion system to stay at this point by matching it with the real or actual value and filling this variability to the controller, in order to alter the speed of generator to minimize error as much as possible. Optimal point of TSR is indicated theoretically or experimentally and memorized as a reference. However this technique appears to be not complex as the wind speed can be measured straightforwardly, an accurate measurement for wind speed is unattainable in actuality and leads to increment in the cost of whole system Kazmi, Goto, Guo, et al. 2010b,Patel and Beik 2021, Q. Q. Wang 2003, Seyed Masoud Barakati 2008, J. Zhang, M. Cheng, Zhe Chen, et al. 2008, Thongam and Ouhrouche 2011.

$$\Omega_{mopt} = \frac{\lambda_{opt} v}{R} (18)$$

TSR control algorithm is included in a block diagram described as shown in Fig.3.5 that determines control strategy for the whole system.

This method can be illustrated as follows:

The two techniques can deal with wind turbine system, There are two points of view can be utilized to make a comparison between these two techniques: first one is the prediction part, the perturb and observe technique depends mainly on the prediction to generate pulse or produce output that can follow reference for any parameter utilized so it takes time to pursue such a reference, while in the other hand the tip speed ratio can follow the reference of any parameter directly with approximately no time as it depends mainly on calculations and mathematical equations of any problem, and the second point of view determines the variable wind speed profile that depends on number of oscillations that are produced or generated from wind turbine system, as when the system utilized P&O method, there will be many oscillations produced. Although, TSR method has a minimum number of oscillations in the contrary of P&O method. Because of that in this part of the chapter, the concentration will be on TSR method.

3.3.2 Perturbation and Observation technique

This mathematical optimization algorithm can be utilized for finding the local optimum point of a certain function, it can be called also hill-climb searching method (HCS). it can be utilized in a wide range in wind energy systems to identify the optimal operating point that will maximize the produced energy. This strategy is based on irritating a control variable in small or large step-size and observing outcomes that alter within the required function until the inclination becomes zero. Within the accessible literature, the rotational speed is perturbed by some creators and mechanical control can be spotted, whereas others checked the yield power of the generator and perturbed inverter input voltage, or one of converter variables, which is named duty cycle(d) Carrillo, Diaz-Dorado, Silva-Ucha, et al. 2010,A. C.-C. Hua and B. C.-H. Cheng 2010, I_{in}Neammanee, Sirisumranukul, and Chatratana 2006, or input voltage, V_{in}Kesraoui, Korichi, and Belkadi 2011. Mechanical sensors are not required for electrical power Calculation, and therefore they are low cost and more reliable. Since P&O strategy does not require earlier information of wind turbine's characteristic curve, it is free, simple, and adaptable. However, when it is used for medium and large inertia wind turbines, it falls short of reaching the highest power peaks in fast wind conditions. Furthermore, taking a suitable step size is not a simple assignment: Despite the fact that bigger step-size implies a faster response and more oscillations around the top point. So, less effectiveness, and less step-size moves forward productivity but reduces the gathering speed Kazmi, Goto, Guo, et al. 2010a, C.-T. Pan and Juan 2009, M. Abdullah, Yatim, and C. Tan 2012. Beside that, initialization of the parameters essentially influences system's enhancement Raza, Goto, Guo, et al. 2008. HCS strategy is additionally affected by estimation of capacitance for converter yield capacitor, whereas bigger capacitance eliminates the system's speed reaction. Necessity of qualification between control variations originating from variation of wind and those resulting from variation within past irritation is one major disadvantage of the tracking technique that might lead to disappointment. Adjusted variable step-size calculations have been presented to improve the productivity and precision of the traditional P&O approach Kazmi, Goto, Guo, et al. 2010a, A. C.-C. Hua and B. C.-H. Cheng 2010.

The step-size is organically updated in adaptive step-size technique in accordance with the working point. If the framework is working on a certain point that's not close to the peak, the step-size ought to be expanded to speed up the following process. Contrarily, such a behaviour is switched to diminish step-size when the working point approaches MPP. Step-size is still decreasing until it reaches near to zero in order to push the working point to be eliminated precisely at the top point. This basic standard eliminates oscillations that happen within the ordinary P&O method, quickens speed to reach the greatest one, and decreases the time required for the following.

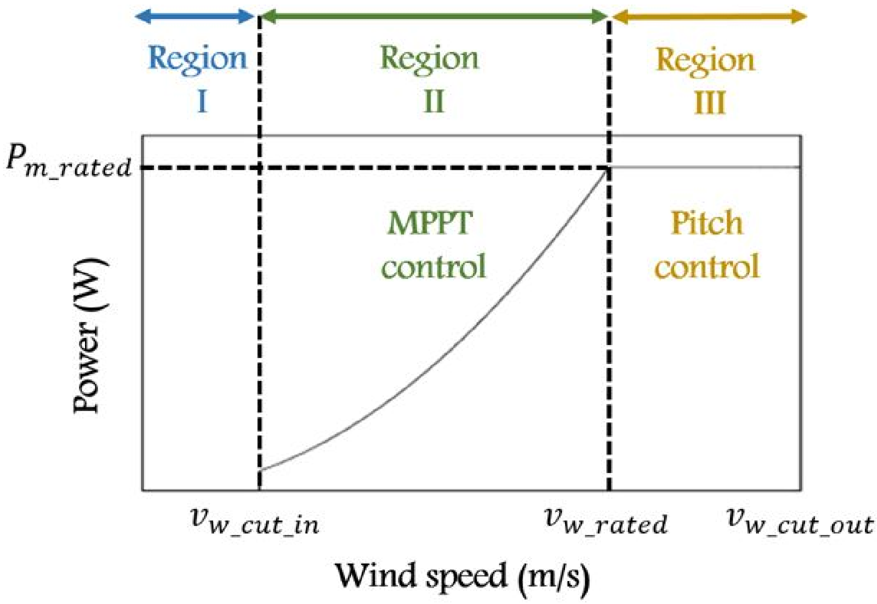

Figure 3.4: Regions of Wind Speed

3.3.3 Controller designs

In this section the examined controller designs are verified and illustrated.

3.3.3.1 PI Controller

The proportional integral control action is given as follows J. Martinez, Arrieta, Vilanova, et al. 2016:

$$\Gamma_{em_ref} = \left(K_p + \frac{K_i}{s}\right) \cdot \left(\Omega_{\text{mopt}}(t) - \Omega_m(t)\right) \quad (19)$$

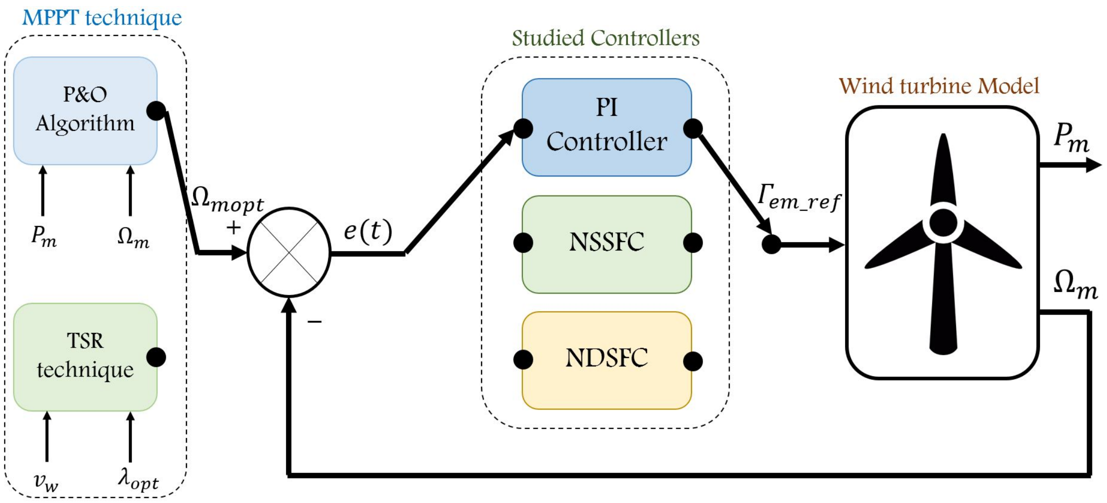

Figure 3.5: Overall control scheme

K_p is the proportional gain and K_i indicates the integral gain and they are the correct parameters to be determined. The transfer function in the closed loop is identical to the previous one which is:

$$\Omega_m(t) = F(s)\cdot\Omega_{\mathrm{mopt}\ (t)} + P(s)\cdot C_g(20)$$

with:

$$F(s) = \frac{K_p\cdot s + K_i}{J.s^2 + \left(f + K_p\right)\cdot s + K_i}(21)$$

and

$$P(s) = \frac{s}{J.s^2 + \left(f + K_p\right)\cdot s + K_i}(22)$$

3.3.3.2 Nonlinear Static State Feedback Controller(NSSFC)

A static state feedback linearization control technique with asymptotic rotor speed following reference0 is utilized. The chosen elements are at that point forced to the rotor speed tracking error $e(t)$ as shown in equation: 23 and the final NSSFC control expression is given by equation: 27 which is described below:

$$e(t) = \Omega_{\mathrm{mopt}}\ (t) - \Omega_m(t)(23)$$

$$\dot{e} + a_0 e = 0(24)$$

$$\dot{\Omega}_{mopt} - \dot{\Omega}_m + a_0 e = 0(25)$$

$$\dot{\Omega}_{mopt} - \frac{1}{J}\left[\Gamma_m - \Gamma_{em} - f\Omega_m\right] + a_0 e = 0(26)$$

$$\Gamma_{em\_ref} = \Gamma_m - f\Omega_m - J\left[\dot{\Omega}_{mopt} + a_0 e\right] (27)$$

3.3.3.3 Nonlinear Dynamic State Feedback Controller(NDSFC)

The static state feedback linearization control technique can not be too durable taking into account the perturbation Isidori 2013, even if the system can be linearized by a static state feedback, one can assess a higher order dynamics to the error tracked for acquiring a dynamic state feedback. It is considered as second order dynamics, the tracking error $e(t)$ is determined by equation:28 described below and the final NDSFC control expression is given by equation: 31 as shown in the following equations:

$$\ddot{e} + b_1\dot{e} + b_0 e = 0 (28)$$

$$\ddot{\Omega}_{mopt} - \ddot{\Omega}_m + b_1\dot{e} + b_0 e = 0 (29)$$

$$\ddot{\Omega}_{mopt} - \frac{1}{J}\left[\dot{\Gamma}_m - \dot{\Gamma}_{em} - f\dot{\Omega}_m\right] + b_1\dot{e} + b_0 e = 0 (30)$$

$$\dot{\Gamma}_{em\_ref} = \dot{\Gamma}_m - f\dot{\Omega}_m - J\left[\ddot{\Omega}_{mopt} + b_1\dot{e} + b_0 e\right] (31)$$

3.4 Simulation Results and Discussion

Maximum power point tracking, step wind speed profile, variable wind speed profile, and robustness for (NSSFC and NDSFC) are the four key aspects described in this section. They are separated into four subsections as follows:

3.4.1 P&O technique versus TSR

This section explains the differences between P&O technique and TSR. The efficiency of the two strategies is seen in Fig.3.6. PI controller is utilized in P&O approach, and such a controller can be used in the TSR technique. Fig. 3.6 includes three different colors that indicate TSR technique, and the other two colors indicate P&O technique but with different step sizes, one at 0.1 step size and the other at 0.03 step size, based on rotational speed reaction. Fig. 3.6 includes four figures: the first shows the TSR and its tracking effectiveness to reference rotational speed, while the second and third show the tracking performance of P&O technique with its reference rotational speed, but with different step sizes, to demonstrate that the step size is important in reducing oscillations, harmonics, and settling time of such a system. These three figures can be summarized in the last one, that show all of these changes in relation to the generator reference rotational speed. It is clear from the figure that the TSR technique is far superior to the P&O technique in terms of oscillations and harmonics; otherwise, if step size is changed, the settling time will be affected. When the step size is adjusted from 0.1 to 0.3, for example, the oscillations are reduced but the convergence time is increased. So, based on the foregoing, we can conclude that TSR is much better that P&O in terms of performance and effectiveness Fig.3.6.

3.4.2 Step wind speed profile

In comparison to PI controller, the usage of two controllers named NSSFC (Nonlinear Static State Feedback Control) and NDSFC (Nonlinear Static State Feedback Control)is introduced now, and this difference can be verified clearly from the maximum power coefficient shown in Fig.3.7, as the PI controller has an unbalanced power coefficient rotating far away from the maximum power coefficient, which is approximately 0.48, It has worse tracking performance than the other two TSR controllers. As a result, TSR necessitates the use of a wind speed sensor. When employing PI controller instead of NSSFC and NDSFC, the conversion performance at each wind variation is low (overshoot).

According to the power point of view, Fig.3.8 shows the differences between NSSFC and NDSFC controllers on one hand, and PI controllers on the other hand. This diagram depicts the maximum theoretical power, which serves as the benchmark against which the control efficiency must be measured. This Fig.3.8 illustrates that the PI controller has poor tracking performance for theoretical power, but the other two controllers (NSSFC and NDSFC) are considerably better in this regard. Additionally, the PI controller has a flaw that is well known from the previous research which is the maximum overshoot. Fig.3.9 verifies and proves the concept of Fig.3.8, but from a different perspective, as will be detailed further down: The dot line indicates the reference rotational speed that should be tracked, and the other three lines determine the other three controllers that are compared (PI, NSSFC, and NDSFC). This figure demonstrates that the PI controller cannot track reference rotational speed as well as the NSSFC, and NDSFC during the transient regime.

3.4.3 Variable wind speed profile for the three controllers

In this section, the controllers with variable wind speed profiles are explored in details utilizing the same parameters as the maximum theoretical power, rotational speed, and maximum power coefficient. In order to assure and evaluate the enhancement and efficiency of controllers used in such a system, Fig.3.10 displays the variable wind speed profile as wind speed varies from 4 m/s to roughly 10 m/s with time range of around 40 seconds. The black dotted line is the maximum theoretical power that should be tracked in a good manner, and the other three lines indicate (PI, NSSFC, and NDSFC) as explained clearly.

The PI controller has an enhancement towards end of the curve because it can track the reference as seen in the third tiny curve, but the other two controllers' tracking is excellent during the initialization and middle of system's operation. The black dotted line represents the stated maximum power coefficient, while the other three lines determine the controllers used in the system. Fig.3.11 validates and proves what happened in the system, but from a different point of view which is the power coefficient. It indicates that PI controller has the least tracking of all controllers, but that the NSSFC controller has less tracking than NDSFC one (This part will be verified clearly in the next part). From the foregoing, it is obvious that the two controllers (NSSFC and NDSFC) are much better than PI controller in terms of performance and tracking approach.

3.4.4 Variable wind speed profile for NSSFC and NDSFC

This section includes the three controllers(NSSFC, NDSFC, and PI), however it is mostly used to demonstrate whether the NSSFC or NDSFC technique is better for usage in such a system. The system and differences between controllers according to the rotational speed used in the system are depicted in Fig.3.12, with the black dotted line indicating the reference tracked rotational speed. The curves zoomed in such a figure show that they have nearly the same performance, but the NDSFC controller has a little bit more enhancement than the NSSFC controller, and Fig.3.13 proves and verifies what happened in Fig.3.12 in terms of rotational speed, and tracking error.

3.4.5 Robustness

This section delves deeper into two controllers (NSSFC and NDSFC) that outperform the PI controller. It examines robustness of NSSFC and NDSFC controllers based on three points of comparison mentioned previously: theoretical power, power coefficient, and rotational speed. It is obvious from the numbers in this section that the normal operating circumstances range from 0 to 25 seconds. A perturbation is applied and used on the control signals for such a system at T=25 seconds. Fig.3.16 which depicts the reference tracked theoretical power at varied wind speed profile, indicates that NSSFC controllers deviate from the reference tracked power, whereas NDSFC controller as indicated in the figure, track reference theoretical power very well after a short period of time. The same thing happens for power coefficient between the two controllers and the reference one, as shown in Fig.3.15, and the reference rotational speed, as shown in Fig.3.14, and all of these figures that already occur at variable wind speed profiles prove that the NDSFC has much better performance as well as better tracking technique than the NSSFC after inserting the perturbation part after time T=25 second and in each of the pictures, the small part zoomed after 25 seconds for Fig.3.15 and Fig.3.14 show tracking performance more clearly to ensure that NDSFC controller is the holder of the upper hand more than NSSFC controller.

3.5 Changing to system's outer loop

All of these results to show our work from the mechanical part point of view that indicates the inner loop in order to get the torque needed as an output from the mechanical part and continuing to reach the electrical part as an input as the electrical part is faster in response and efficiency, so our work now will concentrate on electrical part of the system which is considered to be outer loop of the system. The effect of utilizing non linear proportional integral controller(NPIC) will be studied. Introduction about PI and NPIC controllers will be the starting part.

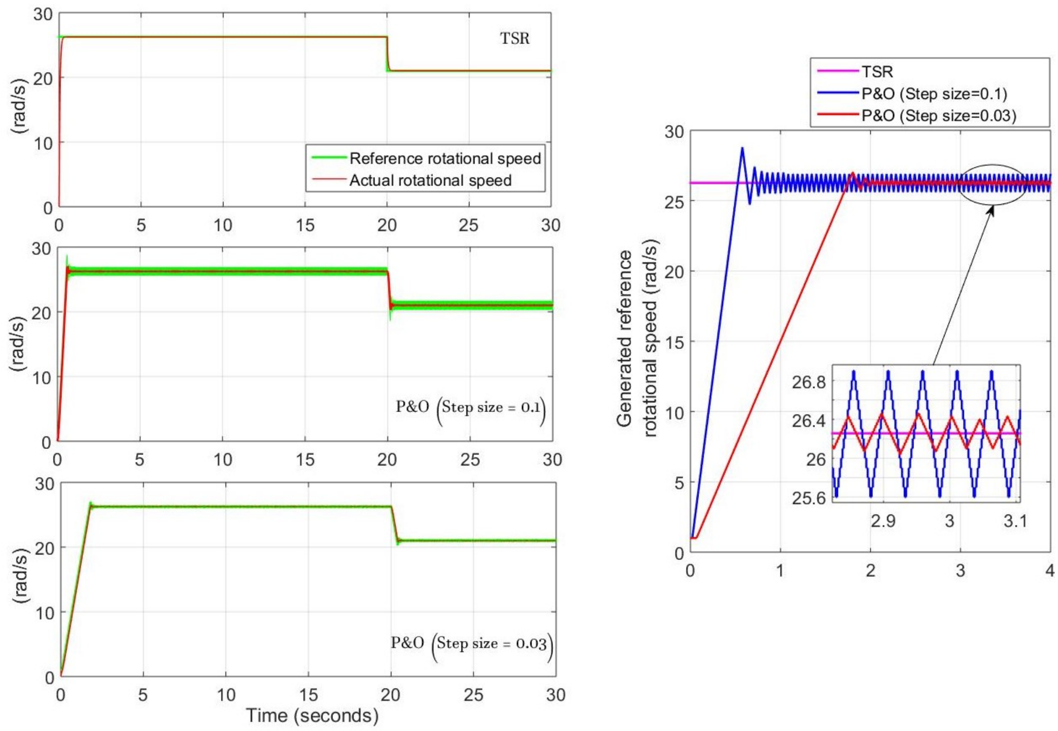

Figure 3.6: Generated reference according to variable step size

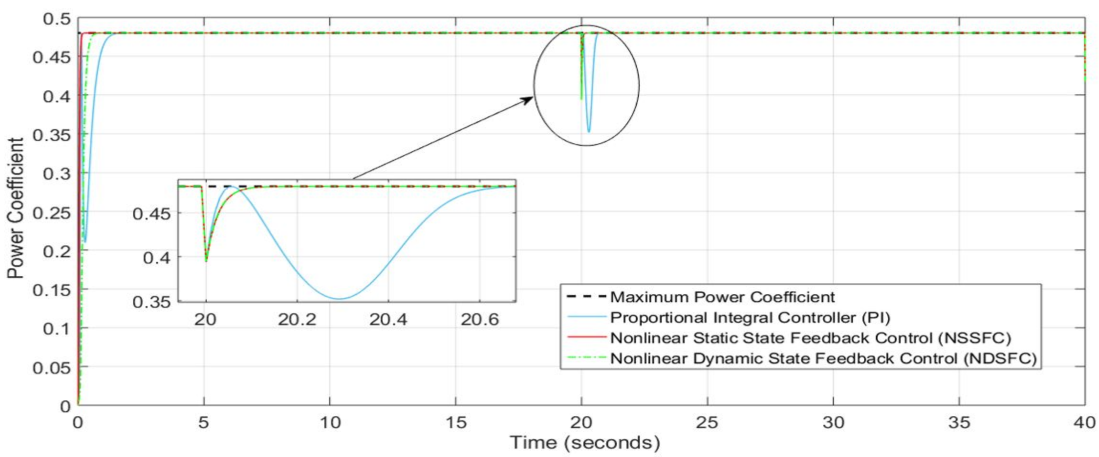

Figure 3.7: Power coefficient VS time(S)

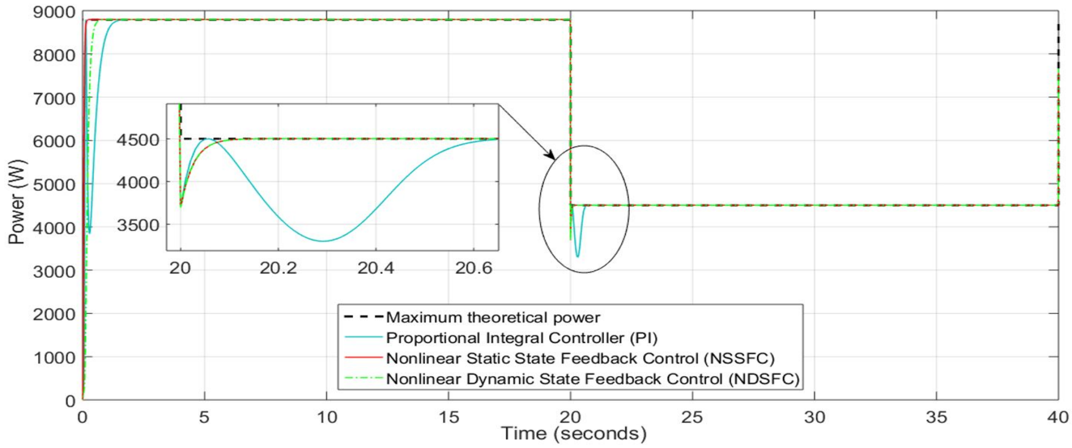

Figure 3.8: Power(W) VS time(S) according to step wind speed profile

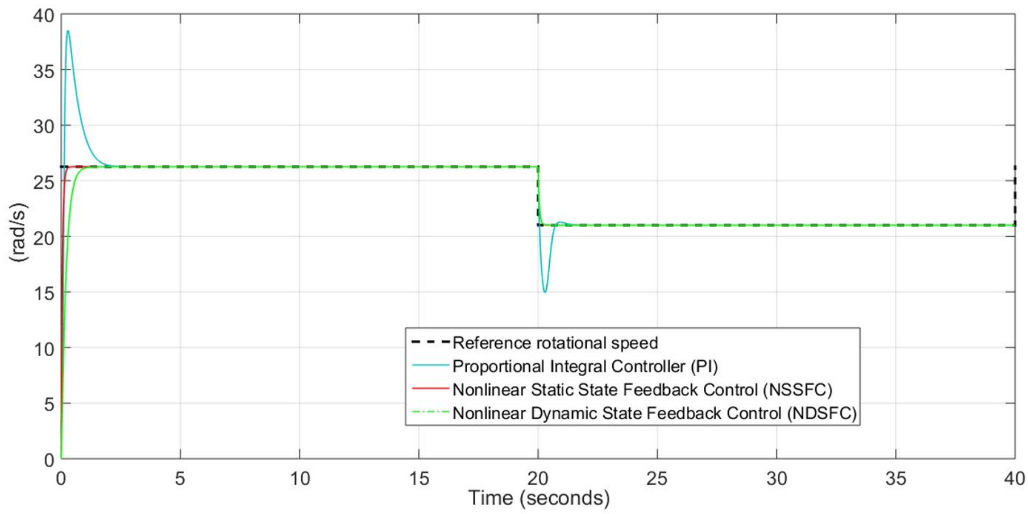

Figure 3.9: Rotational speed(Rad/S) VS time(S) according to step wind speed profile

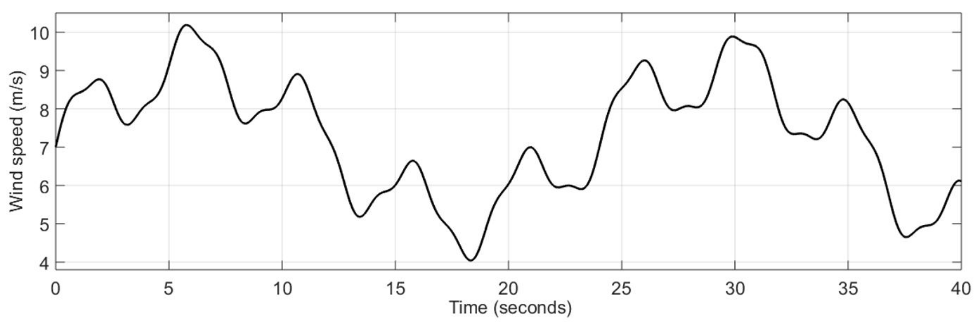

Figure 3.10: Variable wind speed profile

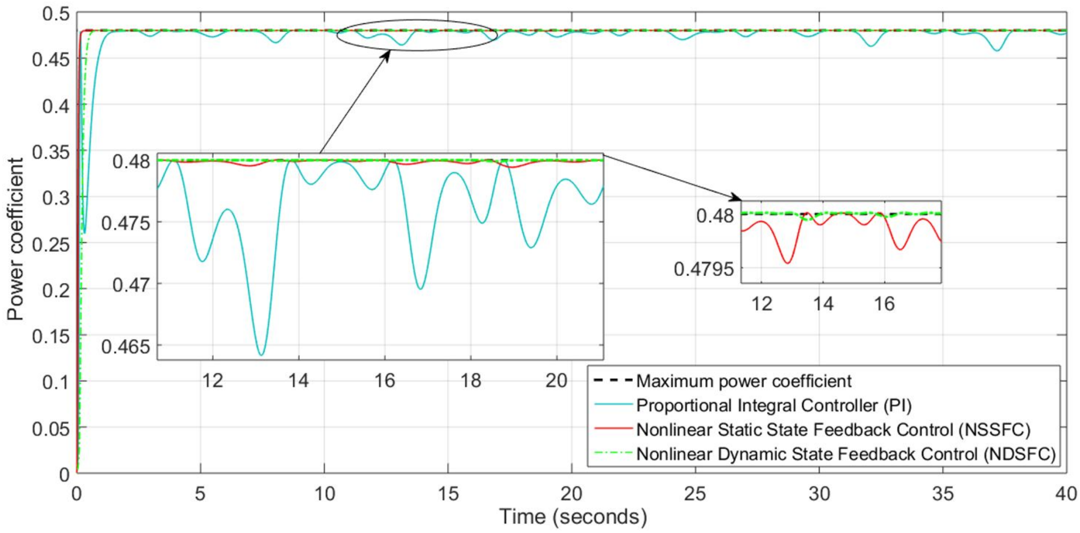

Figure 3.11: Power Coefficient according to variable wind speed profile

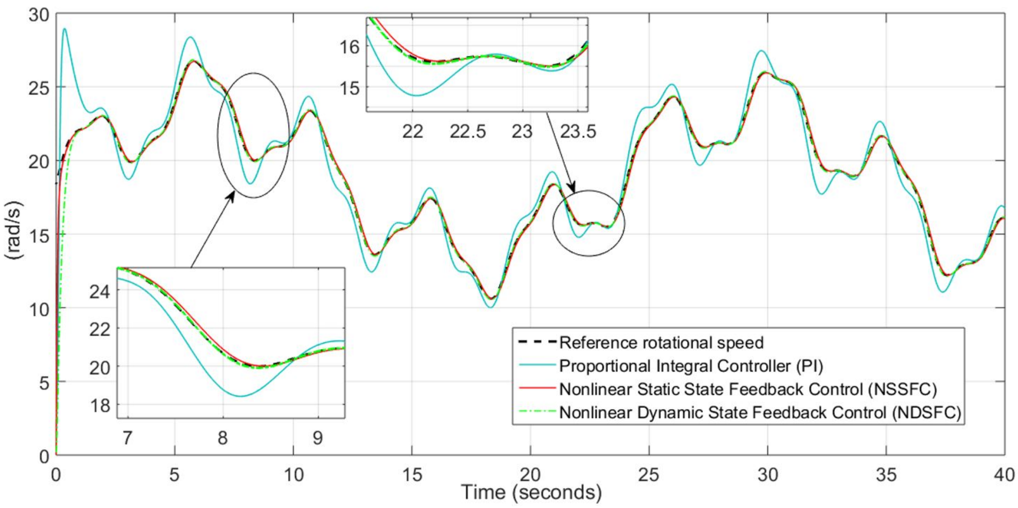

Figure 3.12: Rotational Speed(Rad/S VS Time(S) according to variable wind speed profile

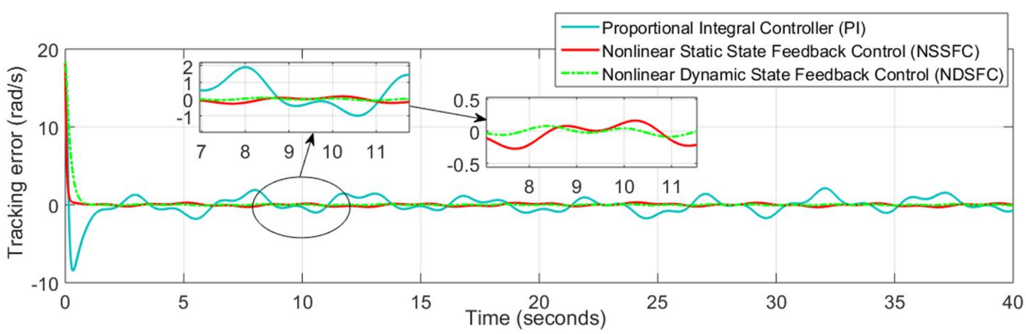

Figure 3.13: Tracking error according to variable wind speed profile

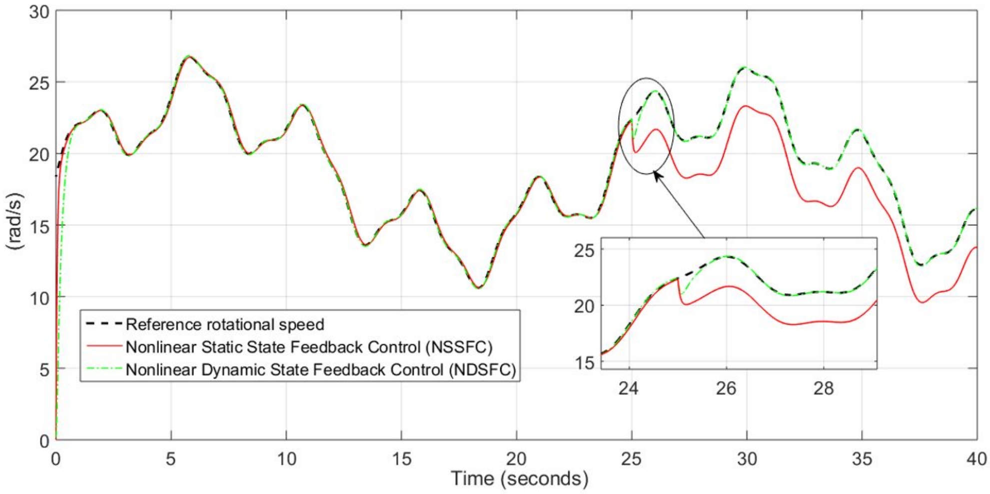

Figure 3.14: NSSFC and NDSFC rotational speed

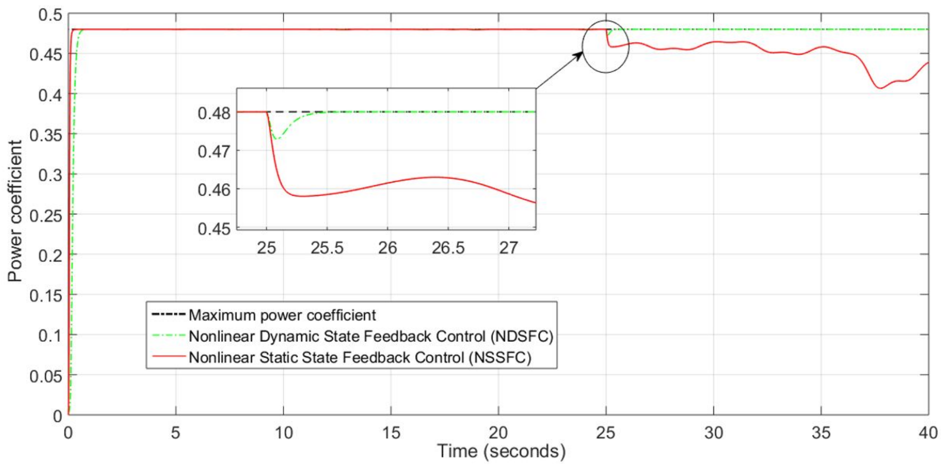

Figure 3.15: NSSFC and NDSFC power coefficient

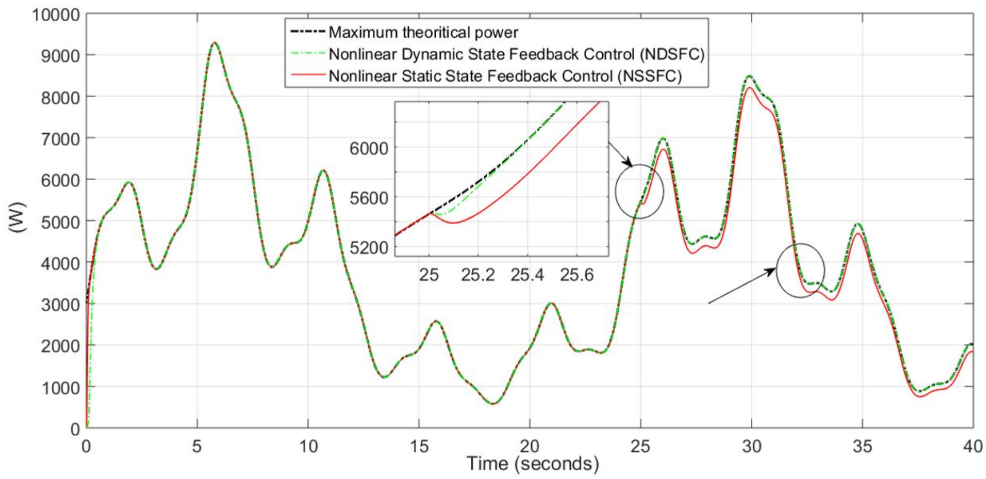

Figure 3.16: NSSFC and NDSFC power robustness

3.5.1 PI Controller

PI controllers are much better than PID controllers(Proportional-Integral-Derivative) nowadays due to the effect of disorder which is created by subsidiary on the control handle Monje, YangQuan Chen, Vinagre, et al. 2010 andStavrov, Nadzinski, Deskovski, et al. 2021. It is noticed that a lot of PID controllers that are utilized within mechanical application are PI controllers. Most of controller frameworks can get sensible results utilizing PI controllers that have two parameters(P and I). Numerous approaches for deciding the parameters of PI controllers have been formulated. The foremost common approaches are the Ziegler-Nichols,Aström-Hagglund, and Cohen-Coon approachesÅström and Hägglund 2001. Because of its straightforward frame, low cost and ease of plan. PI controller is the most broadly utilized in mechanical applications right now. In spite of these merits, when the controlled protest is exceedingly nonlinear and questionable, PI controller can not work anymore.

PI controller will diminish constrained oscillations and consistent state errors, permitting on-off controller and P controller individually to operate appropriately. On the other hand, integral mode contains negative effect on system's reaction time and solidness generally. As a result to that, PI controller will not increment the response time. It's to be anticipated, given that PI controller can not predict what will happen with the error within the close future. To overcome this trouble subsidiary mode can be utilized, which can anticipate what will happen with the error in the close future, diminishing the controller's response time. In industry, PI controllers are regularly utilized, particularly when reaction time isn't a concern. A control without D mode can be utilized when: Part of interference and noise amid the method of operation, no need for the framework to react rapidly. As a result, we would go with the inclination toward protection of benefits for PI controller.

3.5.2 NPIC Controller

Controlling issue has continuously got to be critical work for engineers. These controllers have come into presence since 1950, To control the nonlinear and complex controller frameworks, PID has already prevailed as the structure of this controller is exceptionally simple to plan and its execution is exceptionally inaccurate. This controller is exceptionally conservative from the cost point of viewSpong, Hutchinson, and Vidyasagar 2004, Bucz and Kozáková 2018. However, it was not conveying ideal outcomes and can not deal with the non-linearities and instability to control these problems. All of these strategies are fundamentally depending on the energetic show of the controller framework as they give the perfect path to bargain with complexity and non-linearities Loudini 2013. However, as it is said before that nothing is ideal so there were some disadvantages in these control procedures for conveying the most suitable outcomes. It requires precise scientific show, as well as it is troublesome for pick up planning design to take care of variable operating points V. Kumar and Rana 2017. In order to take care of such framework that has been ineffectively powerful, it can be analyzed as a recent procedure explored like the artificial intelligence which was integrated with the traditional control methods Saxena, J. Kumar, and Deolia 2021. Improvement methods and forming the framework have increased more brilliantly by using ANN and AFLC conjointly, the combination of both that can be named neuro-fuzzy procedure. This combination of controllers allow exceptionally great outcome in expanding capabilities of controllers Kong, Jia, G. Zhang, et al. 2015, W. Zhao and Meng 2019, Saxena, J. Kumar, and Deolia 2021. Fuzzy logic controller gives nearly exact outcome for uncertain framework. Ghanbari, Kazemi, Mehmanpazir, et al. 2013 has proposed this fluffy rationale that is not fair limited between the true and wrong one. Despite that, offer assistance is maintained to bargain with the probabilities that is located between at-most false and at-most true. After that, the FLC has come that is already presented by S. Zhang, Dong, Ouyang, et al. 2018. When these classic control strategies combine with artificial intelligence and neuro fuzzy logic, this permits engineering control better approach and modern drift. It has exchanged to mechanical technology control. This combination procedure are exceptionally much accommodating in controlling nearly all the areas like chemical, nourishment, material, and these controllers are playing a crucial part in controlling mechanical autonomy. They are exceptionally multi input multi yield and much non-linear links of the controller can be minimum, but joins are expanding depending on the particular assignment for which the controller has been outlined with the assistance of other controllers, those areas can be reached as they are not effectively available for welding and collecting. Brilliant methods have arrived in 1990s that the disadvantages of classical and conventional PID controller and combination of PID controller with fuzzy logic totally resolved. This Proposed controller have different points of interest over the conventional controllers like faster speed, more exactness, moreover it gives superior steadiness to framework. PI controller combination offers assistance to completely evacuate steady state error. It has great transient reaction and it is strong enough to take care of non-linearities. Nonlinear controller is outlined with the assistance of time-varying nonlinear factor. The work of this controller depends on the duplication of indispensable gain to alter it in run time and to compensate all instabilities that show up consequently.

3.5.3 Speed observer and estimation techniques

Many speed estimation strategies for various machine types have been studied in the literature: doubly fed induction generator (DFIG), permanent magnet synchronous machine (PMSM). Brushless DC, machine (PMSM), induction motor (IM), BLDC motor, and others. Our concentration for this research on one of the most often utilized generators in Applications for wind energy conversion that are noted for their great efficiency and energy production. The PMSG is a type of generator that utilizes permanent magnets to generate electricity. To estimate the rotational speed information for PMSG, several observers or estimators have been presented. Carranza, Figueres, G. a. Garcerá, et al. 2011 compares five alternative speed estimators used in variable speed PMSGs operated by a three-phase boost rectifier in discontinuous conduction mode. A phase-locked loop (PLL)is the first one. The second is an estimator that starts with the rectifier's DC current and voltage. Starting with the electromotive force, the third method employs an extended Kalman filter, the fourth one employs an extended Kalman filter, but this time begins with the generator output voltages, and the last one uses linear Kalman filter to estimate the generator speed. Three speed estimation algorithms are compared and examined in the wind electric conversion system Brahmi, Krichen, and Ouali 2009, namely MRAS(Model Reference Adaptive System) algorithm based on PI controller, neural networks, and a sliding mode. One of the finest strategies for speed estimation has been validated through all of the research works is the MRAS observer-based generator rotational speed estimation technique W.-M. Lin, C.-M. Hong, and F.-S. Cheng 2011, Khlaief, Boussak, and Chaari 2014. It has gotten a lot of attention and is now a widely utilized approach in many sensorless control systems, and because of that this technique has been applied in this work in order to give the optimal results needed and to enhance and develop the control technique required for this work. It has gotten a lot of attention and is now widely utilized approach in many sensorless control systems. Based on the published literature works, and the previously mentioned advantages offered by the estimation of MRAS technique, this latter has been selected in this part of the chapter and instead of the existing published work in literature, which develop and propose more advanced nonlinear control techniquesMishra, V. Kumar, and Rana 2020 such as sliding mode concept Barambones 2012, back-stepping theory Nadour, Essadki, and Nasser 2017 etc., and that is too complex to implement and requires utilization and measurement of many system states (More sensors and high implementation cost), this part of the chapter proposes classical PI controller improvement, by generating the gains with an online way, this technique is called NPIC (Nonlinear Proportional Integral Controller), this approach has the advantages of being simple from the implementation point of view and offers a low cost solution.

In this discussion, the sections have been classified as follows: Section 3.5 is the introduction including a brief on wind turbine Power electronics, emerging technology challenges for power electronics, wind turbines, PI controller, NPIC controller as it is one of the main parts of the system, and the speed observer and estimation techniques. Section 3.6 is the wind energy conversion system modelling and it has been divided into two subsections which are model of the turbine, and model of PMSG. It is previously mentioned at modelling chapter, however it is written here in order to make this part of chapter in sequence with each other. Section 3.7 presents in details PMSG side converter control that includes the outer loop, inner one, and nonlinear control law. Section 3.8 determines MRAS observer concept that is considered also as a main part with NPIC in such a system. Section 3.9 discusses results for the overall system that contains two main parts: First one includes results using speed sensor, and the second one includes results without speed sensor(sensorless). And section 3.10 is the conclusion.

3.6 Wind Energy Conversion System Modelling

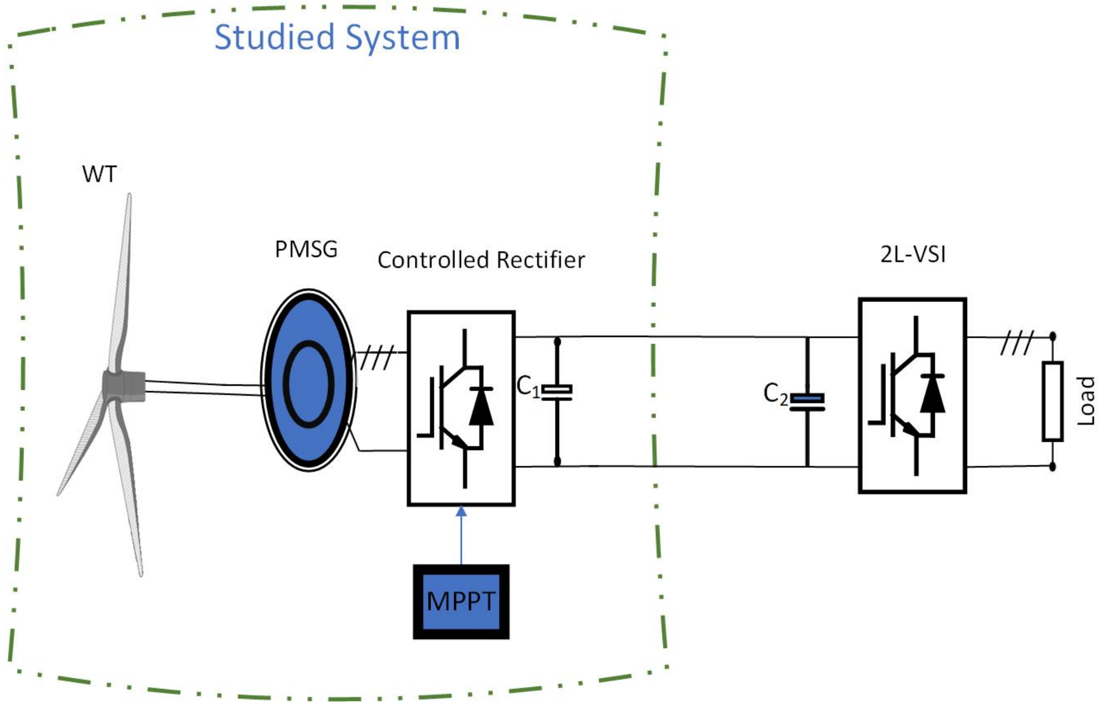

Figure 3.17: schematic diagram for WECS

Renewable energy source is the foremost noteworthy point within the world at present. It was famous that the petroleum subsidiary spares within the world are decreasing rapidly and no stores were recognized. In spite of that, energy era from non-renewable energy source may cause such gigantic number of unwanted issues like global warming, acid rains, and emanation of nursery gasses. Renewable energy sources anticipate essential movement in this sort of condition such as waves, geothermal warm, Sunlight, and Tides. An extraordinary bargain of countries has characterized up an objective to reach 100% of its feasible control from renewable sources later on. For illustration, some organizations have chosen to switch all-out energy supply (versatility, control and cooling/heating) to 100% of the renewable control source by 2050 Toja-Silva, Colmenar-Santos, and Castro-Gil 2013. Among these renewable control sources around the world, the utilization of wind for control era has been amplified rapidly.

For small wind power(not bigger than 100 kW), PMSG is preferred due to its accuracy, effectiveness and cost estimation. Two modules are right now in major utilization with this machine Orlando, Liserre, Monopoli, et al. 2008. In the primary setup Fig.3.17, Wind Turbine connected with PMSG which is driven by active rectifier, accompanied with DC capacitor passing through the two-level voltage source converter connected to three phase load. A vector control is executed where the torque of generator can be controlled by involving i_q which is the quadrature current and the drawbacks can be decreased by i_d which is the direct current. This empowers enhanced high effectiveness and control Baroudi, Dinavahi, and Knight 2007. Beside that, PMSG is carried out with a diode bridge connection, boost converter that can be buck-boost or buck converter also, and DC bus capacitor. Since reactive power is not irreplaceable for PMSG procedure, this coordinate association to a diode bridge is conceivable. The torque already can be controlled by implying voltage or current at the diode bridge yield Esmaili, Xu, and Nichols 2005. With this design, performance of PMSG is much less than the normal one and the harmonics will be increased. In any case, clarity of control, robustness, conversion performance and efficiency, all of which are fundamental highlights in small wind turbines that are significantly progressed and costs are brought down. Another factor is the electric generator and its control strategy Compared to other conceivable generators, PMSGs have a higher productivity as the copper misfortunes within the rotor are small, and its energy density is a little bit larger. Beside that, PMSGs can be utilized at low varying speeds in order to permit the generator to be specifically coupled with wind turbine without employing a gearbox which would diminish the quality of being used for the framework, increment its weight, and its requirement for maintenance Esmaili, Xu, and Nichols 2005. Although, PMSGs are AC machines, a controlled AC/DC converter is essential to supply proficiently the DC load.

MPPT is regular for configuration. In case of identifying characteristics of the framework, P& O technique can be utilized. MPPT is utilized to raise the proficiency, ability of control and its era. P& O is one of the methods which can be utilized with MPPT. Analysts have discovered different MPPT calculations for maximizing output energy which is required such as incremental conductance Elgendy, Zahawi, and Atkinson 2011, P& O Reisi, Moradi, and Jamasb 2013, ripple correlation method Casadei, Grandi, and Rossi 2006, short circuit current strategy H. Kumar and Tripathi 2012, and open circuit voltage strategy H. Kumar and Tripathi 2012, while here the P& O technique because of its simplicity.

3.6.1 Model of the Turbine

It is described before in chapter 2, section: 2.1.2

3.6.2 Model of PMSG

It is described before in chapter 2, section 2.2.

3.7 PMSG side converter control

A vector Control technique is used in AC/DC converter so as to control the generator's speed utilizing NPIC controller, and a flow chart is used to show the operation of the whole system as shown in fig.3.18. Generator' speed (ω_m) can be constrained by changing the electromagnetic torque (T_m) to its reference T^*_{em}. This is happened by acting on the q-axis current I_{qs} utilizing this equation:

$$I_{qs}^* = \frac{2}{3p\psi_0} T_{em}^* (18)$$

The stator current of d-axis I_{ds} part is limited to zero in order to accomplish the generator's optimized torque. The optimum rotational reference speed can be determined utilizing

$$\Omega_{\text{mopt}} = \frac{\lambda^* \cdot v_W}{R} (19)$$

λ^* addresses the optimum tip-speed ratio. The power circuit shown in Fig. 3.19 discusses the control technique for the system across MPPT utilizing online NPIC controller as it has three NPIC controllers and the pulse width modulation tool to manage the switching frequency. The system in Fig.3.20 shows the sensorless control system using both MRAS observer and NPIC controller.

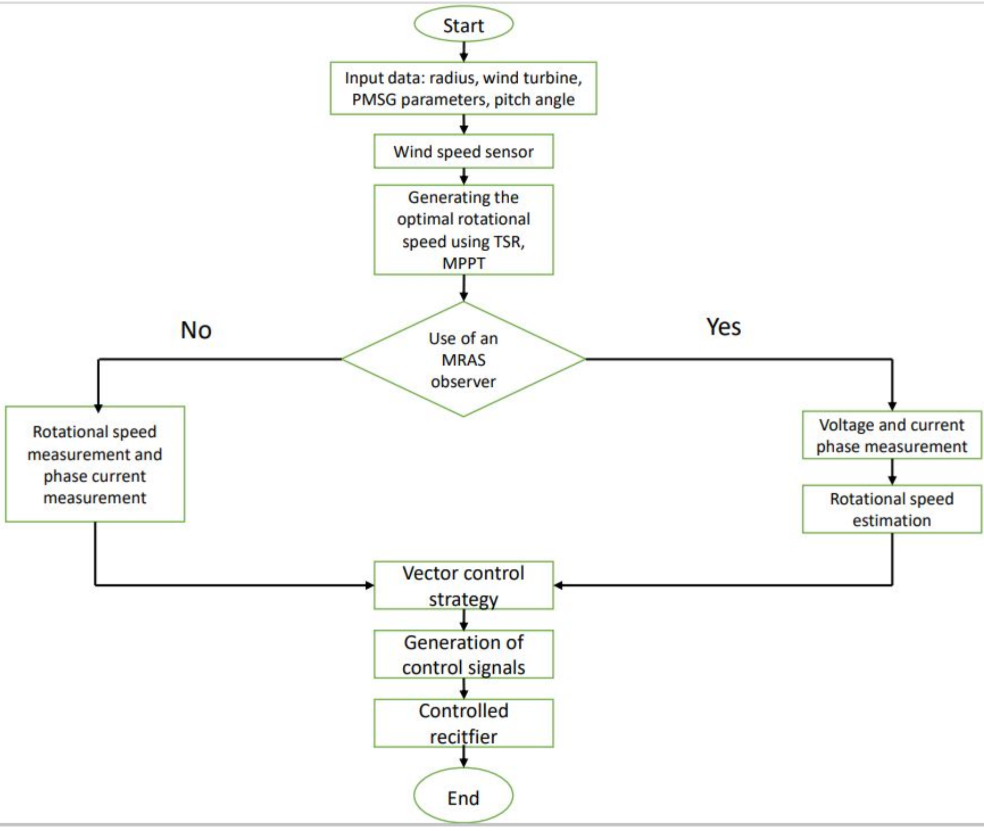

Figure 3.18: Flow chart for the whole system.

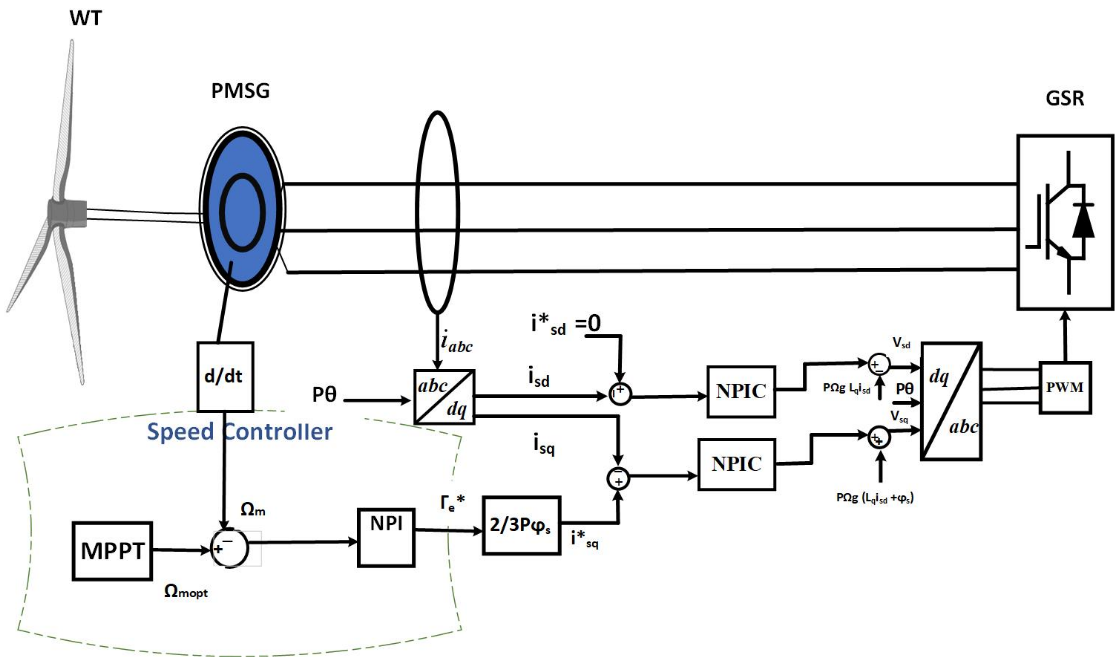

Figure 3.19: Control system strategy based on NPIC

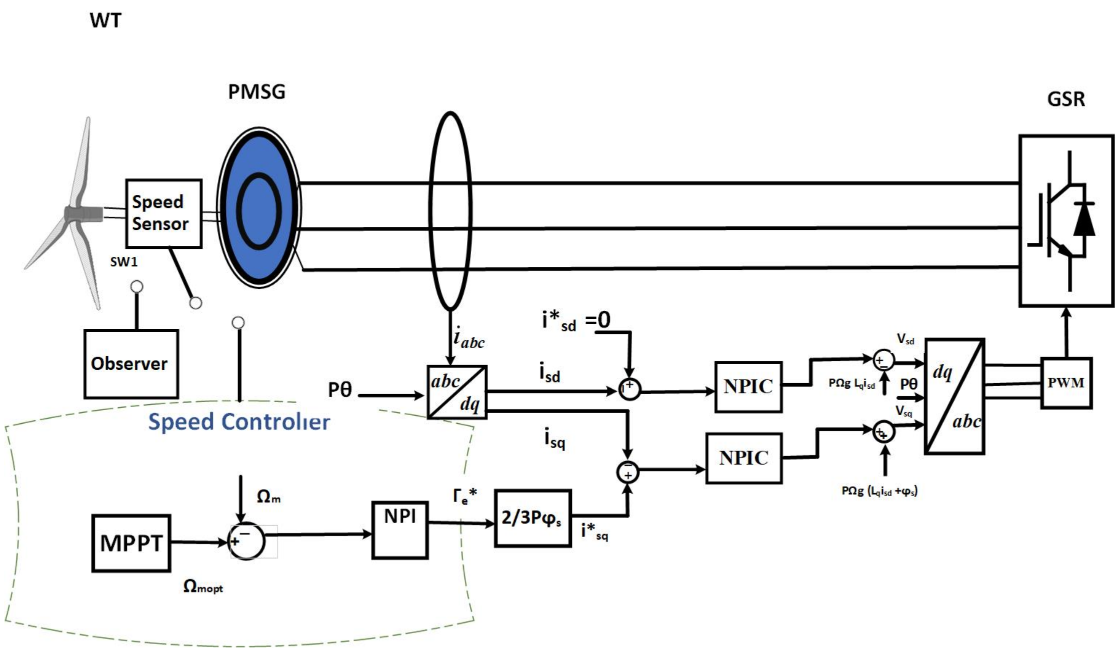

Figure 3.20: Sensorless Control system strategy based on NPIC and MRAS observer

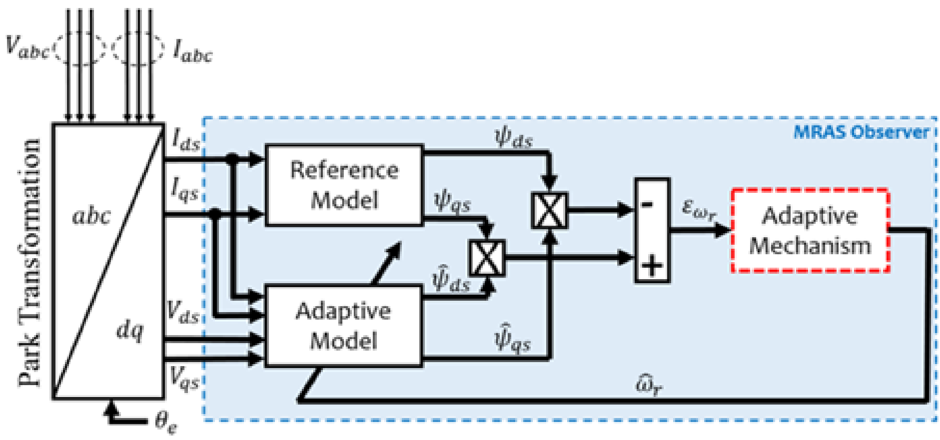

Figure 3.21: MRAS observer scheme

3.7.1 Outer loop

The error expression of speed controller is given as follows :

$$\varepsilon_{\Omega_m}(t) = \Omega_{m_{opt}}(t) - \Omega_m(t)(20)$$

The outer control is used to regulate rotor speed to its reference and provides reference current of the q-axis to the inner current loop. The speed controller is designed using non linear proportional integral controller version to allow dealing with highly non-linear behavior of wind turbines. NPIC speed controller is given in equations as follows:

$$\begin{cases} I_{qs}{}^* = \frac{2}{3p\psi_0}\left(k_{p_o}\varepsilon_{\Omega_m}(t) + \alpha_o(t)k_{i_o}\int \varepsilon_{\Omega_m}(t)dt\right)(21) \\ \alpha_o(t) = \left[1 - \exp\left\{-\left(a\varepsilon_{\Omega_m}{}^2(t) + br_{\Omega_m}{}^2(t)\right)\right\}\right]^2 (22) \end{cases}$$

Where, $I_{qs}{}^*$ is the reference q-axis current provided to the inner current loop, Kp_0 and Ki_0 represent respectively proportional and integral gains of NPIC, and alpha(node) indicates the modification factor.

3.7.2 Inner loop

For regulating the components of current Iqs and Ids to the reference belong to them(i^*_{sd} and i^*_{sq}). The error expression can be illustrated as follows:

$$\begin{cases} \varepsilon_{I_{ds}}(t) = I_{ds}{}^*(t) - I_{ds}(t)(23) \\ \\ \varepsilon_{I_{qs}}(t) = I_{qs}{}^*(t) - I_{qs}(t)(24) \end{cases}$$

The control voltages of q and d axis are planned utilizing NPIC, they can be introduced as follows:

$$\left\{ \begin{array}{c} V_{ds}^{*}(t) = k_{p_{Ids}} \varepsilon_{I_{ds}}(t) + \alpha_{I_{ds}}(t) k_{i_{I_{ds}}} \int \varepsilon_{I_{ds}}(t) dt \\ - p\Omega_m L_q I_{qs} (25) \\ \\ V_{qs}^{*}(t) = k_{p_{I_{qs}}} \varepsilon_{I_{qs}}(t) + \alpha_{I_{qs}}(t) k_{i_{Iqs}} \int \varepsilon_{I_{qs}}(t) dt + p\Omega_m \left(L_d I_{ds} + \psi_0 \right) (26) \end{array} \right\}$$

$$\text{with} \left\{ \begin{array}{l} \alpha_{I_{ds}}(t) = \left[1 - \exp\left\{ -\left(a\varepsilon_{I_{ds}}^2(t) + br_{I_{ds}}^2(t) \right) \right\} \right]^2 (27) \\ \\ \alpha_{I_{qs}}(t) = \left[1 - \exp\left\{ -\left(a\varepsilon_{Iqs}^2(t) + b{r_{Iqs}}^2(t) \right) \right\} \right]^2 (28) \end{array} \right.$$

3.7.3 Nonlinear control law

It is apparent from the nonlinear control law that the portion of exponential one head for moving close to zero, in case either of the two factors "ε" & "r" is significant, making the expression tends to "1" and there is no serious variance will happen within the integral gain. This can be required in the event that either "ε" or "r" is significant, then the integral gain required to be constrained and ought to be adjusted as it is. Taking into consideration a case where, $'\varepsilon'$ is near to zero but 'r' is significant. It is obvious that how alpha changes with respect to $'\varepsilon'$ and 'r'.

3.8 MRAS observer concept

The utilization of mechanical sensor increments essentially the initial cost of wind transformation framework (around 10% of the cost of a wind generator that has a small scale) Al-Ghossini, Locment, Sechilariu, et al. 2016, as well as the maintenance cost of the speed sensor, including the area of working for wind turbines will effortlessly harm the speed sensors. Therefore, the accuracy and precision of wind turbine will be diminished. Correct assessment of rotational speed for generator is exceptionally prescribed and needed to take care of wind turbines. Utilization of speed sensor or assessment may be the leading arrangement to supplant the necessity of physical sensors, annul alteration and the estimation of exactness issues.

MRAS observer as shown in Fig.3.21 permits predicting the generator speed by measuring phase currents and voltages onlyYan, H. Lin, Feng, et al. 2013. It consists of two models: adaptive model and the reference one. Reference model can be utilized to measure the stator flux of d-q. As the stator currents of d-q are the beginning of operation using Eqs. 11 and 12, while the other model which is the adaptive one can be performed by Eqs. 29 and 30, and it can be utilized for predicting stator flux of d-q launching from stator voltages and currents of d-q, and take advantage of the rotor speed predicted by adaptive mechanism as a feedback and convertible parameter. Results for the two models are shown and compared, and the error evaluated can be illustrated by ε_{w_k}. Such an error can be utilized as an input to adaptive mechanism.

$$\hat{\psi}_{ds} = \int \left(V_{ds} - R_s \hat{I}_{ds} + \hat{\omega}_{\mathrm{r}} L_q \hat{I}_{qs} \right) \mathrm{d}t + \psi_0 (29)$$

$$\hat{\psi}_{qs} = \int \left(V_{qs} - R_s \hat{I}_{qs} - \hat{\omega}_{\mathrm{r}} L_d \hat{I}_{ds} - \psi_0 \hat{\omega}_{\mathrm{r}}\right) \mathrm{dt} \quad (30)$$

Adaptive mechanism can be utilized by the classical MRAS observer depending on PI controller for driving the output error vector to zero. Accordingly the estimated rotational speed $\hat{\omega}_r$ changes to its original value. The error between the adaptive and reference d–q axis stator flux models is defined as follows

$$\varepsilon_{\omega_r} = \left[\varepsilon_{\omega_{t1}}, \varepsilon_{\omega_{r2}}\right]^T = \left[\hat{\psi}_{ds} - \psi_{ds}, \hat{\psi}_{qs} - \psi_{qs}\right]^T \quad (31)$$

$$\varepsilon_{w_k} = \hat{\psi}_{ds} \psi_{qs} - \hat{\psi}_{qs} \psi_{ds} \quad (32)$$

The predicted speed is shown as follows:

$$\begin{aligned} \hat{\omega}_{\mathrm{r}} =& k_p \left(\varepsilon_{\omega_{\mathrm{r}1}} \cdot \hat{\psi}_{qs} - \varepsilon_{\omega_{\mathrm{r}2}} \cdot \hat{\psi}_{ds}\right) \\ &+ k_i \int \left(\varepsilon_{\omega_{\mathrm{r}1}} \cdot \hat{\psi}_{qs} - \varepsilon_{\omega_{\mathrm{r}2}} \cdot \hat{\psi}_{ds}\right) \mathrm{d}t + \omega_{\mathrm{r}}(0) \end{aligned} \quad (33)$$

Where:

$$\varepsilon_{\omega_{\mathrm{r}1}} \cdot \hat{\psi}_{qs} - \varepsilon_{\omega_{\mathrm{r}2}} \cdot \hat{\psi}_{ds} = \psi_{qs} \cdot \hat{\psi}_{ds} - \psi_{ds} \cdot \hat{\psi}_{qs} \quad (34)$$

PI controller parameters must be calculated in order to permit the adaptive model output state vector to achieve the reference model. The stability of MRAS observer is identified and proved by Popov's hyper stability criterion, and it has been studied and suggested in the following references Brahmi, Krichen, and Ouali 2009, Krishna and Daya 2016.

3.9 Results and discussion

The simulation studies have been carried out on Matlab/Simulink environment on small scale PMSG wind turbine (10Kw). The system parameters have been taken from Soufyane, Abdelhamid, and Smail 2020.

This section discusses two types of results: one of them shows the system using NPIC controller with the speed sensor, indicates the variation of wind speed with time, as the system does not work on a constant wind speed, it has a lot of variations to show effectiveness of online controller on such a system, power coefficient according to wind turbine efficiency, theoretical maximum mechanical power, three phase current for balancing by proving that they are in phase with each other, rotor speed, and tracking errors according to the d and q axis. While the second type shows MPPT control using MRAS observer based on NPIC controller without speed sensor(sensorless).

3.9.0.1 First part of the results using speed sensor

This part shows the performance of vector control strategy using NPIC Controller utilizing real rotational speed sensor. Fig.3.22 shows variation of wind speed with time, as this is the range of running such a system.

Fig.3.22 shows the variation of wind speed with time, as this is the range of running such a system.

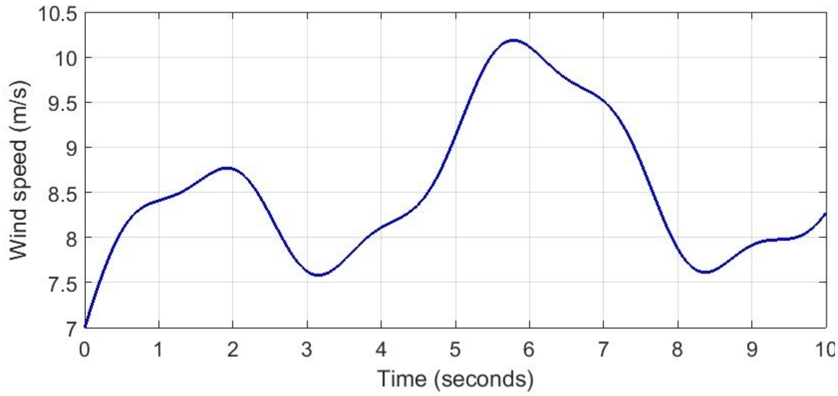

Figure 3.22: Wind speed variation

Fig.3.23 indicates that the power coefficient used in the wind turbine conversion system has reached to its maximum value which is around 0.48.

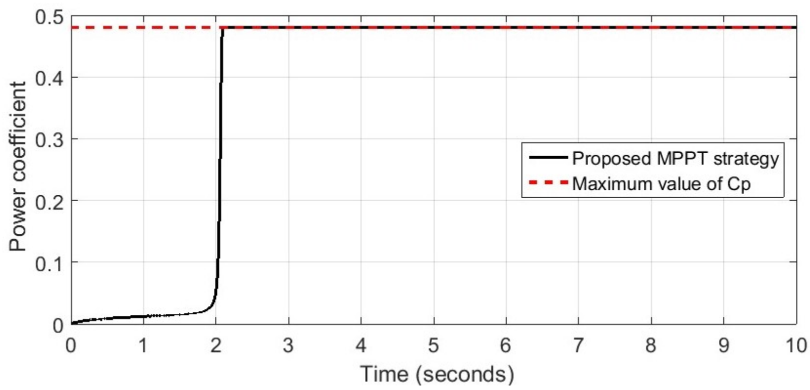

Figure 3.23: Power Coefficient:C_p

Fig.3.24 discusses three main parts of the system which are:

- (1) theoretical maximum mechanical power which has the blue color.
- (2)The extracted mechanical power by using the proposed control strategy based on NPIC that has the red color, the results shows a high tracking performance of the maximum power.
- (3) Absorbed electric power by the load, and the difference between the mechanical and electrical power happened because of the mechanical losses.

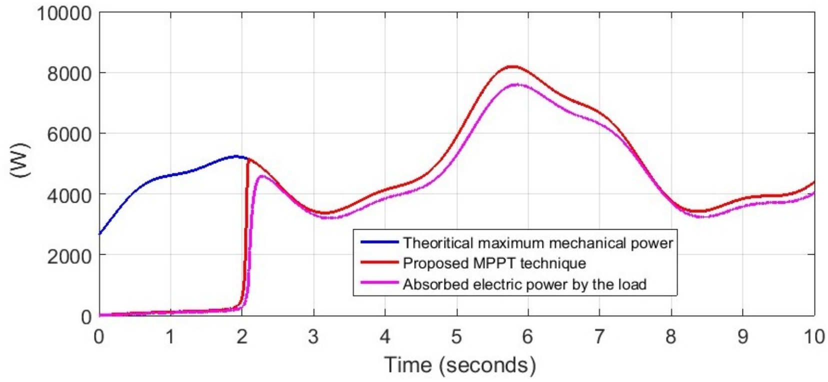

Figure 3.24: Power ratings

Fig.3.25 identifies the performance of balanced three phase currents (abc) and shows that they are in phase with each other and the system is balanced.

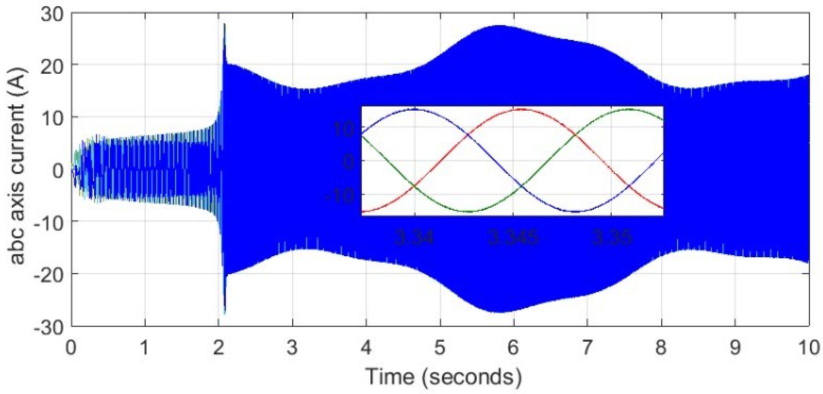

Figure 3.25: Generator three phase current

Fig.3.26 shows the evolution of reference and measured rotational speed, as can be seen the rotational speed tracks its given desired value generated by the TSR technique with high accuracy.

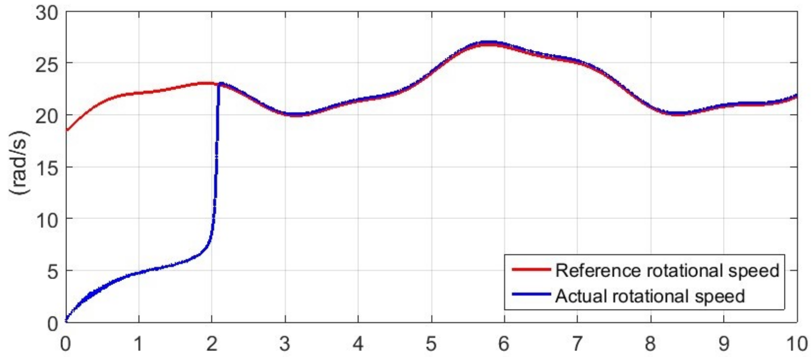

Figure 3.26: Measured, estimated and generated reference rotational speed

Fig.3.27 shows that the tracking error of d and q axis current as well as the tracking error of optimum rotational speed. It is noticed that all errors converge to zero value, which means that the wind turbine is working on its maximum power. The obtained results demonstrate the effectiveness of NPIC control strategy.

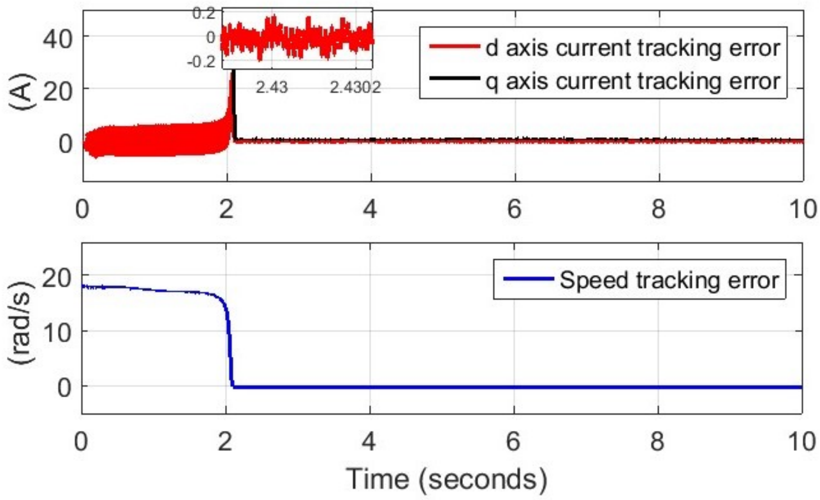

Figure 3.27: D-Q axis current and speed tracking errors

3.9.1 Second part of results without using speed sensor(sensorless)

This part discusses the same system but without speed sensor. Fig.3.28 shows the response of estimated rotational speed using MRAS observer, and the evolution of reference and actual rotational speed. It can be seen that MRAS observer estimate the rotational speed with high accuracy, and the actual rotational speed tracks its given desired reference with a very small error.

Fig.3.29 determines the estimated error with time interval equal to 10 seconds, it is cleared from the figure shown that there is some transient states before the 3rd second but it has been stabilized at zero after that state which indicates the robustness of controller using MRAS observer, and the last Fig.3.30 shows the tracking error with the same time interval and it proves that the error returns to zero after time equals to 3 seconds that indicates the transient state. After the discussion for all results, it is cleared that the sensorless part ensures also power maximization with a high tracking performance, this latter have the advantage of providing a low cost solution to the discussed problem in this part of the chapter, which will considerably reduce the overall system cost, especially for the small scale one.

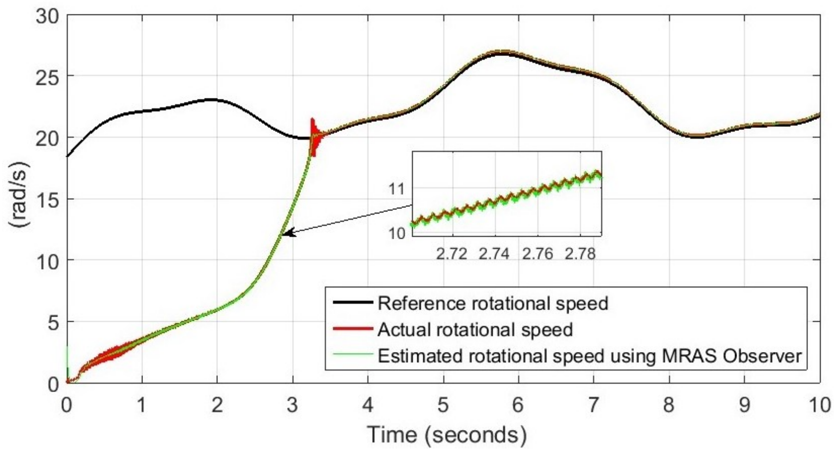

Figure 3.28: Rotational speed estimation error

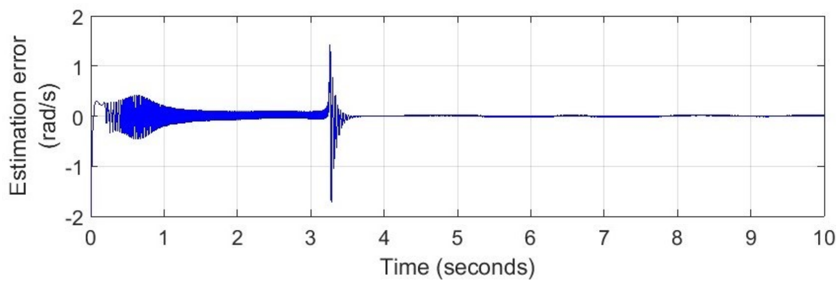

Figure 3.29: Estimated error for overall system

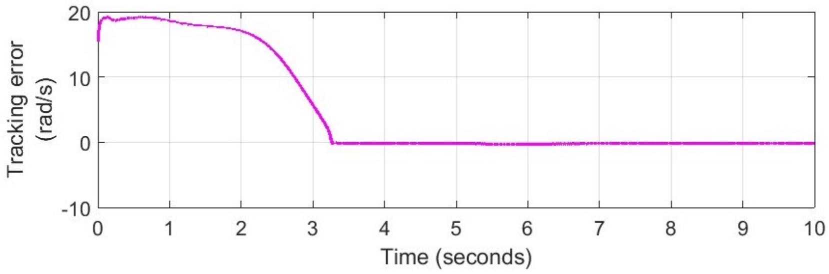

Figure 3.30: Tracking error for overall system

3.10 Conclusion

NSSFC and NDSFC are presented in the first part of this chapter as efficient controllers for wind turbine control, NDSFCs having greater performance and robustness through the wind turbine model. The main goal of this consideration is to keep tracking MPP. After applying this target, it is found that TSR is much better than P&O as it follows the reference more efficiently than P&O. NSSFCs can be affected by perturbation or error, which leads to reduction in following reference, whereas NDSFCs have a robust control on the system, can not be affected by errors, and follows the reference more efficiently than any other technique mentioned. The efficiency and robustness of controllers are verified and illustrated based on various system parameters such as the power coefficient, rotational speed, and theoretical power of such a system, and the controllers can be categorized from best to worst as follows: NDSFC, NSSFC, and finally PI controller, so the presented controller (NDSFC) can significantly overcome the uncertainties compared to NSSFC and PI controller, all of this occur utilizing Simulink/Matlab environment.

The wind turbine in the second part of this chapter is utilized by adding a new online controller technique that assigns well results by using MPPT method. In order to deliver sinusoidal currents, The rectifier is selected and planned, this enhances the PMSG efficiency. Moreover, for increasing power from the wind turbine, MPPT control technique is utilized, the maximum is extracted without using mechanical speed sensor. It is already common and well control method with favorable dynamic performance. PMSG is controlled by NPIC, it assigns very well dynamic performance according to variability of wind speed. Furthermore, the utilized control methods can take advantage of high efficiency, particularly by using PMSG. The stand-alone wind turbine system has been validated by simulation results using Matlab Simulink. The proposed sensorless approach is utilized by a model reference adaptive system for generator rotational speed estimation. This latter needs only three phase voltage and current measurements provided by cheapest electrical sensors. Wind turbine simulation has been developed in an online control program in order to improve the influence, validation of research methods on wind turbine systems and the effectiveness of MPPT control method using variable wind profiles. It is shown and proved according to the results that the sensor-less part is better than the sensor one

as the sensor removal can reduce the cost of the whole system and the its robustness and stability leads to much better performance.

4 Wind Turbine Control(Genetic Algorithm)

Summary

4.0.1 Introduction

This chapter consists of two parts, PI Controller integrating genetic algorithm is studied at the first part according to its impact on the efficiency and performance of wind turbine applications and their whole system. This part of the chapter proposes generating optimized power utilizing wind turbine. A boost converter is connected to the turbine in order to get the proper output voltage. The boost converter has been controlled using Maximum power point tracking (MPPT) control strategy. This part discusses three sections: first section is the steady state performance which is validated for the studied system, output power that varies according to the rated wind speed, rotor diameter of wind turbine, and wind turbine generator rating. Second one is the effect of fault occurrence on the system. Third part is the efficiency enhancement based on genetic algorithm used in such a system, and how it can improve the power output by reducing the transient state as much as possible at different operating ranges.

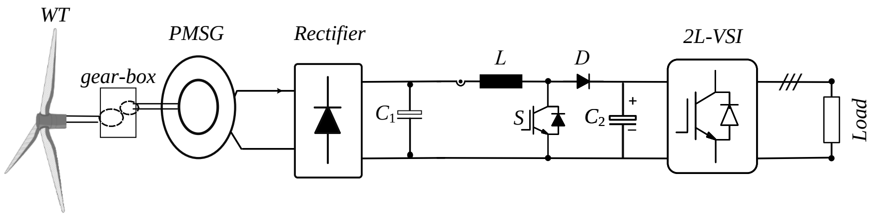

Figure 4.1: Schematic Diagram of The Main System

Wind turbines produce electric force by utilizing the intensity of wind to drive an electric generator Wenehenubun, Saputra, and Sutanto 2015. The generator creates power and moves from the peak to an accessible transformer and changes from the output voltage (generally around 700 V) to an across the nationwide grid (33000 V) or individual use (around 240 V)Kumara, Hettiarachchi, and Jayathilake 2017. Wind power is an appealing and elective force hot spot for both huge scale and little scale forms of wind and appropriated power age applications. One of the most significant focal points of wind energy is being modular and adaptable. Using wind has many features as the dependence on petroleum derivatives additionally is decreased. People pushing ahead into the 21st century with a forceful activity to quicken the advancement of wind innovation, furthermore diminish its expenses to make new openings, and to improve natural quality. Wind energy can be generated from two various techniques: offshore wind farms that are placed in terms of bodies in water, and the other one is the onshore wind farms that consist of wind turbines placed on land and they are the most popular type of wind farms in the mean time Zheng, C. Y. Li, J. Pan, et al. 2016. Capacity and efficiency for wind farms have a great impact on wind forces, that can vary with a great extent across different geographical areas Possner and Caldeira 2017. Consistency of the ability to generate energy is the key difference between offshore and onshore wind farms. Offshore wind farms have the ability to produce more electricity at a steadier rate than their onshore counterparts Kaldellis and Kapsali 2013. On the other hand onshore wind farms need careful analysis when choosing a space for development to make sure that there is sufficient wind speed. One of the merits of onshore wind farms is that they have accessibility more than those placed on offshore environments, so they are connected easily to local power grids Zheng, C. Y. Li, J. Pan, et al. 2016. The abundance of mature onshore wind farms also provides several resources for the improvement of wind farms, efficiency, and developing exactness of wind farm simulations. One of the hugest purposes of correlation among offshore and onshore wind farms is their cost. As for now, onshore wind farms are far less expensive to manufacture and keep up than the offshore wind farms. Onshore wind is an affordable wellspring of electric power, serious than coal or gas plants Walwyn and Brent 2015, Gasch and Twele 2010. Development and maintenance costs are much higher than onshore development and maintenance ones Gipe 1993. Therefore, offshore wind farms are at present falling behind onshore wind farms. Voltage source converter is one of the most important tools in the replication and transformation of electrical power. It has some benefits like regulating active and reactive power, and connecting strength for poor AC networks. A lot of applications have been considered for such a converter like the Uninterruptible power supply (UPS) Cortes, Jose Rodriguez, Vazquez, et al. 2010, andAlhasheem, Dragicevic, Rivera, et al. 2017. There are wide ranges of control structures to choose the used voltage source converter Dragicevic, Alhasheem, Lu, et al. 2017, Jose Rodriguez and Cortes 2012. The control structures that can be applied to such a converter are linear control Mattavelli 2005, Loh and Holmes 2005, MPC(Model Predictive Control) Buso, Fasolo, and Mattavelli 2001, Zhenbin Zhang, Tian, Xiong, et al. 2017, Jos Rodriguez, Jorge Pontt, C. A. Silva, et al. 2007, Mohammed Alhasheem, Blaabjerg, and Davari 2019, and deadbeat control Vazquez, Jose Rodriguez, Marco Rivera, et al. 2016. Different MPPT methods that are necessary for reaching the optimal output power such as perturbation and observation technique Elgendy, Zahawi, and Atkinson 2011, short circuit current technique Reisi, Moradi, and Jamasb 2013, open circuit voltage technique Casadei, Grandi, and Rossi 2006, ripple correlation techniqueH. Kumar and Tripathi 2012, and the incremental conductance oneLambora, Gupta, and Chopra 2019.

System description will be discussed in Section 4.1, genetic algorithm in addition to the PI controller are introduced in Section 4.2. Simulation results and discussion are given in Section 4.3.

4.1 System explanation

The power circuit shown in Fig. 4.24 of three-phase energy management system consists of wind turbine (WT) that is connected to the PMSG which feeds the boost converter passing by three phase parallel *RLC* load. Boost converter is utilized to get the proper output voltage, as it has a big advantage which is the input current waveform that is filtered due to boost inductor, so it can offer high operating efficiency and in order to evaluate the system in terms of efficiency, knowing it can be applicable or not, and the power output would be efficient. Validating operation of the system can be done by discussing and comparing the system parameters utilizing genetic algorithm. Such an algorithm is utilized to discuss its effect on the transient state of power output. MPPT is used to raise efficiency, reliability of power and its generation.

4.1.1 Explanation of system's control strategy

Control strategy has a great impact on the overall system effectiveness, so choosing the right technique is one of our scopes by adding the parameters needed for the system as the proportional and the integral(P and I) to reach the ideal solution needed. Perturbation and observation technique is chosen for this system as it is considered as one of the techniques that is already utilized in MPPT, as it gives the pulse to boost converter through pulse width modulation generator, and it has some advantages like that it has reasonable dynamics, analog and digital implementation, low hardware & software complexity, however it has disadvantages also like power oscillations, drifting, and does not work for partial shading condition (Solar cell problem). This part of chapter discusses the system parameters (voltage, current, and power) with their three phase measurements, results of PI controller integrating genetic algorithm and their best iterations, effect of changing wind speed, effect of fault occurrence, increasing load on the system, and using both of them simultaneously(fault and enlarging the load) on the system. This system operates at switching frequency equal to $5kHz$, such a system operates at different ratings of wind speed which will make a variation in the power output produced.

4.2 Genetic algorithm

4.2.1 Introduction

Many problems exist for which there is not any clear and precise method by means of optimal or best solution can be found out. This type of problems fall into category of combined problems as they can only be solved through random search techniques. The difficulty is that many problems have so many possible solutions and trying all of them for optimal solution is practically not feasible. To cope up with these types of problems, scientists have applied various search methods and heuristics. Optimization process applied in several domains such as computer science, computational biology, drug designing and other fields. Genetic algorithm is the one such optimization process inspired by laws of natural evolution. This part of the chapter demonstrates the basic understanding of Genetic algorithm and principle that works behind it with some of its application and basic implementation. GA (Genetic Algorithm) is an optimization and search techniques based on the principles of Genetics and Natural Selection. Natural selection always tends to pick the fittest individuals dominating over the weaker ones and it always favours the positive adaptation resulting into the best one to survive in the long run. This is what depicted in Darwin's Survival of the fittest theory. GA is a part of the evolutionary optimizing computation inspired by Darwin's survival of the fittest. GA is an adaptive search heuristics that mimics the process of natural evolution which uses techniques like selection, crossover, inheritance and mutation. GA represents an intelligent exploitation of a random search utilized to solve Optimization problems. It is one of the rapidly growing areas of artificial intelligence.

4.2.2 Basic understanding for genetic algorithm

The biological evolution element and Natural selection theory can be used to construct genetic algorithms, which can be used in computing and artificial intelligence for optimization search. Genetic algorithms are the most effective way to search large amounts of unstructured data, and they are commonly used to fix difficult challenges that are limited and uncontrolled Ting 2005.

The genetic algorithm (GA), developed by John Holland and his collaborators in the 1960s and 1970s De Jong 1975a, DeJong 1975b is a model or abstraction of biological evolution based on Charles Darwin's theory of natural selection. Holland was probably the first to use the crossover and recombination, mutation, and selection in the study of adaptive and artificial systems. These genetic operators form the essential part of the genetic algorithm as a problem-solving strategy. Since then, many variants of genetic algorithms have been developed and applied to a wide range of optimization problems, from graph coloring to pattern recognition, from discrete systems (such as the travelling salesman problem) to continuous systems (e.g.: Efficient design of airfoil in aerospace engineering), and from financial markets to multi-objective engineering optimization.

There are many advantages of genetic algorithms over traditional optimization algorithms. Two most notable are: ability of dealing with complex problems and parallelism. Genetic algorithms can deal with various types of optimization, whether the objective (fitness) function is stationary or non-stationary (change with time), linear or nonlinear, continuous or discontinuous, or with random noise. Because multiple off-springs in a population act like independent agents, the population (or any subgroup) can explore the search space in many directions simultaneously. This feature makes it ideal to parallelize the algorithms for implementation. Different parameters and even different groups of encoded strings can be manipulated at the same time.

However, genetic algorithm also has some disadvantages. The formulation of fitness function, utilization of population size, the choice of important parameters such as the rate of mutation and crossover, and the selection criteria of the new population should be carried out carefully. Any inappropriate choice will make it difficult for the algorithm to converge or it will simply produce meaningless results. Despite these drawbacks, genetic algorithm remain one of the most widely used optimization algorithms in modern nonlinear optimization. In order to establish a new population, genetic operators are applied to selected individuals from the current population in each generation. Reproduction, crossover, and mutation are The three major genetic operators that are used in most cases. Speed of convergence can be modified by employing varying probability when using these operators. Crossover and mutation operators must be carefully crafted, since their selection has a significant impact on the overall effectiveness of the genetic algorithm. Genetic Algorithms (GAs) are primarily search-based algorithms that are based on natural selection and heredity principles. GA is a subset of a much larger topic of computation known as evolutionary computation. There is a wide range of solutions for a particular problem in genetic algorithm. The generated solutions are then subjected to recombination and mutation (similar to biological genetics) resulting in the birth of new offspring, and the process is repeated for several generations.

Genetic algorithm is a population based meta heuristic method, it uses techniques inspired from nature, more specifically evolution, to find an optimal or near-optimal solution towards a problem. Meta-heuristics are powerful optimization algorithms that are not problem dependent, this means that their frameworks are not designed specifically for a certain problem, but they can be used for pretty much any optimization problems (unlike heuristic that are usually adapted to the problem at hand). While the traditional optimization algorithms such as greedy algorithms, branch and bound and dantzig's simplex algorithm have short comings. Here are just few of the important reasons on why it is preferable to use meta-heuristics over traditional optimization algorithms:

- Speed and problem size: it is faster than traditional algorithms and can handle larger problems.
- Meta-heuristic algorithms find way to go from a solution to a better one without considering every combination out there.
- Local minima and global minima as it can avoid getting stuck in a local minima and escape it because it uses random numbers to accept worse moves.

Genetic algorithm is used especially when there is availability of population based search methods, as it applies evolution concepts such as reproduction and survival of the fittest to solve a problem. GA belongs to larger class of evolutionary algorithms. GA is a way to optimize a problem by creating many solutions and updating those solutions in certain ways related to evolution concepts to reach a "good enough" solution or the best solution possible. GA is a meta-heuristic technique or method as it does not take into consideration the problem (problem dependent), so it can be applied to broad range of problems, as the meta-heuristic knows nothing about the problem that will be applied, it can treat functions as black boxes. Difference between heuristic and meta-heuristic methods is that the heuristic ones exploit problem-dependent information to find good enough solution to specific problem, while the meta-heuristics are like designs patterns, general algorithmic ideas that can be applied to broad range of problems.

In optimization, input must be provided in such a way that it may provide the "best" output. Precision of the term "best" varies depending on the problem type Monje, YangQuan Chen, Vinagre, et al. 2010. In mathematical terms, it refers to the optimization or minimization of many object functions by providing distinct input guidelines. Genetic algorithm functioning is closely affected by two main factors which are natural selection and genetic dynamics involving different genetic operations like mutation, cross over, fitness scaling, hybrid function, stopping criteria, and the constraint parameters as shown in Fig.4.2. A controller's job is to take the measured process variable (PV) and compare it to the set point (SP) in order to generate an actuating signal (m) that drives the process variable to the desired value. As a result, the controller's inputs are the error (SPPV). Proportional plus reset controller is another name for it. The error e(t) is related to the actuating signal m(t) by equation:

$$m(t) = K_c e(t) + \frac{K_c}{Ti}\int_0 1e(t)dt + ms \tag{4.1}$$

1/Ti is the repeats per minute, while Ti is the integral time constant or reset time.

The contribution of the integral term after Ti minutes with a constant error E is:

$$K_c/T\int_0 T_1 e(t)dt = (\frac{K_c}{Ti}ET_i = K_cE \tag{4.2}$$

In this part of the chapter, the stopping criteria is specified by number of generations and number of populations, the plot functions for the studied system are specified by best fitness and best individual, the constraint parameters are the proportional (P) and the integral (I). The system gives the best value for these certain parameters after running the genetic to give the best iteration needed for PI controller. Nowadays, PI controllers are more favored than the PID controllers(Proportional-Integral-Derivaitve) due to the impact of noise which is generated by derivative on the control process Åström and Hägglund 2001. The controller output in this case:

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \tag{4.3}$$

It has been received that most of PID controllers that are used in the industrial application are PI controllers. Most of control systems can get reasonable results utilizing PI controllers that have already two parameters(P and I), Many approaches for determining the parameters of PI controllers have been devised. The most common approaches are the Ziegler-Nichols,Aström-Hagglund, and Cohen-Coon approaches Åström and Hägglund 2001. Because of its simple form, ease of design, and low cost. PI controller is currently the most extensively used in industrial applications. Despite these benefits, when the controlled object is highly nonlinear and uncertain, the PI controller fails. PI controller will reduce forced oscillations and steady state errors, allowing on-off controller and P controller respectively to function properly. On the other hand, integral mode has a negative impact on system's response time and overall stability. As a result, PI controller will not increase the reaction time. It's to be expected, given that PI controller has no way of knowing what will happen with the error in the near future. This difficulty can be overcome by using derivative mode, which can predict what will happen with the error in the near future, reducing the controller's reaction time. In industry, PI controllers are frequently employed, especially when response time is not a concern. A control without D mode can be used when: Lot of interruptions and noise during the process of operation, system does not need to respond quickly, and the system has significant transport delays. As a result, we'd prefer to preserve the benefits of PI controller. From all of the above, this part of the chapter dealt with PI controller. Controller output in this case:

$$u(t) = K_p e(t) + K_i \int e(t)dt \tag{4.4}$$

The transfer function of PI controller that is used in this chapter:

$$G_c(s) = K_c[1 + \frac{1}{T_i s}] \tag{4.5}$$

Although these approaches unfortunately don't give the results needed. In order to get the best results, genetic optimization tool is used as shown in Fig.4.2. One of The main functions of this technique is that it can use certain parameters in order to give the best response of the system. Table 4.1 clarifies the boundaries and number of iterations utilized in this algorithm.

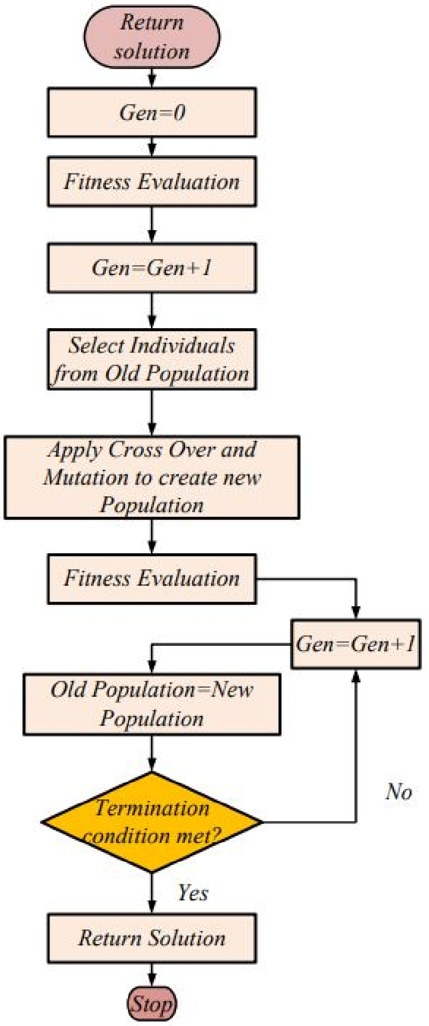

Figure 4.2: Genetic algorithm flow chart

4.3 Results and discussion

This section discusses three main parts which are:

- Performance test of the studied system at different wind speeds and different loads using PMSG passing by boost converter to get the proper output voltage.

MPPT is utilized to make the system more reliable, increasing generation of power as well as the efficiency.

- Fault occurrence on the studied system and how it can change the result of power and voltage applied on such a system.
- Utilizing PI controller integrating genetic algorithm at different operating ranges of power in order to generate a lookup table for PI controller with its parameters (proportional and Integral).

Fig.4.3 shows the power of the studied system at different wind speeds(12.5, 15 m/s) to give about (350, and 500 watt) respectively. this figure shows the steady state for the studied system and its performance in order to ensure the stability of such a system at different wind speeds.

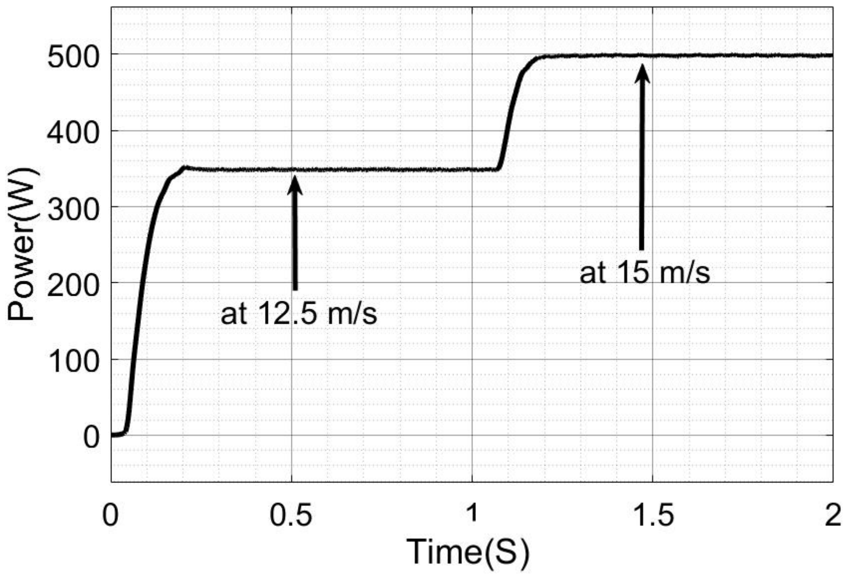

Figure 4.3: Power at different wind speeds

The first main part is discussed and described as follows: Fig.4.4 discusses different power levels depending on the variability of load with constant wind speed. It has two ranges: first one from time (0-1) second shows that the power decreased to 300

Table 4.1: Genetic algorithm parameters

Parameter	**Symbol**	**Value**
Bounds(lower)	B	[0,0]
Bounds(upper)	B	[2,2]
Number of iterations	I	30
Plot function	$P.F$	individual,fitness

watt instead of 350 which was discussed before due to the additional load (20 Ω) that causes this declination. While the second one from time(1-2) second after removing this additional load, the power rises up until it reaches about 500 watt at steady state. The time duration from (1-1.15) second is the transient state.

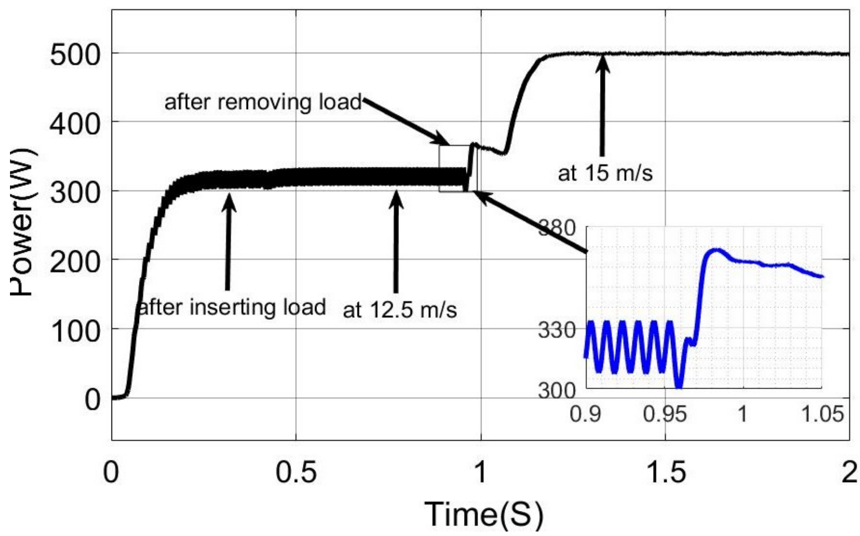

Figure 4.4: Power impact after changing the load

Fig.4.5 shows what already happened to the voltage after boosting with the same parameters of the figure before.

Fig.4.6 shows the three phase voltage measurement with their signals: Three phase voltage (Va,Vb, Vc).

The second part discusses the impact of fault occurrence on the studied system. Fig. 4.7 presents the fault that happened on output power from time 0.8 to 0.9 second. This figure proved that the fault has a huge impact on the system that can not be neglected at all.

Fig.4.8 presents the fault happened from (0.8-0.9) seconds on three phase measurement for voltage and current.

For more validation of the system from this point of view, Fig. 4.9 shows the fault impact on the voltage of this system at the same time.

The third part discusses PI controller usage integrating genetic algorithm at different output power levels. Here is a block diagram for this part to present its principle of work using genetic algorithm as shown in Fig.4.10. This part shows the effect of PI controller integrating genetic algorithm on reducing the transient state of power output.

Fig.4.11 shows that the system can generate 350 watt, while after improving with the genetic algorithm that happens at the best iteration for Proportional=0.9784 and I=0.5515 in order to reduce the transient state as much as possible, the result is as shown in Fig.4.12.

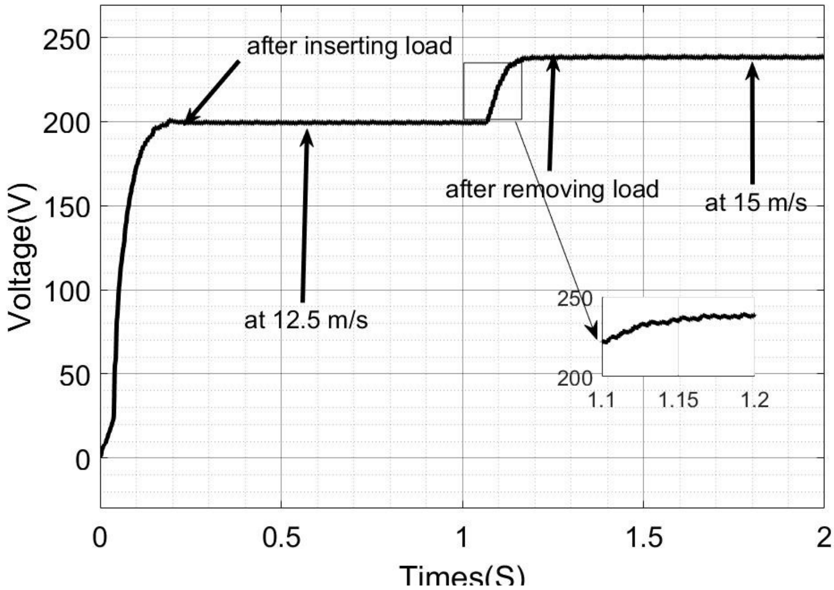

Figure 4.5: Voltage impact after changing the load

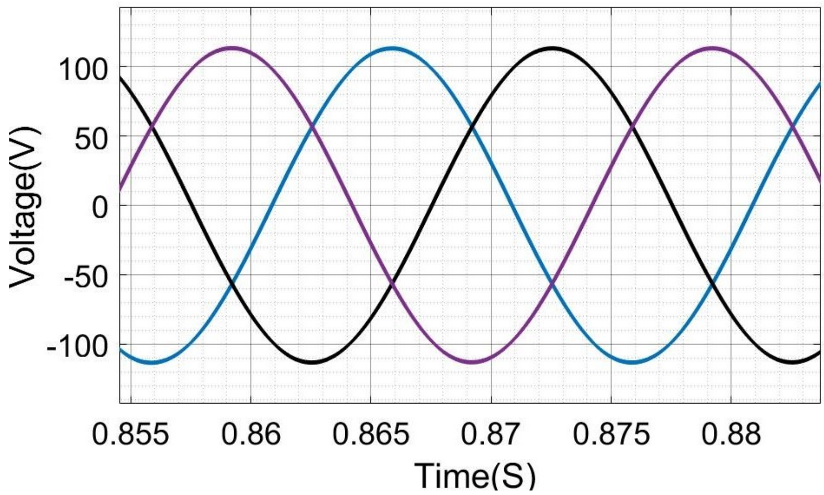

Figure 4.6: Three phase voltage measurement

Another two examples show the effect of this algorithm by generating about 300 watt power. The first one as shown in Fig.4.13 that describes the power without running genetic algorithm.

. While after utilizing genetic algorithm, the figure has improved to be as shown in Fig.4.14, and the best iteration happened in this case at Proportional=1.009 and Integral=0.844.

The second example is the same as the example before but by changing the wind speed to be at 20 m/s, Fig.4.15 determines the output power before using GA and Fig.4.16 shows the power after using GA.

These results can be placed into a lookup table as shown in table 4.2 in order to get the best solution for rated output power at the lowest transient state. and the interval

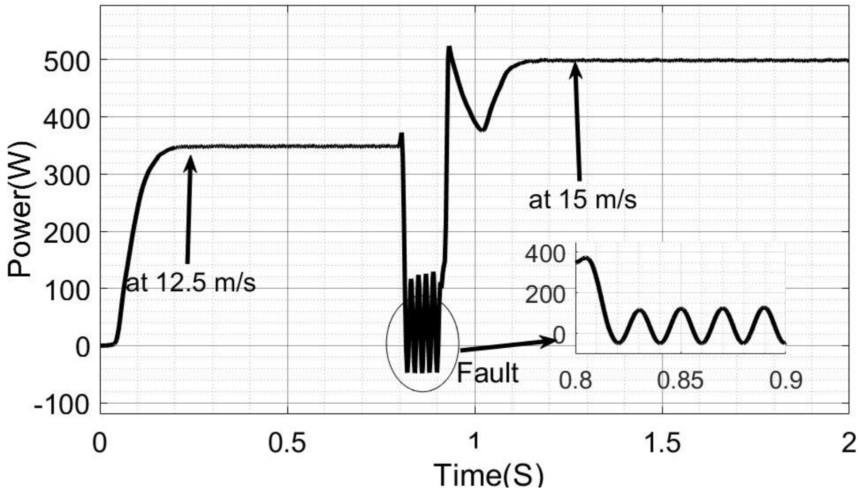

Figure 4.7: System fault at (0.8-0.9) second

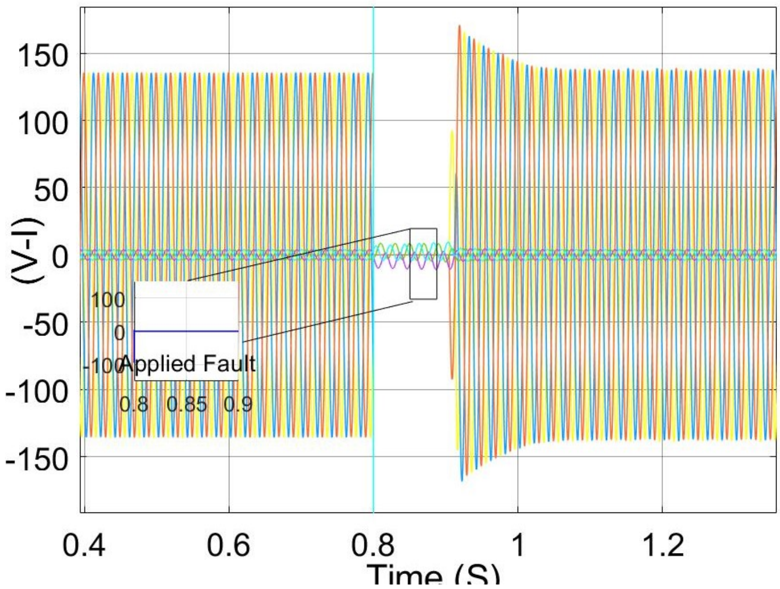

Figure 4.8: Fault impact on three phase measurements

on which the parameters (Proportional and Integral) will work at rate of change about 50 watt each to discuss what is happened at different power ratings.

4.3.1 Experimental results utilizing genetic algorithm

The experimental test bench that has been tested and validated as shown in Fig.4.17 is explained as it includes load, DC motor, Permanent Magnet Synchronous Motor (PMSM), uncontrolled rectifier, Digital Signal Processor (DSP), and oscilloscope, these are the main tools that are connected to validate the genetic algorithm technique that is already applied in the main system utilizing the same cases already utilized in the

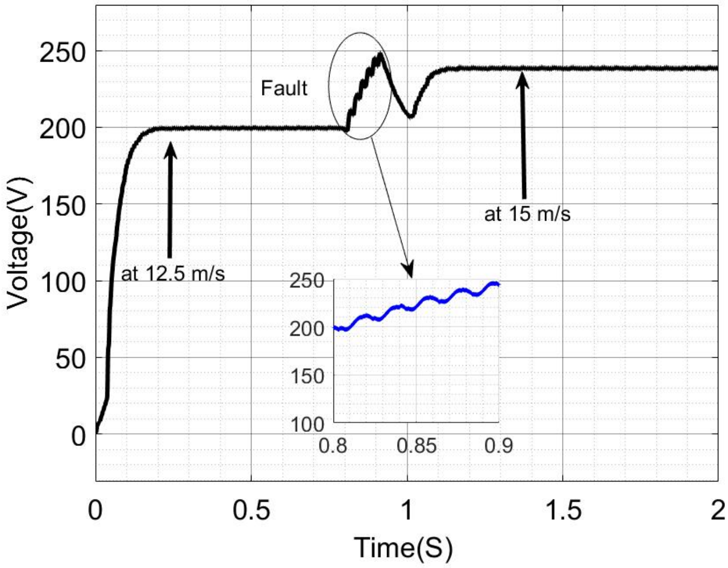

Figure 4.9: Fault impact on system voltage

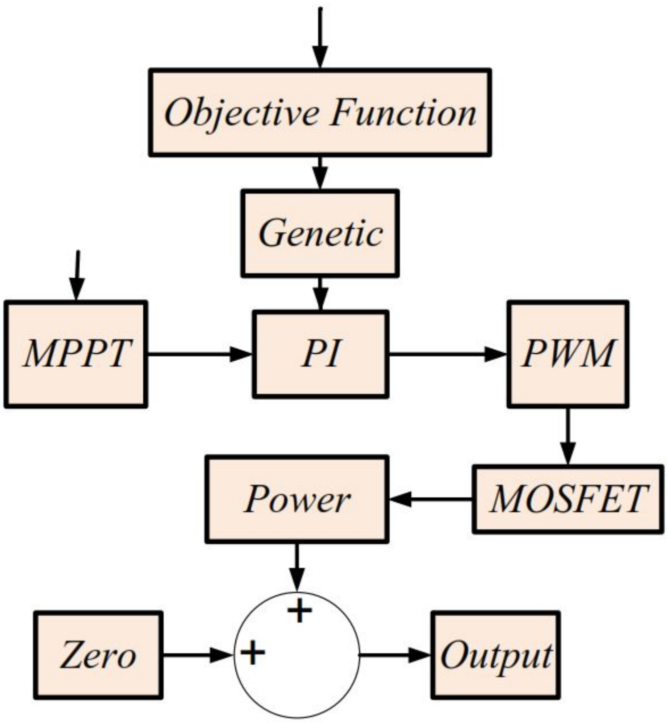

Figure 4.10: Principle of PI corrector optimization by using genetic algorithm

simulation process.
The overall system works at DC motor voltage equal to 56 volts at a rated power output equal to 1.5 KW, not more than that for the stability of system as it can not withstand

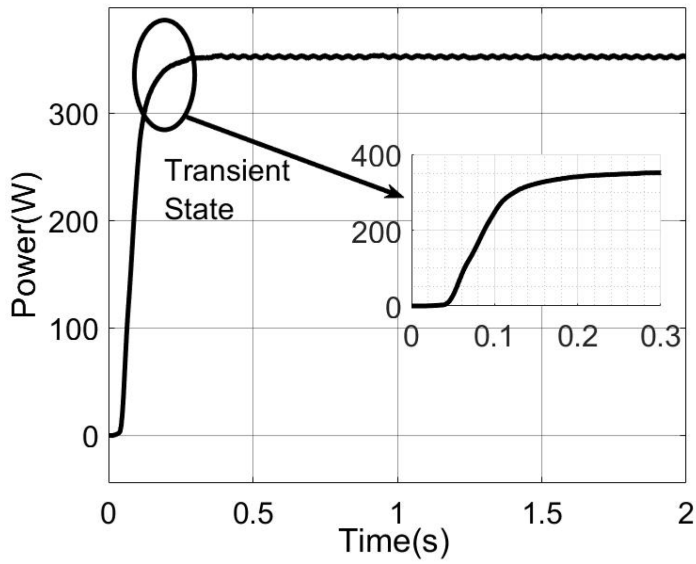

Figure 4.11: Output power at 12.5 m/s without genetic algorithm

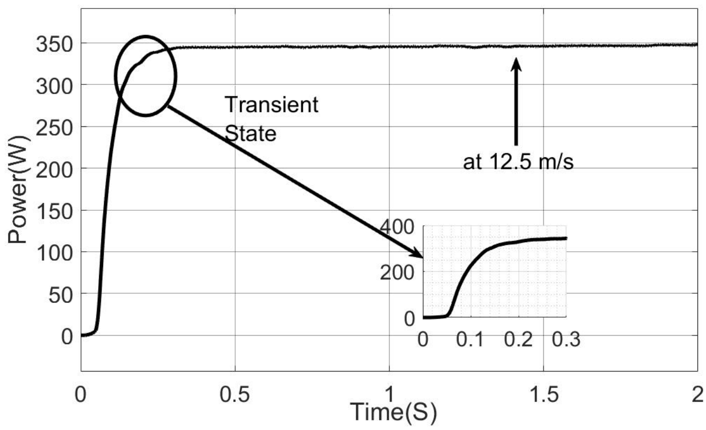

Figure 4.12: Output power using genetic algorithm at 12.5 m/s

more than that. Fig.4.18 shows the result that can be produced from running the system shown in Fig.4.17 according to the speed and DC power. This Fig.4.18 shows firstly in the upper left the DC current (Ampere/time), down left is the three phase voltage/DC voltage, in the upper right verifies the speed(number of turns per second) and finally in the down right determines DC power that can be generated from the system. Fig.4.18 shows the first case that is applied for the system after changing the wind speed like what is happened in the simulation results, while Fig.4.19 shows the second case by making load variation, and the results validate what is happened according to simulation results utilizing genetic algorithm. Explanation of changing the load can be verified as follows: The load has different variations as 5%, 10% and 15% etc...

Running of the system happened usually at 5% and 10% which is equal approximately

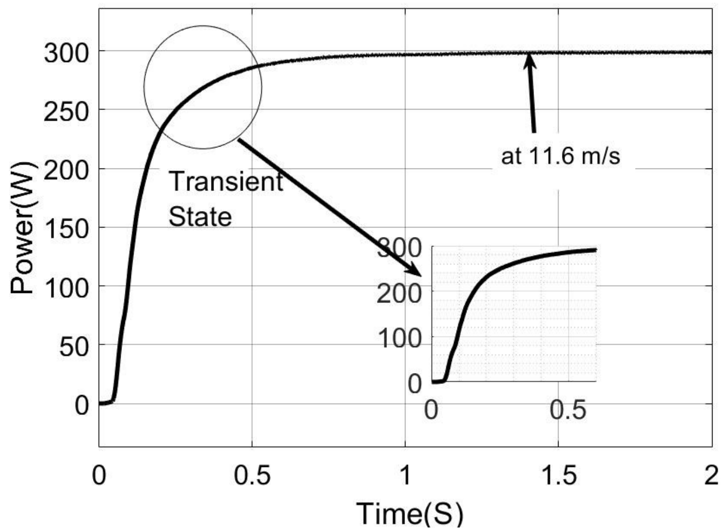

Figure 4.13: Power at 11.6 m/s without genetic algorithm

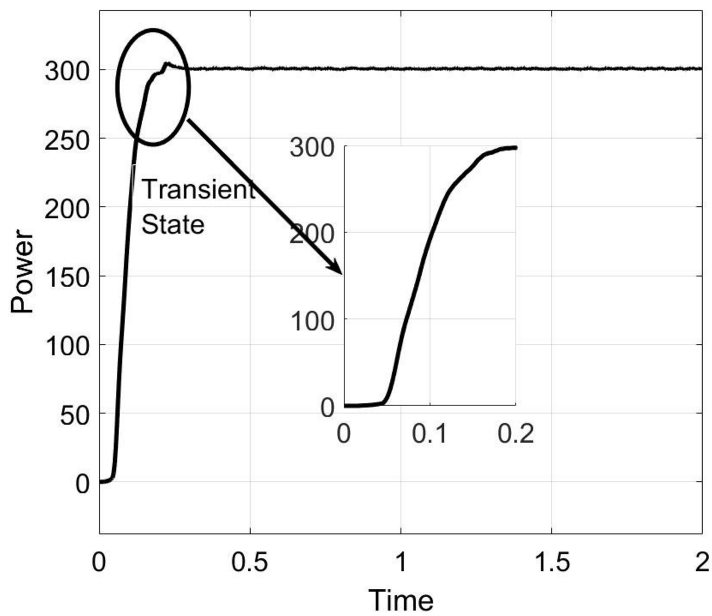

Figure 4.14: Power at 11.6 m/s using genetic algorithm

to 0.488KΩ, while in the second case as shown in Fig.4.19, the load has been changed to be 0.242KΩ to see what is happened exactly in the produced DC power.

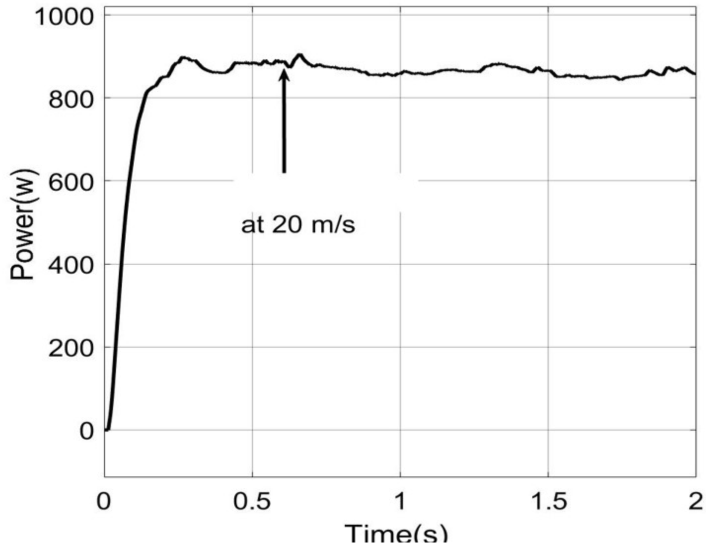

Figure 4.15: Power at 20 m/s without genetic algorithm

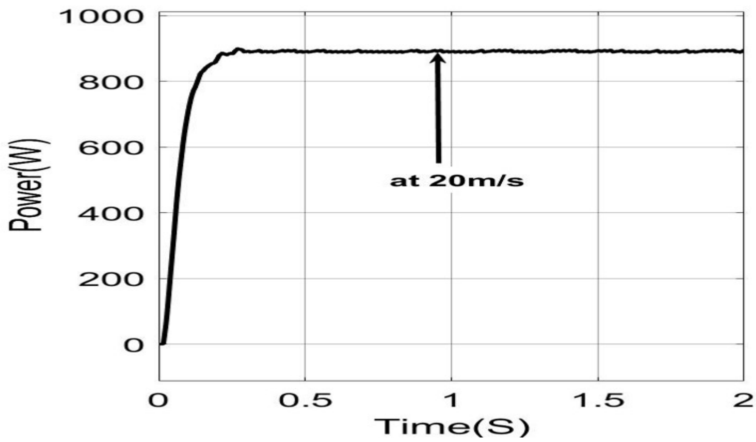

Figure 4.16: Power at 20 m/s using genetic algorithm

4.4 Advances and trends in model predictive control for power converters and drives

4.5 Introduction

Now, the second part of this chapter will be presented and it describes mainly the Model Predictive Controller (MPC) and how it is involved in the system described in this report. MPC is a very attractive solution for controlling power electronic converters. The aim of this part is to present and discuss the latest developments in MPC for power converters and drives, describing the current state of this control strategy and analyzing new trends and challenges applied to power electronic systems. The operating principle of MPC is presented and three key elements in the MPC strategies

Table 4.2: Lookup table for P and I

Power	**Proportional(P)**	**Integral(I)**
0.05KW	1.12	0.952
0.1KW	1.105	0.914
0.15KW	1.053	0.889
0.2KW	0.985	0.875
0.25KW	0.976	0.797
0.3kW	1.009	0.844
0.35KW	0.9784	0.5515
0.4KW	0.8653	0.4369
0.45KW	0.602	0.195
0.5KW	0.499	0.625
0.55KW	0.754	0.321
0.6KW	0.821	0.256
0.7KW	0.654	0.157
0.75KW	0.543	0.238
0.8KW	0.595	0.339
0.85KW	0.534	0.225
0.9kW	0.437	0.367
0.95KW	0.428	0.395
1kw	0.382	0.332

are identified, namely prediction model, cost function and optimization algorithm. The chapter summarizes the most recent research concerning these elements, providing details about the different solutions proposed by the academic and industrial communities. This part presents an enhancement of stand-alone wind turbine system using finite control set model predictive control (FCS-MPC) methodology. The enhancement based on using the predictive control for both boost and inverter power circuits. The control system get two voltage references, one for regulating dc-link voltage and the other to obtain the desired output ac voltage. Accordingly, utilizing such a control scheme can make the system's time response even faster specially at different wind speeds. Moreover, the effectiveness of discussed control system is verified in case of unexpected load changes. The proposed control strategy is tested and verified using MATLAB/Simulink environment.

MPC has been a topic of research and development for more than three decades. Originally, it was introduced in the process industry, but a very innovative and early paper proposed that predictive control to be used in power electronics Holtz 1983. In the recent years, Because of the technological advances in microprocessors, it has been presented and discussed as a promising alternative for controlling drives and power converters J. H. Lee 2011, SAMIR and PATRICIO 2009. MPC proposes multiple merits. For example, it can be utilized in different processes, easy to apply in systems that are multi-variable and can give fast dynamic response. Moreover, it permits

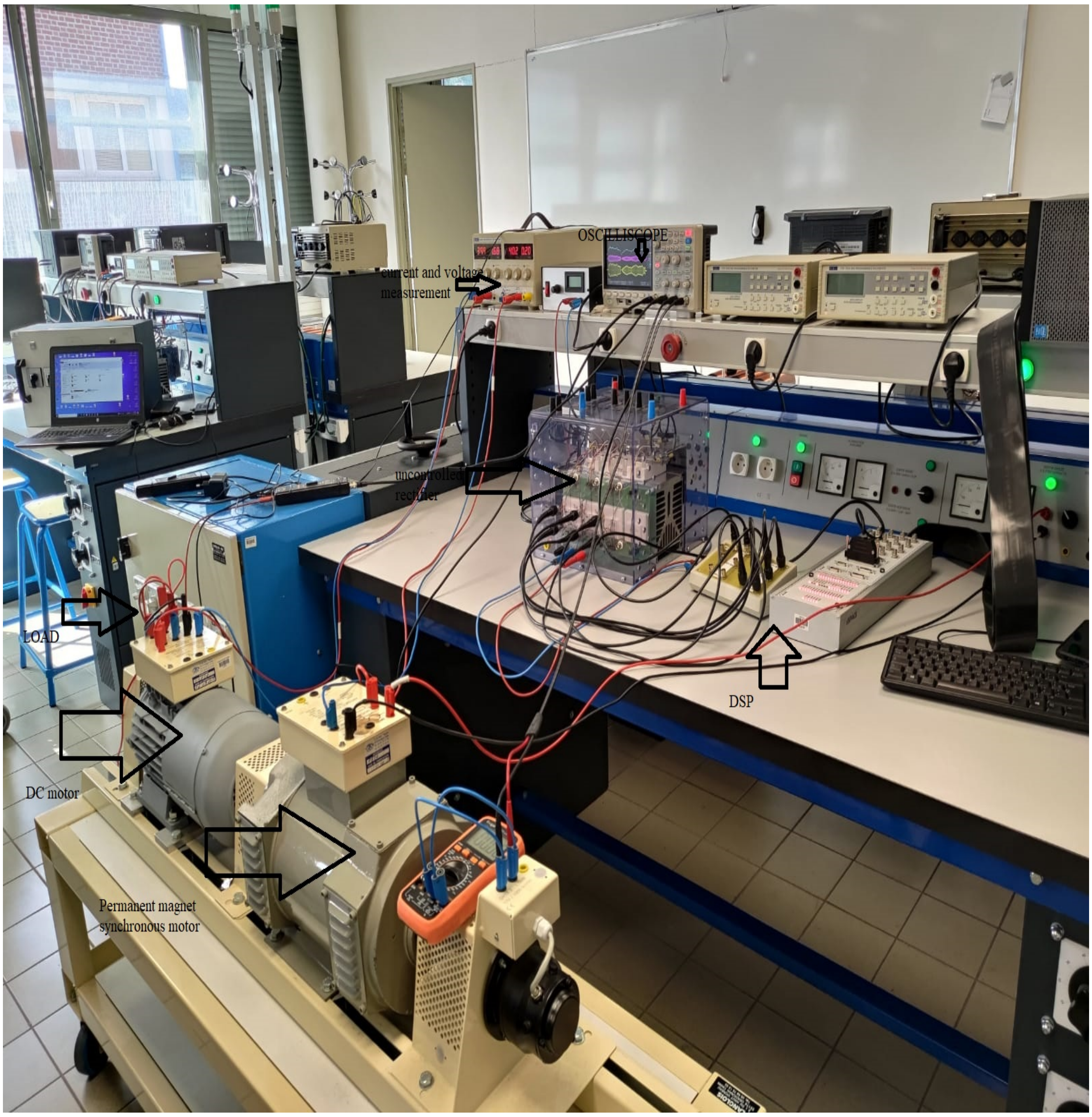

Figure 4.17: Overall system connected to the load

the constraints and non-linearities to be included into the law of control in a direct manner, and it can include nested control loops in one loop only Morari and J. H. Lee 1999, Camacho and Alba 2013. In particular, the applications of power electronics need control responses in the order of tens to hundreds of microseconds to work properly. Although, it is well known that MPC has larger computational burden than other control strategies. For this reason, most of the work focused on this case at the first research stages of MPC for power electronic systems Quevedo, R. P. Aguilera, and Geyer 2014. Nowadays, the literature for most of the applications for power electronics depends mainly on the MPC approaches Vázquez Pérez, León, Garcıéa Franquelo, et al. 2014. The principle cause is that the computational power of modern micro-processors has increased. This has made it possible to implement more complex and

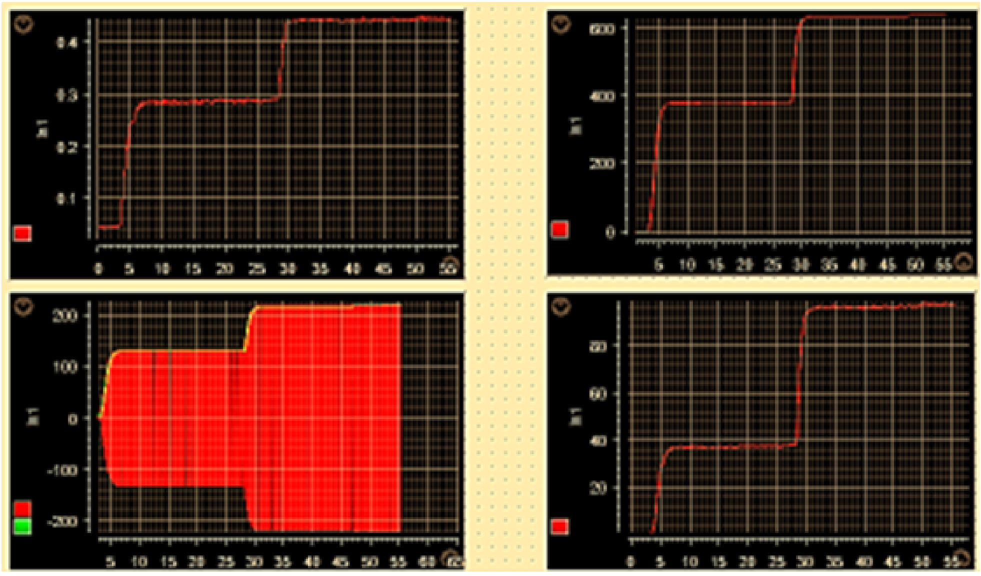

Figure 4.18: System parameters 1

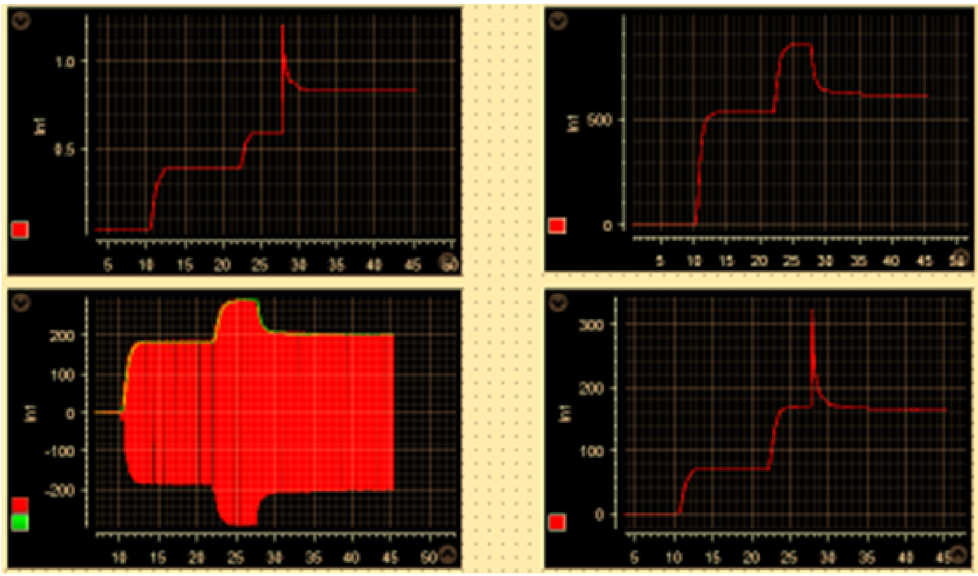

Figure 4.19: System parameters 2

intelligent control strategies, like MPC, in standard control hardware platforms Zhan and X. Li 2012, Bordons and Montero 2015, Kouro, Perez, Jose Rodriguez, et al. 2015, Holtz 2015. From this side, MPC for the drives and power converters has been taken into account as good founded technology in the improvement and research efforts stages. Although, more improvement and research techniques are still important and needed for bringing such a technology to the commercial and industrial level Papafotiou, Demetriades, and Agelidis 2016. The main target of this chapter part is to resolve and summarize the current state and the most recent advances in the application of MPC for drives and power converters. Thus the work presents current challenges and advances of MPC for the applications of power electronics and targets the possible future trends.

Financial improvement of nations is firmly bound up with energy, this has forced weight on non-renewable sources of energy. Hence, renewable energy sources (RESs) are being utilized to diminish utilization of fossil powers and contamination of environment. Wind energy can deliver electric force by using the wind consistency in order to push for electric generator Wenehenubun, Saputra, and Sutanto 2015. Energy storage systems(ESSs) utilize different strategies for energy conversion Ghisellini and Ulgiati 2020. After taking into consideration the estimation of the international energy association (IEA), ESS storage ought to be raised to 266 GW by 2030 to maintain a strategic distance from global warmingElio, Phelan, Villalobos, et al. 2021. Wind control is an elective constrain hot spot and appealing for both tremendous scale and small scale shapes of wind and appropriated control age applications. DC-DC converters are considered one of the imperative circuits inside the family of power circuits. They are utilized to control the energy stream between two DC systems (e.g. well-regulated DC-to-DC control converters are significant for task victory on extent stages). Main target for this equipment is to preserve control of the produced voltage at the required estimation Guldemir et al. 2011, Ahmad 2010. DC-DC converter can be used under different control techniques and can deal with any of them, like here in this work, MPC method is used because of its effectiveness, fast response, allow inherent non-linearity (difficult dynamics), can evaluate future dynamics of the system, and it allows the possibility of delaying time. MPC implementation in power electronics has expanded impressively with the improvement of multitask and high-frequency chip in the latest two decades Abdel-Rahim, Funato, and Haruna 2016, Vázquez Pérez, León, Garcıéa Franquelo, et al. 2014, Aleenejad, Iman-Eini, and Farhangi 2013. According to that, The MPC strategies can be distributed into two fundamental categories Cortés, Kazmierkowski, R. M. Kennel, et al. 2008: the primary one is continues control set model predictive control [CCS-MPC] and the moment one is finite control set model predictive control[FSC-MPC], known as discrete MPC. The nonstop yield of the predictive controller in CCS-MPC is utilized for the switching state of such a generation by utilizing modulator. In the other side, discrete-time model of the framework has the ability to be utilized for accessible switching states of power converter, this is happening in case of optimization in FMPC and suitable transition case ought to be connected within the following model interval. FMPC gives the preferences of being simple to apply and appropriate on nonlinear frameworks Jose Rodriguez and Cortes 2012. latterly, the two MPC categories: CCS-MPC Errouissi, Muyeen, Al-Durra, et al. 2015, Errouissi, Al-Durra, and Muyeen 2016 and FMPC Shadmand, Balog, and Abu-Rub 2014, Sajadian and Ahmadi 2016 are displayed and utilized in the rapid MPPT of wind turbine systems in order to offer increment in the effectiveness of this method within the steady state compared with the traditional strategies. MPC proceedings give a quick energetic reaction with rising solidness edge compared to traditional control platforms, that afford the easy usage of MPPT working beneath quick changing barometric conditions Sajadian and Ahmadi 2017. This work objective is to show the fast response advantage of MPC using the finite control set technique for the boost and the inverter power circuits, to generate the duty cycle with the pulse needed for the DC-DC converter in order to raise the voltage to the desired value, and the work of this chapter part is laid out as shown: section4.5 gives introduction on MPC and its usage, section4.6 studies the overall system description, section4.7 discusses in details FCS-MPC and its relation with the system modelling, section4.8 displays the simulation results and their discussion, while the conclusion is reported in section4.9.

4.5.1 Model predictive control: operating principle

The block diagram of MPC technique or strategy is shown in Fig.4.21 in which the predicted and reference currents at (K+2) can be utilized to recover for digital implementation delay Cortes, Jose Rodriguez, Cesar Silva, et al. 2011. Fig.4.20 shows the main concept of using MPC according to the predictive control and cost function. Such an algorithm is regenerated for each sampling interval and proceeds the next steps:

- The Optimal control job $S(t_k)$ which is calculated at time K-1 requested for the converter.
- Calculation of current i_k is carried out at time K. Reference current i^*_{k+2} for time K+2 can be also determined.
- Predicted model of such a system is utilized to predict the current value $\hat{i}_{k+2}$ at time K+2.
- Cost function can be determined utilizing i^*_{k+2} and $\hat{i}_{k+2}$. The optimal control job $S(t_{k+1})$ to be applied at time K+1 is selected as it can eliminate the cost function's value. A lot of MPC techniques have been successfully carried out for a diversity of power electronic applications.

Fig.4.22 discusses the most shared MPC techniques and strategies that are implemented to power converter and drives. Generalized predictive controller (GPC) is explained in details in references R. Kennel, Linder, and Linke 2001, Judewicz, S. A. González, Echeverrıéa, et al. 2015, explicit model predictive controller (EMPC) in Mariéthoz and Morari 2008, Almér, Mariethoz, and Morari 2012, OSV-MPC (optimal switching vector) in Jose Rodriguez, JORGE Pontt, CESAR Silva, et al. 2004, Geyer and Quevedo 2014, and OSS-MPC (optimal switching sequence) in Larrinaga, Vidal, Oyarbide, et al. 2007, Vazquez, Marquez, R. Aguilera, et al. 2014. Variables i, $\hat{i}$, and i^* indicate set of current predictions, calculations, and references. u_k is the control signal measured at time K and $S_k(t)$ are the firing pulses for the power switches, these values can alter from time k to k+1. $S_t(k)$ are the firing pulses for the power switches, these values are constant from instant k to k+1. MPC methodologies can be distributed depending on the sort of optimization problem. On one side, CCS-MPC calculates continuous control signal and after that utilizes a modulator to produce the needed output voltage in power converter. The technique for modulation could be anyone that is suitable for converter topology under consideration Leon, Kouro, Franquelo, et al. 2016. The principle merit of CCS-MPC is that it generates fixed switching frequency. The probably used CCS-MPC techniques for the applications of power electronics are displayed by EMPC and GPC. EMPC permits the consumer to elaborate with constrained and non-linear models and systems. GPC is helpful for unconstrained and linear problems. The principle trouble of EMPC and GPC when carried out to power converters is that the two of them show complex formulation of MPC problem. On the other side, FCS-MPC takes into consideration the discrete nature of power converter to generate MPC algorithm and does not need external modulator. FCS-MPC can be distributed into two different types: OSS-MPC, and OSV-MPC. Nowadays, the most trendy MPC technique for power electronic applications is the OSV-MPC. OSV-MPC is the first FCS-MPC method utilized for power electronics. Because of this circumstances, it is found in the literature that is related to FCS-MPC. It utilizes the reasonable output voltage vectors of power converter as control set. OSV-MPC only measures predictions for such a control set, also it eliminates the optimal issue to the counted considered algorithm. This helps MPC technique formulation to be very intuitive. The principle merit of OSV-MPC is that the output voltage vector is only one carried out through the complete switching interval. Moreover, if there is no more constraints to be added, the same output voltage vector shall be utilized through different consecutive switching intervals. So, generally, it produces variable switching frequency. OSS-MPC treats this issue by taking into consideration a control set consists of limited number of probable switching sequences per switching interval. From this manner, OSS-MPC takes into consideration the time as further decision variable, i.e., the time that switches alter state, which in a path collects modulator in the optimization issue. Generally, MPC strategies need specific amount of calculations and computations. CCS-MPC has lower computational cost usually than FCS-MPC since it calculates portion or all of the optimization issues offline. Because of that, CCS-MPC has ability to address long prediction horizon issues. For example, GPC utilizes certain expression to measure the control job or action tha can be calculated beforehand, thus eliminating the online computation burden Bordons and Montero 2015. On the other side, EMPC can calculate, compute and put in storage the optimal issue solution offline, so the online calculations are eliminated to a search algorithm. FCS-MPC differs as it needs that the optimization issue, that includes huge amount of measurements, can be fixed online. Because of that, FCS-MPC is always bounded to small prediction horizons in applications of power electronics. By making a comparison between OSS-MPC and OSV-MPC, the former has much more computational cost. Examination and investigation of MPC methodologies when carried out to power converters and drives detects that the key factors for any MPC technique are the prediction pattern, optimization algorithm, and cost function. Potential researches have been utilized in all of these subjects, as well as limitations and different issues have been declared. There are some of these issues solved by the existing work, however there are other issues are not solved yet, in order to investigated later. Furthermore the most important parts that have been well investigated are Jose Rodriguez and Cortes 2012:

- Control horizon and increment prediction.
- Elimination of computational cost.
- Frequency spectrum formatting.
- System performance scheme and balancing.
- Discretization of the prediction pattern or model.

4.5.2 Prediction model

Development of MPC can be effected by quality of prediction pattern or model that mainly rely on certain application taken into consideration Vázquez Pérez, León, Garcıéa Franquelo, et al. 2014. Because of that, wide range of power converters are linked to the load by passive filters for eliminating distortions and commutations in the supply. The inductor and its resistor can be utilized in the first-order passive filters Larrinaga, Vidal, Oyarbide, et al. 2007, Acuna, Morán, Marco Rivera, et al. 2015. Although, high order passive filters like LCL or LC are also carried out in VSC-AFE(Voltage Source Converter-Active Front End) Mariéthoz and Morari 2008, Almér, Mariéthoz, and Morari 2014, motor drives and medium voltage Laczynski and Mertens 2009, VSC-UPS(Voltage Source Converter-Uninterruptible Power Supply)Cortés, Ortiz, Yuz, et al. 2009, Yaramasu, Marco Rivera, Narimani, et al. 2014, matrix convertersMarco Rivera, Rojas, Rodrıéguez, et al. 2011, Marco Rivera, Jose Rodriguez, B. Wu, et al. 2011, etc. MPC task can be made with passive filter topology thus its mathematical model is combined in the prediction pattern. Even-though the filter mathematical model is involved in the prediction pattern, basic MPC methodologies should relieve the impact of resonance issues when a high-order passive filters are utilized. This is serious in FCS-MPC because of variability of switching frequency (f_{sw}) that is already available in such a control strategy, although f_{sw} is eliminated to reach about half of the sampling frequency, and in this work, the concentration on FCS-MPC, so its features will be discussed in the next section. There are variety of solutions that already presented to treat that issue. For example, the resonance impact can be relieved by taking into consideration a hybrid control technique, by involving predictive control with the active damping filter Marco Rivera, Jose Rodriguez, B. Wu, et al. 2011, Scoltock, Geyer, and Madawala 2014, Panten, Hoffmann, and Fuchs 2015. From the other side, input filter design can be facilitated and the danger of resonances can be cancelled by taking into consideration MPC methodologies with fixed switching frequencies Almér, Mariéthoz, and Morari 2014, Mariéthoz and Morari 2008, Almér, Mariethoz, and Morari 2012. MPC techniques are applied in digital hardware platforms as FPGAs and DSPs. Because of that, the system prediction pattern or model requires to be discretized. Discretization is simple and can be done as shown in Cortés, Ortiz, Yuz, et al. 2009, Jose Rodriguez and Cortes 2012 for linear framework. Although, non-linear frameworks need more complex path or approach Nguyen-Van and Hori

2013. A trade-off between the model complexity and quality determines multiple discretization methods, the most trendy nowadays are Taylor series expansion and Euler approximation Vaclavek and Blaha 2013. Another method contains the system in which it is discretized utilizing either multiple-step or one-step Euler approximation. After that, the error of arising discretization is restricted to take it into account for carrying out the predictive controller Kögel and Findeisen 2015.

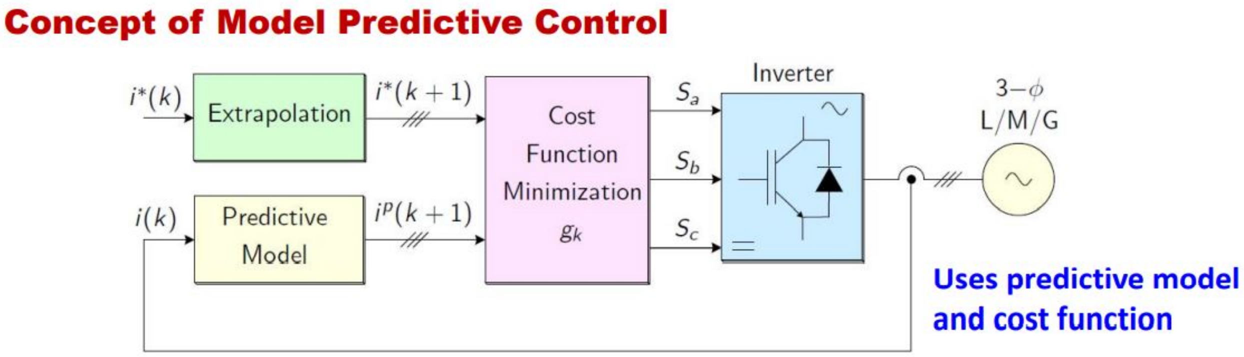

Figure 4.20: Model predictive control concept

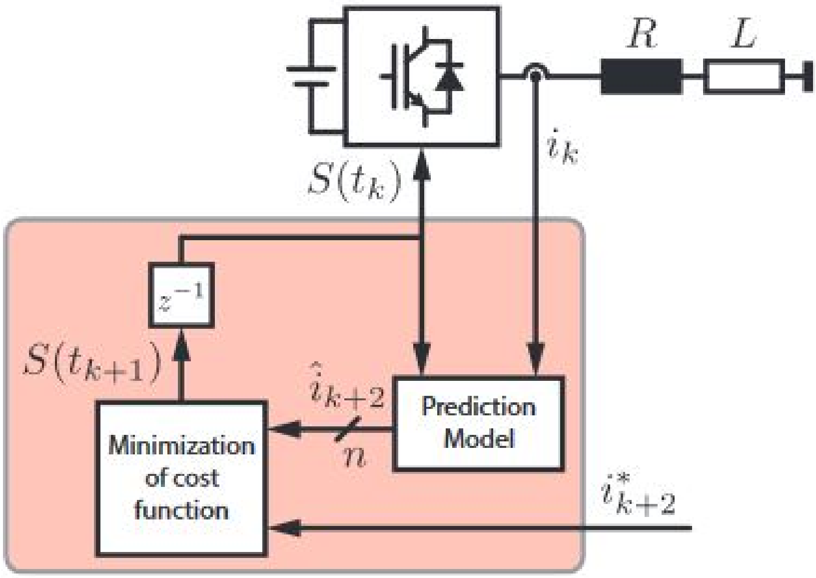

Figure 4.21: Block diagram of MPC strategy utilized for current control in VSI with output RL load

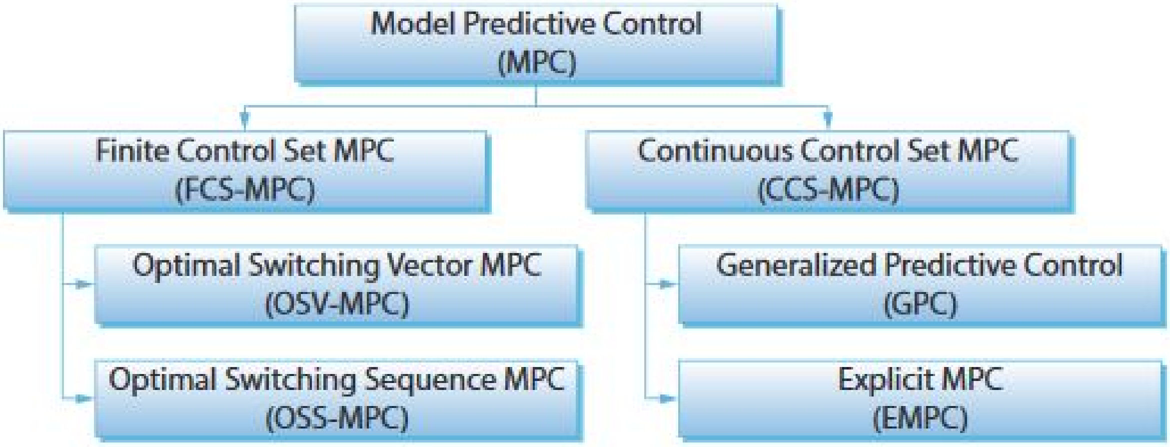

Figure 4.22: Classification of MPC strategies

4.5.3 Main features of FCS-MPC

MPC features particularly the finite control set model predictive control and how it can make the prediction control for a wind turbine connected PMSG. The features of such a technique as shown in fig.4.23 are distributed as follows: They are simple and easy to understand and use, also they can handle the multi-variable problem with decoupling, can be utilized friendly with the digital controller, treats system non-linearity and limitations, compensates perturbations and dead times of the system, eliminates modulation stage, provides fast dynamic and good steady state performance, and also can give finite number of optimizations.

Figure 4.23: Main features of FCS-MPC strategies

4.6 Studied system description

The power circuit shown in Fig.4.24 of three-phase energy management system has studied firstly in Elgharib, Mohammed Alhasheem, Swief, et al. 2021 using PI controller integrating genetic algorithm. This system consists of wind turbine that is connected to PMSG passes by boost converter to get the proper output voltage connected to three phase parallel RLC load. MPPT technique is used usually in such cases for controlling duty factor, increment effectiveness, reliability of power and its generation. As it had different techniques as the perturbation and observation technique, incremental conductance one. While here in this chapter there is modification by adding (FCS-MPC). This strategy will give pulse to boost converter through pulse width modulation generator by having two voltage references, for regulating dc-link voltage and obtaining the desired output ACvoltage. Such a system operates at switching frequency equal to $5kHz$ and switching frequency for the inverter equal to 40 kHz. This chapter discusses mainly the system's time response after the enhancement specially at different wind speeds. Moreover, the effectiveness of the discussed control system at unexpected load changes, boosted voltage, as well as the DC power generated, and to ensure that the modification for such a controller can track the reference voltage efficiently. Table 4.3 shows the parameters used in this system.

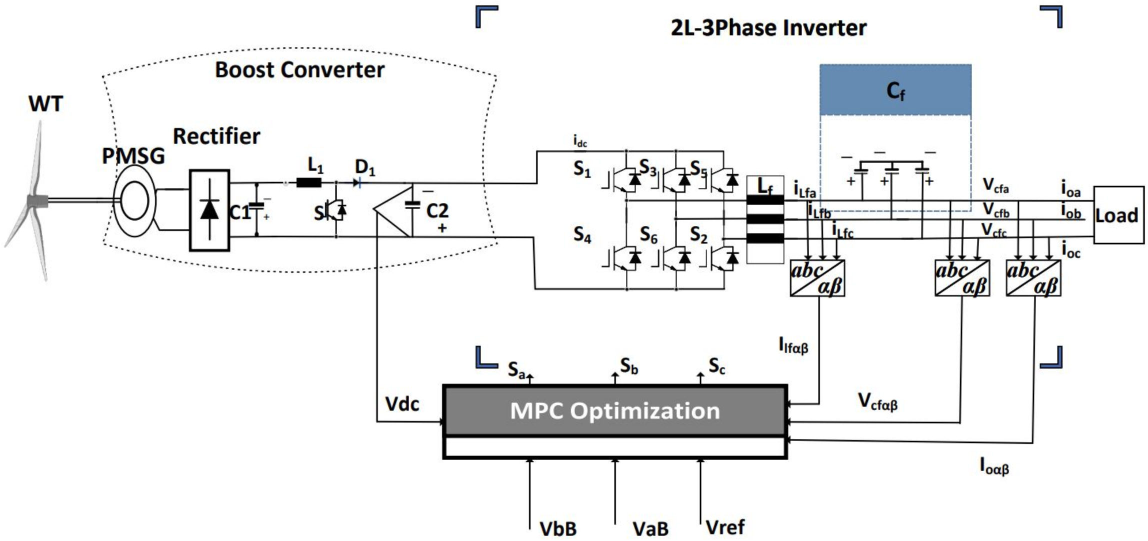

Figure 4.24: Configuration of stand-alone wind turbine system controlled by the proposed FCS-MPC

4.7 System modelling with MPC

The power circuit shown in Fig.4.24 includes three phase VSC that has taken into account with six switches $(S_1, S_2, S_3, S_4, S_5, S_6)$. Two switches work in a complementary mode as (S_1, S_4). The switching state can be shown in terms of Sa, Sb, and Sc. MPC Optimization block feeds the three phase converter that includes parameters that are being listed as follows: V_{bB} indicates the voltage before boosting, while V_{aB} refers to

Table 4.3: System parameters

Parameter	Symbol	Value
Boost converter inductance	Lb	3e-3
Boost converter 1st capacitance	$C1$	200e-6
Boost converter 2nd capacitance	$C2$	220e-6
Inverter sampling time	Ts	25e-6
Load inductance	L	1e-1
Inverter capacitance	C	100e-6

the voltage after boosting, DC is the reference voltage, V_p is the predicted voltage.

$$S_a = \begin{cases} 1 \text{ if } S_1 \text{ on and } S_4 \text{ off} \\ 0 \text{ if } S_1 \text{ off and } S_4 \text{ on} \end{cases}$$
$$S_b = \begin{cases} 1 \text{ if } S_2 \text{ on and } S_5 \text{ off} \\ 0 \text{ if } S_2 \text{ off and } S_5 \text{ on} \end{cases}$$
$$S_c = \begin{cases} 1 \text{ if } S_3 \text{ on and } S_6 \text{ off} \\ 0 \text{ if } S_3 \text{ off and } S_6 \text{ on} \end{cases}$$

The inductance condition of the filter can be communicated in the vectorial frame as follows:

$$L\frac{di_L}{dt} = v_i - v_c(1)$$

From that equation, L indicates the inductance of filter. Voltage of the output has a dynamic behaviour ought to be verified mathematically by:

$$C\frac{dV_C}{dt} = i_L - i_o(2)$$

From that equation, the capacitance of filter is C, so equations in this way can be redesigned in state space model:

$$\frac{dx}{dt} = Ax + Bv_i + B_2 i_o(3)$$

where,

$$x = \begin{bmatrix} i_L \\ V_c \end{bmatrix}(4)$$

$$A = \begin{bmatrix} -R_f/L_f & -1/L_f \\ 1/C_f & 0 \end{bmatrix}(5)$$

$$B = \begin{bmatrix} 1/L_f \\ 0 \end{bmatrix}(6)$$

$$B_2 = \begin{bmatrix} 0 \\ -1/C_f \end{bmatrix}(7)$$

V_c and i_L are voltage and current of filter. The component that can be evaluated counting on formalization of cost function is current of load i_o

v_i is voltage of inverter, it contains voltage variance depending on 8 vectors of switches. a discrete system can be designed from such a system from equation [3] and clarified as shown:

$$x(k+1) = A_q x(k) + B_q v_i(k) + B_{dq} i_o(k)(8)$$

Where:

$$A_q = \exp^{AT_s}(9)$$

$$B_q = \int_0^{T_x} \exp^{A\tau} B d\tau (10)$$

$$B_{dq} = \int_0^{T_s} \exp^{A\tau} B_d d\tau (11)$$

This design is used to make calculation of filter current and voltage prediction for every input voltage available. The required input voltage based on estimation of the cost function (CF). This technique integrated with state space representation for boost converter as follows: Equation for duty factor will be as follows:

$$U = 1 - [V_{in}/V_P](12)$$

where U is duty factor, V_{in} is input voltage, and V_P considered to be predicted output voltage. and such an equation depends on boost converter state space model. Taking the state vector as

$$x = [i_L, V_c](13)$$

where Vc is voltage of capacitor, and general equation that governs boost converter operation:

$$\begin{cases} \dot{x} = A_i x + B_i \\ y = C_i x \end{cases} (14)$$

State space representation combination for that model will be as follows:

$$A = \begin{bmatrix} 0 & -(1-d)/L \\ (1-d)/C & -1/RC \end{bmatrix} (15)$$

$$B = \begin{bmatrix} v_{in}/L \\ 0 \end{bmatrix} (16)$$

$$C = \begin{bmatrix} 0 & 1 \end{bmatrix} (17)$$

After taking into consideration the discrete form generated from the continuous one according to Forward Euler Approximation:

$$x(k+1) = (I + T_s A)\, x(k) + T_s B d(k)(18)$$

and boost converter discrete time state space model is illustrated by the following:

$$\begin{bmatrix} x_1(k+1) \\ x_2(k+1) \end{bmatrix} =$$

$$\begin{bmatrix} 1 & -(1-d(k))T_s/L \\ (1-d(k))T_s/C & 1-(T_s/RC) \end{bmatrix} \begin{bmatrix} x_1(k) \\ x_2(k) \end{bmatrix}$$

$$+ \begin{bmatrix} T_s v_{in}(k)/L \\ 0 \end{bmatrix} (19)$$

According to the work in this chapter, there are two cost functions illustrated here:

L filter with the current control of inductor for VSCs design has CF which is already implemented as follows:

$$g_{conv}\left[t_k\right] = \left(v^*_{c\alpha}\left[t_k\right] - v_{c\alpha}\left[t_{k+1}\right]\right)^2 + \left(v^*_{c\beta}\left[t_k\right] - v_{c\beta}\left[t_{k+1}\right]\right)^2 \quad (20)$$

In which $v_{c\alpha}\left[t_{k+1}\right]$and $v_{c\beta}\left[t_{k+1}\right]$ are the predicted elements for every available switch order, ($v^*_{c\alpha}\left[t_k\right]$) and ($v^*_{c\beta}\left[t_k\right]$) are the imaginary and the real elements in the synchronous indication structure respectively, and $g_{conv}\left[t_k\right]$ is the cost function. The second Cost function used for the predicted voltage control and described by the following:

$$H_{conv}\left[t_k\right] = \left[\left[\left(DC\left[t_k\right)\right] - V_P\left[t_{k+1}\right]\right]\right](21)$$

Where $H_{conv}\left[t_k\right]$ refers to CF, ($DC\left[t_k\right]$) determines the reference voltage and ($V_P\left[t_{k+1}\right]$) is the predicted output voltage.

Algorithm 1 Proposed fixed-switching FCS-MPC Pseudo-code for stand-alone wind turbine system

for Every time step **do**
  Calculate $\mathbf{i}_L(kT), V_{C1}(kT), V_{C2}(kT), U(KT)$
  for All map measurements from $\mathbf{g}(x), h(x)\,vectors(1,8)$, **do**
    Add margin of safety (Eq.: 20,21)
    Calculate $i_L(kT), V_{C1}(kT)$
    Predict $i_{L1}((k+1)T)$, $V_{C1}((k+1)T)$, $i_o((k+1)T)$ at active vector;
    $V_{C2N}((k+1)T)$, $U_P((k+1)T)$ based on $V_x = 0$ using (eq:20,21);
    if $x < 8$ **then**
      $V_{C2}((k+1)T)$, using (eq:20,21);
$U_P(k+1)T$ using (eq:12);
    end if
  end for
  $U_P((k+1)T, V_{C2N}((k+1)T)$;
  $U_1 = U_{opt}$; (Eq.: 12)
  $v_{c2n} = V_{C2N}(opt)$; (Eq.: 20,21)
  $Sa = states(x_{opt,1})$;
  $Sb = states(x_{opt,2})$;
  $Sc = states(x_{opt,3})$;
end for

4.8 Simulation results and discussion

This part discusses the main parts of system that are classified by the following: MPC effectiveness on whole system that focuses mainly on duty factor, finding out the control fast response, and check that response even at different wind speeds, boosted voltage of DC-DC converter, ensure balancing of three phase voltage and current, disclose the stability of DC power after the three phase converter. Moreover, the performance of model predictive control strategy at unexpected load changes. Fig.4.25 shows the duty factor at 25 m/s wind speed and its stability after being in a transient state for 0.2 second and reaches to 0.35 second.

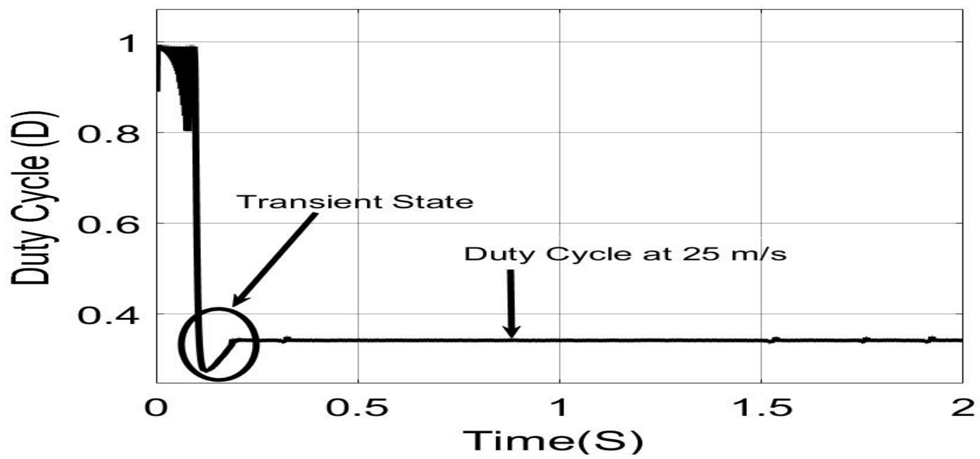

Figure 4.25: Duty cycle At 25m/s wind speed

Fig.4.26 displays the total harmonic distortion (THD) for the output phase current at the same wind speed, and the percentage of THD equal to 0.12 % which is less than 1% that indicates useful rating according to the IEEE standards.

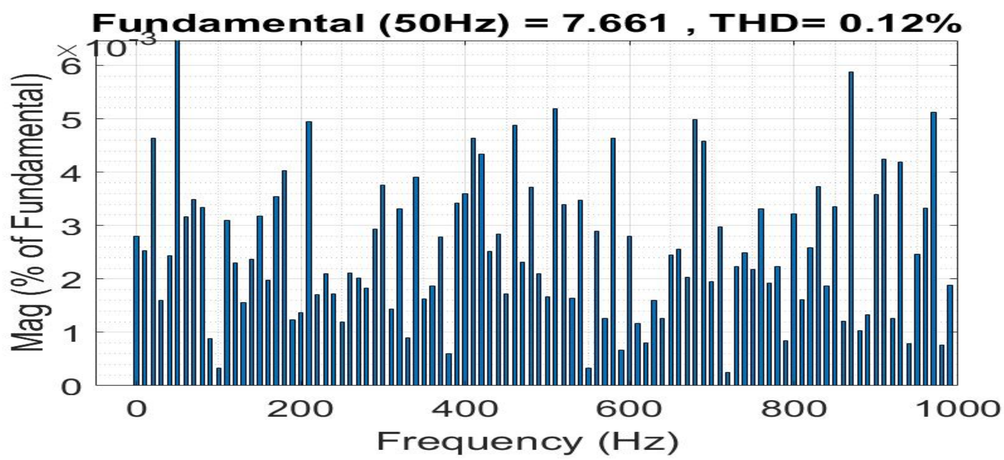

Figure 4.26: FFT spectrum analysis for output phase current at switching frequency $40kHz$

Fig.4.27 presents the DC power generated at the same wind speed that reaches 2500 watts. Fig.4.28 discusses effectiveness of the controller by showing that MPC strategy can track the reference voltage efficiently in order to reach 800 volt at the same wind speed.

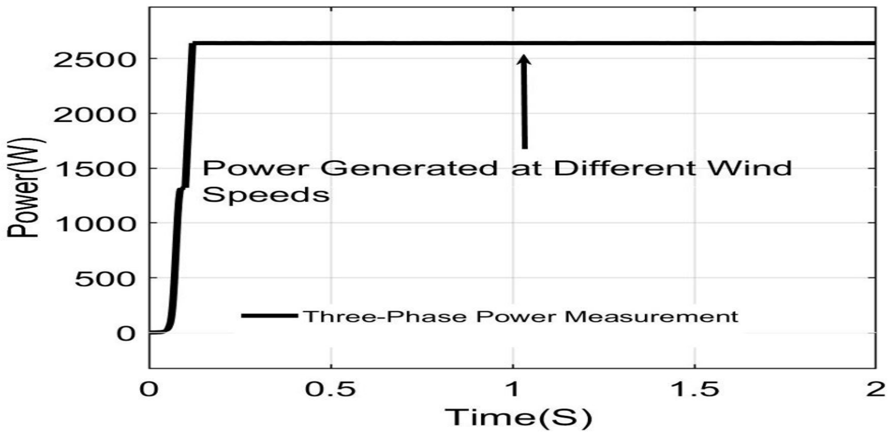

Figure 4.27: DC power At 25 m/s wind speed

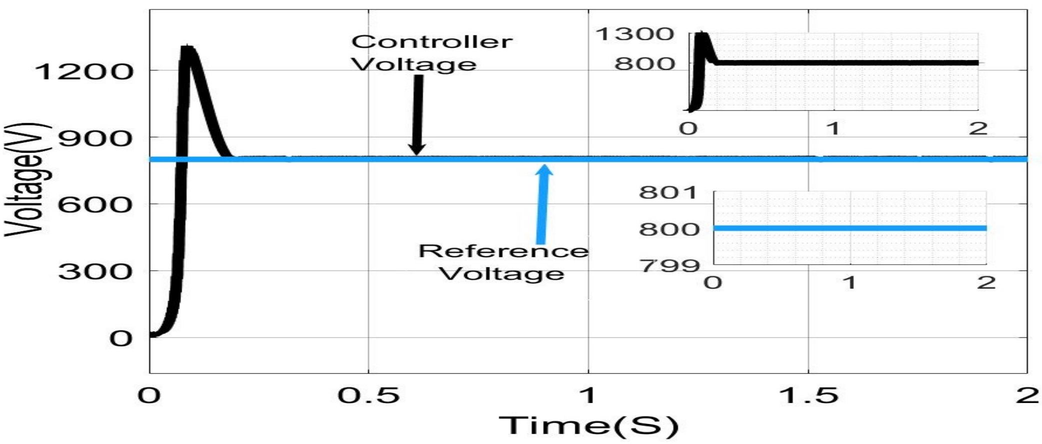

Figure 4.28: Performance of MPC tracking reference voltage

Fig.4.29 and Fig.4.30 determine the balancing state for three phase current and voltage .

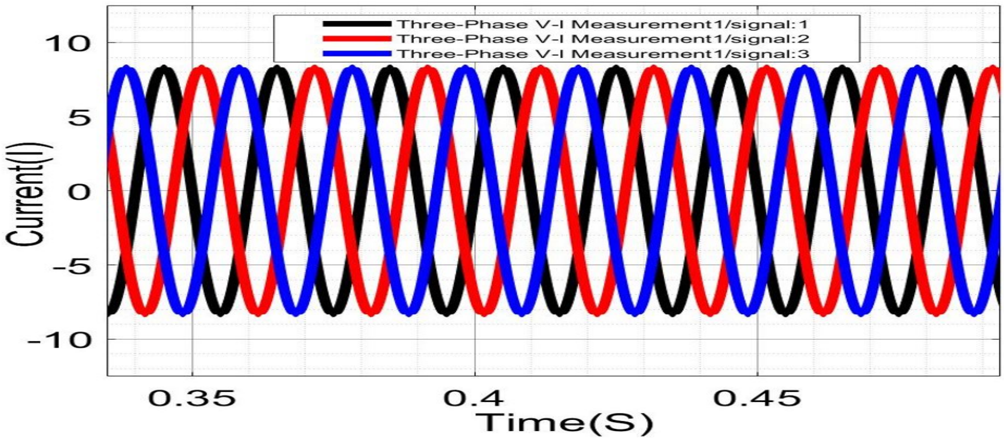

Figure 4.29: Balanced three phase current zoom view

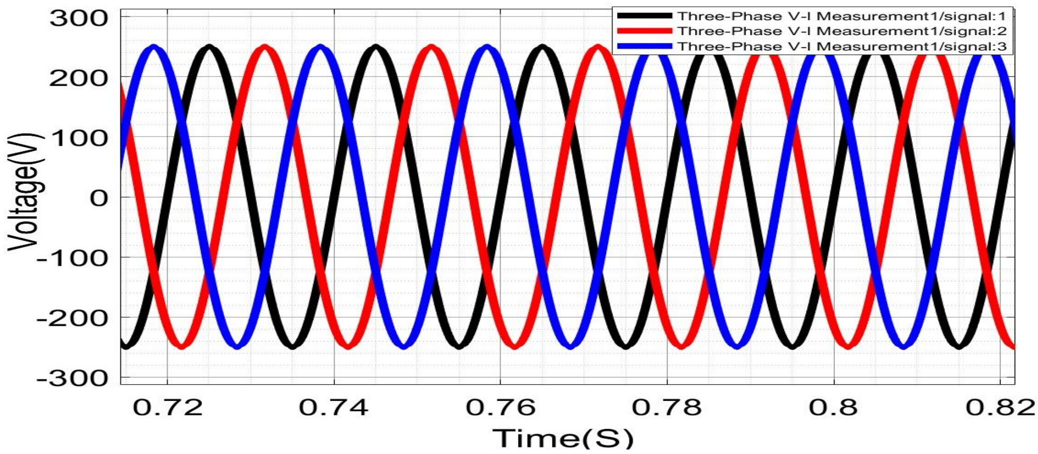

Figure 4.30: Balanced three phase voltage zoom view

Fig.4.31 indicates the DC-DC converter voltage before and after boosting, the voltage before boosting reaches 520 volt after 0.2 transient second while the voltage after boosting equal to 800 watt at the same transient state.

All of that has occured at the same wind speed. Although changing the wind speed can make change in DC-DC Converter voltage, power, duty factor and total harmonic distortion percentage and this will be shown in the next figures. Fig.4.32 indicates the increment of DC power to achieve 3000 watt instead of 2500 watt as shown before, this is already achieved after increasing the wind speed to reach 30 m/s.

Fig.4.33 indicates little-bit change for the percentage of total harmonic distortion to reach 0.1% instead of 0.12% in the first result, and both of them indicate enhancement of system performance.

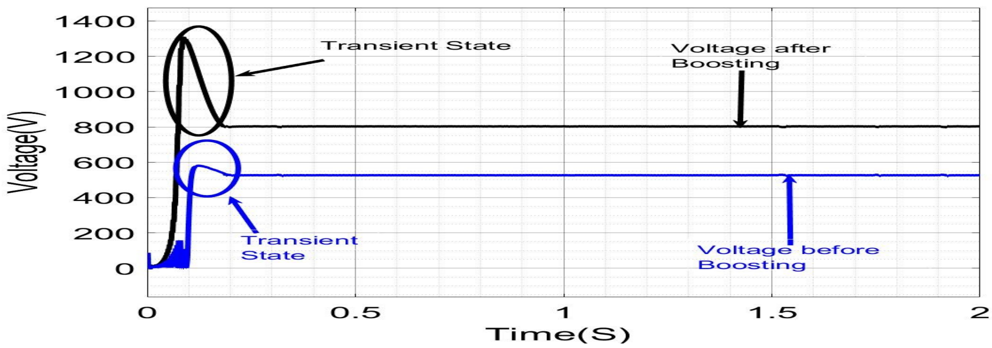

Figure 4.31: Converter voltage before and after boosting

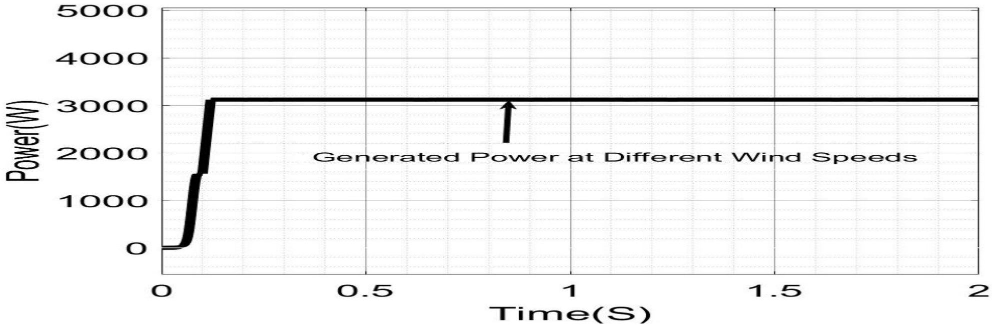

Figure 4.32: DC power at 30 m/s wind speed

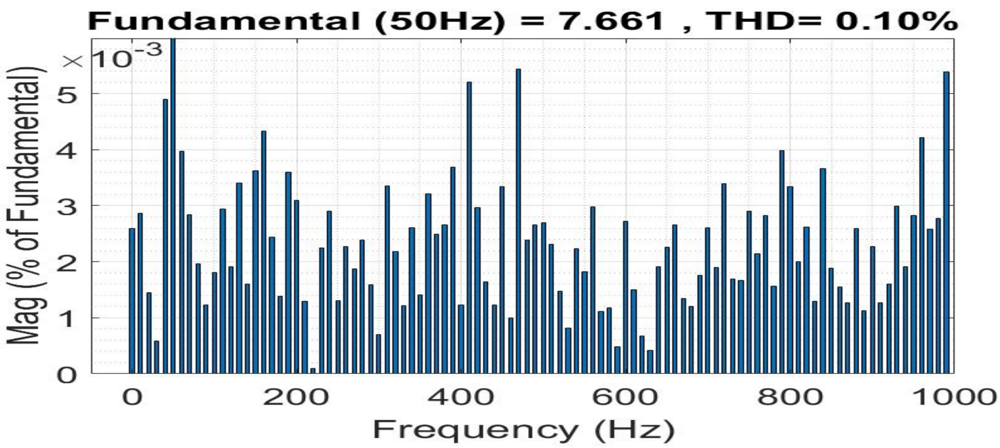

Figure 4.33: FFT spectrum analysis for output phase current at switching frequency $40kHz$

Fig.4.34 shows voltage increment of DC-DC converter before and after boosting [600 → 1000].

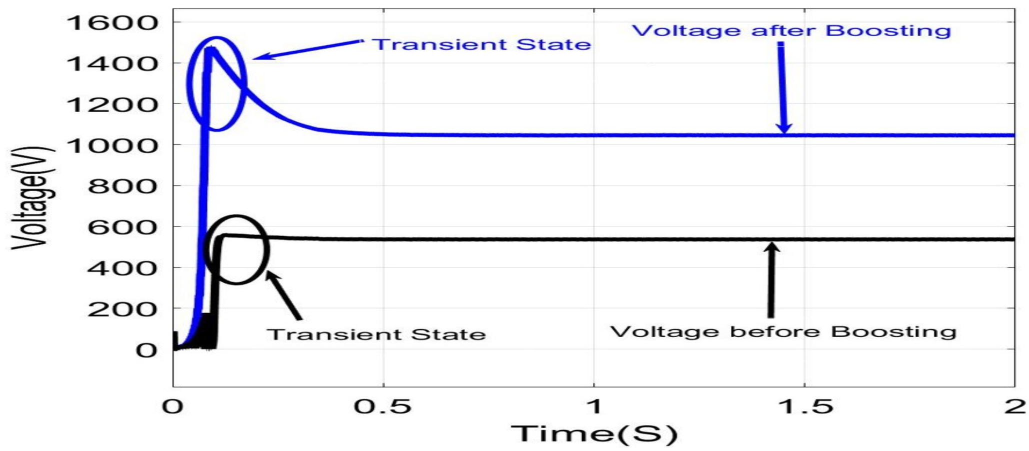

Figure 4.34: Converter voltage before and after boosting according to wind speed variation

Fig.4.35 explains duty factor variation according to wind speed change, as it starts with duty factor 0.2 approximately, then by changing the wind speed, the duty factor changes instantly showing the fast time response of MPC controller technique.

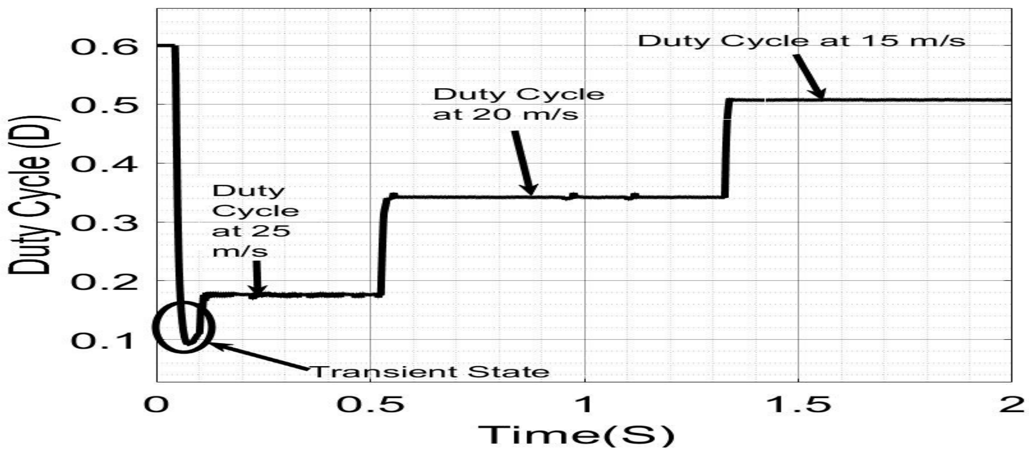

Figure 4.35: Duty cycle variation according to time response of MPC

4.9 Conclusion

The steady state performance is validated for such a system and from the results shown before it is clear that the system is stable, such a system can withstand an output power depending on the speed of wind turbine and wind turbine generator rating. The fault can cause a damage for such a system as it has a huge impact on any studied system.

PI controller integrating the genetic algorithm leads to improvement for the studied system as shown clearly in the first part of this chapter by applying a large number of iterations in order to decrease the transient state for such a system. Running the system with PI controller integrating genetic algorithm at different operating ranges of wind speed to generate the best iteration for each power output in order to generate a lookup table to be sufficient instead of using a transfer function for each operating range. This step has been done to enhance the transient operation of DC-link voltage just before the three phase converter.

The experimental work for such a system that has been tested and validated as it includes the load, DC motor, Permanent Magnet Synchronous Motor (PMSM), uncontrolled rectifier, Digital Signal Processor (DSP), Oscilloscope, these are the main tools that are connected to validate the genetic algorithm applied in the main system by applying the same cases already utilized in the simulation process. The second part of this chapter continues to present and validate the performance of PMSG wind turbine connected system by utilizing another algorithm or controller which is the model predictive one, this part of the chapter determines modification for FCS-MPC of boost circuit and voltage source converter that permits tracking voltages of both power circuits. Such a control system can achieve enhancement in the voltage tracking behaviour, as well as provide high power quality. The integrated system succeeded in preserving the fast time response of voltage regulation of DC-DC converter and its increment change according to variation of wind speed. The presented control strategy helps MPPT speed up the control loop since it predicts error before the switching signal is applied to the selected DC-DC converter. The presented algorithm has been validated using SIMULINK/MATLAB environment.

5 Experimental Work

Summary

5.1 Experimental test bench results and description

5.1.1 Overall System Total description connected to load

The experimental test bench that has been tested and validated as shown in Fig.5.1 is explained as it includes the load, DC motor, PMSM, uncontrolled rectifier, DSP (Digital Signal Processor), and Oscilloscope, these are the main tools that are connected to validate each configuration after that whatever this configuration is open loop one, closed one or cascaded one...
Starting with open loop configuration and its experimental investigation on directly coupled generator with 3-phase load as will be shown in the next subsection. Overall system works at DC motor voltage equal to 56 volts at rated power output equal to 1.5 KW, not more than that for stability of the system as it can not withstand more than that.

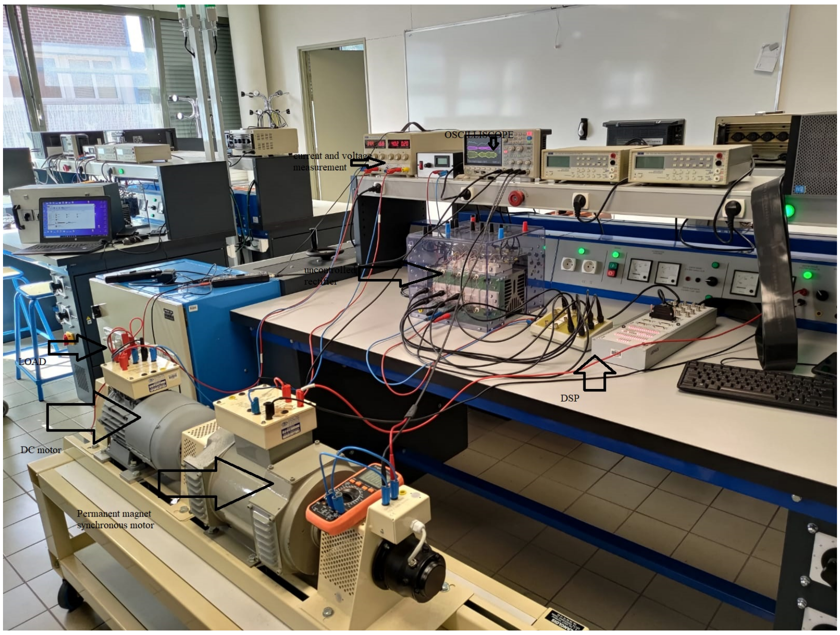

Figure 5.1: Overall system connected to the load

5.1.2 First configuration(Open loop System)

5.1.2.1 Experimental investigation on directly coupled generator with 3-phase load

Fig.5.2 shows the open loop configuration that has been tested and validated according to the experimental test bench, this configuration has been utilized in order to investigate the system without controller. This configuration can be explained as follows: DC motor that is connected with the PMSG through speed sensor passing by uncontrolled rectifier connected to the load. Fig.5.3 shows the measurements of phase voltage and current which are identical on each other in order to validate system balancing and they are in phase with each other, and the last curve shows speed profile of the system. Fig.5.4 shows the same results for the Fig.5.3 after separating voltage from current to present them clearly and Fig.5.5 shows zoomed voltage, current and speed.

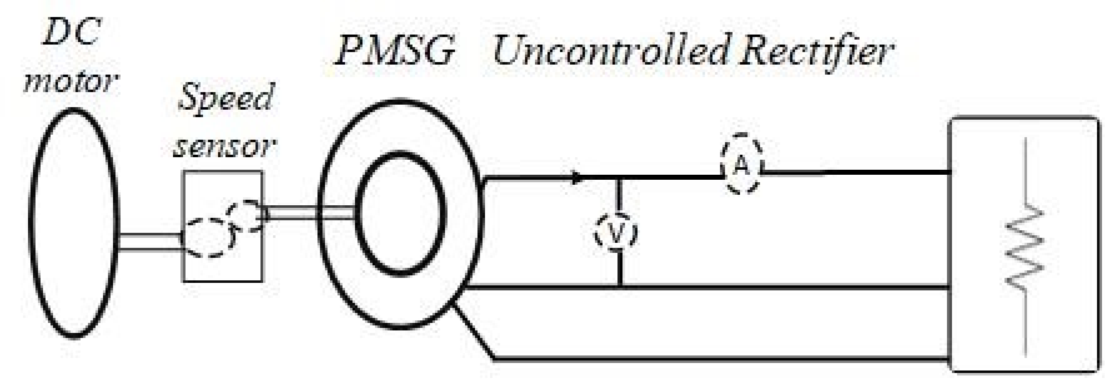

Figure 5.2: Open loop first configuration

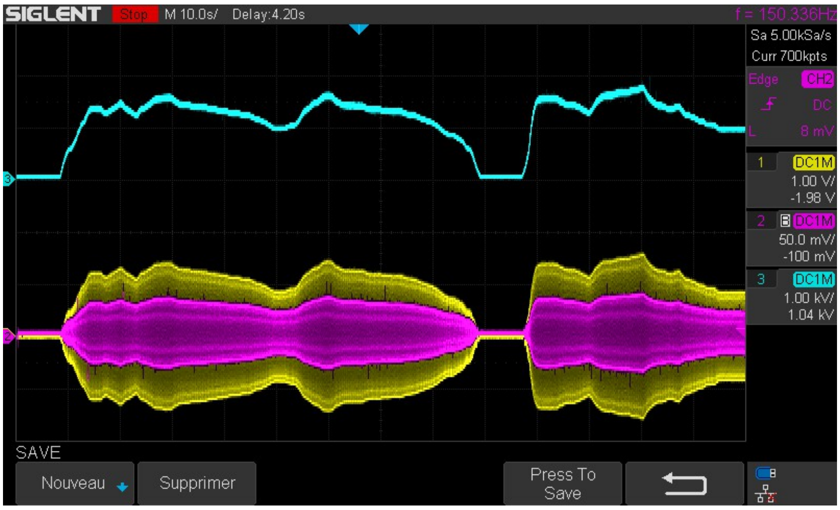

Figure 5.3: First configuration measurements

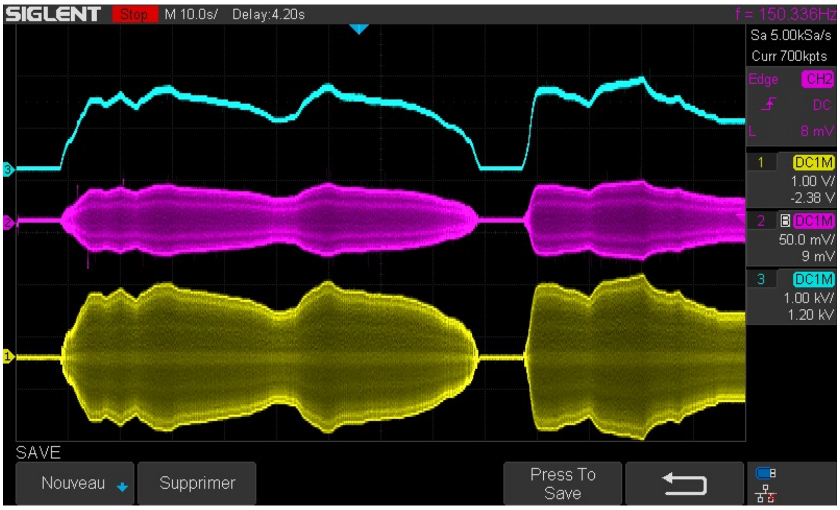

Figure 5.4: First configuration measurements

Figure 5.5: First configuration measurements

In order to check the control signals we have to assure pulse width modulation by oscilloscope and here are the results to ensure stability of the system as shown in Fig.5.6 and Fig.5.7

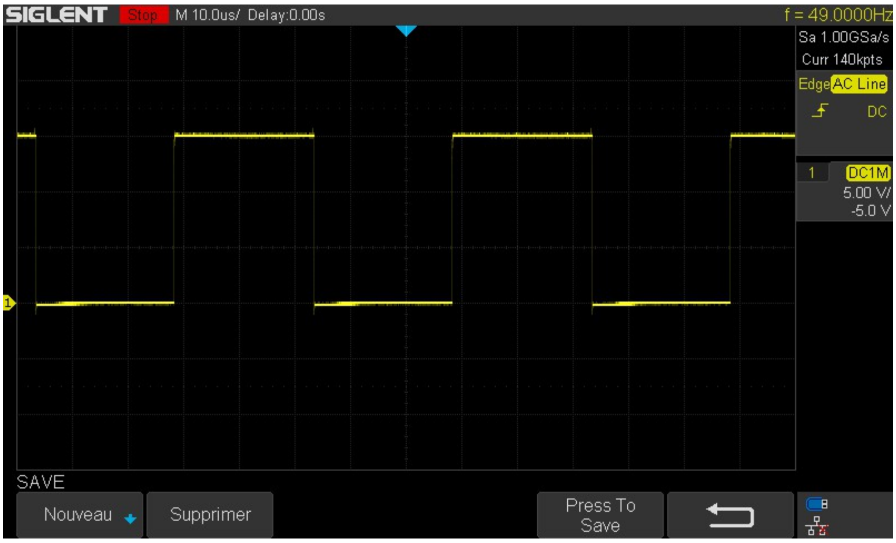

Figure 5.6: PWM control signal

Figure 5.7: Zoomed PWM control signal

5.1.3 Second configuration(Closed loop system)

5.1.3.1 Experimental investigation on generator followed by three phase rectifier

Fig.5.8 shows the second configuration applied for the test bench that is considered to be the DC motor connected to PMSG through the speed sensor passing by rectifier that is connected to the load and the experimental test has been verified through this configuration by making variation for the load and see its effect on the rotational speed as shown in Fig.5.9.

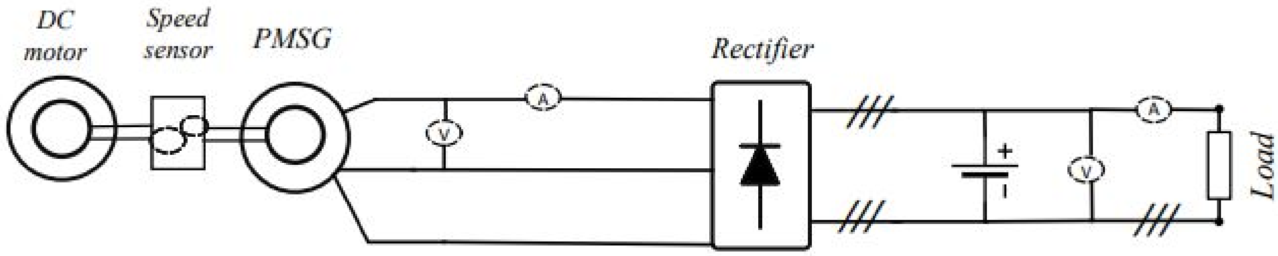

Figure 5.8: Closed loop second configuration

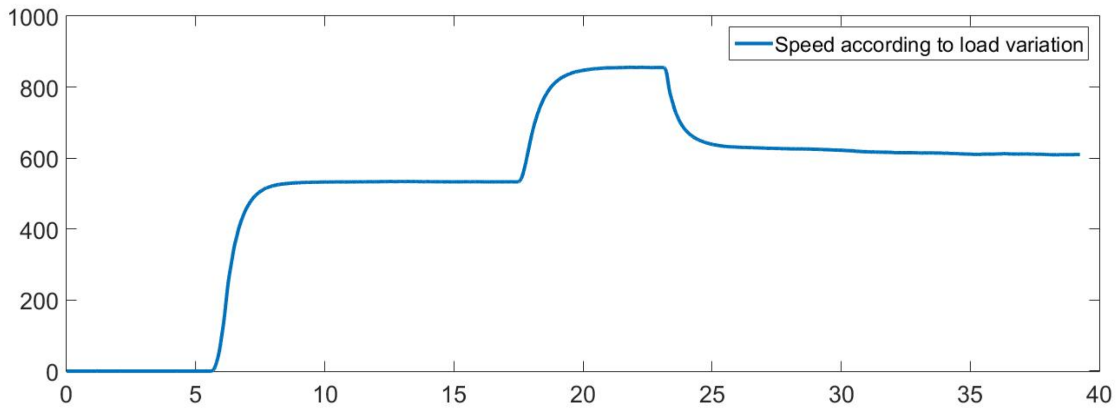

Figure 5.9: Speed according to load variation

5.1.4 Third configuration

5.1.4.1 Uncontrolled rectifier connected to boost converter

The third configuration as shown in Fig.5.10 by adding uncontrolled rectifier and digital signal processor(DSP) in order to analyze and modify a signal to optimize and improve its effectiveness and performance. Fig.5.11 shows the changing system design effect on the resonance for changing rotational speed but still stable after changing its magnitude and movement according to its reference as well.

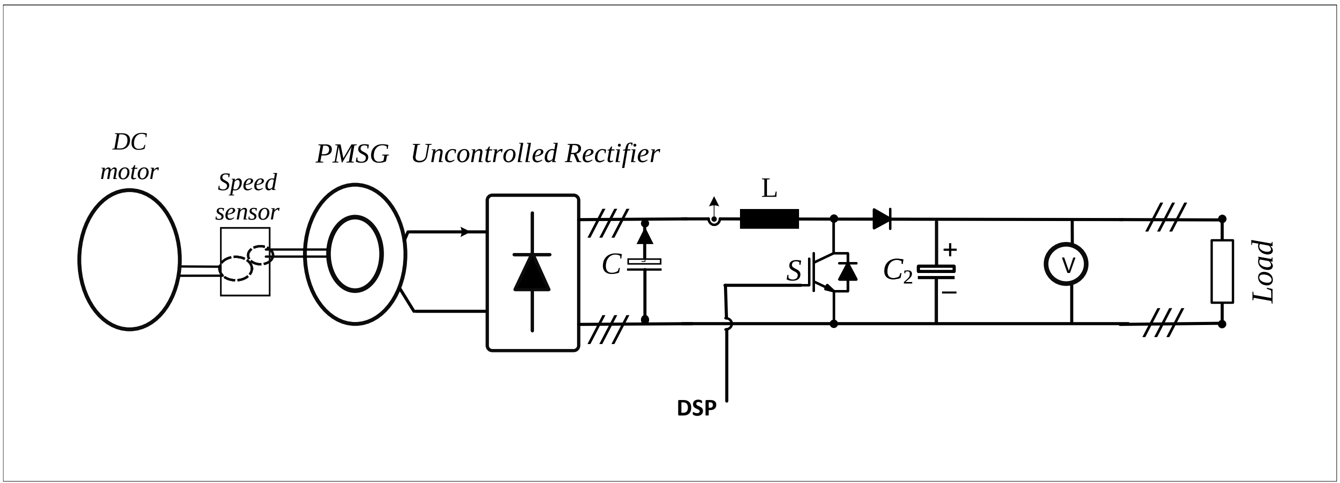

Figure 5.10: Third configuration

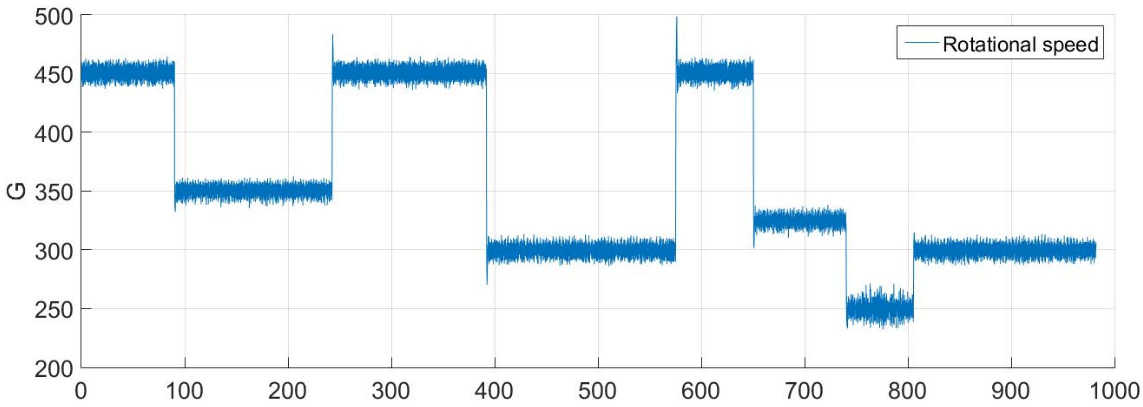

Figure 5.11: Rotational speed profile

Fig.5.12 shows the schematic diagram for wind turbine connected system based on different control strategies like PI controller, genetic algorithm, and model free controller.

5.1.5 Control Law based on Model Free Controller Technique

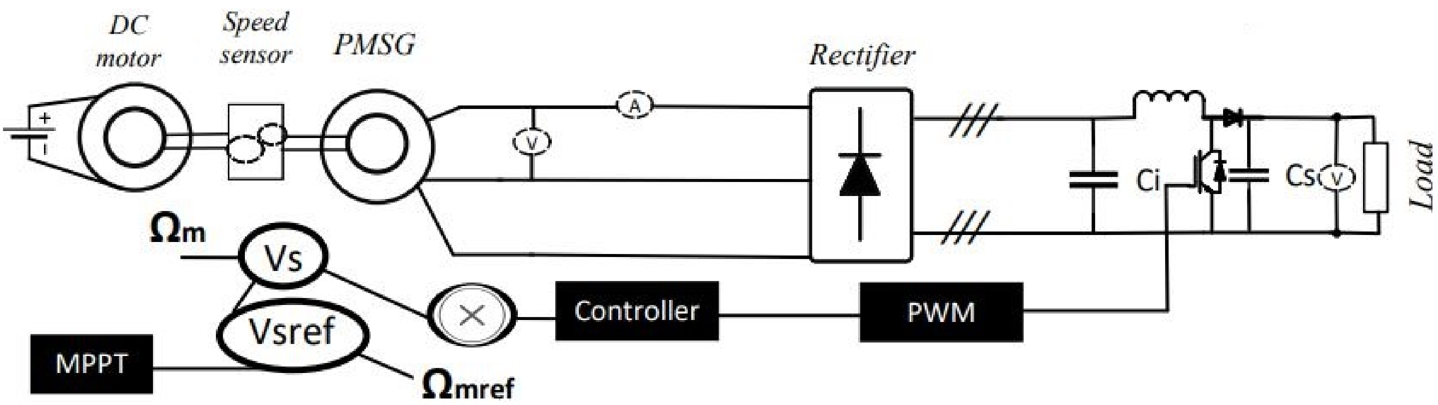

Figure 5.12: Model free controller schematic diagram

Fig.5.12 is presented to describe the connections of model free controller and it is described in schematic diagram as a controller only because it can be changed after that from model free controller to be cascaded one or the inner and outer loop control of PI controller.

Model-free controller and the associated intelligent PID controllers, which have already found success in numerous real-world applications, are given here for the first time as a single entity that takes into account recent developments. The fundamentals of model-free control now make use of some historical functional analysis and simple differential algebra. A recent method of online parameter identification makes the estimated procedures fairly simple. The significance is inferred from the presence of friction for intelligent proportional integral controllers(iPIs), and particularly for iPIs.

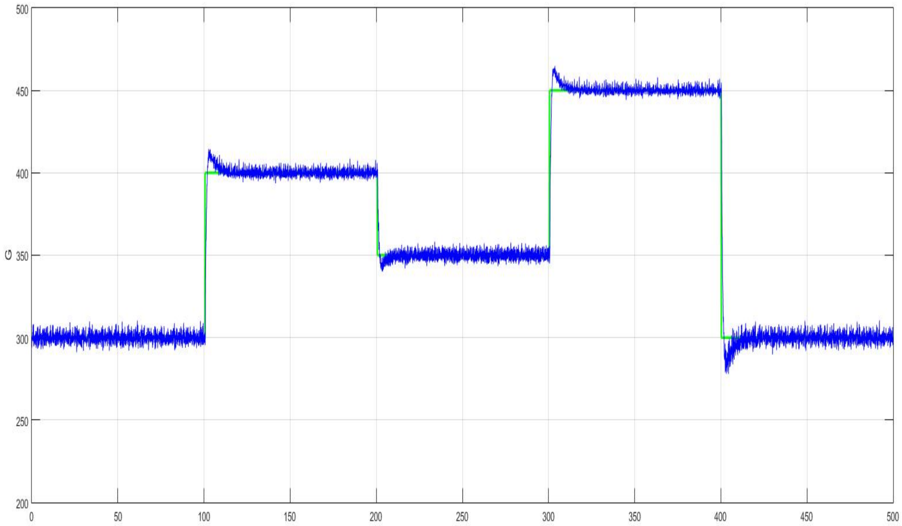

Figure 5.13: Rotational speed with its reference

From their links with iPIDs(intelligent proportional integral controllers), it may be inferred that classic PIDs have an odd industrial ubiquity and that tweaking them in complex scenarios is quite difficult. There are a number of numerical simulations provided, some of which feature infinite-dimensional systems. They show both strength of our clever controllers and how easy it is to tune them. Model-free controller has just recently been developed according to the following references (Fliess and Join 2008, Mboup, Join, and Fliess 2009, and Fliess and RIACHY 2011), but there are already a number of successful concrete applications in a wide range of industries, from energy management to intelligent transportation systems.
Now let's review some of key theoretical concepts influencing our model-free control. For the sake of simplicity, we limit ourselves to systems that have a single control variable, u, and a single output variable, y. An ultra-local model is used in place of the unidentified "complex" mathematical model.

$$y^{(\nu)} = F + \alpha u$$

- $\alpha \epsilon R$ is a constant non-physical parameter. The practitioner selects it so that $\alpha u$and $y^{(\nu)}$ have the same magnitude. The fact that its numerical value is determined through trial and error and not a prior definition should be obvious. Furthermore, it should be highlighted that controlling industrial facilities has traditionally been accomplished through cooperation with engineers who have a thorough understanding of system performance.

- $y^{(\nu)}$ is the order derivative, v is greater than or equal 1 of y.

  The examples given above demonstrate that can always be chosen relatively low.

- F incorporates the poorly understood plant components as well as different potential disturbances without the need to distinguish between them because it is constantly updated.

- A piece-wise constant function is used to approximate F's estimation. The equation is then subjected to the algebraic identification techniques developed by Fliess and Sira–Ramıérez 2003, and Garnier, L. Wang, and Young 2008

$$y^{(\nu)} = \phi + \alpha u$$

where α is unidentified constant parameter.
The estimation

- Simply requires a very brief time delay.

- Is formulated using algebraic formulas that include low-pass filters such iterated time integrals.

- Is resistant to significant noise corruption, as indicated by the new updates of noises via rapid fluctuations.

Fig.5.13 shows the model free controller effect on such a system and how it removes the harmonics in a good manner and the rotational speed follow its reference in an efficient way.

5.1.6 Control Law (Cascaded Conventional One)

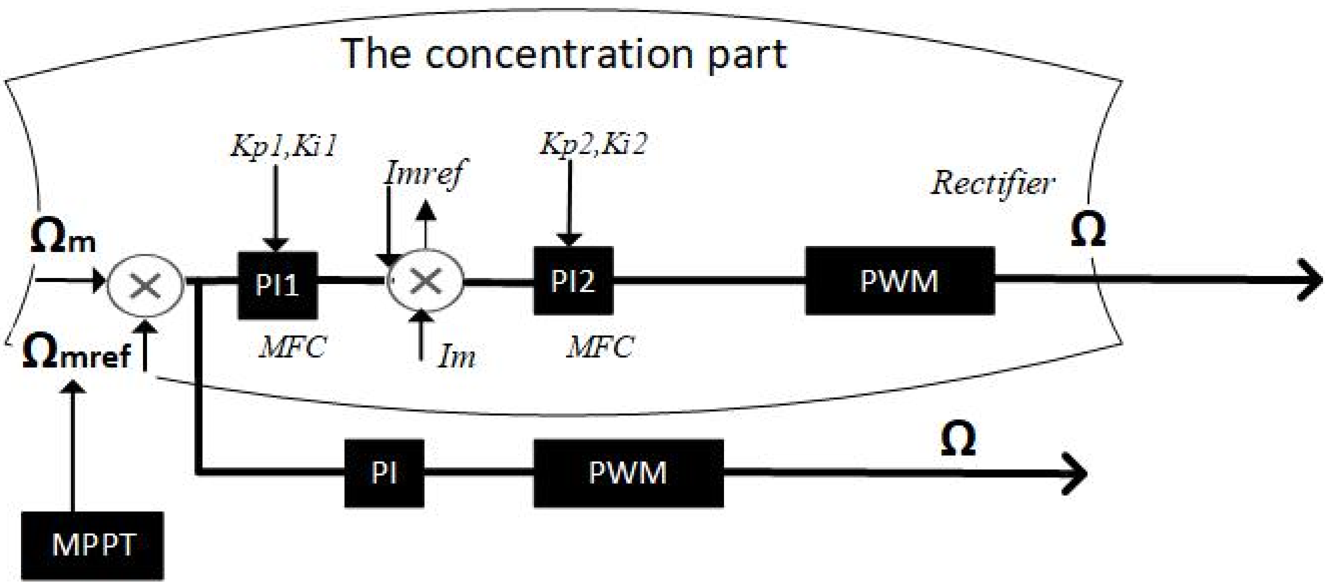

Figure 5.14: Cascaded controller studied schematic part

Fig.5.14 shows the schematic diagram of cascaded conventional controller as multiple of model free controllers will be utilized and there is determination for the concentration part as this part will be the main focus in order to get the system behavior and to know its effect on all parameters of the system like speed, theoretical power, etc.... $\omega_m ref$ will be the rotational speed generated according to the maximum power point tracking technique which will work on that. Here is a comparison can be made very clearly between voltages, like the measurement between the measurement and the reference speed as will be shown in this technique in Fig.5.15

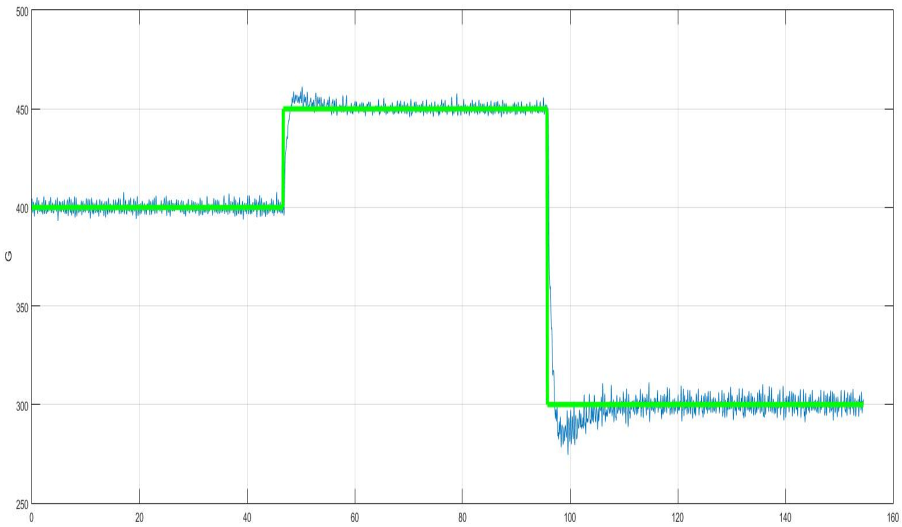

Figure 5.15: Measurement and reference speed according to the cascaded conventional controller

5.1.6.1 PI controller effectiveness by changing speed profile

The effectiveness of PI controller and its performance can be validated by the result shown in Fig.5.16 according to the variable speed profile.

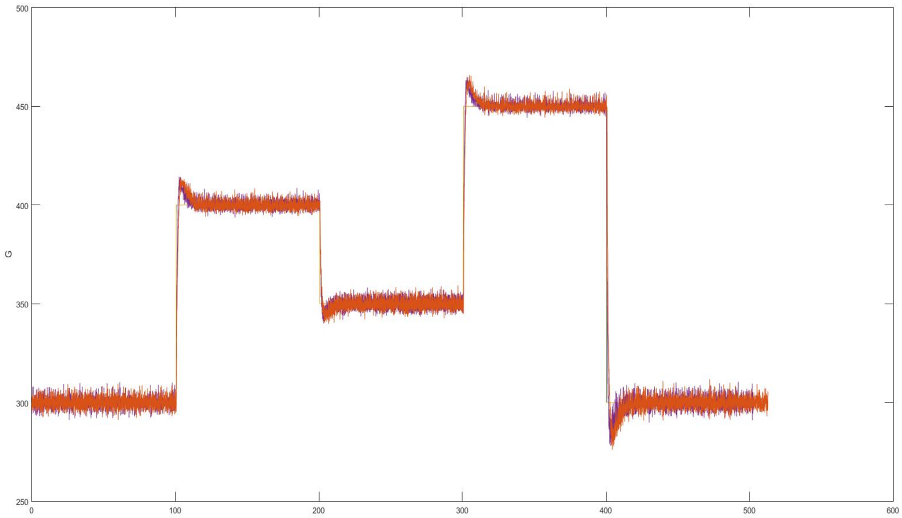

Figure 5.16: PI controller variable speed profile

5.1.6.2 Outer loop control based PI controller

In a double loop cascade system, the action of the secondary loop on the process should be faster than that of the primary one. This ensures that the changes made by the primary output will be reflected quickly in the process and observed when the primary control variable is the next measurement. Fig.5.17 shows tracking of measurement to the reference speed.

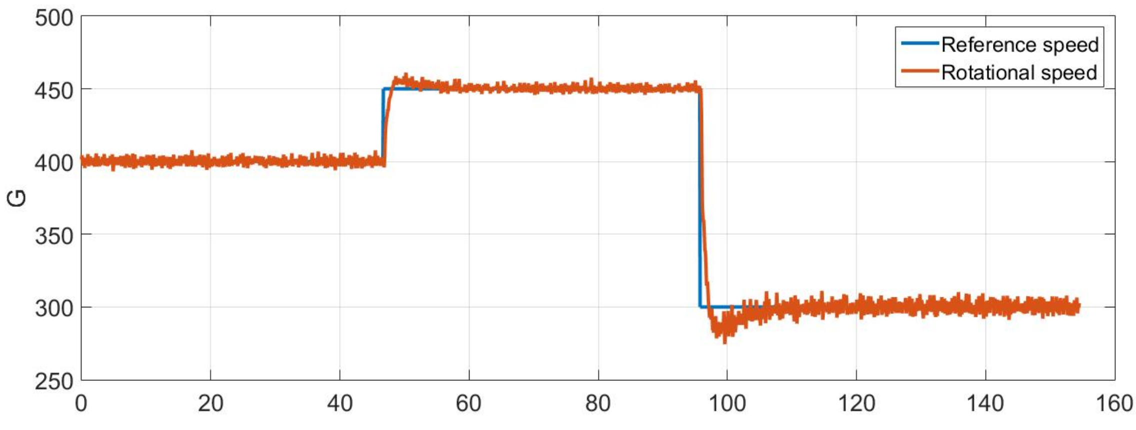

Figure 5.17: Results utilizing cascaded conventional controller technique

5.1.6.3 Inner loop control based PI controller

The inner loop is typically faster than the outer one to reject disturbances before they propagate to the outer loop. Fig.5.18 shows the actual speed as a parameter of the system with its reference.

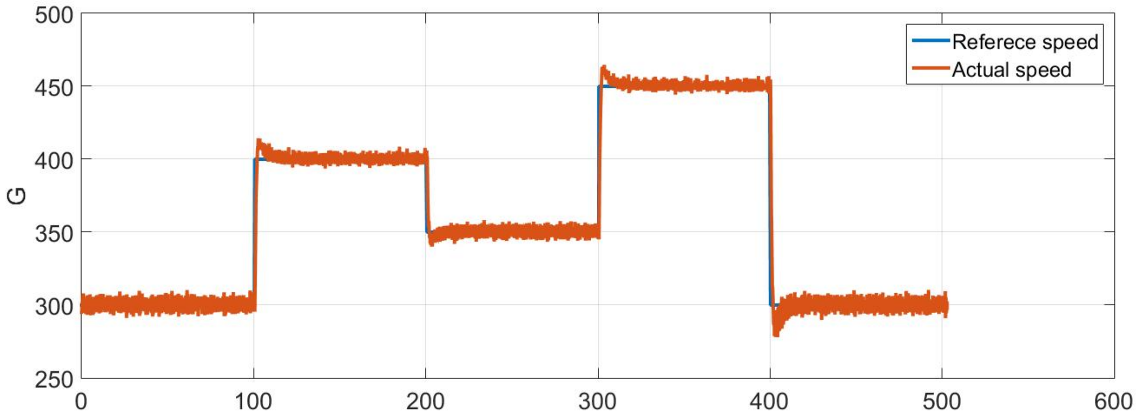

Figure 5.18: More validation for utilizing such a controller

5.1.7 Whole System General Background connected to grid

5.1.7.1 Wind power plant

This wind trainer can be utilized to discuss the operation and design of modern power stations and such an experimental work is determined by utilizing doubly-fed induction generator in order to be validated for all types of generators after that. We have utilized here DFIG instead of PMSG, as the company test bench production deals with PMSG as a motor only, meanwhile we have utilized the DFIG in this test bench while connecting to the grid.

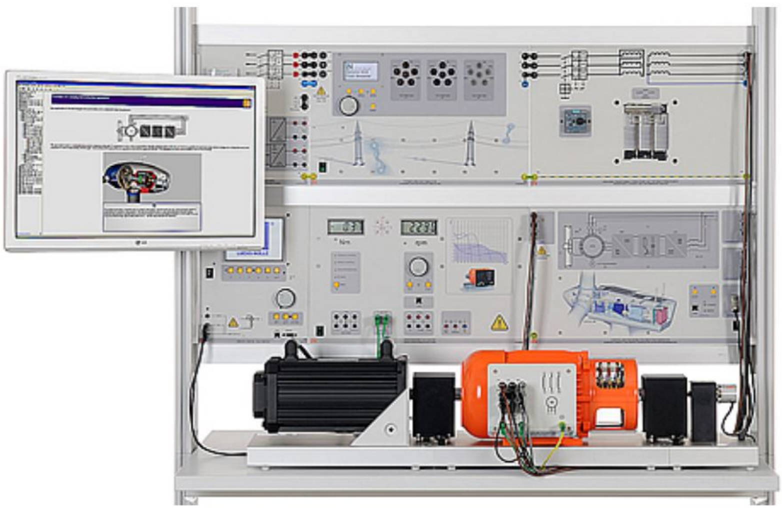

Figure 5.19: DFIG connected Wind power plant

5.1.7.2 Experimental work Aim

- Reactive power generation.
- Limiting the power plant output.
- All system variables are measured and known.
- Wind simulation that replicates wind at shaft mathematically.
- Fault-ride-through (FRT) reaction to grid faults is being investigated.
- Exact replication of technology utilized in today's multi-megawatt wind turbines.
- The generator is connected to 3-phase electricity system via integrated power switch.

5.1.7.3 Wind turbine control unit, doubly fed asynchronous generator

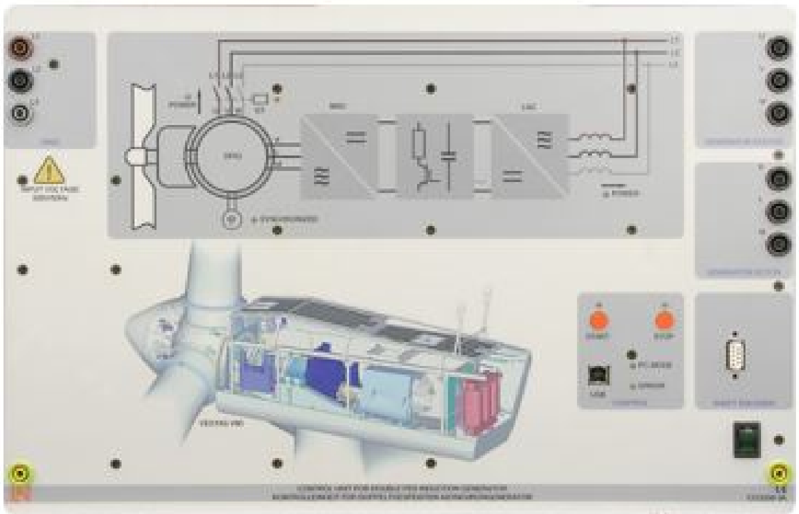

Figure 5.20: Control unit for wind turbine

Double-fed asynchronous generators are used in modern wind power plants to feed electricity into the grid. A speed-variable double-feed asynchronous generator can be controlled and operated in the laboratory using the control unit of double-feed asynchronous generator. All of the practice-relevant operating states can be imitated and studied using the control unit. The included WindSim software ensures easy operation and visualisation of measurement values.

The control unit has the following characteristics:

- Two controlled three phase inverters

- Autonomous control of frequency, voltage, active and reactive power.
- Maximum output power: 1kVA
- Connection voltage: 3*300V, 50...60Hz
- Input for incremental shaft-encoder (sensor).
- Integrated brake chopper for experiments on Fault ride through.
- Automatic and manual synchronization
- USB moderator
- Integrated power switch for connecting generator to three phase electricity grid.

The controller has the following characteristics: Modern wind turbines utilize doubly-fed asynchronous generators to supply power grids with electricity. The controlled employees in this section allows operation and control of variable speed, double-fed induction generator under laboratory conditions. The control unit makes it possible to emulate and study all scenarios of practical relevance. The included software enables easy operation and convenient visualization of measured values.

- Four-quadrant action that is both dynamic and static Torque control, speed control, flywheel, lifting drive, roller/calendar, fan, compressor, winding gear, arbitrarily set time dependent load, manual and automated network synchronization are among the 10 configurable working modes/machine models.
- For voltage and current measurement, an integrated galvanic isolated amplifier is used.
- Speed and torque display.
- USB interface
- Four-quadrant monitor
- Temperature of machine under test is being monitored.
- Presence of shaft cover is checked.
- 400V, 50Hz is the connection voltage.
- 10kVA maximum power output

5.1.7.4 Supplementary Material for Fault Ride Through Experiments

Figure 5.21: Description of supplementary material for fault ride through experiments

The content for such a material can be described as follows:

- Negative sequence components can be compensated.
- Changing the controller's settings.
- The response of wind power facilities to system failures is being investigated.
- Scenarios with symmetrical faults are being investigated.
- Asymmetrical fault scenarios are being investigated.
- Positive phase sequence and negative phase sequence are used to represent variables in the dynamic range.

5.1.7.5 Three phase multi-function machine

Figure 5.22: Three phase multi-function machine 1KW

Three-phase asynchronous motor with slip-rings which can also be used as a synchronous machine.

- Nominal voltage: 400/230V, 50Hz
- Nominal current: 2.0A / 3.5A
- Nominal speed: 1400 / 1500rpm
- Nominal power: 0.8kW
- cos phi: 0.75
- Exciter voltage: 130V AC / 24V DC
- Exciter current: 4A AC / 11A DC
- Weight: 20kg

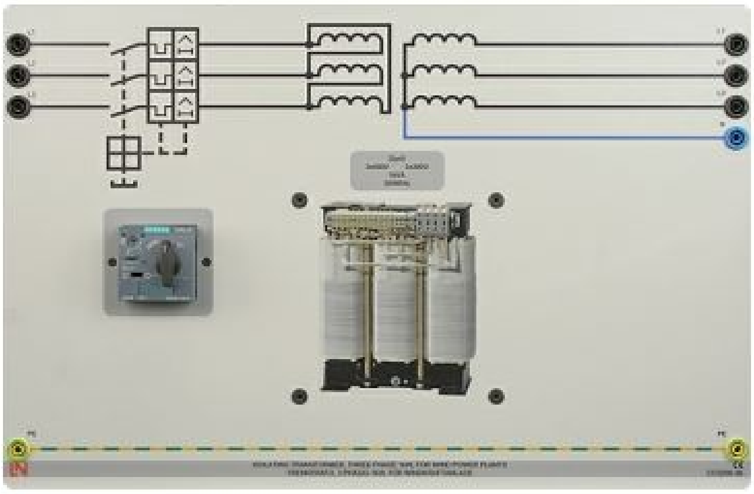

Figure 5.23: Three phase isolation transformer

5.1.7.6 Three phase isolation transformer, 1KW for wind power plants

- Primary voltage: 3 x 400 V
- Secondary voltage : 3 x 300 V
- Rated power: 1000 VA
- Fuse: 1 automatic circuit-breaker 1.6...2.5 A (adjustable)
- Inputs/outputs: 4-mm safety sockets
- Dimensions: 297 x 456 x 150 mm
- Weight: 11kg

5.1.7.7 Incremental position encoder 1024 pulses

Figure 5.24: Incremental position encoder 1024 pulses

The incremental encoder is equipped with the following features:

- 1024 pulses
- Speed: 6000 rpm
- Torque: <= 1Ncm
- Inertia: 35 g cm^2
- Weight: 1.7kg
- One shaft end

5.1.7.8 Dynamic grid fault simulator

Figure 5.25: Incremental position encoder 1024 pulses

Modern wind turbines and photovoltaic power converters are now required to respond to electrical power grid outages without simply shutting down. "Fault ride through" is the term for this type of response. The dynamic grid fault simulator simulates problems in the power grid. This allows you to investigate the response of any downstream equipment related to the malfunction. The grid fault simulator has the following characteristics:

- weight: 18 kilograms.
- 297 x 460 x 210mm Dimensions (HxWxD).
- 3 × 400V, 50...60Hz connector voltage.
- Graphic display.
- Ride-through fault analysis with adjustable starting angle.
- Faults with or without earth contact can be chosen.
- Grid faults can be symmetrical or asymmetrical.
- Power outage that can be adjusted 50ms to 1000ms duration 5-level, adjustable voltage drop for all phases.

The experimental results are carried out on the basis of test bench existing in our laboratory Fig.5.26. As shown in Figure Fig.5.26 the bench is composed of:

- Test bench for servo-driven machines;

- Tachometer;
- Computers for Graphical User Interface.
- Three phase transformer;
- Power supply, alternating, three-phase current and excitation of synchronous machines;
- Control unit;
- Three-phase motor/generator;

The controller techniques for the chapters before are practically applied to DFIG based on wind turbine. The rotor side converter was controlled in order to control the unity power factor at the stator side. While, the Grid Side Converter is controlled to ensure a smooth DC voltage with a unity power factor at the grid side. The different experimental DFIG responses are shown in Fig.5.27, Fig.5.28, Fig.5.29, and Fig.5.30. The experimental results show that all different DFIG responses (Rotational speed, couple and Mechanical Power) are following practically their MPPT values by applying the PI Controller. From experimental results, it can be seen that, the Rotational speed tracks its optimum reference value and achieve successfully the MPPT mode under the wind profile using (see Fig.5.27 and Fig.5.28, Fig.5.29). For both constant zone speed and MPPT mode; the pitch angle is stayed at its minimal value ($\beta = 0$) (see Fig.5.30). Thereby, the WT produces power lower than its available amount in MPPT mode. This precious controller has permitted to avoid any damage of the wind energy conversion system. Consequently, the power injected to the grid side is shown in Fig.5.30 Also, The grid side reactive power is kept at zero value in order to ensure unity power factor to the grid side.

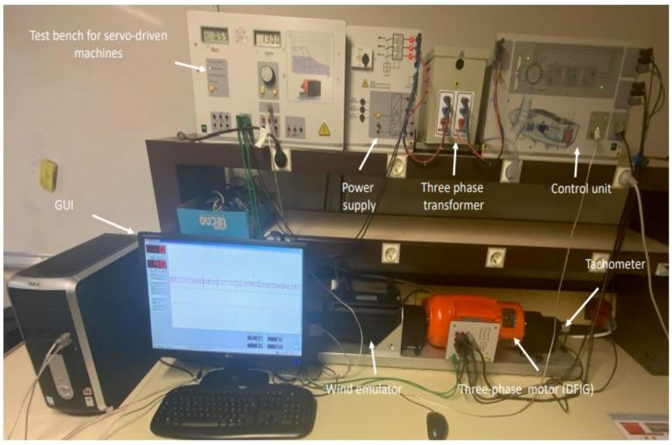

Figure 5.26: Different devices utilized for experimental work

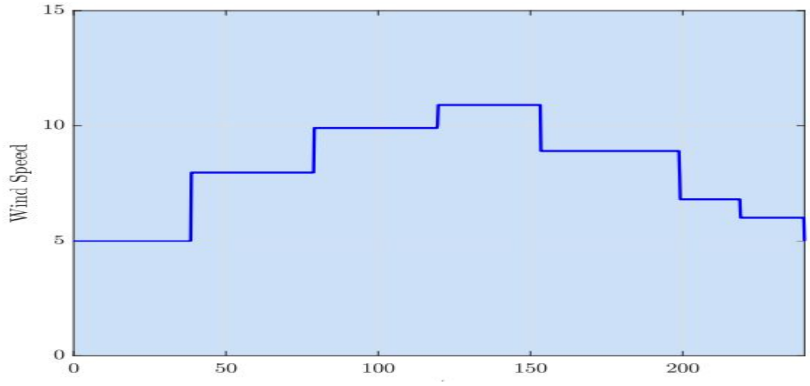

Figure 5.27: Variable wind speed profile (m/s)

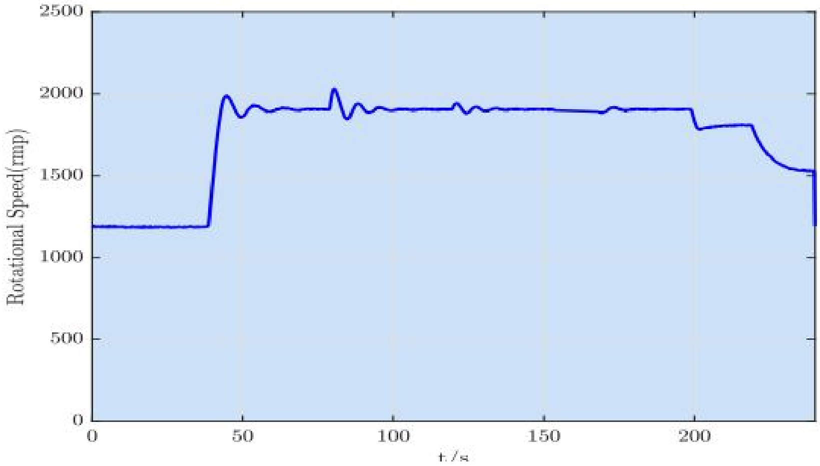

Figure 5.28: Rotational speed(rmp)

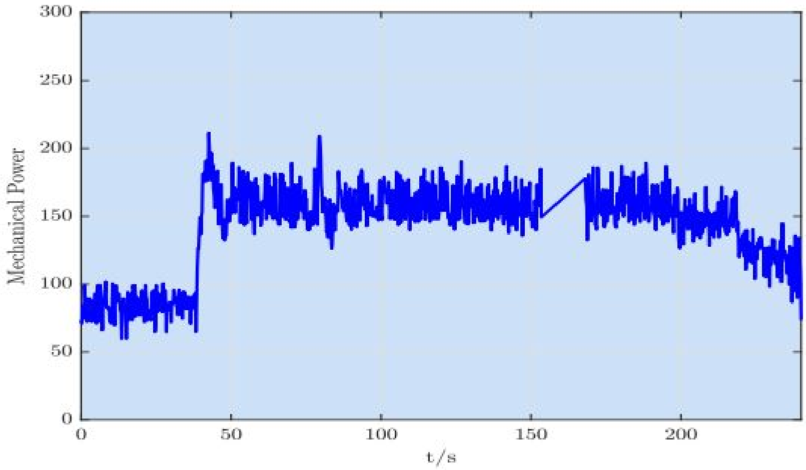

Figure 5.29: Mechanical power(W)

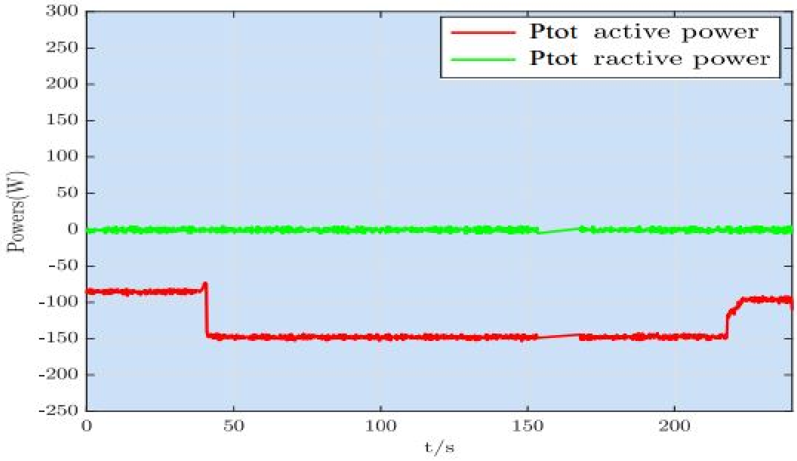

Figure 5.30: Total power injected to grid

5.2 Non-linear controller for mechanical load powered by wind turbine

5.2.1 Introduction and context

Currently, the power produced by Wind Turbine is becoming a very attractive solution in order to guarantee our daily load needs. Their use is increased for many reasons such as pollution on environment and depletion of traditional energy sources (gas and oil . . .). The generated Wind turbine power level depends mainly on wind speed variations. Moreover, types of the chosen controller affects responses and dynamics of these system types. Wind turbine can be used for different applications such as commercial applications, smart grid, smart home and elevators. Concerning driving efficiency, authors proposed novel electric machines such as PMSM as shown in the following references Consoli, Scelba, Scarcella, et al. 2012, Jung, Yoo, Sul, et al. 2012, G. Wang, J. Xu, T. Li, et al. 2013, and Kamiev, Montonen, Ragavendra, et al. 2012, brushless DC-motor and switched reluctance machine Lim, Krishnan, and Lobo 2008, Lim and Krishnan 2007. Furthermore, other work proposed a position control based on P and PI controllers, to improve system efficiency likeFord, Amiri, and Mendrela 2016. However, one of the main drawbacks of this kind of approaches consists of overshot and settling time.

5.2.2 Experimental results

In order to improve the proposed controller performances, an experimental validation is tested to perform the dynamic responses. Our main objective is to analyse and show the controller performance (linear and non-linear classical PI) in order to track the rotational speed reference. The results are carried out on the basis of test bench existing in our laboratory (Fig.5.31). As depicted in Fig.5.31, the list of material utilized in the experiences is given:

- dSPACE;
- Current and Voltage sensors;
- Speed sensor;
- Converters (SEMIKRON);
- Wind turbine (DFIG);
- DC-motor;
- Asynchronous motor;
- Variable resistive load;
- Graphical User Interface (control disc).

The controllers strategies designed previously are applied experimentally to Wind turbine system driving a mechanical load. PI controller is tested and compared experimentally using the same reference profile of DC-motor rotational speed. The different rotational speed responses regulated by PI controller are shown respectively in Fig.5.32, Fig.5.33, and Fig.5.34. The experimental results show that all DC motor speed responses are tracking their reference values of speed by applying PI controller under the same conditions. In the case of PI controller, all the practical responses contain overshoot, steady state-error and long settling time (see Fig.5.32, Fig.5.33, and Fig.5.34). These drawbacks caused significant ripples (chattering phenomena) and vibrations in the machines during experiments, which is no longer desirable in such application. Fig.5.33 shows the reference rotational speed tracking error, and Fig.5.34 illustrates the PWM control signals generated by the conventional drive.

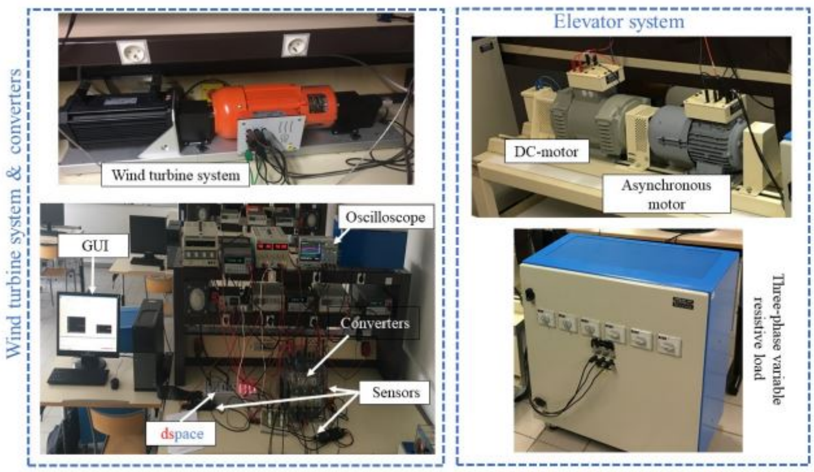

Figure 5.31: Required devices for the experimental test

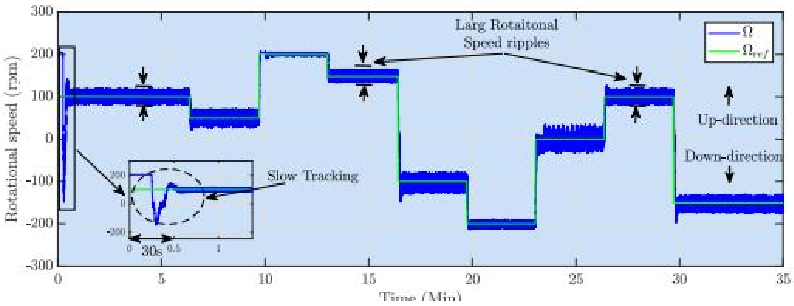

Figure 5.32: Experimental responses of DC motor rotational speed in case of PI controller: Rotational speed (rpm)

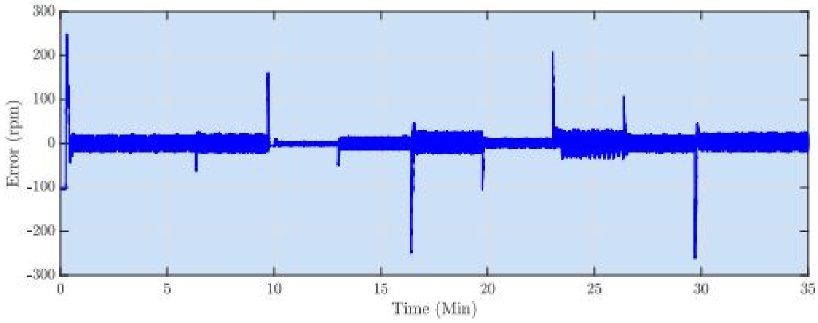

Figure 5.33: Experimental responses of DC motor rotational speed in case of PI controller: Error (rpm)

Figure 5.34: Experimental responses of DC motor rotational speed in case of PI controller: PWM measurement of the controller in case of PI controller

5.3 Conclusion

This chapter includes validation of the system with experimental results according to the test bench utilized in the experimental work. The experimental test is applied to wide variety of configurations as the open loop, closed loop, cascaded (outer loop control-based PI controller, inner loop control-based PI controller) and the control law based on model free controller. There is also another experimental test is applied according to the whole system connected to the grid. All these tests have been made in order to validate and ensure the simulation results that were produced before in the previous chapters.

6 General Conclusion and Perspectives

Summary

There are different types of machines, converters, configurations and control strategies existing in the literature, and more particularly for wind turbine modelling systems. As the main energy source that is already utilized in our system is wind energy, an overview of different types of wind turbines/generators including their advantages and disadvantages is presented in the first part. The appropriate choice should be taken into consideration, cost, reliability, performance and the ability to operate in a completely autonomous manner in the areas and isolated sites. The presented state of art includes the bases on each subsystem which is utilized for such a system at low cost and with excellent service reliability. Such a chapter went over the various WECS kinds, MPPT techniques for variable speed WECSs, and the future of WECS technology.

Recently, the permanent magnet synchronous generator has gained attention by wind turbine manufactures due to advance of control system and power electronics. The wind energy conversion technology of PMSG is very promising in renewable power generation. However, the performance of grid connected PMSGs is greatly affected by grid disturbances because their stator windings are interfaced with the grid directly. This work also demonstrates the effects and the efficiency of PMSG wind turbine which is integrated by different controllers, as well as the wind turbine operating ranges and the converter typologies in details with merits, demerits and applications utilized with the controlled and uncontrolled rectifiers.
Such a work presents different control strategies for wind turbine systems, described in details in chapter three and four, meanwhile the first two controllers presented in this report which are nonlinear static state feedback controller(NSSFC) and nonlinear dynamic state feedback controller(NDSFC) as they are efficient controllers for wind turbine control from the mechanical part point of view, NDSFC has greater performance and robustness through the wind turbine model. The main goal of this consideration is to keep following MPP. According to this operation, TSR is much better than P&O because it follows the reference more efficiently than P&O technique. NSSFCs can be affected by perturbation or error, that leads to reduction in the following reference, whereas NDSFCs have a robust control on such a system, cannot be affected by errors unlike NSSFCs, and follow the reference more efficiently than any other technique mentioned. The efficiency and robustness of controllers

are verified and illustrated based on various system parameters such as the power coefficient, rotational speed, and theoretical power of such a system, and the controllers can be categorized from best to worst as follows: NDSFC, NSSFC, and lastly PI controller, so the presented controller NDSFC can significantly overcome the uncertainties compared to NSSFC and PI controller, These tests have been done utilizing Simulink/Matlab environment.
A wind turbine standalone system based on PMSG is presented clearly in the second part of chapter three, the wind turbine is utilized by adding a new online controller technique and the main focus here is on the electrical part point of view which is considered to be the main target of such a system. Nonlinear proportional integral controller(NPIC) assigns extremely very good results using MPPT method. The rectifier is selected and planned to enhance PMSG efficiency and to deliver sinusoidal currents. Moreover, for increasing wind turbine power, MPPT control technique is utilized, the maximum is extracted without using mechanical speed sensor. It is common and well control method with favorable dynamic performance. PMSG is controlled by NPIC, it assigns useful dynamic performance according to the variability of wind speed. Furthermore, the utilized control method can take advantage of high efficiency, particularly by using PMSG. The stand-alone wind turbine system has been validated by simulation results using Matlab Simulink. The presented sensor-less approach is utilized by model reference adaptive system (MRAS) for generator rotational speed estimation. This latter needs only three phase voltage and current measurements provided by cheapest electrical sensors. Wind turbine simulation has been developed in an online control program in order to improve the influence of research methods on wind turbine systems and MPPT control effectiveness method using variable wind profiles. It is approved from the results shown in such a chapter that the sensor-less part is better than the sensor one from at least two points of view:

- Cost effectiveness due to the sensor removal which can reduce surely the cost of the overall system by using MRAS observer,
- The performance due to the robustness and stability.

Moreover, PI controller integrating genetic algorithm leads to an improvement of assessment of the studied system by applying many iterations in order to decrease the transient state for such a system. Running the system with PI controller integrating the genetic algorithm at different operating ranges of wind speed to generate the best iteration for each power output. This step has been done to enhance the transient operation of the DC-link voltage just before the three-phase converter.
In addition, this work is presenting also another kind of controller techniques which is the model predictive one in order to see the effect of each controller on PMSG wind turbine system that can be described as follows: modification for FCS-MPC of a boost circuit and voltage source converter which permits tracking the voltages of both power circuits. Such a control system can achieve enhancement in the voltage tracking behavior, as well as provide high power quality. The integrated system succeeded in preserving the fast time response of the voltage regulation of DC-DC converter and

its increment change according to variation of wind speed. The presented control strategy helps Maximum Power Point Tracker (MPPT) speed up the control loop since it predicts error before the switching signal is applied to the selected DC-DC converter. The presented algorithm has been validated using SIMULINK/MATLAB environment. Finally, the last chapter of this report includes validation of the system with experimental results according to the test bench utilized in the experimental work. The experimental test is applied to wide variety of configurations as the open loop, closed loop, cascaded (outer loop control-based PI controller, inner loop control-based PI controller), control law based on model free controller, the whole system connected to the grid. All these tests have been applied in order to validate some of the simulation results that were produced before in the previous chapters.

In this context, we will consider assisting the wind turbine with other energy sources such as photovoltaic generator, storage system, etc. This energy management strategy will allow permanent operation of the system in the absence of wind.

New control strategies or updated ones will be added to the wind turbine connected system in order to enhance more in the simulation results according to the transient state, following the reference value for voltage, current, and power. These new strategies can be continuous control set model predictive controller after utilizing here the finite control set one, different form of the artificial intelligence techniques can be added to see what can be happened after running such a system.

Different types of generators can be applied as the doubly fed induction generator to the wind turbine connected system to see its effect on the results generated either the voltage or power developed while running the system.

New experimental results can be applied using these updated and new control techniques.

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ANNEXES

.0.1 Wind turbine control unit

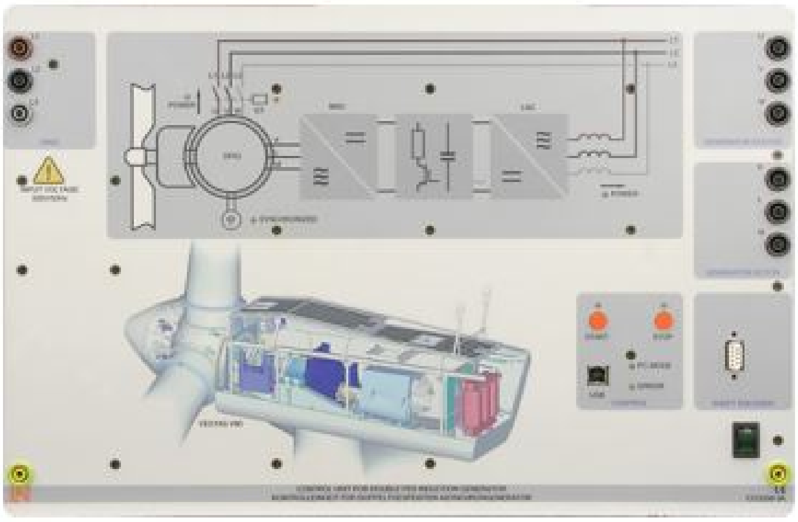

Figure .1: Control unit for wind turbine

The control unit has the following characteristics:

- Two controlled three phase inverters
- Autonomous control of frequency, voltage, active and reactive power.
- Maximum output power: 1kVA
- Connection voltage: 3*300V, 50...60Hz
- Input for incremental shaft-encoder (sensor).
- Integrated brake chopper for experiments on Fault ride through.
- Automatic and manual synchronization
- USB moderator
- Integrated power switch for connecting generator to three phase electricity grid.

.0.2 Three phase multi-function machine

Three-phase asynchronous motor with slip-rings which can also be used as a synchronous machine.

Figure .2: Three phase multi-function machine 1KW

- Nominal voltage: 400/230V, 50Hz
- Nominal current: 2.0A / 3.5A
- Nominal speed: 1400 / 1500rpm
- Nominal power: 0.8kW
- cos phi: 0.75
- Exciter voltage: 130V AC / 24V DC
- Exciter current: 4A AC / 11A DC
- Weight: 20kg

.0.3 Supplementary Material for Fault Ride Through Experiments

Figure .3: Description of supplementary material for fault ride through experiments

The content for such a material can be described as follows:

- Negative sequence components can be compensated.
- Changing the controller's settings.
- The response of wind power facilities to system failures is being investigated.
- Scenarios with symmetrical faults are being investigated.
- Asymmetrical fault scenarios are being investigated.
- Positive phase sequence and negative phase sequence are used to represent variables in the dynamic range.

.0.4 Three phase isolation transformer

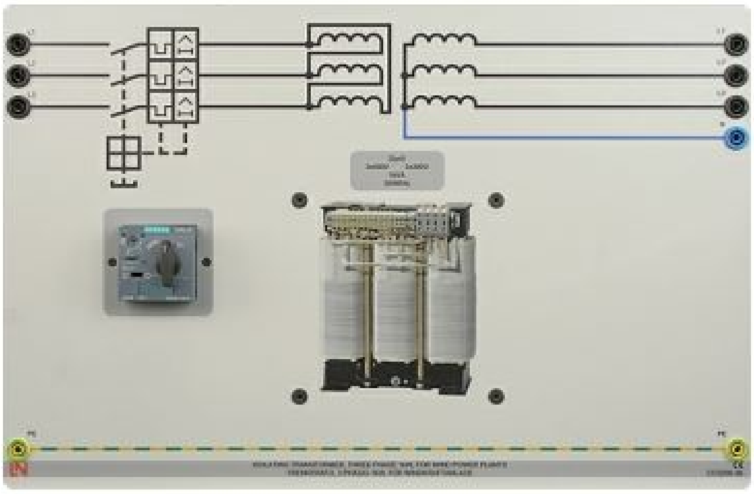

Figure .4: Three phase isolation transformer

.0.4.1 Three phase isolation transformer, 1KW for wind power plants

- Primary voltage: 3 x 400 V
- Secondary voltage : 3 x 300 V
- Rated power: 1000 VA
- Fuse: 1 automatic circuit-breaker 1.6...2.5 A (adjustable)
- Inputs/outputs: 4-mm safety sockets
- Dimensions: 297 x 456 x 150 mm
- Weight: 11kg

.0.5 Incremental position encoder 1024 pulses

Figure .5: Incremental position encoder 1024 pulses

The incremental encoder is equipped with the following features:

- 1024 pulses
- Speed: 6000 rpm
- Torque: <= 1Ncm
- Inertia: 35 g cm^2
- Weight: 1.7kg
- One shaft end