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Performance Analysis of Wind Energy System Integrated into Electrical Grid

تحليل أداء نظام طاقة الرياح المدمجة مع الشبكة الكهربائية

A Thesis Submitted in Partial Fulfillment for the Requirements of the Degree of M.Sc. In Electrical Engineering (Power)

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الآيـة

قال تعالى:

{قَالُوا سُبْحَانَكَ لا عِلْمَ لَنَا إِلاَّ مَا عَلَّمْتَنَا إِنَّكَ أَنْتَ الْعَلِيمُ الْحَكِيمُ}

صدق الله العظيم

سورة البقرة الاية (32)

DEDICATION

I owe my gratitude to my father, my mother, my brothers, my sisters and my family members for all their love and support during my personal and professional education.

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First of all, I would like to express my deep and sincere gratitude to my supervisor **Dr. Nagm Aldeen Abdo Mustafa** for his excellent supervision and helps during this work. It is a pleasure for me to take the opportunity to thank all my colleagues also for support. Also, thank to my father **Bushra Salim Salih** who works at the **General Meteorological Authority** for giving me all information and data I need, and to my grandfather **Omer Babikir Salman** for his huge support in editing the research language. Another thanks to my friends **Eng. Mazin Khalid**, and **Eng. Ahmed Mohamed** at the **National Dispatch Center** for their help in the needed system data.

ABSTRACT

The development of wind turbines and the capacities of wind power plants have increased significantly in the last years, more and more wind farms are being connected into power systems. Integration of large scale wind farms into power systems presents some challenges that must be addressed, such as system operation and control, system stability, and power quality.

Wind power plants must provide the power quality required by new regulations and the reliability of the power system that is interconnected to. It is very important to analyze and understand the sources of disturbances that affect the power quality. In this research, the performance of three different popular wind generators that are connected to the power system have been analyzed.

Based on this analysis a comparison was made for the three wind turbines studied that are: the Squirrel-Cage Induction Generator (SCIG), commonly called the Single-Fed Induction Generator (SFIG), the Doubly-Fed Induction Generator (DFIG), and the Permanent-Magnet Synchronous Generator (PMSG). The fixed speed system is more simple and reliable, but severely limits the energy production of a wind turbine. In case of variable speed systems, comparisons show that generator of similar rating can significantly enhance energy capture. Moreover, the performances of these wind turbines and their characteristics are analyzed in steady-state, and in addition of that after connected to Sudan national grid. Wind turbines systems are modeled in MATLAB/SIMULINK, and ETAP environments. Simulation results matched well with the theoretical turbines operation.

المستخلص

إن التطور في توليد الطاقة الكهربائية من طاقة الرياح والنمو المتزايد في سعات مولداتها ازداد بصورة واضحة في السنوات الأخيرة، كما أن العديد من الحقول المستخدمة لتجميع هذه الطاقة تم دمجها مع الشبكات الكهربائية ولكن دمج هذه الحقول ذات السعات الكبيرة يقابل بالعديد من التحديات التي من المفترض تسليط الضوء عليها كالتشغيل والتحكم في هذه الأنظمة ودراسة استمراريتها وجودتها كذلك.

لابد من توفير الطاقة الكهربائية من طاقة الرياح حسب الجودة والمواصفات ودليل الاعتمادية المحدد لهذا النظام المتصلة معه ومن هذا الأساس فمن المهم فهم وتحليل مصادر الاضطراب والضعف التي تؤثر بصورة كبيرة عل جودة الطاقة المنتجة للمستهلك. وفي هذا البحث تم تحليل أداء أهم ثلاث أنواع من المولدات المستخدمة بصورة كبيرة في هذه الحقول وبناء على هذا التحليل تمت المقارنة بين هذه المولدات والتي هي المولد الحثي ذو القفص السنجابي والذي عادة ما يطلق عليه المولد الحثي آحادي التغذية، ثانيا المولد الحثي ثنائي التغذية، وثالثا المولد التزامني ذو الأقطاب المغناطيسية الدائمة.

من خلال الدراسة والتحليل وجد أن المولدات التي تعمل عند سرعة رياح ثابتة أو محدودة التغيير أنها بسيطة ولكنها ضعيفة في إنتاج الطاقة عكس المولدات التي تعمل عند سرعات متغيرة وعند نفس السعة وجد أنها تعمل على تحسين الطاقة المتولدة وبالإضافة إلى ذالك تحسين الشبكة المرتبطة معها. تم تحليل هذه المولدات بعد إضافتها للشبكة القومية عن مع التركيز على تحليل أثرها على شبكة نقل ولاية الخرطوم عن طريق برنامجين مستخدمين بكثرة هما MATLAB/SIMULINK وETAP للتحليل الدوائر الكهربائية ووجد أن النتائج متطابقة مع المفهوم النظري لطريقة عمل هذه المولدات.

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LIST OF SYMBOLS

Symbol	Meaning
v	Volt
Ω	Ohm
A	Ampere
P	Real Power, Watt
V	Voltage, V
I	Current, A
m	Mass, Kg
Q	Reactive power, VAR
S	Apparent power, VA
v	Speed, m/s
R	Resistance, Ω
X	Reactance, Ω
Z	Impedance, Ω
V_L	Line voltage, v
I_L	Line current, A
ρ	Air density, kg/m^3
A	Cross-sectional area, m^2
P_w	Power in the wind, W

LIST OF ABBSERVATION

HAWT	Horizontal Axis Wind Turbines
VAWT	Vertical Axis Wind Turbines
KVA	Kilo Volt Ampere
KW	Kilo Watt
KVAR	Kilo Volt Ampere Reactive
SFIG	Single-Fed Induction Generator
DFIG	Doubly-Fed Induction Generator
PMSG	Permanent Magnet Synchronous Generator
HP	Horse Power
EHV	Extra High Voltage
CB	Circuit Breaker
AC	Alternating Current
DC	Direct Current
KWh	Kilo Watt hour
KVARh	Kilo Volt Ampere Reactive hour
SCIG	Single Cage Induction Generator
WTG	Wind Turbine Generator
WECS	Wind Energy Conversion System
PI	Proportional Integral
PWM	Pulse Width Modulation
VSI	Voltage Source Inverter
THD	Total Harmonic Distortion
POC	Point of Connection

CHAPTER ONE

INTRODUCTION

1.1 Background

The earth's fossil energy resources are limited, and the global oil, gas and coal production will become beyond their peak in the next decades, and price rises will continue. At the same time there is strong political opposition against strengthening nuclear power in many parts of the world. In this scenario, renewable energies will have to contribute more and more to the world's ever rising need of energy in the future [1]. Renewables are climate-friendly forms of energy, due to the absence of emissions detrimental to the environment. The savings especially in carbon-dioxide and Sulphur dioxide emissions are a significant advantage over fossil power stations. Hence a main role is assigned to renewable energy in the proclaimed fight against climate change [1].

The major source of renewable energies is the sun, with some forms also attributed to the earth and the moon. Utilization of renewables is mostly with conversion into electrical energy. The use of wind power conversion in larger ratings has begun only in the 1980s. Backed by intense technical development, unit ratings have grown fast into the MW range, and wind parks were erected in large numbers with considerable increase rates [1]. The energy from renewable sources is partly already competitive in price, and partly supported by state legislative to promote their share in the market. Wind energy systems are about to reach the competitiveness before long.

The wind is a free, clean, and inexhaustible energy source. It has served mankind well for many centuries by propelling ships and driving wind turbines to grind grain and pump water. The world's first wind turbine used to generate electricity was built by a Dane, Poul la Cour, in 1891. It is especially interesting to note that la Cour used the electricity generated by his turbines to electrolyze water, producing hydrogen for gaslights in the local schoolhouse

[1]. In the United States, the first wind-electric systems were built in the late 1890s, and by the 1930s and 1940s, hundreds of thousands of small-capacity, wind electric systems were in use in rural areas not yet served by the electricity grid. In 1941, a wind turbine comparable in size to the largest ones in operation at the turn of the century went into operation at Grandpa's Knob in Vermont. Interest in wind power lagged, however, when cheap and plentiful petroleum products became available after World War two. The high capital costs and the uncertainty of the wind placed wind power at an economic disadvantage [1]

Sudan is rich in land and water resources. Sudan like most of the oil importing countries suffered a lot from sharp increase of oil prices in the last decades, spending most of its hard currency earnings in importing oil, but could not meet the increasing demand. Oil bill consumes more than 50% of the income earnings. The oil share is only 12% of the total energy consumption. Biomass (wood-fuel, agricultural residues and animal waste) utilized as fuel source is dominating Sudan's energy picture, accounting for about 87% of the country's total energy consumption [2].

The electricity sector represented at most 1% of the total energy supplies (55% from hydropower and 45% from thermal generation) and there is no wind energy for electricity generation in Sudan. The household sector consumed 60% of the total electricity supplies. Renewable energy technologies such as solar, wind, biomass, etc., become more important since there are local resources and indefinite sources of energy. Renewable energy is needed, especially in rural areas and small communities. Renewable sources of energy are regional and site specific [2].

The renewable strategy is well integrated in the national energy plan and clearly spelled out in the national energy policy, but this is not enough. It has to be integrated in the regional development plans. The role of renewable energy is big in solving essential life problems especially in rural areas for people and their resource development like the availing of energy for the medical services for people and animal, provision of water, education, communication and rural small industries [2].

The main source of energy which are applicable in Sudan for rural areas now are solar, wind and biomass for small power supplies for households, rural electrification, communications and special applications, health centers, potable water and irrigation. Sudan is in the process of developing its comprehensive energy policy. The main thrust of this policy will be to lower the cost of energy to the community, in the broadest sense of the term. Other goals are to ensure the reliable supply of energy and potable water, to diversify the fuel mix to attenuate foreign dependence and to conserve energy. Aspects of environmental concern and some use of renewable energy must be included [2].

Over the course of the year typical wind speeds vary from 3m/s to 9m/s (light air to fresh breeze). The highest average wind speed of 6m/s (moderate breeze) occurs around August, at which time the average daily maximum wind speed is 8m/s (fresh breeze). The lowest average wind speed of 3m/s (gentle breeze) occurs around October, at which time the average daily maximum wind speed is 6 m/s (moderate breeze).

1.2 Problem Statement

Integration of large scale wind farms into power systems presents some challenges that must be addressed, such as system operation and control, system stability, and power quality. In Sudan, no wind farms exist in the grid and by the design of them this will create a clean and environmentally friendly source of energy, and after that a study of its effect when it is connected to the network to meet grid interconnection requirements and to ensure the stability of the bulk electric system.

1.3 Objective

The objective of this research is to design a two wind farms (45MW for each one) system and study its performance and effect.

1.4 Methodology

Data of the Sudan national grid has been collected from the national dispatch center, and also the required data of the wind energy has been collected from the general meteorological authority. The network of Sudan has been modelled and simulated using the MATLAB and the ETAP toolbox and connected to the designed wind farms to show the effect of these farms on it.

1.5 Thesis Layout

Chapter two is the basic theory which includes definitions and mathematical relations of the wind energy systems.

Chapter three is a description of grid integration for the wind farms into the transmission system and its requirements.

Chapter four is a simulation and design of the wind farms. Hence, the comparison of the simulation results before and after the addition of the wind farms to the grid.

Chapter five is the conclusion and recommendations of the research.

CHAPTER TWO
LITERATURE REVIEW

2.1 Introduction

Wind power systems can provide electricity whether or not you are tied to the grid. Wind generators can be used in stand-alone systems or combined with solar panels and/or hydro power. While we've been using wind generators off-grid for many years, the grid intertied wind power system is the new kind on the block. Electricity produced by wind generation can be used directly, as in water pumping applications, or it can be stored in batteries for household use when needed. Wind generators can be used alone, or they may be used as part of a hybrid system, in which their output is combined with that of photovoltaics, and/or a fossil fuel generator. Hybrid systems are especially useful for winter backup of home systems where cloudy weather and windy conditions occur simultaneously [3]. The most important decision when considering wind power is determining whether or not your chosen site has enough wind to generate the power for your needs, whether it is available consistently, or available in the season that you need it.

2.1.1 Advantages of wind energy systems

- Wind energy systems are energized by the naturally flowing wind, therefore it can be considered as a clean source of energy. Wind energy does not pollute the air like power plants that rely on combustion of fossil fuels, such as coal or natural gas. Wind turbines do not produce atmospheric emissions that cause acid rain or greenhouse gases.
- Wind energy is available as a domestic source of energy in many countries worldwide and not confined to only few countries, as in the case of oil.
- Wind energy is one of the lowest-priced renewable energy technologies available today.

- Wind turbines can also be built on farms or ranches, thus benefiting the economy in rural areas, where most of the best wind sites are found. Farmers and ranchers can continue to use their land because the wind turbines use only a small fraction of the land. Wind power plant owners make rent payments to the farmer or rancher for the use of the land [4].

2.1.2 Disadvantages of wind energy systems

- Wind power has to compete with conventional power generation sources on a cost basis. Depending on the wind profile at the site, the wind farm may or may not be as cost competitive as a fossil fuel based power plant. The technology requires a higher initial investment than fossil-fueled solutions for power supply.
- The major challenge to using wind as a source of power is that the wind is intermittent and it does not always blow when electricity is needed. Wind energy cannot be stored; and not all winds can be harnessed to meet the timing of electricity demands.
- Good wind sites are often located in remote locations, far from cities where the electricity is needed. In developing countries, there is always the extra cost of laying grid for connecting remote wind farms to the supply network.
- Although wind power plants have relatively little impact on the environment compared to other conventional power plants, there is some concern over the noise produced by the rotor blades, and aesthetic (visual) impacts. Most of these problems have been resolved or greatly reduced through technological development or by properly siting wind plants [4].

2.2 System Components

The wind power system is composed of one or more units, operating electrically in parallel, having the following components [5]:

- The tower.

- The wind turbine with two or three blades.
- The mechanical gear.
- The electrical generator.
- The speed sensors and control.
- The power electronics and batteries.
- The transmission link connecting to the area grid.

The key components to a wind energy conversion system are shown in Figure 2.1. The function of the blades is to convert kinetic energy in the wind into rotating shaft power to spin a generator that produces electric power. Usually, that shaft rotation is too slow to directly couple to a generator, so a gearbox transfers power from the low speed shaft to a higher speed shaft that spins the generator [5].

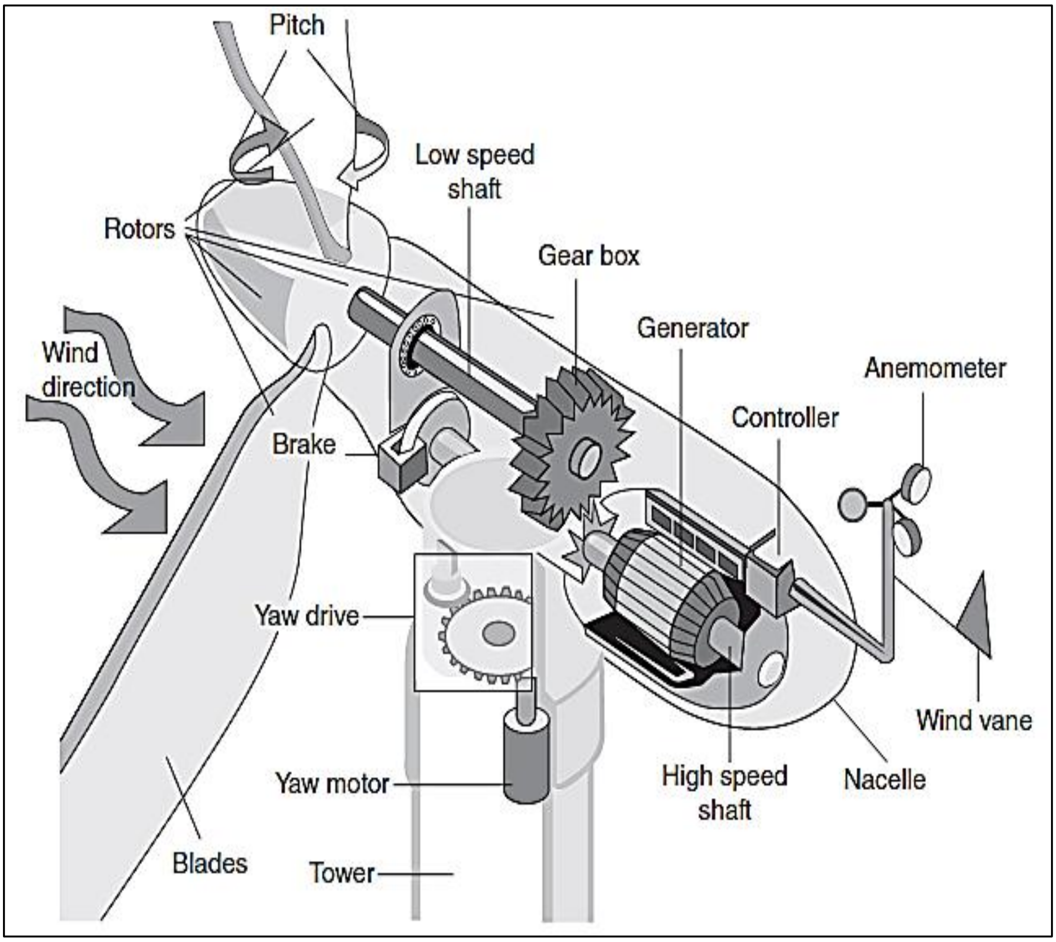


Figure 2.1: Principal components of most wind energy conversion systems

2.3 The tower

The wind tower supports the turbine and the nacelle containing the mechanical gear, the electrical generator, the yaw mechanism, and the stall control. The height of tower in the past was in the 20m to 50m range. For medium and large size turbines, the tower is slightly taller than the rotor diameter. Small turbines are generally mounted on the tower a few rotor diameters high. Otherwise, they would suffer due to the poor wind speed found near the ground surface. Both steel and concrete towers are available and are being used. The construction can be tubular or lattice [5] as shown in the Figure 2.2.

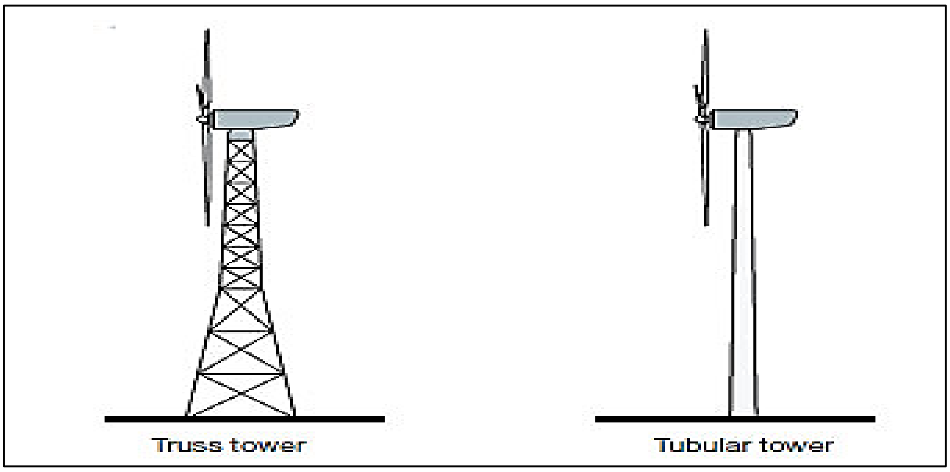


Figure 2.2: Wind energy towers

2.4 Speed control

A rotating turbine blade sees air moving toward it not only from the wind itself, but also from the relative motion of the blade as it rotates. Since the blade is moving much faster at the tip than near the hub, the blade must be twisted along its length to keep the angles right. Up to a point, increasing the angle between the airfoil and the wind (called the angle of attack), improves the lift at the expense of increased drag [6].

Power delivered by a wind turbine increases rapidly with increasing wind speed. At certain wind speed, the generator reaches its maximum capacity at which point there must be some way to shed some of the wind's power or else the generator may be damaged. Three approaches are common on large machines: a passive stall-control design, an active pitch-control system, and an active stall control combination of the two [6].

2.4.1 Stall-controlled machines

The blades are carefully designed to automatically reduce efficiency when winds are excessive. Nothing rotates as it does in pitch-controlled schemes and there are no moving parts, so this is referred to as passive control. The aerodynamic design of the blades, especially their twist as a function of distance from the hub, must be very carefully done so that a gradual reduction in the lift occurs as the blades rotate faster. This approach is simple and reliable, but it sacrifices some power at lower wind speeds. It has been popular on wind turbines less than about 1MW in size [6].

2.4.2 Pitch-controlled turbines

An electronic system monitors the generator output power and if it exceeds specifications, the pitch of the turbine blades is adjusted to shed some of the wind. Physically, a hydraulic system slowly rotates the blades about their axes, turning them a few degrees at a time to reduce or increase their efficiency as conditions dictate. The strategy is to reduce the blade's angle of attack when winds are high. Most large turbines rely on this approach for controlling the power output [6].

2.4.3 Active stall-control

The blades rotate just as they do in the active, pitch-control approach. The difference is, however, that when winds exceed the rated wind speed for the generator, instead of reducing the angle of attack of the blades, it is increased to induce stall [6].

2.5 Wind Turbines

Most early wind turbines were used to grind grain into flour, hence they were named as windmill. Strictly speaking, therefore, calling a machine that pumps water or generates electricity a windmill is somewhat of a misnomer. Instead, people are using more accurate, but generally clumsier, terminology: wind-driven generator, wind generator, wind turbine, Wind Turbine Generator (WTG), and Wind Energy Conversion System (WECS) all are in use [6].

One way to classify wind turbines is in terms of the axis around which the turbine blades rotate. Almost all large machines are Horizontal Axis Wind Turbines (HAWTs), but there are some smaller turbines with blades that spin around a Vertical Axis Wind Turbines (VAWTs). Examples of the two types are shown in Figure 2.3. While virtually all large wind turbines are of the horizontal axis type, there was a period of time when some HAWTs were upwind machines and some were downwind types [6].

A downwind machine has the advantage of letting the wind itself control the yaw (the left–right motion) so it naturally orients itself correctly with respect to wind direction. They do have a problem, however, with wind shadowing effects of the tower. Upwind turbines on the other hand require somewhat complex yaw control systems to keep the blades facing into the wind. In exchange for that added complexity, however, upwind machines operate more smoothly and deliver more power. Essentially all modern wind turbines are of the upwind type [6].

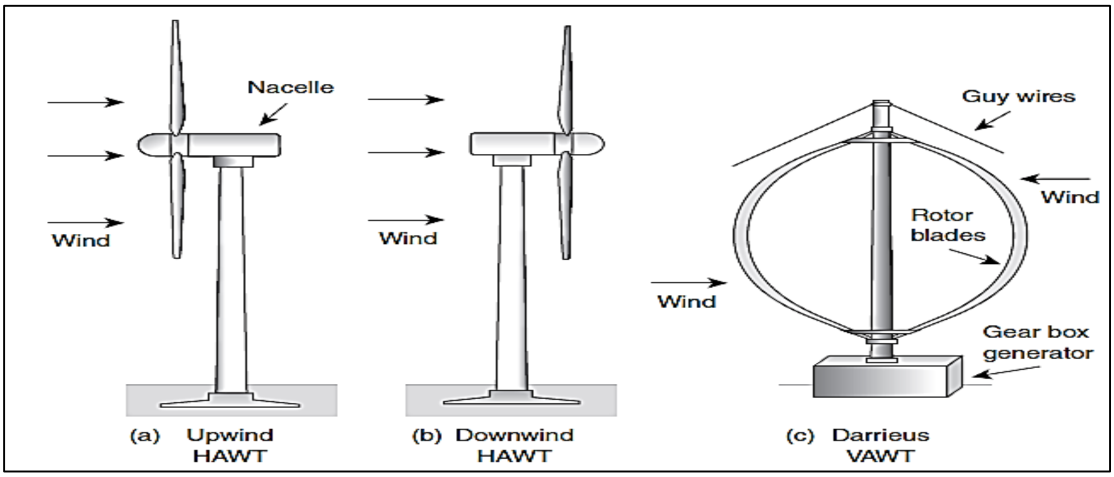


Figure 2.3: HAWT (a) upwind, (b) downwind, and (c) VAWT

The principal advantage of vertical axis machines, such as the Darrieus rotor shown in Figure 2.3(c), is that the heavy generator and gearbox contained in the nacelle can be located down on the ground, where it can be serviced easily. Since the heavy equipment is not perched on top of a tower, the tower itself need not be structurally as strong as that for an HAWT. Another advantage is that they do not need any kind of yaw control to keep them facing into the wind. The principal disadvantage of vertical-axis turbines, which has led to their demise in larger scales, is that the blades are close to the ground where wind speeds are lower [6].

2.6 Generators

The conversion of the mechanical power of the wind turbine into the electrical power can be accomplished by any one of the following types of the electrical machines: the Direct Current (DC) machine, the synchronous machine, and the induction machine. In this research the used type is the induction and synchronous machines, and the description of its component and operation is explained below.

2.6.1 Single-fed induction generator

Most of the electrical power in the industry is consumed by the induction machine driving the mechanical load. For this reason, the induction machine represents a well-established technology. The primary advantage of the induction machine is the rugged brushless construction and no need for separate DC field power. The disadvantages of both the DC machine and the synchronous machine are eliminated in the induction machine, resulting in low capital cost, low maintenance, and better transient performance [5].

The induction generator is extensively used in small and large wind farms and small hydroelectric power plants. The machine is available in numerous power ratings up to several megawatts capacity, and even larger. The induction machine needs Alternating Current (AC) excitation current. The machine is either self-excited or externally excited. Since the excitation current is mainly reactive, a stand-alone system is self-excited by shunt capacitors [5].

2.6.1.1 Principles of operation

Induction generators and motors produce electrical power when their rotor is rotated faster than the synchronous frequency. For a typical four-pole motor (two pairs of poles on stator) operating on a 60Hz electrical grid, synchronous speed is 1800 rotations per minute. Similar four-pole motor operating on a 50Hz grid will have synchronous speed equal to 1500rpm. In normal motor operation, stator flux rotation is faster than the rotor rotation. This is initiating stator flux to induce rotor currents, which create rotor flux with magnetic polarity opposite to stator. In this way, rotor is dragged along behind stator flux, by value equal to slip. In generator operation, a prime mover (turbine, engine) drives the rotor above the synchronous speed. Stator flux still induces currents in the rotor, but since the opposing rotor flux is now cutting the stator coils, active current is produced in stator coils, and motor is now operating as a generator, and sending power back to the electrical grid [7]. In induction generators the magnetizing flux is established by a capacitor bank connected to the machine in case of stand-alone system and in case of grid connection it draws magnetizing current from the grid.

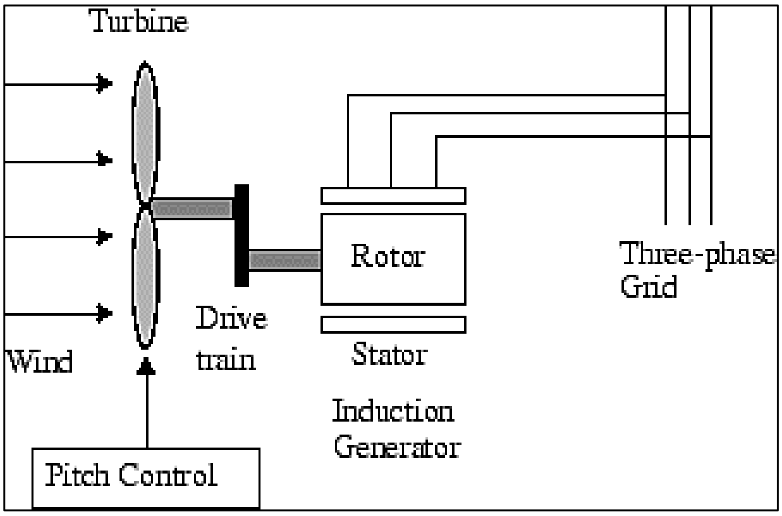


Figure 2.4: Single fed induction generator system

2.6.1.2 Pitch angle control system of the SFIG

A Proportional-Integral (PI) controller is used to control the blade pitch angle in order to limit the electric output power to the nominal mechanical power. The pitch angle is kept constant at zero degree when the measured electric output power is under its nominal value. When it increases above its nominal value the PI controller increases the pitch angle to bring back the measured power to its nominal value [8]. The control system is illustrated in the Figure 2.5.

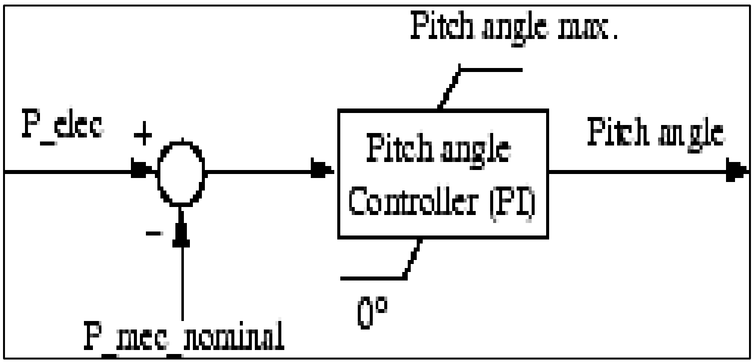


Figure 2.5: Single fed induction generator pitch angle control system

2.6.2 The doubly-fed induction generator

The cage induction generator, with no electrical connections to the rotor, has the significant advantage of simplicity and robustness. On the other hand, it is pretty much a fixed-speed machine whose rotation rate differs only modestly from that of a synchronous generator. Even that modest variation, though, helps when it comes to absorbing shocks caused by rapidly fluctuating winds [7]. The added complexity of a wound rotor induction generator, which needs slip rings to energize the rotor, are often more than justified by the additional flexibility in rotor speed control that they can provide. One of the most popular wind turbine configurations is based on what is referred to as a wound-rotor DFIG [7].

Currently DFIG wind turbines are increasingly used in large wind farms. As shown in Figure 2.6. The AC/DC/AC converter consists of two components: the rotor side converter and grid side converter. These converters are voltage source converters that use forced commutation power electronic device Insulated-Gate Bipolar Transistor (IGBT) to synthesize AC voltage from DC voltage source. A capacitor connected on DC side acts as a DC voltage source. The generator slip rings are connected to the rotor side converter, which shares a DC link with the grid side converter in a so-called back -to-back configuration. The wind power captured by the turbine is converted into electric power by the IG and is transferred to grid by stator and rotor windings. The control system gives the pitch angle command and the voltage commands for rotor converters and grid converters to control the power of the wind turbine, DC bus voltage and reactive power or voltage at grid terminals [7].

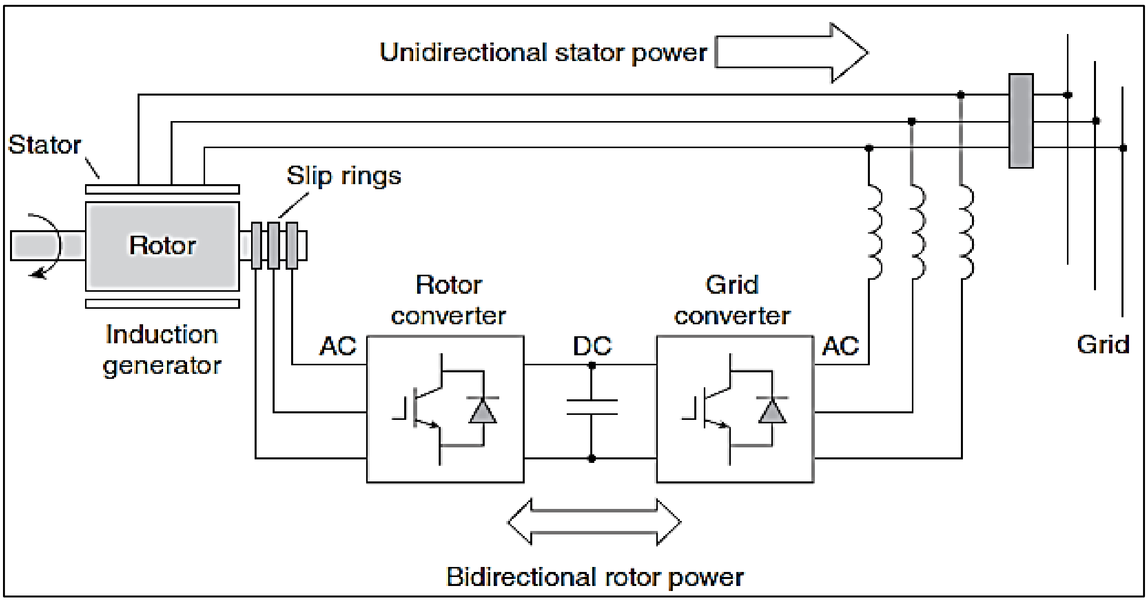


Figure 2.6: A wound-rotor, doubly-fed induction generator

2.6.2.1 Back-to-back converter

The controlled rectifier and controlled inverter based converter is called back-to-back converter consisting of two conventional Pulse Width Modulated (PWM) Voltage Source Inverters (VSIs). It differs from the diode rectifier based converter for the rectification stage, where the diode rectifier with chopper circuit is replaced by controlled rectifier. The controlled rectifier gives the bidirectional power flow capability, which is not possible in the diode rectifier based power conditioning system. Moreover, the controlled rectifier strongly reduces the input current harmonics and harmonic losses. The grid side converter enables to control the active and reactive power flow to the grid and keeps the DC-link voltage constant, improving the output power quality by reducing Total Harmonic Distortion (THD). The generator side converter works as a driver, controlling the magnetization demand and the desired rotor speed of the generator. The decoupling capacitor between grid side converter and generator side converter provides independent control capability of the two converters [9]. Figure 2.7 shows the back-to-back converter based wind turbine generator system.

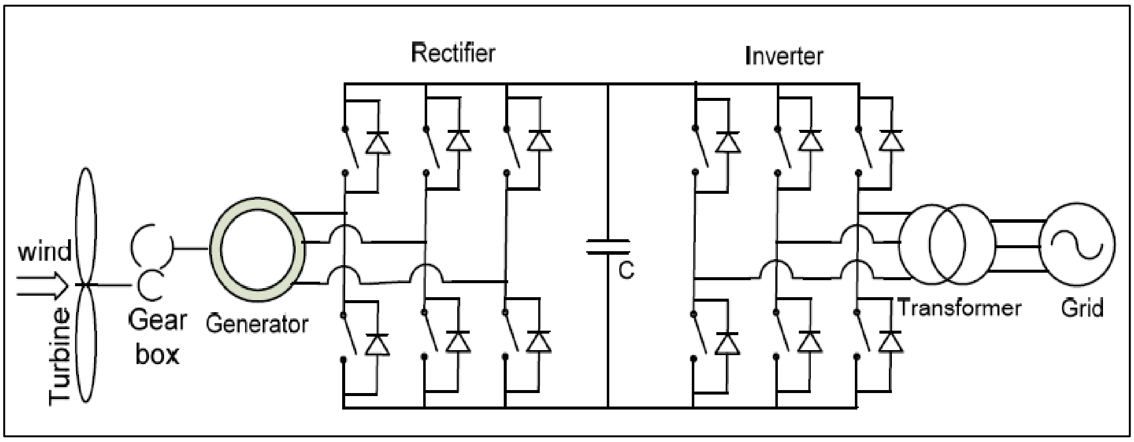


Figure 2.7: Back to back converter based wind turbine generator system

Recently, the back to back converter has also attracted significant interest for partial rating converter applications, where the wind turbine system employs doubly-fed induction generator [9]. To obtain sub- and super-synchronous speed operations the rotor side converter must be able to handle slip power in both directions. When the turbine speed is below the synchronous speed, the power input to the system through the stator winding is balanced by subtracting a small portion of power from the system through the rotor circuit. On the other hand, when the shaft speed is above the synchronous speed the power is balanced by adding a small portion of power to the system through the rotor circuit [9]. The main advantage of back to back converter are:

- The back to back converter is a bidirectional power converter.
- The DC-link voltage can be boosted to a level higher than the amplitude of the grid line to line voltage in order to achieve full control of the grid current.
- The capacitor between the inverter and rectifier makes it possible to decouple the control of the two inverters, allowing the compensation of asymmetry on both the generator side and the grid side.
- The component costs are low (commercially available in a module form) [9].

The main disadvantages are:

- The presence of the heavy and bulky DC-link capacitor increases the costs and reduces the overall lifetime of the system.
- The switching losses. Every commutation in both the grid inverter and the generator inverter between the upper and lower DC-link branch is associated with a hard switching and a natural commutation.
- The high switching speed to the grid may also require extra EMI-filters.
- The combined control of the controlled rectifier and inverter is quite complicated [9].

2.6.2.2 Principles of operation

When the rotor speed is greater than the rotating magnetic field from stator, the stator induces a strong current in the rotor. The faster the rotor rotates, the more power will be transferred as an electromagnetic force to the stator, and in turn converted to electricity which is fed to the electric grid. The speed of asynchronous generator will vary with the rotational force applied to it. Its difference from synchronous speed in percent is called generator's slip.

With rotor winding short circuited, the generator at full load is only a few percent [7].

With the DFIG, slip control is provided by the rotor and grid side converters. At high rotor speeds, the slip power is recovered and delivered to the grid, resulting in high overall system efficiency. If the rotor speed range is limited, the ratings of the frequency converters will be small compared with the generator rating, which helps in reducing converter losses and the system cost [7]. Since the mechanical torque applied to the rotor is positive for power generation and since the rotational speed of the magnetic flux in the air gap of the generator is positive and constant for a constant frequency grid voltage, the sign of the rotor electric power output is a function of the slip sign. Rotor converters and grid converters have the capability of generating or absorbing reactive power and can be used for controlling the reactive power or the grid terminal voltage. The pitch angle is controlled to limit the generator output power to its normal value for high wind speeds. The grid provides the necessary reactive power to the generator [7].

2.6.2.3 Rotor side control system

The rotor-side converter is used to control the wind turbine output power and the voltage (or reactive power) measured at the grid terminals. The power is controlled in order to follow a pre-defined power-speed characteristic, named tracking characteristic. An example of such a characteristic is illustrated in the Figure 2.8 called turbine characteristics and tracking characteristic, by the ABCD curve superimposed to the mechanical power characteristics of the turbine obtained at different wind speeds. The actual speed of the turbine (ω_r) is measured and the corresponding mechanical power of the tracking characteristic is used as the reference power for the power control loop [8].

The tracking characteristic is defined by four points: A, B, C and D. From zero speed to speed of point the reference power is zero. Between point

A and point B the tracking characteristic is a straight line; the speed of point B must be greater than the speed of point A. Between point B and point C the tracking characteristic is the locus of the maximum power of the turbine (maxima of the turbine power vs turbine speed curves). The tracking characteristic is a straight line from point C and point D. The power at point D is one per unit (1 pu) and the speed of the point D must be greater than the speed of point C. Beyond point D the reference power is a constant equal to one per unit (1 pu) [8].

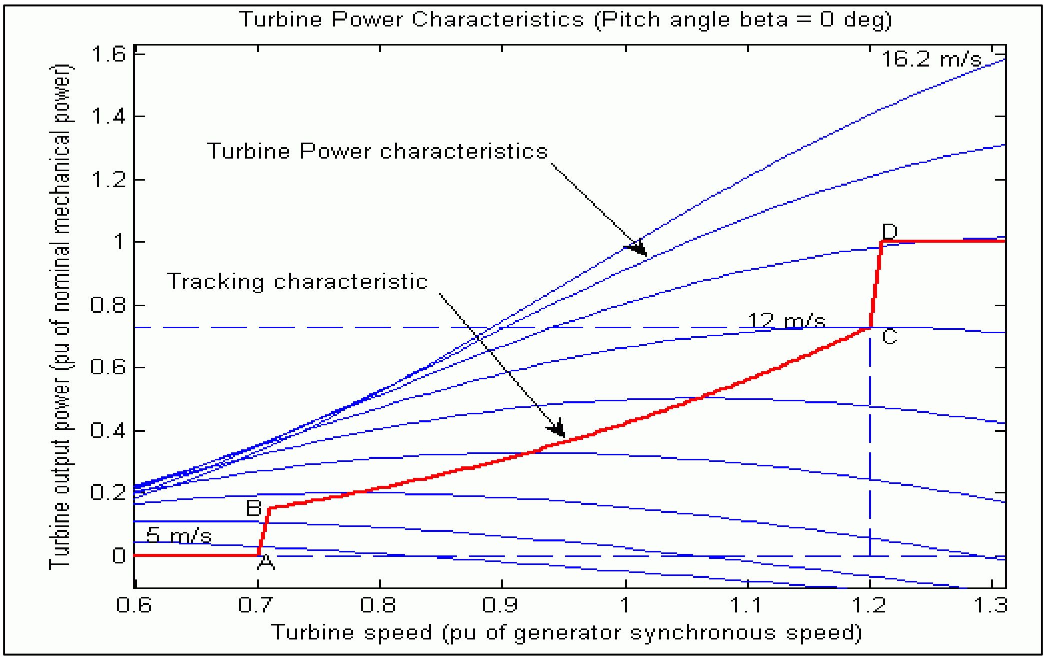


Figure 2.8: Turbine characteristics and tracking characteristic

The generic power control loop is illustrated in the figure called rotor-side converter control system. The actual electrical output power, measured at the grid terminals of the wind turbine, is added to the total power losses (mechanical and electrical) and is compared with the reference power obtained from the tracking characteristic. A PI regulator is used to reduce the power error to zero. The output of this regulator is the reference rotor current $(I_{qr\,ref})$ that must be injected in the rotor by converter (C_{rotor}). This is the current component that produce the electromagnetic torque (T_m). The actual (I_{qr}) component of positive-sequence current is compared to $(I_{qr\,ref})$ and the error is reduced to zero by a current regulator PI. The output of this current controller is the voltage (V_{qr}) generated by (C_{rotor}) [8].

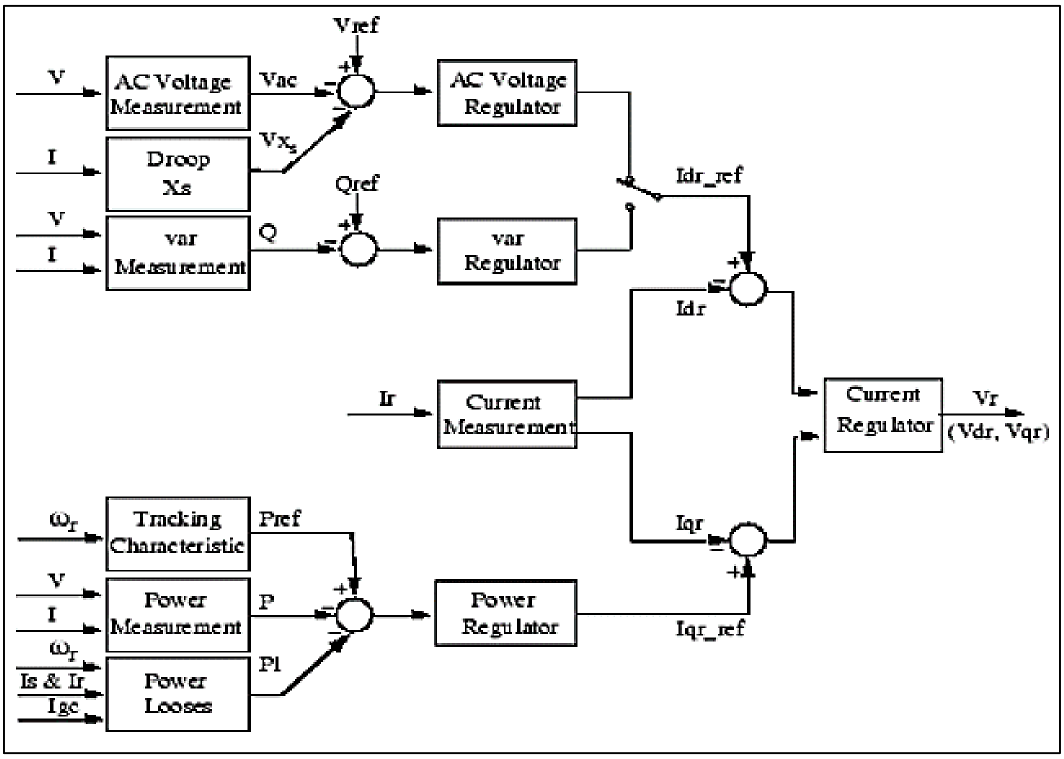


Figure 2.9: Rotor-side converter control system

2.6.2.4 Grid side control system

The converter (C_{grid}) is used to regulate the voltage of the DC bus capacitor. In addition, this model allows using it to generate or absorb reactive power. The control system consists of:

- Measurement systems measuring the d and q components of AC positive-sequence currents to be controlled as well as the DC voltage (V_{dc}).
- An outer regulation loop consisting of a DC voltage regulator. The output of the DC voltage regulator is the reference current ($I_{dgc\,ref}$) for the current regulator.
- An inner current regulation loop consists of a current regulator. The current regulator controls the magnitude and phase of the voltage generated by converters.

The maximum value of this current is limited to a value defined by the converter maximum power at nominal voltage. When ($I_{dgc\,ref}$) and ($I_{q\,ref}$) are such that the magnitude is higher than this maximum value the ($I_{q\,ref}$) component is reduced in order to bring back the magnitude to its maximum value [8]. Figure 2.10 shows the grid side converter control system.

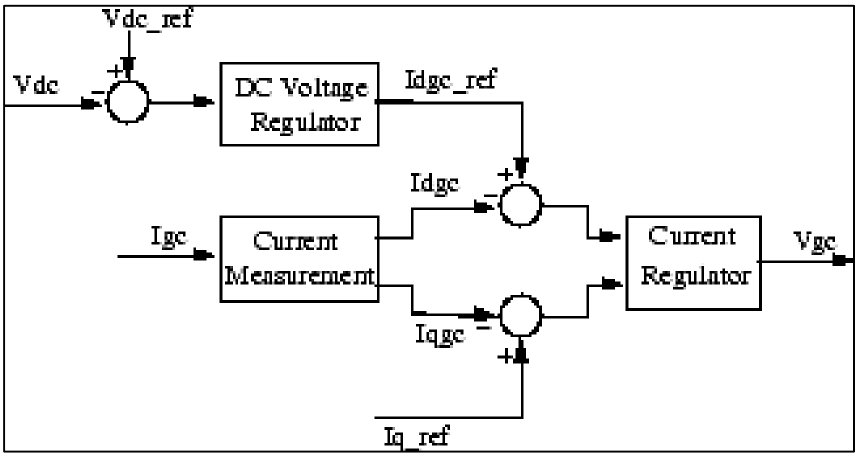


Figure 2.10: Grid-Side Converter Control System

2.6.2.5 Pitch angle control system

The pitch angle is kept constant at zero degree until the speed reaches point D speed of the tracking characteristic. Beyond point D the pitch angle is proportional to the speed deviation from point D speed. The control system is illustrated in the following figure [8].

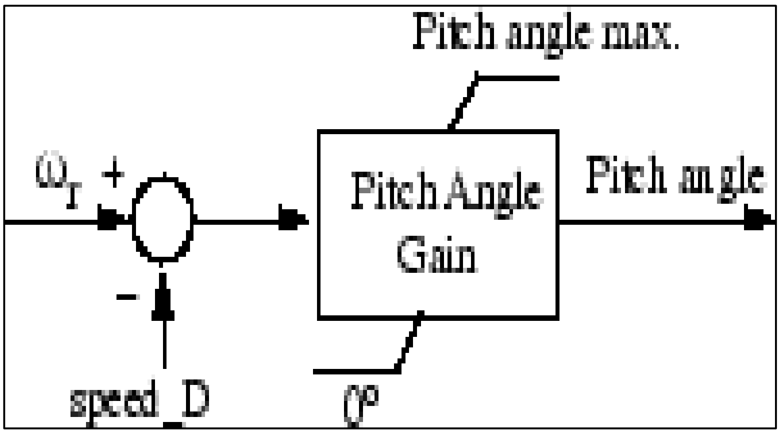


Figure 2.11: Pitch control system

2.6.3 Induction generators transients

The induction generator may experience the following three types of transient currents:

2.6.2.1 Starting Transient

In the grid-connected system, the induction generator is started as the motor in starting the turbine from rest to the super-synchronous speed. Then only it is switched to the generating mode, feeding power to the grid. If full voltage is applied during starting, the motor draws high starting current at zero speed when the slip is one and the rotor resistance is the least. The starting inrush current can be five to seven times the rated current, causing overheating problems, particularly in large machines. Moreover, as seen in Figure 2.12, the torque available to accelerate the rotor may be low, taking a long time to start [5].

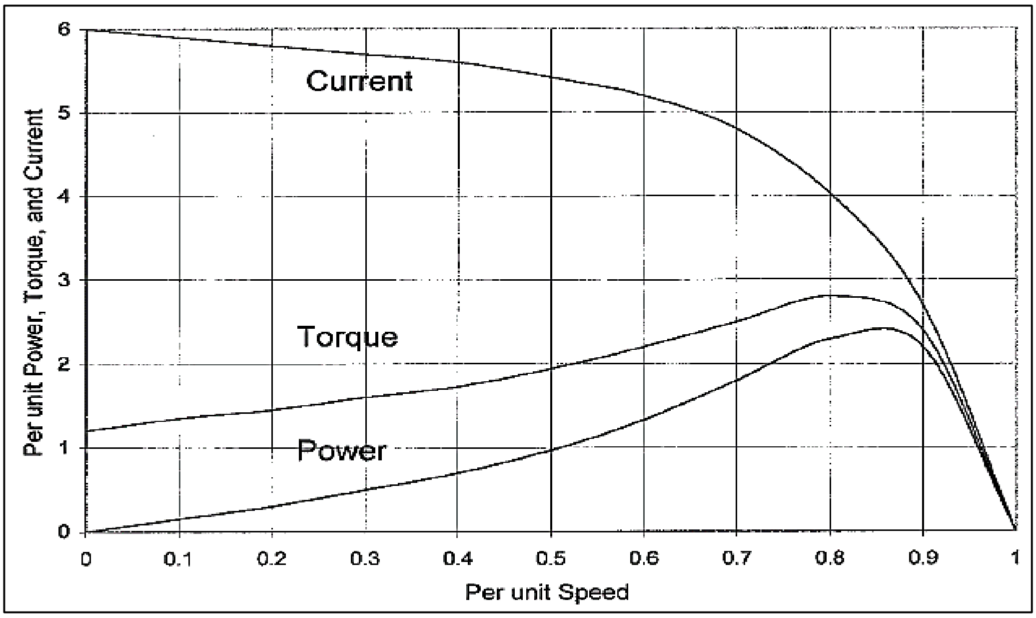


Figure 2.12: Induction machine starting and accelerating characteristic

2.6.2.2 Re-switching transient

A severe transient current can flow in the system if the induction generator operating in a steady state suddenly gets disconnected due to a system fault or any other reason, and then reconnected by an automatic re-switching. The magnitude of the current depends on the instant of the voltage wave when the generator gets reconnected to the grid [5].

2.6.2.3 Short Circuit

When a short circuit fault occurs at or near the generator terminals, the machine significantly contributes to the system fault current, particularly if it is running on light load. The short circuit current is always more severe for a single-phase fault than a three-phase fault. The most important quantity is the first peak current as it determines the rating of the protective circuit breaker needed to protect the generator against such faults. The short circuit current has a slowly decaying DC component, and an AC component. The latter is larger than the direct on-line starting inrush current, and may reach 10-15 times the full load rated current [5].

2.6.4 Permanent-magnet synchronous generators

The DFIG configuration just described uses a relatively small voltage converter, which might be rated at about 30% of the full power of the turbine. And, it is capable of about the same magnitude of speed adjustments. The next step up is to gain complete control of speed with a full-capacity converter powering a synchronous generator (Figure 2.13). The generator can be either a wound-rotor type, in which case slip rings and an exciter circuit are needed, or it can be built with a permanent-magnet rotor that avoids those complications [7].

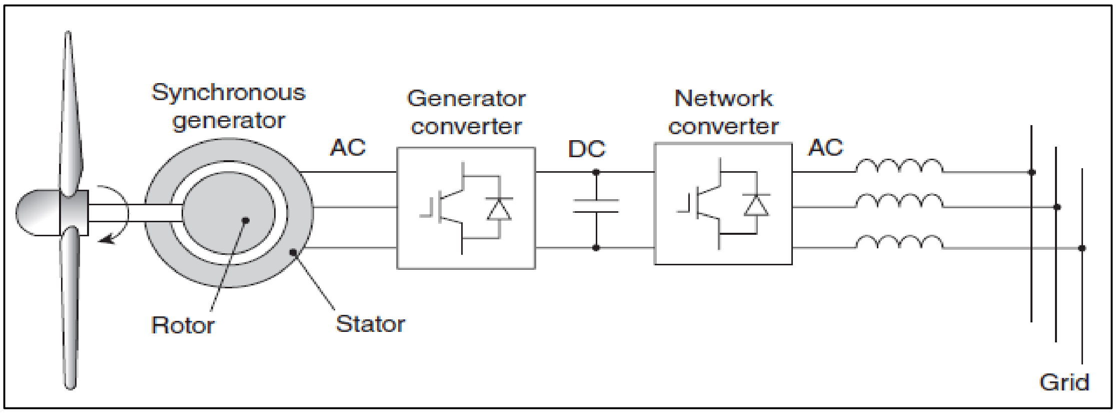


Figure 2.13: A gearless, PMSG with full-capacity Converters

2.6.5 Generator Comparison

The asynchronous machine, especially in the form of cage induction machine, is a robust and low cost generator. In the conventional solution directly coupled to the mains, the required reactive power is drawn from the grid. This constant speed technology may be improved by arranging for a second speed in the pole changing concept, preferably in the ratio 3:2 [1]. When using the wound rotor asynchronous machine, the slip power can be recovered. The modern solution is the so-called doubly-fed asynchronous machine which allows, by means of a converter, to extract or feed power in the rotor circuit. Operation with variable speeds in a ratio of typically 2:1 requires a converter designed for approximately a third of the rated power. Principal mechanical limitations prohibit very high pole numbers, say above 8. Hence asynchronous generators in wind systems are normally driven via a gear box [1].

In the synchronous machine the required magnet flux is provided by permanent magnets or by excitation current fed into a field winding. In the latter case, reactive power and terminal voltage, respectively, are adjustable independent from active load. The “grid-building” property makes the synchronous machine especially suitable as generator for island networks [1]. For variable speed solutions, it is necessary to use a converter designed for the complete rated power to decouple the frequencies. Synchronous machines may be designed with large number of poles, to operate directly driven in wind systems without gear boxes. Pole pitch values can further be reduced by applying special concepts [1].

2.7 Power Electronics

In several systems concepts the generated active power must be adapted in voltage and frequency to the output or consumer side. This is especially the case in variable speed systems. The devices serving for this purpose are power electronic inverters [1]. Power electronic devices contain switching elements in the form of semiconductors. The semiconductor elements are either not controllable (diodes), or controllable by switching on (thyristors) or by switching on and off. During operation currents are commutated from one inverter leg to another. Depending on the source of the e.m.f. required for the commutation process self-commutated and external commutated circuitry is distinguished in inverter technology. External sources are grid, machine or a load as source [1]. Depending on the task the following kinds of power electronics are distinguished

2.7.1 AC/DC inverters (rectifiers)

They transform AC current of a given voltage, frequency and number of phases into DC current. Uncontrolled devices contain diodes, normally in bridge arrangement.

2.7.2 DC/AC inverters

They transform DC current into AC current of a certain voltage, frequency and number of phases. These devices are either external or self-controlled. When the AC side is a grid, these inverters can act also as AC/DC inverters, allowing power exchange in both directions.

2.7.3 AC/AC inverters

They transform AC current of a given voltage, frequency a number of phases into AC current of another voltage, frequency and number of phases.

2.7.4 DC/DC inverters (choppers)

They transform DC current of a given voltage and polarity to DC current of another voltage and polarity. Inverters using an energy storage element and a

Pulse-control scheme is usually called choppers.

2.7.5 Passive compensation equipment (capacitors)

The power quality of generation must be ensured by maintaining the electrical parameters of the network. So, new problems are arising in the management and operation of energy transfer and distribution of renewable energy in the grids. So, the control of electric variables and reactive power control are required in wind farms. Wind farm made up with IG wind turbines can be used as the continuous reactive power source to support system voltage control due to reactive power control capability of IG. Utilizing IG reactive power control capabilities, wind farm can reduce power losses and improve the voltage profiles in the grid system [10].

2.8 Power in the Wind

Consider a “packet” of air with mass *m* moving at a speed *v*. Its kinetic energy, KE, is given by the familiar relationship [6]:

$$KE = \frac{1}{2}mv^2 \tag{2.1}$$

Since power is energy per unit time, the power represented by a mass of air moving at velocity *v* through area *A* will be:

$$Power = \frac{Energy}{Time} \times \frac{1}{2}\left(\frac{Mass}{Time}\right)v^2 \tag{2.2}$$

The mass flow rate $\dot{m}$, through area *A*, is the product of air density *ρ*, speed *v*, and cross-sectional area *A*:

$$\frac{Mass\ passing\ through\ A}{Time} = \dot{m} = \rho A v \tag{2.3}$$

Combining Equation (2.2) with Equation (2.3) gives us:

$$P_w = \frac{1}{2}\rho A v^3 \tag{2.4}$$

The power in the wind increase as the cube of wind speed, and also it is proportional to the swept area of the turbine rotor. For a conventional horizontal axis turbine, the area A is just

$$A = \left(\frac{\pi}{4}\right)D^2 \tag{2.5}$$

So, wind power is proportional to the square of the blade diameter.

2.9 Maximum Power

When wind passes through a wind turbine, the wind approaching from the left is slowed down as a portion of its kinetic energy and is extracted by the turbine as showed in the figure below. The wind leaving the turbine has a lower velocity and its pressure is reduced, causing the air to expand downwind of the machine. An envelope drawn around the air mass that passes through the turbine forms what is called a stream tube [6].

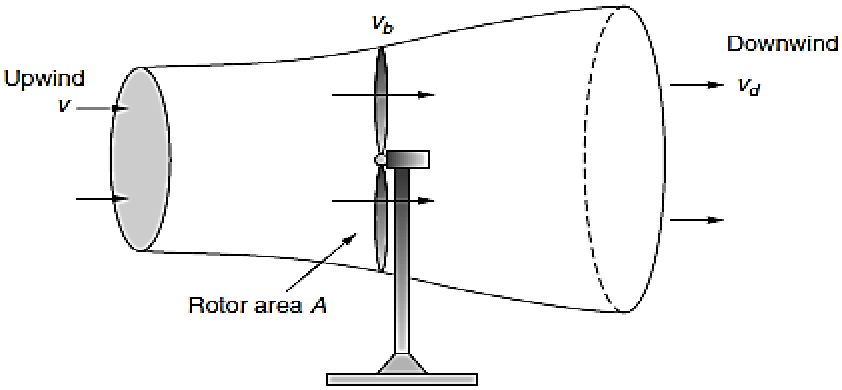


Figure 2.14: Approaching wind slows and expands as aportion of its kinetic energy is extracted by the wind turbine, forming the steam tube

In Figure 2.14 The upwind velocity of the undisturbed wind is v, the velocity of the wind through the plane of the rotor blades is v_b, and the downwind velocity is v_d. The mass flow rate of air within the stream tube is everywhere the same, call it $\dot{m}$. The power extracted by the blades P_b is equal to the difference in kinetic energy between the upwind and downwind air flows [6]:

$$P_b = \frac{1}{2}\dot{m}(v^2 - v_d^2) \qquad (2.6)$$

The easiest spot to determine mass flow rate $\dot{m}$, is at the plane of the rotor where we know the cross-sectional area is just the swept area of the rotor A. The mass flow rate is thus

$$\dot{m} = \rho A v_b \qquad (2.7)$$

If we now make the assumption that the velocity of the wind through the plane of the rotor is just the average of the upwind and downwind speeds, then we can write

$$P_b = \frac{1}{2}\rho A\left(\frac{v+v_d}{2}\right)(v^2 - v_d^2) \tag{2.8}$$

To help keep the algebra simple. Let us define the ratio of downstream to upstream wind speed to be λ:

$$\lambda = \frac{v_d}{v} \tag{2.9}$$

Substituting equation (2.9) in equation (2.8) gives

$$P_b = \frac{1}{2}\rho A\left(\frac{v+\lambda v}{2}\right)(v^2 - \lambda^2 v^2)$$

$$P_b = \frac{1}{2}\rho A v^3 \times \left[\frac{1}{2}(1+\lambda)(1-\lambda^2)\right]$$

$$P_b = Power\ in\ the\ wind \times Fraction\ extracted \tag{2.10}$$

Equation (2.10) shows that the power extracted from the wind is equal to the upstream power in the wind multiplied by the quantity in brackets. The quantity in the brackets is therefore the fraction of the wind power that is extracted by the blades, the efficiency of the rotor usually designated as:

$$Rotor\ efficiency = C_p = \frac{1}{2}(1+\lambda)(1-\lambda^2) \tag{2.11}$$

Then the power delivered by the rotor becomes

$$P_b = \frac{1}{2}\rho A v^3 C_p \tag{2.12}$$

To find maximum possible rotor efficiency, we simply take the derivative of Equation (2.11) with respect to λ and set it equal to zero [6]:

$$\frac{dC_p}{d\lambda} = \frac{1}{2}[(1+\lambda)(-2\lambda) + (1-\lambda^2)]$$

$$\frac{dC_p}{d\lambda} = \frac{1}{2}[(1+\lambda)(-2\lambda) + (1+\lambda)(1-\lambda)]$$

$$\frac{dC_p}{d\lambda} = \frac{1}{2}(1+\lambda)(1-3\lambda) = 0$$

Which has the solution

$$\lambda = \frac{v_d}{v} = \frac{1}{3} \tag{2.13}$$

In other words, the blade efficiency will be a maximum if it slows the wind to one-third of its undisturbed upstream velocity. If we now substitute

$\lambda = 1/3$ into the equation for rotor efficiency (Equation (2.11)), we find the theoretical maximum blade efficiency is

$$Max\ C_p = \frac{1}{2}\left(1+\frac{1}{3}\right)\left(1-\frac{1}{3^2}\right) = \frac{16}{27} = 0.5926 \approx 59.3\% \qquad (2.14)$$

This conclusion that the maximum theoretical efficiency of a rotor is 59.3% is called the Betz efficiency or sometimes Betz law. For a given wind speed, rotor efficiency is a function of the rate at which the rotor turns. If the rotor turns too slowly, the efficiency drops off since the blades are letting too much wind pass by unaffected. If the rotor turns too fast, efficiency is reduced as the turbulence caused by one blade increasingly affects the blade that follows. The usual way to illustrate rotor efficiency is to present it as a function of its Tip Speed Ratio (TSR) [6]. The TSR is the speed at which the outer tip of the blade is moving divided by the wind speed

$$TSR = \frac{Rotor\ tip\ speed}{Upwind\ wind\ speed} = \frac{rpm \times \pi D}{60v} \qquad (2.15)$$

A plot of idealized rotor efficiency for various rotor types versus TSR is given in Figure 2.15.

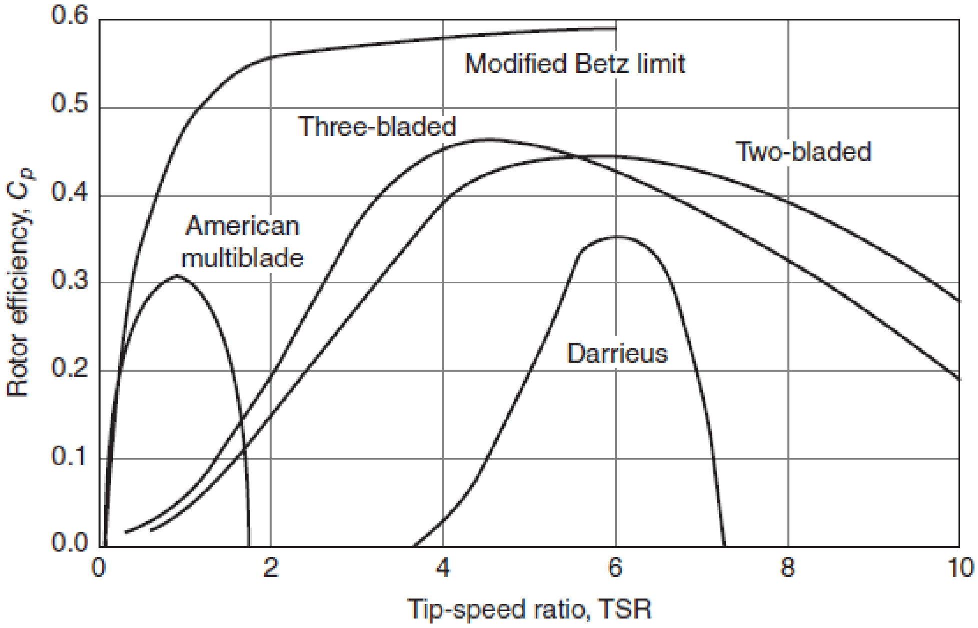


Figure 2.15: Rotors with fewer blades reach their optimum efficiency at higher rotational speeds

2.10 Wind Turbine Power Curve

This graph shows the relationship between wind speed and electrical power expected from the complete system, including blades, gearbox, and generator. A somewhat idealized power curve is shown in Figure 2.16 [6].

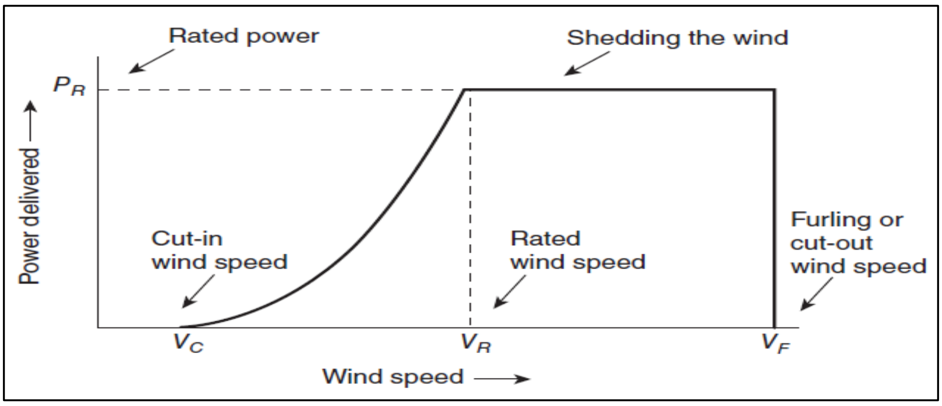


Figure 2.16: Idealized power curve

Cut-in wind speed: Low speed winds may not have enough power to overcome friction in the drive train of the turbine, and even if this does happen and the generator is rotating, the electrical power generated may not be enough to offset the power required by the generator field windings. The cut-in wind speed VC is the minimum needed to generate net power. Since no power is generated at wind speeds below VC that portion of the wind's energy is wasted [6].

Rated wind speed: As velocity increases above the cut-in wind speed, the power delivered by the generator in the idealized curve rises as the cube of wind speed. When winds reach the rated wind speed VR, the generator deliverers as much power as it is designed for. Above VR, there must be some way to shed some of the wind's power or else the generator may be damaged [6]. Cut-out or furling wind speed: At some point, the wind is so strong that there is real danger to the wind turbine. At this wind speed VF, called the cut-out wind speed the machine must be shut down. Above VF mechanical brakes lock the rotor shaft in place, so output power is zero [6].

CHAPTER THREE

MATHIMATICAL MODEL OF THE SYSTEM

3.1 Introduction

The wind power systems have made a successful transition from small stand-alone sites to large grid-connected systems. The utility interconnection brings a new dimension in the renewable power economy by pooling the temporal excess or the shortfall in the renewable power with the connecting grid. This improves the overall economy and the load availability of the renewable plant; the two important factors of any power system [5].

The grid supplies power to the site loads when needed, or absorbs the excess power from the site when available. One KWh meter is used to record the power delivered to the grid, and another kWh meter is used to record the power drawn from the grid. The two meters are generally priced differently. On the wind side, most grid-connected systems are large utility-scale power plants. A typical equipment layout in such plants is shown in Figure 3.1. The site computer, sometimes using multiplexer and remote radio links, controls the wind turbines in response to the wind conditions and the load demand [5].

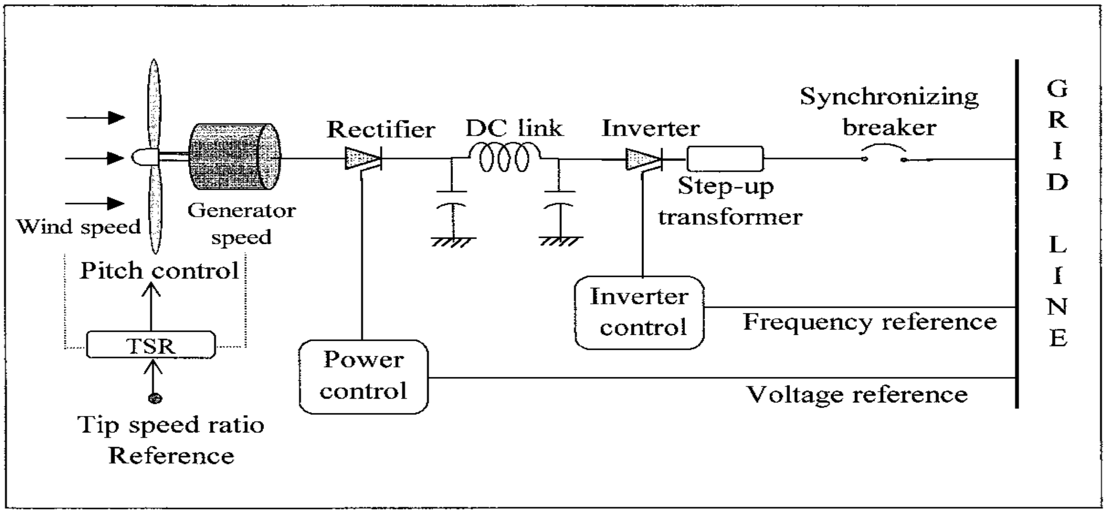
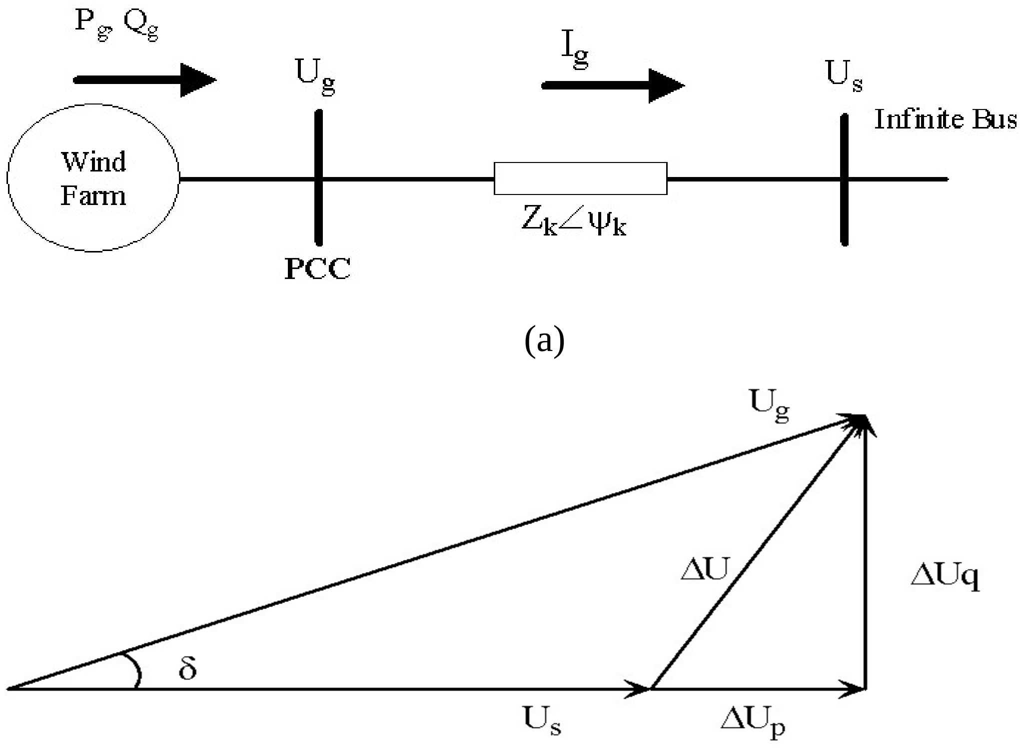


Figure 3.1: Electrical schematic of the grid-connected variable speed wind power system

Large wind systems being installed now tend to have the variable-speed design. The variable-frequency generator output is first rectified into DC, and then inverted into a fixed-frequency AC. Before the inversion, the rectifier harmonics are filtered out from the DC by the inductor and capacitors. The frequency reference for the inverter firing and the voltage reference for the rectifier phase-angle control are taken from the grid lines. The optimum reference value of the tip-speed ratio is stored and continuously compared with the value computed from the measured speeds of the wind and the rotor. The turbine speed is accordingly changed to assure maximum power production at all times [5].

3.2 Basic theory of connection wind farm into grid

A simple way to understand the connection of wind farms into grid can be explained from the one-line diagram as shown in Figure 3.2.



(a)

(b)

Figure 3.2: (a) illustrates an example of one-line diagram of wind farm connection to a grid and (b) shows phasor diagram

Wind farm is connected to the network with equivalent short circuit impedance (Z_k). The network voltage at the assumed infinite busbar and the farm voltages are (U_s) and (U_g), respectively. The output power and reactive power of the wind farm are (P_g) and (Q_g), which corresponds to a current (I_g) [11].

$$I_g = \left(\frac{S_g^*}{U_g^*}\right) = \frac{P_g - JQ_g}{U_g} \tag{3.1}$$

The voltage difference, (ΔU), between the infinite system and the PCC is given by

$$U_g - U_s = \Delta U = Z_k . I_g = (R_k + jX_k)\left(\frac{P_g - JQ_g}{U_g}\right) \tag{3.2}$$

$$\Delta U = \left(\frac{P_g R_K + X_k Q_g}{U_g}\right) + j\left(\frac{P_g X_k - R_k Q_g}{U_g}\right) \tag{3.3}$$

The short circuit impedance, the real and reactive power output of the wind farm determines the voltage difference. The variations of the generated power will result in the variations of the voltage at PCC. When the impedance (Z_k) is small, then the grid can be named as strong and when (Z_k) is large, then the grid can be named as weak. Since strong or weak are relative concepts, for a given electrical wind power capacity (P), the ratio, stated as the measure of the strength, where (S_{sc}) is short circuit power [11]. The grid may be considered as strong with respect to the wind farm installation if (R_{sc}) is above 20. It is obvious from (3.4) that for large wind farm-grid connections, the PCC voltage level has to be as high as possible to limit voltage variations [11].

$$R_{sc} = \frac{S_{sc}}{P} = \frac{U_s^2}{Z_k . P} \tag{3.4}$$

3.3 Power Variation and Grid Reaction

Grid reactions created by wind energy systems appear in different forms. The wind turbine accounts for:

3.3.1 Power variations due to wind gusts

Power variation is defined as the difference between the largest and the lowest power values during 8 periods within one minute. Single machine systems may encounter values between 0.6 and 0.9 rated power in wind parks evening out occurs between systems, so that resulting variations are of magnitudes 0.25 up to 0.4 of rated power. Operation with as little variations as possible is intended by controlling the system on the turbine and/or on the generator side [1].

3.3.2 Power variations due to tower shadow effects

These periodic power variations can only be leveled out by a fast acting control. Torque variations lead to dynamic torsional stress in the drive train which are especially relevant in systems for constant speed. Also unwanted are short-time power variations on the grid side [1].

3.3.3 Switching operations

Switching-on and off the generator may cause voltage fluctuations at the feeding point. To limit inrush-currents in systems with directly coupled asynchronous machines phase-controlled thyristor-circuits are used, as mentioned. On the other hand, the generator power should be controlled to zero before disconnecting (except emergency breaks) [1].

3.3.4 Reactive power

The active factor cos ϕ reflecting the ratio of (fundamental) reactive and active power can be improved by compensation measures, such as fixed capacitor banks or controllable compensation devices [1].

3.3.5 Flicker

Voltage fluctuations of low frequency caused by power variations are called flicker, they give rise to lightness fluctuations of incandescent lamps and also of fluorescent lamps. In a band of around 1000 variations per minute they are experienced extremely inconvenient for the human eye [1].

3.3.6 Harmonics due to inverters

Grid-controlled inverters create current harmonics which give rise to voltage harmonics. The lowest order is determined by the pulse number of the inverter circuit. In six-pulse circuits, as in the three-phase bridge connection, these are the 5 and the 7 harmonics. In self-controlled PWM inverters the pulse frequency and its side-bands are prominent in the harmonic spectrum. Note that transistor inverters may be operated with pulse frequencies up to and exceeding 20 kHz, so that the audible components are above human hearing. Voltage fluctuations in the connection point are influencing the grid voltage quality [1].

Mathematically, harmonics describe a voltage or current (or both) waveform distortion. The term ‘harmonic’ denotes a component of a waveform that occurs at an integer multiple of the fundamental frequency. THD is defined as the summation of all harmonics orders of current or voltage compared to the fundamental frequency component [12]. A perfect sinusoidal waveform is 100%, and the fundamental frequency of the system is 50 or 60Hz. Harmonic distortion is caused by the introduction of waveforms at frequencies in multiplies of the fundamental. For example, the 5th harmonic is five times the fundamental frequency (250 or 300Hz). Total harmonic distortion is a measurement of the sum value of the waveform that is distorted and can be expressed as follows [13]:

$$THD = \frac{\sqrt{V_2^2+V_3^2+V_4^2+\cdots+V_n^2}}{V_1} \times 100 \tag{3.5}$$

3.3.7 Inrush current

The small unavoidable difference between the site and the grid voltages will result in an inrush current to flow between the site and the grid. The inrush current eventually decays to zero at an exponential rate that depends on the internal resistance and inductance. The initial magnitude of this current in the instant the circuit breaker is closed depends on the degree of mismatch between the two voltages. It is not all bad, as it produces the synchronizing power which acts to bring the two systems in synchronous lock. However, it produces a mechanical torque step, setting up the electromechanical oscillations before the two machines come into synchronism and get locked with each other [5].

The magnitude of the inrush current is calculated as follows: Let (ΔU) be the difference between the site voltage and the grid voltage at the closing instant due to any reason. Since this voltage is suddenly applied on the system, the resulting inrush current is determined by the sub-transient reactance of the machine (X_d'') that is as follows:

$$I_{inrrush} = \frac{\Delta U}{X_d''} \tag{3.6}$$

The inrush current is primarily reactive, as is solely determined by(X_d''). Its magnitude is kept within the allowable limit; else the thermal or mechanical damage may result [5]. The synchronizing power produced by the inrush current brings the wind system and the grid in synchronism after the oscillations decay out. Once synchronized, the generator has a natural tendency to remain in synchronism with the grid, although it can fall out of synchronization if excessive load is extracted, large load steps are applied, or during system faults. Small perturbation swings in the load angle decay out over a time, restoring the synchronous condition. The magnitude of the restoring power, also known as the synchronizing power, is highest if the machine is running at no load, and is zero if it is running at its steady state stability limit [5].

3.3.8 Load transient

During steady state operation, if the renewable power system output is fully or partially lost, the grid will pick up the area load. The effect of this will be felt in two ways:

- The grid generators slow down slightly to increase their power angle needed to make up for the lost power. This will result in a momentary drop in frequency.

- Small voltage drop results throughout the system, as the grid conductors carry more load.

The same effects are felt if a large load is suddenly switched in at the green power site, starting the wind turbine as the induction motor draws a large current. This will result in the above effect. Such load transients are minimized by soft-starting large generators. In wind farms consisting of many generators, individual generators are started in sequence, one after another [5].

3.4 Operating Limit

The link line connecting the renewable power site with the utility grid introduces the operating limit in two ways, the voltage regulation and the stability limit. In most cases, the line can be considered as an electrically short transmission line. The ground capacitance and the ground leakage resistance are generally negligible and are ignored. The equivalent circuit of such a line, therefore, reduces to a series resistance R and reactance L. The line carries power from the renewable site to the utility grid, or from the grid to the renewable site to meet local peak demand. There are two major effects of the transmission line impedance, one on the voltage regulation and the other on the maximum power transfer capability of the link line [5].

3.4.1 Voltage regulation

The voltage regulation is defined as the rise in the receiving end voltage, expressed in percent of the full load voltage, when full load at a specified power factor is removed, holding the sending end voltage constant. That is as follows:

$$Percent\ voltage\ regulation = \frac{V_{nl}-V_{fl}}{V_{fl}} \times 100 \qquad (3.7)$$

The voltage regulation is a strong function of the load power factor. For the same load current at different power factors, the voltage drop in the line is the same, but is added to the sending end voltage at different phase angles to derive the receiving end voltage. For this reason, the voltage regulation is greater for lagging power factor, and the least or even negative for leading power factor [5].

3.4.2 Stability limit

The direction of the power flow depends on the sending and receiving end voltages, and the electrical phase angle between the two. However, the maximum power the line can transfer while maintaining stable operation has a limit. We derive below the stability limit assuming that the power flows from the renewable power site to the grid, although the same limit applies in the reverse direction as well. The series resistance in most lines is negligible, hence, is ignored here [5]. The power transferred to the grid by the transmission line is as follows:

$$P = V_r I cos\emptyset \tag{3.8}$$

The current as follows:

$$I = \frac{V_S\, sin\delta}{X} \tag{3.9}$$

The power as follows:

$$P = \frac{V_S . V_r}{X} sin\delta \tag{3.10}$$

Thus, the magnitude of the real power transferred by the line depends on the power angle (δ). If (δ>0), the power flows from the site to the grid. On the other hand, if (δ<0), the site draws power from the grid. The reactive power depends on (Vs, Vr). If $(V_s > V_r)$, the reactive power flows from the site to the grid [5].

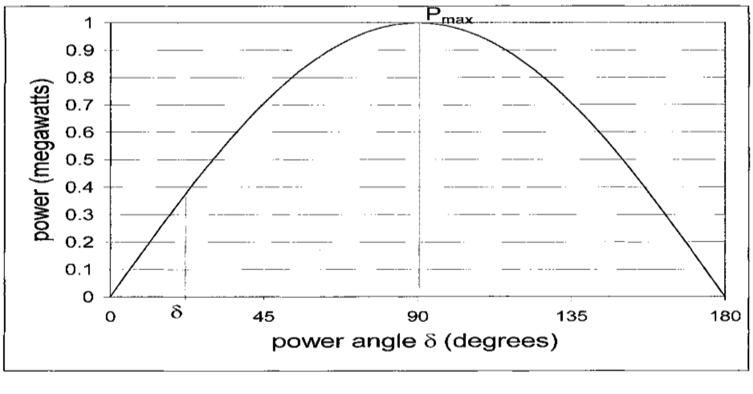


Figure 3.3: Power versus power angle showing static and dynamic stability limits of the link line

Obviously, the power flow in either direction is maximum when δ at 90°. Beyond (P_{max}), the link line becomes unstable and will fall out of synchronous operation. That is, it will lose its ability to synchronously transfer power from the renewable power plant to the utility grid. This is referred to as the steady state stability limit. In practice, the line loading must be kept well below this limit to allow for transients such as sudden load steps and system faults. The maximum power the line can transfer without losing the stability even during system transients is referred to as the dynamic stability limit. In typical systems, the power angle must be kept below 10° to 20° to assure dynamic stability. Since the generator and the link line are in series, the internal impedance of the generator is added in the line impedance for determining the maximum power transfer capability of the link line, the dynamic stability and the steady state performance [5].

3.5 Standards and Requirements of Connection

The main standards and requirements of connection are:

3.5.1 Safety relevant set values

Systems with asynchronous or synchronous generators must be equipped with protective devices, with set values to allow adjustment of lower and upper limits of voltage and frequency. Recommended tripping values are given as shown in Table 3.1 (50Hz rated frequency assumed) [5]:

Table 3.1: Safety relevant set values

Object	Limit	Tripping Value
Voltage Decrease	0.7 Un	0.8Un
Voltage Increase	1.15 Un	1.06Un
Frequency Decrease	48Hz	49.5Hz
Frequency Increase	52Hz	50.5Hz

3.5.2 Lightning protection

It is necessary to provide wind turbines with lightning protection equipment. To this end non-metal blade tips are carrying interception apparatus, from where lightning currents are conducted to the hub by means of appropriate connectors. From the hub the lightning current is conducted to the metal tower construction and from there to the earthing system [1] as shown in Figure 3.4 the Lightning protection of the wind system.

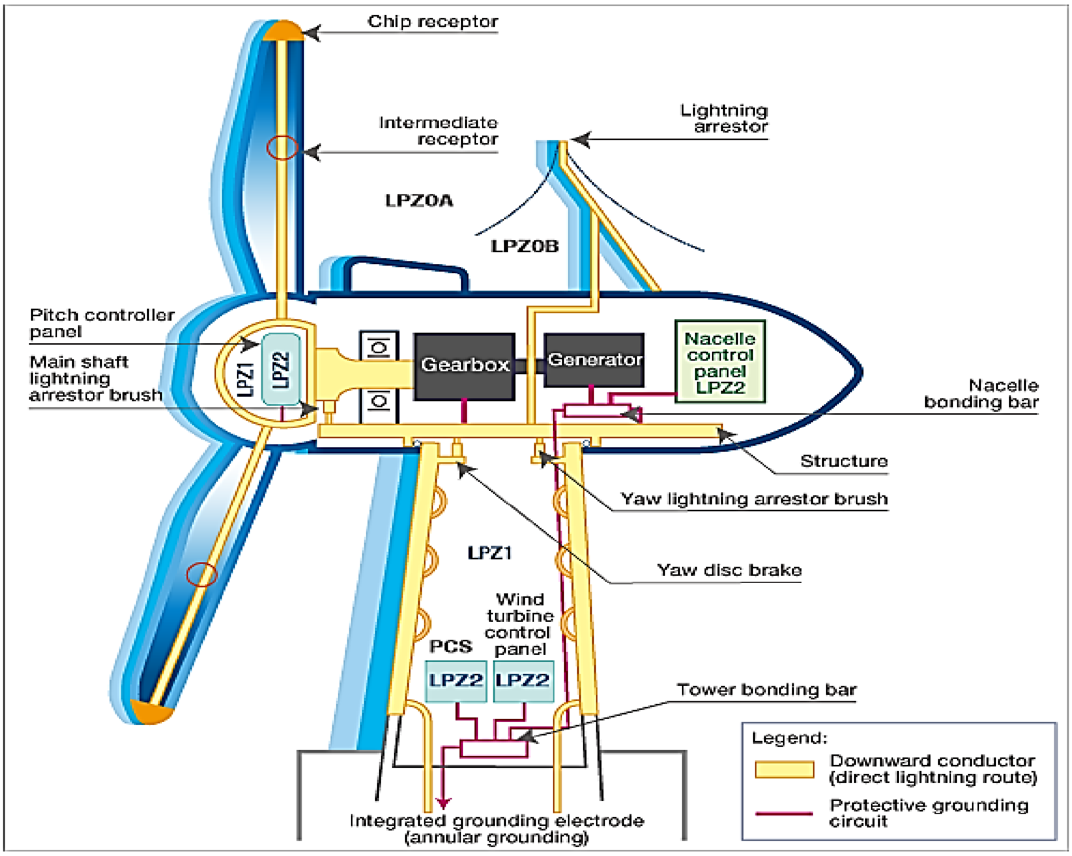


Figure 3.4: The Lightning protection of the wind system

3.5.3 Safety

Safety is a concern when renewable power is connected to the utility grid lines. The interconnection may endanger the utility repair crew working on the lines by continuing to feed power into the grid even when the grid itself went down. This issue has been addressed by including an internal circuit that takes the inverter off line immediately if the system detects grid outage [5]. Since this circuit is critical for human safety, it has a built-in redundancy. The site-grid interface breaker can get suddenly disconnected, accidentally or to meet an emergency situation. The high wind speed cut out is a usual condition when the power is cut off to protect the generator from overloading.

In systems where large capacitors are connected at the wind site for power factor improvement, the site generator would still be in the self-excitation mode, drawing excitation power from the capacitors and generating terminal voltage. In absence of such capacitors, one would assume that the voltage at the generator terminals would come down to zero. The line capacitance, however, can keep the generator self-excited. The protection circuit is designed to avoid both of these situations, which are potential safety hazards to unsuspecting site crew [5]. When the grid is disconnected for any reason, the generator will experience a loss of frequency regulation, as the frequency synchronizing signal derived from the grid lines is now lost. When a change in frequency is detected beyond a certain limit, the automatic control can shut down the system, cutting off all possible sources of excitation [5].

3.5.4 Reactive power compensation

The active factor cos ϕ, in literature often called the power factor, should be adjusted according to agreement. Usual recommendations require values between 0.9 capacitive and 0.8 inductive. Use of capacitor banks is the conventional way to compensate inductive load [14]. In grids where audio-frequency transmission devices are installed, the wind energy system frequency response curve must be adapted by an appropriate inductive choke. To obtain a specified cosϕ value at the Point of Connection (POC), it may be necessary to provide a significantly higher reactive power in the wind park like SVC or STATCOM [15].

3.6 System Modelling and Design

The system modelling and design consists of:

3.6.1 Wind turbine design and characteristics

The wind turbine model is based on the steady-state power characteristics of the turbine. The stiffness of the drive train is infinite and the friction factor and the inertia of the turbine must be combined with those of the generator coupled to the turbine. The output power of the turbine is given by the following equation [16].

$$P_m = \frac{1}{2}\rho A v_{wind}^3 \tag{3.11}$$

A generic equation is used to model $C_p(\lambda, \beta)$. This equation, based on the modeling turbine characteristics is [17]:

$$C_p = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right)e^{\frac{-c_5}{\lambda_i}} + c_6\lambda \tag{3.12}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1} \tag{3.13}$$

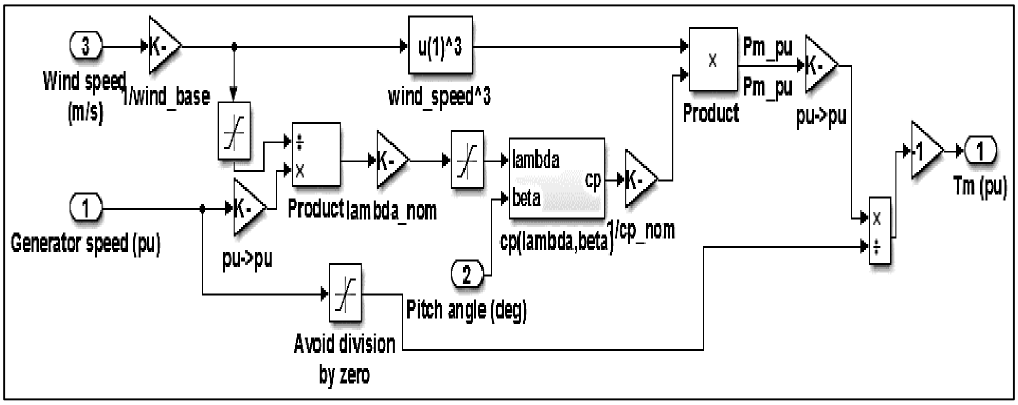


Figure 3.5: Wind turbine Simulink model

3.6.2 Drive train modeling

The shaft dynamic equations are [19]:

$$T_{IN} = J_T\frac{d\omega_T}{dt} + k\Delta\vartheta + B\Delta\omega \tag{3.14}$$

$$k\Delta\vartheta + B\Delta\omega = J_G\frac{d\omega_G}{dt} + T_e \tag{3.15}$$

$$\Delta\omega = \omega_r - \omega_G \tag{3.16}$$

$$\Delta\vartheta = \vartheta_r - \vartheta_G \tag{3.17}$$

Where J_T $(kg.m^2)$is the turbine moment of inertia, J_G $(Kg.m^2)$ is the generator moment of inertia, k $(Kg.m^2.s^{-2})$ is the stiffness of the shaft. B $(Kg.m^2.s^{-1})$ is the absorption of the shaft, T_{IN} $(N.m)$ is the input torque,T_e $(N.m)$ is the generator electromagnetic torque, ω_T, ω_G (rad/sec) are the angular speed of the turbine and of the generator, and ϑ_T, ϑ_G (rad) are the angle of the turbine and generator [19].

3.6.3 Asynchronous generator

The stator and rotor voltages are given below [19]:

$$v_{ds} = R_s i_{ds} + \frac{d\Psi_{ds}}{dt} + \omega_s \Psi_{qs} \tag{3.18}$$

$$v_{qs} = R_s i_{qs} + \frac{d\Psi_{qs}}{dt} + \omega_s \Psi_{ds} \tag{3.19}$$

$$v_{dr} = R_r i_{dr} + \frac{d\Psi_{dr}}{dt} - s\omega_s \Psi_{qr} \tag{3.20}$$

$$v_{qr} = R_r i_{qr} + \frac{d\Psi_{qr}}{dt} + s\omega_s \Psi_{dr} \tag{3.21}$$

Flux linkage is given by:

$$\Psi_{ds} = L_m i_{dr} - L_{sl} i_{ds} \tag{3.22}$$

$$\Psi_{qs} = L_m i_{qr} - L_{sl} i_{qs} \tag{3.23}$$

$$\Psi_{dr} = -L_m i_{ds} - L_{rl} i_{dr} \tag{3.24}$$

$$\Psi_{qr} = -L_m i_{qs} - L_{sl} i_{qr} \tag{3.25}$$

Electromagnetic torque is:

$$T_{el} = \Psi_{qr} i_{dr} - \Psi_{dr} i_{qr} \tag{3.26}$$

Where $v_s, v_r, i_s, i_r, \Psi_s, \Psi_r$ are the stator and rotor voltages, currents, and flux respectively, $d\ and\ q$represent the direct and quadrature axis components. L_m is the mutual inductance, $L_{sl}, and\ L_{rl}$ are the stator and rotor leakage inductances [19].

3.6.4 Synchronous generator

The permanent-magnet synchronous generator can be expressed by the following equations [19]:

$$v_{ds} = -R_s i_{ds} - L_s \frac{di_{ds}}{dt} + L_s \omega_r i_{qs} \tag{3.27}$$

$$v_{qs} = -R_s i_{qs} - L_s \frac{di_{qs}}{dt} - L_s \omega_r i_{ds} + \omega_r \Psi \tag{3.28}$$

The electromagnetic torque is given by:

$$T_e = \frac{3}{2} p \Psi I_{qs} \tag{3.29}$$

3.6.5 Wind farm construction and components

A wind farm consists of (30*1.5MW) wind turbines, divided into three combinations (A, B, and C) each one contains ten wind turbines with output rated power of (15MW), and the whole system is connected to a (110kV) transmission system which exports power to a (110kV) grid through a (10km) -(25kV) feeder. Wind turbines use SFIG, DFIG, and PMSG. Figure 3.6 shows the wind farm construction and all its components in details.

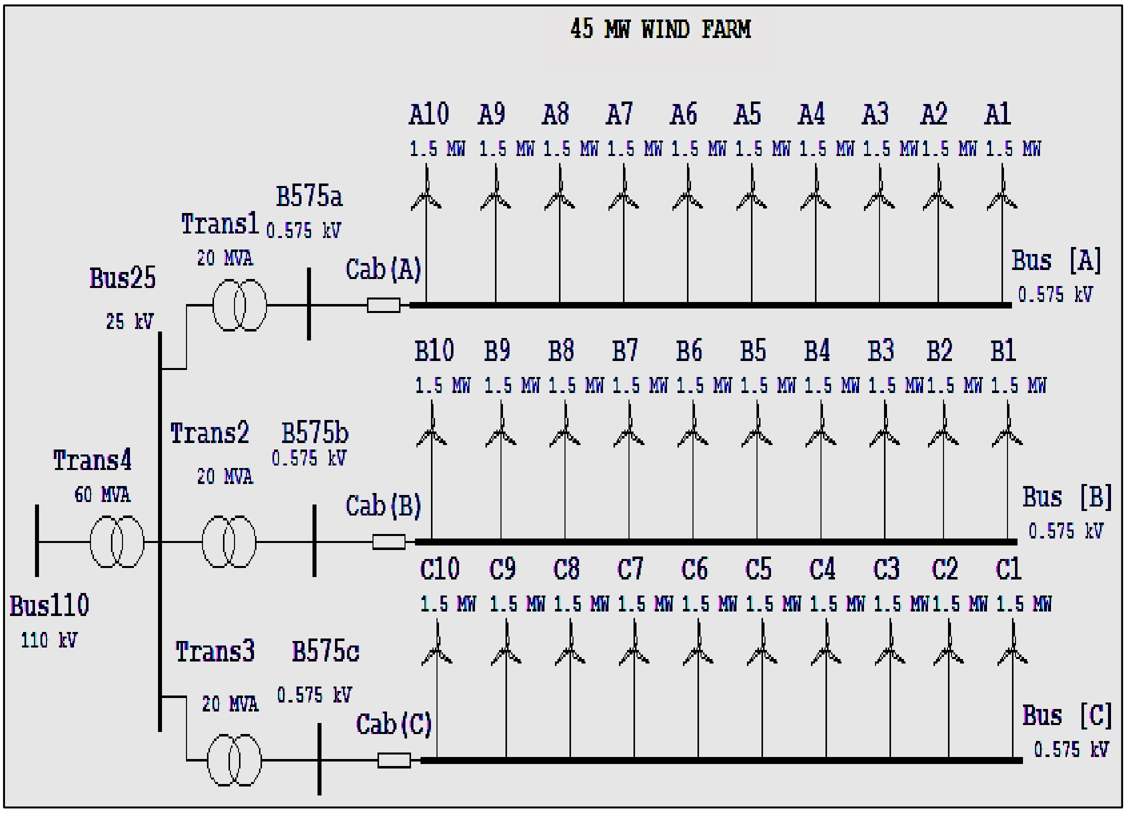


Figure 3.6: Components of the farm

3.6.6 Sudan and khartoum 110KV transmission system

The case study of the Sudan national grid taken here shows that it consists of a number of (57) buses having three different voltage levels

(110KV, 220KV, and 500KV), these buses almost covering the whole country in a good high voltage transmission system. In addition to the buses and the voltage levels there is a number of (106) transmission lines, and (42) PQ buses (load buses). For the generation power plants, there are eight stations: Marawi, Senar, Rosairis, Atbara, Algerba, all which are hydroelectric dams, and three thermal power stations: Bahri, Gari, and Kosti. In addition to that and in a case of shortage, there is a power that comes from the exchange between Ethiopia network. Figure 3.7 shows the single line diagram of the network.

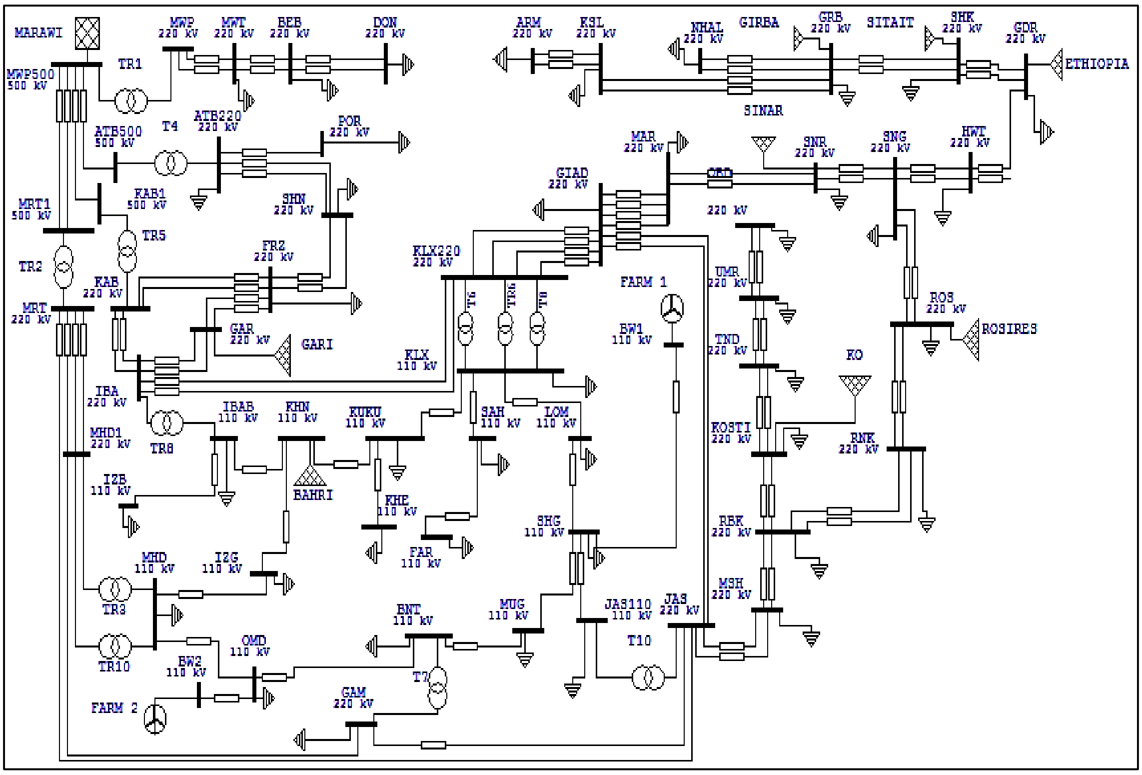


Figure 3.7: Sudan National Grid

The two wind farms are inserted into the grid in Khartoum state in some places which have an available amount of wind energy; one farm between jabel awlia and alshegara, and the other one in Omdurman. Figure 3.8 shows the Khartoum 110KV transmission system and the wind farms locations.

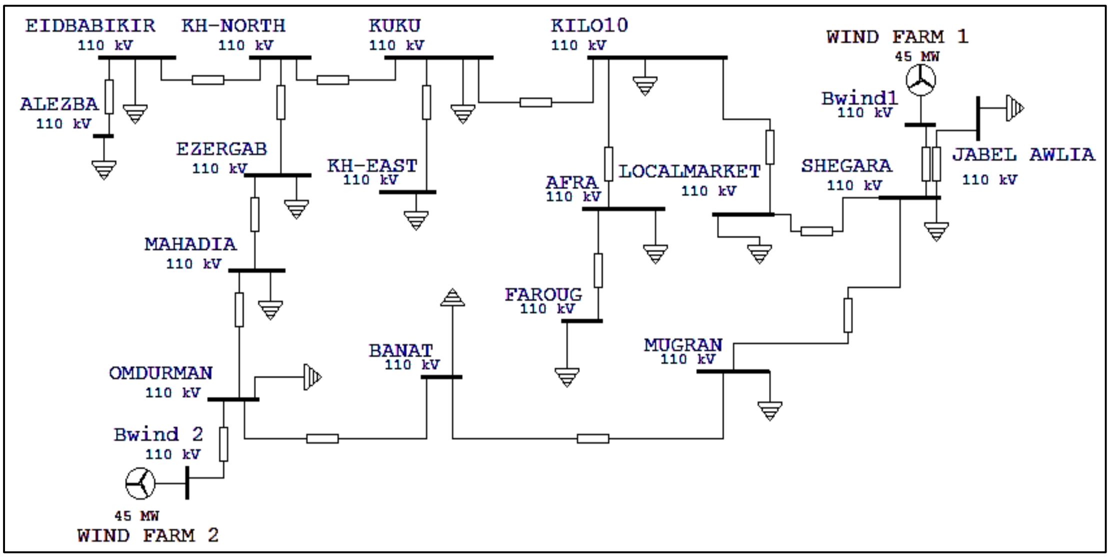


Figure 3.8: Khartoum 110 KV transmission system

CHAPTER FOUR

SIMULATION AND RESULTS

4.1 Introduction

In this chapter, the design of the two wind farms with all its components has been made. Data of the wind energy was collected from the general meteorological authority, and also the required data of the Sudan national grid from the national dispatch center. The characteristics, features, and the results of the design and the simulation are represented in the form of tables and graphs. Typical wind speeds in Sudan vary from (3m/s) to (8m/s). The highest average wind speed of (6m/s) occurs around August. The lowest average wind speed of (3m/s) occurs around October. In this research the wind speed setting value has been selected to vary from (3m/s) to (7.5m/s) which is shown in the Figure 4.1.

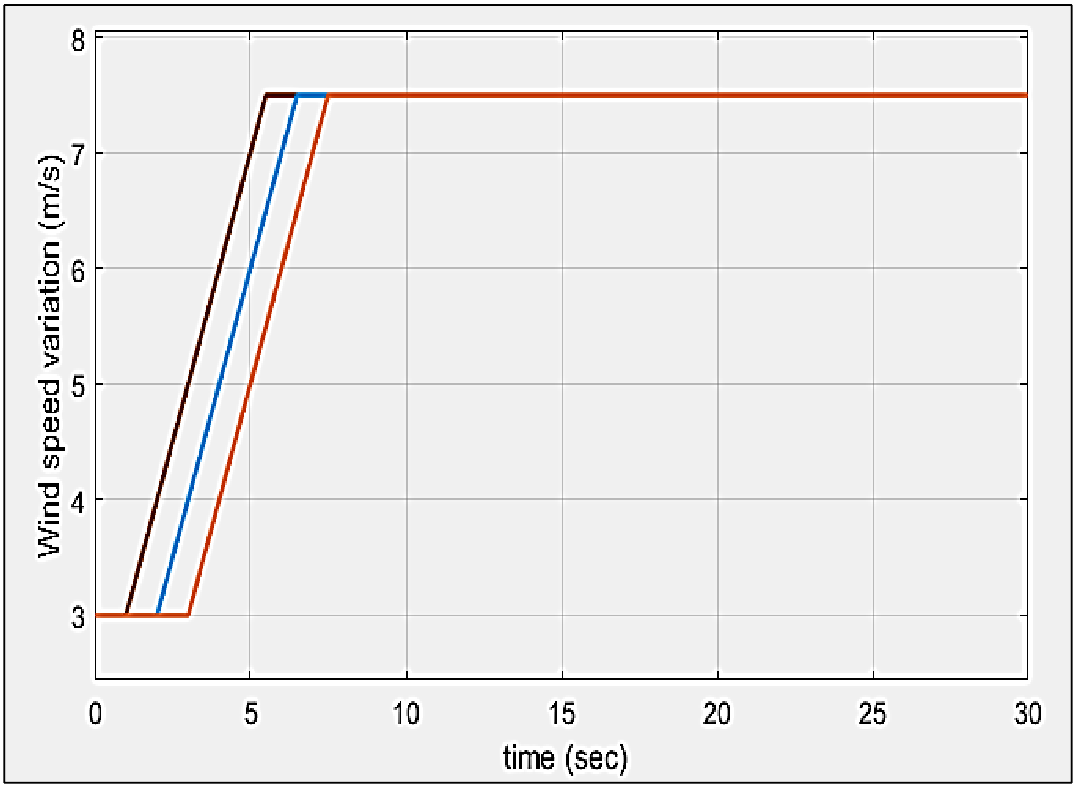


Figure 4.1: Wind speed variation

4.2 Characteristic and Pitch Angle for The Generators

Figures 4.2 to 4.7 show the graphs of the output power characteristics and the variation of the pitch angle of the wind turbines showing the relationship between wind speed and electrical power expected from the complete system, including blades, gearbox, and generator. The comparison between the three types of generators is shown in Table 4.1.

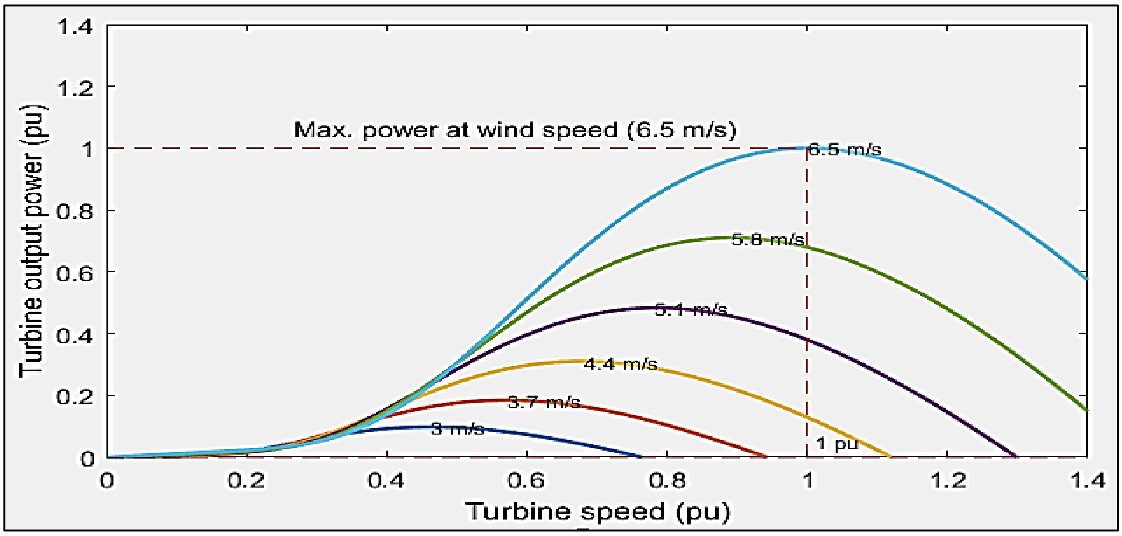


Figure 4.2: Output power Characteristics for turbine connected with SFIG

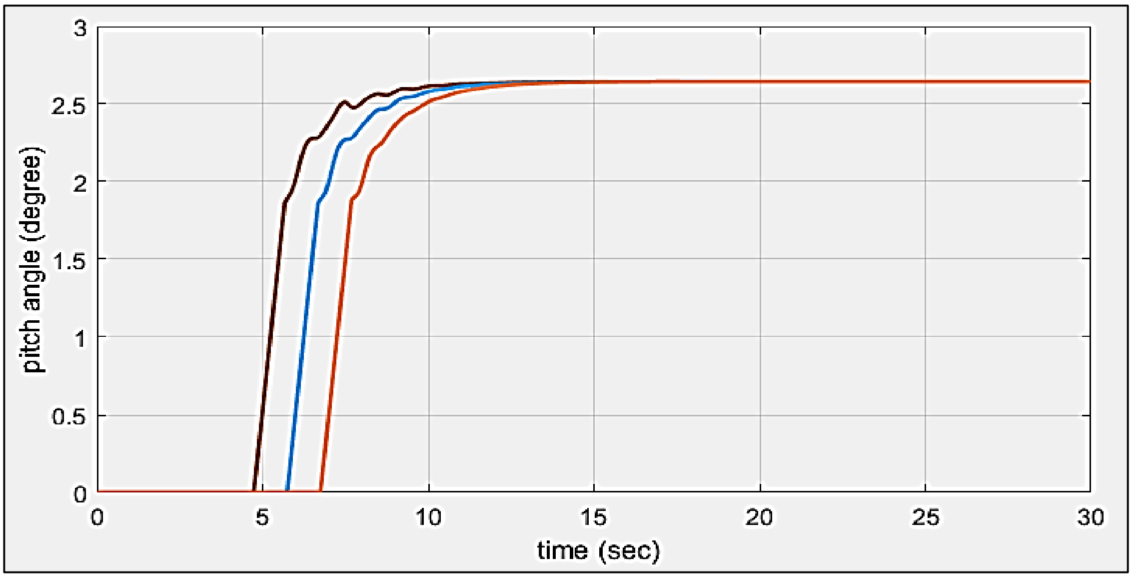


Figure 4.3: Pitch angle variation of SFIG

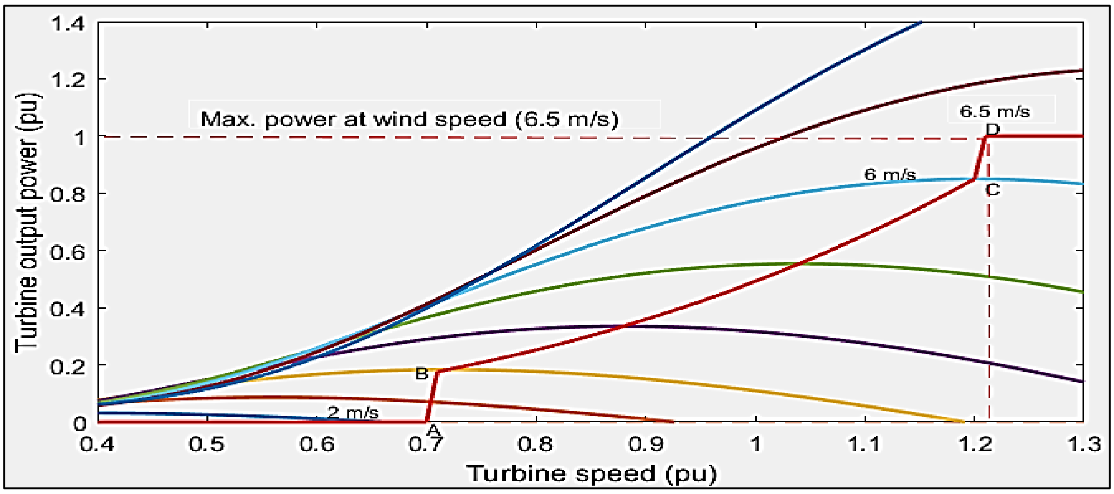


Figure 4.4: Output power Characteristics for turbine connected with DFIG

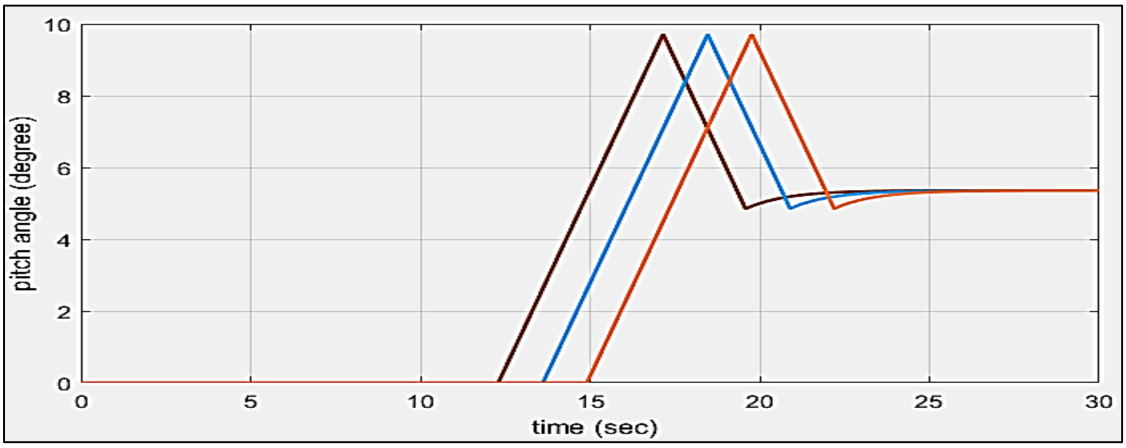


Figure 4.5: Pitch angle variation of DFIG

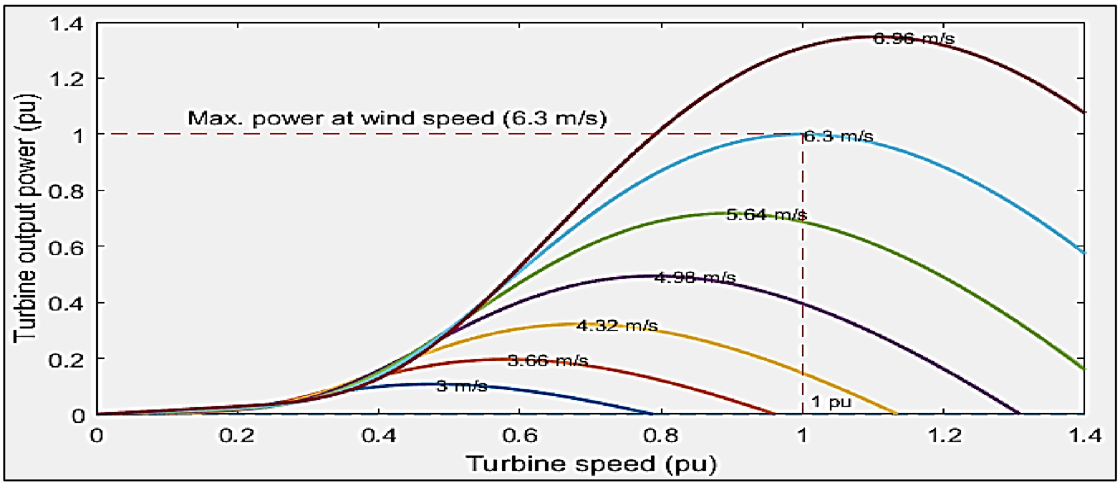


Figure 4.6: Output power Characteristics for turbine connected with PMSG

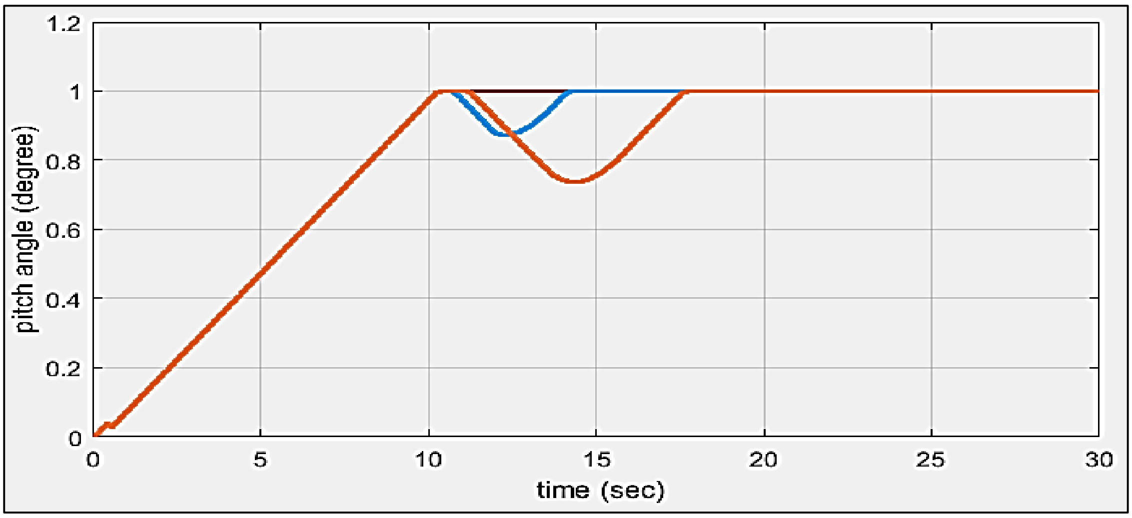


Figure 4.7: Pitch angle variation of PMSG

Table 4.1: Comparison of the characteristics between the three types

Type	Max Output Power	Wind Speed at Max Power	Turbine Speed at Max Power
SFIG	1 pu	6.5m/s	1.004 pu
DFIG	1 pu	6.5m/s	1.220 pu
PMSG	1 pu	6.3m/s	1.000 pu

From Figures 4.2, 4.4, and 4.6, the turbine output power characteristics curves show that the variation of the output power with the turbine speed and also with wind speed which varies from minimum value to its maximum. The output power reaches its maximum rated value at 6.3m/s wind speed in the PMSG and it is less by 0.2 m/s when it is compared to the SFIG and DFIG. The pitch angle control of variable speed wind turbine is concentrated on the extraction of maximum available energy, reduction of torque and output power variations, which gives stresses in the gearbox and mechanical structure. The mechanical efficiency of a wind turbine depends on the power coefficient. The power coefficient depends on tip speed ratio and pitch angle. It is better to keep the pitch angle small so as to gain maximum extracted output power and that is clear from the pitch angle control of the PMSG, which is shown in Figure 4.7.

4.3 Performance of the Farms Using SFIG, DFIG, and PMSG

The performance of the farm is represented by measuring, monitoring, and analysis of the output voltage, active power, reactive power, and other specific quantities.

4.3.1 Voltage profiles

The voltage generated by the turbine is around 575 V three-phase AC. The current is subsequently sent through a transformer next to the wind turbine (or inside the tower) to raise the voltage depending on the standard in the local electrical grid. The Figures 4.8-4.10 show the output voltages from the different wind generators.

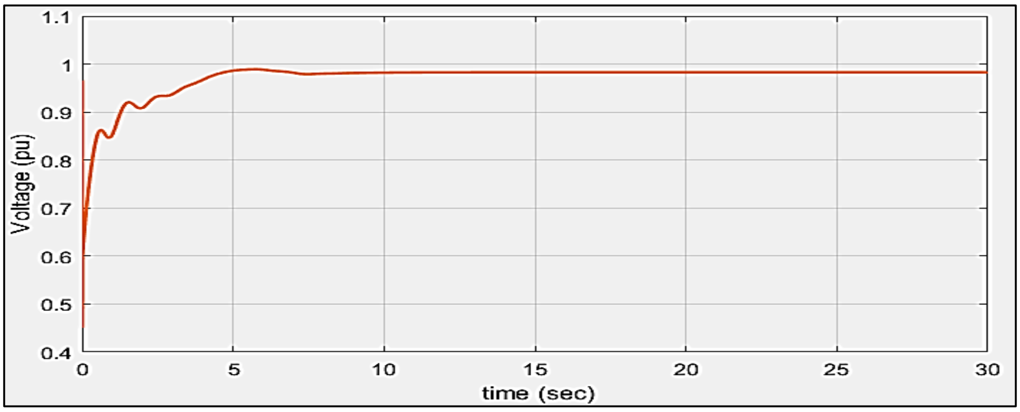


Figure 4.8: Output voltage of SFIG

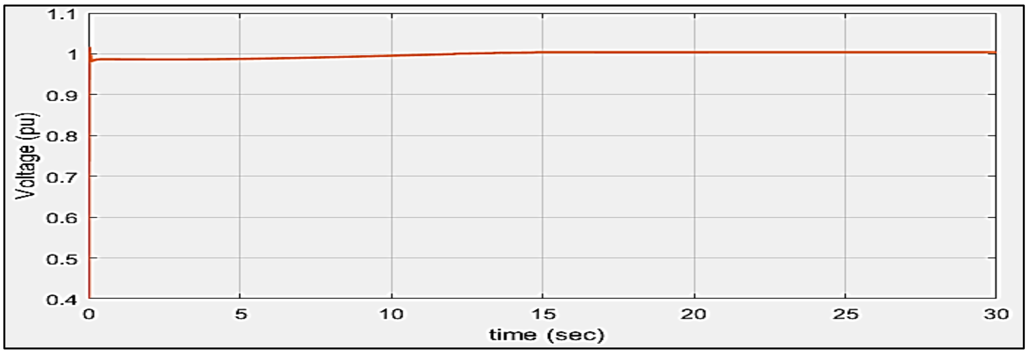


Figure 4.9: Output voltage of DFIG

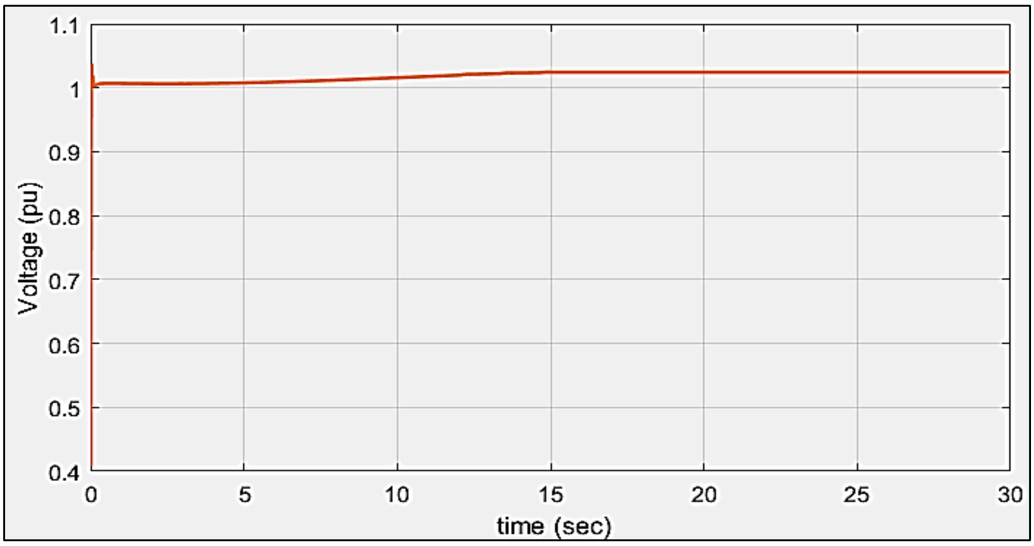


Figure 4.10: Output voltage of PMSG

Table 4.2: Comparison of the voltages of the three types

Type	Oscillation	Settling Time	Steady State
SFIG	High	20sec	0.98 pu
DFIG	Very low	14sec	1.00 pu
PMSG	Very low	16sec	1.02 Pu

From Table 4.2 it’s clear that the oscillations in the voltage in DFIG and PMSG are very low when compared to the SFIG and they reach their steady state in small time. The terminal voltage decrease in SFIG due to the absorbed reactive power from the grid, but the DFIG and PMSG when they operate at voltage regulation mode, maintain the voltage at the terminals in the limits and very close to the rated pu value. With variation of speed in SFIG voltage variation becomes very large and can cause problems while the variation in DFIG and PMSG is controlled.

4.3.2 Active power

The output active power of the wind generators depends on the turbine size and the wind speed through the rotor, Figures 4.11-4.13 explain the output active power from the three types of the generators, and the comparison between them is shown in Table (4.3).

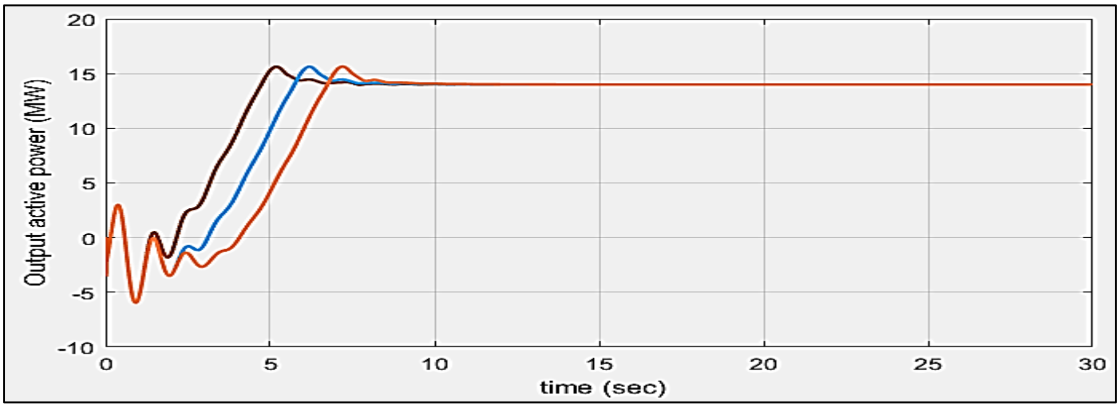


Figure 4.11: Output active power of SFIG

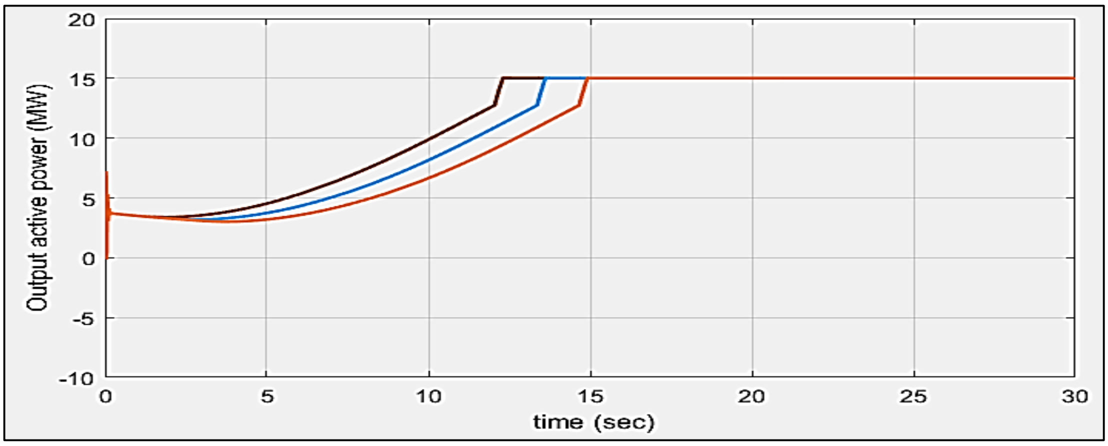


Figure 4.12: Output active power of DFIG

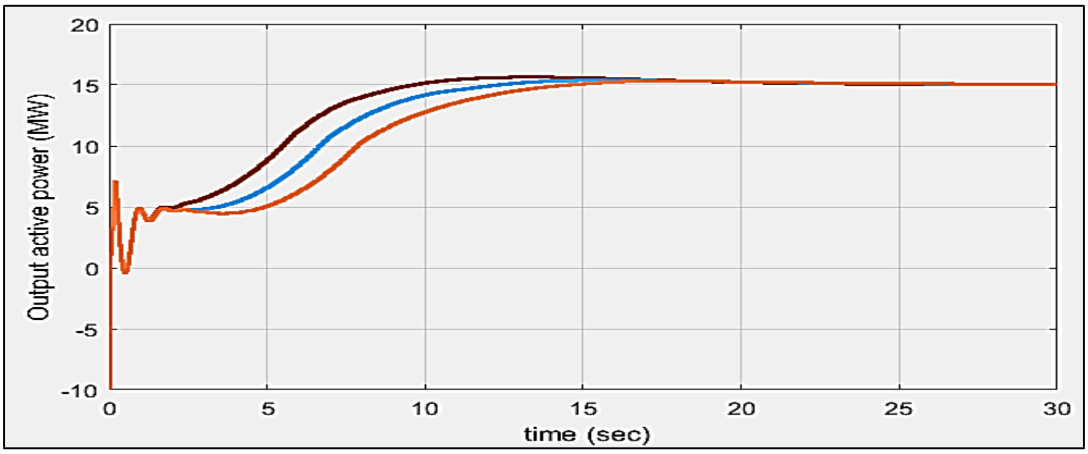


Figure 4.13: Output active power of PMSG

Table 4.3: Comparison of the output active power of the three types

Type	Oscillation	Settling Time
SFIG	Very High	12sec
DFIG	Very low	15sec
PMSG	Low	26sec

The active power supply from the SFIG takes less time to reach its maximum output power but it has more oscillatory as compared to the DFIG and PMSG because the output power from SFIG depends only on the mechanical input transmitted by the shaft of the wind turbine, while it is dependent on the mechanical input and also the behavior of the connected AC/DC/AC converters between the rotor windings and the grid side which they act as controller to the output power.

4.3.3 Reactive power

Figure 4.14 shows the output reactive power from the single fed induction generator, while Figures 4.15 and 4.16 show it from the doubly-fed induction generator and permanent magnet synchronous generator respectively.

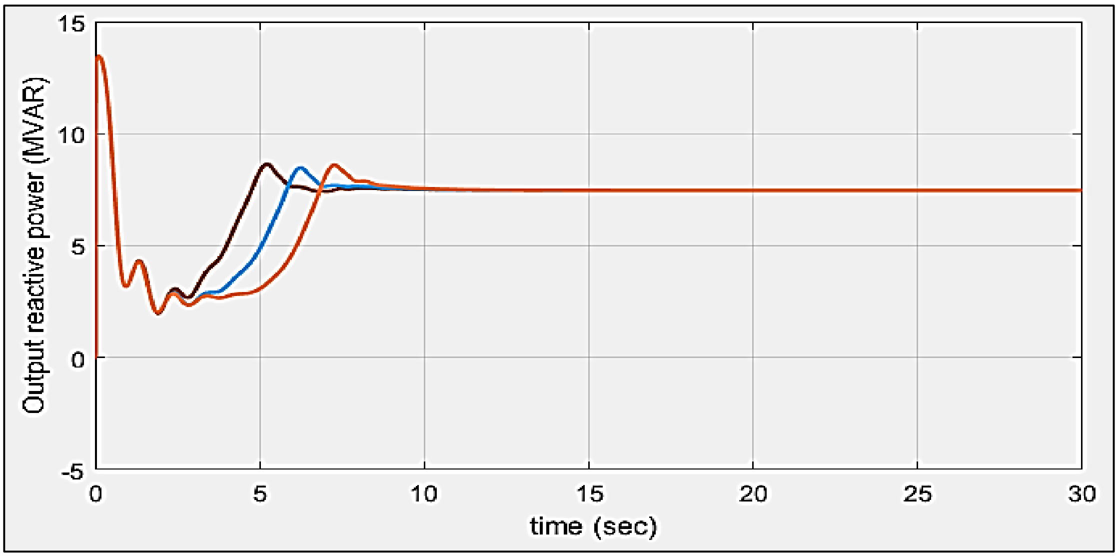


Figure 4.14: Output reactive power of SFIG

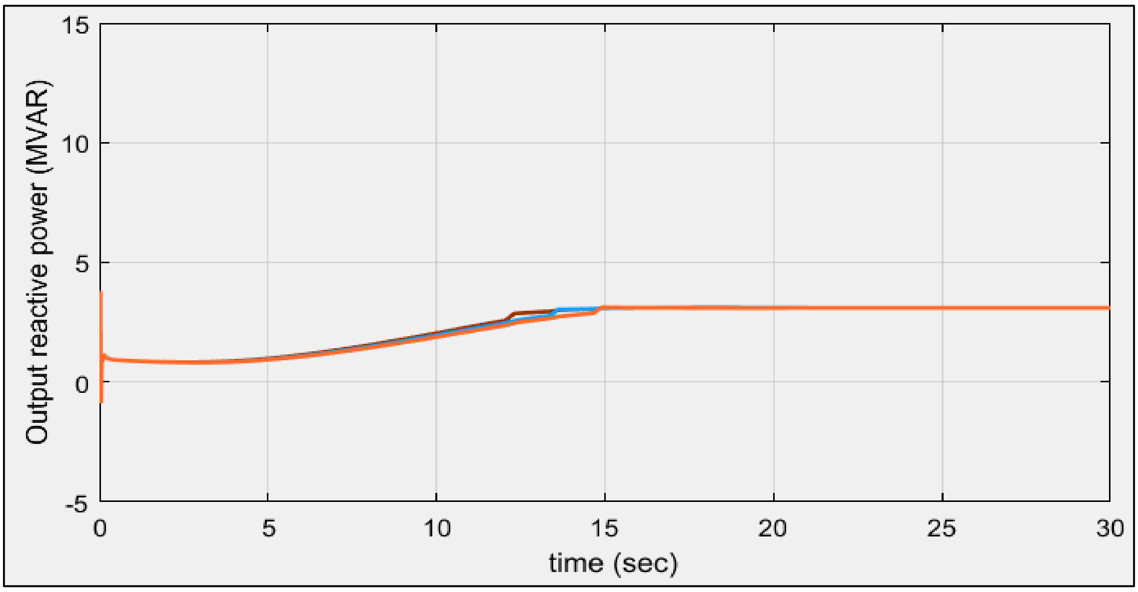


Figure 4.15: Output reactive power of DFIG

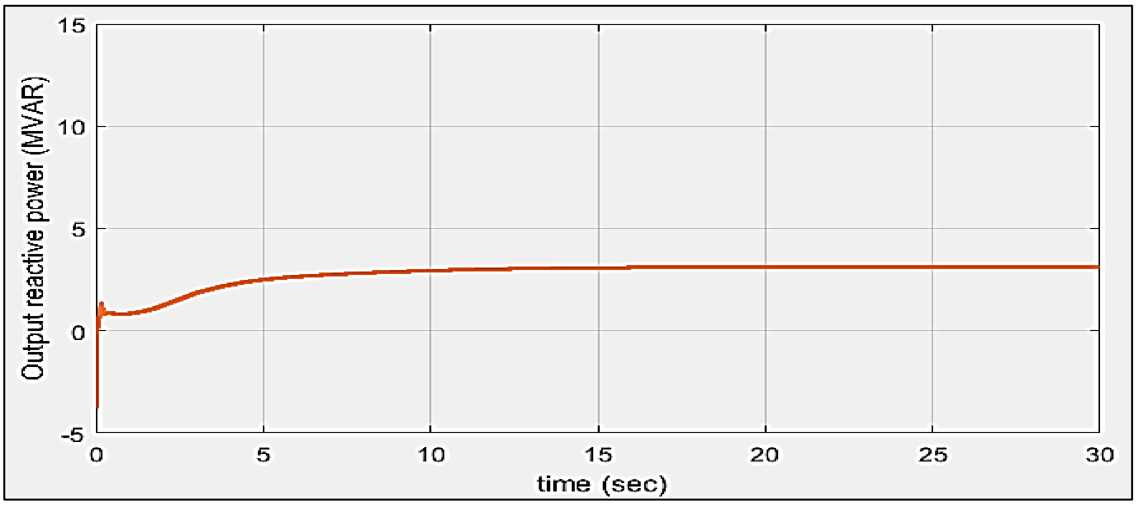


Figure 4.16: Output reactive power of PMSG

Table 4.4: Comparison of the output reactive power of the three types

Type	Oscillation	Settling Time
SFIG	High	12sec
DFIG	Low	15sec
PMSG	Very low	13sec

From Table 4.4 it is clear that the best reactive power regulation in PMSG, in SFIG to create the magnetizing flux in the generator, must receive reactive power from the grid and it is require higher reactive power to produce higher active power while in PMSG and DFIG the magnetizing flux can be generated by stator or rotor windings.

4.3.4 Rotor speed

The rotational speed of the generator varies at the time of the beginning of the turbine rotates, and reach to steady state after that as shown in Figures 4.17- 4.19.

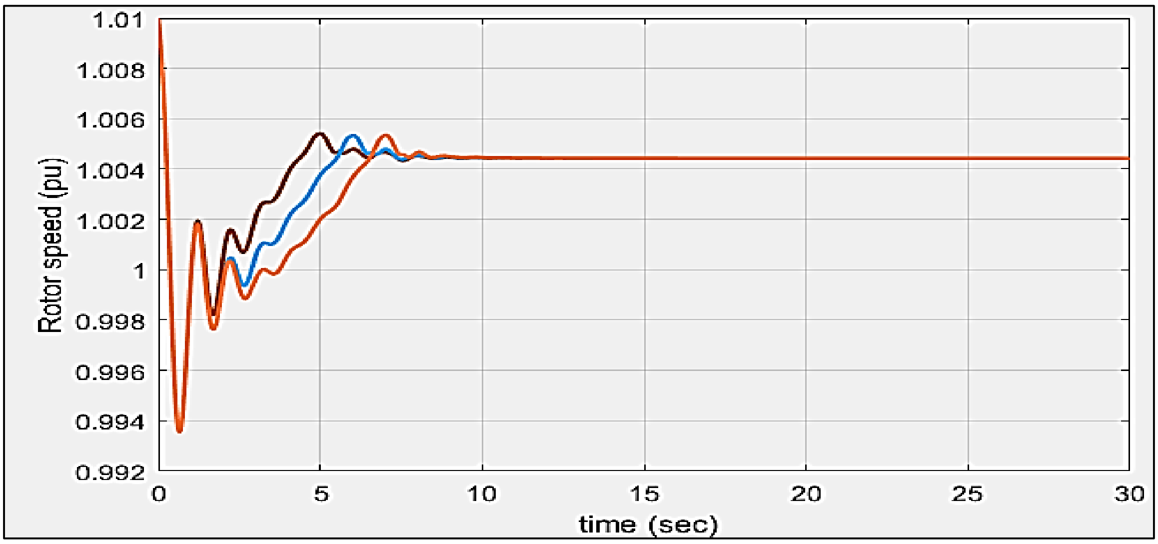


Figure 4.17: Rotor speed variation of SFIG

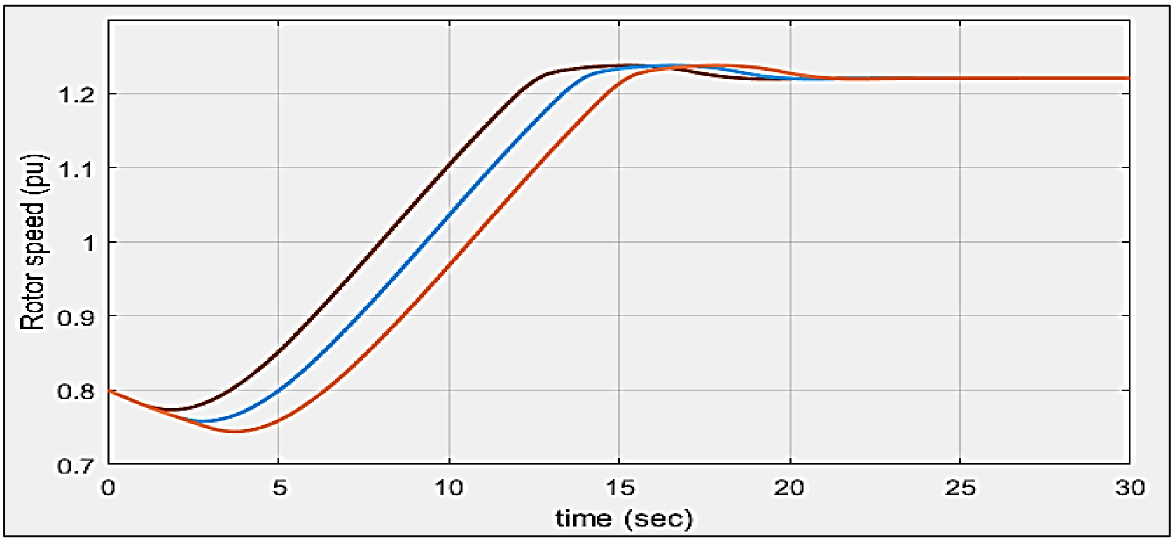


Figure 4.18: Rotor speed variation of DFIG

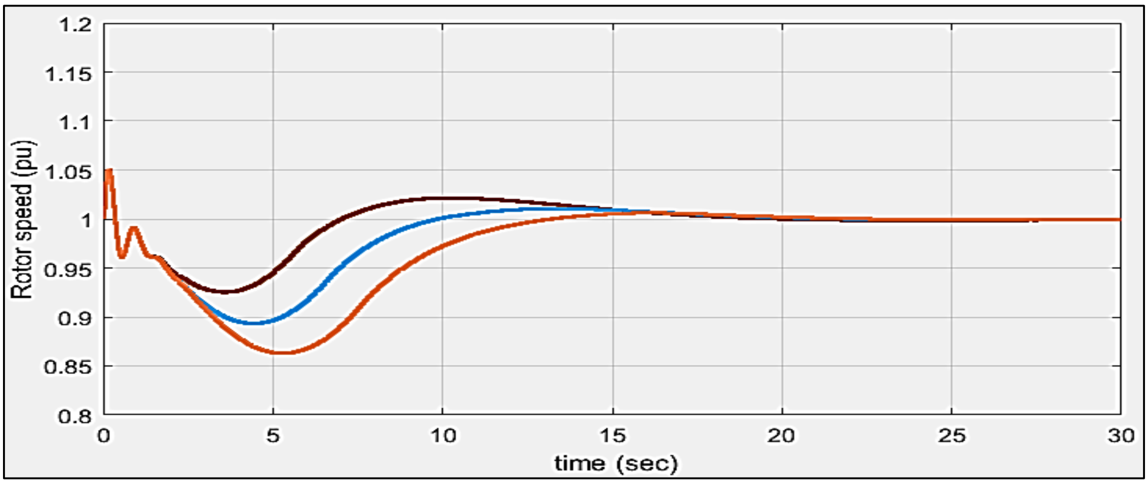


Figure 4.19: Rotor speed variation of PMSG

Table 4.5: Comparison of the rotor speed of the three types

Type	Oscillation	Settling Time	Steady State
SFIG	High	12sec	1.004 pu
DFIG	Low	22sec	1.220 pu
PMSG	Low	30sec	1.000 pu

From the figures 4.17-4.19 and Table 4.5, the rotor speed of the SFIG reaches to its steady state value in much lesser time than PMSG and DFIG, but it varies very much and is affected by the speed of the wind while in the other types continue to grow in time although the wind speed varies till it reaches this steady state.

4.4 Power Flow Analysis

Power flow analysis is the backbone of power system analysis and design. They are necessary for planning, operation, economic scheduling and exchange of power between utilities [20]. The voltage profiles, active and reactive power flows and losses which represent the power flow results are shown in the Tables 4.6-4.8.

Table 4.6: 110KV Khartoum buses voltages

Bus Name	Nominal Voltage (pu)	Without Farms (pu)	SFIG (pu)	DFIG or PMSG (pu)
Afra	1	0.9827	0.9819	0.9830
Alezba	1	0.9521	0.9671	0.9534
Banat	1	0.9559	0.9571	0.9695
Bwind 1	1	0.9743	0.9717	0.9859
Bwind 2	1	0.9587	0.9600	0.9772
Eid babikir	1	0.9708	0.9862	0.9721
Ezergab	1	0.9731	0.9847	0.9801
Faroug	1	0.9735	0.9727	0.9740
Jabel awlia	1	0.9945	0.9937	0.9975
Kh-east	1	0.9772	0.9931	0.9771
Kh-north	1	1	1.0216	1
Kilo 10	1	0.9994	0.9985	0.9991
Kuku	1	0.9863	1.0024	0.9867
Local market	1	0.9885	0.9873	0.9911
Mahadia	1	0.9760	0.9812	0.9877
Mugran	1	0.9566	0.9570	0.9693
Omdurman	1	0.9587	0.9605	0.9757
Shegara	1	0.9743	0.9722	0.9845

From Table 4.6, the voltage profiles for most of the buses when the integration of the SFIG causes voltage drop due to the absorption of reactive power by the induction generator and the variation of the wind speed, while the integration of the DFIG or PMSG the voltage profiles in most of buses improve due to the behavior of the AC/DC/AC back-to-back convertors which they control and regulate the grid side voltage and power.

Table 4.7: 110KV Khartoum active power flows (MW)

From	To	Without	SFIG	DFIG/PMSG
KILO 10	LOCALMARKET	129.853	102.313	104.551
KILO 10	KUKU	43.996	49.262	45.912
KILO 10	AFRA	135.593	135.354	135.521
SHEGARA	LOCALMARKET	35.45	8.21	9.807
SHEGARA	MUGRAN	5.777	12.703	13.193
MUGRAN	BANAT	77.357	70.562	72.219
BANAT	OMDURMAN	14.521	1.534	1.908
EZERGAB	MAHADIA	65.298	74.213	71.24
KH-NORTH	EZERGAB	44.152	38.012	39.608
EIDBABIKIR	ALEZBA	84.825	87.524	85.054
KH-NORTH	EIDBABIKIR	23.897	28.397	30.383
KUKU	KH-NORTH	159.151	160.791	157.209
KUKU	KH-EAST	144.122	148.857	144.104
AFRA	FAROUG	71.536	71.41	71.498
BWIND 1	SHEGARA	0	44.983	45
OMDURMAN	BWIND 2	0	44.983	45
OMDURMAN	MAHADIA	95.208	63.632	66.458
JABELAWLIA	SHEGARA	68.165	56.91	57.838

Table 4.8: 110KV Khartoum reactive power flows (MVAR)

From	To	Without	SFIG	DFIG/PMSG
KILO 10	LOCALMARKET	108.518	118.252	77.402
KILO 10	KUKU	24.124	-20.57	23.2
KILO 10	AFRA	61.246	61.138	61.214
SHEGARA	LOCALMARKET	60.056	70.23	29.767
SHEGARA	MUGRAN	57.851	47.82	48.29
MUGRAN	BANAT	-24.07	-13.888	13.506
BANAT	OMDURMAN	-20.927	-21.275	-39.094
EZERGAB	MAHADIA	-0.716	-33.083	20.441
KH-NORTH	EZERGAB	74.77	109.969	53.896
EIDBABIKIR	ALEZBA	44.627	46.047	44.747
KH-NORTH	EIDBABIKIR	86.31	107.436	80.802
KUKU	KH-NORTH	81.37	130.595	82.275
KUKU	KH-EAST	75.02	77.485	75.011
AFRA	FAROUG	33.494	33.435	33.476
BWIND 1	SHEGARA	-0.043	-27.923	45
OMDURMAN	BWIND 2	-0.042	-27.926	45
OMDURMAN	MAHADIA	87.395	116.016	61.663
JABELAWLIA	SHEGARA	60.98	68.397	36.99

For active and reactive powers flow in the network which are shown in the Tables 4.7 and 4.8, it is noticed that the integration of the farms regulates the power flow and increase the system capability and the amount of the power transfer through the transmission lines and keeps it within the specified limits and without any violations in the rated and maximum value which the lines can carry. For transmission system losses, when used the SFIG it is increased because it is uncontrollable as it is clear from the previous analysis and generate more reactive power which increase the losses, while the integration of the DFIG or PMSG the total system losses decrease. Figures 4.20 and 4.21 and Table 4.9 show the transmission system losses.

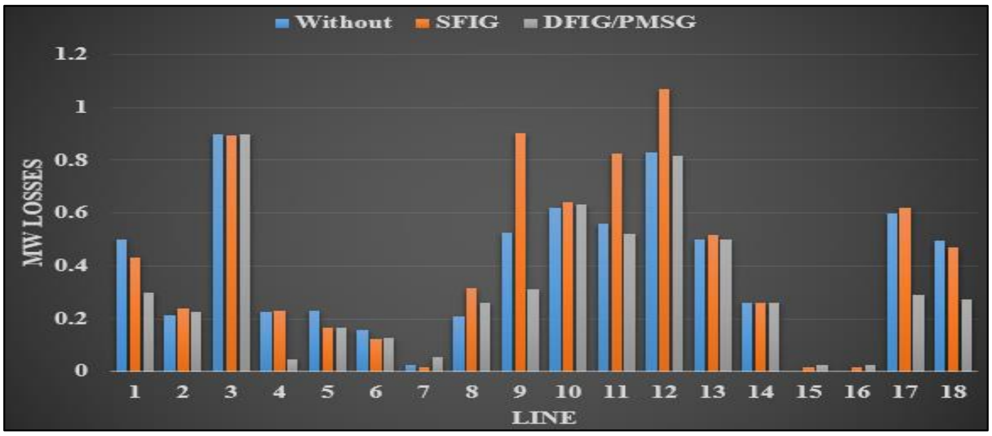


Figure 4.20: 110 KV system MW losses

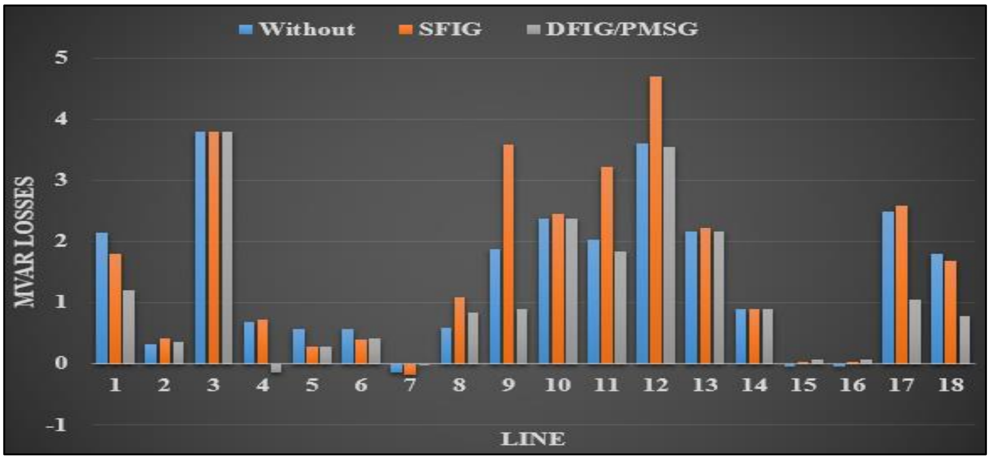


Figure 4.21: 110 KV system MVAR losses

Table 4.9: 110KV Khartoum transmission system losses

Type	MW Losses	MVAR Losses
Without	6.85	25.65
SFIG	7.76	29.76
DFIG/PMSG	5.73	20.44

4.5 Harmonic Analysis

Each Wind Energy Conversion System (WECS) includes either an induction or a synchronous generator within its structure. Moreover, and based on previous research’s, harmonic production in wind turbine systems has increased due to using big rated of power electronics converters circuits. Harmonics filtering techniques generally are classified as either passive or active. Passive filtering is the most common method used in harmonic distortion control and is divided into single tuned and band-pass filters. In general, passive filters operate within a limited frequency range, while active filters can operate in a wide frequency range. Each DFIG and PMSG has a harmonics filters within their structure, and the next analysis will be to measure the value of these harmonics after the filtration process [12]. The total system buses voltage harmonics and total branch current harmonic distortion, and voltage and current wave forms are shown in Figures 4.22 and 4.23 and Tables 4.10, and 4.11.

Table 4.10: Total system buses voltages harmonics (THD (%))

Bus name	Without	SFIG	DFIG	PMSG
AFRA	0.02	0.02	0.02	0.02
ALEZBA	0	0	0	0
BANAT	0.01	0.01	0.01	0
BWIND 1	0.02	0	0	0.01
BWIND 2	0.02	0	0	0.02
EID BABIKIR	0	0	0	0
EZERGAB	0	0	0	0
FAROUG	0.01	0.01	0.01	0.01
JABEL AWLIA	0	0	0	0
KH-EAST	0	0	0	0
KH-NORTH	0	0	0	0
KILO 10	0	0	0	0
KUKU	0.01	0.01	0.01	0.01
LOCAL MARKET	0	0.01	0.01	0.02
MAHADIA	0	0	0	0
MUGRAN	0	0.01	0.01	0
OMDURMAN	0.01	0.01	0.01	0
SHEGARA	0	0	0	0

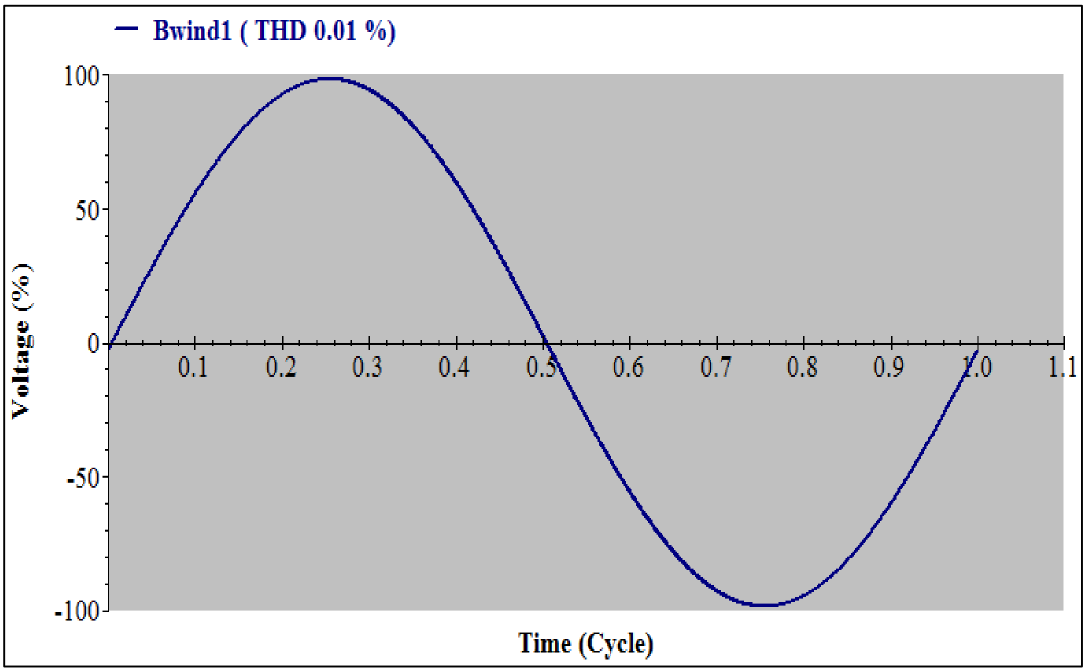


Figure 4.22: Voltage wave forms of the wind farms one

Table 4.11: Total system branch current harmonics (THD (%))

From	To	Without	SFIG	DFIG	PMSG
KILO 10	LOCALMARKET	0	0	0	0
KILO 10	KUKU	0	0	0	0
KILO 10	AFRA	0	0	0	0
SHEGARA	LOCALMARKET	0	0	0	0
SHEGARA	MUGRAN	0	0	0	0
MUGRAN	BANAT	0	0	0	0
BANAT	OMDURMAN	0	0	0	0
EZERGAB	MAHADIA	0	0	0	0
KH-NORTH	EZERGAB	0	0	0	0
EIDBABIKIR	ALEZBA	0	0	0	0
KH-NORTH	EIDBABIKIR	0	0	0	0
KUKU	KH-NORTH	0	0	0	0
KUKU	KH-EAST	0	0	0	0
AFRA	FAROUG	0	0	0	0
BWIND 1	SHEGARA	0	0	0	0
OMDURMAN	BWIND 2	0	0	0	0
OMDURMAN	MAHADIA	0	0	0	0
JABELAWLIA	SHEGARA	0	0	0	0

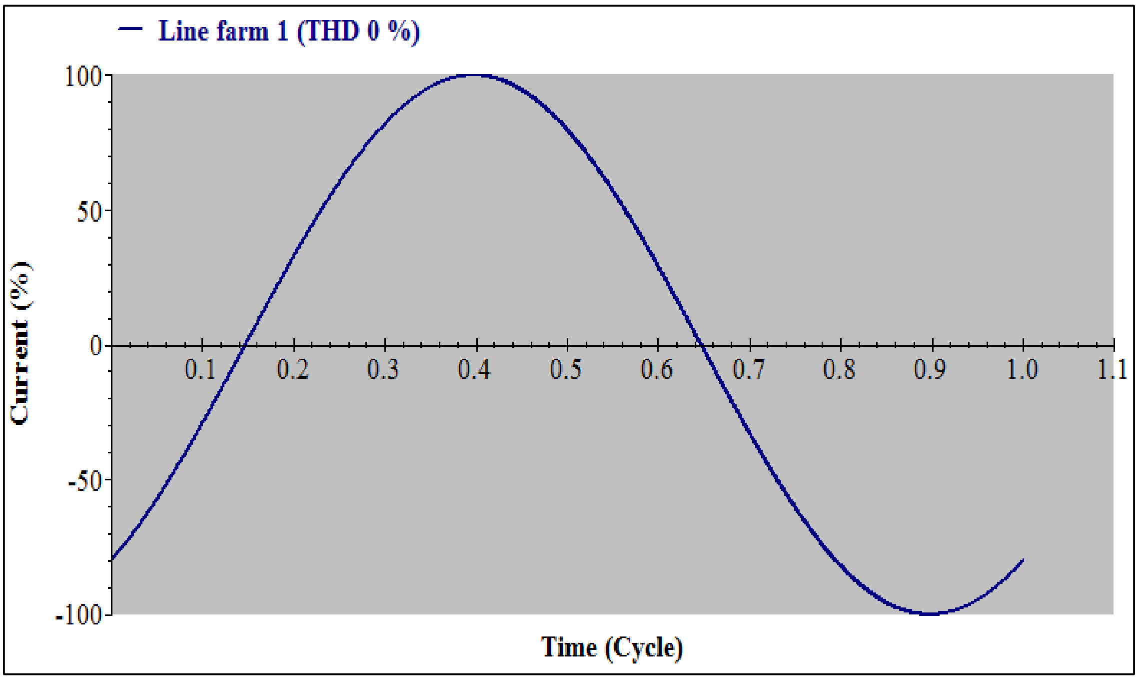


Figure 4.23: Current wave form of the TL from farm one

From Tables 4.10 and 4.11, all the TDH in the voltage or the current in the system limits with or without integration the wind farm, Table 4.12 shows the maximum allowable values of the THD according to the system voltage.

Table 4.12: Total harmonics distortion allowable

System Voltage	THD Limits
400V	5 %
6.6KV, 11KV, 20KV	4 %
22KV to 400KV	3 %

4.6 Transient Fault Analysis

The study of the effects of growing wind power penetration on the stability and reliability of power systems has the most interest in studies. Wherever wind power is installed on a large scale such studies are carried out to prevent severe consequences for the power system considered. The commonly discussed impacts of and on the system voltage. Under transient fault situations the voltage has to be considered to assess the impact of wind power on the system stability [21].

The below case considers the mutual effects of wind power in power systems under transient fault situations when it happens in the farm one after [2sec] and lasting for [0.5sec]. It is analyzed firstly, how the wind turbines behave in the system when it experiences a transient fault and secondly what impact the wind turbines have on the dynamic behavior of the system after a fault. The results shown in Figures 4.24-4.26.

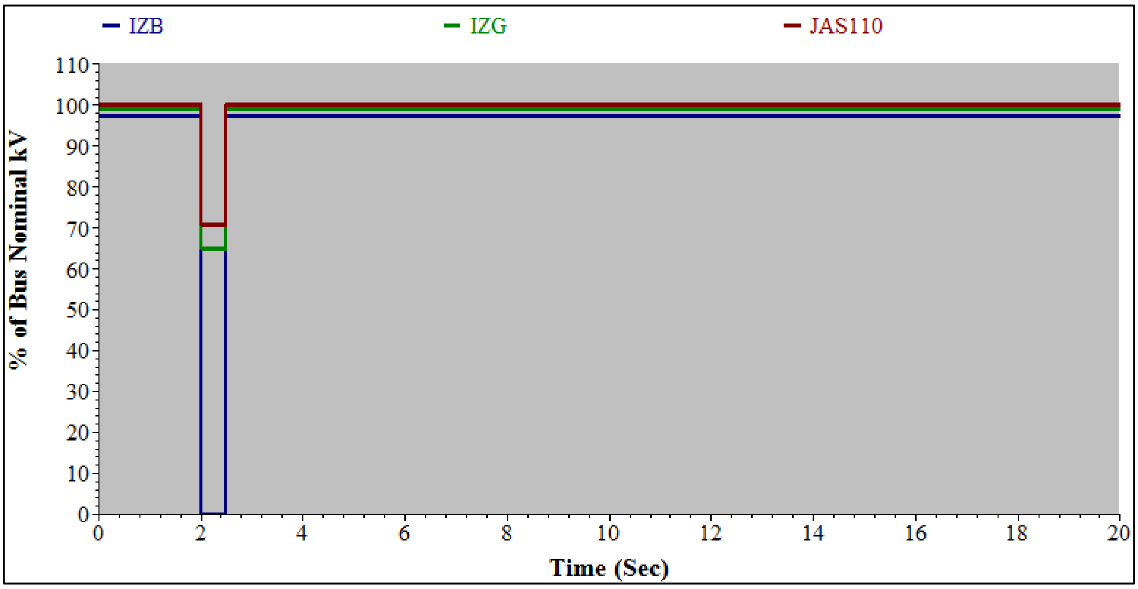


Figure 4.24: Busses voltage during fault without wind farms

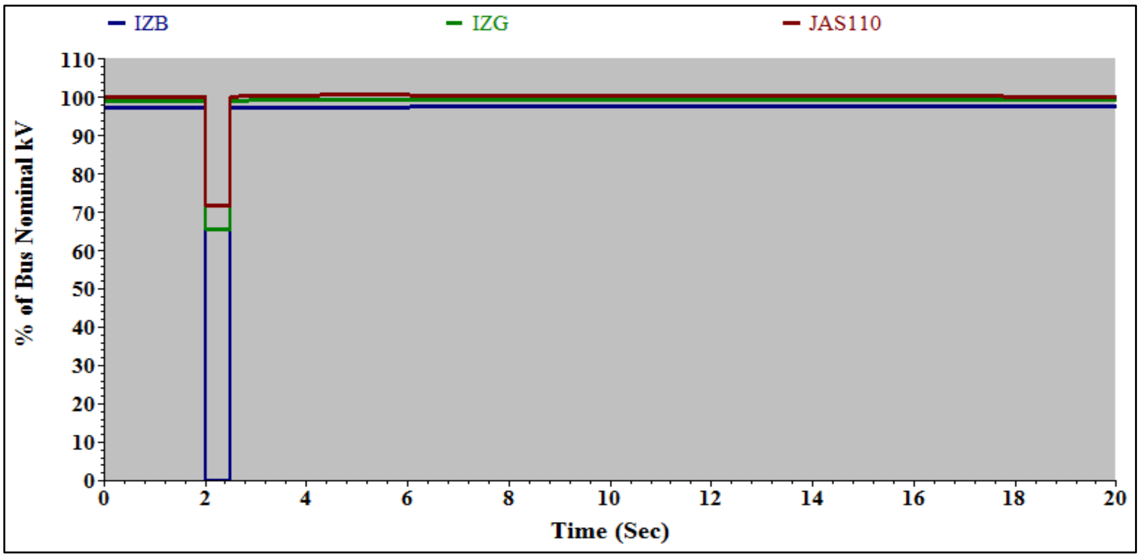


Figure 4.25: Busses voltage during fault with wind farms

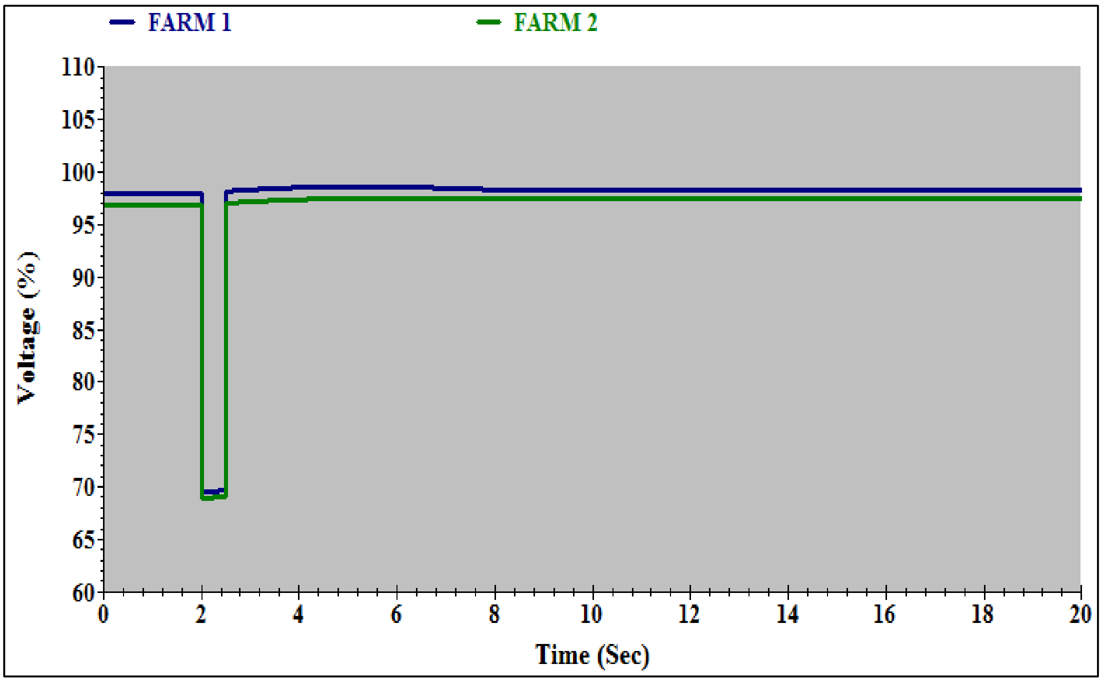


Figure 4.26: Terminal voltage of the farms during in case of faults

The fault which happens disrupts the balance of power (active and reactive) and changes the power flow. Though the capacity of the operating generators adequate, large voltage drops occur suddenly. The unbalance and re-distribution of real and reactive power in the network may force the voltage to vary beyond the boundary of stability limits. In all the situations and with the three types of the wind generators, the result is a short period with low or no voltage followed by a period when the voltage returns. When the fault occurs in the wind farm it causes the voltage at the wind turbines terminals to drop, also this effects on the system busses voltages during fault but the voltage level returns to the steady state after short recovery duration.

In the Table 4.13 there is a summary of a general comparison between the three types of the wind energy generators, the single fed induction generator, the doubly fed induction generator, and the permanent magnet synchronous generator which they used in the farms [22]. The comparison explain the main differences between the three types in their mode of operation, output quantities, performance, and cost.

Table 4.13: Summary of Comparison between the three types

Feature	SFIG	DFIG	PMSG
Operation Speed	Fixed or Limited	Variable	Variable
Terminal Voltage	Drop from the rated value	Constant or near to the rated value	Constant or near to the rated value
Active Power	Varies with wind speed but not optimally	Varies with wind speed but optimally	Varies with wind speed not optimally
Reactive Power	Uncontrollable and need compensation	Controllable	Controllable
Conversion to Grid	Directly	[AC/DC/AC] back-to-back converters	[AC/DC/AC] back-to-back converters
Complexity	Simple	Complex	complex
Cost	Low	High	High

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This research has summarized the most-recent in the field of the wind turbines regarding generators and converters. The three main types of them that have been used during the past 20 years have been evaluated. An extensive study has been carried out of the impacts determined by the connection of induction and synchronous generator to Sudan National Grid, and a detailed study of power flow analysis, harmonics, and impacts of faults in the dynamic voltage characteristics and their effects on the Khartoum 110KV transmission network.

The objective was to determine the main technical differences between these generators. The response of wind turbines connecting to the grid when wind speed variation is presented during steady-state by view point of power quality, has been made clear. The SFIG are only used by small wind turbines because they lack reactive power controlling, the market shares of this one has decreased slightly, whereas the variable speed wind turbines increased. Compared with PMSG, the DFIG seems that is the most-adopted system with a back-to-back converter, due to the lower weight and cost even with low cost power electronics in the future. However, the PMSG is the preferred solution that the robustness, the efficiency, and the reliability related power quality are of paramount importance.

To sum up, it was verified that from the view point of a steady-state terminal voltage profile, active and reactive power, rotor speed, and connection to grids, the usage of doubly-fed induction generator is advantageous and permits to increase the allowable penetration level of wind power generation.

5.2 Recommendations

Based on the above analysis, it is recommended here that:

- There are many types of pitch angle controllers which can be used in the field of wind energy generation beside the integral control like PID, fuzzy logic controllers, Artificial Neural Networks (ANNs), and it is recommended to use and study them to manage and collect maximum output power that can be extracted from the wind farms.
- For the problems of the dropping in the busses voltage when it is integrated to electrical grids, the use of one of the Flexible AC Transmission System (FACTS) devices like Static Var Compensator (SVC), or STATCOM can be the best solution and also will enhance the overall farm performance.
- A Study is needed of another renewable energy resource which is available in Sudan like solar energy and its performance and effects in addition to the wind energy -hybrid renewable system- when it is integrated with Sudan grid.

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APPENDIX A

GENERATORS DATA

A.1 SFIG Data

Stator resistance and inductance Rs=0.004843 pu Ls=0.1248 pu

Rotor resistance and inductance Rr=0.004377 pu Lr=0.1791 pu

Magnetizing inductance Lm=6.77 pu

Inertia constant H=5.04 s

Friction factor F=0.01 pu

Pair of poles= 3

Pitch angle controller gains Kp=5   Ki=25

A.2 DFIG Data

Stator resistance and inductance Rs=0.00706 pu Ls=0.171 pu

Rotor resistance and inductance Rr=0.005 pu Lr=0.156 pu

Magnetizing inductance Lm=2.9 pu

Inertia constant H=5.04 s

Friction factor F=0.01 pu

Pair of poles= 3

Pitch angle controller gains Kp=500

Converter maximum power = 0.5 pu

Grid side coupling inductor L=0.15 pu R=0.15/100 pu

Nominal DC bus voltage= 1200 V

DC bus capacitor= 10000 µF

Grid voltage regulator gain Kp=1.25   Ki=300

Droop Xs=0.02 pu

Power regulator gain Kp=1   Ki=100

DC bus voltage regulator gain Kp=0.002   Ki=0.05

Grid side current regulator gain Kp=1   Ki=100

Rotor side current regulator gain Kp=0.3   Ki=8

A.3 PMSG Data

Reactance in (pu) Xd=1.305 Xd’=0.296 Xd”=0.252
Xq=0.474 Xq”=0.243 Xl=0.18

Time constants in (sec) Td’=4.49 Td”=0.0681 Tq”=0.0513

Resistance Rs=0.006 pu

Inertia constant H=0.62 s

Friction factor F=0.01 pu

Pair of poles= 1

Grid side coupling inductor L=0.15 pu R=0.15/50 pu

Line filters capacitor Q=150 KVAR

Nominal DC bus voltage= 1100 V

DC bus capacitor= 90000 µF

Boost converter inductance L=0.0012 H R=0.005 ohm

DC bus voltage regulator gain Kp=1.1 Ki=27.5

Grid var regulator gain Ki=0.05

Grid voltage regulator gain Ki=2

Grid current regulator gain Kp=1 Ki=50

Speed regulator gain Kp=5 Ki=1

Boost inductors current regulator gain Kp=0.025 Ki=100

Pitch angle controller gains Kp=15

Pitch angle compensation gains Kp=1.5 Ki=6

Field excitation gains Kp=10 Ki=20

APPENDIX B

NETWORK DATA

Table B.1 Generation data

Station	Output MW
Marawi (MWP)	SWING
Rosseris (ROS)	152.6
Sinar (SNP)	9.4
Kosti (KOSTI)	439.6
Bahri (KHN)	249.2
Garri (GAR)	275.9
Interchange	225

Table B.2 Load data

Load bus	MW	MVAR
KLX	38	22.6
LOM	96.1	47.4
SHG	102.3	64
JAS	38.5	14.6
MUG	90.6	36.3
KHE	150.4	76.3
SAH	65.4	24.8
FAR	75.2	34.4
GAD	21.5	26.7
BAG	42.3	22.2
IBAB	67.2	41.6
FRZ	19.4	8.7
IZG	114.8	75.6

KUKU	59.6	27.3
IZB	92.9	46.6
MHD	99.1	50.5
OMD	118.7	69.8
BNT	81.47	48.18
GAM	24.45	11.7
NHS	32.16	18.65
GND	40.8	24.02
HAS	14	8
MAR	82.3	49.6
MAN	36	20
FAO	7	0
HAG	10.8	4.3
SNJ	24.7	10.8
ORBK	0	0
MIN	15	4
SNG	14.5	6.1
ROS	26.2	11.9
RNK	0.75	10
RBK	66.9	50.6
MSH	8.9	9.2
TND	1.9	28.1
UMR	7.1	17.2
OBD	36.9	27.4
SHN	45.7	20.6
ATB	122.2	61.5
MWT	34	17
DEB	35	18
DON	48	28

WWA	1.34	0.67
WHL	3.62	15.68
HWT	2.8	1.8
GDF	20.5	7.7
SWK	1.5	0
GRB	20.8	10
HLF	18.65	10.08
KSL	25.52	14.58
ARM	2.14	2.5
POR	79	22
OGDF	11.7	5