People's Democratic Republic of Algeria

Ministry of Higher Education and Scientific Research

University A.MIRA-BEJAIA

جامعة بجاية Tasdawit n'Bgayet Université de Béjaïa	UNIVERSITY ABDERRAHMANE MIRA BEJAÏA FACULTYOF TECHNOLOGY DEPARTMENTOF ELECTRICALENGINEERING	Faculté de Technologie كلية التكنولوجية Université de Béjaïa

Final project for the Master's degree in

Electrical Engineering

Option: Electrical Networks

Theme:

Impact of the integration of a Distributed Generation on Power System Voltage Stability

Prepared by:

SHONHIWA BEST

Supervised by:

MR.MEDJDOUB Abdallah

Academic year: 2022/2023

ACKNOWLEDGEMENTS

Thanks are due to the Almighty God through Jesus Christ for His inspiration, guidance, protection and provision for the successful completion of this Masters programme.

My profound gratitude goes to my supervisor, **Professor Abdallah Medjdoub**, who gave me all the necessary assistance to ensure that this thesis is completed successfully, thank you sir.

I also appreciate all faculty and staff of the Department for their encouragement and moral support. I say a very big thank you to you all.

DEDICATIONS

I would like to dedicate this thesis and everything I do to my family. In addition to I have always been surrounded with strong supportive from my brothers Wise and Liberty.

I would not be who I am today without the love and support of my father and mother. Although they are far away from me but their moral and financial support has been of great importance. Thank you father and mother.

Table of Contents

ACKNOWLEDGEMENTS ii

DEDICATIONS i

List of figures iv

List of Tables v

List of symbols and abbreviations vi

CHAPTER 1:GENERAL INTRODUCTION

1.General introduction 2

2. Distributed Generation 3

  2.1. Problem statement 3

3. Objectives 3

4. Outline of the Thesis 4

CHAPTER 2:WIND ENERGY AND ELECTRIC GRID

1. Wind energy 6

2 .Wind turbine 6

3. Structure of a modern wind turbine 6

  3.1 How it works 8

4. Electrical Grid 9

  4.1.Definition 9

  4.2.Types of Electrical Grid 9

5.Interconnection of DG(wind energy) on electric grid 10

  5.1.Wind Turbines depending on the generator 10

    5.1.1. Asynchronous Generators 10

    5.1.2. Synchronous Generators 12

  5.2. Wind Turbines depending on the speed control 14

6. Modelling Control System of Doubly Fed Induction Generator 15

  6.1. Mechanical System Control of DFIG 16

  6.2. Turbine Speed Control Model 17

7. Aerodynamic and Pitch Control Model 17

CHAPTER 3:IMPACTS OF DGs ON ELECTRICAL POWER SYSTEM

1. Impacts of DG on power system 21

2. System stability 22

  2.1. Voltage stability 24

2.2.Rotor Angle Stability 24
2.3.Frequency Stability 25
2.4.Transient Stability 26
3.Voltage stability analysis 26
3.1. Dynamic analysis 26
3.2. Static analysis 27
4.Voltage instability 27
4.1.Causes of instability of the voltage 27
5.Power flow analysis 28
5.1.Objective of the power flow study 28
6. P-V and Q-V curves in voltage stability analysis 31
7.Impact of the DG size on voltage stability...38
CHAPTER 4:SIMULATION AND RESULTS
1.Introduction...41
2.Model of power system elements 41
3.Description of the network..41
4.Parameters of 9bus system...43
5 .Application on the standard IEEE 9 bus network...44
5.1.PV and QV curves of 9bus system..47
5.2.Influence of the power factor 49
6.Influence of the DG on voltage stability..51
7.Conclusion 52
General Conclusion...54
References..56

List of figures

Figure 2.1.Wind turbine …………………………………………………………………6
Figure 2.2. Electrical grid…………………………………………………………….….7
Figure 2.3. SCIG wind turbine ………………………………………………….…………9
Figure 2.4. WRIG wind turbine……………………………………………………….……9
Figure 2.5. DFIG wind turbine…………………………………………………………….10
Figure 2.6. WRSG wind turbine………...……………………………...………………11
Figure 2.7. PMSG wind turbine………………………………………...…………………12
Figure 2.8. Typical wind turbine internal structure……………………………………..12
Figure 2.9. Doubly fed induction generator and its controls…………………..…………14
Figure 2.10. Modelling scheme of mechanical system of DFIG……………...…………...14
Figure 2.11. Pitch control and pitch compensation block diagram……………………..……16
Figure 3.1. Classification of system stability……………………………………..….19
Figure 3.2. Two bus system……………………………………………………….……27
Figure 3.3a. Power stability margin ……………………………………………….…..29
Figure 3.3b. Stable and unstable regions in PV curves…………………………..…..29
Figure 3.4. Standardized PV curves for various power factors…………………………..….30
Figure 3.5. PV curve for various reactance..……………………………………..…..31
Figure 3.7. QV Characteristic curve ……………………………………………….…...32
Figure 3.8. QV curve for different reactance……………………...……………………...32
Figure 3.8.QV curve for different power factors.…………………………………….….…...32
Figure 3.9. Impact of a DG unit on voltage stability margin……………………………...33
Figure 3.10. PV enlargement of voltage stability margin …………………………………...34
Figure 4.1. IEEE 9bus network………………………..………………………………36
Figure 4.2. Simulink model of 9bus system……………………………………………….36
Figure 4.3. Simulink results……………………………………………………………….36
Figure 4.4. PV Curves at different bus and different power factors …………………...……40
Figure 4.5. QV Curves at different bus…………………………………………...…….40
Figure 4.6. PV curves at bus 5 at different power factor……………………….…………….41
Figure 4.7. QV curves at bus 5 at different power factor…………………………………….42
Figure 4.8. PV curves at different buses at constant power factor…………...……………...43
Figure 4.9. PV Curves of bus 6 for different DG sizes ……………….……………...…….43

List of Tables

Table1. Transmission line data……………………………………………...………………..37

Table 2. Bus data ………………………………………….……………..……………..37

Table 3. Power flow results ……………………………….…………..……………..38

Table 4.Load Voltages at different buses…………..…………………………..…………….39

List of symbols and abbreviations

DG : Distributed Generation

IEEE : Institute of Electrical and Electronics Engineers

SCIG : Squirrel Cage Induction Generator

WRIG : Wound Rotor Induction Generator

DFIG : Doubly Fed Induction Generator

WRSG : Wound Rotor Synchronous Generator

PMSG :Permanent Magnet Synchronous Generator

PV : Active Power and Voltage

QV : Reactive Power and Voltage

P_{inj} : Active Power injection

AC : Alternating Current

DC : Direct Current

CCT :The critical clearing time

$\boldsymbol{C_p}$ **:** Aerodynamic power efficiency

$\boldsymbol{V_w}$ **:** Wind speed

P_{wind} : Wind Power

P_{aero} : Aerodynamic Power

P_{mec} : Mechanical Power

P_{mec} : Electrical Power

Q_{min} : Minimum Reactive Power

Q_{max} : Maximum Reactive Power

Y_{bus} : Admittance Matrix

α : Acceleration factor

AR: Lagging power factor

AV: Leading power factor

CHAPTER 1: GENERAL INTRODUCTION

1.General introduction

Nowadays power system is a large complex interconnected network that consists of many buses and generators. The existing electric power generation systems worldwide primarily rely on fossil fuels such as coal, oil, and natural gas, as well as nuclear power and hydropower [1] .The network is developing everyday with the increase in demand. Currently, the demand for electrical energy has increased and has become an essential factor in technological, industrial and socio-economic development of different countries. The electrical power system must constantly maintain a balance between generation and consumption and keep the voltage and frequency within the limits corresponding to the needs of the consumers and the proper functioning of the network. Since the demand is higher nowadays the establishment of new power generation facilities and transmission lines or the expansion of the existing infrastructure are necessary and many countries prefer to use DG to supply some part of their power demand. Consequently, the current transmission lines are under significant load, which increases the risk of stability issues after a disturbance. Therefore, ensuring voltage stability is an essential aspect of maintaining the normal operation of a power system .

Voltage instability issues and voltage collapse commonly arise in power systems that cannot meet the demand for reactive power or are heavily loaded and/or experiencing faults. As the load in a typical network increases, there is a corresponding rise in the demand for reactive power, leading to a further decline in voltage levels. If the demand exceeds a critical threshold, voltage collapse and network instability become unavoidable. Consequently, it is essential to incorporate voltage stability considerations in the planning and operation of distribution systems [2].

The concept of Distributed Generation (DG) is gaining increasing attention. The advancement of DGs presents new opportunities for conventional distribution networks.

2. Distributed Generation

IEEE [1] defines DG as "the generation of electricity by facilities that are sufficiently smaller than central generating plants so as to allow interconnection at nearly any point in a power system. " IEEE compared the size of the DG to that of a conventional generating plant.DG refers to small sources ranging between 1 kW and 50 MW electrical power generations, which are normally placed close to consumption centers [2].

2.1. Problem statement

When DG units are integrated into distribution systems, various procedures, including voltage profile, power flow, power quality, stability, dependability, and protection, may be affected. Voltage stability, angle stability, and frequency stability are the three problems that the DG units have an impact on when it comes to stability. Voltage stability is thought to be the most important factor in distribution systems because both angle and frequency stability are uncommon. The following details, however, make this situation different:

- The load demands on distribution networks are rapidly rising as the economy grows. Distribution networks are therefore working increasingly closely to the bounds of voltage instability.
- The integration of DG in distribution system introduces possibility of encountering some active/reactive power mismatches resulting in some stability concerns at the distribution level. Motivated by these facts, the target of this project is to investigate, analyze and enhance the voltage stability of distribution systems with penetration of DG.

3. Objectives

The objectives of this research are:

- To investigate the impact of DG on voltage stability of distribution networks (2 bus test system, IEEE 9-bus system).We are going to use one of the static methods which are the PV and QV curves

- To simulate and analyze the voltage stability of distribution systems.

4. Outline of the Thesis

This thesis contains 5 chapters. It is organized as follows:

Chapter 1 is containing the introduction, problem statement, objective of the thesis.

Chapter 2 presents wind energy, the electrical grid, the structure of a wind turbine and how it works followed by different methods of interconnection of wind turbine on electric grid.

Chapter 3 represents the study of the impacts of renewable energy(wind energy) production on electrical networks.

Chapter 4 discusses the power system voltage stability ,impacts of DG on electric networks,

Chapter 4 represents the results of simulation runs using MATLAB.In the last chapters, we study an IEEE 9bus power system, calculating the power flow from a MATLAB program, and then we present the results obtained from the voltage stability analysis using the PV and

QV curves. We end our work with a general conclusion.

CHAPTER 2: WIND ENERGY AND ELECTRICAL GRID

1. Wind energy

Wind power is another way of producing electricity using the wind. The force of wind drives the rotor blades, which in turn drive the generator of the wind turbine.A wind turbine is a revolving device that uses ac generators of the synchronous and induction varieties to transform wind energy first into mechanical energy and subsequently into electrical energy. The wind turbine is connected to these generators. Turbine blades, a rotor, a shaft, a coupling mechanism, a gear box, and a nacelle make up a wind turbine. A wind farm is a collection of wind turbines that have been placed in a particular area.A farm should be built in a windy area since the amount of wind will determine how much electricity it can produce. The wind turbine's total efficiency ranges from 20 to 40%, and its power output ranges from 0.3 to 7 MW [3]. When compared to other renewable energy sources, wind energy is the least expensive technology and offers the benefits of being a clean energy source.

Intermittency and grid reliability are the key problems with wind power technology [4]. Since wind electricity is produced by natural forces, it cannot be distributed instantly. On the other side, utilities must balance electricity supply and demand closely. So, the integration of wind turbines into the electric network will require more consideration as the share of wind energy increases. The accessibility of transmission is another obstacle. This is due to the fact that the greatest places for wind farms might occasionally be found in distant regions without easy access to an appropriate transmission line[4].

2 .Wind turbine

A wind turbine is a revolving device that uses ac generators of the synchronous and induction varieties to transform wind energy first into mechanical energy and subsequently into electrical energy.

3. Structure of a modern wind turbine

- **Tower**

The nacelle and rotor of the wind turbine are mounted on the tower. In general, having a high tower is advantageous because wind speeds increase as distance from the ground increases.

Additionally, the tower's construction must absorb enormous static loads brought on by the fluctuating wind power in addition to supporting the weight of the nacelle and the rotor blades. Often, a steel or concrete tubular construction is used.

- **Rotor and Rotor blade**

The rotor hub is the component that, with the aid of the rotor blades, transforms the energy in the wind into rotary mechanical movement. The rotor blades catch wind energy and transfer its power to it. The three-blade, horizontal axis rotor currently reigns supreme.The rotor blades are mainly made of glass-fiber or carbon-fiber reinforced plastics (GRP, CFRP). The blade profile is similar to that of an airplane wing.[5]

- **Nacelle and drivetrain**

The gearbox and electrical generator, two of the wind turbine's most important parts, are both located inside the nacelle, which also houses the rest of the machinery. It is attached to the tower by bearings because it needs to be able to rotate in order to follow the direction of the wind, and the gearbox quickens the generator's shaft's rotation.[5]

- **Electronic components**

The electronic equipment of a wind turbine is composed of the generator, the system for the grid in-feed of the electricity, and various sensors. The sensors for measuring temperature, wind direction, wind speed and many other things can be found in and around the nacelle, and assist in turbine control and monitoring.[5]

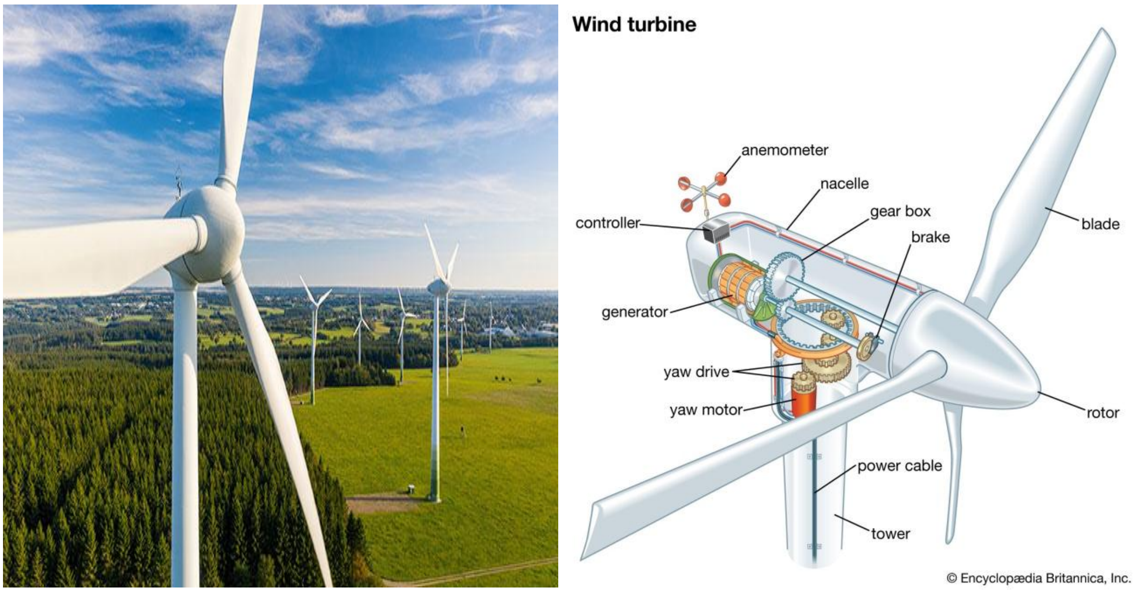


Figure 2.1 Schematic diagram of a wind turbine

3.1 How it works

Modern wind-harvesting equipment consists of blades attached to a rotor, a gearbox, brakes, a turbine, and a generator.The section of a wind turbine that contains the generating parts is called a nacelle. Figure (2.1) shows how the rotor links the blades to a shaft inside the nacelle, which in turn links to a generator. When the wind moves towards the turbine, the aerodynamically constructed blades produce a lifting force that causes the rotor to spin. The rotational speed of the turning blades is not fast enough to generate electricity, so a gear box is needed to increase the rotational speed of the shaft.

An anemometer and wind vane connected to the top of the wind turbine measure wind speed and direction to provide signals to an incoming wind flow and pitch-system[7]. These systems make sure that the wind turbine is pointed toward the direction of the incoming wind and that the blades are inclined just enough to effectively exploit the wind's lift power. The anemometer also alerts the brake system to very turbulent winds in order to guard against harm to the generator, gearbox, and rotor.

Normally, you will see wind turbines grouped together to make a wind farm.They can generate bulk electrical power and can be sized to the site, application, and energy needs[8]

4. Electrical Grid

4.1.Definition:

The electrical grid or power grid is defined as the network which interconnects the generation, transmission, and distribution unit. It supplies the electrical power from generating unit to the distribution unit. A large amount of power is transmitted from the generating station to the load centre at 220kV or higher. The network form by these high voltage lines is called the super grid.[9]

4.2.Types of Electrical Grid

The power station of the grid is located near the fuel source which reduces the transportation cost of the system. But it is located far away from the populated areas. The power which is generated at high voltage is stepped down by the help of step down transformer in the substation and then supply to the consumers. The electrical grid is mainly classified into two types. They are:

1. **Regional Grid –** The Regional grid is formed by interconnecting the different transmission systems of a particular area through the transmission line.
2. **National Grid-**It is formed by interconnecting the different regional grid.

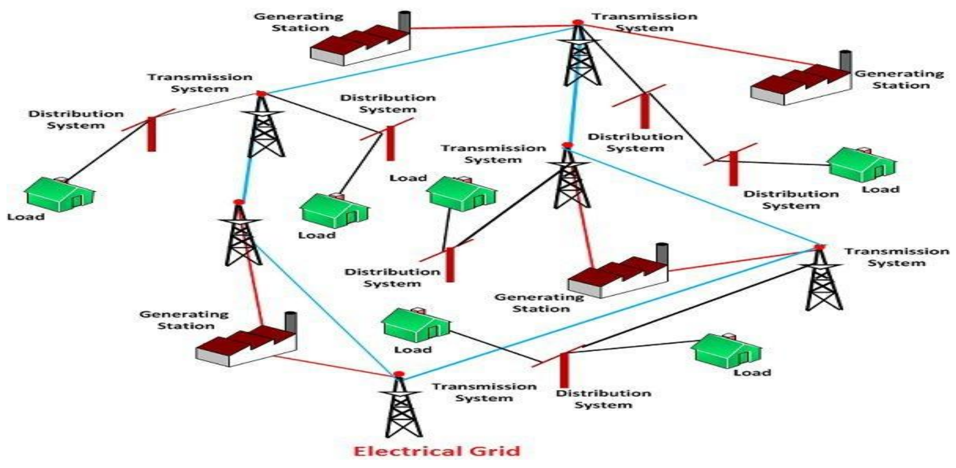


Figure 2.2 Electrical Grid

5.Connection of wind energy on electric grid

Power electronics converters are used to indirectly connect DG technologies to the grid, with the exception of a handful that employ synchronous or induction generators [10]. Photovoltaic panels and fuel cells that use DC current are connected to a DC/DC converter that is coupled to an AC/DC converter.The ripple current's variations are tamed by the DC link that connects the two converters. The grid is connected to the DC/AC converter's output (Figure 2.3).

As micro -turbines and variable-speed (wind turbine) based DG cannot be connected to the grid directly, an AC/DC converter coupled with a DC/AC converter serves as the link.

Synchronous or induction generators are connected to wind turbines. In the past, wind turbines ran at set speeds and were directly connected to the grid.

5.1.Wind Turbines depending on the generator

This group of generators, which includes both synchronous and asynchronous models, is related to the electrical system of the turbine. Any type of three-phase generator can be installed in a wind turbine, usually with the use of a power electronic frequency converter. Nonetheless, several generator types that are more popular in wind turbines will be described below.

5.1.1. Asynchronous Generators

The first group corresponds to the asynchronous or induction generators, which is the most common type inside the wind turbines. It is cheaper and less complicated than the synchronous. The fundamental issue with this generator is that it must absorb reactive power in order to produce a magnetic field, hence reactive power flows in the opposite direction as active power [11]. When there is not enough reactive power to provide the loads, the system may collapse, and this may become a serious issue. However, the mentioned issue can be avoided if this reactive power comes from the grid or a power electronic device.

Asynchronous generators have two alternative rotor designs [12,13,14]:

- **Squirrel-cage rotor**: corresponds to the Squirrel Cage Induction Generator (SCIG) and this type is directly connected to the grid. These generators are used in fixed speed

wind turbines, as they are designed to achieve the maximum efficiency at a certain wind speed, but sometimes are equipped with two windings so that it is possible to have maximum efficiency for two different wind velocities. The diagram of this generator is shown in figure (2.3)

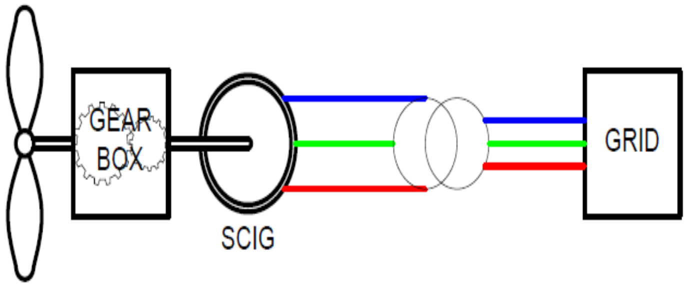


Figure 2.3:Example of a typical SCIG wind turbine.

- **Wound rotor**: corresponds to the Wound Rotor Induction Generator (WRIG), which is an evolution of the SCIG. Within the group of wound rotor asynchronous generators there are another two types:

  1. In the first one, the generator has an additional external variable resistance that is attached to the rotor windings and is controlled by power electronics. The inclusion of resistance enables the adjustment of the overall rotor resistance, providing a restricted range for controlling the speed. The extent of speed control depends on the magnitude of the external resistance and is typically referred to as a limited variable speed generator. Figure (2.4) illustrates an example diagram showcasing this concept.

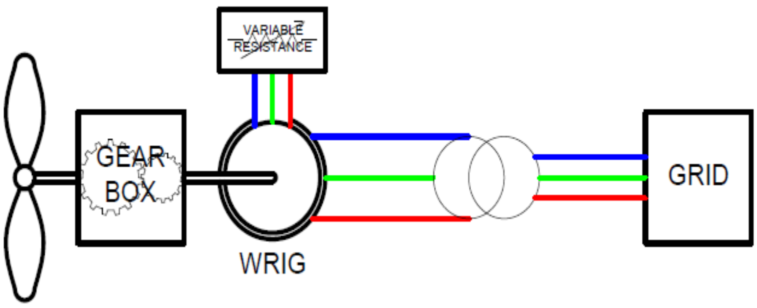


Figure 2.4:Example of a typical WRIG wind turbine.

2. The second type of generator commonly employed in the wind industry is known as the Doubly Fed Induction Generator (DFIG). It comprises a Wound Rotor Induction Generator (WRIG) with the rotor windings connected to an AC-AC converter, typically referred to as a back-to-back converter. The term "doubly-fed" arises from the fact that the stator voltage is supplied by the grid, while the rotor voltage is provided by the converter. This generator allows for variable-speed operation within a limited range.The converter itself is composed of two converters with distinct functions: the rotor-side converter and the grid-side converter. Figure 2.5 illustrates a common representation of this generator.

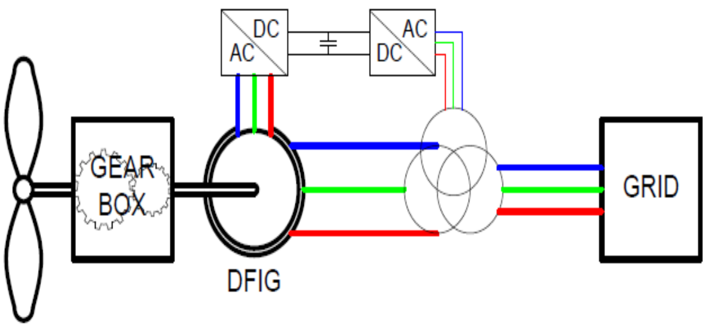


Figure2.5:Example of a typical DFIG wind turbine.

The rotor side converter is responsible for regulating the active and reactive power produced by the wind turbine, while the grid side converter maintains the DC link voltage at a predetermined value. The significant advantage of the Doubly Fed Induction Generator (DFIG) is its ability to independently control the reactive power without relying on grid magnetization. This allows the DFIG to supply reactive power to the grid, which is a notable advantage compared to other types of generators mentioned earlier.

5.1.2. Synchronous Generators

Synchronous generators are the most common ones for power plants but they are more expensive and complex than the asynchronous generators. On the other side, this kind of generators don't have the biggest disadvantage of the induction generators, as they do not need a reactive magnetising current [13]. In the synchronous generators group there are also two types [12; 13; 14]:

- **Wound rotor**: Once again, a similar rotor design can be found in synchronous generators, specifically in the case of the Wound Rotor Synchronous Generator (WRSG). In this configuration, the stator of the generator is directly connected to the grid, while the rotor windings are supplied with DC power. The rotor itself generates the exciter field, which rotates at the synchronous speed determined by the grid frequency. Some manufacturers have designed this type of generator to operate without a gearbox, and it is typically connected to a full-scale frequency converter that serves a similar purpose as the Doubly Fed Induction Generator (DFIG). This WRSG generator allows for variable speed operation, and its representation can be seen in Figure (2.6).

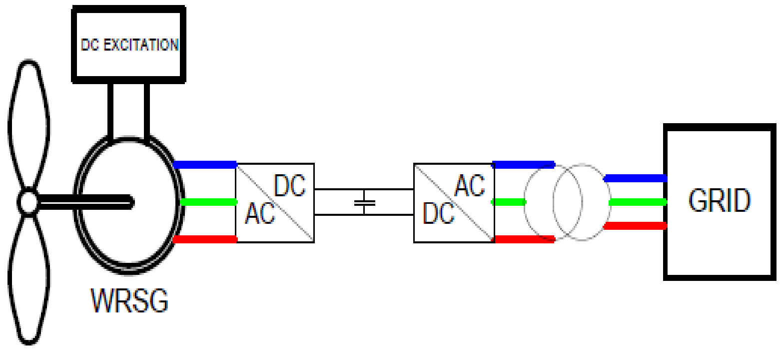


Figure 2.6: Example of a typical WRSG wind turbine.

- **Permanent Magnet Synchronous Generator (PMSG)**: This generator is a unique type that replaces one of its windings, typically the rotor windings, with permanent magnets. These magnets enable self-excitation, making this generator an appealing and increasingly popular choice in the wind industry. While it may not always require a gearbox, it usually necessitates a comprehensive converter.However, this technology is considered expensive primarily because of the high cost of the permanent magnets. Figure (2.7) depicts this particular generator.

.

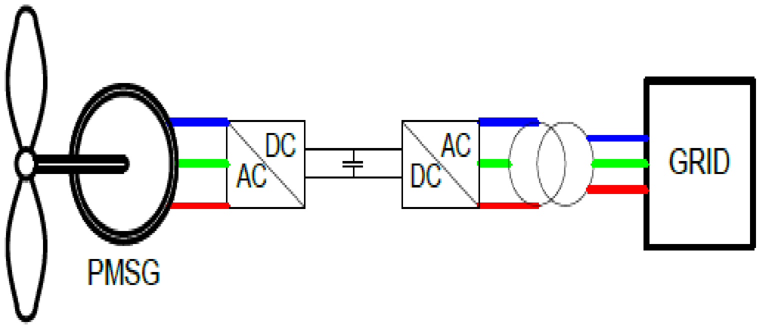


Figure 2.7: Example of a typical PMSG wind turbine.

5.2. Wind Turbines depending on the speed control

This category differentiates the generating system and leads to different types: fixed-speed and variable-speed wind turbines [12]. Before analysing both types an illustration of a general wind turbine as a help to follow the text is shown in Figure (2.8)[15].

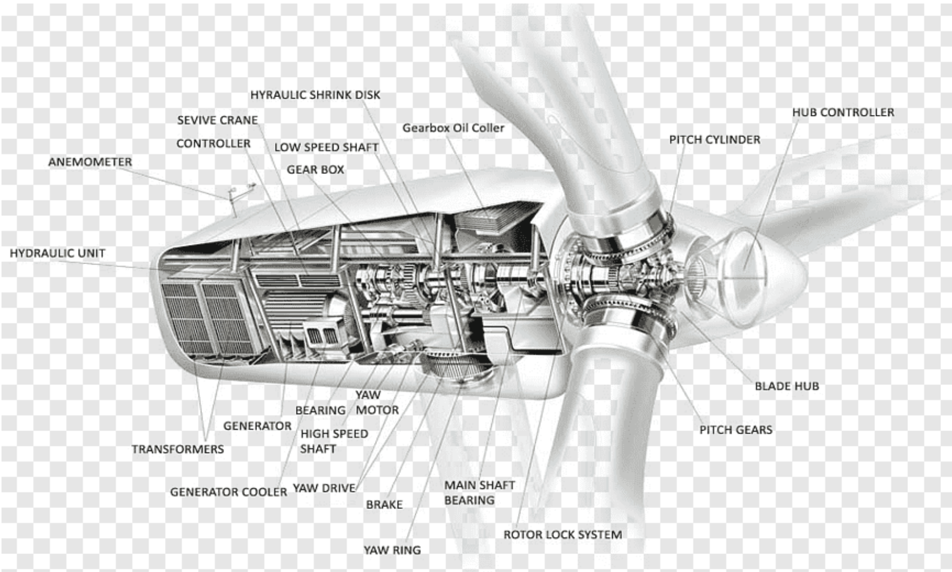


Figure 2.8. Diagram of a typical Wind Turbine.[15]

- **Fixed-speed wind turbines**: these turbines are equipped with an induction generator (asynchronous machine), either wound rotor or squirrel cage, that is coupled to a fixed frequency and rotates always almost at the same speed no matter the wind speed [12; 14; 13].

- **Variable-speed wind turbines:** In recent years, the variable-speed wind turbine has become the most prevalent type, although it is considerably more intricate compared to the fixed-speed variant. It is equipped with either asynchronous or synchronous generators and is connected to the grid through a grid converter, allowing the generation to be decoupled from the system frequency. The converter's main function is to regulate the generator speed, as it varies based on the wind speed, unlike in other types where it remains constant[12; 14; 13].

  As a result, variable-speed generators have a greater amount of electronic components within the turbine, making it a more complex and expensive system. However, this increased complexity also provides greater control over the turbine's operations. Among the four types of wind turbines, the variable-speed wind turbine with a Doubly-Fed Induction Generator (DFIG) has been described in detail.

6. Control System of Doubly Fed Induction Generator

A DFIG system is basically a wound rotor induction generator with slip rings, with the stator directly connected to the grid and with the rotor interfaced through a back-to-back partial-scale power converter.The converter is made up of two standard converters that is a rotor-side converter and a line-side converter along with a shared DC bus, as shown in Figure2.9. The DFIG is doubly fed, which means that the grid supplies the voltage to the stator and the power converter induces the voltage to the rotor. Depending on the size of the converter, this technology enables variable speed operation over a broad but restricted range.The voltage source converter supplies the rotor windings with variable voltage and frequency.In addition to the DFIG's ability to feed the rotor with power of variable frequency, a distinct aspect of the DFIG is that it has a fast current control. This means that the DFIG control can, within limits, hold the electrical power constant in spite of fluctuating wind, thus temporarily storing the rapid fluctuations in power as kinetic energy. The use of partial-scale converter to the generator rotor makes this concept on one hand attractive from an economic point of view. On the other hand, this converter arrangement requires an advanced protection system, as it is very sensitive to disturbances on the grid. Without such protection, high transient currents induced in the rotor can damage the power converter device. [16]

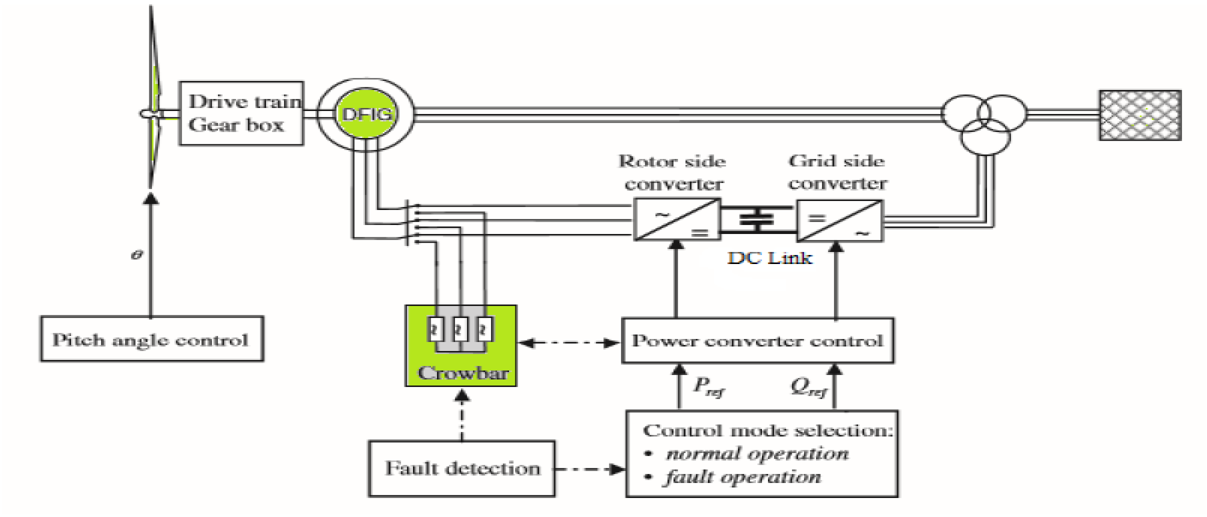


Figure 2.9: Model of Doubly fed induction generator and its main components of the controls[16]

Double-fed induction generators (DFIGs) are used in many big modern wind power facilities because they have important benefits over full-sized converters, including the ability to manage reactive power and being smaller and less expensive.

6.1. Mechanical System Control of DFIG

Using accurate models for both the electrical and mechanical aspects of wind turbines is crucial for the development of advanced control strategies in variable speed wind turbines. It is also important to study their interaction with the power system, particularly during grid faults. Additionally, it is necessary to design and coordinate the control of the mechanical system, such as the blade angle control, with the control of the electrical system.

The mechanical components of a wind turbine encompass various elements, including the wind speed model, the aerodynamic model, the blade pitching mechanism, and the drive train with gearbox. Figure 2.10 illustrates the mechanical model of a Doubly Fed Induction Generator (DFIG) wind turbine and its control in dynamic power system studies.

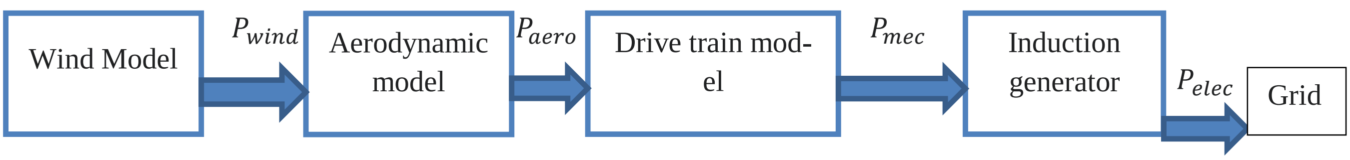


Figure 2.10: Modelling scheme of mechanical system of DFIG[16]

6.2. Turbine Speed Control Model

The primary objective of the wind turbine control system is to maximize the power obtained from the wind. The equipment power ratings serve as the limiting factor that determines the amount of energy extracted from the wind. To prevent damage to the mechanical components, the input mechanical power must be restricted when it exceeds the equipment power ratings. This is achieved by adjusting the turbine blades to reduce the input mechanical power. This adjustment is known as pitch control of the turbine blades. The dynamics of the pitch control are reasonably fast and can significantly impact the results of dynamic simulations.

Conversely, when the available wind power is lower than the equipment ratings, the turbine blades are set at a specific pitch angle to maximize power generation from the wind. In this scenario, the turbine control model calculates the power required based on the available wind speed and sends a power order to the electrical control. The electrical control system then instructs the converter to deliver the specified power amount to the grid.

7. Aerodynamic and Pitch Control Model

When conducting power system simulations that incorporate grid disturbances and fault-ride through capability, it is crucial to incorporate the aerodynamic model. The rotor's aerodynamic behaviour is effectively captured using a quassi-static aerodynamic model, which is based on the aerodynamic equation (2.1). In this model, the mechanical power delivered to the turbine is determined by the wind speed, blade pitch angle, and shaft speed.

$$P_m = \frac{1}{2} A_r \rho {V_w}^3 C_p\ (\lambda, \theta) \qquad (2.1)$$

P_m mechanical output power of the wind turbine (W), ρ is the air density [kg/m3], A_r is the area swept by the rotor blades [m^2] or $A = \pi r^2$, V_w is the wind speed [m/sec], and C_P is the is aerodynamic power efficiency, which is a function of λ and θ. λ is the ratio of the rotor blade tip speed and the wind speed, θ is the blade pitch angle.

In this wind turbine model the aerodynamic power efficiency $\boldsymbol{C_p}$depends on the actual pitch angle θ and the tip speed ratio.

The relationship between blade tip speed and generator rotor speed is a constant (λ) and it is defined as :

$$\lambda = \frac{r * \omega}{V_w} \tag{2.2}$$

Where $\boldsymbol{r}$ is the rotor blade radius; $\boldsymbol{\omega}$ is turbine angular speed; and $\boldsymbol{V_w}$ is wind speed.

Figure (2.11) depicts the pitch angle controller, which encompasses both the pitch control and pitch compensation. Additionally, Figure (2.11) also illustrates the block diagram for controlling active power, incorporating the pitch controller, pitch compensator, and drive train models.

Within the diagram, various variables are represented: the voltage measured at the wind turbine terminal, the current injected from the wind turbine to the grid, the wind turbine rotating shaft speed, the wind speed, the output electrical power measured at the wind turbine terminal, the mechanical input power to the shaft, the command power, and the pitch angle.[17]

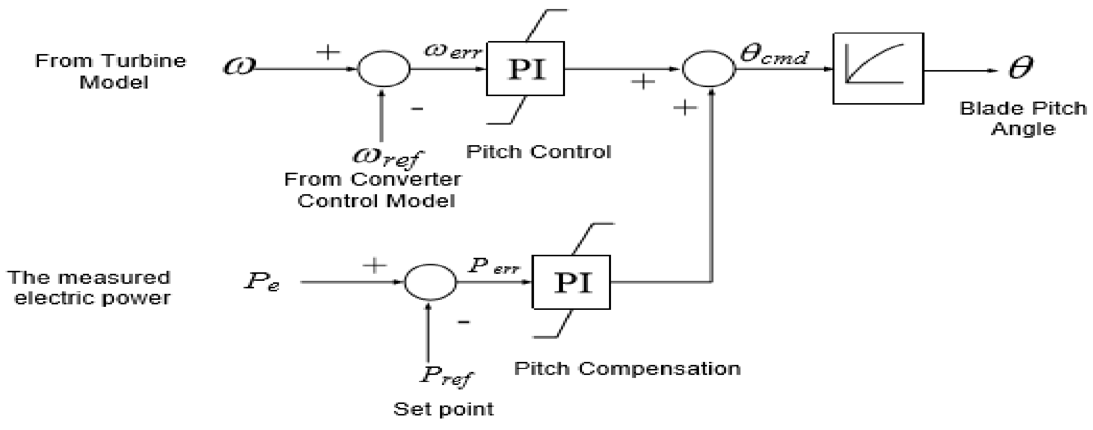


Figure 2.11: Pitch control and pitch compensation block diagram

CHAPTER 3: IMPACTS OF DGs ON ELECTRIC POWER SYSTEM

1. Impacts of DG on power system

Although DG unit integration in electrical systems has several advantages, complexity is increased. As a result, the DG units have an impact on the performance of the system, including the voltage profile, power flow, system losses, power quality, stability, dependability, and protection.[5,19]

- **Voltage profile-**Customers must receive power from the utility at a voltage that falls within a certain range. However, if the capacity of the connected DG is quite large or the connection between transmission and distribution system is relatively poor, the steady state voltage rise may be an issue[5].
- **Power quality**-Frequency fluctuation, persistent over voltages, high frequency noise, harmonic distortions, high voltage spikes, and voltage sags and swells are some of the most frequently recognized power quality events. When DG has a huge capacity or is coupled to a poor distribution system, the power quality may decrease.
- **Protection** -The installation of DG changes the intensity, duration, and direction of a fault current, demanding equivalent modifications to the current protection system.
- **Stability** - As DG's capacity increases, it becomes clear that it is becoming increasingly crucial to the stability of the electricity system. Therefore more considerations are required in this aspect[19].
- **Security**-DG energizes the system at numerous locations, complicating the isolation and earthing procedures for safety before maintenance work is done.

A high penetration of DG will affect the steady-state and the dynamics of the distribution system. These effects primarily include[20,21]:

- **Voltage regulation** -The utilities forbid DG from controlling the voltage at the common connection point (PCC). Only a constant power factor control should be used for DG operation.

- **Short circuit level**- When numerous DG are connected to the same feeder during a fault, a fuse and breaker coordination issue may arise, which may cause an unforeseen fuse operation. The system's dependability is severely impacted.
- **Voltage flicker**-Voltage flicker can be brought on by connecting and disconnecting a single DG. Moreover, there may be significant illumination flicker due to variations in the output of each DG and variations in the load. Mitigation strategies can be used to minimize these swings. Reduced voltage starts are necessary for induction generators, tighter voltage matching and synchronization for synchronous generators, and a cap on inrush currents and output changes for DGs with power electronic interfaces.
- **Harmonic distortions**- Depending on the converter technology and the interconnection setup, DGs may add harmonics to the system.

The primary goal of this research is to examine the voltage stability as a result of the widespread use of DG units. The effect of the DG units on system stability is thus presented in the following section of this chapter.

2. System stability

The supply and demand of electricity must be balanced at all times for a power system to function properly. Hence, a power system should be able to keep this balance both under steady-state conditions and following disturbances (transient).The stability of a power system is defined as a property of a power system that permits it to remain in an equilibrium state under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance [22].

Physical characteristics, such as the magnitude and phase angle of the voltage at each bus and the active/reactive power flowing in each line, are used to define the operational state of a power system. The system is said to be in steady state if these quantities remain constant throughout time; if not, the system is seen to be in disturbance [23]. Depending on where they come from and how big they are, the disruptions can be little or massive. Little disturbances include, for instance, slight variations in load and generation, whereas big disturbances include faults, significant changes in load, and the loss of generating units [23].

Distribution system networks are essentially made to take power from transmission lines and distribute it to clients. Real and reactive power both flow in one direction as a result. However, the directions of the real and reactive power may be reversed when DG units are deployed in distribution systems. As a result, stability is affected by the penetration of DG units into distribution systems and becomes increasingly problematic as penetration levels rise.

Any fault occurring in the distribution system might cause voltage and angle instability [24].The primary variables that affect stability in distribution systems with embedded DG units are the DG units' control techniques, energy storage systems, the kinds of loads in the system, the locations of faults, and the motor's inertia constant [25].However, in general system stability describes the ability of power systems to maintain synchronicity and steadiness at any given key parameter setting. In this regard, there are three classifications that are often associated with power system stability: rotor or power angle stability, frequency stability and voltage stability. Figure (3.1) shows overall power system stability classification [22].

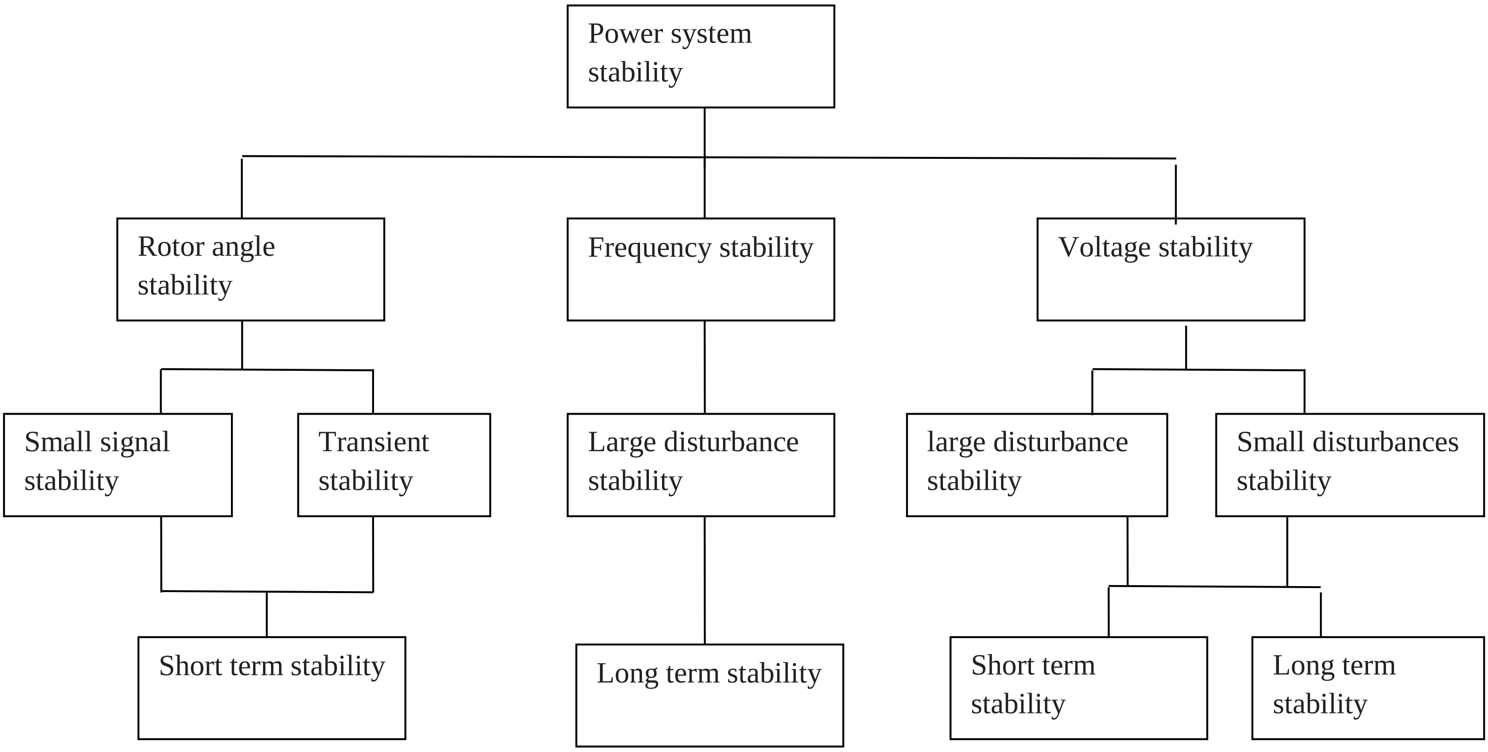


Figure 3.1. Classification of system stability[22]

2.1. Voltage stability

The capacity of a power system to maintain consistent and appropriate voltages at all of its buses in the face of a disturbance from a specific initial operating condition is referred to as voltage stability. The inability to supply the reactive power demand is the main cause of voltage instability [22].Voltage instability develops when load dynamics try to restore power demand beyond what the generation system is capable of. This might cause loads to trip, transmission lines to trip, and certain generators' synchronization to lose [26]. At the final stage of voltage instability, voltage collapse frequently happens when extremely low bus voltages cause a partial or complete blackout of the system [22,27].

Depending on the type of disturbance, voltage stability can be divided into minor and big categories:

- Large disturbance voltage stability refers to the ability of power systems to maintain and control voltages following large perturbations, such as loss of generation or system faults.
- Small disturbance stability refers to the ability of power systems to maintain and control voltages following small perturbations, such as incremental change in loads.

When this is happening, voltage stability issues can occur for a few seconds to tens of minutes. The degree of voltage stability may therefore be a short- or long-term phenomenon.

2.2.Rotor Angle Stability

Rotor angle or power angle stability refers to synchronous generators' capacity to re-establish synchronism or return to normal conditions following physical disturbances. The research of electromechanical oscillation in power systems is necessary to solve the rotor angle stability problem. The way that synchronous machines behave when their rotor angle changes is a key factor in this situation. The speed remains constant and each machine's input of mechanical torque and electrical torque are balanced in a steady state situation. The system becomes out of equilibrium when a disturbance occurs, which causes the rotor of a machine to speed up or slow down.The spinning rates of all machines do not synchronize if one machine is unexpectedly spinning more quickly than another. This results in angular deviations in location. This usually causes the fast machine to alternately inject or absorb power into the slow machine. Also, if angular separation increases, the power transfer will decrease or the bus voltage will drop, which causes instability. Major power system components could experience cascade outages and system failure as a result of an unstable system[29].Rotor angle or power angle stability problems can be categorised into two distinct areas:

- Small signal rotor angle (steady state) stability is the ability of the power system to maintain synchronism under small perturbations. The usual problems may cause small stability disturbances, such as HVDC control, FACTS controller, inter-area oscillation mode and load changes. The time frame for small signal stability problems is ten to twenty seconds following perturbations.
- Large signal rotor angle stability (transient stability) is the ability of the power system to maintain synchronism after having been subjected to severe perturbation, such as short-circuit and switching operation. The time frame for large signal stability problem is three to five seconds following perturbation.

2.3.Frequency Stability

The ability of power systems to retain stable frequency within a permitted range in the wake of a significant system disruption is referred to as frequency stability. Large fluctuations of frequency, voltage, power flows, and other system parameters are impacted by unstable frequency because it causes a significant imbalance between generation and load. Frequency stability issues are usually brought on by poor system utilities, a lack of control coordination, and advanced protective mechanisms. Depending on how the control and device react, the time limit for frequency stability issues can be extended from a second to minutes[29].

2.4.Transient Stability

Large-disturbance angle stability (Transient stability) is a subcategory of rotor angle stability and consists of the ability of the power system to maintain angle stability after being subjected to a large disturbance (such as a short-circuit on a transmission line, or the disconnection of a generator). Instability problems are aperiodic and are mainly due to insufficient synchronizing torque [22,27]. The critical clearing time (CCT) is defined as the maximum time duration between the occurrence of the fault and itsclearing that the power system can regain stability. Due to the highly nonlinear characteristics of transient stability, time domain simulation is used to solve the differential and algebraic equations of a power system using a step-by-step calculation procedure.

3.Voltage stability analysis

Voltage stability can be evaluated by two different methods of analysis: static and dynamic, the details of which are presented in the following subsection

3.1. Dynamic analysis

Dynamic analysis can show the real behaviour of the system such as loads ,DG units, automatic voltage and frequency control equipment, and the protection systems. The overall power system is represented by a first order differential equation given in equation (3.1).

$$\dot{X} = f(x,V) \qquad (3.1)$$

and the following algebraic equation (3.2)

$$I(x,V) = Y_N V \qquad (3.2)$$

with a set of known initial conditions (X_0, V_0)

where:

X: state vector of the system

V: bus voltage vector

I: current injection vector

Y_N: network node admittance matrix

Equations (3.1) and (3.2) can be solved in a time domain using numerical integration methods. This study provides time domain results; therefore, the system can be modelled and simulated with the help of different simulation software such as MATLAB.

3.2. Static analysis

This method examines the viability of the equilibrium point represented by a specified operating condition of the power system**.** It involves only the solution of algebraic equations and therefore is computationally much more efficient than the dynamic analysis. Static analysis captures snapshots of system conditions at various time frames along the time-domain trajectory [2]. At each time frame, time derivatives of the state variables in Equation (3.1) are assumed to be zero. Although voltage stability is a dynamic phenomenon by nature, static analyses are used in many studies, due to its lower computation time and useful information for voltage stability assessment.

4.Voltage instability

Voltage stability is defined as the ability to maintain a consistently acceptable bus voltage at each node in the network, under normal operating conditions. The state of the network is said to be voltage unstable when a disturbance, an increase in load or a change in the condition of the network leads to a gradual and uncontrollable drop in voltage, resulting in a loss of power know as voltage collapse[18].

4.1.Causes of instability of the voltage

Voltage instability is due to several causes, among them, an increase in electrical loads, an increase in reactive power as well as the transport of active power over long transmission lines. Voltage instability usually occurs in the weak areas/buses of the power system and leads the system to voltage collapse most of the time.

So the main causes of voltage instability can be listed as follows:

- ✓ **Lack of reactive power**

Voltage collapse typically occurs on heavily loaded power systems that have a reactive power deficiency. Voltage collapse is associated with reactive power demands from loads that are not met due to limitations on the generation and transmission of reactive power [18].

- ✓ **Load too high**

  This is one of the causes of voltage instability that can occur especially when the load is greater than expected and the risk is even greater when the reactive consumption is also greater than expected [18].

- ✓ **Production too far from consumption**

  In general, the generating units are sufficiently distributed on the grid so that there are no large transmission distances. However, it may happen that the generators close to a point of consumption are all shut down, either because they have broken down or because it is not economic to run them during certain periods.

5.Power flow analysis

Power-flow analysis, usually referred to as load-flow, is frequently used in big, complicated networks. In order to better understand the voltage stability indices discussed in the following chapter, a brief introduction to power-flow analysis and its application to voltage stability will be provided in this part.

5.1.Objective of the power flow study

The calculation of the power flow is carried out in order to [28] :

- ✓ **Set the status of the network**

  The purpose of calculating the power flow of a network is to determine the state of the network according to the connected load and their distribution on all network accesses. This calculation provides an accurate picture of the active and reactive power flow of each element of the transmission network and the voltage level of each node.

This calculation is based on the following assumptions:

The grid is stable and the generator provides energy in the form of sinusoidal alternating current and balanced three-phase voltage [28].

- ✓ **Calculation of the current flow**

The value of the current flowing through each component of the network (line, cable or transformer) will not exceed the rated current of these components .If the actual value is too high, the component may over heat and even explode [28].

- ✓ **Calculation of losses in line**

Power flow calculations are used to access the power losses in the lines and transformers due to current flow. Excessive losses can lead to a reconfiguration of the network in order to minimise the overall network losses .In this study we used Newton Raphson method.

5.2.Definition of Newton Raphson Method

The Newton-Raphson method is an iterative numerical technique used in power flow analysis to solve a set of nonlinear equations representing the power flow equations in an electrical power system.

- ➢ **Classification of bus sets**

Bus bar scan be classified into three categories:

- Reference bus(**slack** or **swing bus**) where V and θ are defined.
- Load bus-bar (type PQ bus) where the active power P and the reactive power Q are defined.
- Voltage controlled bus-bar (PV bus type) where the active power P and the voltage modulus V are defined.

- ➢ **Application of Newton Raphson Method**

The Newton-Raphson method is used in this research work because of its faster convergence that makes it to find its relevance in large power systems. The number of iterations required to obtain a solution is not dependent on the size of the network. In addition, the Newton-Raphson method is well suited for software computations. Simply stated, it has a very high convergence speed compared to other iterative solution methods.

Power flows and voltages of a transmission network are calculated for certain terminal or bus circumstances as part of the power-flow (load-flow) study. It is assumed that the system is balanced. Active power P, reactive power Q, voltage magnitude V, and voltage angle θ are the four variables linked to each bus. Node equations can be used to visualize the relationships between network bus voltages and currents [2]. The following are the network equations expressed in terms of the node admittance matrix:

The complex power and current injected into the *i*th bus:

$$S_i = V_i I_i^* = P_i + jQ_i \quad (3.3)$$

$$I_i = \sum_{j=1}^{n} Y_{ij} V_j \quad (3.4)$$

In polar form ,equation 3.4 can be written as:

$$I_i = \sum_{j=1}^{n} \left|Y_{ij}\right| |V_i| \angle \left(\theta_{ij} + \delta_j\right) \quad (3.5)$$

Complex power at bus *i* is:

$$S_i^* = P_i - jQ_i \quad (3.6)$$

$$P_i - jQ_i = |V_i| \angle(-\delta_j) \sum_{j=1}^{n} \left|Y_{ij}\right| |V_i| \angle (\theta_{ij} + \delta_j) \quad (3.7)$$

Separating real and imaginary parts ,we have

$$P_i = \sum_{j=1}^{n} \left|Y_{ij}\right| |V_i| |V_i| cos\,(\theta_{ij} - \delta_i + \delta_j) \quad (3.8)$$

$$Q_i = -\sum_{j=1}^{n} \left|Y_{ij}\right| |V_i| |V_i| sin\,(\theta_{ij} - \delta_i + \delta_j) \quad (3.9)$$

After expanding equations 3.8 and 3.9 in a Taylor series the final equation is

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \theta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \theta} & \frac{\partial Q}{\partial V} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} \quad (3.10)$$

ΔP and ΔQ represent differences between specified values and calculated values respectively, ΔV and $\Delta \delta$ represent voltage magnitude and voltage angle respectively in incremental forms and $\begin{bmatrix} \frac{\partial P}{\partial \theta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \theta} & \frac{\partial Q}{\partial V} \end{bmatrix}$ forms the Jacobian matrix.

The scheduled and the calculated values of the power residuals of the term $\Delta P_i{}^k$ and $\Delta Q_i{}^k$

Are given as:

$$\Delta P_i{}^k = P_i{}^{sch} - P_i{}^k \quad (3.11)$$

$$\Delta Q_i{}^k = Q_i{}^{sch} - Q_i{}^k \quad (3.12)$$

The new estimates for the voltage angles and magnitudes are respectively given as:

$$\delta_i{}^{k+1} = \delta_i{}^k + \Delta\delta_i{}^k \quad (3.13)$$

$$\left|V_i{}^{k+1}\right| = \left|V_i{}^k\right| + \Delta\left|V_i{}^k\right| \quad (3.14)$$

The calculation is repeated until

$$\left|\Delta \boldsymbol{P_i}{}^{\boldsymbol{k}}\right| \leq \boldsymbol{\varepsilon}$$
$$\left|\Delta Q_i{}^k\right| \leq \boldsymbol{\varepsilon}$$

Where $\boldsymbol{\varepsilon}$ is the tolerence **.**

6. P-V and Q-V curves in voltage stability analysis

- ✓ **PV curves**

PV curve is a basic tool of static voltage stability analysis based on voltage stability mechanism, in which P can be expressed as the total load of a certain area,and V is the key bus voltage.By establishing the relationship between load and node voltage, PV curve can visually and continuously show the process of system voltage reduction and even collapse with the increase of load. At the same time, by calculating the PV curve of each node in the system, two important parameters about the voltage stability of the system can be obtained: the critical voltage and the power limit of the load point, which can be used to indicate the voltage stability margin of the system and to represent the ability of each load node to maintain the voltage stability.

A simple example is given using PV and QV curves, which are two widely used power flow methods to visualize and determine the voltage stability phenomenon in the case of a two buses system.

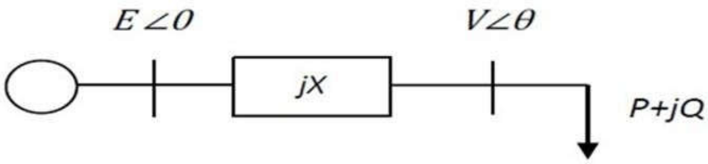


Figure 3.2.Two bus system

The model in Figure.3.2 considers a constant voltage source of magnitude *E* and a purely reactive transmission impedance *jX*. Using the load flow equations:

The voltage across the load is given by:

$$\bar{V} = \bar{E} - j\overline{XI} \quad (3.15)$$

The apparent power is given by

$$\mathrm{S} = P + jQ = \overline{VI^*} = \bar{V}\,\frac{\overline{E^*} - \overline{V^*}}{-j\bar{X}} \quad (3.16)$$

$$\mathrm{S} = \frac{j}{X}(EV\cos\theta + jEV\,sin\,\theta - V^2) \quad (3.17)$$

By identification:

$$\mathrm{P} = -\frac{EV}{X}\sin\theta \quad (3.18)$$

$$\mathrm{Q} = \left(\frac{EV}{X}\cos\theta - \frac{V^2}{X}\right) \quad (3.19)$$

Where :

P is the active power transfer from the source to the load ,Q is the reactive power transfer from the source to the load , **E** = E∠0 is the voltage at the source,**V** = V∠θ is the voltage at the load,X= impedance of the line,

Summing the equation (3.18) and (3.19),we have

$$P^2 + (Q + \frac{V^2}{X})^2 += \frac{E^2V^2}{X^2} \quad (3.20)$$

$$P^2 + Q^2 + \frac{2QV^2}{X} + \frac{V^4}{X^2} = \frac{E^2V^2}{X^2}$$

$$V^4 + 2QXV^2 + X^2(P^2 + Q^2) = E^2V^2$$

After developing ,we have

$$V^4 + V^2(2QX - E^2) + X^2(P^2 + Q^2) = 0 \qquad (3.21)$$

Let V^2=Y

$$Y^2 + Y(2QX - E^2) + X^2(P^2 + Q^2) = 0 \qquad (3.22)$$

We have a second order equation,

Then: $\Delta=(2QX - E^2)^2 - 4(X^2(P^2 + Q^2))$

- $\Delta>0$ two distinct real solutions;
- $\Delta= 0$ double solution;
- $\Delta<0$ no real solution;

The solution of equation (3.22) is given by:

$$V^2 = Y = \frac{E^2}{2} - QX \pm \sqrt{\frac{E^4}{4} - X^2P^2 - XE^2Q} \qquad (3.23)$$

We assume that:

$p = \frac{PX}{E^2}$, $q = \frac{QX}{E^2}$, $v = \frac{V}{E}$;

substituting in equation (3.23), we have :

$$v^2 = \frac{1}{2} - q \pm \sqrt{\frac{1}{4} + p^2 - q} \qquad (3.24)$$

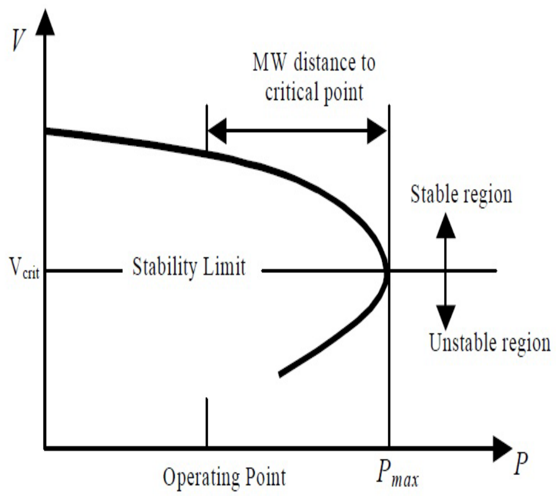
Equation (3.19) will allow us to plot different PV and QV curves

The solutions to this load voltage are often presented in PV or QV curves, also known as nose curves or voltage profiles.Equation (3.24) produces two voltage solutions for each given set of load flow, which are illustrated by the upper and lower portions of the PV-curve. In equation (3.24), the "+" sign represents the upper voltage solution, which is stable, and the "-" sign represents the lower voltage solution, which is unstable [3]. The tip of the “nose curve” is called the maximum loading point or critical point.

It's important to note that there are two solutions for each load power below the loadability limit: one uses a high voltage and low current, while the other uses a low voltage and high current. It is rare for a power system to function at the lower section of the curve since it is preferable to operate at a voltage close to that of the infinite bus.

Operation near the stability limit is impractical and sufficient power margin, that is, distance to the limit, has to be allowed , as represented in Fig.(3.3b).

In P-V curve shown in Figure (3.3a), there are three regions related to real power load P. In the first region up to loadability limit, power flow equation has two solutions for each P of which one is stable voltage and other is unstable voltage. If load is increased , two solutions will coalesce and P is maximum. If load is further increased, power flow equation doesn't have a solution. Voltage corresponding to “maximum loading point" is called as critical voltage.[30]



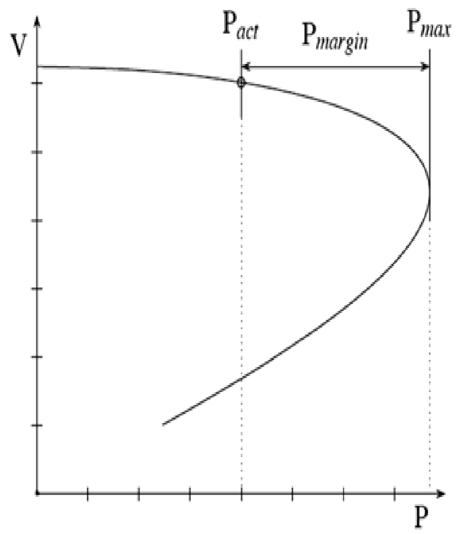


Figure3.3a: Stable and unstable regions in PV curves**Figure3.3b:**Power stability margin

- PV curves for varying power factor

It can be clearly seen from Figure3.4 that the inductive load (AR) has the minimum power compared to the resistive and capacitive loads, while the capacitive load(AV) corresponds to the maximum power. On the other hand, it can be noticed that the voltage drop is improved in the case of (AV) with respect to unitary and inductive.

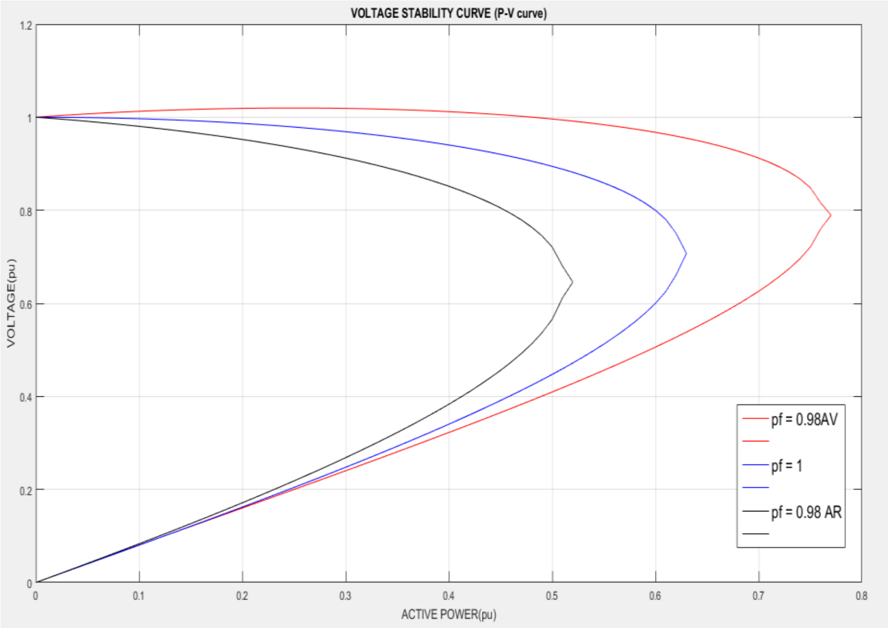


Figure 3.4 : Standardized *PV* curves for various power factors

- PV curves for different reactance of the line

Figure 3.5. shows the influence of the line reactance on the PV characteristic obtained, for different values of *X*, unlike the figure 3.4, it can be seen that when varying the reactance and increasing the power, the voltage drop remains the same throughout the three variations and it shows that the voltage stability margin increases when the line reactance decreases because from the equation 3.13 it's clear that increase in the reactance of the line will cause decrease in the transmission power.We can reduce the value of reactance by applying series capacitor compensation.

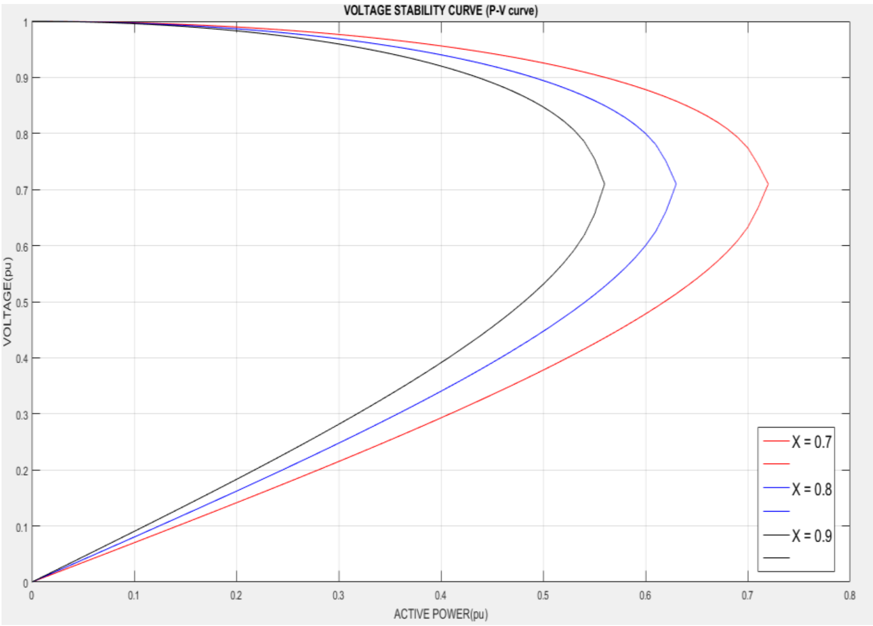


Figure 3.5: PV curve for various reactance(X)

- ✓ **QV curves**

Often, a more useful characteristic for certain aspects of voltage stability analysis is the QV curves. These can be used for assessing the requirements for reactive power compensation since they show the sensitivity and variation of bus voltages with respect to reactive power injections or absorptions.

Figure.3.7 shows a Q-V curve. Similar to the P-V curves, Q-V curves have a voltage stability limit, which is the bottom of the curve, where dQ/dV is equal to zero. The right hand side is stable since an increase in Q is accompanied by an increase in V. The left hand side is unstable since an increase in Q represents a decrease in V, which is one of the instability factors that judges that a system is voltage unstable if, for at least one bus in the system, the bus voltage magnitude decreases as the reactive power injection in the same bus is increased.[3]

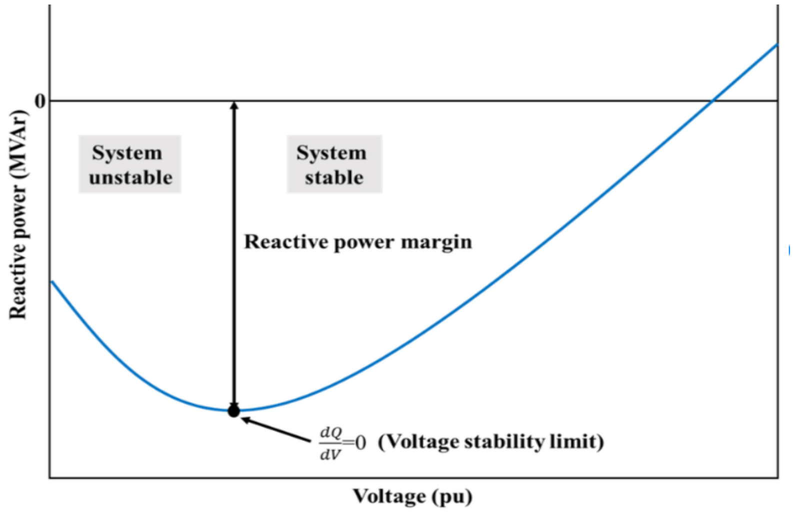


Figure 3.7:QV Characteristic curve

- QV curves for different reactance

Figure 3.8 shows the QV characteristics by varying the reactance. We can clearly see that the stability margin is increasing as the reactance of the line decreases .The value of the reactance can be reduced by shunt compensation so that the Q margin can be improved so as the voltage level and voltage stability.

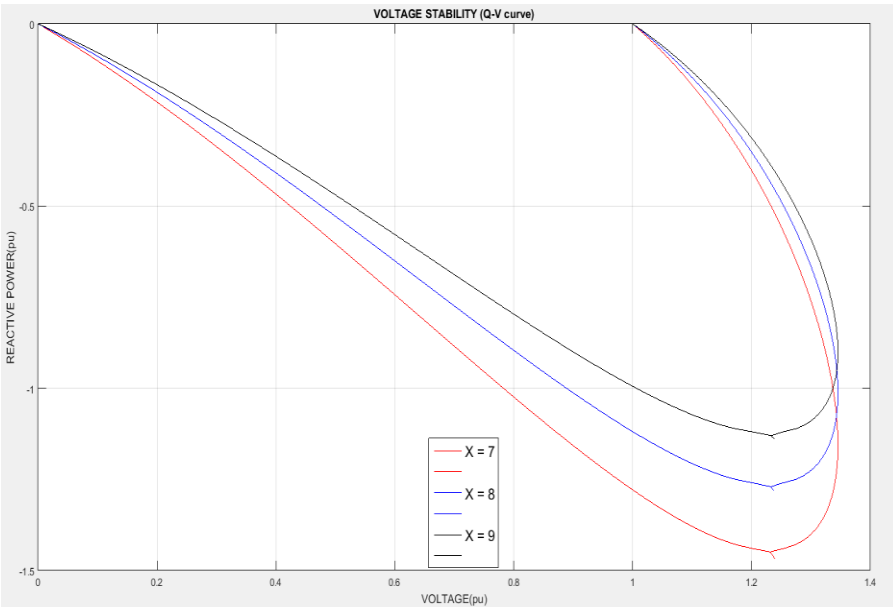


Figure 3.8:QV curve for different reactance (X)

- QV curves for different power factor

Figure 3.8 shows the QV characteristics by varying the power factor.

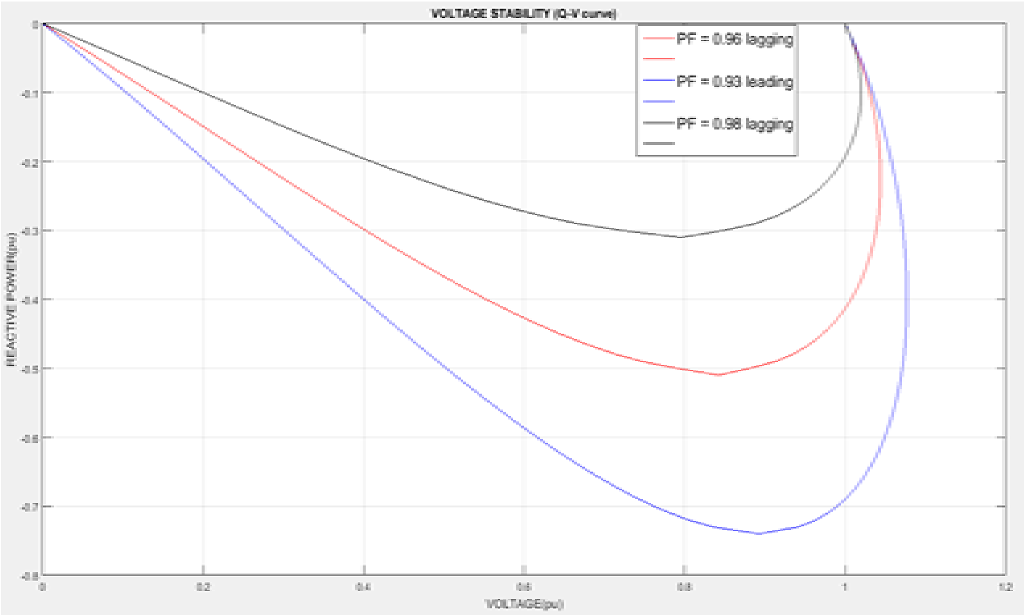


Figure 3.9:QV curve for different power factor

It can be clearly seen that changing the power factor from lagging to leading can potentially increase the voltage stability margin, allowing the system to operate at higher voltages before reaching the stability limit.

7.Impact of the DG size on voltage stability

Currently, most installed DGs are connected to operate at unity power factor to avoid interference with the voltage regulation devices connected to the system [32]. For this reason, this study assumes that the DG unit are operating at unity power factor Figure 3.9 visualizes the impact of a DG unit on voltage stability margin and maximum loadability. The x-axis represents λ, which is the scaling factor of the load demand at a certain operating point.λ varies from zero to the λ_{max}. Due to real power injection of a DG unit, the normal operating point of the voltage increases from V_1toV_2, and at the same time the maximum loadability increases from $\lambda_{max1}$to λ_{max2}.[31,32]

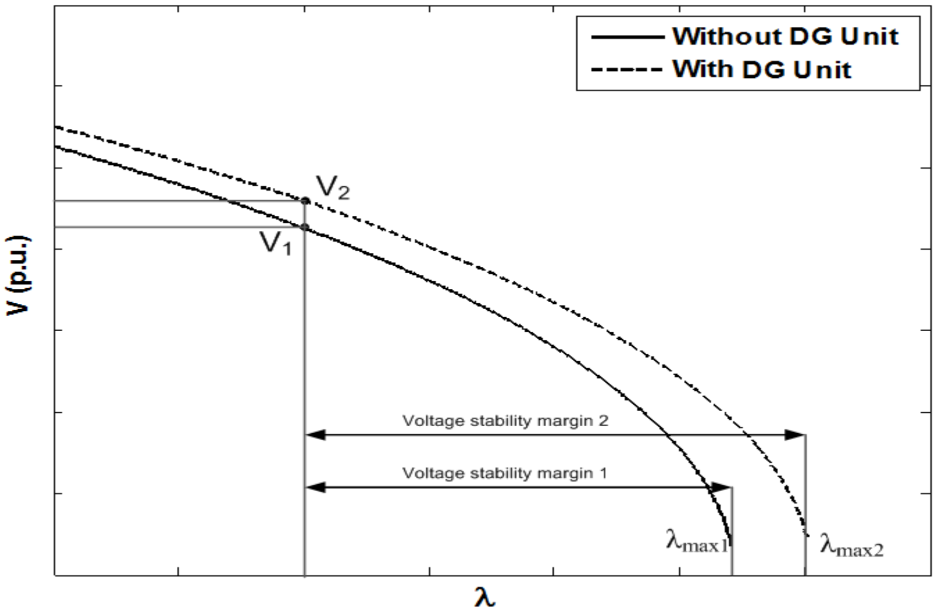


Figure 3.9: Impact of a DG unit on maximum loadability and voltage stability margin

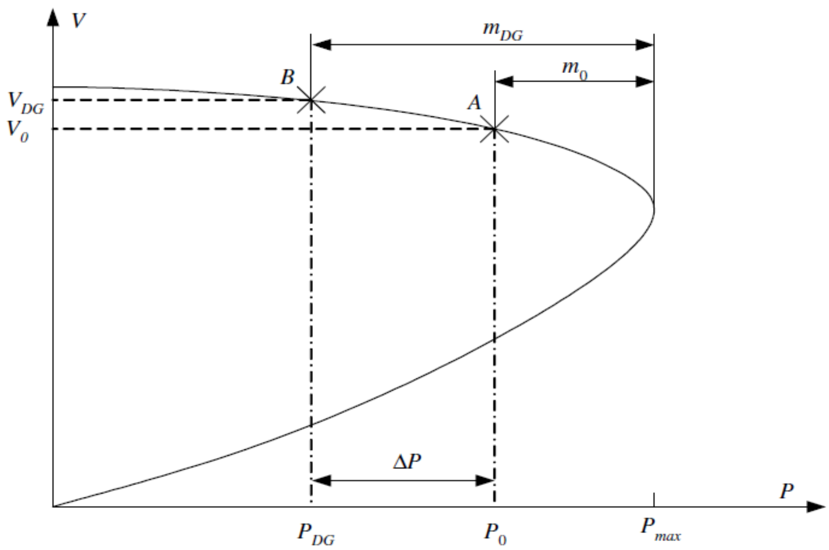


Figure 3.10: *P*-*V* curve: Enlargement of voltage stability margin[33]

Figure 3.10 shows the impact of a synchronous generator on voltage stability of a hypothetic node. As can be seen in the figure, the installation of a distributed generator of ΔP MW shifts the operation point on the associated *P*-*V* curve from point *A* to point *B*, which results in a raise of the node voltage by the amount V_{DG} - $V_0$and enhanced voltage security: the stability margin increases from m_0 to m_{DG}. An immediate conclusion to be drawn here is: the installation of a distributed generation will most likely enhance the voltage stability of the grid as long as the DG rating is smaller than twice the local loading level.[33]

CHAPTER 4: SIMULATION AND RESULTS

1.Introduction

The analysis of voltage stability in power systems is crucial. The purpose of this analysis is to maintain the balance of the system. In this chapter, we will perform an analysis using the PV and QV curves on the standard IEEE 9-bus network. First, we will perform a power flow calculation using the Newton Raphson method. Then, we will implement the program in MATLAB to visualize, first, the different PV and QV curves of the different buses.

2.Model of power system elements

In this chapter, the steady state models are used:

• The transmission system is modelled as an infinite bus.

• The electrical network is mathematically modelled as a nodal admittance matrix.

• The load is modelled as a constant PQ component.

• The DG is modelled as a PQ generator. However, when enough capacities of the shunt compensator are assumed in operation, they together will be modelled as a PV generator.

3.Description of the network

The network studied is the standard IEEE9-bus network shown in figure4.1.It consists of one swing bus,two generation PV buses and six load PQ buses.The base power of the network is 100MVA and the frequency is 60HZ.The line and load parameters are given in the table1 and table2 with:

Vbase = 230KV,Sbase = 100MVA,Zbase=529ohms .

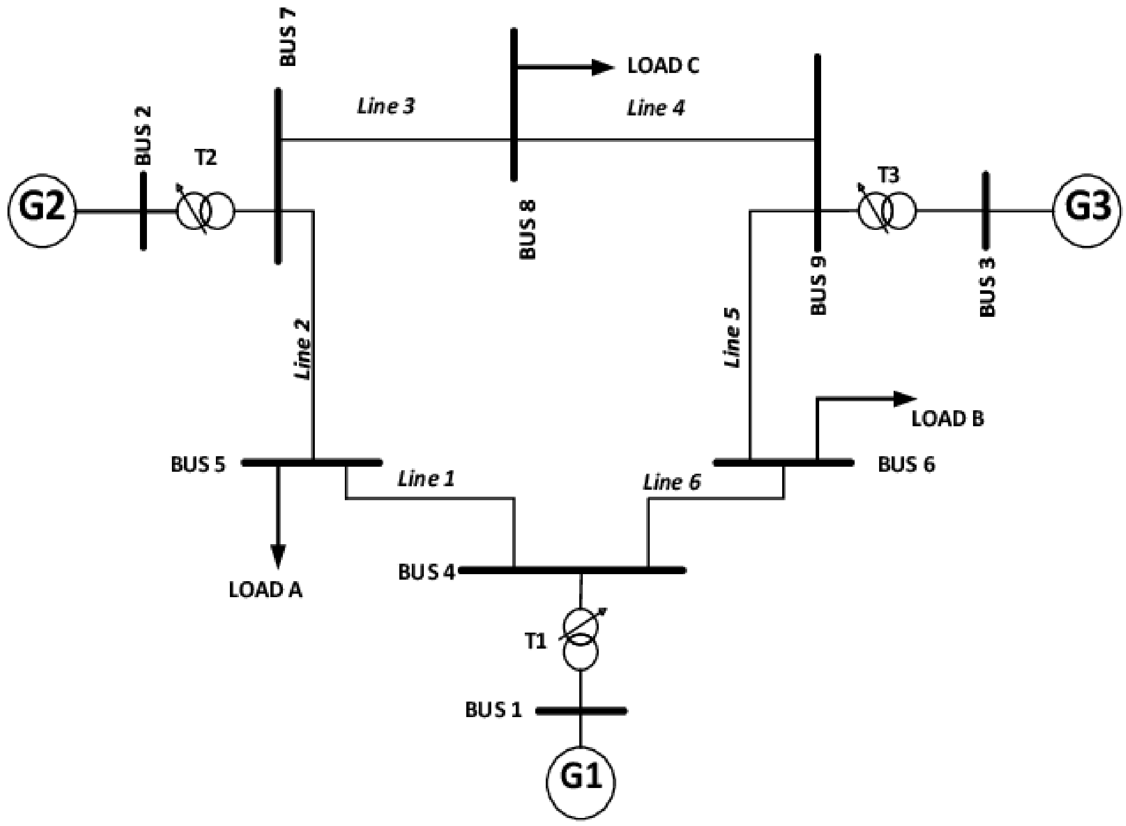


Figure4.1.IEEE9 bus network

The buses 1,2 and 3 are the strong buses since they are close to the generators .Thus ,the study will concern buses 5,6 and 8 where there is connected loads.

4.Parameters of 9bus system

Table1.Transmission Line Data

Line From	Line To	Resistance (R)pu	Reactance (X)pu	Susceptance (B)pu
1	4	0	0.0576	0
2	7	0	0.0625	0
3	9	0	0.0586	0
4	5	0.01	0.085	0.176
4	6	0.017	0.092	0.158
7	5	0.032	0.161	0.306
7	8	0.0085	0.072	0.149
9	8	0.0119	0.1008	0.209
9	6	0.039	0.17	0.358

Table 2.Bus Data

Bus number	Bus type	Bus Voltage (KV)	Bus Voltage (pu)	Angle(degree)	Generator		Load	
					P(MW)	Q(MVar)	P(MW)	Q(MVar)
1	Slack	16.5	1.04	0	0	0	0	0
2	PV	18	1.025	0	163	0	0	0
3	PV	13.8	1.025	0	85	0	0	0
4	PQ	230	1	0	0	0	0	0
5	PQ	230	1	0	0	0	125	50
6	PQ	230	1	0	0	0	90	30
7	PQ	230	1	0	0	0	0	0
8	PQ	230	1	0	0	0	100	35
9	PQ	230	1	0	0	0	0	0

- ✓ **Admittance matrix formation**

The formulation of the network admittance matrix is the first step in the analysis of the power system. It is based on the different parameters of the system lines.The admittance matrix is given as:

$$\text{Ybus} = \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} & Y_{14} & Y_{15} & Y_{16} & Y_{17} & Y_{18} & Y_{19} \\ Y_{21} & Y_{22} & Y_{23} & Y_{24} & Y_{25} & Y_{26} & Y_{27} & Y_{28} & Y_{29} \\ Y_{31} & Y_{32} & Y_{33} & Y_{34} & Y_{35} & Y_{36} & Y_{37} & Y_{38} & Y_{39} \\ Y_{41} & Y_{42} & Y_{43} & Y_{44} & Y_{45} & Y_{46} & Y_{47} & Y_{49} & Y_{49} \\ Y_{51} & Y_{52} & Y_{53} & Y_{54} & Y_{55} & Y_{56} & Y_{57} & Y_{58} & Y_{59} \\ Y_{61} & Y_{62} & Y_{63} & Y_{64} & Y_{65} & Y_{66} & Y_{67} & Y_{68} & Y_{69} \\ Y_{71} & Y_{72} & Y_{73} & Y_{74} & Y_{75} & Y_{76} & Y_{77} & Y_{78} & Y_{79} \\ Y_{81} & Y_{82} & Y_{83} & Y_{84} & Y_{85} & Y_{86} & Y_{87} & Y_{88} & Y_{89} \\ Y_{91} & Y_{92} & Y_{93} & Y_{94} & Y_{95} & Y_{96} & Y_{97} & Y_{98} & Y_{99} \end{bmatrix}$$

Where :

$$\begin{cases} Y_{ij} = \dfrac{1}{Z_{ij}} = \dfrac{1}{R_{ij} + jX_{ij}} \\ Y_{ii} = \sum_{j=0}^{n} y_{ij} \;\; j \neq i \\ Y_{ij} = Y_{ji} = -y_{ij} \end{cases}$$

5 .Application on the standard IEEE 9 bus network

The Simulink model of a standard 9 bus network system was designed and the results on figure4.2 were obtained.

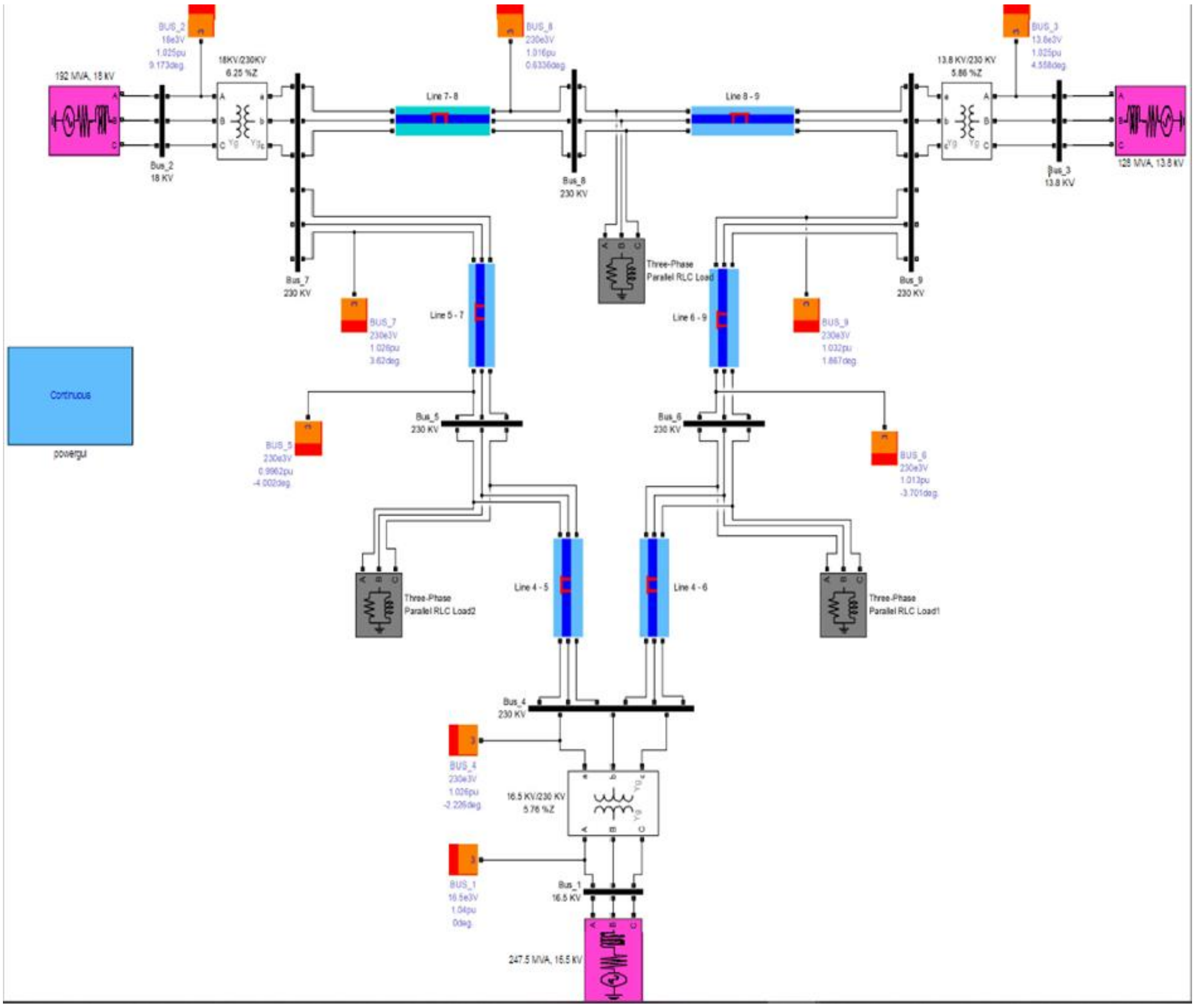


Figure 4.2:Simulink model of 9Bus system

	Block type	Bus type	Bus ID	Vbase (kV)	Vref (pu)	Vangle (deg)	P (MW)	Q (Mv...	Qmin (Mvar)	Qmax (Mvar)	V_LF (pu)	Vangle_LF (deg)	P_LF (MW)	Q_LF (Mvar)	Block Name
1	Vsrc	swing	BUS_1	16.50	1.0400	0.00	0.00	0.00	-Inf	Inf	1.0400	0.00	72.19	26.80	247.5 MVA, 16.5 kV
2	Bus	-	BUS_4	230.00	1	0.00	0.00	0.00	0.00	0.00	1.0261	-2.23	0.00	0.00	Load Flow Bus1
3	RLC load	PQ	BUS_5	230.00	1	0.00	125.00	50.00	-Inf	Inf	0.9962	-4.00	125.00	50.00	Three-Phase Parallel RLC Load2
4	RLC load	PQ	BUS_6	230.00	1	0.00	90.00	30.00	-Inf	Inf	1.0131	-3.70	90.00	30.00	Three-Phase Parallel RLC Load1
5	Bus	-	BUS_7	230.00	1	0.00	0.00	0.00	0.00	0.00	1.0259	3.62	0.00	0.00	Load Flow Bus4
6	Bus	-	BUS_9	230.00	1	0.00	0.00	0.00	0.00	0.00	1.0324	1.87	0.00	0.00	Load Flow Bus5
7	RLC load	PQ	BUS_8	230.00	1	0.00	100.00	35.00	-Inf	Inf	1.0160	0.63	100.00	35.00	Three-Phase Parallel RLC Load
8	Vsrc	PV	BUS_2	18.00	1.0250	0.00	163.00	0.00	-Inf	Inf	1.0250	9.17	163.00	6.69	192 MVA, 18 kV
9	Vsrc	PV	BUS_3	13.80	1.0250	0.00	85.00	0.00	-Inf	Inf	1.0250	4.56	85.00	-10.78	128 MVA, 13.8 kV

Figure 4.3.Results from 9bus Simulink model

The implementation of the power flow calculation program on MATLAB software allowed us to obtain the following results:

Table3:Power flow results

Bus Number	Generated Power		Load power		Bus Voltage (pu)	Angle (degrees)
	P(MW)	Q(MVar)	P(MW)	Q(MVar)		
1	71.6	27	0	0	1.04	0
2	163	6.7	0	0	1.025	9.3°
3	85	-10.9	0	0	1.025	4.7°
4	0	0	0	0	1.026	-2.2°
5	0	0	125	50	0.996	-4°
6	0	0	90	30	1.013	-3.7°
7	0	0	0	0	1.026	3.7°
8	0	0	100	35	1.016	0.7°
9	0	0	0	0	1.032	2°

Ybus =

$$\begin{bmatrix} 17.3611i & 0 & 0 & 17.3611i & 0 & 0 & 0 & 0 & 0 \\ 0 & -16i & 0 & 0 & 0 & 0 & 16i & 0 & 0 \\ 0 & 0 & -17.0648i & 0 & 0 & 0 & 0 & 0 & 17.0648i \\ 17.3611i & 0 & 0 & 3.3074-39.1419i & -1.3652+11.6041i & -1.9422+10.5107i & 0 & 0 & 0 \\ 0 & 0 & 0 & -1.3652+11.6041i & 2.5528-17.0972i & 0 & -1.1876+5.9751i & 0 & 0 \\ 0 & 0 & 0 & -1.9422+10.5107i & 0 & 3.2242-15.5829i & 0 & 0 & -1.282+5.5882i \\ 0 & 16i & 0 & 0 & -1.1876+5.9751i & 0 & 2.8047-35.2181i & -1.6171+13.698i & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1.6171+13.6980 & 2.7722-23.1242i & -1.1551+9.7843i \\ 0 & 0 & 17.0648i & 0 & 0 & -1.2820+5.5882i & 0 & -1.1551+9.7843i & 2.4371-31.870i \end{bmatrix}$$

We can clearly see that the results from power flow calculations and those from Matlab Simulink are almost the same.

5.1.PV and QV curves of 9bus system

PV and QV curves of the 9bus system for different power factor on different buses, was performed and the results are displayed on the table4.

Table 4: Load voltages at different bus and power factor

Load voltage at bus 5, θ =-45◦			Load voltage at bus 6 , θ = 30◦			Load voltage at bus 8, θ =15◦		
P(MW)	Q(MVar)	V(pu)	P(MW)	Q(MVar)	V(pu)	P(MW)	Q(MVar)	V(pu)
0	0	1.047	0	0	1.0492	0	0	1.0437
10	-10	1.055	10	6	1.0434	10	3	1.0417
55	-55	1.0886	25	14	1.0352	30	8	1.0382
105	-105	1.1217	40	23	1.0257	45	12	1.0351
120	-120	1.1309	50	28	1.0201	60	16	1.0317
150	-150	1.1484	75	43	1.0031	75	20	1.0282
165	-165	1.1567	95	55	0.9885	90	24	1.0244
180	-180	1.1648	110	64	0.9769	110	29	1.0193
200	-200	1.1751	130	75	0.9616	135	36	1.0117
215	-215	1.1826	140	81	0.953	150	40	1.007
230	-230	1.1898	170	98	0.9263	180	48	0.9967
245	-245	1.1969	190	109	0.907	200	54	0.9887
260	-260	1.2036	210	121	0.8845	220	59	0.9808
300	-300	1.2207	230	133	0.8594	230	62	0.9763
400	-400	1.2573	245	141	0.8397	240	64	0.9724
500	-500	1.2857	250	144	0.8322	330	88	0.9232
700	-700	1.3162	270	156	0.7986	410	110	0.8558
900	-900	1.2753	290	167	0.7588	460	123	0.7841
			310	179	0.6988	500	134	
BLACKOUT CONDITION IS REACHED								

Figure4.4 and Figure 4.5 shows the PV and QV curves for the power flow results in table4

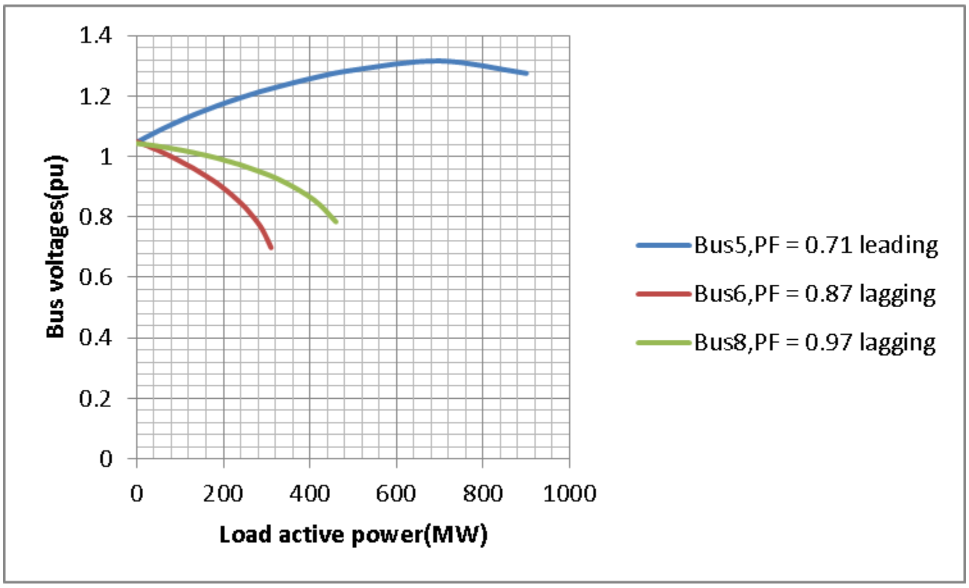


Figure 4.4:PV Curves at different bus

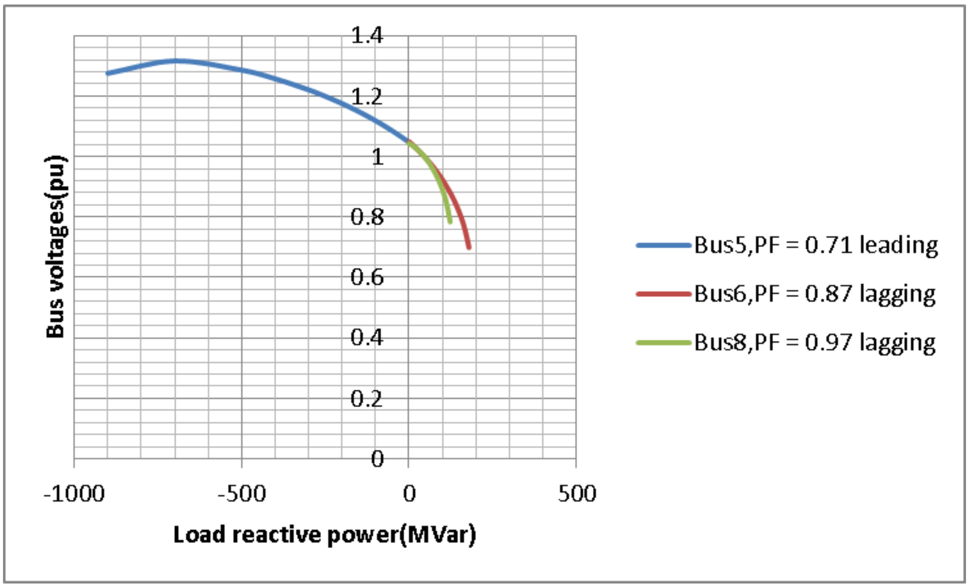


Figure 4.5:QV Curves at different buses

Interpretation

It is observed from the PV and QV curves that the load power factor values have the significant effects on the enhancement of power system voltage stability.As the load power factor varies from lagging to leading , the loading capabilities of power systems also go on increasing due to continuous increment in load angle.The study of such curves also suggests that various voltage stability control methods and devices should be properly introduced in critically affected buses in order to avoid chances of system **blackouts.**

5.2.Influence of the power factor

Since bus 5 is on of the weakest bus, this study will focus on this bus.

- **PV Characteristic**

Figure 4.6 shows the PV characteristics of bus 5 for different values of power factor.

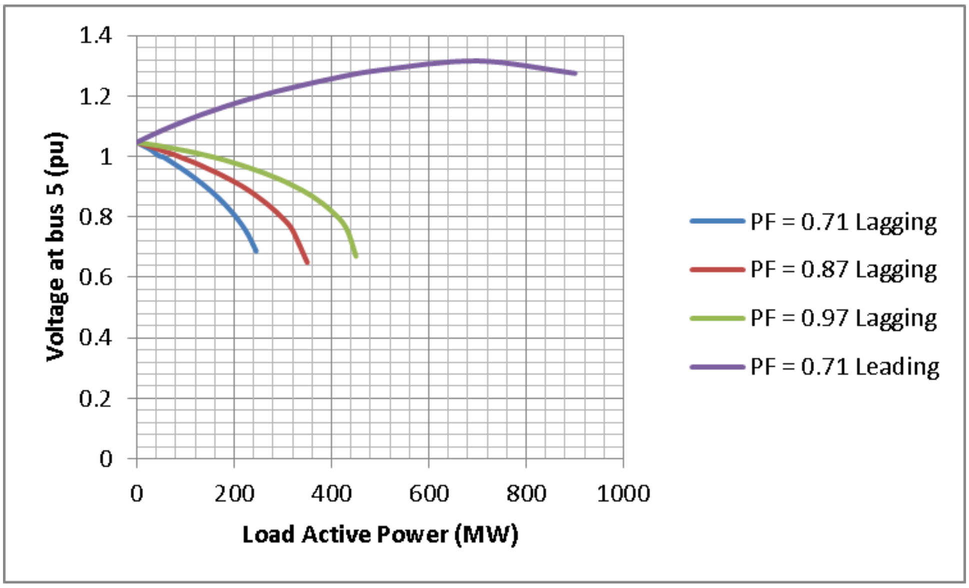


Figure 4.6:PV curves at bus 5

Interpretation

The PV curves of the 5th bus, shown in Figure 4.6, illustrate the influence of different power factors on the voltage stability. It can be seen that when the power factor changes from an inductive to a capacitive load, the power transmitted through the line increases and the voltage drop decreases.

- **QV Characteristics**

Figure 4.7 shows the QV characteristics of bus 5 for different values of power factor.

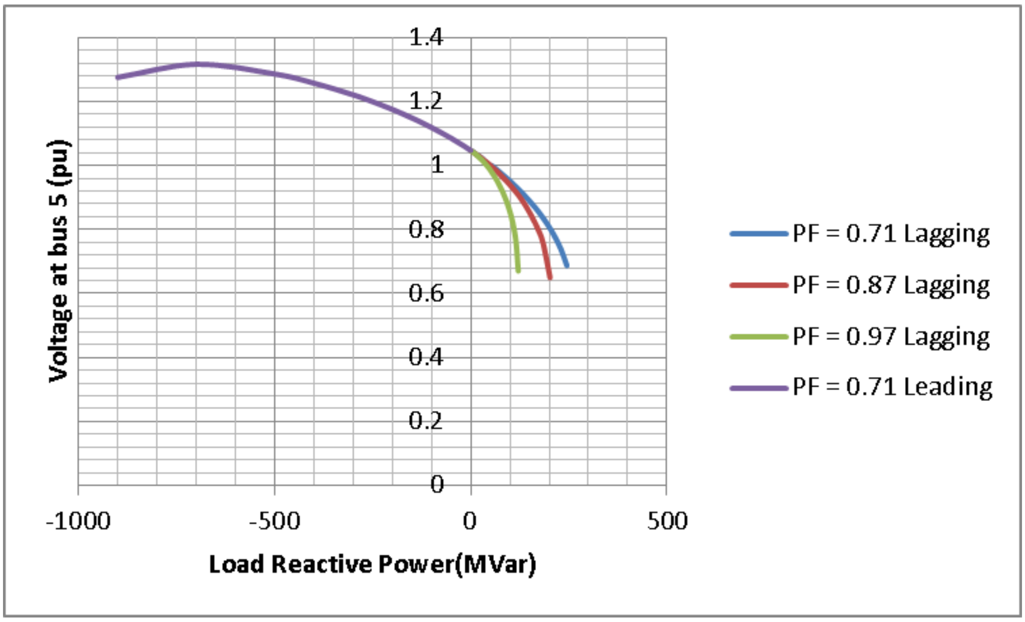


Figure 4.7:QV curves at bus 5

Interpretation

The QV curves of 5th bus shown in figure 4.7, illustrate the influence of different power factors on voltage stability. It can be seen that for lagging power factors, the load bus voltages falls rapidly, VAR compensation is necessary to maintain voltage stability. When the power factor changes from an inductive to a capacitive load, the reactive power decreases, hence the stability margin increases.

- **PV curves at different buses**

The PV curves of the different buses for constant power factor are shown in Figure 4.8.

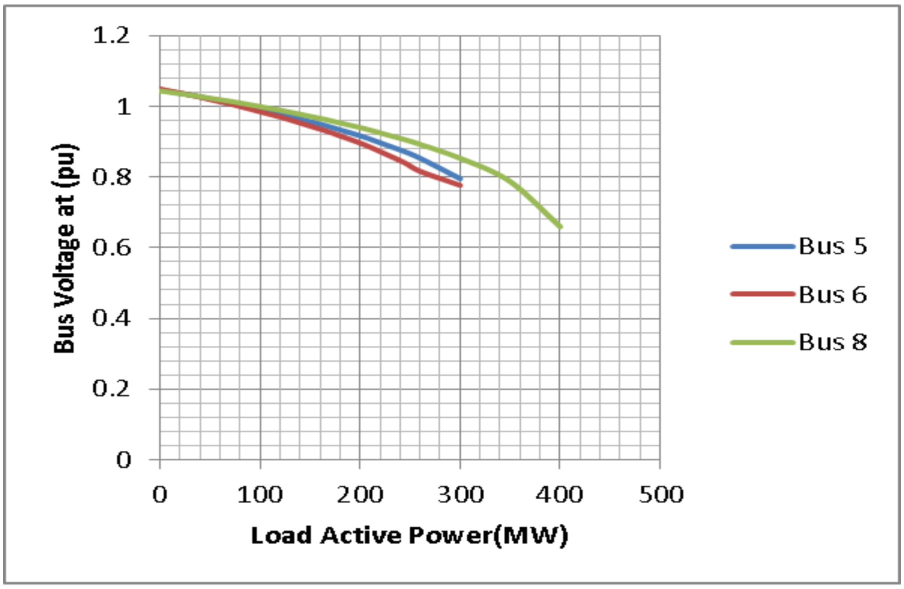


Figure4.8.PV curves at different buses

Interpretation

It can be seen that bus 8 is the strongest bus among the three buses because it has the largest stability margin because it is located between two generators.Bus 5 and 6 have almost similar stability margin smaller than that of bus 8.It can be seen that Bus 6 is the weakest bus because of its weakest stability margin.The further analysis was done on the system by integrating DG at bus 6.This choice was made since it has the weakest stability in order to improve it.

6.Influence of the DG on voltage stability

In this study,PV and QV curves are used to examine how DG integration affects a power system’s voltage stability margin and voltage drop.A series of power flow was done,and then figure4.9 shows the obtained PV curves .

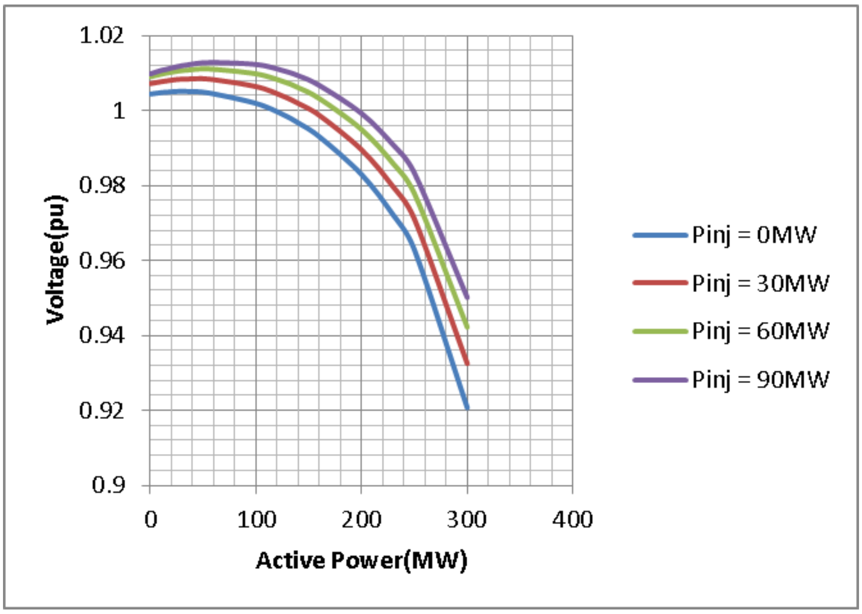


Figure4.9.PV Curves of bus 6 for the different DG sizes(different active power injected)

Interpretation

The analysis was done on the system by connecting different sizes of DGs at bus 6.This choice was made because the stability margin of bus 6 is the weakest and in order to improve it.It can be seen that the critical voltage point increase when increasing DG size(power active injection) hence generates an improvement in the stability of the bus. Also the stability margin is improving with augmentation of the size of DG.

7.Conclusion

In this chapter, we have performed a static voltage stability analysis for a standard IEEE 9-bus network in order to study the voltage drop and the stability margin, in a first step. Then, in a second step, the influence of the power factor on the voltage stability of this system. The last part we studied the influence of DG on the voltage stability of this system .We used the Newton Raphson method to make a power flow, as well as to obtain the PV and QV curves for the analysis of the voltage stability. With the help of these curves, the impact of the power factor and DG on the voltage stability of this system was observed.

GENERAL CONCLUSION

General Conclusion

The purpose of the study presented in this thesis was to analyse the impact of DG on voltage stability of a standard IEEE 9-busnetwork, using one of the static methods, the PV and QV curves.

In a first step, this study defined the DG, the type of DG and it's structures, the electric grid and the different ways of connecting DG to the electric grid.

In a second step, this study defined the stability of electrical networks, exposed the different types of this stability, voltage instability and its causes and the methods of voltage stability analysis. Finally the impact of DG on voltage stability and power system in general.

In the third step, this study allowed the power flow to be performed ,PV and QV curves to be plotted, allowing a static voltage stability analysis.

Finally ,a voltage stability analysis of a standard IEEE9-bus network was performed using the PV and QV curves analysis.

From these curves, the influence of the power factor on the voltage stability can also be seen .When the power factor changes from an inductive load to a capacitive load, the power transmitted through the line increases, the voltage drop decreases and the reactive power decreases, that means the stability margin increases.

This study allowed us to identify the weakest bus of the network so that necessary measures can be taken to prevent a black out in a power system.

Concerning the impacts of DG on the voltage stability of power systems, the

following conclusions are drawn:

- In general the integration of DG improves the voltage stability of the distribution system.
- The Location of the DG has main effect on voltage stability.

PV and QV curves are two simple approaches to find the critical voltage point and the stability margin when the system is in a steady state.

REFERENCES

References

[1] IEEE Std 1547-2003, "IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems,", 2003,K Kauhaniemi, L. K, “Impact of Distributed Generation on the Protection of Distribution Networks”, University of Vaasa, Finland, VTT Technical Research Centre of Finland, Finland. (2004).

[2]P. Kundur, Power System Stability and Control. New York: McGraw-Hill, 1994.

[3] T. Van Cutsem and C. Vournas, Voltage Stability of Electric Power Systems. Norwell, MA:Kluwer, 1998.

[4] IEA, Renewable Energy, Market and Policy Trends in IEA Countries,International Energy Agency, France, 2004

[5] I. Munteanu, A. Bratcu, N. Cutululis, and E. Ceanga, Optimal Control of Wind Energy Systems, T. Ackermann, Wind Power in Power Systems.

[6] https://justenergy.com/blog/everything-you-need-to-know-about-wind-energy/

[7] “The Inside of a Wind Turbine.” Energy.gov. US Department of Energy. Web. 21 Sept. 2016.

[8] “Wind Energy Basics.” Wind Energy Basics. Wind Energy EIS. Web. 21 Sept. 2016

[9]https://www.technicalbookspdf.com/electrical-grid/

[10] J. Enslin, “Interconnection of distributed power to the distribution network,” 2004

IEEE PES Power Syst. Conf.and Exposition, pp. 726-731 vol.2.

[11] T. Wildi, Electrical Machines, Drives, and Power Systems. Prentice Hall, 2002.

[12] I. Munteanu, A. Bratcu, N. Cutululis, and E. Ceanga, Optimal Control of Wind Energy Systems: Towards a Global Approach, ser. Advances in Industrial Control. Springer London, 2008. [Online]. Available: https://books.google.es/books?id=WwBjirAXql0C

[13] T. Ackermann, Wind Power in Power Systems. Wiley, 2012. [Online].Available:https://books.google.dz/books?id=y7430s86pQAC&printsec=frontcover&hl=fr&source=gbs_ge_summary_r&cad=0

[14] G. Abad, J. Lopez, M. Rodriguez, L. Marroyo, and G. Iwanski, Doubly Fed Induction Machine: Modeling and Control for Wind Energy Generation, ser. IEEE Press Series on Power Engineering. Wiley, 2011. [Online]. Available:

https://books.google.es/books?id=JzvjOp8pY8QC

[15] T. R. E. H. UK. (2018) How does a wind turbine work? [Online]. Available:

https://www.renewableenergyhub.co.uk/main/wind-turbines/how-does-a-wind-turbine-work/

[16] Anca D. Hansen,Gabriele Michalke,Poul Sørensen and Torsten LunCo-ordinated Voltage Control of DFIG Wind Turbines in Uninterrupted Operation during Grid Faults WIND ENERGY Denmark 2006

[17] MOHAMMAD SEYEDI ."Evaluation of the DFIG Wind Turbine Built-in Model in PSS/E".Sweden, 2009.

[18] Oukrid.J, Mahtout.A,« impact des productions distribuées sur le réglage de la tension», mémoire de fin d'études, université A. MIRA, 2018/2019.

[19] G. Abad, J. Lopez, M. Rodriguez, L. Marroyo, and G. Iwanski, Doubly Fed Induction Machine: Modeling and Control for Wind Energy Generation

[20] P. Barker and R. De Mello, "Determining the impact of distributed generation on power systems. I. Radial distribution systems," 2000 IEEE Power Eng. Soc. Winter Meeting, pp. 1645-1656 vol. 3.

[21] N. Jenkins, R. Allan, I.O.E. Engineers, P. Crossley, D. Kirschen, and G. Strbac,Embedded generation, IET, 2000.

[22]P. Kundur, N. J. Balu, and M. G. Lauby, Power System Stability and Control: McGraw-Hill Professional, 1994.

[23] J. J. Grainger and W. D. Stevenson, Power System Analysis: McGraw-Hill Inc., 1968.

[24] CIGRE, "CIGRE Technical Brochure on Modeling New Forms of Generation and Storage,"CIGRE TF 38.01.10, November 2000.

[25] N. Jayawarna, X. Wu, Y. Zhang, N. Jenkins, and M. Barnes, "Stability of a MicroGrid," inIET International Conference, Power Electronics, Machines and Drives, 2006. , 2006, pp.316-320

[26] T.V. Cutsem and C. Vournas, Voltage stability of electric power systems, Springer,1998.

[27] P. Kundur, J. Paserba, V. Ajjarapu, G. Andersson, A. Bose, C. Canizares, N.Hatziargyriou, D. Hill, A. Stankovic, C. Taylor, T. Van Cutsem, and V. Vittal,"Definition and classification of power system stability IEEE/CIGRE joint task force on stability terms and definitions," IEEE Trans. Power Syst., vol. 19, 2004,pp. 1387-1401

[28]Idri.S, Khaldi.F, « Amélioration des performances de la tension et la stabilité d'un réseau électrique par la compensation de la puissance réactive. », mémoire de fin d'études, épatement génie électrique, université A. MIRA, 2017/2018.

[29] P. Kundur, J. Paserba, V. Ajjarapu, G. Andersson, A. Bose, C. Canizares, N. Hatziargyriou,D. Hill, A. Stankovic, C. Taylor, T. Van Cutsem, and V. Vittal, "Definition and classification of power system stability IEEE/CIGRE joint task force on stability terms and definitions,"IEEE Trans. Power Syst., vol. 19, pp. 1387-1401, 2004.

[30] V. Ajjarapu, Computational Techniques for Voltage Stability Assessment and Control.New York: Springer Science, 2006.

[31] R. A. Walling, R. Saint, R. C. Dugan, J. Burke, and L. A. Kojovic, "Summary of Distributed Resources Impact on Power Delivery Systems," IEEE Trans. Power Del., vol. 23, pp. 1636-1644, 2008.

[32] H. H. Zeineldin, E. F. El-Saadany, and M. M. A. Salama, "Distributed generation micro-grid operation: control and protection," in Power Systems Conference: Advanced

Metering,Protection, Control, Communication, and Distributed Resources, pp. 105-111, 2006.

[33] J.V. Milanovic and T.M. David. Stability of distribution networks with embedded generators and induction motors. IEEE PES Winter Meeting,2:1023–1028, 2002.