ROLE OF DISTRIBUTED GENERATION ON POWER SYSTEM STABILITY

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ABSTRACT

According to the increasing utilization in power system, the transmission lines and power plants often operate in stability boundary. Systems probably lose its stable condition when over loading or occurring any disturbance. The decline of voltage stability level will restrict the increase of load served by distribution companies. Increasing distributed Generation (DG) in distribution power systems has the ability to meet some of the growing energy. The development of DGs will bring new chances to traditional power systems. DGs connected to distribution networks are potential to improve the system voltage stability. One of the DG technologies is wind turbines, integration of wind turbine may have significant impacts on power system operation. Generation of electricity from wind power has received considerable attention because it is plentiful, renewable, produces no greenhouse gas emissions during operation and uses little land. This research investigates the effect of fixed speed grid connected wind turbine on the voltage stability of a 2-bus test system, standard IEEE 14-bus system and IEEE 30-bus system. The wind turbine considered as squirrel cage induction generator (SCIG) with a fixed speed because it is simple, reliable, cheap, requires very little maintenance. The voltage stability for the network is determined by its corresponding notch P-V curve, obtained from continuity power flow (CPF). The studies include examining the voltage stability, voltage magnitude and loading margin of the system. The modelling and simulation is done with MATLAB and a toolbox for stability purposes, called PSAT (Version 2.1.6).

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ABSTRAK

Berdasarkan kepada peningkatan penggunaan tenaga didalam sistem kuasa, talian penghantaran dan loji kuasa sering beroperasi dalam keadaan stabil. Kemungkinan untuk sistem hilang kestabilan adalah tinggi semasa keadaan lebih muatan atau semasa gangguan berlaku. Penurunan tahap kestabilan voltan akan menghalang peningkatan tahap beban permintaan yang diperlukan oleh syarikat penghantaran. Dengan meningkatkan penjanaan dan pengagihan (DG) didalam sistem pengagihan kuasa akan membantu untuk memenuhi sebahagian daripada permintaan tenaga yang semakin meningkat. Pembangunan didalam penjanaan dan pengagihan (DG) akan membawa peluang baharu kepada sistem kuasa tradisional. Penjanaan dan pengagihan (DG) akan dihubungkan dengan rangkaian pengagihan yang berpotensi untuk meningkatkan tahap kestabilan sistem voltan. Salah satu diantara penjanaan dan pengagihan (DG) ialah turbin angin; penyepaduan turbin angin boleh memberi kesan yang besar kepada operasi sistem kuasa. Penjanaan kuasa elektrik daripada kuasa angin menerima perhatian yang menggalakkan kerana ia banyak, boleh diperbaharui, tidak menghasilkan pembebasan gas rumah hijau semasa beroperasi dan menggunakan keluasan tanah yang sedikit. Kajian ini adalah untuk mengkaji kesan grid kelajuan tetap yang disambungkan dengan turbin angin pada sistem kestabilan sistem ujian voltan 2-bas, IEEE standard 14-bas sistem dan IEEE 30-bas sistem. Turbin angin dianggap sebagai penjana aruhan sangkar tupai (SCIG) dengan kelajuan yang telah ditetapkan kerana ia mudah, kebolehpercayaan, murah dan memerlukan penyelenggaraan yang sedikit. Tahap kestabilan voltan untuk rangkaian ditentukan oleh takuk pada lengkung P-V berkaitan, yang diperolehi daripada aliran kuasa berterusan (CPF). Kajian yang dijalankan termasuklah mengkaji kestabilan voltan, magnitud voltan dan margin muatan sistem. Pemodelan dan simulasi dilakukan dengan menggunakan MATLAB dan menggunakan PSAT (Version 2.1.6) untuk tujuan kestabilan.

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LIST OF SYMBOLS AND ABBREVIATIONS

A_r	-	Area swept by the rotor
b_c	-	Fixed capacitor conductance
C_p	-	Performance coefficient
I	-	Complex current
K	-	Stress direction
n_b	-	Number of blades
P_D	-	Active power demand
P_G	-	Generated active power
P_i	-	Injected active power
P_{ij}	-	Active power transmitted from bus i to bus j
PL	-	Active power losses
Q_D	-	Reactive power demand
Q_G	-	Generated reactive power
Q_i	-	Injected reactive power
Q_{ij}	-	Reactive power trasmitted from bus i to bus j
Q_L	-	Reactive power losses
r_S	-	Stator resistance
R	-	Resistance
S_D	-	Complex power demand
S_i	-	Complex injected power
S_{ij}	-	Complex power transmitted from bus i to bus j
V	-	Bus voltage magnitude
v_t	-	blade tip speed
V_i	-	Voltage magnitude at bus i
V_w	-	Wind upstream the rotor
X	-	Total line reactance

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y_{ij}	-	Elements of bus admittance matrix
Y_T	-	Shunt admittance
Z_L	-	Series impedance
θ	-	Bus voltage angle
λ	-	Load parameter
ρ	-	Resistivity
ω_{wr}	-	Rotor speed
η_{GB}	-	Gear box ratio
ΔP	-	The incremental change in bus real power
ΔQ	-	The incremental change in bus reactive power
ΔV	-	The incremental change in bus voltage magnitude
Δθ	-	The incremental change in bus voltage angle
[B]	-	Susceptance matrix
[G]	-	Conductance matrix
[J]	-	Jacobian matrix
[Y]	-	Admittance matrix
AVR	-	Automatic voltage regulator
CIGRE	-	International Council on Large Electric Systems
CIRED	-	The International Conference on Electricity Distribution
CPF	-	Continuation Power Flow
DFIG		Doubly Fed Induction Generator
DG	-	Distributed Generation
FC	-	Fuel Cell
IC	-	Internal Combustion
IEEE	-	Institute Of Electrical And Electronics Engineers
Lm	-	Loading margin
MT	-	Microturbine
PV	-	Photovoltaic
PSAT	-	Power System Analysis Toolbox
PL	-	Penetration Level
SCIG	-	Squirrel Cage Induction Generator
WT	-	Wind Turbine
WTGS	-	Wind Turbine Generating System

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CHAPTER 1

INTRODUCTION

1.1 General

Nowadays power system is a large complex interconnected network that consists of many buses and generators. The network is developing everyday with the increase in demand and energy demand is expected to grow at an annual rate of 53 percent between 2008 and 2035 [1]. The conventional electric power generation systems in the world are based on fossil fuels (coal, oil and natural gas), nuclear power and hydropower [2]. Either new installation of power generating stations and transmission lines is required or the existing infrastructure operation has to be extended to limits. As a result, the existing transmission lines are heavily loaded than ever before and one consequence of this is the threat of losing stability following a disturbance. So the voltage stability is an unavoidable factor in the normal operation of a power system [3, 4].

Voltage instability problems and voltage collapse typically occur in power systems which are unable to meet the demand for reactive power or they are heavily loaded and/or faulted [5]. Due to load increasing in a typical network, reactive power demand increases consequently and it redounds to more voltage decrease. If the demand goes over this critical point, voltage collapse and network instability will be inevitable. Therefore, it is necessary to consider voltage stability constraints for planning and operation of distribution systems [6].

Distributed generation (DG) is increasingly drawing great attention of people. The development of DGs will bring new chances to traditional distribution networks.

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1.2 Distributed Generation

DG refers to small sources ranging between 1 kW and 50 MW electrical power generations, which are normally placed close to consumption centers as shown in Figure 1.1. Specifically, DGs connected to networks have the potential to improve system voltage stability [7].

DG renders a group of advantage such as economic, environmental, and technical. The economic advantages are the reduction of transmission and distribution costs, reduction of electricity price, and saving of fuel. Environmental advantages entail reductions of sound pollution and emissions of greenhouse gases. The technical advantages cover a wide variety of benefits, such as line loss reduction, peak shaving, and increased system voltage profile. Hence, increased power quality relieved transmission and distribution congestion as well as grid reinforcement. It can also provide stand-alone remote applications with the required power [8].

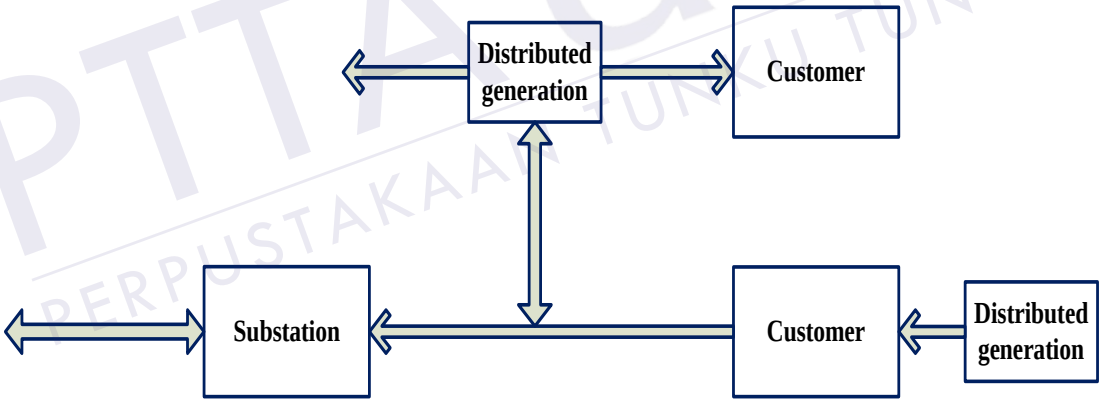

Figure 1.1: Illustration of the distributed generation concept with generation capacity closer to the customer base

The researches on the voltage stability can be classified into static and dynamic analysis. This project uses the static analysis to discuss the impacts of DGs on the voltage stability in distribution systems. In static voltage stability study, continuation power flow (CPF) method is the main analysis technique and it is used to find voltage stability margin or loading margin (Lm) of the system. The CPF technique involves in solving a series of load flow calculation with predictor and corrector steps [9].

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1.3 Problem Statement

Integrating DG units into distribution systems can have an impact on different practices such as voltage profile, power flow, power quality, stability, reliability, and protection. The impact of the DG units on stability problem can be further classified into three issues: voltage stability, angle stability, and frequency stability. As both angle and frequency stability are not often seen in distribution systems, voltage stability is considered to be the most significant in such systems. However, the following facts alter this situation:

- With the development of economy, load demands in distribution networks are sharply increasing. Therefore, the distribution networks are operating more close to the voltage instability boundaries.
- 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.

1.4 Objectives

The objectives of this research are:

i) To investigate the impact of DG (fixed speed wind turbine systems) on voltage stability of distribution networks (2 bus test system, IEEE 14-bus system and IEEE 30-bus system.

ii) To simulation and analyze the voltage stability of distribution systems.

iii) To enhance and improve the voltage stability of distribution systems with penetration of DG.

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1.5 Scopes

The main scope for this project is:

i) The DG technology has been limited to fixed speed wind turbine, which are based on induction generators.

ii) To evaluate the wind penetration level in the test network in the system, voltage stability for the developed network is determined by its corresponding P-V curve that obtained from CPF.

iii) The simulation analysis was established on network by PSAT/MATLAB, which gives access to an extensive library of grid components and relevant wind turbine model.

1.6 Outline of the Thesis

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

Chapter 1 is containing the introduction, problem statement, objective and scopes to the thesis.

Chapter 2 presents a literature survey on DG and system stability. In the distributed generation part, different definitions, types of DGs, types of interfacing and the impact of the DGs on power system are discussed. The second part of the survey is dedicated to system stability beginning with introducing the power system stability and its types. The impacts of DG units on system stability are presented in this part. Also, it provides a survey on a method to place and size DG units to improve the voltage stability margin in a distribution system.

Chapter 3 includes the project methodology. This will explain how the project is organized and the flow of the process in completing this project. Details about tools (CPF) and equipment that have been used.

Chapter 4 presents the results of simulation runs using PSAT/MATLAB for 2 bus test system, IEEE 14-bus system and IEEE 30-bus system.

Lastly, in Chapter 5 the conclusions and future recommendation of this project are presented.

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CHAPTER 2

LITERATURE REVIEW

This chapter presents the state of the art and literature review on distributed generation and voltage stability.

2.1 Distributed Generation

Based on the literature, there is no consistent definition of DG. The definition can be diversified based on voltage level, unit connection, type of prime-mover, generation not being dispatched, and maximum power rating.

Institute of Electric and Electronic Engineers (IEEE) 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 [10]. A more precise definition is provided by the International Council on Large Electric Systems (CIGRE) [11] and The International Conference on Electricity Distribution (CIRED) [12], which defines DG based on size, location, and type. CIGRE defines distributed generation as "all generation units with a maximum capacity of 50 MW to 100 MW, that are usually connected to the distribution network and that are neither centrally planned nor dispatched." CIRED defines DG to be "all generation units with a maximum capacity of 50 MW to 100MW that are usually connected to the distribution network." Chambers looks into the economic side in his definition. He defines distributed

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generation as “the relatively small generation units of 30MW or less that are sited at or near customer sites to meet specific customer needs, to support economic operation of the distribution grid, or both” [13]. Dondiet defines distributed generation as “a small source of electric power generation or storage (typically ranging from less than a kW to tens of MW) that is not a part of a large central power system and is located close to the load” [14]. He includes the storage facilities on his definition.

2.2 DG Technologies

DG can be divided into two main groups: renewable DG and fueled DG. Most fueled DG technologies use fossil fuels as their primary energy resource to generate electricity, or as a means to produce alternative fuels. Fuel based technologies include conventional steam and combustion turbines, internal combustion (IC) engine generators, microturbines (MT), and fuel cells (FC). Renewable energy resources are becoming more important due to fossil fuel resource depletion, priceassociated risks, and environmental concerns. On the other hand, renewable energy resources are sustainable and environmentally friendly. Renewable resource-based technologies include photovoltaic cells (PV), wind turbines (WT), and small-scale hydro-generation as shown in Figure 2.1 [15].

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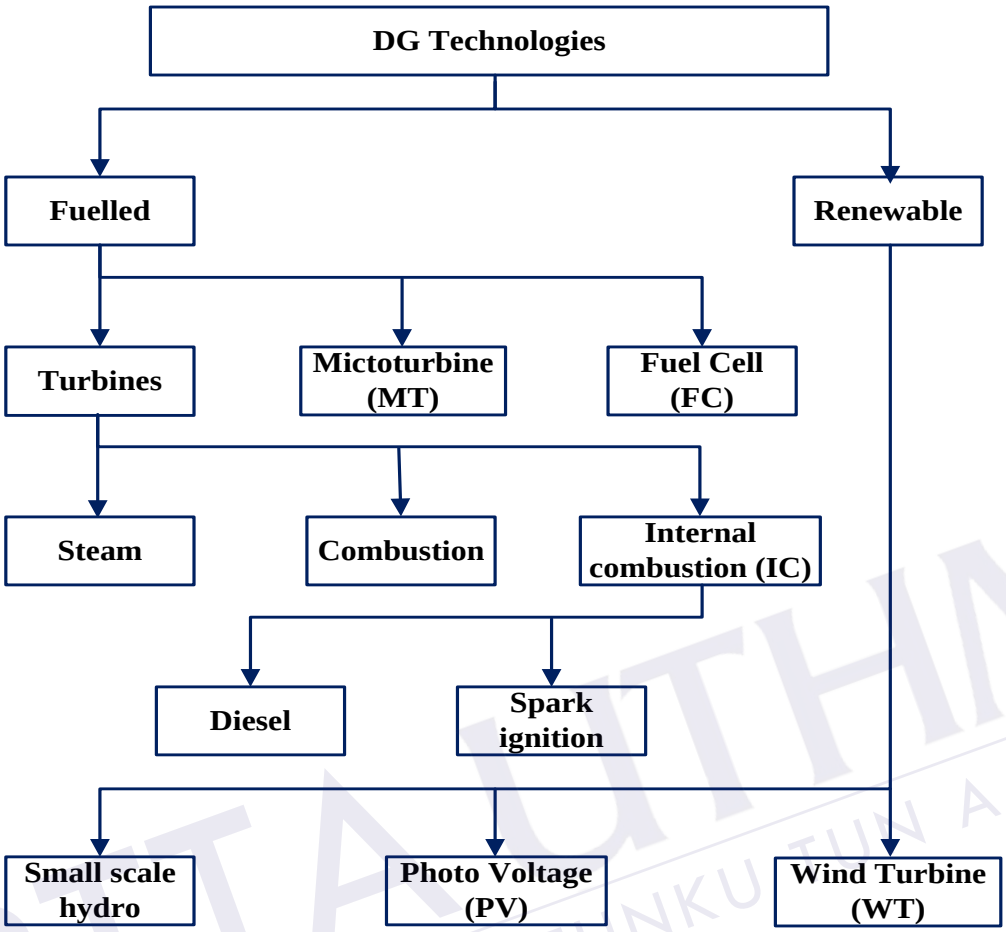

Figure 2.1: A classification of DG technologies

2.3 Impacts of DG Units on Power System

Although the integration of the DG units in electric systems has multifarious benefits, they increase the complexity. Therefore, the DG units have impacts on the system performance such as voltage profile, power flow, system losses, power quality, stability, reliability, and protection. The main target of this research is to study the voltage stability due to the penetration of the DG units.

2.3.1 Power Systems Stability

At any given time, there must be a balance between the electricity supply and the demand. To maintain this balance under both normal conditions (steady-state) and after

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disturbances (transient). The stability of a power system is defined as "a property of a power system that enables it to remain in a state of equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance" [16].

In basic terms, distribution system networks are designed to receive power from the transmission line and then distribute it to customers. Thus, real power and reactive power both flow in one direction. However, when DG units are installed in distribution systems, the directions of the real and reactive power may be reversed. Therefore, the penetration of DG units into distribution systems affects the stability of the system, and as the penetration level increases, stability becomes a significant issue [17].

The stability of a power system divided into three main categories: the first one is the rotor angle stability, the second one is the voltage stability and the third one is the frequency stability.

Analyzing rotor angle and frequency stability are not in the scope. In this research will focus on impact DG on voltage stability in steady state.

2.3.1.1 Voltage Stability

Voltage stability refers to the ability of a power system to maintain steady and acceptable voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition. It depends on the ability to maintain/restore equilibrium between load demand and load supply from the power system. Any resulting instability occurs in the form of a progressive fall or rise of voltages of some buses. Major contributory factors to voltage instability are power system configuration, generation and load patterns [5].

Voltage problems typically occur in power systems which are heavily loaded faulted and/or have reactive power shortages [18]. Among the various factors which affect voltage stability issues, there is a special correlation between voltage instability problems and insufficient reactive power reserves [19]. Voltage collapse is related to reactive power demands of loads not being met because of limitations on the available reactive power reserves and transmission of reactive power [20].

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2.4 Analysis Methods for the Voltage Stability

Some of the tools used for the analysis of voltage stability are the methods based on dynamic analysis and those based in static analysis [5].

2.4.1 Static Analysis

Static voltage instability is mainly associated with reactive power imbalance. Reactive power support that the bus receives from the systems can limit loadability of that bus. If the reactive power support reaches the limit, the system will approach the maximum loading point or voltage collapse point [21].

In static voltage stability, slowly developing changes in the power system occur that eventually lead to a shortage of reactive power and declining voltage. This phenomenon can be seen from the plot of the voltage at receiving end versus the power transferred. The plots are popularly referred to as P-V curve or "Nose" curve. As the power transfer increases, the voltage at the receiving end decreases. Eventually, the critical point, the point at which the system reactive power is out of use, is reached where any further increase in active power transfer will lead to very rapid decrease in voltage magnitude. Before reaching the critical point, the large voltage drop due to heavy reactive power losses can be observed. The maximum load that can be increased prior to the point at which the system reactive power is out of use is called static voltage stability margin or loading margin of the system. The only way to save the system from voltage collapse is to reduce the reactive power losses in the transmission system or to add additional reactive power prior to reaching the point of voltage collapse. This has to be carried out in the planning stage with several system wide studies.

This method examines the viability of the equilibrium point represented by a specified operating condition of the power system. This method allows the examination of a wide range of system conditions. Continuation Power flow based methods, P-V curves and Q-V curves are widely used. These two methods determine steady-state loadability limits which are related to voltage stability [22].

The static method is evaluated by means of a variety of techniques such as:

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a) The real power flow-voltage level (P-V) curve margin

The P-V curves, active power-voltage curve, are the most widely used method of predicting voltage stability. They are used to determine the MW distance from the operating point to the critical voltage. P-V and Q-V curves are generated by executing a large number of power flows using power flow methods. This methodology has the benefit of providing an indication of proximity to voltage collapse throughout the range of load levels. With power transfer increase in a special region, its voltage profile will become lower until a point of collapse is reached.

In this case, a power system is typically modeled with non-linear differential algebraic equations.

$$\dot{x} = f(x, \lambda) \tag{2.1}$$

Where

$\dot{x}$ differential state vector

$x \in R^n$ represents a state vector, including the bus voltage magnitude (V) and angles (δ).

$\lambda \in R^m$ is a parameter vector that represents the real and reactive power demand at each load bus.

The parameter vector λ is subject to variations due to variations in the load. Therefore, the power flow solution varies as λ varies. The power system's power flow is represented by [23].

$$0 = f(x, \lambda) \tag{2.2}$$

The static technique can be analyzed by using the relation between the receiving power (P) and the voltage (V) at a certain bus in a system. The critical point λ_{max} (saddle-node bifurcation point) in the P-V curve represents the maximum loading of a system. This point corresponds to a singularity of the Jacobian of the power flow equations. The stability margin can be defined by the MW distant from the operating point to the critical point. The penetration of the DG units in a distribution system can increase or decrease

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the voltage stability margin depending on their operation at unity, lead or lag power factors as well as their location.

Figure 2.2 illustrates a P-V curve of an electrical system. 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 maximum loading (λ_{max}).

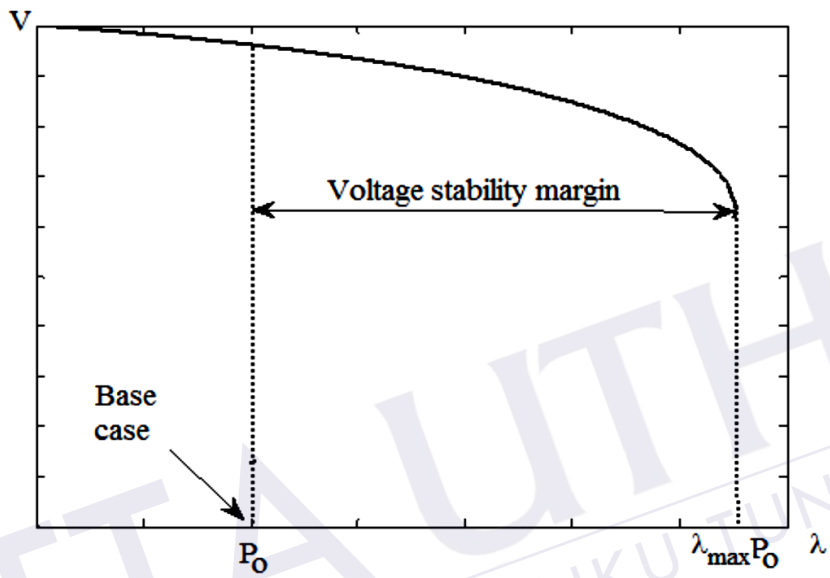

Figure 2.2: P-V curve or nose curve

b) The reactive power flow-voltage level (Q-V) curve margin

In this method, the network is represented by a power flow equation that can be linearized, as given in equation (2.3) [24].

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\theta} & J_{PV} \\ J_{Q\theta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} \tag{2.3}$$

Where

ΔP: the incremental change in bus real power

ΔQ: incremental change in bus reactive power

ΔV: incremental change in bus voltage magnitude

Δθ: incremental change in bus voltage angle

J: the Jacobian matrix $J_{P\theta} = \frac{\partial P}{\partial \theta}$, $J_{PV} = \frac{\partial P}{\partial \theta}$, $J_{Q\theta} = \frac{\partial Q}{\partial \theta}$ and $J_{QV} = \frac{\partial Q}{\partial \theta}$

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With the assumption of the real load power being constant, the incremental change in the bus real power ΔP equals to zero. Then, using the partial inversion of equation (2.3) gives

$$\Delta Q = \left(J_{QV} - J_{Q\theta}\, J_{P\theta}^{-1}\, J_{PV}\right)\Delta V \tag{2.4}$$

Or

$$\Delta V = \left(J_{QV} - J_{Q\theta}\, J_{P\theta}^{-1}\, J_{PV}\right)^{-1}\Delta Q \tag{2.5}$$

The V-Q sensitivity can be calculated by solving equation (2.3). The V-Q sensitivity at a bus represents the slope of the Q-V curve as shown in Figure 2.3 at a given operating point. A positive V-Q sensitivity is indicative of stable operation, and a negative sensitivity is indicative of unstable operation [5].

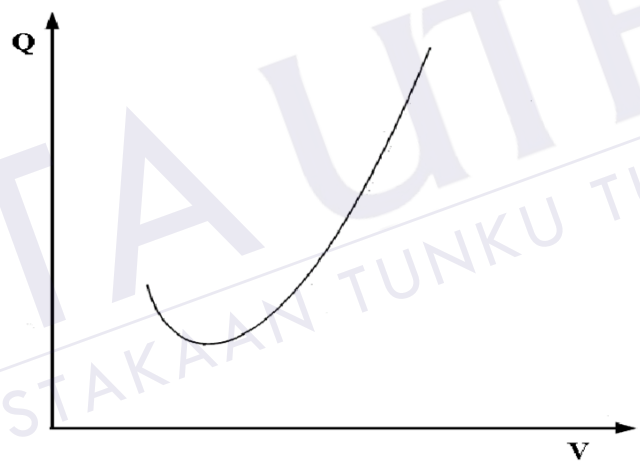

Figure 2.3: Q-V characteristic curve

2.4.2 Dynamic analysis

Dynamic analysis can show the real behaviour of the system such as loads (dynamic and static), DG units, automatic voltage and frequency control equipment, and the protection systems. The overall power system is represented by a set of first order differential equations, as given in equation (2.5).

$$\dot{X} = f(x, V) \tag{2.6}$$

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And a set of algebraic equations

$$I(x, V) = Y_N V \tag{2.7}$$

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 (2.6) and (2.7) can be solved in a time domain using numerical integration methods. This study provides time domain results; therefore, the system can be modeled and simulated with the help of different simulation software such as MATLAB.

In this research will not focus on static voltage stability.

The objective of stability analysis is to avoid any of the above consequences of instability by providing appropriate solutions to the causes of instability. Such solutions will be increasing of synchronizing power, optimizing the design and selection of rotating equipment, reducing the reactance of the transmission system. Many other solutions may present themselves based on the characteristics of the system concerned. With the development of economy, load demands in distribution networks increase sharply. Hence, the distribution networks are operating closer to the voltage instability boundaries. The decline of voltage stability margin is one of the most important factors which restrict the increase of load served by distribution companies [25]. Therefore, it is necessary to consider voltage stability with the integration of DG units in distribution systems. The literature has covered this impact from different points of view. For example, [25-29] studied the impact of induction generators due to small and large disturbances.

The authors of [30, 31] investigated the impact of distributed generation technology such as PV, fuel cells and micro-turbines that are grid coupled through a power electronic converter.

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The authors of [32] presented an assessment of the effect of DG capacity and location on voltage stability enhancement of distribution networks. In [33] selection of the site and size of DG units to be investigated to the system and to check the system performance as follows evaluating the integration of DG units to a real distribution system.

2.5 Proximity to voltage instability

As mentioned before, the static technique can be analyzed by using the relation between the receiving power and the voltage at a certain bus in a system, which is known as a P-V curve or nose curve as shown in Figure 2.2. The P-V curve is obtained by applying the continuous power flow method [34]. The critical point λ_{max} (saddle-node bifurcation point) in the P-V curve represents the maximum loading of a system. This point corresponds to a singularity of the Jacobian of the power flow equations. The stability margin can be defined by the MW distant from the operating point to the critical point. The penetration of the DG units in a distribution system can increase or decrease the voltage stability margin depending on their operation at unity, lead or lag power factors as well as their location. Figure 2.2 illustrates a P-V curve of an electrical system. The x-axis represents λ, which is the scaling factor of the load demand at a certain operating point as given in equation (2.8). λ varies from zero to the λ_{max}.

$$P_i = \lambda P_{o,i}$$
$$Q_i = \lambda Q_{o,i} \tag{2.8}$$

However, static analysis cannot determine the control action and the interaction between the integrated DG units in the system. Proximity to the voltage instability method can be used to determine those issues.

2.6 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 [35, 36]. For this reason, this study assumes that the DG unit are operating at unity power factor.

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Figure 2.4 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 as given in equation (2.8). 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_1 to V_2, and at the same time the maximum loadability increases from λ_{max1} to λ_{max2}.

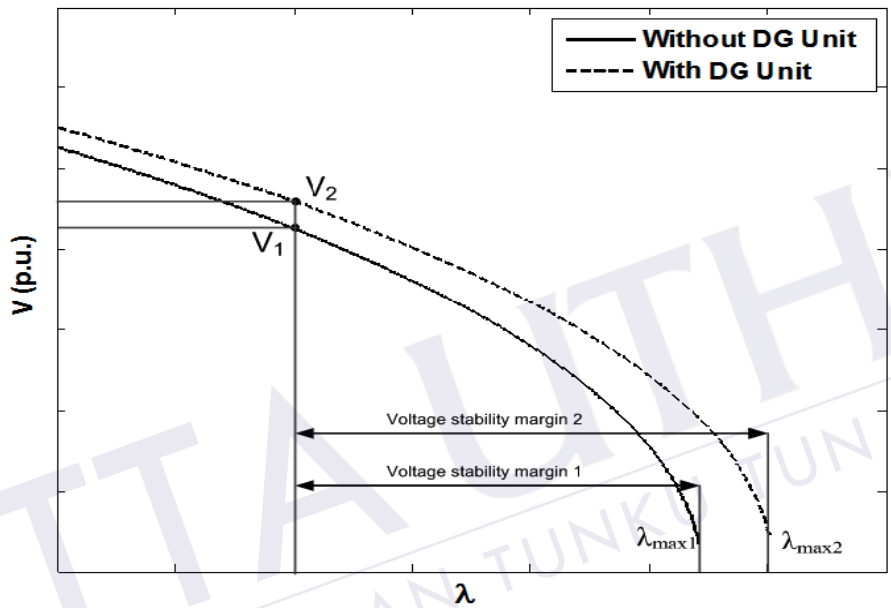

Figure 2.4: Impact of a DG unit on maximum loadability and voltage stability margin

2.7 Selection of the Candidate buses

In the literature, the candidate buses for the DG installation can be selected randomly, by recommended location, or by selecting sensitive buses to the voltage profile. Because this study is focusing on improving the voltage stability of the system, it uses voltage sensitivity analysis to select the candidate buses. In addition, the candidate buses should be located on the main feeders of the system. The method is conducted by testing the voltage sensitivity to the change of the DG injected power, and can be explained as follows.

Power systems are typically modeled with non-linear differential algebraic equations [23]. The system model can be linearized as in equation (2.3). With the assumption that the reactive load power is constant, the incremental change in bus

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reactive power ΔQ equals to zero. Then, using the partial inversion of equation (2.3) gives:

$$\Delta P = \left(J_{PV} - J_{P\theta} J_{Q\theta}^{-1} J_{QV}\right)\Delta V \tag{2.9}$$

Or,

$$\Delta V = \left(J_{RPV}\right)^{-1} \Delta P \tag{2.10}$$

Where J_{RPV} is a reduced Jacobian matrix, which gives the voltage magnitude variations due to DG active power injection variations. If the buses are modeled as PQ buses, $J_{Q\theta}^{-1}$ is a feasible and square matrix. Therefore, this situation normally occurs in distribution systems where the slack bus is the only bus that keeps the voltage magnitude at a fixed point.

The aim of the static methods is to find the steady state voltage stability limit of a system. The results are based on a series of power flow solutions for small disturbances. The small disturbances typically used are small variations in loading. The assumption used in the static methods is that the system frequency remains constant. Under such an assumption, the total generation equals the load plus losses and hence a power flow solution can be applied for determining the stability of the system.

The modelling of three basic elements of a power system; generators, loads and the transmission network is discussed in next chapter describes the solution methodologies used in two static voltage stability analysis tools; power flow and continuation power flow.

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CHAPTER 3

METHODOLOGY

3.1 Introduction

In recent years, wind energy has become an important part of DGs technology for electrical power generation in many countries. Making use of wind energy reduces the environmental pollution as well as the fuel cost of the power system, which brings considerable economic benefits. At present, wind farms are connected to both distribution and bulk power systems [37]. Wind power has been effectively specified as constant power factor model where it is assumed to supply constant real power to the system. A parallel capacitor is present at each wind turbine to supply the required reactive power to the induction machines [11].

In this project, extensive simulations have been carried out on a 2 bus test system, IEEE 14-bus and IEEE 30-bus distribution system using the continuous power flow method. These simulations are achieved using PSAT which is a public domain solver. The effect of penetration of wind power on the static voltage stability has been investigated. In static voltage stability study, CPF is the main analysis techniques and it is used to find voltage stability margin of the system. The CPF technique involves in solving a series of load flow calculation with predictor and corrector steps.

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3.2 Power Flow

Power flow analysis is very important and basic tool for the analysis of any power system as it is used in the planning and design stages as well as during the operations. A distribution system originates at a substation and continues to a lower voltage for delivery to the customers. It is relevant to classify the power flow problems into two categories. Firstly, well conditioned case, where the power flow solution exists and is reachable, using a flat initial guess and a standard Newton-Raphson method. This case is the most common situation. Secondly, ill conditioned case, where the solution of the power flow problem does exist, but standard solution methods fail to get this solution starting from a flat initial guess.

Unlike a transmission system, a distribution system typically has a radial topological structure. The radial structure, along with the higher resistance/reactance (R/X) ratio of the lines, means distribution systems are ill-conditioned and hence the Jacobian of a Newton-Raphson power flow becomes singular at the steady state voltage stability limit [38]. In fact, this stability limit, also called the critical point, is often defined as the point where the power flow Jacobian is singular. As a consequence, attempts at power flow solutions near the critical point are prone to divergence and error for most distribution power flow problems.

Continuation methods are efficient tools for solving this kind of problem, since different parameterizations are used in order to avoid such ill conditioned cases, with close to singular Jacobian matrices, such as the maximum loading point of power systems. Some parameterization techniques have been proposed to avoid matrix singularity and successfully solve those cases. The PSAT is based on the application of Newton-Raphson method. The continuation method sequentially predicts a solution and corrects this predicted solution to return to the P-V curve. It uses an augmented Jacobian of the system to predict a solution in the predictor step [39].

The underlying principle of a power flow problem is that given the system loads, generation, and network configuration, bus voltages and line flows can be calculated by solving the nonlinear power flow equations.

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3.3 Reformulation of the Power Flow Equations

3.3.1 Bus System

The sample system shown in Figure 3.1 consists of two generator buses connected via a transmission line characterized by its π model, consisting on its series impedance and its shunt admittance, represented in future equations by Z_L and Y_T, respectively. In addition, each bus contains loads with both active and reactive power.

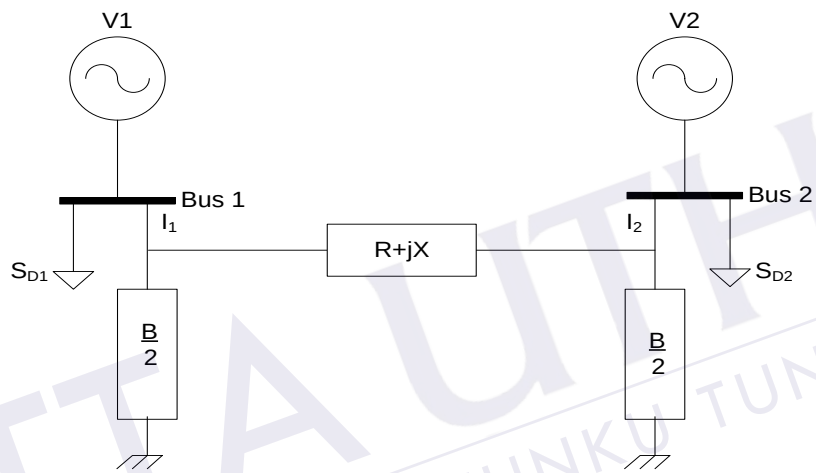

Figure 3.1: Schematic diagram of a sample power system

Applying Kirchoff's law to each node:

$$I_1 = \frac{Y_T}{2}V_1 + \frac{1}{Z_T}(V_1 - V_2) \tag{3.1}$$

$$I_2 = \frac{Y_T}{2}V_2 + \frac{1}{Z_T}(V_2 - V_1) \tag{3.2}$$

V_1 and V_2 are the sending end and receiving end voltages respectively. I_1 and I_2 are the sending end and receiving end current respectively. And rearranging these equations as follow

$$I_1 = y_{11}V_1 + y_{12}V_2 \tag{3.3}$$

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$$I_2 = y_{21}V_1 + y_{22}V_2 \tag{3.4}$$

$$y_{11} = y_{22} = \frac{Y_T}{2} + \frac{1}{Z_T} \tag{3.5}$$

$$y_{12} = y_{21} = -\frac{1}{Z_T} \tag{3.6}$$

It is obtained the elements of the bus admittance matrix:

$$[Y] = \begin{bmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{bmatrix} \tag{3.7}$$

Plus, defining the current and voltage vectors as:

$$[I] = \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}; \qquad [V] = \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} \tag{3.8}$$

Equations (3.7) and (3.8) can be expressed in a metrical format:

$$[I] = [Y] * [V] \tag{3.9}$$

3.3.2 N-Bus System

Implementing the same process for a generic n-bus system and introducing line k, representing the connection between buses i and j, the application of the Kirchoff's law leads to the following general equation:

$$I_i = \sum_{\substack{j=1 \\ j\neq i}}^{n} \frac{Y_{L_K}}{2} V_i + \sum_{\substack{j=1 \\ j\neq i}}^{n} \frac{1}{Z_{L_K}} (V_i - V_j)$$

$$I_i = \sum_{\substack{j=1 \\ j\neq i}}^{n} \left(\frac{Y_{L_K}}{2} + \frac{1}{Z_{L_K}} \right) V_i + \sum_{\substack{j=1 \\ j\neq i}}^{n} \left(-\frac{1}{Z_{L_K}} \right) V_j \tag{3.10}$$

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Similarly to the 2-bus system, the diagonal element of each node is the sum of admittances linked to it:

$$y_{ii} = \sum_{\substack{j=1 \\ j \neq i}}^{n} \left(\frac{Y_{L_K}}{2} + \frac{1}{Z_{L_K}} \right) \tag{3.11}$$

The off-diagonal element is equal to the negative of the admittance between the nodes:

$$y_{ij} = y_{ji} = -\frac{1}{Z_{L_K}} \tag{3.12}$$

Analyzing the previous equations, it is shown that the matrix is symmetric along the leading diagonal, a property most used in the attempt to reduce the time consumption of power flow programs, especially when computing very large power systems.

The bus admittance matrix is then defined as *n* x *n* a complex matrix:

$$[Y] = \begin{bmatrix} y_{11} & \cdots & y_{1n} \\ \vdots & \ddots & \vdots \\ y_{n1} & \cdots & y_{nn} \end{bmatrix} \tag{3.13}$$

3.3.3 Power-Flow Solution

The problem consists of determining the magnitudes and phase angles of voltages at each bus and active and reactive power flow in each line. In solving a power flow problem, the system is assumed to be operating under balanced conditions and a single-phase model is used. Four quantities are associated with each bus. There are voltage magnitude (V), phase angle (δ), real power (P), and reactive power (Q). The system buses are generally classified into three types they are:

i) **Swing bus**: A bus, known as reference bus or slack bus, where the voltage magnitude and phase angle are specified. At this bus, the active power and the reactive power are unknown.

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ii) **Load buses**: At these buses are called PQ buses. The active and reactive powers are specified; the voltage magnitude and voltage angle are unknown.

iii) **Generator buses**: At these buses are called PV or regulated buses. The real power and the voltage magnitude are specified; the voltage angle and the reactive power are unknown.

3.3.4 Power Flow Equations

The injected current at a specific bus may be expressed as a function of the injected complex power:

$$I_i = \frac{S_i^*}{V_i^*} \tag{3.14}$$

Equation (3.9) can now be written as follows:

$$\left[\frac{S_i^*}{V_i^*}\right] = [Y][V] \tag{3.15}$$

Additionally, the injected power at that bus is the difference between generation and load powers in the bus. Thus:

$$S_i = P_i + jQ_i = P_{Gi} - P_{Di} + j(Q_{Gi} - Q_{Di}) \tag{3.16}$$

$$P_i + jQ_i = P_{Gi} - P_{Di} + j(Q_{Gi} - Q_{Di}) = y_{ii}V_i + \sum_{j=1}^{n} y_{ij}V_i \tag{3.17}$$

Where

S_i: net injected power into the network

P_{Gi}, Q_{Gi}: real and reactive power generation of DG

P_{Di}, Q_{Di}: real and reactive power load

Equation (3.17) constitutes the complex power flow equation for a generic n-bus system. Though, in power flow computation, this equation is written in real form, leading to two

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equations per bus: one concerning active power injection and the other reactive power injection.

Separating real and imaginary parts of the admittance matrix, the conductance and the susceptance matrices are obtained, respectively:

$$[Y] = [G] + j[B] \tag{3.18}$$

Expressing the bus voltage in polar form:

$$V_i = V_i e^{j\theta_i} \tag{3.19}$$

And decomposing it in real and imaginary parts, using Euler's formula, it is possible to write equation (3.17) in real form, as intended:

$$P_i = P_{Gi} - P_{Di} = \sum_{j=1}^{n} V_i V_j \left[G_{ij} cos\left(\theta_i - \theta_j\right) + B_{ij} sin\left(\theta_i - \theta_j\right)\right] \tag{3.20}$$

$$Q_i = Q_{Gi} - Q_{Di} = \sum_{j=1}^{n} V_i V_j \left[G_{ij} sin\left(\theta_i - \theta_j\right) + B_{ij} cos\left(\theta_i - \theta_j\right)\right] \tag{3.21}$$

3.4 Voltage stability in power system

The most common methods used to ensure voltage stability are CPF, minimum singular value, point of collapse method and the optimization method. To evaluate the wind penetration level in the test network in the system, voltage stability for the developed network is determined by its corresponding P-V curve, obtained from CPF.

The effect of wind power penetration on the total system active loss and voltage collapse with corresponding loading is investigated by increasing gradually a rate of wind power penetration in the nearest bus at the wind site. One important application of power flow studies is to trace and predict the system's response to load variation in order to avoid system collapse and to ensure the security, economy and control of electrical energy distribution.

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The evaluation of the P-V characteristic curve, presented in Figure 3.2, provides crucial information concerning, for instance, voltage stability and load ability limits, at steady-state conditions. At the tip of the curve, the system reaches its critical point of operation where, normally, it can no longer meet the demand for reactive power. Thus, the upper curve represents the stable operation, while the bottom curve is the unstable region.

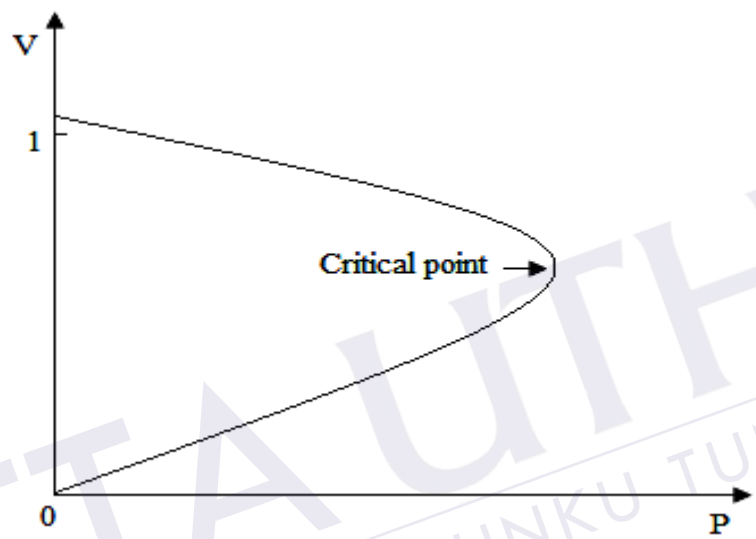

Figure 3.2: Typical P-V curve

The conventional power flow computation began with Gauss-Seidel method. Then it was overcome by Newton-Raphson method, in which the continuation method is based, due to the faster convergence time [40].

3.4.1 Newton-Raphson Method

Considering the following standard equation system:

$$f(x_1, \ldots\ldots, x_n) = y \tag{3.22}$$

Where f the vector is composed by differential functions of the variables $x_1, \ldots\ldots, x_n$ and y stands for a vector of constants. For the initial guess x^0 we have:

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