ANALYSIS OF POWER SYSTEMS PROBLEMS USING
POWER SYSTEM ANALYSIS TOOLBOX (PSAT)

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DECLARATION OF ORIGINALITY

I declare that this report entitled “Analysis of power systems problems using power systems toolbox (PSAT)” is my own work except as cited in the references. The report has not been accepted for any degree and is not being submitted concurrently in candidature for any degree or other award.

Signature: __________________________

Name: __________________________

Date: __________________________
Acknowledgements

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ABSTRACT

The Power System Analysis toolbox PSAT has been developed to assist in typical Electrical Power System Analysis. The one of the objectives of this project is to develop an educational toolbox for Electrical Power System students and lecturers in order to solve some of Power System problems: Power Flow Analysis, Voltage Stability Analysis and Transient Stability Analysis. All this kinds of problems consists of various methods of mathematical calculation which is difficult to perform by using manual calculation (formula and calculator). The existence of this educational toolbox will help the user to calculate the calculation become faster and easier. For this purpose, three power systems case studies were chosen to model for each type of problems, which were mentioned above

The simulation results of the three case studies gained by PSAT were proved that the PSAT can be used reliably for education and researches purposes to solve electrical power system problems.
المستخلص

تم تطوير الأداة الصندوقية لتحليل أنظمة القدرة الكهربائية PSAT للمساعدة في تحليل أنظمة القدرة الكهربائية. أحد أهداف هذا المشروع هو تطوير أداة صندوقية تعليمية بالنسبة لمحاضري وطلاب أنظمة القدرة الكهربائية لحل مسائل أنظمة القدرة مثل تحليل تدفق القدرة وتحليل الاتزان الجهد وتحليل الاتزان العابر. كل أنواع التحليل السابقة تحتاج لحسابات رياضية والتي يمكن من الصعوبة القيام بهديا أو باستخدام الآلة الحاسبة. لذلك بإمكان أداء الصندوق التعليمية المساعدة لجعل الاحاسب أسرع وأسهل. من أجل القيام بعملية التحليل تم اختيار ثلاثة حالات للدراسة لكل نوع من أنواع تحليل أنظمة القدرة سابقة الذكر. النتائج المتحصل عليها من محاكاة حالات الدراسة الثلاثة باستخدام PSAT أثبتت أنه يمكن اعتماد استخدام PSAT لأغراض البحث والتعليم لحل مسائل أنظمة القدرة الكهربائية.
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Chapter 1

1.1 Introduction

Power System Analysis is an analysis that is so important nowadays. It is not only important in economic scheduling, but also necessary for planning and operation for a system. Based on that, in recently years, there are many researches, new developments and analysis was introduced to people in order to mitigate the problems that involving Power System Analysis such as Load Flow Analysis, transient stability analysis and voltage stability Analysis on Power Generation.

Load Flow or power flow Analysis is important to analyze any planning for power system improvement under steady state conditions such as to build new power generation capacity, new transmission lines in the case of additional or increasing of loads, to plan and design the future expansion of power systems as well as in determining the best operation of existing systems. Stability Analysis is necessary for reliable operation of power systems to keep synchronism after minor and major disturbances.

All the analysis discussed above is an importance tool involving numerical analysis that applied to a power system. In this analysis, there is no known analytical method to solve the
problem because it depends on iterative technique. Iterative technique is one of the analysis that using a lot of mathematical calculations which takes a lot of times to perform by hand. So, to solve the problems, the development of toolboxes based on MATLAB with Graphical User Interface (GUI) will help the analysis become quick and easy.

Traditionally, most available power system software packages are commercial products that can only be used by acquiring costly licenses. This drastically limits education and research, particularly in developing nations. In contrast, the deployment of Free and Open Source Software (FOSS) emerges as an alternative platform to distribute an educational and research tool which can be obtained by anyone around the world, and seamlessly creates a community of users/learners that interact and collaborate with each other. An underlying reason behind the success of a variety of FOSS projects (see for example the Linux, Perl and LATEX experiences) is the freedom of the users of the software as well as the spirit of collaboration between them. If applied to the power system academic community, the FOSS approach allows the deployment of tools suitable for education and research, and at the same time to create a community of learners. Remarkable efforts have been made by the academic community to provide educational software for teaching power system topics. However, most available tools do not fully apply the FOSS. The educational computer packages mentioned above, and other tools such as UWPFLOW, PST, and MATPOWER, are not distributed under the General Public License (GPL). The lack of a GPL restricts the freedom of the users to modify, enhance and redistribute a program that they have modified.

This thesis presents authors’ and users’ experience in the development and usage of the Power System Analysis Toolbox (PSAT), a Free and Open Source Software (FOSS). PSAT is currently used in several Universities all around the world.

1.2 Power System Analysis Toolbox (PSAT)

In this section, history, an overview of PSAT features and a comparison with other Matlab toolboxes for power system analysis would be provided.

1.2.1 History of PSAT

PSAT is written by Federico Milano, in September 2001, while he was studying as Ph.D. student at the Universita di Genova, Italy. First public version of PSAT completed in November
2002, when he was a Visiting Scholar at the University of Waterloo, Canada. Now Federico Milano is working as assistant professor at the Universidad de Castilla-La Mancha, Ciudad Real, Spain but he maintains PSAT in the spare time [1].

### 1.2.2 Overview of PSAT

PSAT is a Matlab toolbox for electric power system analysis and control. PSAT includes Power Flow, continuation power flow, optimal power flow, small signal stability analysis and time domain simulation. All PSAT operations can be assessed by means of graphical user interfaces (GUIs) and a Simulink-based library provides an user friendly tool for network design [2]. PSAT core is the power flow routine, which also takes care of state variable initialization. Once the power flow has been solved, further static and/or dynamic analysis can be performed. These routines are:

1. Optimal power flow (OPF)
2. Continuation Power flow (CPF)
3. Small signal stability analysis
4. Time domain simulations
5. Phasor measurement unit (PMU) placement.

### 1.2.3 Useful features of PSAT

The Useful features of PSAT are:

- Mathematical Models & Utilities
- A variety of utilities
- Bridges to other programs
- Data Format Conversion capability

#### 1.2.3.1 Mathematical Models

In order to perform accurate power system analysis, PSAT supports a variety of static and dynamic component models, as follows:
1- Power Flow Data
2- CPF and OPF Data
3- Switching Operations
4- Loads
5- Machines
6- Controls
7- Regulating Transformers
8- FACTS
9- Other Models

1.2.3.2 PSAT utilities

a. Simulink library for drawing networks:

PSAT provides a Simulink graphical model library that enables the user to draw one line network diagrams using pictorial blocks. The PMC (Physical Model Component) library of PSAT provides a complete set of Simulink blocks for network design, which are grouped as follows: connections, power flow data, OPF & CPF data, faults & breakers, measurements, loads, machines, controls, regulating transformers, FACTS, wind turbines, other models, and sub transmission equivalent areas respectively.

The PSAT is Matlab based and the Simulink environment is used only as a graphical tool. Thus, running time domain simulations from the Simulink model menus produces no effect, since no Simulink dynamic model is associated with PSAT blocks. Simulink network models built with the PCM library are read by PSAT to exploit the network topology and extract component data. An advantage of this approach is that the PSAT can run on GNU/Octave, which doesn’t provide a Simulink environment.

b. GUIs for settings system and routine parameters.
c. User defined model construction and installation.
d. GUI for plotting results.
e. Filters for converting data to and from other formats.
f. Command logs.

1.2.3.3 PSAT bridges to other programs

PSAT includes bridges to GAMS and UWPFLOW programs. These bridges highly extend PSAT ability of performing optimization and continuation power flow analysis. Fig 1.1 depicts the structure of PSAT.
Fig 1.1: PSAT at a glance

1.2.4 Power Flow analysis on PSAT

PSAT provides several options to solve power flow, namely:

1- Newton-Raphson method
2- Fast Decoupled Power Flow (XB and BX)
3- Power Flow with a distributed slack bus model

The theory of these methods, in which PSAT bases the models and routines, are presented in [3, 4, 5] and discussed in chapter 2.

The distributed slack bus model power flow is a feature which it’s only available in PSAT among other Matlab based power system programs.

1.2.5 Time Domain Simulations on PSAT

PSAT also provides the option to perform time domain simulations. For this it uses two different integration methods (Trapezoidal rule and backward Euler) to solve 1 together using the
SI (Simultaneous-implicit) method, this is also an option only available in PSAT among other Matlab-based packages for power system analysis.

PSAT is able to introduce common disturbances by means of embedded functions. This embedded functions are useful to simulate common perturbations for transient analysis such as faults and breaker operations. Step perturbations can be obtained by changing parameter or variable values after completing the power flow. Any other disturbance can be defined through a custom made perturbation function; this functions can modify and include any global structure of the system.

1.2.6 Comparison between PSAT & Other Matlab Power System Toolboxes

The differences between power systems Toolboxes were shown in Table 1.1

<table>
<thead>
<tr>
<th>Package</th>
<th>PF</th>
<th>CPF</th>
<th>OPF</th>
<th>SSSA</th>
<th>TDS</th>
<th>EMT</th>
<th>GUI</th>
<th>CAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>MatEMTP</td>
<td>√</td>
<td></td>
<td>√</td>
<td></td>
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<td>PST</td>
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<tr>
<td>SPS</td>
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<tr>
<td>VST</td>
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</tbody>
</table>

Table 1.1: The differences between power systems Toolboxes

The key words of Table 1.1 were shown below:

- standard power flow (PF)
- continuation power flow and/or voltage stability analysis (CPF-VS)
- optimal power flow (OPF)
- Small signal stability analysis (SSSA)
- time domain simulation (TDS)
- Electro Magnetic Transient analysis (EMT)
- graphical user interface (GUI)
- graphical network construction (CAD)

1.3 Objectives

The main objectives that are wants to be achieved in this project are:

i) To develop an educational toolbox in order to solve Power System Analysis problems.
ii) To obtain simulation and analysis of three power systems case studies by using PSAT program.

1.4 Scope of Project

In this project, the thesis will focused on:

1. Study the theory of Power System Analysis that involves power flow Analysis, transient stability analysis and voltage stability Analysis of Power Generation.
2. This thesis will concentrates on PSAT simulink with Graphical User Interface (GUI).

1.5 Thesis layout

Chapter 1 gives a generally introduction for Matlab Power System Toolboxes. In addition, it provides history and overview of PSAT features. Finally it shows objective scope and Overview of this thesis.

Chapter 2 provides a formulation of the load-flow problem and its associated solution strategies. An understanding of the fundamentals of three-phase systems is assumed, including per-unit calculations, and circuit-analysis techniques.

Chapter 3 illustrates the nature of transient stability problems, identifies factor influencing them, and describes modeling consideration and analytical techniques applicable to transient stability analysis.

Chapter 4 illustrates the basic concept related to voltage stability and characterize the voltage avalanche phenomena. The dynamic and static approaches to voltage stability analysis will be described.

Chapter 5 illustrates the three case studies, which were chosen for three types of power system analysis to investigate their results using PSAT program. Also it shows how case studies were modelled and how the respective input data was entered to them.

Chapter 6 provides details on the simulation results with discussion.

Chapter 7 concludes the thesis with a final regard to the findings and suggests improvements for future development.
Chapter 2

2.1 Introduction

The Power flow or load flow problem models the nonlinear relationships among bus power injections, power demands, and bus voltages and angles, with the network constants providing the circuit parameters. It is the heart of most system-planning studies and also the starting point for transient and dynamic stability studies. This Chapter provides a formulation of the load-flow problem and its associated solution strategies. An understanding of the fundamentals of three-phase systems was assumed, including per-unit calculations, and circuit-analysis techniques.

2.2 Necessity for Power Flow Studies

Power flow studies are undertaken for various reasons, some of which are the following [6]:
I. The line flows
2. The bus voltages and system voltage profile
3. The effect of change in configuration and incorporating new circuits on system loading.
4. The effect of temporary loss of transmission capacity and (or) generation on system loading and accompanied effects.
5. The effect of in-phase and quadrative boost voltages on system loading
6. Economic system operation
7. System loss minimization
8. Transformer tap setting for economic operation
9. Possible improvements to an existing system by change of conductor sizes and System voltages.

2.3 The Power Flow problem

2.3.1 Developing Power Flow Equations

Consider an n-bus system the bus voltages are given by

$$V = \begin{bmatrix} v_1 < \delta_1 \\ \vdots \\ v_n < \delta_n \end{bmatrix} \quad (2.1)$$

The bus admittance matrix

$$[Y] = [G] + j[B] \quad (2.2)$$

where

$$y_{ik} = |y_{ik}| < \theta_{ik} = g_{ik} + j b_{ik}$$

$$v_i = |v_i| < \delta_i = |v_2| \cos \delta_i + j \sin \delta_i \quad (2.3)$$

$$V_k^* = |V_k| < \delta_i = |V_k| \cos \delta_k + j \sin \delta_k \quad (2.4)$$

The current injected into the network at bus ‘i’
\[ I_i = Y_{i1}V_1 + Y_{i2}V_2 + \cdots + Y_{in}V_n \rightarrow \text{where} \ n \text{ is the number of buses} \]

\[ I_i = \sum_{k=1}^{n} Y_{ik}V_k \quad (2.5) \]

The complex power into the system at bus 'i'

\[ S_i = P_i + jQ_i = V_iI_i^* \]

\[ = V_i \sum_{k=1}^{n} Y_{ik}V_k^* \]

\[ = \sum_{k=1}^{n} |V_i V_k V_{ik}| \exp(\delta_i - \delta_k - \theta_{ik}) \quad (2.6) \]

Equating the real and imaginary parts

\[ P_i = \sum_{k=1}^{n} |V_i V_k V_{ik}| \cos(\delta_i - \delta_k - \theta_{ik}) \quad (2.7) \]

and \[ Q_i = \sum_{k=1}^{n} |V_i V_k V_{ik}| \sin(\delta_i - \delta_k - \theta_{ik}) \quad (2.8) \]

where \( i=1,2,\ldots,n \)

Excluding the slack bus, the above power flow equations are 2 \((n - 1)\) and the variables are \(P_i, Q_i, |V|\) and \(<d_i\).

Simultaneous solution to the \(2 (n - 1)\) equations

\[ P_{gi} - P_{di} - \sum_{k=1}^{n} |V_i V_k V_{ik}| \cos(\delta_i - \delta_k - \theta_{ik}) = 0 \quad (2.9) \]

\( k \neq \text{slack bus} \)

\[ Q_{gi} - Q_{di} - \sum_{k=1}^{n} |V_i V_k V_{ik}| \sin(\delta_i - \delta_k - \theta_{ik}) = 0 \quad (2.10) \]

\( k \neq \text{slack bus} \).

The voltage magnitudes and the phase angles at all load buses are the quantities to be determined. They are called state variables or dependent variables. The specified or scheduled values at all buses are the independent variables. \(Y\) matrix interactive methods are based on solution to power flow equations using their current mismatch at a bus given by

\[ \Delta I_i = I_i - \sum_{k=1}^{n} Y_{ik}V_k \quad (2.11) \]

or using the voltage form

\[ \Delta V_i = \frac{\Delta I_i}{Y_{ii}} \quad (2.12) \]
At the end of the interactive solution to power flow equation, \( \Delta I_i \) or more usually \( \Delta V_i \) should become negligibly small so that they can be neglected.

### 2.3.2 Classification of Buses

The general practice in power-flow studies is to identify three types of buses in the network. At each bus two of the four quantities \( \delta \), \(|V|\), \(P\) and \(Q\) are specified and the remaining two are calculated. Specified quantities are chosen according to the following discussion [6]:

(a) **Load bus**: A bus where there is only load connected and no generation exists is called a load bus. At this bus real and reactive load demand \(P_d\) and \(Q_d\) are drawn from the supply. The demand is generally estimated or predicted as in load forecast or metered and measured from instruments. Quite often, the reactive power is calculated from real power demand with an assumed power factor. A load bus is also called a \(P, Q\) bus. Since the load demands \(P_d\) and \(Q_d\) are known values at this bus. The other two unknown quantities at a load bus are voltage magnitude and its phase angle at the bus. In a power balance equation \(P_d\) and \(Q_d\) are treated as negative quantities since generated powers \(P_g\) and \(Q_g\) are assumed positive.

(b) **Voltage controlled bus or generator bus**: A voltage controlled bus is any bus in the system where the voltage magnitude can be controlled. The real power developed by a synchronous generator can be varied by changing the prime mover input. This in turn changes the machine rotor axis position with respect to a synchronously rotating or reference axis or a reference bus. In other words, the phase angle of the rotor \(\delta\) is directly related to the real power generated by the machine. The voltage magnitude on the other hand, is mainly, influenced by the excitation current in the field winding. Thus at a generator bus the real power generation \(P_g\) and the voltage magnitude \(|V_g|\) can be specified. It is also possible to produce vars by using capacitor or reactor banks too. They compensate the lagging or leading vars consumed and then contribute to voltage control. At a generator bus or voltage controlled bus, also called a \(PV\)-bus the reactive power \(Q_g\) and \(\delta_g\) are the values that are not known and are to be computed.

(c) **Slack bus** In a network as power flows from the generators to loads through transmission lines power loss occurs due to the losses in the line conductors. These losses when included, we get the power balance relations
where \( P_g \) and \( Q_g \) are the total real and reactive generations, \( P_d \) and \( Q_d \) are the total real and reactive power demands and \( P_L \) and \( Q_L \) are the power losses in the transmission network. The values of \( P_g \), \( Q_g \), \( P_d \) and \( Q_d \) are either known or estimated.

Since the flow of cements in the various lines in the transmission lines are not known in advance, \( P_L \) and \( Q_L \) remains unknown before the analysis of the network. But, these losses have to be supplied by the generators in the system. For this purpose, one of the generators or generating bus is specified as 'slack bus' or 'swing bus'. At this bus the generation \( P_g \) and \( Q_g \) are not specified. The voltage magnitude is specified at this bus. Further, the voltage phase angle \( \delta \) is also fixed at this bus. Generally it is specified as 0° so that all voltage phase angles are measured with respect to voltage at this bus. For this reason slack bus is also known as reference bus. All the system losses are supplied by the generation at this bus.

Further the system voltage profile is also influenced by the voltage specified at this bus. The three types of buses are illustrated in Fig 2.1.

**Fig 2.1 : The three types of Buses**

Bus classification is summarized in Table 2.1.


<table>
<thead>
<tr>
<th>Bus</th>
<th>Specified variables</th>
<th>Computed variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slack- bus</td>
<td>Voltage magnitude and its phase angle</td>
<td>Real and reactive powers</td>
</tr>
<tr>
<td>Generator bus (PV-bus or voltage controlled bus)</td>
<td>Magnitudes of bus voltages and real powers (limit on reactive powers)</td>
<td>Voltage phase angle and reactive power.</td>
</tr>
<tr>
<td>Load bus</td>
<td>Real and reactive powers</td>
<td>Magnitude and phase angle of bus voltages</td>
</tr>
</tbody>
</table>

Table 2.1: Bus classification

2.4 Numerical methods for solving the power-flow equations

There are three popular numerical methods for solving the power-flow equations. These are the Gauss-Seidel (G-S), the Newton-Raphson (N-R) Methods and the fast decoupled power-flow.

2.4.1 Gauss-Seidel Method

Gauss-Seidel method is a technique used to solve a linear system of equations. The method is named after the German mathematicians Carl Friedrich Gauss and Philipp Ludwig von Seidel. The method is an improved version of the Jacobi method. It is defined on matrices with non-zero diagonals, but convergence is only guaranteed if the matrix is either diagonally dominant or symmetric and positive definite [6].

2.4.2 Newton-Raphson method

In numerical analysis, Newton's method (also known as the Newton–Raphson method or the Newton–Fourier method) is perhaps the best known method for finding successively better approximations to the zeros (or roots) of a real-valued function. Newton's method can often converge remarkably quickly; especially if the iteration begins "sufficiently near" the desired
root. Just how near "sufficiently near" needs to be and just how quickly "remarkably quickly" can be depends on the problem[7].

Unfortunately, far from the desired root, Newton's method can easily lead an unwary user astray with little warning. Thus, good implementations of the method embed it in a routine that also detects and perhaps overcomes possible convergence failures.

### 2.4.3 Fast decoupled method

The Fast decoupled power flow solution requires more iterations than the Newton-Raphson method, but requires considerably less time per iteration and a power flow solution is obtained rapidly. This technique is very useful in contingency analysis where numerous outages are to be simulated or a power flow solution is required for on-line control.

For large scale power system, usually the transmission lines have a very high X/R ratio. For such a system, real power changes $\Delta P$ are less sensitive to changes in voltage magnitude and are most sensitive to changes in phase angle $\Delta \delta$. Similarly, reactive power is less sensitive to changes in angle and most sensitive on changes in voltage magnitude.[7]

### 2.4.4 Conditions for Successful Operation of a Power System

There are the following:

1. There should the adequate real power generation to supply the power demand at various load buses and also the losses.
2. The bus voltage magnitudes are maintained at values very close to the rated values.
3. Generators, transformers and transmission lines are not over loaded at any point of time or the load curve[6].
Chapter 3

3.1 Introduction

Transient stability is the ability of the power system to maintain synchronism when subjected to severe transient disturbance such as the fault on transmission facilities, loss of generation or loss of large load. The system response to such disturbance involves large excursions of generator rotor angle, power flows, bus voltages, and other system variables. Transient stability is influenced by the nonlinear characteristics of the power system. If the resulting angular separation between the machines in the system remains within certain bounds, the system maintains synchronism. Loss of synchronism is because of transient stability, if it occurs, will usually be evident within 2 to 3 seconds of the initial disturbance.

In this chapter, the nature of transient stability problems, identifies factor influencing them, and describes modeling consideration and analytical techniques applicable to transient stability analysis would be illustrated [8].
3.2 Elementary view of transient stability

Consider the system shown in Fig 3.1. Consisting of a generator delivering power to a large system represented by an infinite bus throw two transmission circuits. An infinite bus represents a voltage source of constant voltage magnitude and constant frequency.

Fig 3.1: single machine infinite bus system.

Fig 3.2: system representation
The analysis of this system is evaluated neglecting resistance and the speed governor effects. The corresponding system representation is shown in Fig 3.2. The voltage behind the transient reactance ($X'_a$) is denoted by $E'$. The rotor angle $\delta$ represents the angle by which $E'$ leads $E_B$. When the system is perturbed, the magnitude of $E'$ remains constant at its predisturbance value and $\delta$ change as the generator rotor speed deviates from synchronous speed $\omega_0$.

The system model can be reduced to the form shown in Fig 3.2a. The generator’s electrical power output is:

$$P_e = \frac{E' V_B}{X_T} \sin \delta = P_{\text{max}} \sin \delta$$  \hspace{1cm} (3.1)

$$P_{\text{max}} = \frac{E' V_B}{X_T}$$  \hspace{1cm} (3.2)

Since we have neglected the stator resistance, $P_e$ represented the air gap power as well as the terminal power. The power angle relationship is shown in Fig 3.2 as curve 1. With mechanical input power input of $P_m$, the steady-state electrical power output $P_e$ is equal to $P_m$, and the operating conditions is represented by point a on the curve. The corresponding rotor angle is $\delta_a$ (I/S) and (O/S) means in service and out service respectively.

**Fig 3.3: power and angle relationship**
If one of the circuits is out of service, the effective reactance $X_T$ is higher. The power angle relationship with circuit 2 out of service is shown in Fig 3.3 as curve 2. The maximum power is now lower. With a mechanical input power $P_m$, the rotor angle is now $\delta_b$ corresponding to the operating point $b$ on curve 2; with a higher reactance, the rotor angle is higher in order to transmit the same steady state power.

During a disturbance, the oscillation of $\delta$ is superimposed on synchronous speed $\omega_o$, but the speed deviation ($\Delta\omega_r \approx \frac{d\delta}{dt}$) is very much smaller than $\omega_o$, and the per unit air gap torque may be considered to be equal to the air gap power. We well there for use torque and power interchangeably when referring to the swing equation.

The equation of motion or the swing equation may be written as

$$\frac{2H}{\omega_o} \frac{d^2\delta}{dt^2} = P_m - P_{max} \sin \delta \quad (3.3)$$

Where:

- $P_m$ = mechanical power input, in p.u.
- $P_{max}$ = maximum electrical power output, in p.u.
- $H$ = inertia constant, in MW.s/MVA.
- $\delta$ = rotor angle, in electrical radian.
- $t$ = time in sec.

3.2.1 Response to a step change in $P_m$

Let us now examine the transient behaviour of the system. With both circuits in service, by considering a sudden increase in the mechanical power input from an initial value of $P_{m0}$ to $P_{m1}$ as shown in Fig 3.4a. Because of the inertia of the rotor, the rotor angle cannot change instantly from the initial value of $\delta_0$ to $\delta_1$ corresponding to the new equilibrium point $b$ and which $P_m$. The mechanical power is now in excess of the electrical power. The resulting accelerating torque causes the rotor to accelerate from the initial operating point $a$ toward the
new equilibrium point b, tracing the $P_e - \delta$ curve at a rate determined by the swing equation. The difference between $P_{m1}$ and $P_e$ at any instant represents the accelerating power.

![Power-angle variations and Rotor angle time response](image)

**Fig 3.4: response to a step load in mechanical power input**

When point b is reached, the accelerating power is zero, but the rotor speed is higher than the synchronous speed $\omega_0$ (which corresponds to the frequency of the infinite bus voltage). Hence, the rotor angle continues to increase. For values of $\delta$ higher than $\delta_1$, $P_e$ is greater than $P_{m1}$ and the rotor decelerates. At some peak value $\delta_m$, the rotor speed recovers to the synchronous value $\omega_0$, but $P_e$ is higher than $P_{m1}$. The rotor continues to decelerate with the speed dropping below $\omega_0$; the operating point retraces the $P_e - \delta$ curve from c to b and then to a. The rotor angle oscillates indefinitely about the new equilibrium angle $\delta_1$ with constant amplitude as shown by the time plot of $\delta$ in **Fig 3.4b**.

### 3.2.2 Equal-area criterion

For the system model considered above, it is not necessary to formally solve the swing equation to determine whether the rotor angle increases indefinitely or oscillates about an equilibrium position. Information regarding the maximum angle excursion ($\delta_m$) and the stability limit may be obtained graphically by using the power-angle diagram shown in **Fig 3.4**. Although this method is not applicable to multi-machine systems with detailed representation of...
synchronous machines, it helps in understanding basic factors that influence the transient stability of any system.

From Equation (3.3), we have the following relationship between the rotor angle and the accelerating power:

\[
\frac{d^2\delta}{dt^2} = \frac{\omega_o}{2H} (P_m - P_e) \tag{3.4}
\]

Now \( P_e \) is a nonlinear function of \( \delta \), and therefore the above equation cannot be solved directly. If both sides are multiplied by \( d\delta/dt \), then

\[
2 \frac{d\delta}{dt} \frac{d^2\delta}{dt^2} = \frac{\omega_o(P_m-P_e)}{H} \frac{d\delta}{dt} \tag{3.5}
\]

\[
\frac{d}{dt} \left[ \frac{d\delta}{dt} \right]^2 = \frac{\omega_o(P_m-P_e)}{H} \frac{d\delta}{dt} \tag{3.5}
\]

\[
\left[ \frac{d\delta}{dt} \right]^2 = \int \frac{\omega_o(P_m-P_e)}{H} \, d\delta \tag{3.6}
\]

The speed deviation \( d\delta/dt \) is initially zero. It will change as a result of the disturbance. For stable operation, the deviation of angle \( \delta \) must be bounded, reaching maximum value as at point c in Fig 3.4 and then changing direction.

This requires the speed deviation \( d\delta/dt \) to become zero at same time after the disturbance. Therefore, from Equation (3.6), as a criterion for stability we may write
Where $\delta_0$ is the initial rotor angle and $\delta_m$ is the maximum rotor angle, as illustrated in Fig 3.4. Thus, the area under the function $P_m - P_e$ plotted against $\delta$ must be zero if the system is to be stable. In Fig 3.4, this is satisfied when area $A_1$, is equal to area $A_2$. Kinetic energy is gained by the rotor during acceleration when $\delta$ changes from $\delta_0$ to $\delta_1$. The energy gained is

$$E_1 = \int_{\delta_0}^{\delta_1} (P_m - P_e) \, d\delta = \text{area } A_1 \quad (3.8)$$

$$E_2 = \int_{\delta_1}^{\delta_m} (P_e - P_m) \, d\delta = \text{area } A_2 \quad (3.9)$$

As we have not considered any losses, the energy gained is equal to the energy lost; therefore, area $A_1$ is equal to area $A_2$. This forms the basis for the equal-area criterion. It enables us to determine the maximum swing of $\delta$ and hence the stability of the system without computing the time response through formal solution of the swing equation.

The criterion can be readily used to determine the maximum permissible increase in $P_m$ for the system of Fig 3.1. The stability is maintained only if an area $A_2$ at least equal to $A_1$ can be located above $P_{m1}$. If $A_1$ is larger than $A_2$, then $\delta_m > \delta_L$, and stability will be lost. This is because, for $\delta_m > \delta_L$, $P_{m1}$ is larger than $P_e$ and the net torque is accelerating rather than decelerating.

### 3.2.3 Response to a short circuit fault

Let us consider the response of the system to a three-phase fault at location F on transmission circuit 2, as shown in Fig 3.5a, the corresponding equivalent circuit, assuming a classical generator model, is shown in Fig 3.5b. The fault is cleared by opening circuit breakers at both ends of the faulted circuit, the fault-clearing time depending on the relaying time and breaker time.

If the fault location F is at the sending end (HT bus) of the faulted circuit, no power is transmitted to the infinite bus. The short-circuit current from the generator flows through pure reactances to the fault. Hence, only reactive power flows and the active power $P_e$ and
the corresponding electrical torque $T_e$ at the air-gap are zero during the fault. If we had included generator stator and transformer resistances in our model, $P_e$ would have a small value, representing the corresponding resistive losses.

If the fault location $F$ is at some distance away from the sending end as shown in Fig 3.5a and Fig 3.5b, some active power is transmitted to the infinite bus while the fault is still on.

![Diagram](image)

(a) Single-line diagram  (b) Equivalent circuit

![Graphs](image)

(c) Response to a fault cleared in $t_{c1}$ seconds - stable case  
(d) Response to a fault cleared in $t_{c2}$ seconds - unstable case

**Fig 3.5:** illustration of transient stability phenomenon

Fig 3.5c and Fig 3.5d show $P_e-\delta$ plots for the three network conditions:
(i) Perrault (both circuits in service)

(ii) With a three-phase fault on circuit 2 at a location some distance from the sending end.

(iii) Post fault (circuit 2 out of service).

**Fig 3.5c** considers the system performance with a fault-clearing time of \((t_{c1})\) and represents a stable case. **Fig 3.5d** considers a longer fault-clearing time \((t_{c2})\) such that the system is unstable. In both cases \(P_e\) is assumed to be constant.

Let us examine the stable case depicted by **Fig 3.5c**. Initially, the system is operating with both circuits in service such that \(P_e = P_m\) and \(\delta = \delta_0\). When the fault occurs, the operating point suddenly changes from \(a\) to \(b\). Owing to inertia, angle \(\delta\) cannot change instantly. Since \(P_m\) is now greater than \(P_e\), the rotor accelerates until the operating point reaches \(c\), when the fault is cleared by isolating circuit 2 from the system. The operating point now suddenly shifts to \(d\). Now \(P_e\) is greater than \(P_m\), causing deceleration of the rotor. Since the rotor speed is greater than the synchronous speed \(\omega_0\), \(\delta\) continues to increase until the kinetic energy gained during the period of acceleration (represented by area \(A_1\)) is expended by transferring the energy to the system. The operating point moves from \(d\) to \(e\), such that area \(A_2\) is equal to area \(A_1\). At point \(e\), the speed is equal to \(\omega_0\) and \(\delta\) has reached its maximum value \(\delta_m\). Since \(P_e\) is still greater than \(P_m\), the rotor continues to retard, with the speed dropping below \(\omega_0\). The rotor angle \(\delta\) decreases, and the operating point retraces the path from \(e\) to \(d\) and follows the \(P_e-\delta\) curve for the postfault system farther down. The minimum value of \(\delta\) is such that it satisfies the equal-area criterion for the post fault system. In the absence of any source of damping, the rotor continues oscillate with constant amplitude.

With the delayed fault clearing, as shown in **Fig 3.5d**, area \(A_2\) above \(P_m\) is less than \(A_1\). When the operating point reaches \(e\), the kinetic energy gained during the acceleration period has not yet been completely expended; consequently, the speed is still greater than \(\omega_0\) and \(\delta\) continues to increase. Beyond point \(e\), \(P_e\) is less than \(P_m\), and the rotor begins to accelerate again. The rotor speed and angle continue to increase, leading to loss of synchronism.
Chapter 4

4.1 Introduction

Voltage stability deals with the ability to control the voltage level within a narrow band around normal operating voltage. The consumers of electric energy are used to rather small variations in the voltage level and the system behaviour from the operators point of view is fairly well known in this normal operating state. Equipment control and operation are tuned towards specified set points giving small losses and avoids power variations due to voltage sensitive loads.

Once outside the normal operating voltage band many things may happen of which some are not well understood or properly taken into account today. A combination of actions and interactions in the power system can start a process which may cause a completely loss of voltage control. The system will experience a voltage collapse and this result in a rapid loss of electrical supply in wide areas, sometimes affecting millions of people.

The origin of a significant voltage deviation is in most cases some kind of contingency where a generator in a vital power plant shuts down or an important transmission line is disconnected from the power grid. This initiates a voltage change and alters the system
characteristics. The system is normally designed to withstand these kinds of single contingencies occurring many times a year. However, abnormal operating conditions, several independent contingencies occurring almost simultaneously in time or completely unexpected phenomena may violate the normal design conditions. This leads to an insecure operating condition threatening the voltage stability of the system. The goal is therefore to try to understand the course of events after such a contingency and propose remedial actions when the control of voltage is insecure.

In this chapter would be the basic concept related to voltage stability and characterize the voltage avalanche phenomena illustrated. The dynamic and static approaches to voltage stability analysis also would be described.

### 4.2 Voltage stability definitions

Recently IEEE/CIGRE task force [9] proposed various definitions related to power system stability including voltage stability. **Fig 4.1** summarizes these definitions.

![Fig 4.1: Classification of power System stability](image)

In general terms, voltage stability is defined as the ability of a power system to maintain steady voltages at all the 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. Instability that may result appears in the form of a progressive fall or rise of voltages of some buses. A possible outcome of voltage instability is loss of load in an area, or tripping of transmission lines and the other elements by their protection leading to cascading outages that in turn may lead to loss of synchronism of some generators.

This task force further classified the voltage stability into four categories: **large disturbance voltage stability**, **small disturbance voltage stability**, **short-term voltage stability** and **long-term voltage stability**. A short summary of these classifications is given below.

### 4.2.1 Large-disturbance voltage stability

It is refers to the system's ability to maintain steady voltages following large disturbances such as system faults, loss of generation, or circuit contingencies. This ability is determined by the system and load characteristics, and the interactions of both continuous and discrete controls and protections. The study period of interest may extend from a few seconds to tens of minutes.

### 4.2.2 Small-disturbance voltage stability

It is refers to the system's ability to maintain steady voltages when subjected to small perturbations such as incremental changes in system load. This form of stability is influenced by the characteristics of loads, continuous controls, and discrete controls at a given instant of time.

### 4.2.3 Short-term voltage stability

It is involves dynamics of fast acting load components such as induction motors, electronically controlled loads and HVDC converters. The study period of interest is in the order of several seconds, and analysis requires solution of appropriate system differential equations.

### 4.2.4 Long-term voltage stability

It is involves slower acting equipment such as tap-changing transformers, thermostatically controlled loads and generator current limiters. The study period of interest may extend to several or many minutes, and long-term simulations are required for analysis of system
dynamic performance. Instability is due to the loss of long-term equilibrium, post-disturbance steady-state operating point being small disturbance unstable, or a lack of attraction towards the stable post disturbance equilibrium. The disturbance could also be a sustained load build up.

4.3 Voltage instability concept

Voltage instability may be caused by various system aspects. Generators, transmission lines and loads are among the most important components. Generators play an important role for providing enough reactive powder support for the powder systems. The maximum generator reactive powder output is limited by field current limit and armature current limit. Even though reactive power plays an important role in voltage stability, the instability can involve a strong coupling between active and reactive power.

When generator reactive capability is constrained by field current limit, the reactive output becomes voltage dependent. The maximum load power is severely reduced when the field current of the local generator becomes limited. Generator limits may also cause limit-induced bifurcation when voltage collapses occur right after the generator limits are reached [10]. Transmission networks are other important constraints for voltage stability. The maximum deliverable power is limited by the transmission network eventually. Power beyond the transmission capacity determined by thermal or stability considerations cannot be delivered.

The third major factor that influences voltage instability is system loads. There are several individual load models due to variety of load devices. Static load models and dynamic load models are two main categories for load modelling. Constant power, constant current and constant impedance load models are representatives of static load models; while dynamic load models are usually represented by differential equations [11]. The common static load models include polynomial or constant impedance, constant current or constant power known as ZIP models. Induction motor is a typical dynamic load model. In real power systems, loads are aggregates of many different devices and thus parameters of load models may be the composite among individual load parameters. Another important load aspect is the Load Tap Changing (LTC) transformer which is one of the key mechanisms in load restoration. During the load recovery process, LTC tends to maintain constant voltage level at the low voltage end. Therefore, load behaviour observed at high voltage level is close to constant power which may exacerbate voltage instability.
### 4.3.1 Transmission System Characteristics

The characteristics of interest are the relationships between the transmitted power ($P_R$), receiving end voltage ($V_R$), and the reactive power injection ($Q_i$). For complex systems with a large number of voltage sources and load buses, similar characteristics can be determined by using power-flow analysis.

![Schematic diagram](image)

**Fig 4.2: Characteristics of a simple radial system**

Let us briefly review the characteristics of the simple radial system. For reference the schematic diagram of the system is produced in **Fig 4.2a**. The current $I$ and receiving end voltage $V_R$ and power $P_R$ are given by the following equations:

$$I = \frac{1}{\sqrt{F}} \frac{Z_s}{Z_{LN}}$$  \hspace{1cm} (4.1)

$$V_R = \frac{1}{\sqrt{F}} \frac{Z_{LD}}{Z_{LN}} E_S$$  \hspace{1cm} (4.2)

$$P_R = \frac{Z_{LD}}{F} \left[ \frac{E_S}{Z_{LN}} \right] \cos \phi$$  \hspace{1cm} (4.3)

where

$$F = 1 + \left[ \frac{Z_{LD}}{Z_{LN}} \right]^2 + 2 \left[ \frac{Z_{LD}}{Z_{LN}} \right] \cos (\theta - \phi)$$

Plots of $I$, $V_R$, and $P_R$ are shown in **Fig 4.2b** as a function of load demand ($\frac{Z_{LN}}{Z_{LD}}$), for the case with $\tan \theta = 10.0$ and $\cos \phi = 0.95$. To make the results applicable to any value of $Z_{LN}$, the values of $I$, $V_R$ and $P_R$ are appropriately normalized. As load demand increases ($Z_{LD}$ decreases),
\( P_R \) increases rapidly at first and then slowly before reaching a maximum, and finally decreases. There is thus a maximum value of active power that can be transmitted through impedance from a constant voltage source. The power transmitted is maximum when the voltage drop in the line is equal in magnitude to \( V_R \), i.e., when \( Z_{LD} / Z_{LN} = 1 \). The conditions corresponding to maximum power represent the limits of satisfactory operation. The values of \( V_R \) and I corresponding to maximum power are referred to as critical values.

For a load demand higher than the maximum power, control of power by varying the load would be unstable, i.e., an increase in load admittance would reduce power. In this region, the load voltage may or may not progressively decrease depending on the load-voltage characteristic. With a constant-admittance load characteristic, the system condition stabilizes at a voltage level that is lower than normal. On the other hand, if the load is supplied by a transformer with ULTC, the tap-changer action will try to raise the load voltage, which has the effect of reducing effective \( Z_{LD} \). This lowers \( V_R \) still further and leads to a progressive reduction of voltage. This is the phenomenon of voltage instability.

### 4.3.2 Generator characteristics

Generator AVRs are the most important means of voltage control in power system. Under normal conditions of low–system voltages, the reactive power demand on generators may exceed their field current and/or armature current limits. When the reactive power output is limited, the terminal voltage is no longer maintained constant.

The generator field current is automatically limited by an overexcitation limiter (OXL). With constant field current, the point of constant voltage is behind the synchronous reactance. This effectively increases the network reactance significantly, further aggravating the voltage collapse condition.

On most generators, the armature current limit is realized manually by operators responding to alarms. The operator reduces reactive and/or active power output to bring the armature current within safe limits. On some generators, automatic armature current limiters with time delay are used to limit reactive power output through the AVR [12].
4.3.3 Load Characteristics

Load characteristics and distribution system voltage control devices are among the key factors influencing system voltage stability.

Loads whose active and reactive components vary with voltage interact with the transmission characteristics by changing the power flow through the system. The system voltages settle at values determined by the composite characteristic of the transmission system and loads.

Distribution system voltage regulators and substation transformer ULTCs attempt to hold constant voltage at the point of consumption. Within the normal control range, loads appear effectively as constant MVA loads. This may have a destabilizing effect during conditions of voltage collapse.

When the ULTCs reach the end of their tap range, distribution system voltages begin to drop. The residential active and reactive loads will drop with voltage. This will in turn reduce line loading and, hence, the line reactive losses. The industrial loads, with large components of induction motors, will change little. However, the capacitors in the industrial area will supply less reactive power, thereby causing a net increase in the reactive load [13].

When the distribution voltages remain low for a few minutes, thermostats and other load regulation devices, as well as manual controls, tend to restore load. For example, heating-type loads will run longer to bring the temperature to the level called for by the thermostats. Consequently, more such devices will be operating at any given time. Many loads of this type will be restored to their normal full voltage value over a 10 to 15 minute period [14]. As voltage-sensitive controlled loads creep back, transmission and distribution voltages will drop further.

At voltages below 85 to 90% of the nominal value, some induction motors may stall and draw high reactive current. This brings the voltages down further. Industrial and commercial motors are usually controlled by magnetically held contactors; therefore, the voltage drop will cause many motors to drop out. The loss of load will result in the recovery of voltages. After some time, the motors are restored to service. This may cause voltages to drop again if the original cause of the voltage problem still persists.

It is evident from the above discussion that, for accurate analysis of voltage
stability, the network representation must include the effects of distribution transformer tap-changer action and capacitors in the distribution systems. Depending on the scope of the study, the representation of load characteristics should take into consideration the effects of thermostats and other load regulation devices. In industrial areas, motors and capacitors may need to be represented explicitly.

### 4.3.4 Characteristics of Reactive Compensating Devices

#### 4.3.4.1 Shunt capacitors

By far the most inexpensive means of providing reactive power and voltage support is the use of shunt capacitors. They can be effectively used up to a certain point to extend the voltage stability limits by correcting the receiving end power factor. They can also be used to free up "spinning reactive reserve" in generators and thereby help prevent voltage collapse in many situations.

Shunt capacitors, however, have a number of inherent limitations from the viewpoint of voltage stability and control:

- In heavily shunt capacitor compensated systems, the voltage regulation tends to be poor.
- Beyond a certain level of compensation, stable operation is unattainable with shunt capacitors.
- The reactive power generated by a shunt capacitor is proportional to the square of the voltage; during system conditions of low voltage the var support drops, thus compounding the problem.

#### 4.3.4.2 Regulated shunt compensation

A static var system (SVS) of finite size will regulate up to its maximum capacitive output. There are no voltage control or instability problems within the regulating range. When pushed to the limit, an SVS becomes a simple capacitor. The possibility of this leading to voltage instability must be recognized.
A synchronous condenser, unlike an SVS, has an internal voltage source. It continues to supply reactive power down to relatively low voltages and contributes to a more stable voltage performance.

4.3.4.3 Series capacitors

Series capacitors are self-regulating. The reactive power supplied by series capacitors is proportional to square of the line current and is independent of the bus voltages. This has a favourable effect on voltage stability. Series capacitors are ideally suited for effectively shortening long lines. Unlike shunt capacitors, series capacitors reduce both the characteristic impedance \(Z_C\) and the electrical length \(\theta\) of the line. As a result, both voltage regulation and stability are significantly improved.

4.4 Voltage Collapse

Voltage collapse is the process by which the sequence of events accompanying voltage instability leads to a low unacceptable voltage profile in a significant part of the power system. Voltage collapse may be manifested in several different ways. We will describe a typical scenario of voltage collapse, and then provide a general characterization of the phenomenon based on actual incidents of collapse.

4.4.1 Typical Scenario of Voltage Collapse

When a power system is subjected to a sudden increase of reactive power demand following a system contingency, the additional demand is met by the reactive power reserves carried by the generators and compensators. Generally there are sufficient reserves and the system settles to a stable voltage level. However, it is possible, because of a combination of events and system conditions that the additional reactive power demand may lead to voltage collapse, causing a major breakdown of part or all of the system. A typical scenario of a voltage collapse would be as follows [15]:

- The power system is experiencing abnormal operating conditions with large generating units near the load centres being out of service. As a result, some EHV
lines are heavily loaded and reactive power resources are at a minimum.

- The triggering event is the loss of a heavily loaded line which would cause additional loading on the remaining adjacent lines. This would increase the reactive power losses in the lines (Q absorbed by a line increases rapidly for loads above surge impedance loading), thereby causing a heavy reactive power demand on the system.

- Immediately following the loss of the EHV line, there would be a considerable reduction of voltage at adjacent load centres due to extra reactive power demand. This would cause a load reduction, and the resulting reduction in power flow through the EHV lines would have a stabilizing effect. The generator AVRs would, however, quickly restore terminal voltages by increasing excitation. The resulting additional reactive power flow through the inductances associated with generator transformers and lines would cause increased voltage drop across each of these elements. At this stage, generators would likely be within the P-Q output capabilities, i.e., within the armature and field current heating limits. The speed governors would regulate frequency by reducing MW output.

- The EHV level voltage reduction at load centres would be reflected into the distribution system. The ULTCs of substation transformers would restore distribution voltages and loads to prefault levels in about 2 to 4 minutes. With each tap change operation, the resulting increment in load on EHV lines would increase the line \( X_l^2 \) and \( R_l^2 \) losses, which in turn would cause a greater drop in EHV levels. If the EHV line is loaded considerably above the SIL, each MVA increase in line flow would cause several MVARs of line losses.

- As a result, with each tap-changing operation, the reactive output of generators throughout the system would increase. Gradually, the generators would hit their reactive power capability limits (imposed by maximum allowable continuous field current) one by one. When the first generator reached its field current limit, its terminal voltage would drop. At the reduced terminal voltage for a fixed MW output, the armature current would increase. This may further limit reactive output to keep the armature current within allowable limits. Its share of reactive loading would be transferred to other generators, leading to overloading of more and more generators. With fewer generators on automatic excitation control, the system would be much more prone to voltage instability. This would likely be compounded by
the reduced effectiveness of shunt compensators at low voltages. The process will eventually lead to voltage collapse or avalanche, possibly leading to loss of synchronism of generating units and a major blackout.

4.4.2 General Characterization Based on Actual Incidents

There have been a number of voltage collapse incidents worldwide (see references [12],[13],[16] and [17] for descriptions). Based on these incidents, voltage collapse may be characterized as follows:

1. The initiating event may be due to a variety of causes: small gradual system changes such as natural increase in system load, or large sudden disturbances such as loss of a generating unit or a heavily loaded line. Sometimes, a seemingly uneventful initial disturbance may lead to successive events that eventually cause system collapse.

2. The heart of the problem is the inability of the system to meet its reactive demands. Usually, but not always, voltage collapse involves system conditions with heavily loaded lines. When transport of reactive power from neighbouring areas is difficult, any change that calls for additional reactive power support may lead to voltage collapse.

3. The voltage collapse generally manifests itself as a slow decay of voltage. It is the result of an accumulative process involving the actions and interactions of many devices, controls, and protective systems. The time frame of collapse in such cases could be on the order of several minutes. The duration of voltage collapse dynamics in some situations may be much shorter, being on the order of a few seconds. Such events are usually caused by unfavourable load components such as induction motors or dc converters. The time frame of this class of voltage instability is the same as that of rotor angle instability. In many situations, the distinction between voltage and angle instability may not be clear, and some aspects of both phenomena may exist. This form of voltage instability may be analyzed by conventional transient stability simulations, provided appropriate models are used to represent the devices, particularly induction motor loads, and various control and protection associated with
the generators and transmission equipment.

4. Voltage collapse is strongly influenced by system conditions and Characteristics. The following are the significant factors contributing to voltage instability/collapse:

- Large distances between generation and load
- ULTC action during low voltage conditions
- Unfavourable load characteristics
- Poor coordination between various control and protective systems

5. The voltage collapse problem may be aggravated by excessive use of shunt capacitor compensation. Reactive compensation can be made most effective by the judicious choice of a mixture of shunt capacitors, static var systems, and possibly synchronous condensers.

### 4.5 Voltage stability analysis

The analysis of voltage stability for a given system state involves the examination of two aspects [18]:

1- Proximity to voltage instability: How close is the system to voltage instability? Distance to instability may be measured in terms of physical quantities, such as load level, active power flow through a critical interface, and reactive power reserve. The most appropriate measure for any given situation depends on the specific system and the intended use of the margin; for example, planning versus operating decisions. Consideration must be given to possible contingencies (line outages, loss of a generating unit or a reactive power source, etc.).

2- Mechanism of voltage instability: How and why does instability occur? What are the key factors contributing to instability? What are the voltage-weak areas? What measures are most effective in improving voltage stability?

Time-domain simulations, in which appropriate modelling is included, capture the
events and their chronology leading to instability. However, such simulations are time-consuming and do not readily provide sensitivity information and the degree of stability. System dynamics influencing voltage stability are usually slow. Therefore, many aspects of the problem can be effectively analyzed by using static methods, which examine the viability of the equilibrium point represented by a specified operating condition of the power system. The static analysis techniques allow examination of a wide range of system conditions and, if appropriately used, can provide much insight into the nature of the problem and identify the key contributing factors. Dynamic analysis, on the other hand, is useful for detailed study of specific voltage collapse situations, coordination of protection and controls, and testing of remedial measures. Dynamic simulations also examine whether and how the steady-state equilibrium point will be reached.

In this section, we discuss static as well as dynamic analysis techniques and we illustrate how the two approaches can be used in a complementary manner.

4.5.1 Dynamic Analysis

The general structure of the system model for voltage stability analysis is similar to that for transient stability analysis. The overall system equations, comprising a set of first-order differential equations, may be expressed in the following general form:

\[ \dot{x} = f(x, V) \]  \hspace{1cm} (4.4)

and a set of algebraic equations

\[ I(x, V) = YNV \]  \hspace{1cm} (4.5)

with a set of known initial conditions \((x_0, V_0)\), where

\[ x \quad = \text{state vector of the system} \]
\[ V \quad = \text{bus voltage vector} \]
\[ I \quad = \text{current injection vector} \]
\[ YN \quad = \text{network node admittance matrix} \]

Since we include the representation of transformer tap-changer and phase-shift angle controls, the elements of YN change as a function of bus voltages and time. The current injection vector I is a function of the system states x and bus voltage vector V,
replicating the boundary conditions at the terminals of the various devices (generating units, nonlinear static loads, motors, SVSs, HVDC converters, etc.). Due to the time-dependent nature of devices such as field current limiters, the relationship between I and x can be a function of time.

Equations (4.4) and (4.5) can be solved in time-domain by using any of the numerical integration methods and network power-flow analysis methods. The study period is typically on the order of several minutes. With the inclusion of special models representing the "slow system dynamics" leading to voltage collapse, the stiffness of the system differential equations is significantly higher than that of transient stability models. Implicit integration methods are ideally suited for such applications. Facilities to automatically change the integration time step, as the solution progresses and fast transients decay, greatly enhance the computational efficiency of such techniques.

4.5.2 Static Analysis

The static approach captures snapshots of system conditions at various time frames along the time-domain trajectory. At each of these time frames, time derivatives of the state variables (i.e., \( \dot{x} \)) in Equation (4.4) are assumed to be zero, and the state variables take on values appropriate to the specific time frame. Consequently, the overall system equations reduce to purely algebraic equations allowing the use of static analysis techniques.

In the past, the electric utility industry has largely depended on conventional power-flow programs for static analysis of voltage stability. Stability is determined by computing the V-P and Q-V curves at selected load buses. Generally, such curves are generated by executing a large number of power flows using conventional models. While such procedures can be automated, they are time-consuming and do not readily...
Chapter 5

5.1 Introduction

This chapter will be illustrated the three case studies, that are chosen for three types of power system analysis to investigate their results using PSAT program. Also it shows how case studies were modeled and how the respective input data was entered to them. All data in this chapter was entered according to the standard of PSAT Parameters entry, and this standard was written by Federico Milano with all documentation of PSAT [2].
5.2 Case study (1): Power flow solution

Case study 1 of power flow was represented in Fig 5.1 is chosen from reference [20]. This example examined power flow solution to determine the unknown variables V, P, Q, and δ for every bus.

![System representation of case study (1)](image)

**Fig 5.1: system representation of case study (1)**

The input data parameters and their result for this example are found in Appendix A.

5.2.1 Simulation of Case study 1:

Case 1 was modelled using PSAT simulink library as shown in Fig 5.2. Power and frequency ratings are (100 MVA, and 60 Hz) respectively.

![Model of case 1 in PSAT simulink](image)

**Fig 5.2: The model of case 1 in PSAT simulink**
In this case, voltage ratings will vary according to the voltage level by entering the voltage ratio in transformers. Input data that was entered in PSAT blocks for this case were shown in Table (5.1, 5.2, 5.3, 5.4, 5.5 and 5.6).

<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>1.0</td>
<td>5.2</td>
<td>1.05</td>
</tr>
</tbody>
</table>

Table 5.1: input data for PV generator 1 (case study 1)

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>1.0</td>
<td>1.0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5.2: input data for slack generator 1 (case study 1)

<table>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>1.0</td>
<td>60</td>
<td>0.0437</td>
<td>0.0015</td>
<td>0.02</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>1.0</td>
<td>60</td>
<td>0.0437</td>
<td>0.00075</td>
<td>0.01</td>
</tr>
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</table>

Table 5.3: input data for transformer 1 and 2 (case study 1)

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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>23</td>
<td>60</td>
<td>0</td>
<td>0.009</td>
<td>0.1</td>
<td>1.72</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>23</td>
<td>60</td>
<td>0</td>
<td>0</td>
<td>0.93</td>
<td>0.88</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>23</td>
<td>60</td>
<td>0</td>
<td>0</td>
<td>0.93</td>
<td>0.44</td>
</tr>
</tbody>
</table>

Table 5.4: input data for lines (case study 1)
### Table 5.5: input data for PQ load (case study 1)

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>1.0</td>
<td>8</td>
<td>2.8</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>1.0</td>
<td>0.8</td>
<td>0.4</td>
</tr>
</tbody>
</table>

### Table 5.6: Bus input data (case study 1)

<table>
<thead>
<tr>
<th>Bus</th>
<th>Voltage rating [kV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>23</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>23</td>
</tr>
<tr>
<td>5</td>
<td>23</td>
</tr>
</tbody>
</table>

### 5.3 Case study 2: The transient stability analysis

This system was taken from reference [8], examined the transient stability of a thermal generation station consisting of four 555 MVA, 24 kV, 60 Hz units supplying power to an infinite bus through two transmission circuits as shown in **Fig 5.3**.

**Fig 5.3: single machine infinite bus system**

The network reactances shown in the **Fig (5.3)** are in per unit on 2220 MVA, 24 kV base (referred to the LT side of the step-up transformer). Resistances are assumed to be neglected.
The initial system-operating condition, with quantities expressed in p.u on 2220 MVA and 24 kV base, is as follows:

\[
P = 0.9 \quad Q = 0.436 \quad E_B = 0.90081
\]

The generators are modeled as a single equivalent generator in p.u on 2220 MVA, 24 kV base: \( X'_{d} = 0.3 \quad H = 3.5 \text{ MW.s/MVA} \quad K_p = 0 \)

Circuit 2 experiences a solid three-phase fault at point F, and the fault is cleared by isolating the faulted circuit.

The transient stability analysis can be attained by determining the critical fault-clearing time and the critical clearing angle by computing the time response of the rotor angle, using numerical integration method. Also the system value of critical clearing angle can be verified using the equal area criterion.

The critical fault-clearing time and the critical clearing angle results of this example are shown in Appendix B.

### 5.3.1 Simulation of Case study 2

In this case the infinite bus was represented with slake bus and PQ load to maintain a constant voltage of 0.90081 to bus 3. Power and frequency ratings are (100 MVA, and 60 Hz) respectively. Fault time was set to 1sec, breaker First invention time and fault clearing time were entered randomly to get a suitable critical clearing time. System was modeled as shown in Fig 5.4.

![Fig 5.4: the model of case 2 in PSAT simulink](image)
Input data for this case is shown in Table (5.7, 5.8, 5.9, 5.10, 5.11, 5.12, 5.13 and 5.14), and all buses at voltage ratings of 1 kV; because, all system at the same voltage level.

<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>1.0</td>
<td>0.925</td>
<td>1.0</td>
</tr>
</tbody>
</table>

**Table 5.7: input data for PV generator (case study 2)**

Active power p.u = \( \frac{\text{system power in MVA}}{\text{base MVA} \times V_{\text{base}}} \) = \( \frac{2220}{100 \text{ MVA} \times 24 \text{kV}} \) = 0.925 p.u

Voltage magnitude p.u = \( \frac{\text{system voltage in kV}}{V_{\text{base}}} \) = \( \frac{24 \text{kV}}{24 \text{kV}} \) = 1.0 p.u

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>1.0</td>
<td>1.0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Table 5.8: input data for slack generator (case study 2)**

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>1.0</td>
<td>60</td>
<td>1.0</td>
<td>0</td>
<td>0.15</td>
</tr>
</tbody>
</table>

**Table 5.9: input data transformer 1 (case study 2)**

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>1.0</td>
<td>60</td>
<td>0</td>
<td>0</td>
<td>0.15</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>1.0</td>
<td>60</td>
<td>0</td>
<td>0</td>
<td>0.93</td>
</tr>
</tbody>
</table>

**Table 5.10: input data for lines (case study 2)**
### Table 5.11: input data for PQ load (case study 2)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>PQ load</td>
<td>100</td>
<td>1.0</td>
<td>0.9</td>
<td>0.436</td>
</tr>
</tbody>
</table>

### Table 5.12: input data for Synchronous generator 1 (case study 2)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>Voltage Frequency ratings [MVA kV HZ]</td>
</tr>
<tr>
<td>Machine order</td>
<td>2</td>
</tr>
<tr>
<td>$[X_d X'_d X''_d]$</td>
<td>[0.3 0.3 0.3]</td>
</tr>
<tr>
<td>$[X_q X'_q X''_q]$</td>
<td>[0.3 0.3 0.3]</td>
</tr>
<tr>
<td>$R_a$</td>
<td>0</td>
</tr>
<tr>
<td>$X_i$</td>
<td>0</td>
</tr>
<tr>
<td>$[T'<em>{d0} T''</em>{d0}]$</td>
<td>[100 100]</td>
</tr>
<tr>
<td>$[T'<em>{q0} T''</em>{q0}]$</td>
<td>[100 100]</td>
</tr>
<tr>
<td>$M = 2H$</td>
<td>7</td>
</tr>
</tbody>
</table>

### Table 5.13: input data for breaker 1 (case study 2)

<table>
<thead>
<tr>
<th>Breaker</th>
<th>Power rating [MVA]</th>
<th>Voltage rating [kV]</th>
<th>Frequency rating [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>1</td>
<td>60</td>
</tr>
</tbody>
</table>

### Table 5.14: input data for fault 1 (case study 2)

<table>
<thead>
<tr>
<th>fault</th>
<th>Power rating [MVA]</th>
<th>Voltage rating [kV]</th>
<th>Frequency rating [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>750</td>
<td>60</td>
</tr>
</tbody>
</table>
5.4 Case study 3: The voltage stability analysis

In this example the analysis of large disturbance voltage stability of the system shown in Fig 5.5, using time domain simulation. The test system considered here is based on the system originally described in reference [8] for analysis of various aspects of voltage stability.

![Fig 5.5: Test system for voltage stability](image)

The test system input data and results for this case study is found in Appendix C.

5.4.1 Simulation of Case study 3:

All voltage levels were guessed in appropriate manner to suit this case study because the voltage levels of buses were not attached with example in reference [8]. Power and frequency ratings are (100 MVA, and 60 Hz) respectively. The load of bus 11 is modelled as PQ load and ZIP load the simulink model of case 3 is illustrated in Fig 5.6
Fig 5.6: The model of case 3 in PSAT simulink.

All input data of this case are shown in Table (5.15, 5.16, 5.17, 5.18, 5.19, 5.20, 5.21, 5.22, 5.23 and 5.24). These input data entered in PSAT simulink model for load level 1 only.

<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>100</td>
<td>11</td>
<td>17.36</td>
<td>0.9646</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>11</td>
<td>11.54</td>
<td>0.1.04</td>
</tr>
</tbody>
</table>

Table 5.15: input data for PV generators (case study 3)

<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>1.0</td>
<td>0.98</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5.16: input data for slack generator (case study 3)
### Table 5.17: input data for transformers (case study 3)

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>11</td>
<td>60</td>
<td>0.1466</td>
<td>0</td>
<td>0.02</td>
<td>0.8857</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>11</td>
<td>60</td>
<td>0.1466</td>
<td>0</td>
<td>0.0045</td>
<td>0.8857</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>11</td>
<td>60</td>
<td>0.1466</td>
<td>0</td>
<td>0.00125</td>
<td>0.9024</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>11</td>
<td>60</td>
<td>7.5</td>
<td>0</td>
<td>0.0045</td>
<td>1.0800</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>11</td>
<td>60</td>
<td>7.5</td>
<td>0</td>
<td>0.0026</td>
<td>1.0800</td>
</tr>
</tbody>
</table>

### Table 5.18: input data for ULTC transformer (case study 3)

<table>
<thead>
<tr>
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<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>5 (ULTC)</td>
<td>100</td>
<td>100</td>
<td>9.09</td>
<td>0 &amp; 0.001</td>
<td>1.1</td>
<td>0.9</td>
<td>0.00625</td>
<td>0.92</td>
</tr>
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</table>

### Table 5.19: input data for lines (case study 3)

<table>
<thead>
<tr>
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<th></th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>750</td>
<td>60</td>
<td>0</td>
<td>0.004</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>750</td>
<td>60</td>
<td>0.0015</td>
<td>0.0288</td>
<td>1.173</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>750</td>
<td>60</td>
<td>0.0015</td>
<td>0.93</td>
<td>1.173</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>750</td>
<td>60</td>
<td>0.0015</td>
<td>0.0288</td>
<td>1.173</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>750</td>
<td>60</td>
<td>0.0015</td>
<td>0.0288</td>
<td>1.173</td>
</tr>
<tr>
<td>6</td>
<td>100</td>
<td>750</td>
<td>60</td>
<td>0.0015</td>
<td>0.0288</td>
<td>1.173</td>
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<tr>
<td>7</td>
<td>100</td>
<td>100</td>
<td>60</td>
<td>0.001</td>
<td>0.003</td>
<td>0</td>
</tr>
</tbody>
</table>

The shunt capacitors at buses (7, 8, and 9) were modeled as PQ load (3, 4 and 5) respectively, with zero active power and negative reactive power as shown in Table 5.20.
### Table 5.20: Input data for PQ load (case study 3)

<table>
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<tr>
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</thead>
<tbody>
<tr>
<td>1</td>
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<td>100</td>
<td>32.71</td>
<td>10.15</td>
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<tr>
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<td>100</td>
<td>11</td>
<td>33.84</td>
<td>9.71</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>11</td>
<td>0</td>
<td>-7.63</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>11</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>11</td>
<td>0</td>
<td>-17.1</td>
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</table>

### Table 5.21: Input data for AVR 2 and 3 (case study 3)

<table>
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<tr>
<th>Parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automatic voltage regulator type</td>
<td>1</td>
</tr>
<tr>
<td>Maximum voltage regulator [p.u]</td>
<td>5</td>
</tr>
<tr>
<td>Minimum voltage regulator [p.u]</td>
<td>-5</td>
</tr>
<tr>
<td>Regulator gain [p.u/p.u]</td>
<td>50</td>
</tr>
<tr>
<td>First regulator pole [s]</td>
<td>0.02</td>
</tr>
<tr>
<td>First regulator zero [s]</td>
<td>0.01</td>
</tr>
<tr>
<td>Second regulator pole [s]</td>
<td>0.01</td>
</tr>
<tr>
<td>Second regulator zero [s]</td>
<td>0.01</td>
</tr>
<tr>
<td>Time constant of the field current [s]</td>
<td>0.38</td>
</tr>
<tr>
<td>Time delay of the Measurement System [s]</td>
<td>0.001</td>
</tr>
<tr>
<td>Coefficient of the ceiling function [A B]</td>
<td>[0.0006 0.9]</td>
</tr>
<tr>
<td>Number of input signals for AVR2 &amp; AVR3 respectively</td>
<td>0 &amp; 1</td>
</tr>
</tbody>
</table>

### Table 5.22: Input data for OXL (case study 3)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrator time constant T0 [s]</td>
<td>1</td>
</tr>
<tr>
<td>Maximum field current [p.u]</td>
<td>3.02</td>
</tr>
<tr>
<td>Maximum output signal</td>
<td>3.85</td>
</tr>
</tbody>
</table>
### Table 5.23: input data for ZIP load (case study 3)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power voltage and frequency rating [MVA kV Hz]</td>
<td>[100 11 60]</td>
</tr>
<tr>
<td>Percentage of resistant active current &amp; active power [% % %]</td>
<td>[0.50 0.50 0.50]</td>
</tr>
<tr>
<td>Percentage of reactant reactive current &amp; reactive power [% % %]</td>
<td>[0.50 0.50 0.50]</td>
</tr>
</tbody>
</table>

### Table 5.24: input data for breaker 1 (case study 3)

<table>
<thead>
<tr>
<th>Breaker</th>
<th>Power rating [MVA]</th>
<th>Voltage rating [kV]</th>
<th>Frequency rating [Hz]</th>
<th>First invention time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>750</td>
<td>60</td>
<td>1</td>
</tr>
</tbody>
</table>
Chapter 6

6.1 Introduction

In this chapter, details on the simulation results with discussion would be provided. In discussion, the PSAT simulation result compared with case studies result, those were mentioned in chapter 5.

6.2 Simulation result of Case study 1 (power flow)

The PSAT power flow report of case study 1 is shown below in Fig 6.1
Fig 6.1: case study 1 power flow report

6.2.1 Discussion on case study 1 results

The PSAT power flow report shown in Fig 6.1 illustrated the power flow result that identical to bus output data in Table A.4 and line flows result that were very close to line flow result in Appendix A in Table A.5 and Table A.5.

Note: in PSAT the transformers flow result shown as line flows.
6.3 Simulation of Case study 2 (Transient stability)

Fig 6.2, Fig 6.3, and Fig 6.4 Show plots of δ as a function of time, for three values of fault clearing time \( t_c \): 0.07 s, 0.086 s, and 0.87s. The corresponding values of clearing angle \( \delta_c \) are 48.58°, 52.04°, and 52.30°, respectively. The time of first intervention breaker near so as to give the exact switching time fault clearing time.

Fig 6.5 shows plot of generator power as function of time prefault, during fault and post fault.

*Note*: in PSAT the angles in radian.

![Fig 6.2: Rotor angle response for clearing time=1.07s](image1)

![Fig 6.3: Rotor angle response for clearing time=1.086s](image2)
6.3.1 Discussion on case study 2 results

From the simulation results shown in Fig 6.2, Fig 6.3, and Fig 6.4, we see that the system is stable with $t_c=0.86$ s, ($\delta_c=52.04^0$), and unstable with $t_c=0.87$ s ($\delta_c=52.30^0$). So that the critical time is, there for $0.0865\pm0.0005$, and the critical angle is $52.17^0\pm0.13^0$.

The generator power prefault occur was 0.925 pu and during fault will become 0.0 pu to postfault will try to return to its value before the fault occur, but it value will oscillates
approximately at 0.77 pu and never back to 0.925. These simulation results of transient stability are very similar to result of case study 2 shown in Appendix B in Fig B.1 and Fig B.2.

6.4 Simulation of Case study 3 (Voltage stability)

Fig 6.6, Fig 6.7 and Fig 6.8 shows the time responses of the voltage at buses 11, 10 and 7 following the loss of one of the lines between buses 6 and 7, for each of the only load level 1. The corresponding terminal voltage of generator G3 is shown in Fig 6.9.
6.4.1 Discussion on case study 3 results

The effect of the loss of the line is to cause the system to drop initially. For load level 1, the ULTC action of transformer T6 restores bus 11 voltages to nearly its reference value in about 50 second as shown in Fig 6.6, but not 40 second as shown in result found in Appendix C in Fig C.1. That is small difference in time, it is not has a value because the system behaves in normal manner.
The voltages of buses 10 and 7 settle at values below the predisturbance value as shown in Fig 6.7 and Fig 6.8, equal to reference values shown in Appendix C in Fig C.2 and Fig C.3. The system voltage is stable.

The simulation result shown in Fig 6.8, the terminal voltage of generator G3 is maintained at the initial value by the AVR. That is value is very similar to the terminal voltage of generator G3 shown in Appendix C in Fig C.4.

The results gained from PSAT simulation and results in Appendix C of this case study of voltage stability shows that the system is stable under load level 1.
Introduction

In this chapter, a conclusion for this thesis and mentioning about further work development and research would be discussed.

Conclusion

It could be said that, this thesis has fulfilled its intended objectives of development MATLAB based power system simulation package, power systems analysis toolbox (PSAT) as an educational toolbox for electrical power system students, lecturers, and researchers in order to solve three power system problems. Those problems are Power Flow Analysis, voltage Stability Analysis and Transient Stability Analysis.

In chapter 1, the history, an overview of PSAT features a comparison with other Matlab toolboxes for power system analysis, to give small glance about the program that was used to investigate the power systems problems.
In chapters 2, 3 and 4 the concepts and theory for the three type power systems problems, which are used to meet the objectives and purposes for this thesis.

In chapter 5, the three case studies, those were chosen for three types of power system analysis to investigate their results using PSAT program. Also it showed how case studies were modelled and how the respective input data was entered to them. At this stage of project, many problems were faced, because some input data was not found. The program result resembles the manual calculation, yet it uses some typical values that are not required in manual calculation. But these problems was solved by many methods mentioned this chapter.

In chapter 6, the simulation results gained using PSAT were compared with the results output data of our three case studies and found very similar to each other.

Finally, this thesis proved that, The Power System PSAT software was found versatile and allowing some of the typical problems to be solved by several methods. This feature will enables students to investigate alternative solution techniques.

7.3 Future work

From the conclusion of this thesis, there are many further future works that can be done in power systems analysis toolbox (PSAT) more suitable as an educational toolbox for electrical power system students, lecturers, and researchers.

In this thesis, PSAT was used to investigate only three types of power system problems: power flow analysis, voltage stability analysis and transient stability analysis. But PSAT provides other additional types of analysis to investigate as future work such as:

- Optimal power flow (OPF)
- Continuation Power flow (CPF)
- Small signal stability analysis (SSSA)
- Electro Magnetic Transient analysis (EMT)
- Saddle-node Bifurcation
- Limit-Induced Bifurcation
- N-1 Contingency Analysis
- Eigenvalue analysis
REFERENCES


[12] CIGRE Task 38-02-10, Modelling of Voltage Collapse Including Dynamic Phenomena, 1993


Appendix A: Case study (1)

The input data parameters for this example are shown in Table A.1, A.2 and A.3.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Swing</td>
<td>1.0</td>
<td>0</td>
<td>--</td>
<td>--</td>
<td>0</td>
<td>0</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>2</td>
<td>Load</td>
<td>--</td>
<td>--</td>
<td>0</td>
<td>0</td>
<td>8.0</td>
<td>2.8</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>3</td>
<td>Voltage</td>
<td>1.05</td>
<td>--</td>
<td>5.2</td>
<td>--</td>
<td>0.8</td>
<td>0.4</td>
<td>4.0</td>
<td>-2.8</td>
</tr>
<tr>
<td>4</td>
<td>Load</td>
<td>--</td>
<td>--</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>5</td>
<td>Load</td>
<td>--</td>
<td>--</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

Table A.1: bus input data (case study (1))

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2-4</td>
<td>0.00900</td>
<td>0.100</td>
<td>0</td>
<td>1.72</td>
<td>12.0</td>
</tr>
<tr>
<td>2-5</td>
<td>0.00450</td>
<td>0.050</td>
<td>0</td>
<td>0.88</td>
<td>12.0</td>
</tr>
<tr>
<td>4-5</td>
<td>0.00225</td>
<td>0.025</td>
<td>0</td>
<td>0.44</td>
<td>12.0</td>
</tr>
</tbody>
</table>

Table A.2: lines data (case study (1))

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1-5</td>
<td>0.00150</td>
<td>0.02</td>
<td>0</td>
<td>0</td>
<td>6.0</td>
</tr>
<tr>
<td>3-5</td>
<td>0.00075</td>
<td>0.01</td>
<td>0</td>
<td>0</td>
<td>10.0</td>
</tr>
</tbody>
</table>

Table A.3: transformer input data (case study (1))

The results written for this example are shown in Table A.4, A.5 and A.6.
### Table A.4: Bus output data (case study (1))

<table>
<thead>
<tr>
<th>Bus</th>
<th>Voltage Magnitude[p.u]</th>
<th>Generation</th>
<th>Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.000</td>
<td>3.948</td>
<td>1.144</td>
</tr>
<tr>
<td>2</td>
<td>0.834</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>3</td>
<td>1.050</td>
<td>5.200</td>
<td>3.376</td>
</tr>
<tr>
<td>4</td>
<td>1.019</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>5</td>
<td>0.974</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

### Table (A.5): Load flow in lines (case study (1))

<table>
<thead>
<tr>
<th>Line</th>
<th>Bus-to-bus</th>
<th>P [p.u]</th>
<th>Q[p.u]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2-4</td>
<td>-2.92</td>
<td>-1.392</td>
</tr>
<tr>
<td></td>
<td>4-2</td>
<td>3.036</td>
<td>1.216</td>
</tr>
<tr>
<td>2</td>
<td>2-5</td>
<td>-5.080</td>
<td>-1.408</td>
</tr>
<tr>
<td></td>
<td>5-2</td>
<td>5.256</td>
<td>2.532</td>
</tr>
<tr>
<td>3</td>
<td>4-5</td>
<td>1.344</td>
<td>1.504</td>
</tr>
<tr>
<td></td>
<td>5-4</td>
<td>-1.332</td>
<td>-1.824</td>
</tr>
</tbody>
</table>

### Table (A.6): Load flow in transformers (case study (1))

<table>
<thead>
<tr>
<th>Line</th>
<th>Bus-to-bus</th>
<th>P [p.u]</th>
<th>Q[p.u]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1-5</td>
<td>3.948</td>
<td>1.144</td>
</tr>
<tr>
<td></td>
<td>5-1</td>
<td>-3.934</td>
<td>-0.804</td>
</tr>
<tr>
<td>2</td>
<td>3-4</td>
<td>4.400</td>
<td>2.976</td>
</tr>
<tr>
<td></td>
<td>4-3</td>
<td>4.380</td>
<td>-2.720</td>
</tr>
</tbody>
</table>
Appendix B: *Case study 2*

The critical fault-clearing time and the critical clearing angle results of this case are shown in Fig B.1 and Fig B.2.

![Diagram of rotor angle and time](image)

**Fig B.1:** Results for critical fault clearing times (case study (2))

![Diagram of area and angle](image)

**Fig B.2:** Results for equal area criterion (case study (2))
Appendix C: Case study 3

The test system input data:

- Transmission lines:

<table>
<thead>
<tr>
<th>line</th>
<th>R [pu]</th>
<th>X [pu]</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-6</td>
<td>0.0000</td>
<td>0.0040</td>
<td>0.0000</td>
</tr>
<tr>
<td>6-7</td>
<td>0.0015</td>
<td>0.0288</td>
<td>1.1730</td>
</tr>
<tr>
<td>9-10</td>
<td>0.0010</td>
<td>0.0030</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

Table C.1: Transmission lines (100 MVA base) (case study (3))

Transformers:

<table>
<thead>
<tr>
<th>Transformer</th>
<th>R [pu]</th>
<th>X [pu]</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>0.0000</td>
<td>0.0020</td>
<td>0.8857</td>
</tr>
<tr>
<td>T2</td>
<td>0.0000</td>
<td>0.0045</td>
<td>0.8857</td>
</tr>
<tr>
<td>T3</td>
<td>0.0000</td>
<td>0.0125</td>
<td>0.9024</td>
</tr>
<tr>
<td>T4</td>
<td>0.0000</td>
<td>0.0030</td>
<td>1.0664</td>
</tr>
<tr>
<td>T5</td>
<td>0.0000</td>
<td>0.0026</td>
<td>1.0800</td>
</tr>
<tr>
<td>T6</td>
<td>0.0000</td>
<td>0.0010</td>
<td>0.9750 (load level 1)</td>
</tr>
</tbody>
</table>

Table C.2: Transformers (100 MVA base) (case study (3))

- Shunt capacitors:

<table>
<thead>
<tr>
<th>Bus</th>
<th>MVAr</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>763</td>
</tr>
<tr>
<td>8</td>
<td>600</td>
</tr>
<tr>
<td>9</td>
<td>1710</td>
</tr>
</tbody>
</table>

Table C.3: Shunt capacitors (case study (3))
- **Loads**

<table>
<thead>
<tr>
<th>Bus</th>
<th>P (MW)</th>
<th>Q (MVAr)</th>
<th>(load level)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>3271</td>
<td>1010</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>3320</td>
<td>1030</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>3345</td>
<td>1038</td>
<td>3</td>
</tr>
<tr>
<td>11</td>
<td>3384</td>
<td>971</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>3435</td>
<td>985</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>3460</td>
<td>993</td>
<td>3</td>
</tr>
</tbody>
</table>

**Table C.4: PQ Loads (case study (3))**

- **Generators:**

<table>
<thead>
<tr>
<th>Bus</th>
<th>P (MW)</th>
<th>V (pu)</th>
<th>(load level)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>3981</td>
<td>0.9800</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>4094</td>
<td>0.9800</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>4152</td>
<td>0.9800</td>
<td>3</td>
</tr>
<tr>
<td>G2</td>
<td>1736</td>
<td>0.9646</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1736</td>
<td>0.9646</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>1736</td>
<td>0.9646</td>
<td>3</td>
</tr>
<tr>
<td>G3</td>
<td>1154</td>
<td>1.0400</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1154</td>
<td>1.0400</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>1154</td>
<td>1.0400</td>
<td>3</td>
</tr>
</tbody>
</table>

**Table C.5: Generation Data (case study (3))**

- **ULTC** for transformer T6 between buses 10 and 11:

  Dead band: ±1% p.u bus voltage

  Tap range: ± 16 steps

  Step size: 0.00625

- **Machine parameters:**

  Machine 1: Infinite bus

  Machine 2: H = 2.09, MVA rating = 2200MVA
Machine 2: \( H = 2.33 \), MVA rating = 1400MVA

Parameter of machine 2 and 3 on their respective MVA ratings:

\[
\begin{align*}
X_d &= 2.07 & X_d' &= 0.28 & X_d'' &= 0.215 \\
X_q &= 1.99 & X_q' &= 0.49 & X_q'' &= 0.215 \\
R_q &= 0.0046 & \\
T_d' &= 4.10 & T_d'' &= 0.033 \\
T_q' &= 0.56 & T_q'' &= 0.062
\end{align*}
\]

- **Exciter:**

Machine 2 and 3 have thyristor exciter with gain 400 and the sensing circuit-time constant of 0.02 seconds.

Over excitation limiter for machine 3:

\[
I_{f,d\text{ max}} = 3.02 \text{ p.u} \quad I_{LIM} = 3.85 \text{ p.u}
\]

- **Load level:**

Load level 1: 6655 MW, 1986 MVAr

The load in bus 11 is modeled as 50% constant impedance and 50% constant current for both active and reactive components. The load in bus 8 is modeled as constant MVA for both active and reactive components. The transformer T4 is assumed to have a fixed tap.

Results for this case study obtained as follows:

*Fig C.1, C.2 and C.3* shows the time responses of the voltage at buses 11, 10 and 7 following the loss of one of the lines between buses 6 and 7, for each of the three load levels. The corresponding terminal voltage of generator G3 is shown in *Fig C.4*.

The effect of the loss of the line is to cause the system to drop initially. For load level 1, the ULTC action of transformer T6 restores bus 11 voltages to nearly its reference value in about 40 second. The terminal voltage of generator G3 is maintained at the initial value by the AVR. The voltages of buses 10 and 7 settle at value below the predisturbance value. The system voltage is stable.

C-3
Fig C.1: Bus 11 voltage (case study (3))

Fig C.2: Bus 10 voltage (case study (3))
Fig C.3: Bus 10 voltage (case study (3))

Fig C.4: Generator 3 terminal voltage case study (3)