25753: ELECTRIC ENERGY SYSTEMS ANALYSIS ONE

POWER WORLD TUTORIAL
POWER FLOW ANALYSIS

Due: Sunday 28 , 10, 1402

Group 1

Power flow analysis is a fundamental requirement for study of power systems. Since load centers are usually located far away from generators, the electrical power should be carried over a long distance, through the transmission network, to be delivered to the users. We need to know the power system performance in order to control its power flow, while satisfying the safety and efficiency requirements. Additionally, Power flow study is required for further studies of the power system. It is not only important from the power system operation point of view, but also to examine the system stability under any possible abnormal situation. It helps the authorities to take decisions for planning of the power system network. For example deciding to install a new power plant in a growing suburb, or whether evaluate the consequences of loss of a single transmission line on the system operation and the magnitude of loss of loads. A typical power system usually operates under slowly changing conditions. Furthermore, the systems are under balanced or near balanced conditions during most of the time of their operation. Therefore, the power flow study is usually processed as a steady state power flow analysis of a balanced three-phase power system.

PART 1: POWER FLOW PROBLEM

The power flow problem (also known as load flow problem) can be defined as: To solve for any unknown bus voltages and complex power flows in the network components, for a given power network, with known complex powers of loads and a set of requirements or restrictions on power generations and bus voltages.

The power flow study in the power system network assumes to have a three-phase-balanced network and analyse its power flow under steady state operating condition. Thus, a simplified single phase model known as one-line diagram can be used to represent the power system. One-line diagrams are widely used in power flow calculation, as long as the loads on each phase are balanced. Under this condition, the power flows in each phase are numerically the same, however are different in phase. Thus, only one phase can be modelled and considered in power flow calculations.

Another important simplified notation in power flow analysis is per-unit system. In a power system, transformers at various voltage levels are involved. Per-unit system allows the system quantities being analysed regardless of the voltage level. The basic per-unit scaling equation is

$$p.u. = \frac{\text{actual quantity}}{\text{base value of quantity}}.$$

Generally, only two base quantities are defined, base voltage V_{base} and base complex power S_{base}. The V_{base} is usually the same as the nominal voltage of the transformer, while S_{base} is arbitrarily chosen.

The formulation of power flow equations can be obtained by using a simple example. Figure 1.1 shows the simple example of a three-bus power system. All the quantities are in per unit.

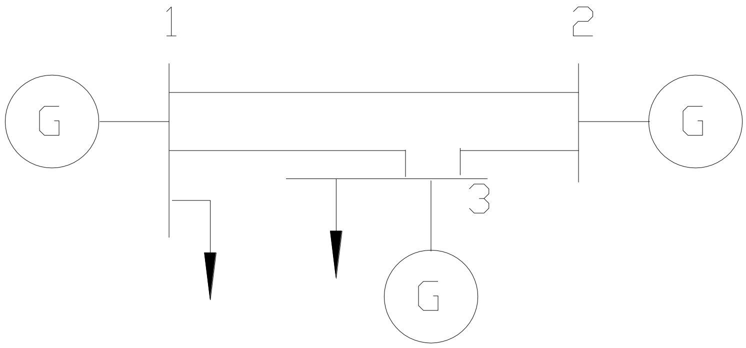

Figure 1.1 A three-bus power system

Each bus can be considered as a node. The relation between the voltage V at a certain bus and the current I injected into the bus are given as:

$$\mathbf{I} = \mathbf{YV} \qquad (1.1)$$

$\mathbf{Y}$ is an $n \times n$ matrix, where n is the number of buses in the system.

The voltage equation can be written as follows:

$$\overline{I}_i = \overline{Y}_{i1}\overline{V}_1 + \overline{Y}_{i2}\overline{V}_2 + \overline{Y}_{i3}\overline{V}_3 \quad \text{(i = 1, 2, 3)} \qquad (1.2)$$

The node current expressed by nodal power and voltage is as follows:

$$\overline{I}_i = \frac{\overline{S}_i^*}{\overline{V}_i^*} = \frac{\overline{S}_{Gi}^* - \overline{S}_{LDi}^*}{\overline{V}_i^*} = \frac{(P_{Gi} - P_{LDi}) - j(Q_{Gi} - Q_{LDi})}{\overline{V}_i^*} \quad \text{(i = 1, 2, 3)} \qquad (1.3)$$

Where

$\overline{S}_{Gi}$ — the complex power flow into node i from the generator;

$\overline{S}_{LDi}$ — the complex power flow out from node i to the load;

$\overline{S}_i$ — the net complex power injected into node i.

Substituting this result into Equation 1.2,

$$\frac{(P_{Gi} - P_{LDi}) - j(Q_{Gi} - Q_{LDi})}{\overline{V}_i^*} = \overline{Y}_{i1}\overline{V}_1 + \overline{Y}_{i2}\overline{V}_2 + \overline{Y}_{i3}\overline{V}_3 \quad \text{(i = 1, 2, 3)} \qquad (1.4)$$

For an n-buses network, the equation is given as follows:

$$\frac{P_i - jQ_i}{\overline{V}_i^*} = \sum_{j=1}^{n} \overline{Y}_{ij}\overline{V}_j \quad \text{(i, j = 1, 2, 3)} \qquad (1.5)$$

or

$$P_i + jQ_i = \overline{V}_i \sum_{j=1}^{n} \overline{Y}_{ij}^* \overline{V}_j^* \quad \text{(i, j = 1, 2, 3)} \qquad (1.6)$$

where P_i is the net real power injected into bus i, and Q_i is the net reactive power injected into bus i.

where:

$$Y_{ij} = Y_{ij} e^{j\theta_{ij}} \qquad (i,j = 1,2,3) \qquad (1.7)$$

$$V_j = V_j e^{j\delta_j} \qquad (i,j = 1,2,3) \qquad (1.8)$$

Equation 1.6 can be rearranged as:

$$P_i + jQ_i = V_i \sum_{j=1}^{n} Y_{ij} V_j e^{j(\delta_i - \delta_j - \theta_{ij})} \qquad (i,j = 1,2,3) \qquad (1.9)$$

By separating the real part and the imaginary part, two following equations can be derived from Equation 1.9 for each node:

$$P_i = V_i \sum_{j=1}^{n} Y_{ij} V_j \cos(\delta_i - \delta_j - \theta_{ij}) \quad (i,j = 1,2,3) \qquad (1.10)$$

$$Q_i = V_i \sum_{j=1}^{n} Y_{ij} V_j \sin(\delta_i - \delta_j - \theta_{ij}) \quad (i,j = 1,2,3) \qquad (1.11)$$

There are four variables in the Equations 1.10 and 1.11. They are:
P — the real power;
Q — the reactive power;
V — the magnitude of the bus voltage;
δ— the angle of the bus voltage.
At least two out of these four variables must be specified in order to be able to solve these equations. Based on that which two quantities of those four variables are specified, system buses can be classified into three categories:

- Swing bus

There is at least a bus with unspecific real power value, which is adjusted during the solution to insure the real power balance in the power system as a whole, until the power flow problem has been solved. This bus is called the swing bus, also known as slack bus, of which real and reactive power are unknown. The swing bus is usually treated as a reference bus, thus the voltage angle of swing bus is set to zero, and the voltage is also specified. Only one swing bus is chosen for a certain power system.

- Load bus

Any bus of which both the real and reactive power are specified can be classified as a load bus. This is the most prevalent bus in the power systems. Load buses may be the buses connected with generators with specified real and reactive power outputs. And the buses in the substations can be considered as load buses as well.

- Generator bus

In a generator bus, the injected real power and voltage magnitude are specified. A generator bus is known as a voltage control bus, as it requires sufficient reactive power capacity to maintain its designated voltage level. Generally, the buses in a power plant with reactive power storage and those in a substation with adjustable reactive power sources can be considered as generator buses.

Table 1.1 The knowns and unknowns of each bus type.

Bus type	P	Q	V	δ
Swing bus	Unknown	Unknown	Known	Known
Load bus	Known	Known	Unknown	Unknown
Generator bus	Known	Unknown	Known	Unknown

Table 1.1 shows the known and unknown variables of each bus type. With the specified variables, the unknown quantities can be evaluated by solving the Equation 1.10 and 1.11. Once the bus voltages have been found, the complex power flows and power losses can be worked out.

PART 2: RESTRICTIONS ON POWER FLOW PROBLEM

The results evaluated from the equations mentioned in previous section are mathematical answers only. Besides that, they must satisfy the restrictions known as the operation requirements at the same time to enable the normal operation of the power system. Generally, these restrictions include:

- the voltage magnitude of all the buses

$$V_{imin} \le V_i \le V_{imax} \quad (i = 1, 2, \ldots, n); \qquad (1.12)$$

- the real and reactive power of all the buses

$$\left.\begin{array}{ll} P_{imin} \le P_i \le P_{imax} & (i = 1,2,\cdots,n) \\ Q_{imin} \le Q_i \le Q_{imax} & (i = 1,2,\cdots,n) \end{array}\right\} ; \qquad (1.13)$$

- the voltage phase difference between certain buses

$$|\delta_i - \delta_j| \le |\delta_i - \delta_j|_{max} \quad (i, j = 1, 2, \ldots, n). \qquad (1.14)$$

SOLUTION METHODS

The solutions of the nonlinear equations require the use of iterative techniques. A general iterative procedure is as follows:

$$x^{(k)} = g\left[x^{(k)}\right] \quad (k = 0, 1, 2, \ldots) \qquad (1.15)$$

where $x^{(k)}$ is the ith guess, and $g\left(x^{(k)}\right)$ is the correction function for the guess. The iteration results should converge to a unique solution finally.

There are several approaches to solve these nonlinear equations, but only two methods will be discussed here.

PART 3 : Gauss-Seidel Iterative Method

The Gauss-Seidel method is well-known as a solution of linear equations. Consider a set of linear equations:

$$y = \mathbf{A}x \qquad (1.16)$$

where **A** is an $N \times N$ square matrix, x and y are vectors of length N. **A** and y are already given, while x is unknown.

By considering the ith equation of the Equation 1.16,

$$y_i = A_{i1}x_1 + A_{i2}x_2 + \cdots + A_{ii}x_i + \cdots + A_{iN}x_{\mathrm{N}} \qquad (1.17)$$

x_{i} can be solve from equation (3.22), that is

$$\begin{aligned} x_i &= \frac{1}{A}[y_i - (A_{i1}x_1 + \cdots + A_{i,i-1}x_{i-1} + A_{i,i+1}x_{i+1} + \cdots + A_{iN}x_N)] \\ &= \frac{1}{A}\left[y_i - \sum_{n=1}^{i-1} A_{in}x_n - \sum_{n=i+1}^{N} A_{in}x_n\right] \end{aligned} \qquad (1.18)$$

In Gauss-Seidel method, the new value $x_{\mathrm{i}}^{(\mathrm{k}+1)}$ can be generated from the equation:

$$x_i^{(k+1)} = \frac{1}{A_{ii}}\left[y_i - \sum_{n=1}^{i-1} A_{in}x_n^{(k+1)} - \sum_{n=i+1}^{N} A_{in}x_n^k\right] \qquad (1.19)$$

where $x_i^{(k)}$ is kth iterative solution to x_{i}.

The Equation 1.19 can be written in matrix format as

$$x^{(k+1)} = (\mathbf{D} + \mathbf{L})^{-1}\left[y - \mathbf{U}x^{(k)}\right] \qquad (1.20)$$

where
D is the diagonal portion of **A**;
L is the lower triangular portion of **A**;

U is the upper triangular portion of **A**.

In power flow problem, the nodal equations, $\mathbf{I} = \mathbf{YV}$, are a set of linear equations, which have the same form with $y = \mathbf{A}x$. Thus, applying the Gauss-Seidel method, the nodal equations can be yield as follows

$$V_i^{(k+1)} = \frac{1}{Y_{ii}}\left[I_i - \sum_{n=1}^{i-1} Y_{in} V_n^{(k+1)} - \sum_{n=i+1}^{N} Y_{in} V_n^{k} \right] \tag{1.21}$$

However, the power flow bus data usually consists of P_i and Q_i of load buses or P_i and V_i of generation buses, and the current vector **I** is unknown. In this case, we can not solve the Equation 1.21 by simply applying Gauss-Seidel Method.

For each load bus, with P_i and Q_i are given,

$$I_i = \frac{P_i - jQ_i}{V_i^*} \tag{1.22}$$

Substituting this equation into the Equation 1.21,

$$V_i^{(k+1)} = \frac{1}{Y_{ii}}\left[\frac{P_i - jQ_i}{V_i^{*(k)}} - \sum_{n=1}^{i-1} Y_{in} V_n^{(k+1)} - \sum_{n=i+1}^{N} Y_{in} V_n^{k} \right] \tag{1.23}$$

For a generation bus, with P_i and V_i are given, Q_i can be evaluated from the Equation 1.11. Thus,

$$Q_{Gi} = Q_i + Q_{\mathrm{Li}} \tag{1.24}$$

where Q_{Gi} is the reactive power output of the generator, Q_i is the net reactive power injected into the bus i, and Q_{Li} is the reactive power that flows into the load.

If the calculated value of Q_{Gi} satisfies the generation limitation, $V_i^{(k+1)}$ can be calculate by substituting Q_{Gi} into Equation 1.23. With

$$V_i^{(k+1)} = \mathrm{V}_i^{k+1} \angle \delta_i^{k+1}, \tag{1.25}$$

the angle $\angle \delta_i^{k+1}$ of the generation buses can be calculated from Equation 1.23 as well.

If the calculated value of Q_{Gi} exceeds its limit during the iteration process, the bus type should be changed from generation bus to load bus with Q_{Gi} set to its limit value. And the value of V_i requires to be recalculated, since the voltage controlling device is unable to maintaining its specified value of V_i any longer.

For the swing bus, no iterations are require since the value of V_1 and δ_1 are already given. After the iteration results have converged, P_1 and Q_1 can be calculated from Equation 1.24 and 1.25.

Experience from power-flow studies has shown that Newton-Raphson has better convergence ability than that of the Gauss-Seidel method in many cases. In addition, the number of required iterations of the Newton-Raphson method is smaller than that of the Gauss-Seidel method, especially in large-scale power system. This is because that the number required for the Newton-Raphson is independent of the dimension N, but increases with N for the Gauss-Seidel. However, the Newton-Raphson method needs more computer storage space and time to perform one iteration.

PART 4: Newton-Raphson Method

The Newton-Raphson algorithm, which is a successive approximation process to the real root of $f(x) = 0$, has been widely applied in solving power flow equations.

A single variable nonlinear equation is as follows:

$$f(x) = 0 \qquad (1.26)$$

An initial guess $x^{(0)}$, which is close to the real root, is given. With involving the error between $x^{(0)}$ and the real root which is $\Delta x^{(0)}$, the Equation 1.16 can be written as:

$$f\left(x^{(0)} + \Delta x^{(0)}\right) = 0 \qquad (1.27)$$

The Taylor series expansion of the function on the left-hand side of the Equation 1.17 is:

$$f(x^{(0)} + \Delta x^{(0)}) = f(x^{(0)}) + f'(x^{(0)})\Delta x^{(0)} + f''(x^{(0)})\frac{(\Delta x^{(0)})^2}{2!} + \cdots + f^{(n)}(x^{(0)})\frac{(\Delta x^{(0)})^2}{n!} \qquad (1.28)$$

If $\Delta x^{(0)}$ is small enough, the higher-order terms can be ignore, the Equation 1.18 can be simplified as:

$$f\left(x^{(0)} + \Delta x^{(0)}\right) = f\left(x^{(0)}\right) + f'\left(x^{(0)}\right)\Delta x^{(0)} = 0 \qquad (1.29)$$

Therefore

$$\Delta x^{(0)} = -\frac{f\left(x^{(0)}\right)}{f'\left(x^{(0)}\right)} \qquad (1.30)$$

Correcting $x^{(0)}$ by using the result above,

$$x^{(1)} = x^{(0)} + \Delta x^{(0)} = x^{(0)} - \frac{f\left(x^{(0)}\right)}{f'\left(x^{(0)}\right)} \qquad (1.31)$$

$x^{(1)}$ is closer to real root compared with $x^{(0)}$, and this method can be iterated. With more iteration, $x^{(n)}$ will be more closer to the real root.

Geometrically, the Newton-Raphson method is a kind of secant method. Figure 1. illustrates one iteration step in Newton-Raphson method. The curve is defined by the function $y = f(x)$, and its intersection with x axis is the real root of $f(x) = 0$.

Assume x_1 is a root which is close to the real root. The tangent to the curve $y = f(x)$ at point (x_1, $y = f(x_1)$) intersect with x axis at x_2. Obviously, x_2 is closer to the real root compared with x_1. By repeating the steps, x_n is getting closer and closer to the real root.

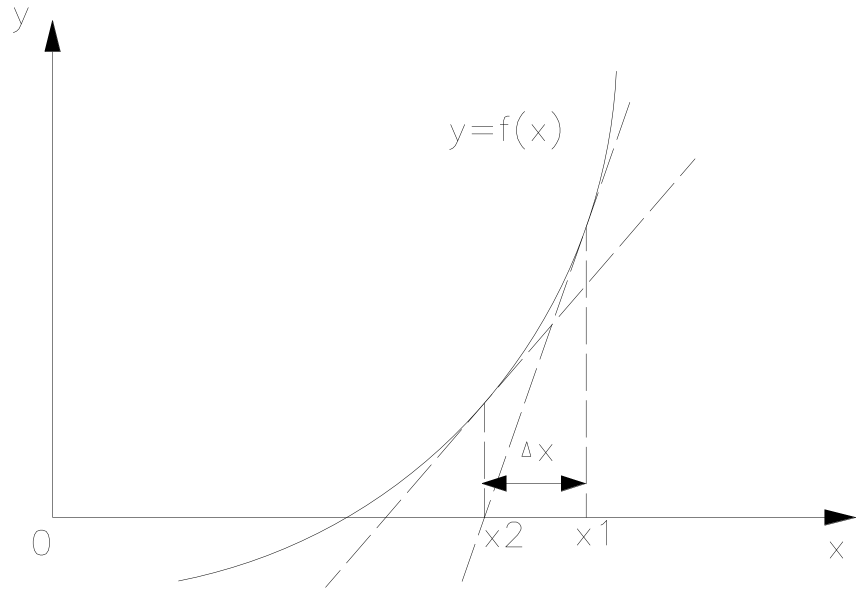

Figure 1.2 One iteration of Newton-Raphson method.

In general, where there are n equations with n unknowns, the Equation 1.30 and 1.31 can be written in matrix form as:

$$\mathbf{F}\left(\mathbf{X}^{(k)}\right) = -\mathbf{J}^{(k)}\mathbf{\Delta X}^{(k)} \qquad (1.32) \qquad \text{and}$$

$$\mathbf{X}^{(k+1)} = \mathbf{X}^{(k)} + \mathbf{\Delta X}^{(k)} \qquad (1.33)$$

Where:

$$\mathbf{F}\left(\mathbf{X}^{(k)}\right) = \begin{bmatrix} f_1\left(x_1^{(k)}, x_2^{(k)}, \cdots, x_n^{(k)}\right) \\ f_2\left(x_1^{(k)}, x_2^{(k)}, \cdots, x_n^{(k)}\right) \\ \vdots \\ f_n\left(x_1^{(k)}, x_2^{(k)}, \cdots, x_n^{(k)}\right) \end{bmatrix}, \ \mathbf{J}^{(k)} = \begin{bmatrix} \left.\frac{\partial f_1}{\partial x_1}\right|_k & \left.\frac{\partial f_1}{\partial x_2}\right|_k & \cdots & \left.\frac{\partial f_1}{\partial x_n}\right|_k \\ \left.\frac{\partial f_2}{\partial x_1}\right|_k & \left.\frac{\partial f_2}{\partial x_2}\right|_k & \cdots & \left.\frac{\partial f_2}{\partial x_n}\right|_k \\ \vdots & \vdots & & \vdots \\ \left.\frac{\partial f_n}{\partial x_1}\right|_k & \left.\frac{\partial f_n}{\partial x_2}\right|_k & \cdots & \left.\frac{\partial f_n}{\partial x_n}\right|_k \end{bmatrix}, \ \mathbf{\Delta X}^{(k)} = \begin{bmatrix} \Delta x_1^{(k)} \\ \Delta x_2^{(k)} \\ \\ \Delta x_n^{(k)} \end{bmatrix}.$$

The procedure will be repeated until the error reaches a reasonable tolerance

$$\max\left\{\left|\Delta x_i^k\right|\right\} < \varepsilon_1 \qquad (1.34)$$

or

$$\max\left\{\left|f_i\left(x_1^{(k)}, x_2^{(k)}, \cdots x_n^{(k)}\right)\right|\right\} < \varepsilon_2 \qquad (1.35)$$

In a power system, the bus voltage is:

$$\overline{V}_i = V_i \angle \delta_i = V_i\left(\cos\delta_i + j\sin\delta_i\right) \qquad (1.36)$$

And the self admittance is:

$$Y_{ij} = Y_{ij}e^{j\theta_{ij}} = G_{ij} + jB_{ij} \qquad (1.37)$$

The Equation 1.20 and 1.11 can be rewritten as follows

$$\left.\begin{aligned} P_i &= V_i \sum_{j=1}^{n} V_j\left(G_{ij}\cos\delta_{ij} + B_{ij}\sin\delta_{ij}\right) \\ Q_i &= V_i \sum_{j=1}^{n} V_j\left(G_{ij}\cos\delta_{ij} - B_{ij}\sin\delta_{ij}\right) \end{aligned}\right\} \qquad (1.38)$$

In an n-buses power system, suppose bus 1~ m are load buses (PQ buses), bus (m+1) ~ (n-1) are generator buses (PV buses), and bus n is the swing bus. With V_n and δ_n is given, and the voltage of PV buses are known, which means V_{m+1}~ V_{n-1} is known, only δ_1~δ_{n-1} and V_1~V_m require calculation.

Actually, every PQ bus or every PV bus has two unbalanced power equations at least:

$$\left.\begin{aligned} \Delta P_i &= P_{is} - P_i = P_{is} - V_i \sum_{j=1}^{n} V_j\left(G_{ij}\cos\delta_{ij} + B_{ij}\sin\delta_{ij}\right) = 0 \\ \Delta Q_i &= Q_{is} - Q_i = Q_{is} - V_i \sum_{j=1}^{n} V_j\left(G_{ij}\cos\delta_{ij} - B_{ij}\sin\delta_{ij}\right) = 0 \end{aligned}\right\} \qquad (1.39)$$

where P_{is} is the given real power magnitude of bus i, and Q_{is} is the given reactive power magnitude of bus i.

The equation 1.38 contains n-1+m equations, and the number of the equations equals to that of unknowns. The correction equations can be derived from this equation and written in matrix format as follows:

$$\begin{bmatrix} \mathbf{\Delta P} \\ \mathbf{\Delta Q} \end{bmatrix} = -\begin{bmatrix} \mathbf{H} & \mathbf{N} \\ \mathbf{K} & \mathbf{L} \end{bmatrix} \begin{bmatrix} \mathbf{\Delta \delta} \\ \mathbf{V_{D_2}^{-1}\Delta V} \end{bmatrix} \qquad (1.40)$$

Where:

$$H_{ij} = \frac{\partial \Delta P_i}{\partial \delta_j}, \ N_{ij} = V_j \frac{\partial \Delta P_i}{\partial V_j}, K_{ij} = \frac{\partial \Delta Q_i}{\partial \delta_j}, L_{ij} = V_j \frac{\partial \Delta Q_i}{\partial V_j}$$

$$\mathbf{\Delta P} = \begin{bmatrix} \Delta P_1 \\ \Delta P_2 \\ \vdots \\ \Delta P_{n\text{-}1} \end{bmatrix}, \mathbf{\Delta Q} = \begin{bmatrix} \Delta Q_1 \\ \Delta Q_2 \\ \vdots \\ \Delta Q_m \end{bmatrix}, \mathbf{\Delta \delta} = \begin{bmatrix} \Delta \delta_1 \\ \Delta \delta_2 \\ \vdots \\ \Delta \delta_{n\text{-}1} \end{bmatrix}, \mathbf{\Delta V} = \begin{bmatrix} \Delta V_1 \\ \Delta V_2 \\ \vdots \\ \Delta V_m \end{bmatrix}, \mathbf{V_{D_2}} = \begin{bmatrix} V_1 & & & \\ & V_2 & & \\ & & \ddots & \\ & & & V_m \end{bmatrix}.$$

The Newton-Raphson method is popular due to its fast convergence. However, it is not necessarily work in all the cases.

PART 5: CONTINGENCY ANALYSIS

Contingency analysis is an evaluation of existing or proposed power system, like considering whether to accept an energy trade, or determining the stability and security of a certain system. It is an important part of power system analysis. This analysis requires not only the assessment of the system behaviour during an actual outage situation, but also the evaluation of the system before the outage.

The analysis uses a power flow solution, like the Newton-Raphson solution, to analyse each contingency and is typically based on security criterion. The most general security criteria is the “N-1” criteria, which stipulates that the system operates in a stable and secure manner even after losing a single transmission or generation element. In some cases, the lost of element may be more than one, and this turns the criterion from “N-1” to “N-2”, or to “N-x”, with “x” is the number of lost element. When x becomes larger, especially in large-scale system, the state of the system can be driven far away from its acceptable condition.

PART 6: POWERWORLD SIMULATOR

The “PowerWorld” Simulator is a power system analysis and simulation software package which is now widely used throughout the electricity industry. It was originally developed at the University of Illinois at Urbana-Champaign in 1994, and was commercially released by “PowerWorld” Corporation since 1996. This simulator is interactive and graphical designed with friendly interface to simulate the operation of high-voltage power system.

System models can be built or modified with a few mouse clicks by using the Simulator. Details of most elements can be viewed on the one-line diagram by right-click on them, and the data of the buses can be output in Matlab format. It also provides a convenient and animated way for simulating the power system behaviour over time, like what is shown as in Figure 1.3.

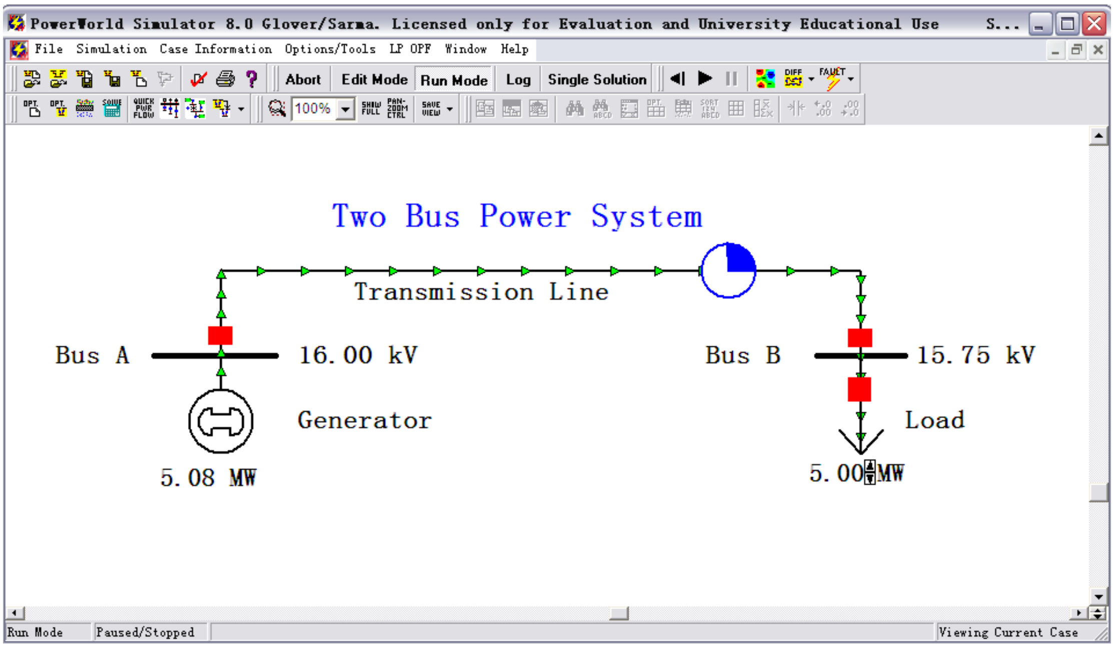

Figure 1.3 A simple two bus system.

In PowerWorld Simulator, power flow problems can be solved either by the Gauss-Seidel method or the Newton-Raphson method. The results will be indicated on the one-line diagram by arrows with different sizes and speeds. Various schedules can be prescribed so as to illustrate issues within the power system operation.

In addition, the PowerWorld Simulator well integrates with economic dispatch, optimal power flow, short circuit analysis and contingency analysis.

The LP OPF dialog, as shown below, consists of three general pages: general options, constraint options and solution results. User is allowed to customize the OPF solution in these pages. User can also view the details of the OPF results in this dialog from the LP basic variables, the LP basic matrix and the bus marginal price details page.

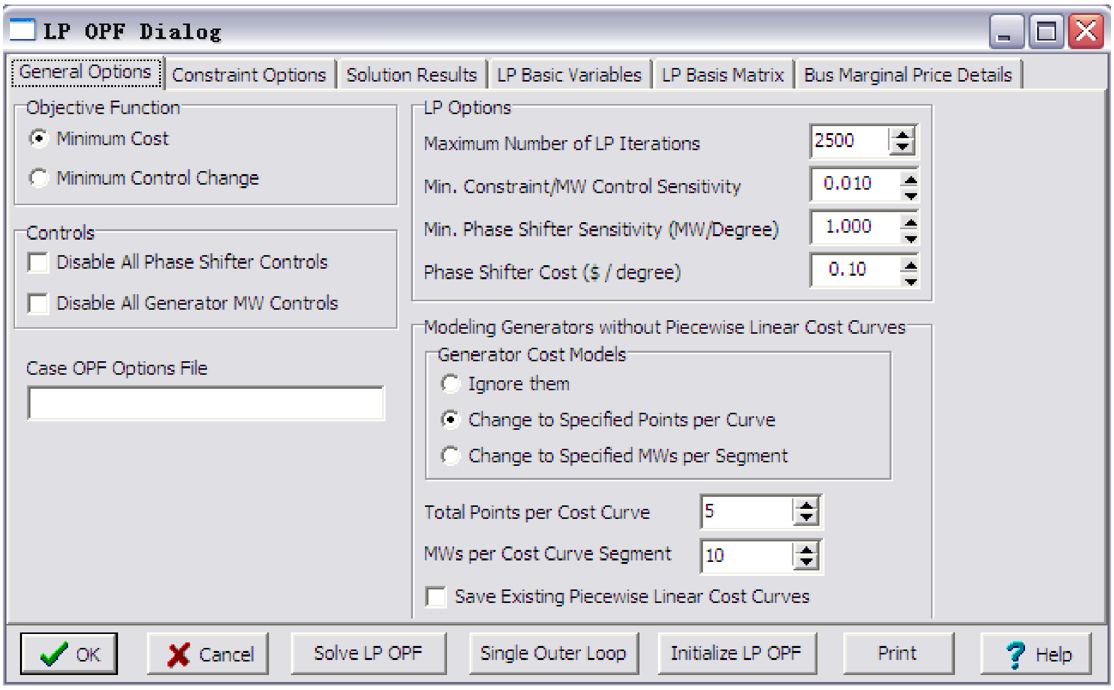

Figure 1.4 The LP OPF dialog.

Fault analysis dialog is used to perform a fault analysis study on the power system. Four types of faults are included in this program: the single line-to-ground, the line-to-line, the three-phase line-to-ground and the double line-to-ground fault. The impedance and the location of the faults can be specified in this dialog as well.

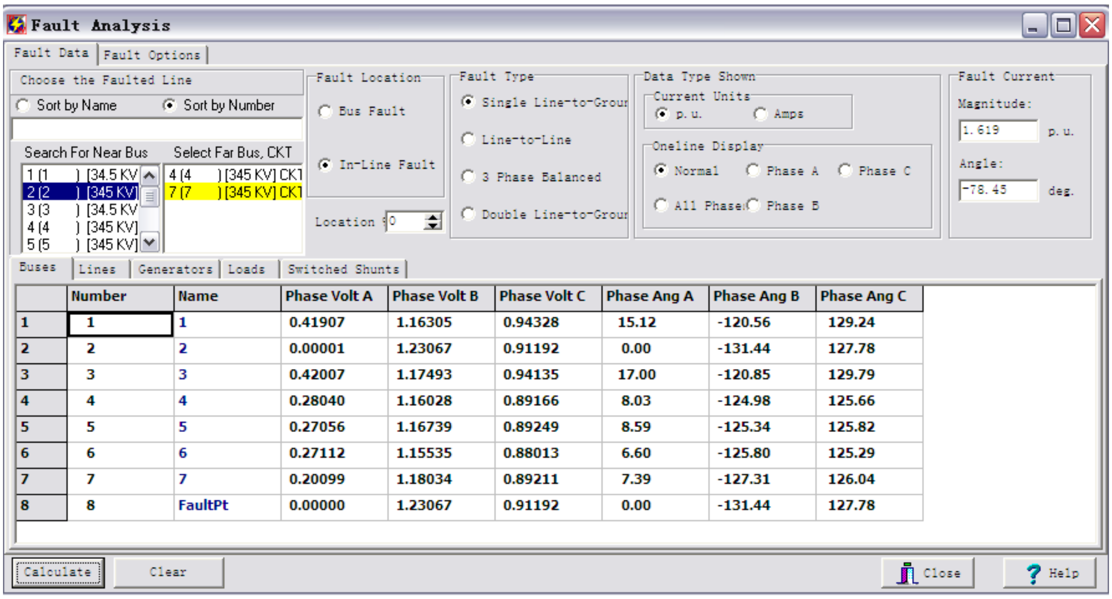

Figure 1.5 The fault analysis dialog.

Experiment : Power Flow Analysis

PROCEDURE:

Part I: The Gauss-Seidel method and the Newton-Raphson method

A 7-bus system consisting of 2 generators and 4 loads is given in Figure 1.6. Two capacitor banks are connected to the bus 3 and 7 respectively in order to regulate the bus voltages.

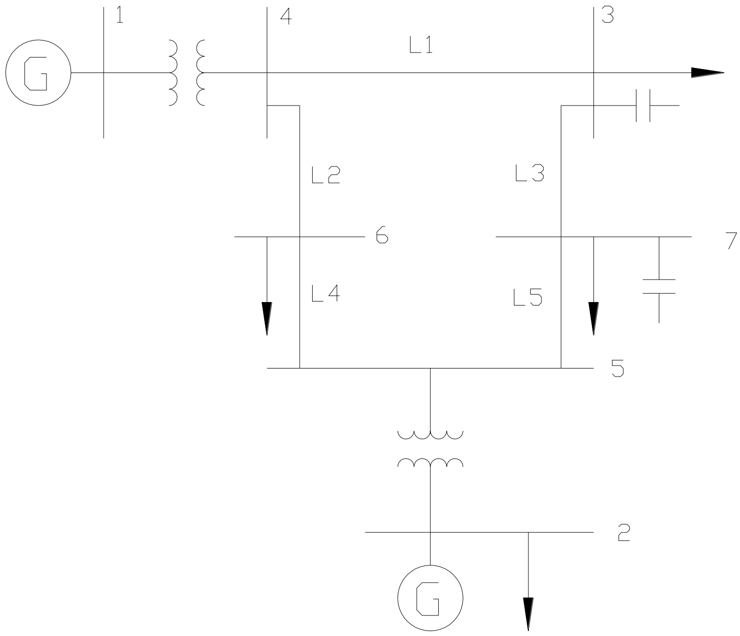

Figure 1.6 Single-line diagram of a seven-bus system

The line impedances for the 345kV transmission lines are

$$Z = 0.1019 + j0.5912\Omega / km \ .$$

And

$$L1 = 500km,\ L2 = 100km,\ L3 = 300km,\ L4 = 200km,\ L5 = 100km.$$

The reactances of the transformers are

$$Z = j0.1580 pu.$$

The bus data is shown in Table 1Table 1..2 The maximum MW outputs of the generators are 100MW, and Participation Factor Control is available for the area control. The transmission limits for the 345kV transmission lines are 100MVA, while those for the transformers are 150MVA. The participation factor of the generator at bus 1 is 4, and that for the generator at bus 2 is 6. The parameters which are not given are as default.

Table 1.2 Bus data

Bus No.	P Generate (MW)	Q Generate (MVar)	P Loaded (MW)	Q Loaded (MVar)	Bus Type*	Q Generate Max.(MVar)	Q Generate Min.(MVar)	Voltage Level (kV)
1	55.0	32.0	0.0	0.0	2	40.0	-6.0	34.5
2	82.0	33.0	26.0	0.0	1	40.0	-6.0	34.5
3	0.0	37.0	50.0	34.0	3	0.0	0.0	345
4	0.0	0.0	0.0	0.0	3	0.0	0.0	345
5	0.0	0.0	0.0	0.0	3	0.0	0.0	345
6	0.0	0.0	40.0	23.0	3	0.0	0.0	345
7	0.0	10.0	20.0	15.0	3	0.0	0.0	345

Bus Type: (1) swing bus, (2) generator bus, (3) load bus.

Assume the base power is $S_{base} = 100MVA$. Build the model of the given power system by using Power World Simulator.

(1) Power Flow Analysis Using Gauss-Seidel method

Switch into the **Run Mode**. Solve the power flow of the system by the Gauss-Seidel method step by step, and observe the convergence process. To solve the power flow step by step, open the **PowerWorld Simulator Options** dialog and check the **Do Only One Iteration** box.

To achieve the result quickly, uncheck the **Do Only One Iteration** box and increase the **Maximum Number of Iterations** to 100 (Since larger number of iteration is required in large-scale system by the Gauss-Seidel method). To view the power flows of the entire system, we use the **Bus Power Flows** list by selecting **Case Information, Power Flow List…** from the main menu. The **Bus Real and Reactive Power Mismatches** lists the mismatches at each bus. To display it, select **Case Information, Mismatches…**.

(2) Power Flow Analysis Using Newton-Raphson Method
Repeat (1) and solve the power flow by the Newton-Raphson method. The Jacobian matrix can be displayed by selecting **Case Information, Other, Power Flow Jacobian…**.

(3) Assume the voltage at the buses should be limited between 0.95 and 1.05p.u. Is there any violation out of these bus voltage limitations? What happens if the shunt capacitor bank at the bus 3 is disconnected? Note down the changes of the bus voltages and the system losses. (The bus voltage limits can be specified in the **Limit Monitoring Settings** dialog.)

(4) Increase the voltage magnitude of bus 3 to 1.0 p.u. by changing the tap ratio of the transformer connected between bus 1 and 4. Observe the changes of the bus voltages. Notice that voltage magnitude of each bus should not exceed the limits.

(5) Add a new transformer between buses 1 and 4. The parameters of the new transformer are the same as the existing one. Find out the power dispatch on these two transformers. What if the reactance of the new transformer is twice of the existing one?

(6) The transmission line between buses 3 and 4 is out of service because of an accident. How much load should be cut to maintain the voltage magnitude of bus 3 above 0.95 p.u.?

(7) A new transmission line is installed between buses 3 and 4. The parameters of the new transmission line are the same with the existing one. Find out its impacts on the power flow of the transmission lines and the total loss of the system.

Part II: Contingency Analysis
PowerWorld Simulator offers a set of tools for contingency analysis. Open the contingency analysis dialog, and select **Options/Tools, Contingency Analysis…**The simulator uses a full Newton solution by default to perform the analysis. By using this simulator, we can study whether the given system can still operate under an acceptable state in certain contingencies. Assume the bus voltages should be limited within 5% of the rated voltage. Investigate whether the system will remain secure

a. When the transmission line between bus 3 and 4 is out of service.
b. When the transmission line between bus 5 and 7 is out of service.
c. When the generator on bus 2 is out of service however, instead of that a similar generator is added to bus3

DISCUSSION:

1. What are the advantages of the Gauss-Seidel method and the Newton-Raphson method respectively?

2. Comment on the effects of presence of enough shunt capacitors in power system operation.

3. Comment on the data required for optimum power flow analysis in this software

4. Comment on the possible ways to improve reliability and resilience of system operation.