Load Flow Analysis

I Objectives

- To demonstrate load flow concepts.
- To study system performance under different operating conditions.
- To experience the real feel of power system operation
- To familiarize with simulator SCADA system

II Background

2.1 General

Load flow analysis is probably the most important of all network calculations since it concerns the network performance in its normal operating conditions. It is performed to investigate the magnitude and phase angle of the voltage at each bus and the real and reactive power flows in the system components.

Load flow analysis has a great importance in future expansion planning, in stability studies and in determining the best economical operation for existing systems. Also load flow results are very valuable for setting the proper protection devices to insure the security of the system. In order to perform a load flow study, full data must be provided about the studied system, such as connection diagram, parameters of transformers and lines, rated values of each equipment, and the assumed values of real and reactive power for each load.

2.2 Bus Classification

Each bus in the system has four variables: voltage magnitude, voltage angle, real power and reactive power. During the operation of the power system, each bus has two known variables and two unknowns. Generally, the bus must be classified as one of the following bus types:

1. **Slack or Swing Bus**
   This bus is considered as the reference bus. It must be connected to a generator of high rating relative to the other generators. During the operation, the voltage of this bus is always specified and remains constant in magnitude and angle. In addition to the generation assigned to it according to economic operation, this bus is responsible for supplying the losses of the system.

2. **Generator or Voltage Controlled Bus**
   During the operation the voltage magnitude at this the bus is kept constant. Also, the active power supplied is kept constant at the value that satisfies the economic operation of the system. Most probably, this bus is connected to a generator where the voltage is controlled using the excitation and the power is controlled using the prime mover control (as you have studied in the last experiment). Sometimes, this bus is connected to a VAR device where the voltage can be controlled by varying the value of the injected VAR to the bus.
3. Load Bus
This bus is not connected to a generator so that neither its voltage nor its real power can be controlled. On the other hand, the load connected to this bus will change the active and reactive power at the bus in a random manner. To solve the load flow problem we have to assume the complex power value (real and reactive) at this bus.

2.3 Load Flow Equations
Assuming a system having n buses, the injected current to the bus (node) k can be expressed as:

\[ I_k = \sum_{n=1}^{N} Y_{kn} V_n \]  \hspace{1cm} (1)

Where \( Y_{kn} \) is the proper element in the bus admittance matrix \( Y_{Bus} \) and,

\[ Y = |Y| \angle \theta, \hspace{0.5cm} V = |V| \angle \delta \]

The complex power at bus k (\( k = 1, 2, ..., n \)) is given as:

\[ S_k^* = \bar{V}_k^* I_k = P_k - j Q_k \]  \hspace{1cm} (2)

\[ P_k - j Q_k = \bar{V}_k^* \sum_{n=1}^{N} Y_{kn} \bar{V}_n \]

\[ P_k = |V_k| \sum_{n=1}^{N} |Y_{kn}| \bar{V}_n \cos (\delta_n - \delta_k + \theta_{kn}) \]  \hspace{1cm} (4)

\[ Q_k = |V_k| \sum_{n=1}^{N} |Y_{kn}| \bar{V}_n \sin (\delta_n - \delta_k + \theta_{kn}) \]  \hspace{1cm} (5)

Where, \( P_k \) and \( Q_k \) are the active and reactive power injection at bus k respectively. Thus, at each bus we have two equations and four variables (\( P, Q, \delta, V \)). Note that \( Y \)'s and \( \theta \)'s are known from network data. Actually, at each bus we have to specify two variables and solve for the remaining two unknowns. Thus, for an N bus system 2N equations are solved. These 2N equations are nonlinear equations as they involve products of variables as well as sine and cosine functions.

2.4 Techniques of Solution
Because of the nonlinearity and the difficulty involved in the analytical expressions for the above power flow equations, numerical iterative techniques must be used such as:

1. Gauss-Seidel method (G-S).

The first method (G-S) is simpler but the second (N-R) is reported to have better convergence characteristics and is faster than (G-S) method.

III The Power System Simulator: SCADA

3.1 Introduction
The real-time assessment and control of an integrated power system is made possible by an Energy Management System (EMS). Assessment of plant condition and system loading requires the collection of system data from relays and plant controllers at local substations. ‘Remote
terminal units’ (RTUs) are used to collect and transmit data to Control Centres at local level, area level or a higher, central coordinating control. The collected data from relays and RTUs needs to be presented at Control Centres in a visual and meaningful way to enable system control and maintenance to be carried out. This is achieved by a Supervisory Control and Data Acquisition (SCADA) system. The SCADA displays the information on a PC screen; usually by colored one-line mimic diagrams. The PC is referred to as the ‘master station’.

At the Central Control level, the SCADA system feeds into an Alarm Management System and the EMS. An Alarm Management subsystem processes the SCADA information to give warning of system abnormality not detected at local level. The EMS processes SCADA information and combines the data produced with load flow data to determine the ‘state’ of the system. Such a computational procedure, using mathematical methods, is called ‘state estimation’.

3.2 Functions of SCADA Systems

A SCADA System typically provides the following functions:
- comprehensive monitoring of primary and secondary plant
- secure control of primary plant
- supervision of secondary plant
- operator controlled display of non-SCADA data
- alarm management
- event logging
- sequence of events recording
- trend recording

All functions must be provided with a high level of security and reliability. The control system itself must be highly self-monitoring and problems brought immediately to the operator’s attention. Operator access must also be protected by a security system. In addition, certain performance standards are required, for both data acquisition and the user interface. For example, time recording of events to one millisecond resolution is now possible. Whilst user interface performance is less critical, operators expect that their actions will result in display delays measured in only a few seconds: for example, from the execution of a circuit breaker control, to the change of indications on the display.

3.3 SCADA Components

A SCADA system has three essential components to provide the functions listed above.
1) Relays, or Intelligent Electronic Devices (IEDs)
2) A Communication Interface
3) A User Interface

3.4 The Simulator Control Panel

The Control Panel, Figure 5, contains controls for the resistive and inductive loads, the Generator, the Dynamic Load and the Manual Fault CB and the Timer Fault CB. Loadbank 1 contains controls for the Generator 1 loads, L1 and R1. Loadbank 2 and 3 contains controls of the Distribution Bus Loads, R2 and L2, and R3 and L3. Loadbank 4 contains controls for the Generator 2 loads, Loads L4 and R4.

The Resistive and Inductive loads each have 'Raise' (+) and 'Lower' (-) buttons; one for each of the red, yellow and blue phases, and two longer buttons for raising (+) or lowering (-) the load for
all three phases together. 'Raise' and 'Lower' refer to load current. These buttons do not work (greyed out) until the load switches on the PSS are set to 'variable'. The grey lights turn red, yellow and blue when the corresponding phase button is clicked. The raise and lower buttons control motorised pots on the PSS. These pots vary the voltage applied to the resistors and inductors. A 'Reset Loads' button is shown at the bottom right of the Screen. When clicked on, this control will return the load currents to zero.

Continuous monitoring of the line currents and line voltages (Vab, Vbc, Vca), power and power factor are provided at four points in the PSS; they are: MB, MD, MM and MP.

Generator Control Panel
This panel controls many of the functions of the Generator 1, but not the synchronisation of the generator to the Grid Supply via CB8, which has to be carried out manually on the PSS. The panel shows 'Start' and 'Stop' buttons for the induction motor driving the generator. The buttons change from black to green and to red, correspondingly, when activated. When the induction motor has been started, a spinning symbol appears, just above the start button. The speed of the generator can be raised or lowered by means of the 'Raise' (+) and 'Lower' (-) buttons, and the speed observed in the Generator Control panel. When the generator is synchronised, the speed/power pot controls the output power of the generator to the Grid, which can be observed on meters MD and MB.

Excitation of the generator can be raised or lowered following closure of the 'Field CB'. The 'Field CB' button shows the status of the circuit breaker: 'closed' or 'open'. The output voltage of the generator can be viewed on meter MD.

**Figure 5 The Control Panel**

**Part II: Load Flow Study**

**IV Experimental Procedure**

4.1 Study system
The system to be studied in this experiment is the three bus system shown in Figure 6. The load flow problem may be formulated by specifying bus 1 as the reference bus, thus define $V_1$ and $\delta_1$ (usually 0°, as
In our experiment, the following parameters have been selected:

\[
Z_{12} = j0.1 \text{ p.u.}, \quad Z_{23} = j0.15 \text{ p.u.} \quad \text{and} \quad Z_{31} = j0.25 \text{ p.u.}
\]

2.3.2 Routing diagram
Referring to Figure 4, the set up of the study system on the power simulator can be implemented by using the grid bus as the infinite system, the generator#1 to simulate G1 and the lines: line_1, line_2 and line_4 to simulate line 1-2, line 2-3 and line 3-1 respectively. To allow the use of the digital meters for measuring the power flow on the lines, the double bus bar system should be used. The routing diagram proposed for this set-up is shown in Figure 7, while the corresponding Operation scheme is given in Table 2.2.

Figure 6 Three Bus System
4.3 Operating Assumptions and Case Studies

The system under study will be operated under different loading conditions. The resistive load $r_2$ and the inductive load $L_2$ are used for this purpose. Two values will be selected for each of them: 50% and 100% loading. The percentage of the resistive load is an indication of the loading condition: light (50%) or heavy (100%), while the ratio of the inductive load to the resistive load is an indication of the load power factor. Using 0% inductive power means that the power factor of that load is improved using a capacitor bank.

The power to be generated from generator 1 is assumed to be 50% of the total generation of the system; i.e., equal power share between G1 and the grid.

The effect of changing the terminal voltage of generator 1 on the whole performance of the system is studied by using two values or the voltage; 1 p.u. (220V) and 1.05 p.u. (231V).

The case studies to be performed in this experiment are listed in Table 2.3.

Each student will be assigned a case study to carry out.

4.4 Starting-Up procedure

The group of students will perform, under the supervision of the instructor, the following steps:

1- With the PSS switched off and all CBs open, apply the route shown in Figure 7 using connecting cables between the sockets indicated in Table 2.2.

2- Simulator start up procedure: start up the simulator as indicated in subsection 1.4.1, then close CB2, CB3, and CB4 to route the grid supply (220V, 60 Hz) to Grid Bus.

3- Generator 1 Start Up Procedure: Use G1 Control Panel as shown in subsection 1.4.2, then close CB6, CB12, and CB14 to prepare for the synchronization.

4- Synchronization Procedure: Follow the proper procedure to synchronize G1(incoming) with the grid system (running) using Synchroscope as shown in subsection 1.4.4.

5- Connect the load through closing the switches and breakers listed in Table 22.

4.5 Setting Up a Case Study

The student has to use the control panel of the SCADA to adjust the operating condition of the case study assigned to him (refer to Table 2.3). The warnings of subsection 1.4.5 must be considered. After the setting up of the condition, the student has to print the readings of the relevant meters.

4.6 Summary of Results

The obtained measurements have to be use to calculate the values to be recorded in Table 2.4. The voltage base is 220V and the power base is 2 kVA. Assume the capacity of any line is 5 A.

4.7 Shutting-Down the Simulator

Follow the proper procedure to shut down all the network sections (Refer to 1.4.3).

V Computer Procedure

The student has to use the PowerWorld Simulator model shown in Figure 8 to verify his case study. The system simulates the same system experimented using the power system simulator with the
following scaling factors: 1 V in actual system is represented by 1 kV in the computer model and the 1 W in real system is represented by 1 MW. The operation of this system is controlled by changing:

a- the real power generated from G2.
b- the voltage magnitude at bus 2.

To change the value of the power just click the arrows of the generator to increase (UP) or decrease (DOWN) the value. To change the value of the voltage at bus 2 ($V_2$) the following procedure is required: i- Right click the icon of Generator at bus-2, ii- Select "Information Dialog…" from the menu, iii- Select the tab "MW and Voltage Control", iv- In the "Voltage Control" portion, change "SetPoint Voltage" to the required value, v- Press OK.

Three values have to be set: the voltage at the slack bus, the voltage at bus#2 and the power generated from generator at bus#2. The simulator of PS3 provides the values of the bus voltages, the real power flows in the lines, in addition to the line losses.

![Figure 8 Computer Experiment PS3 Under PowerWorld Simulator](image-url)
Your report should contain the following:

1. A one-page summary of the objectives and theoretical background.
2. The experiment data sheets (Tables and/or graphs).
3. The answers to the questions that will follow.
4. Comment on results and a general conclusion.

1) From what you have learned from the experiment, summarize the functions of the SCADA system of the power simulator.

2) What is the purpose of load flow analysis?

3) What are the input data to a power flow program? What are its output data?

4) Explain why a voltage-control bus is sometimes called a generator-bus? Must there be a generator at this bus? Explain your answer.

5) Complete the data of Table 2, i.e., calculate the power losses.

6) Use the data of Table 2 to plot the variation of the voltage profile against the load variation for two cases: \( V_2 = 220 \text{V} \) and \( V_2 = 226 \text{V} \). Comment on the results.

7) Use the data of Table 2 to plot the variation of the system losses against the load variation for two cases: \( V_2 = 220 \text{V} \) and \( V_2 = 226 \text{V} \). Comment on the results.

8) Use the data of Table 2 to plot the variation of the lines loading against the load variation for two cases: \( V_2 = 220 \text{V} \) and \( V_2 = 226 \text{V} \). Comment on the results.

9) Based on (6), (7) and (8), specify the suitable value of \( V_2 \).

10) Using the PoweWorld model, adjust \( V_1, V_2 \) and \( P_{G2} \) to the values of your Case Study. Compare between the experimental and computer results as illustrated by Table 3. Specify the causes of having differences between experimental and computer cases.

**Table 1  Load Flow Case Studies**

<table>
<thead>
<tr>
<th>Case #</th>
<th>R</th>
<th>L</th>
<th>( V_2 )</th>
<th>( P_{G2} )</th>
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<tbody>
<tr>
<td>1</td>
<td>50%</td>
<td>50%</td>
<td>220 V</td>
<td>( P_{G2}=P_{G1} )</td>
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<tr>
<td>2</td>
<td>100%</td>
<td>0%</td>
<td>220 V</td>
<td>( P_{G2}=P_{G1} )</td>
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<tr>
<td>3</td>
<td>100%</td>
<td>50%</td>
<td>220 V</td>
<td>( P_{G2}=P_{G1} )</td>
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<tr>
<td>4</td>
<td>100%</td>
<td>100%</td>
<td>220 V</td>
<td>( P_{G2}=P_{G1} )</td>
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<td>5</td>
<td>50%</td>
<td>50%</td>
<td>226 V</td>
<td>( P_{G2}=P_{G1} )</td>
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<td>6</td>
<td>100%</td>
<td>0%</td>
<td>226 V</td>
<td>( P_{G2}=P_{G1} )</td>
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<td>7</td>
<td>100%</td>
<td>50%</td>
<td>226 V</td>
<td>( P_{G2}=P_{G1} )</td>
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<tr>
<td>8</td>
<td>100%</td>
<td>100%</td>
<td>226 V</td>
<td>( P_{G2}=P_{G1} )</td>
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<tr>
<td>9</td>
<td>100%</td>
<td>100%</td>
<td>226 V</td>
<td>( P_{G2}=P_{G1}/2 )</td>
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Table 2 Summary of Measurements

<table>
<thead>
<tr>
<th>Case#</th>
<th>Voltage profile (V)</th>
<th>Real Power (W)</th>
<th>Reactive Power (VAR)</th>
<th>Line Loading (A)</th>
<th>Power Loss in % of the total load</th>
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<tr>
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<td>$V_2$ (MD)</td>
<td>$V_3$ (MJ)</td>
<td>$P_{G1}$ (MB)</td>
<td>$P_{G2}$ (MD)</td>
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Table 3 Comparison between Computer Results and Experimental Measurements for studied case

<table>
<thead>
<tr>
<th>Case</th>
<th>Voltage profile (p.u.)</th>
<th>Real Power (V)</th>
<th>Reactive Power (VAR)</th>
<th>Line Loading %</th>
<th>Power Loss in % of the total load</th>
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<td>$P_{G2}$</td>
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