PPT ON
POWER SYSTEM ANALYSIS (R16)

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Prepared
By

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UNIT-I
POWER SYSTEM NETWORK MATRICES

INTRODUCTION

The most known particles are photons, electrons and neutrons with different masses. Their masses are

$$m_e = 9.10x\ 10\text{-}^{31} \text{ kilograms}$$

$$m_p = 1.67x\ 10\text{-}^{27} \text{ kilograms}$$

these masses leads to gravitational force between them, given as

$$F = G\ m_e\ m_p\ /\ r^2$$

The force between two opposite charges placed 1cm apart likely to be $5.5x10\text{-}^{67}$ and force between two like charges placed 1cm apart likely to be $2.3x10\text{-}^{24}$.this force between them is called as electric force .

Electric force is larger than gravitational force. Gravitational force due to their masses. Electric force is due to their properties. Neutron has only mass but no electric force.

INTRODUCTION

We should be able to analyze the performance of power systems both in normal operating conditions and under fault (short-circuit) condition. The analysis in normal steady-state operation is called a **power-flow study** (**load-flow study**) and it targets on determining the voltages, currents, and real and reactive power flows in a system under a given load conditions.

The purpose of power flow studies is to plan ahead and account for various hypothetical situations. For instance, what if a transmission line within the power system properly supplying loads must be taken off line for maintenance. Can the remaining lines in the system handle the required loads without exceeding their rated parameters?

Basic techniques for power-flow studies.

The equations used to update the estimates differ for different types of busses. Each bus in a power system can be classified to one of three types:

1. Load bus (PQ bus) – a buss at which the real and reactive power are specified, and for which the bus voltage will be calculated. Real and reactive powers supplied to a power system are defined to be positive, while the powers consumed from the system are defined to be negative. All busses having no generators are load busses.

2. Generator bus (PV bus) – a bus at which the magnitude of the voltage is kept constant by adjusting the field current of a synchronous generator on the bus (as we learned, increasing the field current of the generator increases both the reactive power supplied by the generator and the terminal voltage of the system). We assume that the field current is adjusted to maintain a constant terminal voltage V_T. We also know that increasing the prime mover's governor set points increases the power that generator supplies to the power system. Therefore, we can *control and specify the magnitude of the bus voltage and real power supplied*.

Basic techniques for power-flow studies

3. Slack bus (swing bus) – a special generator bus serving as the reference bus for the power system. Its voltage is assumed to be fixed in both magnitude and phase (for instance, $1\angle 0^{\circ}$ pu). The real and reactive powers are uncontrolled: the bus supplies whatever real or reactive power is necessary to make the power flows in the system balance.
In practice, a voltage on a load bus may change with changing loads. Therefore, load busses have specified values of P and Q, while V varies with load conditions.

Real generators work most efficiently when running at full load. Therefore, it is desirable to keep all but one (or a few) generators running at 100% capacity, while allowing the remaining (swing) generator to handle increases and decreases in load demand. Most busses with generators will supply a fixed amount of power and the magnitude of their voltages will be maintained constant by field circuits of generators. These busses have specific values of P and $|V_i|$.

The controls on the swing generator will be set up to maintain a constant voltage and frequency, allowing P and Q to increase or decrease as loads change.

Constructing Y_{bus} For Power-flow Analysis

The most common approach to power-flow analysis is based on the bus admittance matrix Y_{bus}. However, this matrix is slightly different from the one studied previously since the internal impedances of generators and loads connected to the system are not included in Y_{bus}. Instead, they are accounted for as specified real and reactive powers input and output from the busses.

Example 11.1: A simple power system has 4 busses, 5 transmission lines, 1 generator, and 3 loads. Series per-unit impedances are:

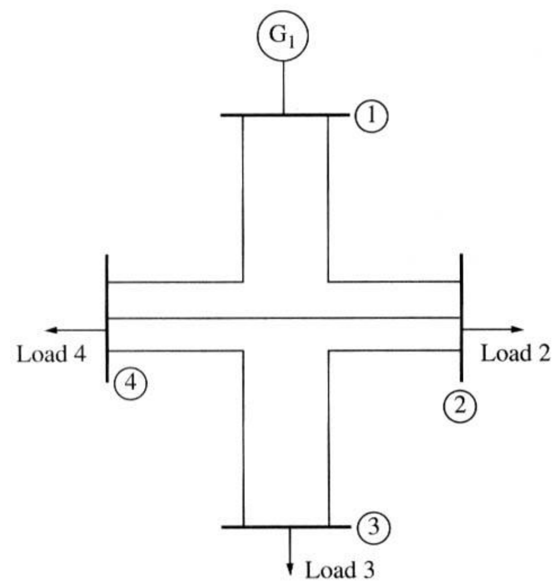


Table of Busses:

Bus 1	Slack bus
Bus 2	Load bus
Bus 3	Load bus
Bus 4	Load bus

1	1-2	0.1+j0.4	0.5882-j2.3529
2	2-3	0.1+j0.5	0.3846-j1.9231
3	2-4	0.1+j0.4	0.5882-j2.3529
4	3-4	0.5+j0.2	1.1765-j4.7059
5	4-1	0.5+j0.2	1.1765-j4.7059

Constructing Y_{bus} For Power-flow Analysis

The shunt admittances of the transmission lines are ignored. In this case, the Y_{ii} terms of the bus admittance matrix can be constructed by summing the admittances of all transmission lines connected to each bus, and the Y_{ij} $(i \neq j)$ terms are just the negative of the line admittances stretching between busses *i* and *j*. Therefore, for instance, the term Y_{11} will be the sum of the admittances of all transmission lines connected to bus 1, which are the lines 1 and 5, so Y_{11} = 1.7647 – j7.0588 pu.

If the shunt admittances of the transmission lines are not ignored, the self admittance Y_{ii} at each bus would also include half of the shunt admittance of each transmission line connected to the bus.

The term Y_{12} will be the negative of all the admittances stretching between bus 1 and bus 2, which will be the negative of the admittance of transmission line 1, so Y_{12} = -0.5882 + j2.3529.

Power-flow Analysis Equations

The basic equation for power-flow analysis is derived from the nodal analysis equations for the power system:

$$Y_{bus}V = I$$

For the four-bus power system shown above, becomes

$$\begin{bmatrix} Y_{11} & Y_{12} & Y_{13} & Y_{14} \\ Y_{21} & Y_{22} & Y_{23} & Y_{24} \\ Y_{31} & Y_{32} & Y_{33} & Y_{34} \\ Y_{41} & Y_{42} & Y_{43} & Y_{44} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} = \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix}$$

where Y_{ij} are the elements of the bus admittance matrix, V_i are the bus voltages, and I_i are the currents injected at each node. For bus 2 in this system, this equation reduces to

$$Y_{21}V_1 + Y_{22}V_2 + Y_{23}V_3 + Y_{24}V_4 = I_2$$

Power-flow Analysis Equations

However, real loads are specified in terms of real and reactive powers, not as currents. The relationship between per-unit real and reactive power supplied to the system at a bus and the per-unit current injected into the system at that bus is:

$$S = VI^* = P + jQ$$

where *V* is the per-unit voltage at the bus; *I** - complex conjugate of the per-unit current injected at the bus; P and Q are per-unit real and reactive powers. Therefore, for instance, the current injected at bus 2 can be found as

$$V_2 I_2^* = P_2 + jQ_2 \quad \Rightarrow \quad I_2^* = \frac{P_2 + jQ_2}{V_2} \quad \Rightarrow \quad I_2 = \frac{P_2 + jQ_2}{V_2^*}$$

Substituting (11.10.2) into (11.9.3), we obtain

$$Y_{21}V_1 + Y_{22}V_2 + Y_{23}V_3 + Y_{24}V_4 = \frac{P_2 + jQ_2}{V_2^*}$$

Power-flow Analysis Equations

Solving the last equation for V_2, yields

$$V_2 = \frac{1}{Y_{22}}\left[\frac{P_2 - jQ_2}{V_2^*} - \left(Y_{21}V_1 + Y_{23}V_3 + Y_{24}V_4\right)\right]$$

Similar equations can be created for each load bus in the power system.

(11.11.1) gives updated estimate for V_2 based on the specified values of real and reactive powers and the current estimates of all the bus voltages in the system. Note that the updated estimate for V_2 will not be the same as the original estimate of V_2^* used in (11.11.1) to derive it. We can repeatedly update the estimate wile substituting current estimate for V_2 back to the equation. The values of V_2 will converge; however, this would NOT be the correct bus voltage since voltages at the other nodes are also needed to be updated. Therefore, all voltages need to be updated during each iteration!

The iterations are repeated until voltage values no longer change much between iterations.

Power-flow Analysis Equations

This method is known as the Gauss-Siedel iterative method. Its basic procedure is:

1. Calculate the bus admittance matrix Y_{bus} including the admittances of all transmission lines, transformers, etc., between busses but exclude the admittances of the loads or generators themselves.
2. Select a slack bus: one of the busses in the power system, whose voltage will arbitrarily be assumed as $1.0\angle 0^\circ$.
3. Select initial estimates for all bus voltages: usually, the voltage at every load bus assumed as $1.0\angle 0^\circ$ (flat start) lead to good convergence.
4. Write voltage equations for every other bus in the system. The generic form is

$$V_i = \frac{1}{Y_{ii}}\left(\frac{P_i - jQ_i}{V_i^*} - \sum_{\substack{k=1\\k\neq i}}^{N} Y_{ik}V_k\right)$$

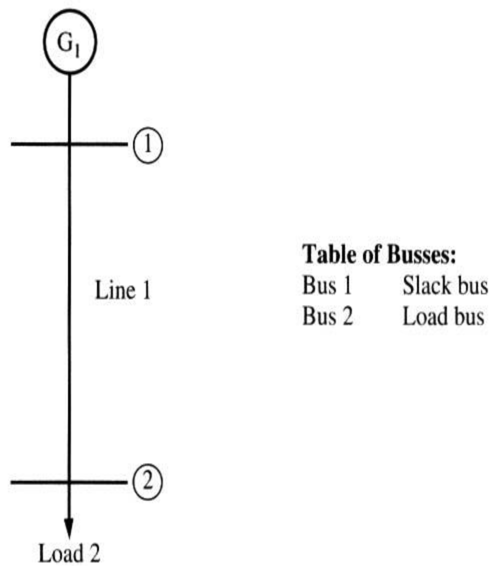
Power-flow Analysis Equations

5. Calculate an updated estimate of the voltage at each load bus in succession using (11.12.1) except for the slack bus.

6. Compare the differences between the old and new voltage estimates: if the differences are less than some specified tolerance for all busses, stop. Otherwise, repeat step 5.

7. Confirm that the resulting solution is reasonable: a valid solution typically has bus voltages, whose phases range in less than 45˚.

Example 11.2: in a 2-bus power system, a generator attached to bus 1 and loads attached to bus 2. the series impedance of a single transmission line connecting them is 0.1+j0.5 pu. The shunt admittance of the line may be neglected. Assume that bus 1 is the slack bus and that it has a voltage $V_1 = 1.0\angle 0^\circ$ pu. Real and reactive powers supplied to the loads from the system at bus 2 are $P_2 = 0.3$ pu, $Q_2 = 0.2$ pu (powers supplied to the system at each busses is negative of the above values). Determine voltages at each bus for the specified load conditions.



Power-flow Analysis Equations

1. We start from calculating the bus admittance matrix Y_{bus}. The Y_{ii} terms can be constructed by summing the admittances of all transmission lines connected to each bus, and the Y_{ij} terms are the negative of the admittances of the line stretching between busses i and j. For instance, the term Y_{11} is the sum of the admittances of all transmission lines connected to bus 1 (a single line in our case). The series admittance of line 1 is

$$Y_{line1} = \frac{1}{Z_{line1}} = \frac{1}{0.1 + j0.5} = 0.3846 - j1.9231 = Y_{11}$$

Applying similar calculations to other terms, we complete the admittance matrix as

$$Y_{bus} = \begin{bmatrix} 0.3846 - j1.9231 & -0.3846 + j1.9231 \\ -0.3846 + j1.9231 & 0.3846 - j1.9231 \end{bmatrix}$$

2. Next, we select bus 1 as the slack bus since it is the only bus in the system connected to the generator. The voltage at bus 1 will be assumed $1.0\angle 0^\circ$.

Power-flow Analysis Equations

3. We select initial estimates for all bus voltages. Making a flat start, the initial voltage estimates at every bus are $1.0\angle 0^\circ$.

4. Next, we write voltage equations for every other bus in the system. For bus 2:

$$V_2 = \frac{1}{Y_{22}}\left[\frac{P_2 - jQ_2}{V_{2,old}^*} - Y_{21}V_1\right] \qquad (11.15.1)$$

Since the real and reactive powers supplied to the system at bus 2 are P_2 = -0.3 pu and Q_2 = -0.2 pu and since Ys and V_1 are known, we may reduce the last equation:

$$\begin{aligned} V_2 &= \frac{1}{0.3846 - j1.9231}\left[\frac{-0.3 - j0.2}{V_{2,old}^*} - \left(\left(-0.3846 + j1.9231\right)V_1\right)\right] \\ &= \frac{1}{1.9612\angle -78.8^\circ}\left[\frac{0.3603\angle -146.3^\circ}{V_{2,old}^*} - \left(1.9612\angle 101.3^\circ\right)\left(1\angle 0^\circ\right)\right] \end{aligned} \qquad (11.15.2)$$

Power-flow Analysis Equations

5. Next, we calculate an updated estimate of the voltages at each load bus in succession. In this problem we only need to calculate updated voltages for bus 2, since the voltage at the slack bus (bus 1) is assumed constant. We repeat this calculation until the voltage converges to a constant value.

The initial estimate for the voltage is $V_{2,0} = 1\angle 0^\circ$. The next estimate for the voltage is

$$V_{2,1} = \frac{1}{1.9612\angle -78.8^\circ}\left[\frac{0.3603\angle -146.3^\circ}{V_{2,old}^*} - \left(1.9612\angle 101.3^\circ\right)\left(1\angle 0^\circ\right)\right]$$
$$= \frac{1}{1.9612\angle -78.8^\circ}\left[\frac{0.3603\angle -146.3^\circ}{1\angle 0^\circ} - \left(1.9612\angle 101.3^\circ\right)\right]$$
$$= 0.8797\angle -8.499^\circ \qquad (11.16.1)$$

This new estimate for V_2 substituted back to the equation will produce the second estimate:

Power-flow Analysis Equations

$$V_{2,2} = \frac{1}{1.9612\angle -78.8^\circ}\left[\frac{0.3603\angle -146.3^\circ}{0.8797\angle -8.499^\circ} - (1.9612\angle 101.3^\circ)(1\angle 0^\circ)\right]$$
$$= 0.8412\angle -8.499^\circ$$

The third iteration will be

$$V_{2,3} = \frac{1}{1.9612\angle -78.8^\circ}\left[\frac{0.3603\angle -146.3^\circ}{0.8412\angle -8.499^\circ} - (1.9612\angle 101.3^\circ)(1\angle 0^\circ)\right]$$
$$= 0.8345\angle -8.962^\circ$$

The fourth iteration will be

$$V_{2,4} = \frac{1}{1.9612\angle -78.8^\circ}\left[\frac{0.3603\angle -146.3^\circ}{0.8345\angle -8.962^\circ} - (1.9612\angle 101.3^\circ)(1\angle 0^\circ)\right]$$
$$= 0.8320\angle -8.962^\circ$$

The fifth iteration will be

$$V_{2,5} = \frac{1}{1.9612\angle -78.8^\circ}\left[\frac{0.3603\angle -146.3^\circ}{0.8320\angle -8.962^\circ} - (1.9612\angle 101.3^\circ)(1\angle 0^\circ)\right]$$
$$= 0.8315\angle -8.994^\circ$$

Power-flow Analysis Equations

6. We observe that the magnitude of the voltage is barely changing and may conclude that this value is close to the correct answer and, therefore, stop the iterations.

This power system converged to the answer in five iterations. The voltages at each bus in the power system are:

$$\begin{aligned} V_1 &= 1.0\angle 0° \\ V_2 &= 0.8315\angle -8.994° \end{aligned} \qquad (11.18.1)$$

7. Finally, we need to confirm that the resulting solution is reasonable. The results seem reasonable since the phase angles of the voltages in the system differ by only 10˚. The current flowing from bus 1 to bus 2 is

$$I_1 = \frac{V_1 - V_2}{Z_{line1}} = \frac{1\angle 0° - 0.8315\angle -8.994°}{0.1 + j0.5} = 0.4333\angle -42.65° \qquad (11.18.2)$$

Power-flow Analysis Equations

The power supplied by the transmission line to bus 2 is

$$S = VI^* = (0.8315\angle -8.994°)(0.4333\angle -42.65°)^* = 0.2999 + j0.1997$$

This is the amount of power consumed by the loads; therefore, this solution appears to be correct.

Note that this example must be interpreted as follows: if the real and reactive power supplied by bus 2 is 0.3 + j0.2 pu and if the voltage on the slack bus is $1\angle 0°$ pu, then the voltage at bus 2 will be $V_2 = 0.8315\angle -8.994°$.

This voltage is correct only for the assumed conditions; another amount of power supplied by bus 2 will result in a different voltage V_2.

Therefore, we usually postulate some reasonable combination of powers supplied to loads, and determine the resulting voltages at all the busses in the power system. Once the voltages are known, currents through each line can be calculated.

The relationship between voltage and current at a load bus as given by is fundamentally nonlinear! Therefore, solution greatly depends on the initial guess.

Power-flow Analysis Equations

At a generator bus, the real power P_i and the magnitude of the bus voltage $|V_i|$ are specified. Since the reactive power for that bus is usually unknown, we need to estimate it before applying to get updated voltage estimates. The value of reactive power at the generator bus can be estimated by solving for Q_i:

$$V_i = \frac{1}{Y_{ii}}\left(\frac{P_i - jQ_i}{V_i^*} - \sum_{\substack{k=1 \\ k\neq i}}^{N} Y_{ik}V_k\right) \Leftrightarrow P_i - jQ_i = V_i^*\left(Y_{ii}V_i - \sum_{\substack{k=1 \\ k\neq i}}^{N} Y_{ik}V_k\right) \quad (11.20.1)$$

Bringing the case $k = I$ into summation, we obtain

$$P_i - jQ_i = V_i^* \sum_{k=1}^{N} Y_{ik}V_k \Rightarrow Q_i = -\operatorname{Im}\left\{V_i^* \sum_{k=1}^{N} Y_{ik}V_k\right\} \quad (11.20.2)$$

Once the reactive power at the bus is estimated, we can update the bus voltage at a generator bus using P_i and Q_i as we would at a load bus. However, the magnitude of the generator bus voltage is also forced to remain constant. Therefore, we must multiply the new voltage estimate by the ratio of magnitudes of old to new estimates.

Adding generator busses to power-flow studies

Therefore, the steps required to update the voltage at a generator bus are:

1. Estimate the reactive power Q_i according to (11.20.2);
2. Update the estimated voltage at the bus according to (11.12.1) as if the bus was a load bus;
3. Force the magnitude of the estimated voltage to be constant by multiplying the new voltage estimate by the ratio of the magnitude of the original estimate to the magnitude of the new estimate. This has the effect of updating the voltage phase estimate without changing the voltage amplitude.

Adding generator busses to power-flow studies

Example 11.3: a 4-bus power system with 5 transmission lines, 2 generators, and 2 loads. Since the system has generators connected to 2 busses, it will have one slack bus, one generator bus, and two load busses. Assume that bus 1 is the slack bus and that it has a voltage $V_1 = 1.0\angle 0^\circ$ pu. Bus 3 is a generator bus. The generator is supplying a real power $P_3 = 0.3$ pu to the system with a voltage magnitude 1 pu. The per-unit real and reactive power loads at busses 2 and 4 are P_2 =

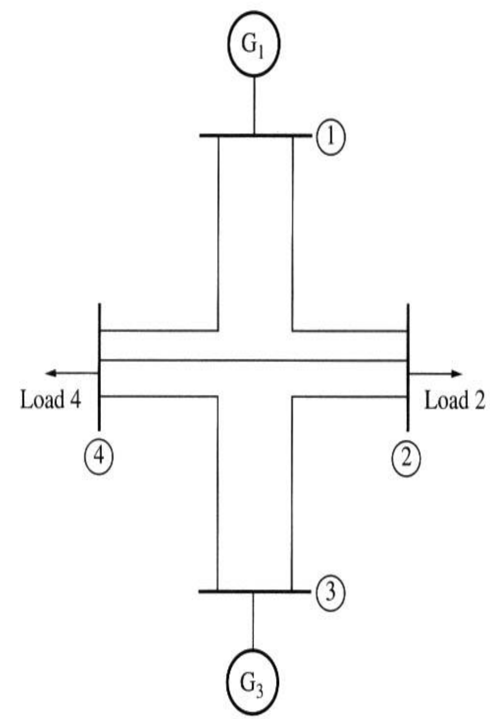


Table of Buses:

Bus 1	Slack bus
Bus 2	Load bus
Bus 3	Generator bus
Bus 4	Load bus

0.3 pu, $Q_2 = 0.2$ pu, $P_4 = 0.2$ pu, $Q_4 = 0.15$ pu (powers supplied to the system at each busses are negative of the above values). The series impedances of each bus were evaluated in Example 11.1. Determine voltages at each bus for the specified load conditions.

Adding generator busses to power-flow studies

The bus admittance matrix was calculated earlier as

$$Y_{bus} = \begin{bmatrix} 1.7647 - j7.0588 & -0.5882 + j2.3529 & 0 & -1.1765 + j4.7059 \\ -0.5882 + j2.3529 & 1.5611 - j6.6290 & -0.3846 + j1.9231 & -0.5882 + j2.3529 \\ 0 & -0.3846 + j1.9231 & 1.5611 - j6.6290 & -1.1765 + j4.7059 \\ -1.1765 + j4.7059 & -0.5882 + j2.3529 & -1.1765 + j4.7059 & 2.9412 - j11.7647 \end{bmatrix}$$

Since the bus 3 is a generator bus, we will have to estimate the reactive power at that bus before calculating the bus voltages, and then force the magnitude of the voltage to remain constant after computing the bus voltage. We will make a flat start assuming the initial voltage estimates at every bus to be $1.0\angle 0^{\circ}$.

Therefore, the sequence of voltage (and reactive power) equations for all busses is:

Adding generator busses to power-flow studies

$$V_2 = \frac{1}{Y_{22}}\left[\frac{P_2 - jQ_2}{V_{2,old}^*} - \left(Y_{21}V_1 + Y_{23}V_3 + Y_{24}V_4\right)\right]$$

$$Q_3 = -\operatorname{Im}\left\{V_3^* \sum_{k=1}^{N} Y_{ik}V_k\right\}$$

$$V_3 = \frac{1}{Y_{33}}\left[\frac{P_3 - jQ_3}{V_{3,old}^*} - \left(Y_{31}V_1 + Y_{32}V_2 + Y_{34}V_4\right)\right]$$

$$V_3 = V_3 \frac{\left|V_{3,old}\right|}{\left|V_3\right|}$$

$$V_4 = \frac{1}{Y_{44}}\left[\frac{P_4 - jQ_4}{V_{4,old}^*} - \left(Y_{41}V_1 + Y_{42}V_2 + Y_{43}V_3\right)\right]$$

Adding generator busses to power-flow studies

The voltages and the reactive power should be updated iteratively, for instance, using Matlab.

Computations converge to the following solution:

$$V_1 = 1.0\angle 0^\circ \ pu$$
$$V_2 = 0.964\angle -0.97^\circ \ pu$$
$$V_3 = 1.0\angle 1.84^\circ \ pu$$
$$V_4 = 0.98\angle -0.27^\circ \ pu$$

The solution looks reasonable since the bus voltage phase angles is less than 45˚.

The information derived from power-flow studies

After the bus voltages are calculated at all busses in a power system, a power-flow program can be set up to provide alerts if the voltage at any given bus exceeds, for instance, ±5% of the nominal value. This is important since the power needs to be supplied at a constant voltage level; therefore, such voltage variations may indicate problems…

Additionally, it is possible to determine the net real and reactive power either supplied or removed from the each bus by generators or loads connected to it. To calculate the real and reactive power at a bus, we first calculate the net current injected at the bus, which is the sum of all the currents leaving the bus through transmission lines.

The current leaving the bus on each transmission line can be found as:

$$I_i = \sum_{\substack{k=1 \\ k \neq i}}^{N} Y_{ik} \left(V_i - V_k \right)$$

The information derived from power-flow studies

The resulting real and reactive powers injected at the bus can be found from

$$S_i = -V_i I_i^* = P_i + jQ_i$$

where the minus sign indicate that current is assumed to be injected instead of leaving the node.

Similarly, the power-flow study can show the real and reactive power flowing in every transmission line in the system. The current flow out of a node along a particular transmission line between bus i and bus j can be calculated as:

$$I_{ij} = Y_{ij}\left(V_i - V_j\right)$$

where Y_{ij} is the admittance of the transmission line between those two busses. The resulting real and reactive power can be calculated as:

$$S_{ij} = -V_i I_{ij}^* = P_{ij} + jQ_{ij}$$

The information derived from power-flow studies

Also, comparing the real and reactive power flows at either end of the transmission line, we can determine the real and reactive power losses on each line.In modern power-flow programs, this information is displayed graphically. Colors are used to highlight the areas where the power system is overloaded, which aids “hot spot” localization.Power-flow studies are usually started from analysis of the power system in its normal operating conditions, called the base case. Then, various (increased) load conditions may be projected to localize possible problem spots (overloads). By adding transmission lines to the system, a new configuration resolving the problem may be found. This estimated models can be used for planning.

Another reason for power-flow studies is modeling possible failures of particular lines and generators to see whether the remaining components can handle the loads.

Finally, it is possible to determine more efficient power utilization by redistributing generation from o locations to other. This variety of power-flow studies is called economic dispatch.

UNIT-II
POWER FLOW STUDIES AND LOAD FLOWS

Modeling Voltage Dependent Load

So far we've assumed that the load is independent of the bus voltage (i.e., constant power). However, the power flow can be easily extended to include voltage depedence with both the real and reactive load. This is done by making P_{Di} and Q_{Di} a function of $|V_i|$:

$$\sum_{k=1}^{n} |V_i||V_k|(G_{ik}\cos\theta_{ik} + B_{ik}\sin\theta_{ik}) - P_{Gi} + P_{Di}(|V_i|) = 0$$

$$\sum_{k=1}^{n} |V_i||V_k|(G_{ik}\sin\theta_{ik} - B_{ik}\cos\theta_{ik}) - Q_{Gi} + Q_{Di}(|V_i|) = 0$$

Voltage Dependent Load Example

In previous two bus example now assume the load is constant impedance, so

$$P_2(\mathbf{x}) = |V_2|(10\sin\theta_2) + 2.0|V_2|^2 = 0$$

$$Q_2(\mathbf{x}) = |V_2|(-10\cos\theta_2) + |V_2|^2(10) + 1.0|V_2|^2 = 0$$

Now calculate the power flow Jacobian

$$J(\mathbf{x}) = \begin{bmatrix} 10|V_2|\cos\theta_2 & 10\sin\theta_2 + 4.0|V_2| \\ 10|V_2|\sin\theta_2 & -10\cos\theta_2 + 20|V_2| + 2.0|V_2| \end{bmatrix}$$

Voltage Dependent Load Example

$$\text{Again set } v = 0, \text{ guess } \mathbf{x}^{(0)} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

Calculate

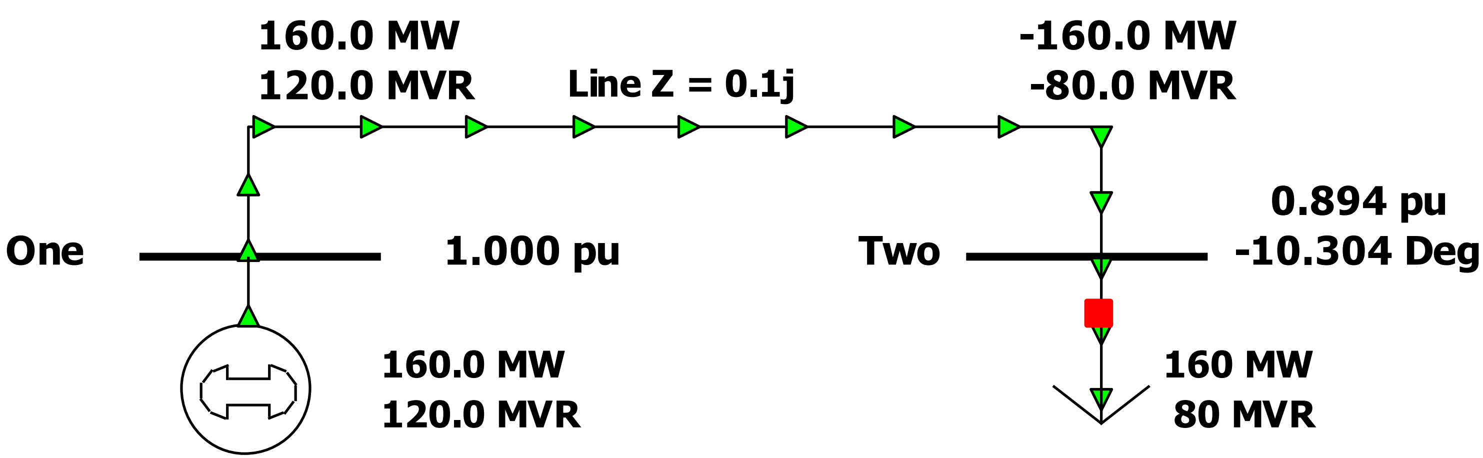
$$\mathbf{f}(\mathbf{x}^{(0)}) = \begin{bmatrix} |V_2|(10\sin\theta_2) + 2.0|V_2|^2 \\ |V_2|(-10\cos\theta_2) + |V_2|^2(10) + 1.0|V_2|^2 \end{bmatrix} = \begin{bmatrix} 2.0 \\ 1.0 \end{bmatrix}$$

$$\mathbf{J}(\mathbf{x}^{(0)}) = \begin{bmatrix} 10 & 4 \\ 0 & 12 \end{bmatrix}$$

$$\text{Solve } \mathbf{x}^{(1)} = \begin{bmatrix} 0 \\ 1 \end{bmatrix} - \begin{bmatrix} 10 & 4 \\ 0 & 12 \end{bmatrix}^{-1} \begin{bmatrix} 2.0 \\ 1.0 \end{bmatrix} = \begin{bmatrix} -0.1667 \\ 0.9167 \end{bmatrix}$$

Voltage Dependent Load Example

With constant impedance load the MW/Mvar load at bus 2 varies with the square of the bus 2 voltage magnitude. This if the voltage level is less than 1.0, the load is lower than 200/100 MW/Mvar



Dishonest Newton Raphson Method

- Since most of the time in the Newton-Raphson iteration is spend calculating the inverse of the Jacobian, one way to speed up the iterations is to only calculate/inverse the Jacobian occasionally
- known as the "Dishonest" Newton-Raphson
- an extreme example is to only calculate the Jacobian for the first iteration

$$\text{Honest:} \qquad \mathbf{x}^{(v+1)} = \mathbf{x}^{(v)} - \mathbf{J}(\mathbf{x}^{(v)})^{-1}\mathbf{f}(\mathbf{x}^{(v)})$$

$$\text{Dishonest:} \quad \mathbf{x}^{(v+1)} = \mathbf{x}^{(v)} - \mathbf{J}(\mathbf{x}^{(0)})^{-1}\mathbf{f}(\mathbf{x}^{(v)})$$

$$\text{Both require } \left\| \mathbf{f}(\mathbf{x}^{(v)}) \right\| < \varepsilon \text{ for a solution}$$

Dishonest Newton Raphson Method

Use the Dishonest Newton-Raphson to solve

$$f(x) = x^2 - 2 = 0$$

$$\Delta x^{(v)} = -\left[\frac{df(x^{(0)})}{dx}\right]^{-1} f(x^{(v)})$$

$$\Delta x^{(v)} = -\left[\frac{1}{2x^{(0)}}\right]((x^{(v)})^2 - 2)$$

$$x^{(v+1)} = x^{(v)} - \left[\frac{1}{2x^{(0)}}\right]((x^{(v)})^2 - 2)$$

Dishonest Newton Raphson Method

$$x^{(v+1)} = x^{(v)} - \left[\frac{1}{2x^{(0)}}\right]((x^{(v)})^2 - 2)$$

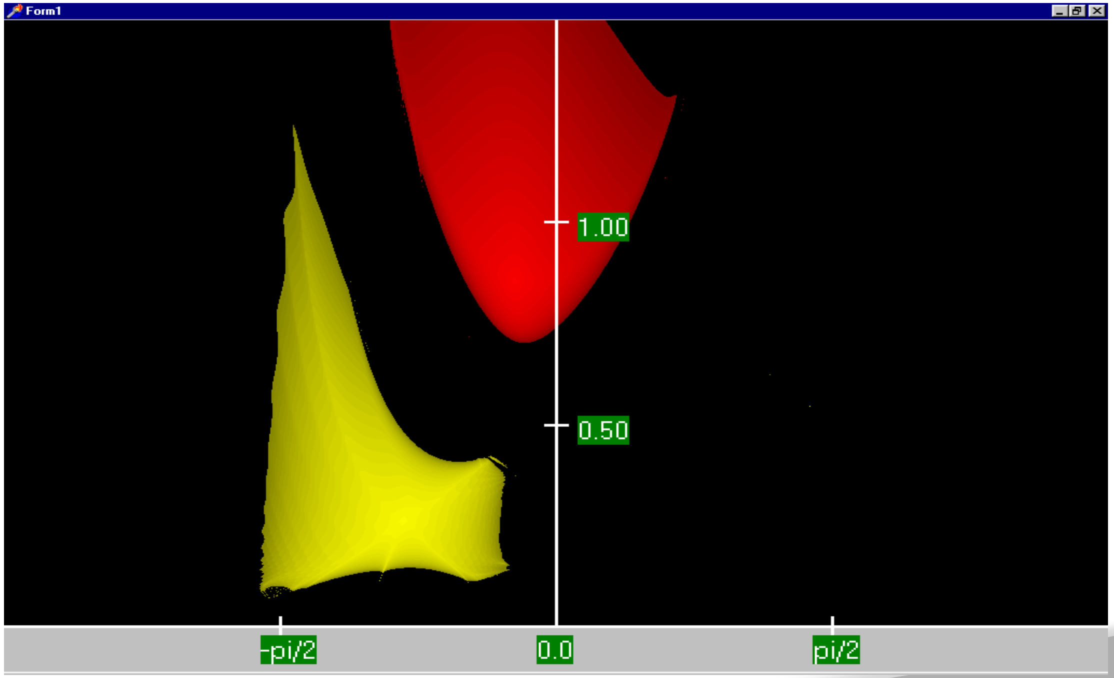
Guess $x^{(0)} = 1$. Iteratively solving we get

v	$x^{(v)}$ (honest)	$x^{(v)}$ (dishonest)
0	1	1
1	1.5	1.5
2	1.41667	1.375
3	1.41422	1.429
4	1.41422	1.408

We pay a price in increased iterations, but with decreased computation per iteration

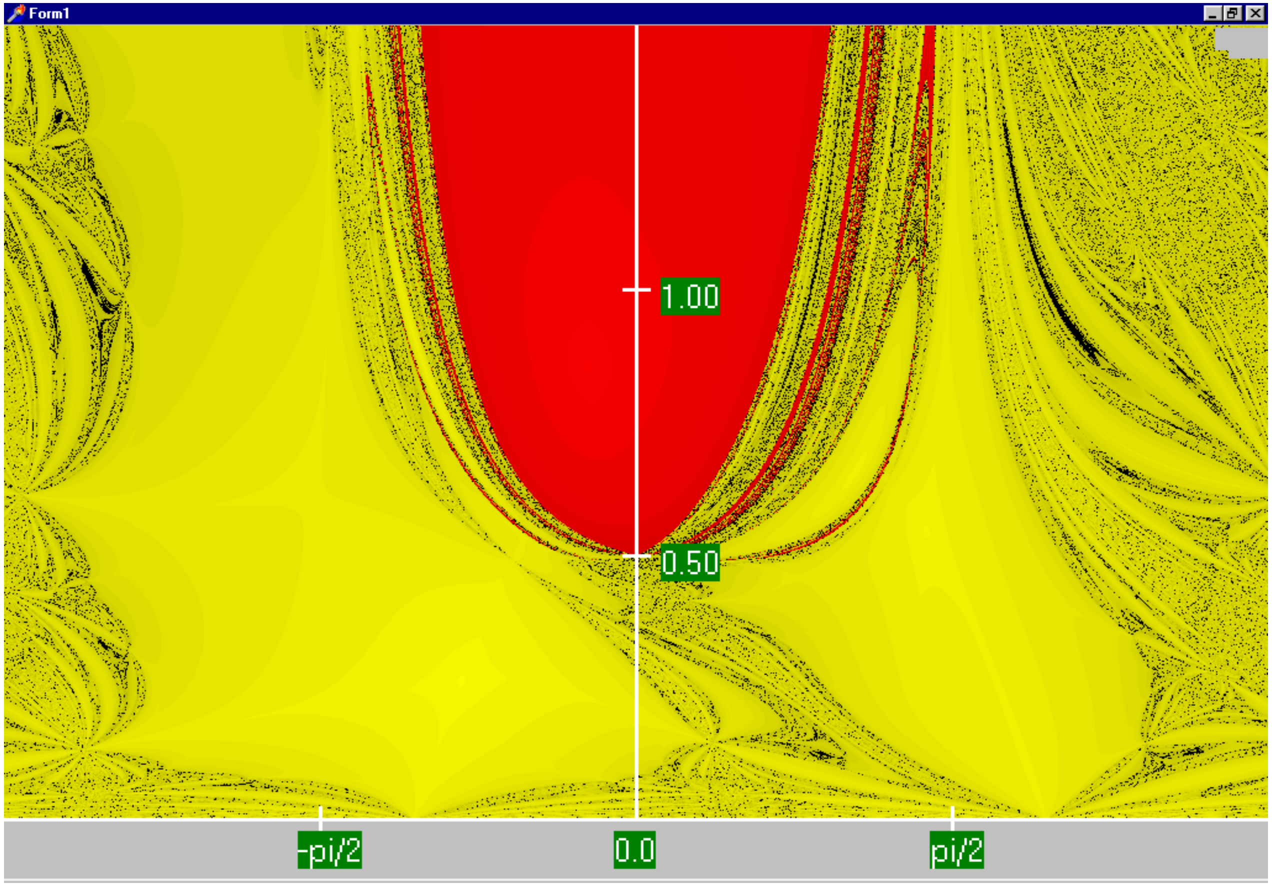
Two Bus Dishonest ROC

Slide shows the region of convergence for different initial guesses for the 2 bus case using the Dishonest N-R



Red region converges to the high voltage solution, while the yellow region converges to the low voltage solution

Honest N-R Region Of Convergence



Maximum of 15 iterations

Decoupled Power Flow

- The completely Dishonest Newton-Raphson is not used for power flow analysis. However several approximations of the Jacobian matrix are used.
- One common method is the decoupled power flow. In this approach approximations are used to decouple the real and reactive power equations.

Decoupled Power Flow

General form of the power flow problem

$$-\begin{bmatrix} \dfrac{\partial \mathbf{P}^{(v)}}{\partial \boldsymbol{\theta}} & \dfrac{\partial \mathbf{P}}{\partial |\mathbf{V}|}^{(v)} \\ \dfrac{\partial \mathbf{Q}^{(v)}}{\partial \boldsymbol{\theta}} & \dfrac{\partial \mathbf{Q}}{\partial |\mathbf{V}|}^{(v)} \end{bmatrix} \begin{bmatrix} \Delta \boldsymbol{\theta}^{(v)} \\ \Delta |\mathbf{V}|^{(v)} \end{bmatrix} = \begin{bmatrix} \Delta \mathbf{P}(\mathbf{x}^{(v)}) \\ \Delta \mathbf{Q}(\mathbf{x}^{(v)}) \end{bmatrix} = \mathbf{f}(\mathbf{x}^{(v)})$$

where

$$\Delta \mathbf{P}(\mathbf{x}^{(v)}) = \begin{bmatrix} P_2(\mathbf{x}^{(v)}) + P_{D2} - P_{G2} \\ \vdots \\ P_n(\mathbf{x}^{(v)}) + P_{Dn} - P_{Gn} \end{bmatrix}$$

Decoupling Approximation

Usually the off-diagonal matrices, $\dfrac{\partial \mathbf{P}}{\partial |\mathbf{V}|}^{(v)}$ and $\dfrac{\partial \mathbf{Q}}{\partial \boldsymbol{\theta}}^{(v)}$

are small. Therefore we approximate them as zero:

$$-\begin{bmatrix} \dfrac{\partial \mathbf{P}}{\partial \boldsymbol{\theta}}^{(v)} & \mathbf{0} \\ \mathbf{0} & \dfrac{\partial \mathbf{Q}}{\partial |\mathbf{V}|}^{(v)} \end{bmatrix} \begin{bmatrix} \Delta \boldsymbol{\theta}^{(v)} \\ \Delta |\mathbf{V}|^{(v)} \end{bmatrix} = \begin{bmatrix} \Delta \mathbf{P}(\mathbf{x}^{(v)}) \\ \Delta \mathbf{Q}(\mathbf{x}^{(v)}) \end{bmatrix} = \mathbf{f}(\mathbf{x}^{(v)})$$

Then the problem can be decoupled

$$\Delta \boldsymbol{\theta}^{(v)} = -\left[\dfrac{\partial \mathbf{P}}{\partial \boldsymbol{\theta}}^{(v)}\right]^{-1} \Delta \mathbf{P}(\mathbf{x}^{(v)}) \quad \Delta |\mathbf{V}|^{(v)} = -\left[\dfrac{\partial \mathbf{Q}}{\partial |\mathbf{V}|}^{(v)}\right]^{-1} \Delta \mathbf{Q}(\mathbf{x}^{(v)})$$

Off-diagonal Jacobian Terms

Justification for Jacobian approximations:

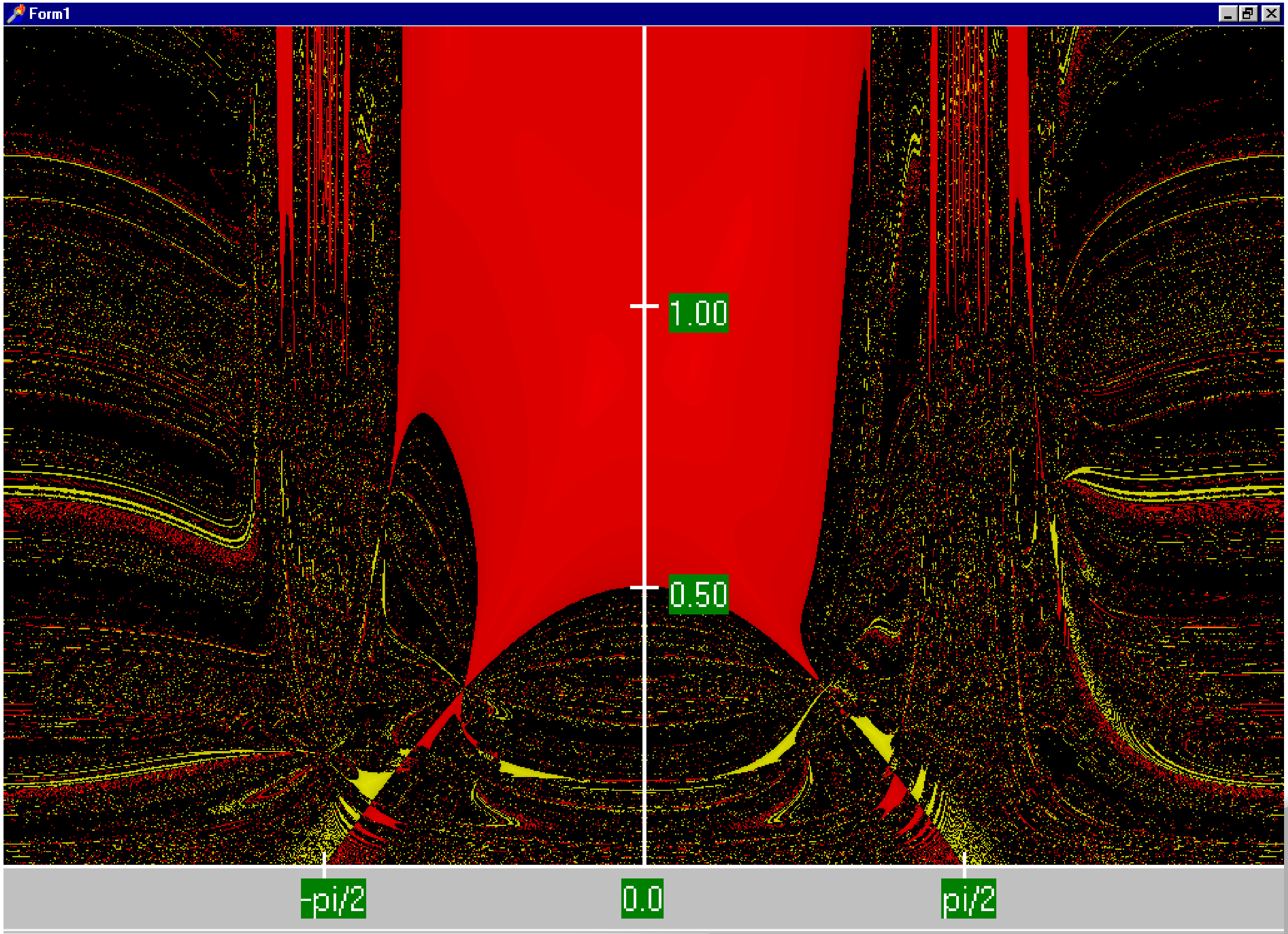
1. Usually r □ x, therefore $\left|G_{ij}\right| \square \left|B_{ij}\right|$
2. Usually θ_{ij} is small so $\sin\theta_{ij} \approx 0$

Therefore

$$\frac{\partial \mathbf{P}_i}{\partial \left|\mathbf{V}_j\right|} = \left|V_i\right|\left(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}\right) \approx 0$$

$$\frac{\partial \mathbf{Q}_i}{\partial \boldsymbol{\theta}_j} = -\left|V_i\right|\left|V_j\right|\left(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}\right) \approx 0$$

Decoupled N-R Region Of Convergence



Fast Decoupled Power Flow

- **By continuing with our Jacobian approximations we can actually obtain a reasonable approximation that is independent of the voltage magnitudes/angles.**
- **This means the Jacobian need only be built/inverted once.**
- **This approach is known as the fast decoupled power flow (FDPF)**
- **FDPF uses the same mismatch equations as standard power flow so it should have same solution**
- **The FDPF is widely used, particularly when we only need an approximate solution**

FDPF Approximations

The FDPF makes the following approximations:

1. $\left|G_{ij}\right| = 0$
2. $\left|V_i\right| = 1$
3. $\sin\theta_{ij} = 0 \qquad \cos\theta_{ij} = 1$

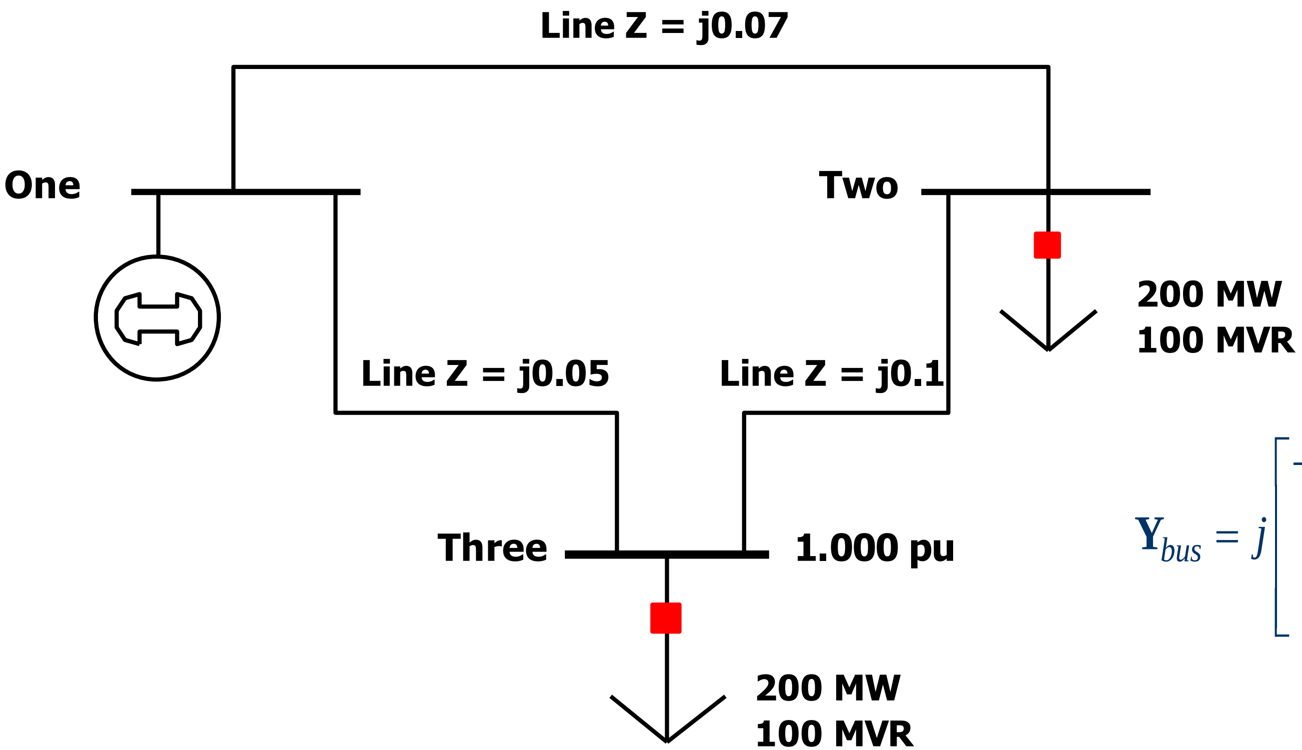
Then

$$\Delta\boldsymbol{\theta}^{(v)} = \mathbf{B}^{-1}\frac{\Delta\mathbf{P}(\mathbf{x}^{(v)})}{\mathbf{V}^{(v)}} \qquad \Delta\left|\mathbf{V}\right|^{(v)} = \mathbf{B}^{-1}\frac{\Delta\mathbf{Q}(\mathbf{x}^{(v)})}{\mathbf{V}^{(v)}}$$

Where $\mathbf{B}$ is just the imaginary part of the $\mathbf{Y}_{\text{bus}} = \mathbf{G} + j\mathbf{B}$, except the slack bus row/column are omitted

FDPF Three Bus Example

Use the FDPF to solve the following three bus system



$$\mathbf{Y}_{bus} = j\begin{bmatrix} -34.3 & 14.3 & 20 \\ 14.3 & -24.3 & 10 \\ 20 & 10 & -30 \end{bmatrix}$$

FDPF Three Bus Example

$$\mathbf{Y}_{bus} = j\begin{bmatrix} -34.3 & 14.3 & 20 \\ 14.3 & -24.3 & 10 \\ 20 & 10 & -30 \end{bmatrix} \rightarrow \mathbf{B} = \begin{bmatrix} -24.3 & 10 \\ 10 & -30 \end{bmatrix}$$

$$\mathbf{B}^{-1} = \begin{bmatrix} -0.0477 & -0.0159 \\ -0.0159 & -0.0389 \end{bmatrix}$$

Iteratively solve, starting with an initial voltage guess

$$\begin{bmatrix} \theta_2 \\ \theta_3 \end{bmatrix}^{(0)} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \qquad \begin{bmatrix} |V|_2 \\ |V|_3 \end{bmatrix}^{(0)} = \begin{bmatrix} 1 \\ 1 \end{bmatrix}$$

$$\begin{bmatrix} \theta_2 \\ \theta_3 \end{bmatrix}^{(1)} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} + \begin{bmatrix} -0.0477 & -0.0159 \\ -0.0159 & -0.0389 \end{bmatrix}\begin{bmatrix} 2 \\ 2 \end{bmatrix} = \begin{bmatrix} -0.1272 \\ -0.1091 \end{bmatrix}$$

FDPF Three Bus Example

$$\begin{bmatrix} |V|_2 \\ |V|_3 \end{bmatrix}^{(1)} = \begin{bmatrix} 1 \\ 1 \end{bmatrix} + \begin{bmatrix} -0.0477 & -0.0159 \\ -0.0159 & -0.0389 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \end{bmatrix} = \begin{bmatrix} 0.9364 \\ 0.9455 \end{bmatrix}$$

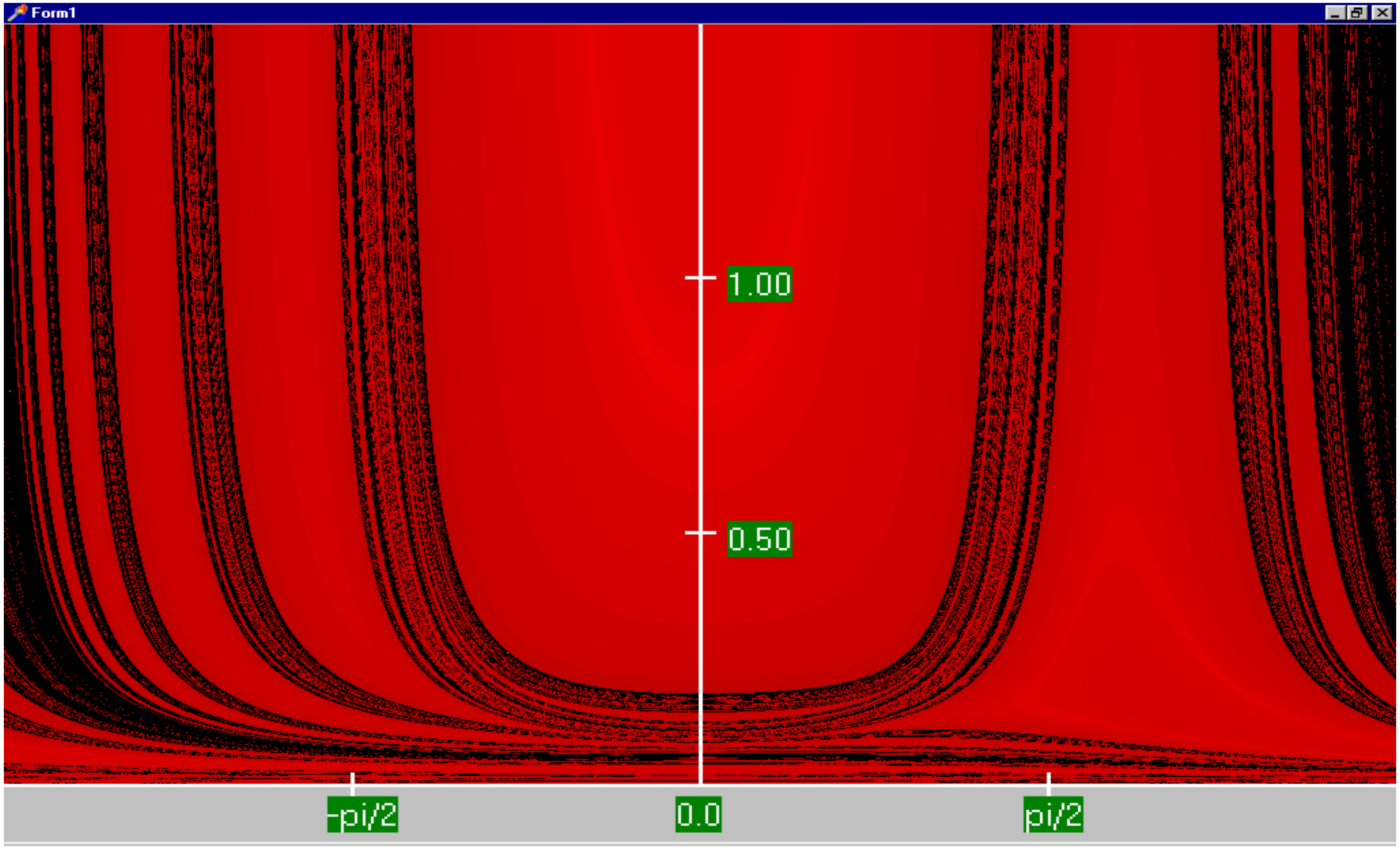
$$\frac{\Delta \mathrm{P_i}(\mathbf{x}\ \ )}{|\mathrm{V_i}|} = \sum_{k=1}^{n} |V_k| (G_{ik} \cos\theta_{ik} + B_{ik} \sin\theta_{ik}) + \frac{P_{Di} - P_{Gi}}{|\mathrm{V_i}|}$$

$$\begin{bmatrix} \theta_2 \\ \theta_3 \end{bmatrix}^{(2)} = \begin{bmatrix} -0.1272 \\ -0.1091 \end{bmatrix} + \begin{bmatrix} -0.0477 & -0.0159 \\ -0.0159 & -0.0389 \end{bmatrix} \begin{bmatrix} 0.151 \\ 0.107 \end{bmatrix} = \begin{bmatrix} -0.1361 \\ -0.1156 \end{bmatrix}$$

$$\begin{bmatrix} |V|_2 \\ |V|_3 \end{bmatrix}^{(2)} = \begin{bmatrix} 0.924 \\ 0.936 \end{bmatrix}$$

$$\text{Actual solution: } \boldsymbol{\theta} = \begin{bmatrix} -0.1384 \\ -0.1171 \end{bmatrix} \qquad \mathbf{V} = \begin{bmatrix} 0.9224 \\ 0.9338 \end{bmatrix}$$

FDPF Region Of Convergence



"DC" Power Flow

- The "DC" power flow makes the most severe approximations:
  - completely ignore reactive power, assume all the voltages are always 1.0 per unit, ignore line conductance
- This makes the power flow a linear set of equations, which can be solved directly .

$$\boldsymbol{\theta} = \mathbf{B}^{-1}\,\mathbf{P}$$

Power System Control

1) A major problem with power system operation is the limited capacity of the transmission system.
2) lines/transformers have limits (usually thermal)
3) no direct way of controlling flow down a transmission line (e.g., there are no valves to close to limit flow)
4) open transmission system access associated with industry restructuring is stressing the system in new ways
5) We need to indirectly control transmission line flow by changing the generator outputs

DC Power Flow Example

EXAMPLE 6.17

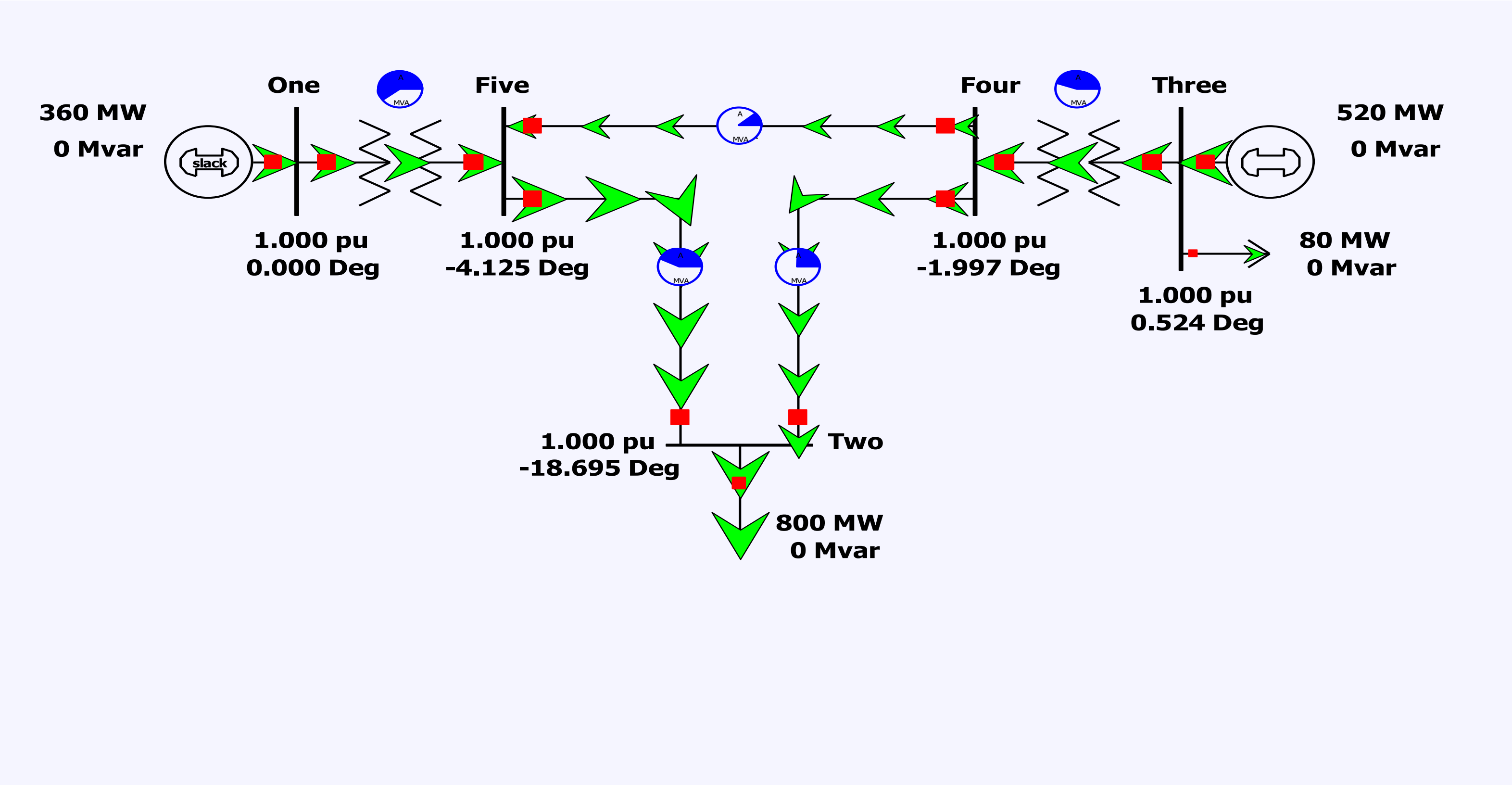
Determine the dc power flow solution for the five bus from Example 6.9.

SOLUTION With bus 1 as the system slack, the **B** matrix and **P** vector for this system are

$$\mathbf{B} = \begin{bmatrix} -30 & 0 & 10 & 20 \\ 0 & -100 & 100 & 0 \\ 10 & 100 & -150 & 40 \\ 20 & 0 & 40 & -110 \end{bmatrix} \quad \mathbf{P} = \begin{bmatrix} -8.0 \\ 4.4 \\ 0 \\ 0 \end{bmatrix}$$

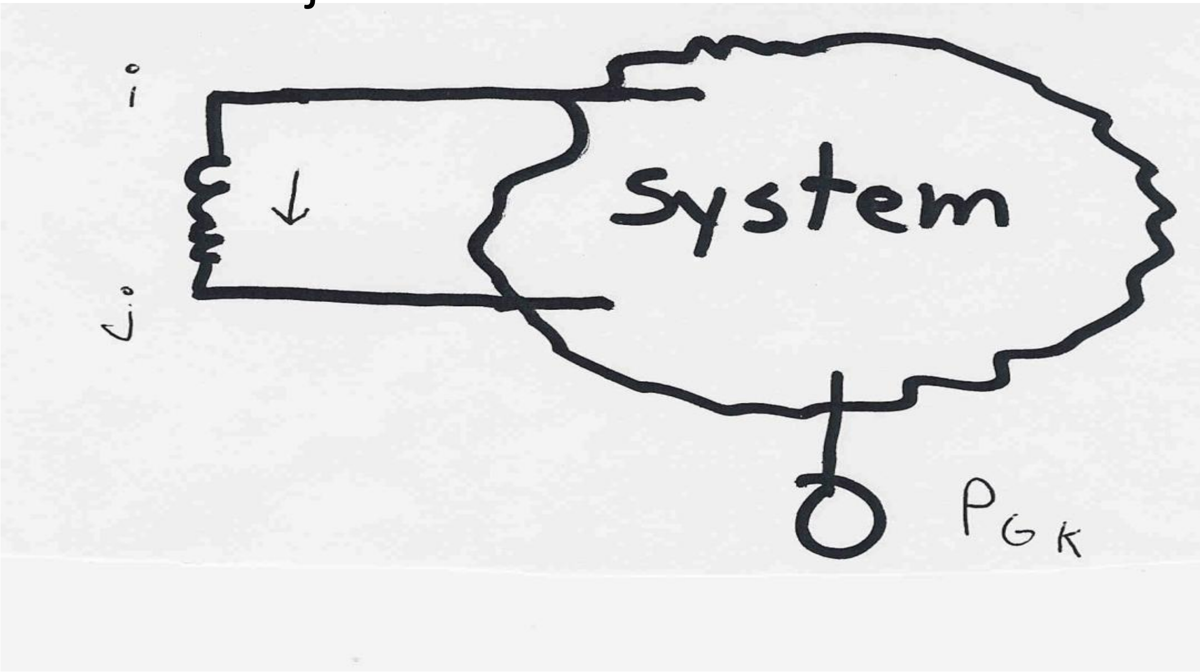
$$\delta = -\mathbf{B}^{-1}\mathbf{P} = \begin{bmatrix} -0.3263 \\ 0.0091 \\ -0.0349 \\ -0.0720 \end{bmatrix} \text{radians} = \begin{bmatrix} -18.70 \\ 0.5214 \\ -2.000 \\ -4.125 \end{bmatrix} \text{degrees}$$

DC Power Flow 5 Bus Example



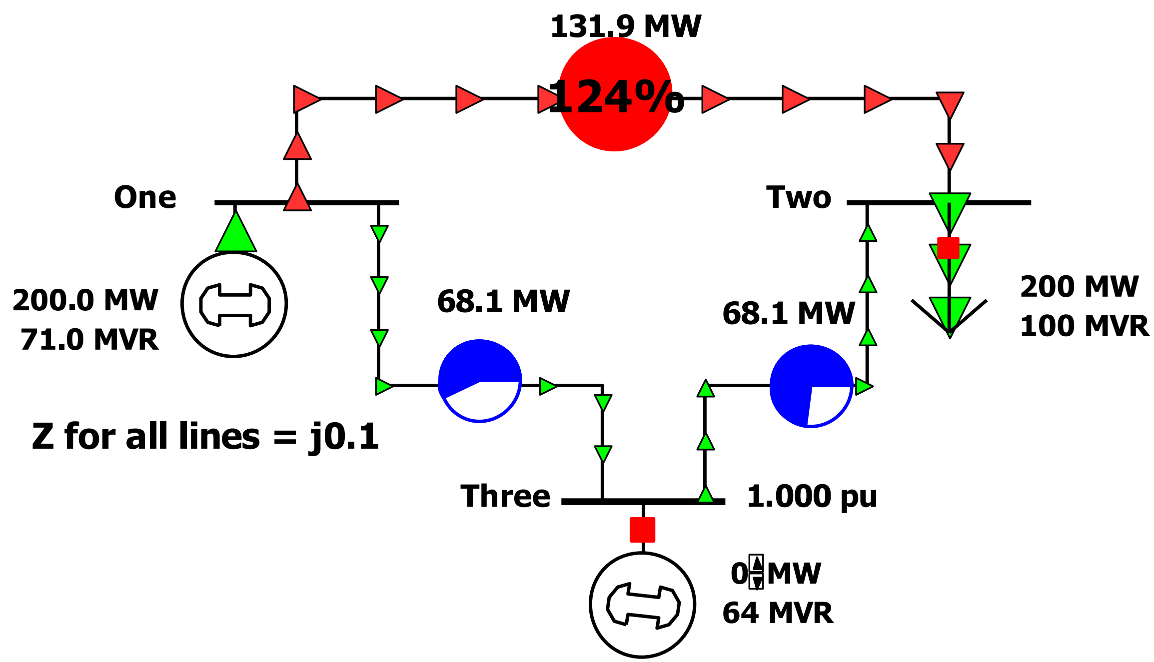
Indirect Transmission Line Control

What we would like to determine is how a change in generation at bus k affects the power flow on a line from bus i to bus j.



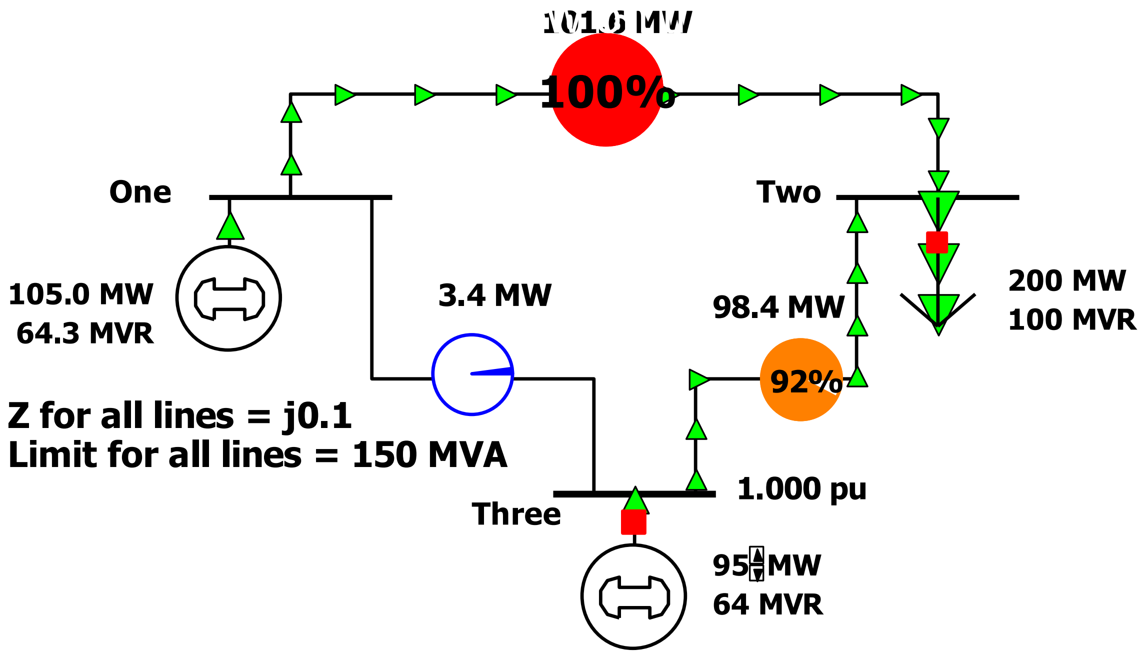
The assumption is
that the change in generation is absorbed by the slack bus

Power Flow Simulation - Before



Power Flow Simulation - After

Power Flow Simulation - After



Analytic Calculation of Sensitivities

Calculating control sensitivities by repeat power flow solutions is tedious and would require many power flow solutions. An alternative approach is to analytically calculate these values

The power flow from bus i to bus j is

$$P_{ij} \approx \frac{|V_i||V_j|}{X_{ij}} \sin(\theta_i - \theta_j) \approx \frac{\theta_i - \theta_j}{X_{ij}}$$

So $\Delta P_{ij} \approx \dfrac{\Delta\theta_i - \Delta\theta_j}{X_{ij}}$ We just need to get $\dfrac{\Delta\theta_{ij}}{\Delta P_{Gk}}$

Analytic Sensitivities

From the fast decoupled power flow we know

$$\Delta\boldsymbol{\theta} = \mathbf{B}^{-1}\Delta\mathbf{P}(\mathbf{x})$$

So to get the change in $\Delta\boldsymbol{\theta}$ due to a change of generation at bus k, just set $\Delta\mathbf{P}(\mathbf{x})$ equal to all zeros except a minus one at position k.

$$\Delta\mathbf{P} = \begin{bmatrix} 0 \\ \vdots \\ -1 \\ 0 \\ \vdots \end{bmatrix} \leftarrow \text{Bus k}$$

UNIT-III

SHORT CIRCUIT ANALYSIS PER UNIT SYSTEM OF REPRESENTATION

Per-Unit System

In the per-unit system, the voltages, currents, powers, impedances, and other electrical quantities are expressed on a per-unit basis by the equation:

$$\textit{Quantity per unit} = \frac{\textit{Actual value to}}{\textit{Base value of quantity}}$$

It is customary to select two base quantities to define a given per-unit system. The ones usually selected are voltage and power.

Per-Unit System

Assume:

$$V_b = V_{rated}$$

$$S_b = S_{rated}$$

Then compute base values for currents and impedances:

$$Z_b = \frac{V_b}{I_b} = \frac{V_b^{\,2}}{S_b}$$

$$I_b = \frac{S_b}{V_b}$$

Per-Unit System

And the per-unit system is:

$$V_{p.u.} = \frac{V_{actual}}{V_b}$$

$$I_{p.u.} = \frac{I_{actual}}{I_b}$$

$$S_{p.u.} = \frac{S_{actual}}{S_b}$$

$$Z_{p.u.} = \frac{Z_{actual}}{Z_b}$$

$$Z\% = Z_{p.u.} \times 100\%$$

Percent of base Z

An electrical lamp is rated 120 volts, 500 watts. Compute the per-unit and percent impedance of the lamp. Give the p.u. equivalent circuit.

Solution:

(1) Compute lamp resistance

$$P = \frac{V^2}{R} \Rightarrow R = \frac{V^2}{P} = \frac{(120)^2}{500} = 28.8\Omega$$

power factor = 1.0

$$Z = 28.8\angle 0\Omega$$

Per-Unit System

(2) Select base quantities

$$S_b = 500VA$$

$$V_b = 120V$$

(3) Compute base impedance

$$Z_b = \frac{V_b^2}{S_b} = \frac{(120)^2}{500} = 28.8\Omega$$

(4) The per-unit impedance is:

$$Z_{p.u.} = \frac{Z}{Z_b} = \frac{28.8\angle 0}{28.8} = 1\angle 0\, p.u.$$

Per-Unit System

(5) Percent impedance:

$$Z\% = 100\%$$

(6) Per-unit equivalent circuit:

$$Z = 1\angle 0\, p.u.$$

$$V_S = 1\angle 0\, p.u.$$

Per-unit System For 1- ϕ Circuits

One-phase circuits

$$S_b = S_{1-\phi} = V_\phi I_\phi$$

where

$$V_\phi = V_{line-to-neutral}$$

$$I_\phi = I_{line-current}$$

$$V_{bLV} = V_{\phi LV}$$

$$V_{bHV} = V_{\phi HV}$$

$$I_{bLV} = \frac{S_b}{V_{bLV}}$$

$$I_{bHV} = \frac{S_b}{V_{bHV}}$$

Per-unit System For 1- ϕ Circuits

$$Z_{bLV} = \frac{V_{bLV}}{I_{bLV}} = \frac{(V_{bLV})^2}{S_b} \qquad Z_{bHV} = \frac{V_{bHV}}{I_{bHV}} = \frac{(V_{bHV})^2}{S_b}$$

$$S_{pu} = \frac{S}{S_b} = V_{pu} I_{pu}^*$$

$$P_{pu} = \frac{P}{S_b} = V_{pu} I_{pu} \cos\theta$$

$$Q_{pu} = \frac{Q}{S_b} = V_{pu} I_{pu} \sin\theta$$

Transformation Between Bases

Selection 1

$$S_{b1} = S_A \qquad V_{b1} = V_A$$

Then

$$Z_{b1} = \frac{V_{b1}^2}{S_{b1}} \qquad Z_{pu1} = \frac{Z_L}{Z_{b1}}$$

Selection 2

$$S_{b2} = S_B \qquad V_{b2} = V_B$$

Then

$$Z_{b2} = \frac{V_{b2}^2}{S_{b2}} \qquad Z_{pu2} = \frac{Z_L}{Z_{b2}}$$

Transformation Between Bases

$$\frac{Z_{pu2}}{Z_{pu1}} = \frac{Z_L}{Z_{b2}} \times \frac{Z_{b1}}{Z_L} = \frac{Z_{b1}}{Z_{b2}} = \frac{V_{b1}^2}{S_{b1}} \times \frac{S_{b2}}{V_{b2}^2}$$

$$Z_{pu2} = Z_{pu1}\left(\frac{V_{b1}}{V_{b2}}\right)^2 \times \left(\frac{S_{b2}}{S_{b1}}\right)$$

"1" – old
"2" - new

$$Z_{pu,new} = Z_{pu,old}\left(\frac{V_{b,old}}{V_{b,new}}\right)^2 \times \left(\frac{S_{b,new}}{S_{b,old}}\right)$$

Transformation Between Bases

Generally per-unit values given to another base can be converted to new base by by the equations:

$$(P,Q,S)_{pu\_on\_base\_2} = (P,Q,S)_{pu\_on\_base\_1} \frac{S_{base1}}{S_{base2}}$$

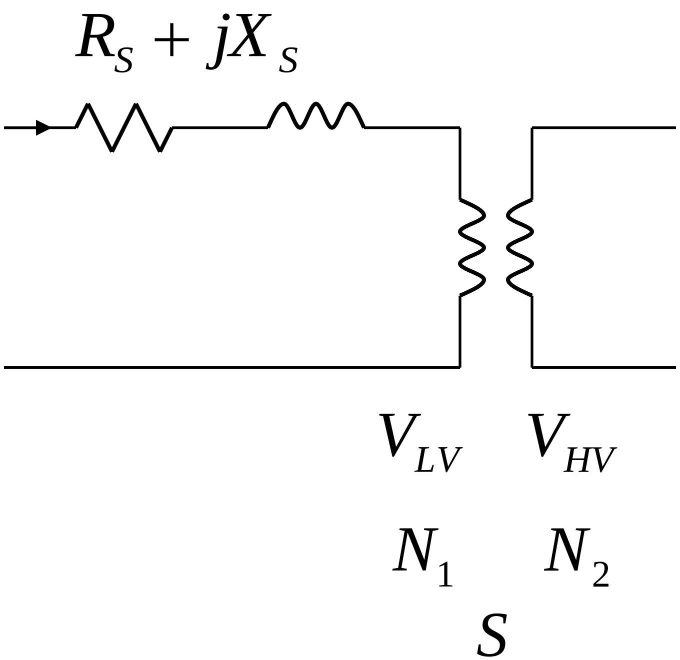
$$V_{pu\_on\_base\_2} = V_{pu\_on\_base\_1} \frac{V_{base1}}{V_{base2}}$$

$$(R,X,Z)_{pu\_on\_base\_2} = (R,X,Z)_{pu\_on\_base\_1} \frac{(V_{base1})^2 S_{base2}}{(V_{base2})^2 S_{base1}}$$

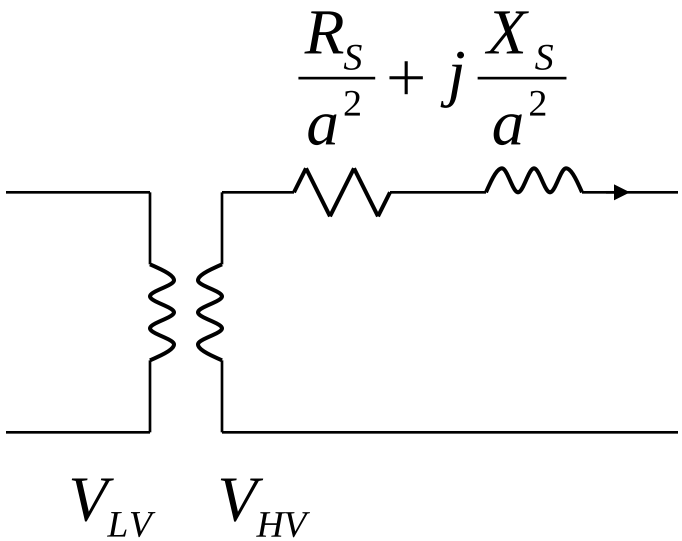
When performing calculations in a power system, every per-unit value must be converted to the same base.

Per-unit System For 1-ϕ Transformer

Consider the equivalent circuit of transformer referred to LV side and HV side shown below:



(1) Referred to LV side



Define $$a = \frac{V_{LV}}{V_{HV}} = \frac{N_1}{N_2} < 1$$

(2) Referred to HV side

Per-unit System For 1-ϕ Transformer

Choose:

$$V_{b1} = V_{LV,rated}$$

$$S_b = S_{rated}$$

Normal choose rated values as base values

Compute:

$$V_{b2} = \frac{V_{HV}}{V_{LV}} V_{b1} = \frac{1}{a} V_{b1}$$

$$Z_{b1} = \frac{V_{b1}^2}{S_b} \qquad Z_{b2} = \frac{V_{b2}^2}{S_b}$$

$$\frac{Z_{b1}}{Z_{b2}} = \frac{V_{b1}^2}{V_{b2}^2} = \frac{V_{b1}^2}{(\frac{1}{a} V_{b1})^2} = a^2$$

Per-unit System For 1-ϕ Transformer

Per-unit impedances are:

$$Z_{p.u.1} = \frac{R_S + jX_S}{Z_{b1}}$$

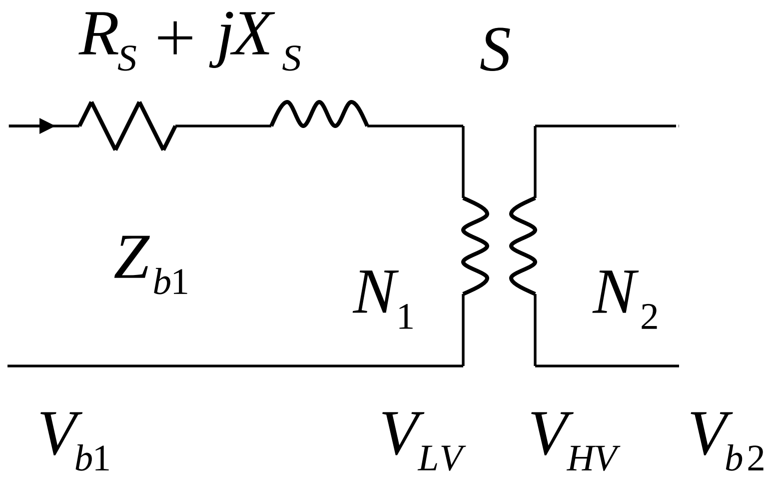
$$Z_{p.u.2} = \frac{\frac{R_S}{a^2} + \frac{jX_S}{a^2}}{Z_{b2}} = \frac{\frac{R_S}{a^2} + \frac{jX_S}{a^2}}{\frac{Z_{b1}}{a^2}} = \frac{R_S + jX_S}{Z_{b1}}$$

So:

$$Z_{p.u.1} = Z_{p.u.2}$$

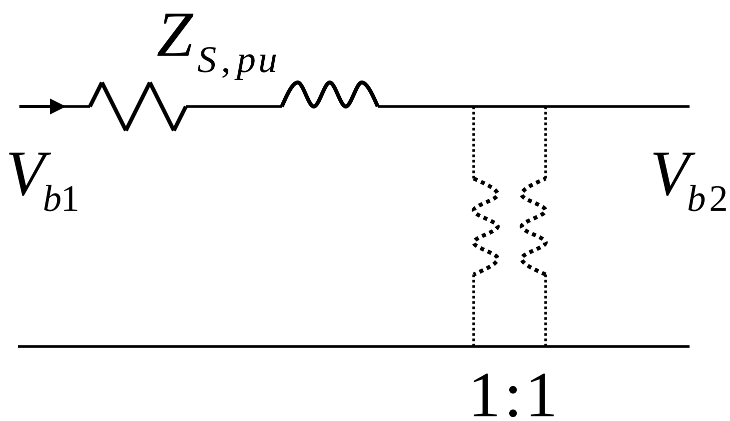
Per-unit equivalent circuits of transformer referred to LV side and HV side are identical !!

Per-unit Eq. Ckt For 1-ϕ Transformer



$$a = \frac{V_{LV}}{V_{HV}} = \frac{N_1}{N_2} < 1$$

Fig 1. Eq Ckt referred to LV side



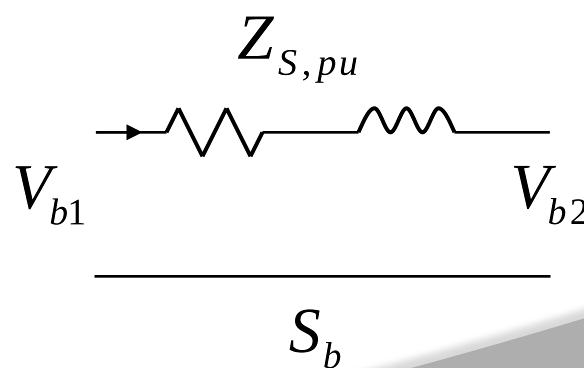
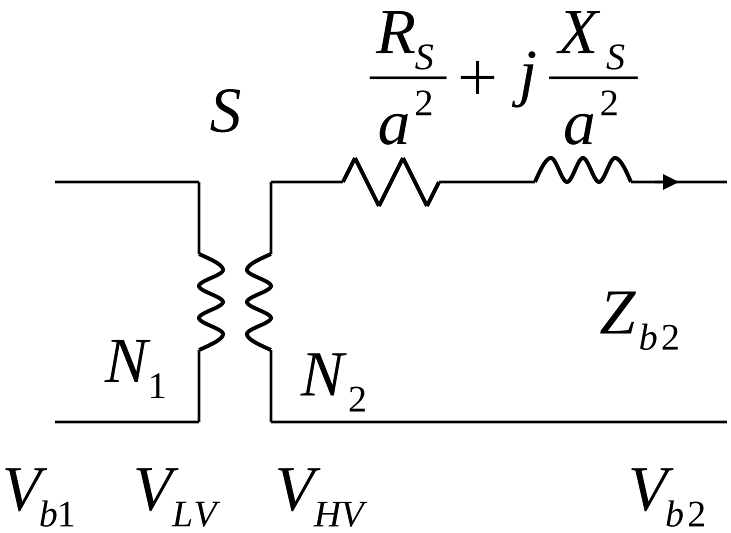


Fig 2. Per-unit Eq Ckt referred to LV side

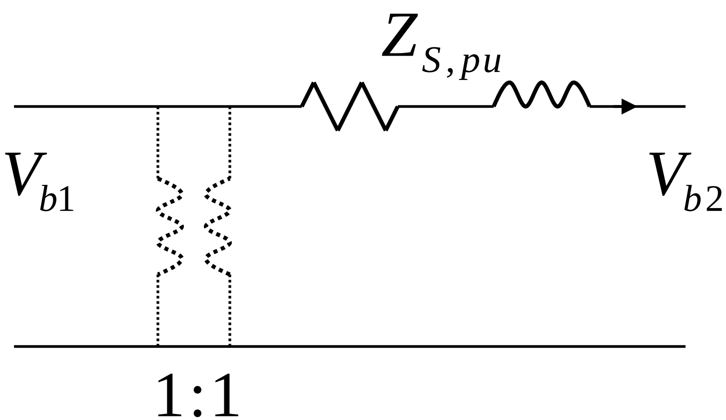
Fig 3.

Per-unit Eq. Ckt For 1-ϕ Transformer



$$a = \frac{V_{LV}}{V_{HV}} = \frac{N_1}{N_2} < 1$$

Fig 4. Eq Ckt referred to HV side



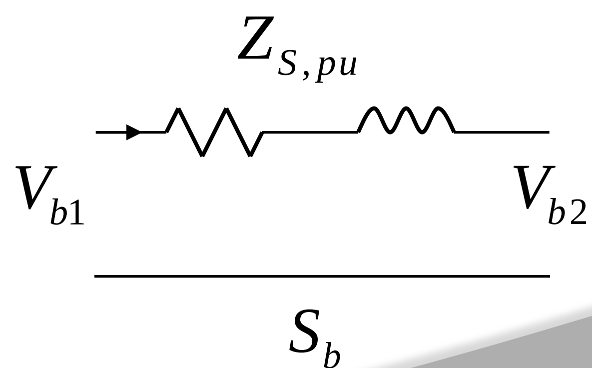


Fig 5. Per-unit Eq Ckt referred to HV side

Fig 6.

Voltage Regulation

Voltage regulation is defined as:

$$VR = \frac{\left|V_{no-load}\right| - \left|V_{full-load}\right|}{\left|V_{full-load}\right|} \times 100\%$$

In per-unit system:

$$VR = \frac{\left|V_{pu,no-load}\right| - \left|V_{pu,\,full-load}\right|}{\left|V_{pu,\,full-load}\right|} \times 100\%$$

$V_{full\text{-}load}$: Desired load voltage at full load. It may be equal to, above, or below rated voltage

$V_{no\text{-}load}$: The no load voltage when the primary voltage is the desired voltage in order the secondary voltage be at its desired value at full load

Voltage Regulation

A single-phase transformer rated 200-kVA, 200/400-V, and 10% short circuit reactance. Compute the VR when the transformer is fully loaded at unity PF and rated voltage 400-V.

Solution:

$$V_{b2} = 400V$$

$$S_b = 200kVA$$

$$S_{load,pu} = 1\angle 0\, pu$$

$$X_{S,pu} = j0.1pu$$

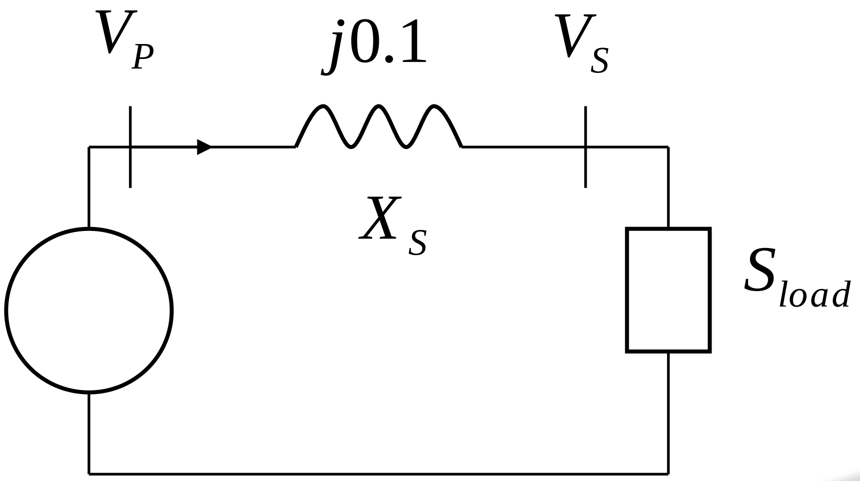


Fig 7. Per-unit equivalent circuit

Voltage Regulation

Rated voltage:

$$V_{S,pu} = 1.0\angle 0\, pu$$

$$I_{load,pu} = \left(\frac{S_{load,pu}}{V_{S,pu}}\right)^{*} = \left(\frac{1.0\angle 0}{1.0\angle 0}\right)^{*} = 1.0\angle 0\, pu$$

$$V_{P,pu} = V_{S,pu} + I_{pu} X_{S,pu}$$

$$= 1.0\angle 0 + 1.0\angle 0 \times j0.1 = 1 + j0.1$$

$$= \boxed{1.001\angle 5.7^{o}\, pu}$$

Voltage Regulation

Secondary side:

$$V_{pu,\,full-load} = V_{S,pu} = 1.0\angle 0\,pu$$

$$V_{pu,no-load} = V_{P,pu} = 1.001\angle 5.7^{o}\ pu$$

Voltage regulation:

$$VR = \frac{\left|V_{pu,no-load}\right| - \left|V_{pu,\,full-load}\right|}{\left|V_{pu,\,full-load}\right|} \times 100\%$$

$$= \frac{1.001 - 1.0}{1.0} \times 100\% = 0.1\%$$

Per-unit System For 3-ϕ Circuits

$$I_{bLV} = \frac{S_b}{\sqrt{3}V_{bLV}} \qquad I_{bHV} = \frac{S_b}{\sqrt{3}V_{bHV}}$$

$$Z_{bLV} = \frac{V_{\phi LV}}{I_{\phi LV}} = \frac{V_{bLV}}{\sqrt{3}} \frac{\sqrt{3}V_{bLV}}{S_b} = \frac{(V_{bLV})^2}{S_b}$$

$$Z_{bHV} = \frac{(V_{bHV})^2}{S_b}$$

$$S_{pu} = \frac{S_{3\phi}}{S_b} = \frac{\sqrt{3}V_L I_L^*}{\sqrt{3}V_b I_b} = V_{pu} I_{pu}^*$$

INTRODUCTION

1. The Bulk Power Supply
2. Reliability criteria
   - The 2 components
   - Security assessment from operators view
   - NERC
3. Requirements of a reliable electric service
4. System dynamic performance
   - Power system stability
   - Definitions
5. Reliability criteria
   - How are they used
   - Disturbance-performance table
   - Security states
   - Normal design vs. extreme contingency
6. Types of stability studies
7. Stability issues today
8. Two important approximations

INTRODUCTION

1. **The Bulk Power Supply**

- **Elaborate, complex, interconnection of power components which make up an interconnected power system.**

- **When we talk about reliability and security of power systems, we are interested in what we call "THE BULK POWER SUPPLY SYSTEM"**

- **The part of the network which connects the power plants, the major substations, and the main EHV/HV lines.**

- **Interruptions in the bulk power supply are very serious**
  - **- Many users are affected by these interruptions**
  - **- They can be costly**

INTRODUCTION

RELIABILITY

Power Systems are built and operated with the following goal:

TO ACHIEVE A RELIABLE and ECONOMIC ELECTRIC POWER SUPPLY.

For the consumer to have a reliable and economic electric power supply, a complex set of engineering analysis and design solutions need to be implemented.

Reliability of a power system refers to the probability of its satisfactory operation over the long run. It denotes the ability to supply adequate electric service on a nearly continuous basis, with few interruptions over an extended time period. - IEEE Paper on Terms & Definitions, 2004

UNIT-IV

STEADY STATE STABILITY

STAEDY STATE STABILITY

- Steady-state and transient voltages and frequency must be held within close tolerances
- Steady-state flows must be within circuit limits
- Synchronous generators must be kept running in parallel with adequate capacity to meet the load demand
- Maintain the “integrity” of the bulk power network (avoid cascading outages)

NERC, North American Electric Reliability Corporation: Mission is to ensure reliability of the bulk power system in North America. They develop/enforce reliability standards; assess reliability annually via 10-year and seasonal forecasts; monitor the bulk power system; evaluate users, owners, and operators for preparedness; and educate, train, and certify industry personnel. NERC is a self-regulated organization, subject to oversight by the U.S. Federal Energy Regulatory Commission & governmental authorities in Canada. It is composed of 9 regional reliability councils & encompasses virtually all power systems in US & Canada. NERC’s activities play an essential role in preventing contingencies and mitigating their consequences.

STAEDY STATE STABILITY

In designing and operating the interconnected power network, system dynamic performance is taken into account because:

- The power system is subjected to changes (small and large). It is important that when the changes are completed, the system settles to new operating conditions such that no constraints are violated.
- Not only should the new operating conditions be acceptable (as revealed by steady-state analysis) but also the system must survive the transition to these conditions. This requires dynamic analysis.

ONE ASPECT OF SYSTEM SECURITY IS THE ABILITY OF THE SYSTEM TO “STAY TOGETHER.” THE KEY IS THAT THE GENERATORS CONTINUE TO OPERATE “IN SYNCHRONISM,” OR NOT TO “LOSE SYNCHRONISM” OR NOT TO “GO OUT OF STEP.” THIS IS THE PROBLEM OF

“POWER SYSTEM STABILITY”

STAEDY STATE STABILITY

- Generators must be kept in synchronism; if their relative motion begins to change too much, uncontrollable oscillations may appear in the grid causing damage to generators and to equipment.

- Therefore, relays are used to detect this condition and trip generators before the damage occurs. Although tripping prevents the damage, it results in under-frequency, and possibly load interruption, and in the worst case, cascading outages and blackout.

STAEDY STATE STABILITY

- **Power System**: A network of one or more electrical generating units, loads, and/or power transmission lines, including the associated equipment electrically or mechanically connected to the network.

- **Operating Quantities of a Power System**: Physical quantities, measured or calculated, that can be used to describe the operating conditions of a power system. Operating quantities include real, reactive, and apparent powers, & rms phasors of alternating voltages & currents.

- **Steady-State Operating Condition of a Power System**: An operating condition of a power system in which all the operating quantities that characterize it can be considered to be constant for the purpose of analysis.

STAEDY STATE STABILITY

- **<u>Synchronous Operation</u>:**

  - **<u>Synchronous Operation of a Machine</u>: A machine is in synchronous operation with a network or another machine(s) to which it is connected if its average electrical speed (product of its rotor angular velocity and the number of pole pairs) equals the angular frequency of the ac network or the electrical speed of the other machine(s).**

  - **<u>Synchronous Operation of a Power System</u>: A power system is in synchronous operation if all its connected synchronous machines are in synchronous operation with the ac network and with each other.**

STAEDY STATE STABILITY

- **<u>Asynchronous or nonsynchronous operation</u>:**
  - **<u>Asynchronous Operation of a Machine</u>: A machine is in asynchronous operation with a network or another machine to which it is connected if it is not in synchronous operation.**
  - **<u>Asynchronous Operation of a Power System</u>: A power system is in asynchronous operation if one or more of its connected synchronous machines are in asynchronous operation.**
- **<u>Hunting of a Machine</u>: A machine is hunting if any of its operating quantities experience sustained oscillations.**

change or a sequence of changes in one or more parameters of the system, or in one or more of the operating quantities.

- Small Disturbance In a Power System: A small disturbance is a disturbance for which the equations that describe the dynamics of the power system may be linearized for the purpose of accurate analysis.
- Large Disturbance In a Power System: A large disturbance is a disturbance for which the equations that describe the dynamics of the power system cannot be linearized for the purpose of accurate analysis.

- Steady-State Stability of a Power System: A power system is steady-state stable for a particular steady-state operating condition if, following any *small* disturbance, it reaches a steady-state operating condition which is identical or close to the pre-disturbance operating condition. This is also known as *Small Disturbance Stability of a Power System*. It should NOT be called "*dynamic stability*."

- Transient Stability of a Power System: A power system is transiently stable for a particular steady-state operating condition *and for a particular disturbance* if, following that disturbance, it reaches an acceptable steady-state operating condition.

STAEDY STATE STABILITY

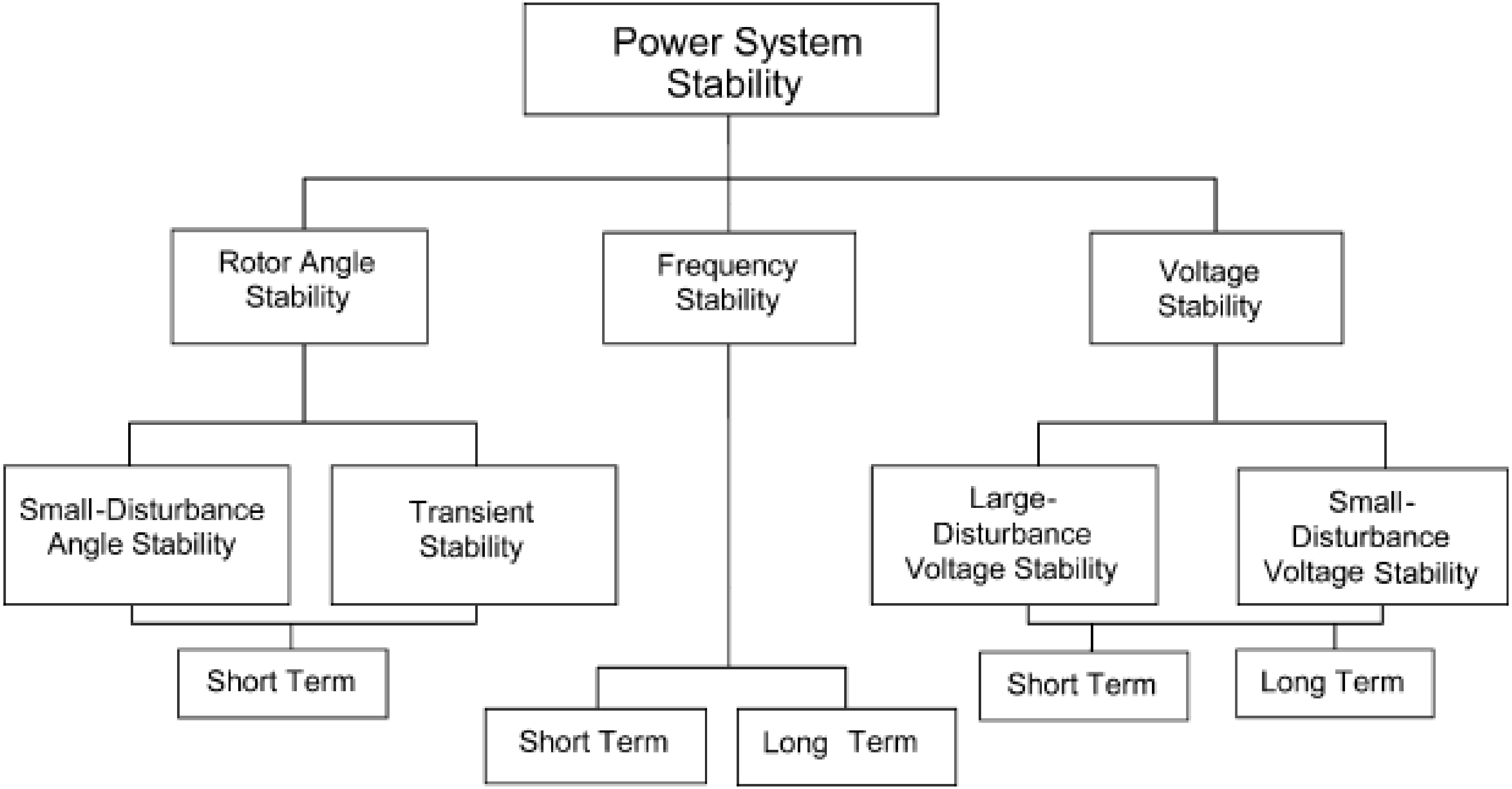
- **<u>Power system stability</u>: Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact.**
- **…Stability of a power system… refers to the continuance of intact operation following a disturbance. It depends on the operating condition and the nature of the physical disturbance.**
- **An equilibrium set of a power system is stable if, when the initial state is in the given starting set, the system motion converges to the equilibrium set, and operating constraints are satisfied for all relevant variables along the entire trajectory.**
  - **IEEE Terms and definitions, 2004.**

- If the oscillatory response of a power system during the transient period following a disturbance is damped and the system settles in a finite time to a new steady operating condition, we say the system is stable. If the system is not stable, it is considered unstable.
  – Anderson & Fouad, pg. 5.

STAEDY STATE STABILITY

- Reliability is the overall objective in power system design and operation. To be reliable, the power system must be secure most of the time. To be secure, the system must be stable but must also be secure against other contingencies that would not be classified as stability problems e.g., damage to equipment such as an explosive failure of a cable, fall of transmission towers due to ice loading or sabotage. As well, a system may be stable following a contingency, yet insecure due to post-fault system conditions resulting in equipment overloads or voltage violations
- System security may be further distinguished from stability in terms of the resulting consequences. For example, two systems may both be stable with equal stability margins, but one may be relatively more secure because the consequences of instability are less severe.
- Security and stability are time-varying attributes which can be judged by studying the performance of the power system under a particular set of conditions. Reliability, on the other hand, is a function of the time-average performance of the power system; it can only be judged by consideration of the system's behavior over an appreciable period of time.

STAEDY STATE STABILITY



STAEDY STATE STABILITY

Disturbance

Table I. Transmission System Standards – Normal and Emergency Conditions

Category	Contingencies	System Limits or Impacts		
	Initiating Event(s) and Contingency Element(s)	System Stable and both Thermal and Voltage Limits within Applicable Rating[a]	Loss of Demand or Curtailed Firm Transfers	Cascading Outages
A No Contingencies	All Facilities in Service	Yes	No	No
B Event resulting in the loss of a single element.	Single Line Ground (SLG) or 3-Phase (3Ø) Fault, with Normal Clearing: 1. Generator 2. Transmission Circuit 3. Transformer Loss of an Element without a Fault	 Yes Yes Yes Yes	 No[b] No[b] No[b] No[b]	 No No No No
	Single Pole Block, Normal Clearing[e]: 4. Single Pole (dc) Line	Yes	No[b]	No
C Event(s) resulting in the loss of two or more (multiple) elements.	SLG Fault, with Normal Clearing[e]: 1. Bus Section 2. Breaker (failure or internal Fault)	 Yes Yes	Planned/ Controlled[c] Planned/ Controlled[c]	 No No
	SLG or 3Ø Fault, with Normal Clearing[e], Manual System Adjustments, followed by another SLG or 3Ø Fault, with Normal Clearing[e]: 3. Category B (B1, B2, B3, or B4) contingency, manual system adjustments, followed by another Category B (B1, B2, B3, or B4) contingency	Yes	Planned/ Controlled[c]	No
	Bipolar Block, with Normal Clearing[e]: 4. Bipolar (dc) Line Fault (non 3Ø), with Normal Clearing[e]: 5. Any two circuits of a multiple circuit towerline[f]	 Yes Yes	 Planned/ Controlled[c] Planned/ Controlled[c]	 No No
	SLG Fault, with Delayed Clearing[e] (stuck breaker or protection system failure): 6. Generator 7. Transformer 8. Transmission Circuit 9. Bus Section	 Yes Yes Yes Yes	 Planned/ Controlled[c] Planned/ Controlled[c] Planned/ Controlled[c] Planned/ Controlled[c]	 No No No No

STAEDY STATE STABILITY

D [d] Extreme event resulting in two or more (multiple) elements removed or Cascading out of service.	3Ø Fault, with Delayed Clearing [e] (stuck breaker or protection system failure): 1. Generator 2. Transmission Circuit 3. Transformer 4. Bus Section 3Ø Fault, with Normal Clearing[e]: 5. Breaker (failure or internal Fault) 6. Loss of towerline with three or more circuits 7. All transmission lines on a common right-of way 8. Loss of a substation (one voltage level plus transformers) 9. Loss of a switching station (one voltage level plus transformers) 10. Loss of all generating units at a station 11. Loss of a large Load or major Load center 12. Failure of a fully redundant Special Protection System (or remedial action scheme) to operate when required 13. Operation, partial operation, or misoperation of a fully redundant Special Protection System (or Remedial Action Scheme) in response to an event or abnormal system condition for which it was not intended to operate 14. Impact of severe power swings or oscillations from Disturbances in another Regional Reliability Organization.	Evaluate for risks and consequences. ▪ May involve substantial loss of customer Demand and generation in a widespread area or areas. ▪ Portions or all of the interconnected systems may or may not achieve a new, stable operating point. ▪ Evaluation of these events may require joint studies with neighboring systems.

a) Applicable rating refers to the applicable Normal and Emergency facility thermal Rating or system voltage limit as determined and consistently applied by the system or facility owner. Applicable Ratings may include Emergency Ratings applicable for short durations as required to permit operating steps necessary to maintain system control. All Ratings must be established consistent with applicable NERC Reliability Standards addressing Facility Ratings.

b) Planned or controlled interruption of electric supply to radial customers or some local Network customers, connected to or supplied by the Faulted element or by the affected area, may occur in certain areas without impacting the overall reliability of the interconnected transmission systems. To prepare for the next contingency, system adjustments are permitted, including curtailments of contracted Firm (non-recallable reserved) electric power Transfers.

c) Depending on system design and expected system impacts, the controlled interruption of electric supply to customers (load shedding), the planned removal from service of certain generators, and/or the curtailment of contracted Firm (non-recallable reserved) electric power Transfers may be necessary to maintain the overall reliability of the interconnected transmission systems.

d) A number of extreme contingencies that are listed under Category D and judged to be critical by the transmission planning entity(ies) will be selected for evaluation. It is not expected that all possible facility outages under each listed contingency of Category D will be evaluated.

e) Normal clearing is when the protection system operates as designed and the Fault is cleared in the time normally expected with proper functioning of the installed protection systems. Delayed clearing of a Fault is due to failure of any protection system component such as a relay, circuit breaker, or current transformer, and not because of an intentional design delay.

f) System assessments may exclude these events where multiple circuit towers are used over short distances (e.g., station entrance, river crossings) in accordance with Regional exemption criteria.

STAEDY STATE STABILITY

A) In System Planning or Design

- Make decisions on size, type and timing of new generation and transmission facilities
- Design transmission network to withstand normal & prescribed abnormal conditions
- The latter includes such things as short circuits (faults) followed by loss of major components (to isolate the fault).

B) In System Operation

- Establish most economic operating conditions under “normal” conditions
- Operate the system such that if an unscheduled event occurs, it does not result in violation of reliability criteria.
- Establish “Safe Operating Limits” for all situations

STAEDY STATE STABILITY

The most salient feature of reliability criteria is a philosophy captured by the following statement taken from the WSCC criteria for transmission system planning, which describes its disturbance-performance table:

“The table is based on the planning philosophy that a HIGHER level of PERFORMANCE is required for disturbances generally having a higher frequency of occurrence.”

Or stated another way,

“The table is based on the planning philosophy that a LOWER level of SEVERITY is required for disturbances generally having a higher frequency of occurrence.”

Considering risk ~ frequency $\times$ severity, we see that the criteria suggests a uniform maximum risk for different kinds of contingencies.

STAEDY STATE STABILITY

A. Steady-state instability

Use linear system analysis techniques to study modal system response

Calculation input: (a) pre-disturbance system conditions (the power flow solution); (b) the dynamic models.

Typical purpose of such studies:

- Obtain safe operating limits and guidelines
- Identify poorly damped modes of oscillation
- Setting of controls (e.g., exciters, power system stabilizers)

UNIT-V
TRANSIENT STABILITY

B. Transient instability

- Use of non-linear system analysis tools to study the system response to (large) disturbances.
  - Traditional method is to use time-d
  - omain simulation to "track" the evolution of system states & parameters during the transient
  - Simulation input: (a) pre-disturbance system conditions (the power flow solution), (b) the dynamic models. (c) the switching sequence.
  - Simulation results: short-term (2-20 seconds) trajectory of all system parameters and final (post-disturbance) conditions.
  - Any change in input WILL change the results, the question that one needs to answer based on judgment is "how much?"

TRANSIENT STABILITY

- The simplest switching sequence is “no-disturbance.” Why would we ever want to do that?
- The next simplest is:
  - 0 cycles: remove circuit 10-29
  - 10 seconds: end simulation
- The next simplest, and most common, is:
  - 0 cycles: apply fault at bus 2339
  - 4 cycles: clear fault
  - 4 cycles: remove circuit 2339-2337
  - 10 seconds: end simulation
- The most complicated (ever?) is the WECC islanding scheme – 44 steps.

TRANSIENT STABILITY

- "First-swing" or "early-swing" (1-5 secs) is a standard problem for which analysis is performed where a large disturbance (fault) is applied to see if the system remains in synchronism during first one or two swings. But often, large disturbances also create damping problems (oscillatory instability) which require 10-20 seconds of simulation time.

- Why not run simulations for 3 minutes of simulation time?
  - Build-up of numerical error for most common type of integration technique
  - Usually, models are for short-term analysis only and do not include, for example, boiler dynamics, thermostatic load models, load tap changers, AGC, etc.
  - If you eliminate numerical error from integration scheme, and use appropriate models, you can perform mid- or long-term simulation (EUROSTAG)

TRANSIENT STABILITY

- **Typical purpose of such studies**
  - **New generation studies (to meet reliability criteria)**
  - **Transmission planning studies (to analyze plans for future transmission expansion, and to meet reliability criteria)**
  - **Operations planning studies (to check that a given system configuration (and operations schedule) meets reliability criteria)**
  - **Special control to maintain stability (e.g., generation tripping, braking resistor insertion, etc.)**
  - **Severe disturbance (extreme contingency) studies**
  - **Special purpose studies (e.g., verifying known system upsets, and system restoration.)**

TRANSIENT STABILITY

Frequency instability is the ability of a power system to maintain steady frequency following a severe system upset resulting in a significant imbalance between generation and load. It depends on the ability to maintain/restore equilibrium between system generation and load, with minimum unintentional loss of load. Instability that may result occurs in the form of sustained frequency swings leading to tripping of generating units and/or loads.

TRANSIENT STABILITY

A. Stability is now considered a problem for system operations in many systems

Here is a quote from a recent paper by B.C. Hydro Engineers about their on-line dynamic

security assessment scheme:

"Conventionally, dynamic security assessment has been performed using off-line calculations. In this process, detailed stability analysis is conducted for each credible contingency under a variety of operating conditions. In real system operations, conditions frequently do not match those studied off-line. Consequently, the guidelines and limits produced are usually provided on the conservative side. Power system networks nowadays operate more and more in a stressed state where conservative operation often results in significant financial consequences. A more effective approach is to assess only those contingencies likely to cause dynamic violations for the operating condition encountered in real time. The new B. C. Hydro EMS system offered an opportunity for implementation of an on-line transient stability assessment (TSA).

TRANSIENT STABILITY

The need is to enable on-line dynamic security analysis.
It is not enough to just say a particular contingency is acceptable or not – we also need to know the “limit.”

Thus we need to:

- Use faster or more computers
  - Parallelization
  - Continuous computing
- Enhance algorithm computational efficiency
  - Direct methods
  - “Smarter” integration schemes
- Limit contingencies to be analyzed
  - Filtering techniques

TRANSIENT STABILITY

Important approximations inherent to all that we will do:

- **Network electromagnetic transients (DC and higher harmonics) are neglected; we are therefore only interested in current and voltage variations associated with the fundamental (60 Hz).**
- **We use phasor representation of voltages and currents. Thus, we regard the network, during the electromechanical (as opposed to electromagnetic) transient conditions, as though it were passing directly from one electromagnetic steady-state to another. In other words, we consider only the variations in the amplitude-envelope of the fundamental.**
- **Impedances:**
  - **are represented using lumped (not distributed) parameter models**
  - **are independent of frequency variation (computed at 60 Hz).**
- **We may model different fault types, but we study the effects of disturbances on only the positive sequence network, therefore the network is modeled as a per-phase network.**

TRANSIENT STABILITY

B. Context of Stability Analysis May Change

- **The nature of the problems, and the required answers required may change**
  - **Enhance modeling (e.g., wind!)**
  - **Mid-term and long-term analysis: need extended models for this (boiler, tap changers, thermostatic loads, induction motors)**
  - **Large disturbance voltage instability**
  - **New types of answers are required (e.g., if a new transaction is requested the stability implications, consequences, and the amount of additional flow which can reliably be transacted will need to be known in a relatively short interval of time)**
  - **Very fast computational capability is needed**
- **Reliability criteria as they exist today are deterministic**
  - **To relieve the constraints of conservative limits obtained from deterministic criteria, it may be essential to incorporate concepts of probability and risk.**
  - **New criteria involving probability and risk would have to be translated into meaningful operating guidelines in order to find acceptance with system operators.**

TRANSIENT STABILITY

- Your and my goals

Your goal is to obtain a clear understanding of the physical aspects of each phenomena, be able to use the appropriate representation of the power system to analyze the phenomena, and apply new or existing tools in an original and creative manner to provide needed answers.

My goal in this course is to motivate and channel your thought process towards your goal and provide the various building blocks, tools, and relevant reference material you will need.