

Advanced Power System Analysis

Lecture 4

Load Flow Studies

Lecturer: Teshome Goa (Assist. Prof.)

Lecture learning outcomes:

At the end of this lecture, you will be able to:

- i. Understand the types of power network buses
- ii. Identify the voltage controlling methods for load buses
- iii. Develop the power flow equations

Outlines

1. Introduction

2. Types of Power Network buses (TPNB)

3. Power Flow Equation Formulation (PFEF)

Summary

References

1. Introduction

- Buses are essential nodes where various system elements (such as generators, loads, and transmission lines) are connected in power system analysis.
- Important electrical parameters including phase angle, voltage magnitude, power generation, and power demand are described or computed at each bus.
- Based on known and unknown electrical factors, buses are divided into three primary kinds to make power flow studies easier to understand[1]:
 1. Load bus
 2. Generator bus
 3. Swing bus

Introduction

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- The classification is just to determine the unknown parameters based on the known parameter as presented in Table 1.

Table 1. Types of Power Network Buses

Types of bus	Known Variables	Unknown Variables	Unknown variables are re commuted using
Load Bus/PQ Buses (Uncontrolled bus)	-Load real power -Load reactive power	-Bus Voltage -Bus Voltage angle	-Load flow analysis
PV bus/generator bus (Voltage controlled bus)	-Real Power of generator -Bus voltage	-Reactive Power -Bus voltage angle	-Load flow analysis
Swing/ Slack Buses	-Bus voltage -Bus voltage angle	-Real Power -Reactive power	-Load flow analysis

2. Types of Power Network Buses (TPNB)

A. Load bus:

- A bus where there is only loads connected and no generation exists (both P_{Gi} and Q_{Gi} are zero) is called a load bus[2].
- At this bus, the real power demand (P_{Di}) and reactive power demand (Q_{Di}) are drawn from the supply.
- In a power balance equation P_{Di} and Q_{Di} are **treated as negative** quantities since generated powers P_{Gi} and Q_{Gi} are assumed positive.

Load buses represent locations in the power system where electrical energy is consumed, such as:

- Residential buildings
- Industrial plants
- Commercial complexes

- The voltage magnitude (V) and its angle(δ) are not specified at load bus and needs to be determined through power flow analysis
- Load bus is also known as uncontrolled bus, because its voltage is not directly controlled but fluctuates according to the network's power balance.
- Particularly, the **distribution of generation and reactive** power support, determines the **voltage at this** bus, which is not directly under the control of demand side.
- Accordingly, the voltage at the load bus is considered as a dependent variable.

- Which is based on the system equations and **cannot be fixed or controlled**, in contrast to a generator bus (PV bus) or slack bus.
- However, the power system operation and its stability depend heavily on **controlling the voltage** in a load bus, which is influenced by both real and reactive power flow.
- Accordingly, based on the **equipment available and** the complexity of the system, there are a number of ways to control the voltage on a load bus, including the following common methods[3]:

i. Compensation for Reactive Power

- Voltage levels are directly impacted by reactive power and it can be managed using:
- **Shunt Capacitors:** Boosts voltage, reactive power should be added to the system.

- **Shunt Reactors:** it is used for voltage reduction in power network
- Reactor absorb the system's reactive power during operation
- **Synchronous Condensers:** it is used for reactive power control either by supplying or absorbing as required.
- With the aid of a speed drive, a **little steed motor accelerates** the synchronous condenser to network synchronous speed.
- The voltage and power factor will be fully related to the excitation.

- Depending on the voltage and power factor reference, the **regulator will begin** to function.
- The network breaker will **be closed once the** synchronous condenser and the network are in synchronization.
- The SC is operational online as presented in Fig.1.
- The pony motor will be de-energised and run idle with the SC upon successful synchronization.
- **STATCOMs and Static VAR Compensators (SVC):** it is a devices that works based on power electronics that regulate reactive power dynamically[4].
- Common reactive power compensators are presented in Fig.2

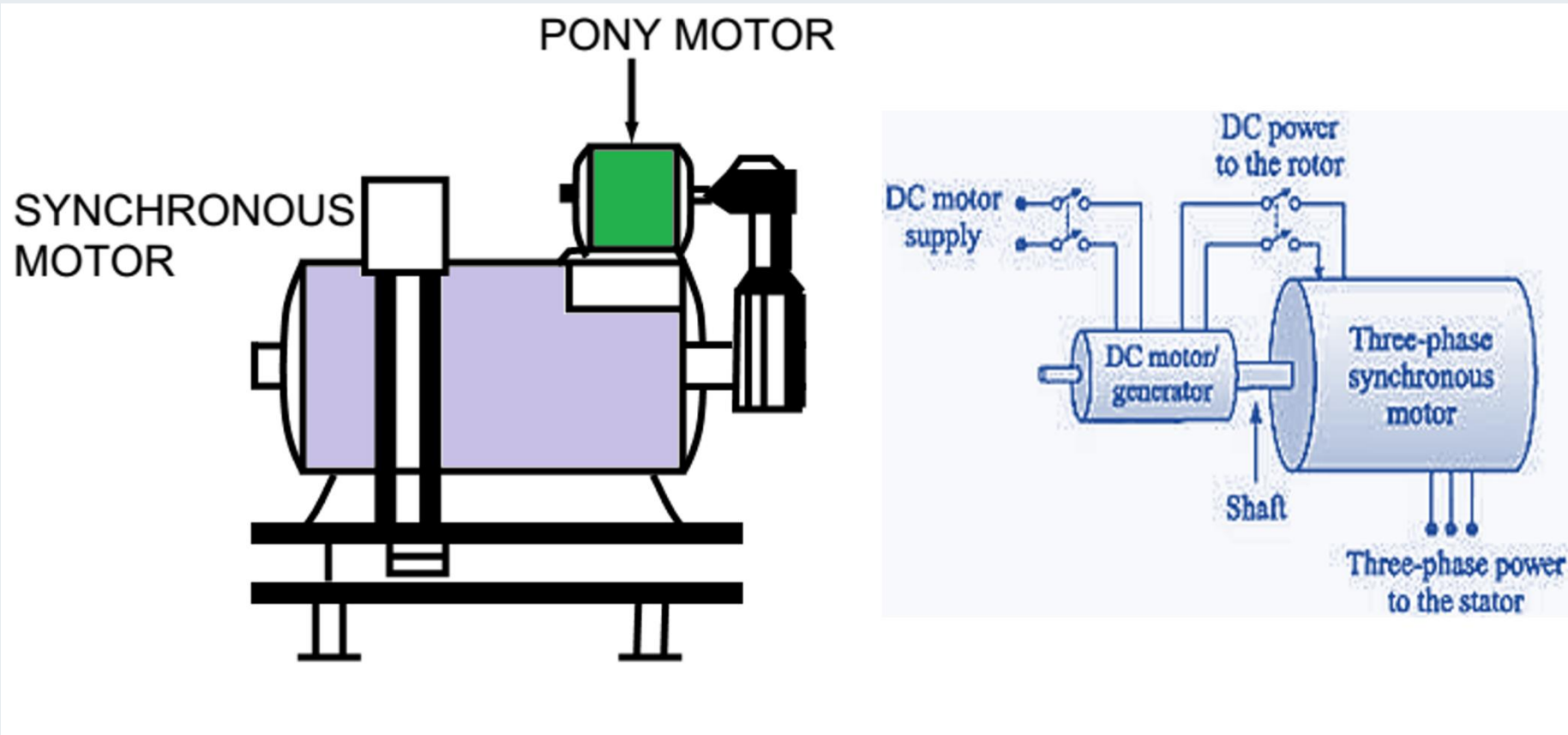


Figure 1. Synchronous Condensers Operating Principle.

Url: <https://www.electricaldesks.com/2023/01/starting-methods-of-synchronous-motor.html>

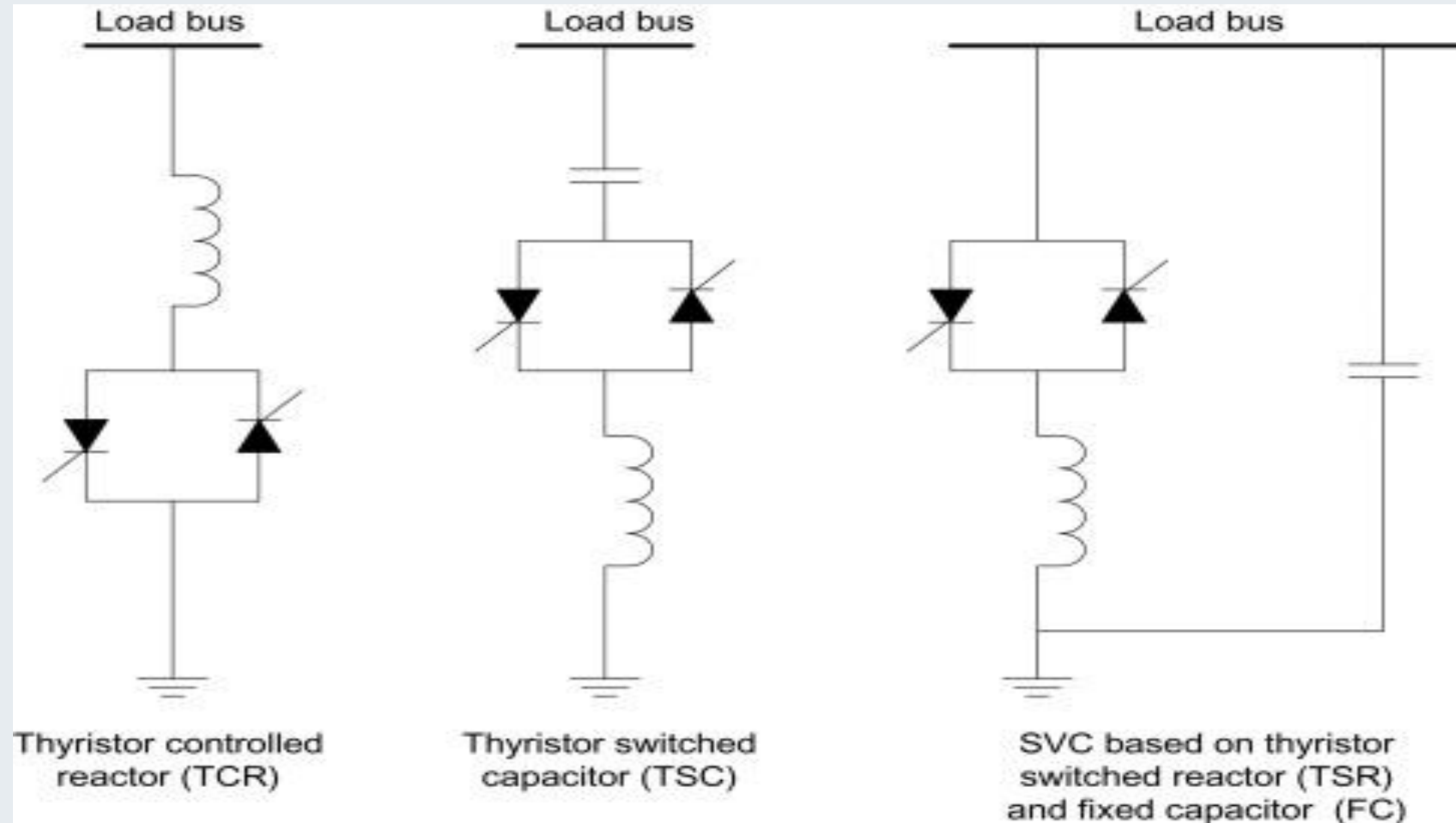


Figure 2. Three different types of Reactive power compensators.

Url: <https://ars.els-cdn.com/content/image/3-s2.0-B9780081025925000090-f09-43-9780081025925.jpg>

ii. Tap-Changing Transformers:

- Modifies the transformer's turn ratio based on eqn.1 as given in Fig.3:

$$\frac{N_1}{N_2} = \frac{V_1}{V_2} \quad \text{eqn.(1)}$$

- On-Load Tap-Changing Transformers (OLTCs) control voltage at the secondary (load) side.
- It's commonly used for both the transmission and distribution system.

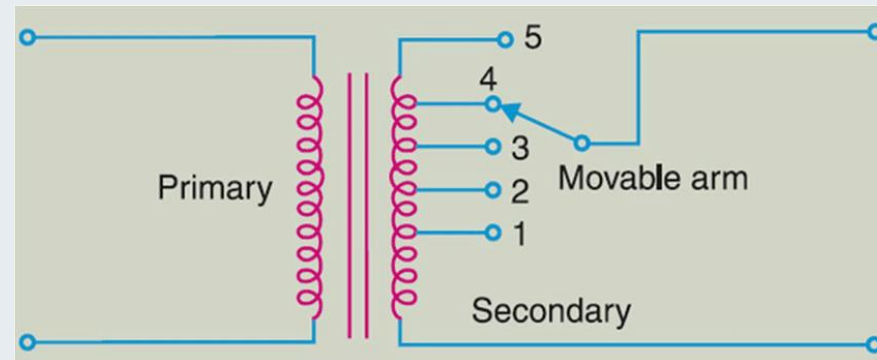


Figure 3. Transformer Tap-changing control

Url: <https://www.researchgate.net/publication/325947632/figure/fig1/AS:640662626107392@1529757281303/Tap-changer-with-tapings-on-secondary-side.png>

iii. Automatic voltage regulator(AVR) or Generator voltage control:

- **If a generator is near the** load bus: generators' Automatic Voltage Regulators (AVRs) can be changed to affect the voltage of nearby buses.
- Reactive power can be added to the grid by generators.
- However, the regulator can be manual or automatic as presented as presented in Fig.4

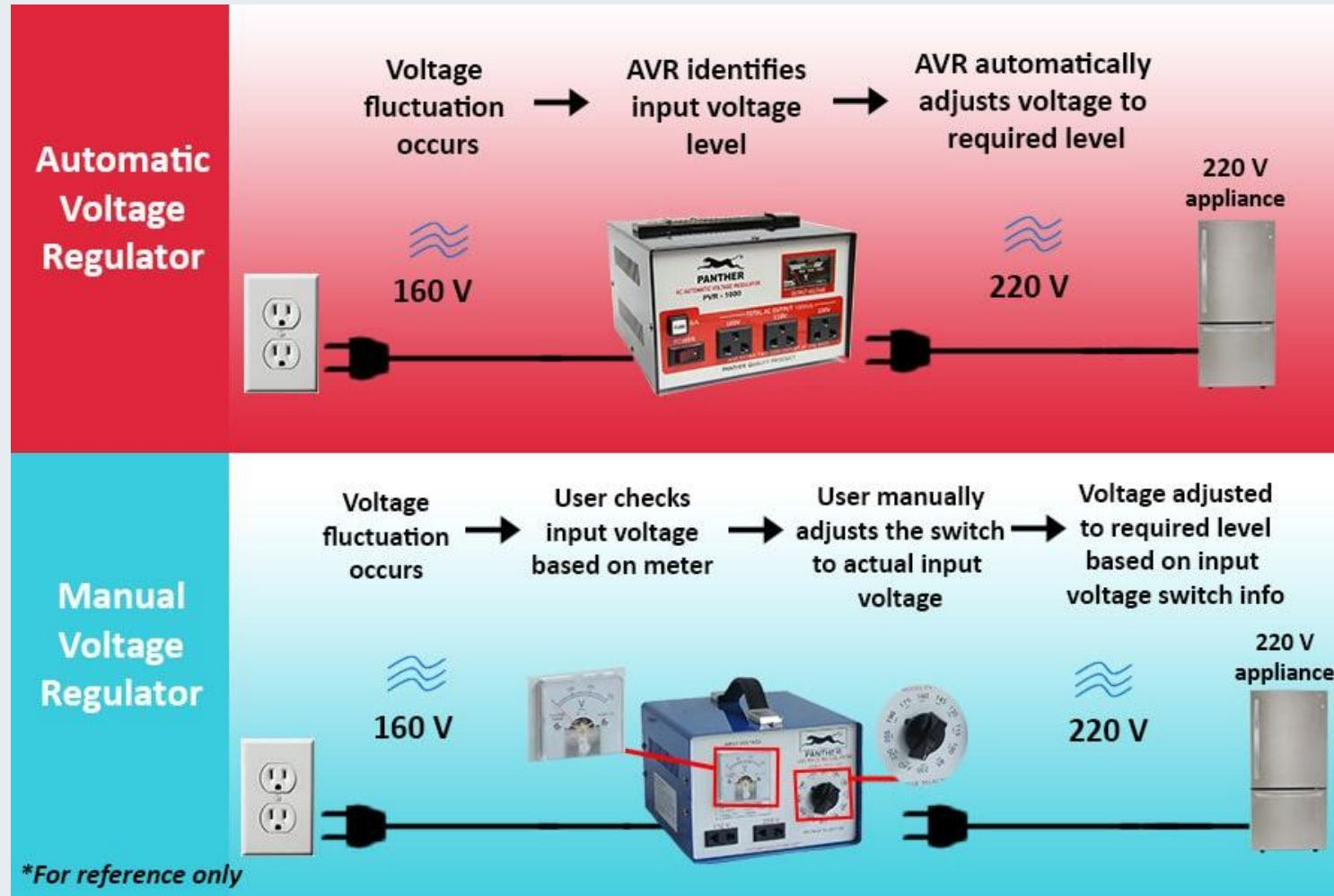


Figure 4 . Automatic voltage regulator (AVR)

Url: <https://panther.ph/wp-content/uploads/2020/06/Visual-Graphic-of-AVR-vs-Manual-min.jpg>

iv. Shifting or Load Shedding

- If an overload is causing the voltage to drop:
- Remove non-essential loads.
- Transfer loads to off-peak times.

v. Automation of Distribution and Smart Grid Management

- Utilize control algorithms, communication networks, and sensors to: Track voltage in real time
- Automate reactive power device switching
- Modify the output of distributed generation such as solar inverters controlled by

Volt-VAR

- Generally, the voltage of load is controlled using the formula presented in eqn.2 for all cases

$$V = V_s - jQX / V \quad \text{eqn.(2)}$$

- Where, V is the load bus voltage, Vs is the sending bus voltage, Q is reactive power demand at the bus,

X is the line reactance

- Accordingly increasing Q (load) drops voltage, and supplying Q (compensation) raises voltage.

2. PV or Voltage controlled bus/ generator bus[5]:

- A voltage controlled bus is any bus in the system where the voltage magnitude **can be controlled**.
- At each bus to which there is an alternator connected, the MW generation can be controlled by **adjusting the prime mover as presented in Fig.5**.
- Means, the phase angle of the rotor is directly related to the real power generated by the machine.
- The voltage magnitude can be controlled by adjusting generator excitation.

- The real power(P) and Voltage (V) are known, whereas, the voltage phase angle and reactive power (Q) are needs to be determined.
- The limits on the value of the reactive power are also specified.

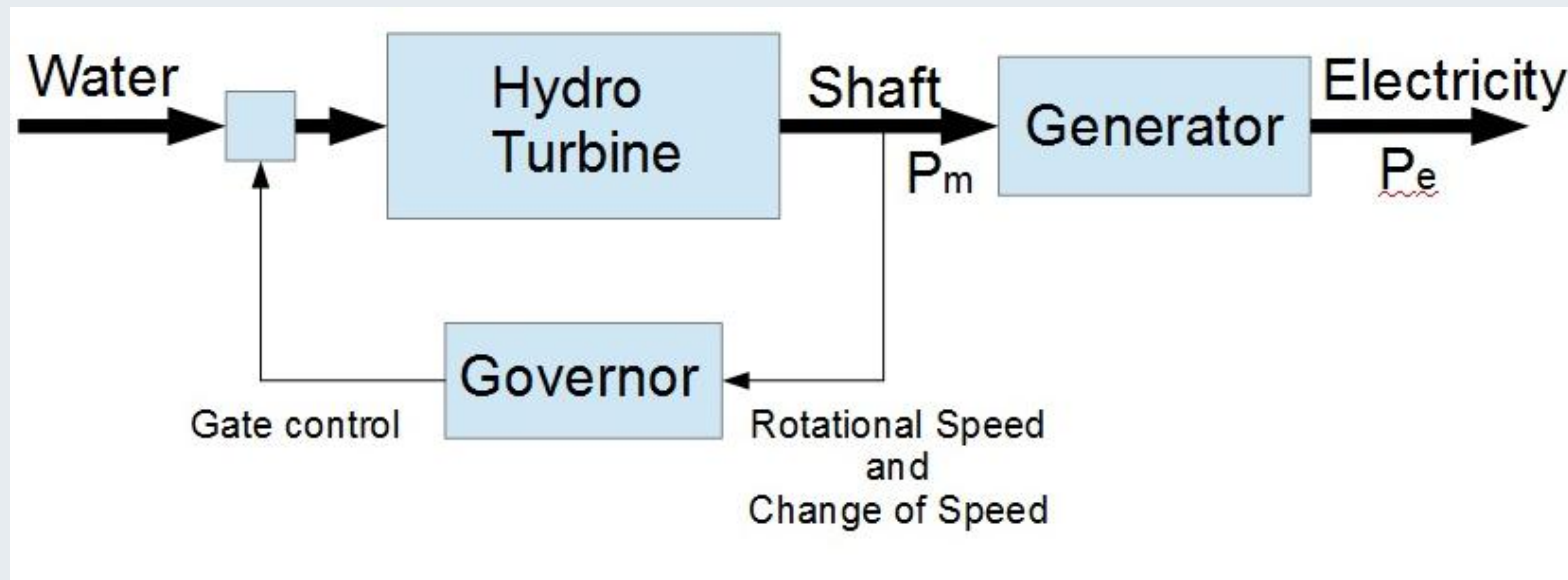


Figure 5. The MW control Adjusting Prim mover.

<https://www.kiwithinker.com/wp-content/uploads/2017/06/Simple-Governor-2.jpg>

3. Slack/ Swing bus:

- The place where total energy balance or power mismatch is determined.
- In a power flow study, the Slack Bus, also known as the Swing Bus, serves as a reference bus.
- After all other buses have been calculated, it supplies or absorbs the remaining power, particularly real and reactive power, to balance the system.
- Its voltage magnitude and angle are specified, usually $V=1.0$ p.u, $\delta=0^\circ$
- It absorbs system losses.

- Slack bus is normally needed to maintain the energy or power flow conservation as given by:

$$\sum_{i=1}^n P_{Gi} = \sum_{j=1}^n P_{Dj} + P_{Loss}$$

eqn.(3)

- However, the loss is not known prior to power flow and needs to select the reference bus.
- Accordingly, one generator bus should be selected as the slack bus, which determines the total power flow mismatches(Real and reactive power flow)

- In reality a physical bus that is **always slack does** not exist.
- For simulation purposes, the slack can be any generator (or a collection of generators).
- **Participation factors or distributed** slack buses are employed in multi-area systems.
- **Limitation:** It could become impractical if the slack bus ends up providing too much power as a result of high losses or excessive demands
- Thus, it requires caution in large or complicated systems; numerous swing buses or dispersed slack may be required.

- Generally, the slack bus **is not considered in power flow** iterative solutions in the same way as PQ and PV buses.
- After finding out the parameters for other bus, the slack bus's real and reactive power are determined as outputs
- In summary, slack bus maintains the balance of reactive and actual power.
- Essential for resolving power flow problems.
- This depicts the generator or generators that manage imbalances in the system.

3. Power Flow Equation Formulation (PFEF)

- The relationship between bus current and voltage in the linear network can be defined by the following node eqns.[6].

$$I = Y * V \quad \text{eqn.(4)}$$

Thus,

$$I_i = \sum_{j=1}^n Y_{i,j} V_j, \quad i = 1, 2, 3, \dots, N \quad \text{eqn.(5)}$$

- Where, I_i and V_j are the injected current at bus i and voltage at bus j , respectively.
- Not that the power system parameters(voltage at sending and receiving end, impedance between the sending and receiving end bus are given in polar form as given by:

$$\begin{aligned} V_i &= V_i e^{j\delta_i} \\ V_j &= V_j e^{j\delta_j} \\ Y_{ij} &= Y_{ij} e^{j\theta_{ij}} \end{aligned} \quad \text{eqn.(6)}$$

- Then, the voltage at a typical bus 'i' of the system and at any bus 'j' and impedance between bus 'i' and j in polar coordinates are given by:

$$\begin{aligned} V_i &= V_i \angle \delta_i \\ &= V_i [\cos \delta_i + j \sin \delta_i] \end{aligned} \quad \text{eqn.(7)}$$

$$\begin{aligned} V_j &= V_j \angle \delta_j \\ &= V_j [\cos \delta_j + j \sin \delta_j] \end{aligned} \quad \text{eqn.(8)}$$

$$\begin{aligned} Y_{i,j} &= Y_{i,j} \angle \phi_{i,j} \\ &= Y_{i,j} [\cos \phi_{i,j} + j \sin \phi_{i,j}] \end{aligned} \quad \text{eqn.(9)}$$

PFEF

Cont....

- Generally, the complex power injected by the source into bus 'j' is given by:

$$S_i = V_i I_i^* \quad \text{eqn.(10)}$$

Where, i is the network bus equivalent to $i = 1, 2, \dots, n$ bus.

- Substituting eqn.(5) instead of the current at i^{th} bus, I_i in eqn.(10) gives;

$$\begin{aligned} S_i &= V_i I_i^* \\ &= V_i * \left(\sum_{j=1}^n Y_{i,j} * V_j \right), \quad j = 1, 2, \dots, n \end{aligned} \quad \text{eqn.(11)}$$

- The complex power at any bus 'i' is also given by:

$$S_i = P_i + jQ_i \quad \text{eqn.(12)}$$

- Which implies that the complex power is equivalent to:

$$\begin{aligned} P_i + jQ_i &= V_i I_i^* \\ \Leftrightarrow P_i - jQ_i &= V_i^* I_i \end{aligned} \quad \text{eqn.(13)}$$

PFEF

Cont....

- Relating eqn.(11) and eqn.(13) gives:

$$P_i - jQ = V_i^* I_i$$

eqn.(14)

$$\Rightarrow P_i - jQ = V_i^* \left(\sum_{i=1}^n Y_{i,j} * V_j \right), \quad j = 1, 2, \dots, n$$

- Then, using the polar coordinate of each parameter gives:

$$P_i - jQ = |V_i| [\cos \delta_i + j \sin \delta_i]^* \left(\sum_{i=1}^n |Y_{i,j}| [\cos \phi_{i,j} + j \sin \phi_{i,j}] * |V_j| [\cos \delta_j + j \sin \delta_j] \right), \quad j = 1, 2, \dots, n$$

eqn.(15)

Separating real and imaginary part gives:

$$P_i = |V_i| \left(\sum_{i=1}^n |Y_{i,j}| * |V_j| [\cos(\delta_i + \delta_j + \phi_{i,j})] \right), \quad j = 1, 2, \dots, n$$

eqn.(16)

$$Q_i = |V_i| \left(\sum_{i=1}^n |Y_{i,j}| * |V_j| [\sin(\phi_{i,j} + \delta_j - \delta_i)] \right), \quad j = 1, 2, \dots, n$$

- Eqn.16, reveals the polar form of the load **flow equations or static load flow equations**.
- They are usually expressed in the following forms as mathematical models of the load flow problem.

$$\Delta P_i = P_{i,sch} - P_{i,cal} = (P_{Gi} - P_{Di}) - P_{i,cal} \quad \text{eqn.(17)}$$

$$\Delta Q_i = Q_{i,sch} - Q_{i,cal} = (Q_{Gi} - Q_{Di}) - Q_{i,cal}$$

- But during operating condition all the power system variables are not kept constant at rated values and iterative solution is needed

PFEF

Cont....

- In case of iterative techniques, the solution is obtained in an orderly fashion starting from its **initial approximate** solution based on initial guess.
- **The number of steps needed to obtain** real solution depends on the *initial guess's* , *problem size and the iterative technique* used.
- Thus, based on the named constraints, the approximate solution may **converge, diverge or oscillate**.
- The round-off error in this case goes on getting corrected in each step.

PFEF

Cont....

Commonly used iterative load flow techniques are;

- Gauss–Seidel Load Flow Method
- Newton–Raphson Load Flow Method
- Fast decoupled Load Flow Method

Example: Three bus System Power Network Power Flow

Example: For the data given in Fig.6, find the power flow results, real and reactive power at bus 2 and 3 during operating condition. Assume bus 1 is slack bus, whereas, bus 2 and 3 are the load buses.

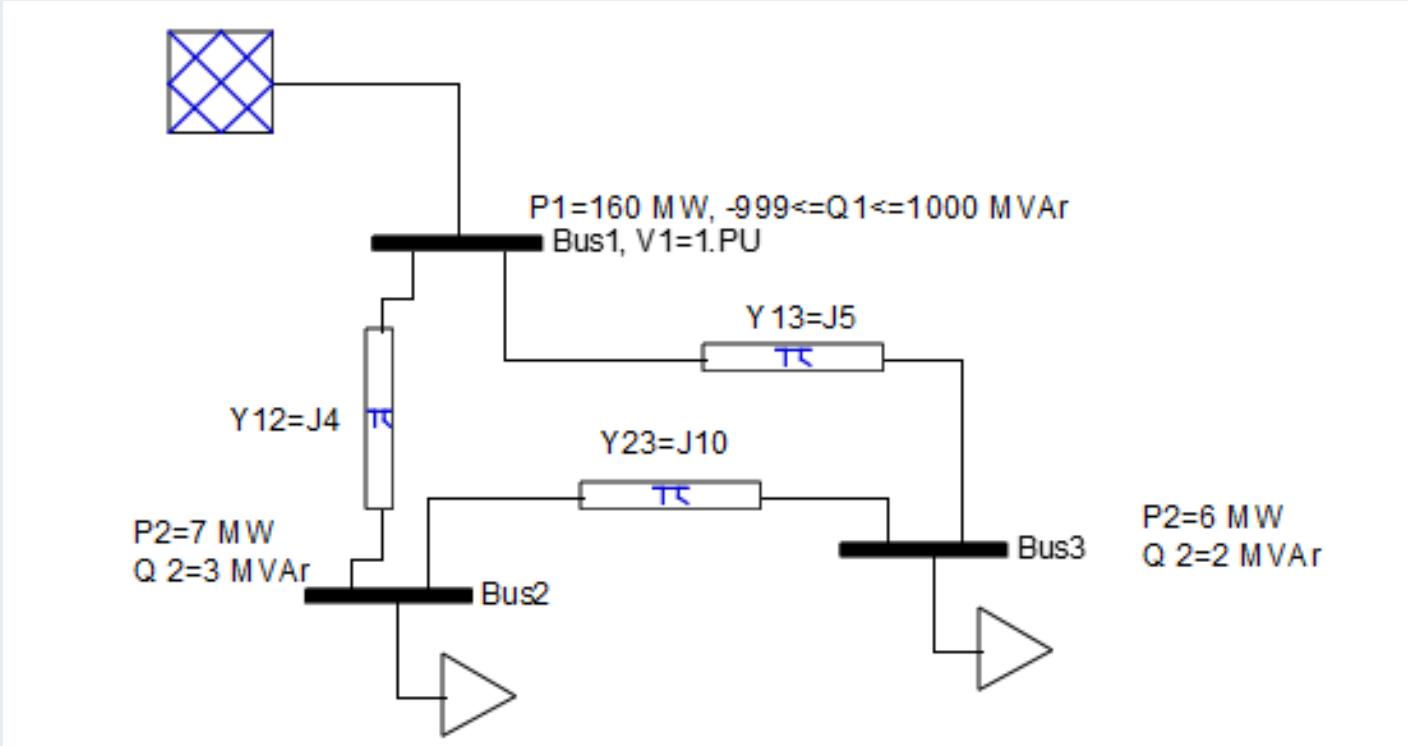


Figure 6. Three bus system power network data

Example

Cont.....

Solution:

- Step 1: determine the Y-bus matrix. $Y=3*3$ matrix

$$Y = \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} \\ Y_{21} & Y_{22} & Y_{23} \\ Y_{31} & Y_{32} & Y_{33} \end{bmatrix}$$

- The solution for diagonal elements and off diagonal elements are:

$$\begin{aligned} Y_{11} &= Y_{12} + Y_{13} = j5 + j4 \\ &= j9 \end{aligned}$$

$$\begin{aligned} Y_{22} &= Y_{21} + Y_{23} = j4 + j10 \\ &= j14 \end{aligned}$$

$$\begin{aligned} Y_{33} &= Y_{31} + Y_{32} = j10 + j5 \\ &= j15 \end{aligned}$$

$$Y_{12} = Y_{21} = -j4$$

$$Y_{13} = Y_{31} = -j5$$

$$Y_{23} = Y_{32} = -j10$$

Example

Cont.....

- Based on equation 16, the power flow equation at bus-2 and 3 are given by:

$$P_2 = |V_2| \left(\sum_{i=1}^n |Y_{2,i}| * |V_i| [\cos(\delta_2 + \delta_i + \phi_{i,2})] \right)$$

$$Q_2 = |V_2| \left(\sum_{i=1}^n |Y_{2,i}| * |V_i| [\sin(\phi_{i,2} + \delta_i - \delta_2)] \right)$$

- Assume the voltage and its angle at load buses are 1p.u and 0 degree for each. Then, the real and reactive power at bus two is calculated as

$$\begin{aligned} P_2 &= |V_2| \left(\sum_{i=1}^n |Y_{2,i}| * |V_i| [\cos(\delta_2 + \delta_i + \phi_{i,2})] \right) \\ &= 1 * [((4 * 1) \cos(0 - 90)) + ((10 * 1) \cos(60 - 90))] \\ &= 8.66 MW \end{aligned}$$

$$\begin{aligned} Q_2 &= |V_2| \left(\sum_{i=1}^n |Y_{2,i}| * |V_i| [\sin(\phi_{i,2} + \delta_i - \delta_2)] \right) \\ &= 1 * [((4 * 1) \sin(-120)) + ((10 * 1) \sin(-90))] \\ &= -13.46 MVA \end{aligned}$$

Example

Cont.....

- For bus 3, it's given as:

$$\begin{aligned} P_3 &= |V_3| \left(\sum_{i=1}^n |Y_{3,i}| * |V_i| [\cos(\delta_3 + \delta_i + \phi_{i,3})] \right) \\ &= 1 * [((5 * 1) \cos(0 - 90)) + ((10 * 1) \cos(30 - 90))] \\ &= 5MW \end{aligned}$$

$$\begin{aligned} Q_3 &= |V_3| \left(\sum_{i=1}^n |Y_{3,i}| * |V_i| [\sin(\phi_{i,3} + \delta_i - \delta_3)] \right) \\ &= 1 * [((5 * 1) \sin(-120)) + ((10 * 1) \sin(-90))] \\ &= -14.46MVA_r \end{aligned}$$

- Then, the real and reactive power during operation is given by

$$\Delta P_i = P_{ischd} - P_{ical}$$

$$\Delta P_2 = 9MW - 8.66MW$$

$$= 0.34MW$$

$$\Delta P_3 = 6MW - 5MW$$

$$= 1MW$$

and

$$\Delta Q_i = Q_{ischd} - Q_{ical}$$

$$\Delta Q_2 = 3MVA_r - (-13.436MVA_r)$$

$$= 16.436MVA_r$$

$$\Delta Q_3 = 2MVA_r - 14.46MVA_r$$

$$= 16.46MVA_r$$

Summary

- In this lecture, one of the important parameters for power flow analysis called power network bus type is discussed
- The three types of buses namely swing bus, generator bus and load bus based on the known and unknown parameters
- The load bus is known as uncontrolled bus , whereas, the generator buses are called voltage controlled bus
- The place where total power mismatch takes place is called swing/slack bus
- The voltage of load bus is controlled using compensators

References

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Thank you !