

Advanced Power System Analysis

Lecture 3

Load Flow studies

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Lecture learning outcomes:

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

- i. Understand the Basics of Load Flow Analysis
- ii. Know the Importance of Power Flow Analysis
- iii. Model Power System Network for Load Flow Studies
- iv. Demonstrate how to formulate the Y-bus Admittance Matrix

Outlines

1. Introduction
2. Objectives of Power Flow Analysis(OPFA
3. Power System Network Model
4. Bus Admittance Matrix Formulation

Summary

References

1. Introduction

- Power system analysis is very important for the development of any country.
- Thus, knowing the operating characteristic of power system is crucial for the sustainable development goals of any country.
- **Power network has the following characteristics:**
 - It can be easily converted to electric energy from other different energy resources and hence it can be also converted to other forms of energy.
 - **It can be transmitted and distributed over large** area and long distance: **Comprising** the generation units, transformers, high voltage substations, transmission lines, medium and low voltage substations , and loads

Introduction

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- Energy **should be optimized**, because it can be generated in large quantities at one location and distributed to sites where the energy is needed.
- Accordingly, the load flow analysis is **a very important** and fundamental tool in power system analysis.
- Its results play the major role to operators in terms of controlling the system and economic schedule, as well as during the **expansion and design stages**.
- Accordingly, the purpose of any load flow analysis is to compute precise steady-state voltages and voltage angles of all buses in the network[1].
- Then, to determining the lines real and reactive power flow and the total power mismatch at generation units.

- It helps to observe **whether the lines and transformers** are loaded or not, which is very important for reliable, efficient and affordable power supply.
- The **load flow solution also** gives the base conditions of the system elements when the transient or fault response behavior of the system is to be studied.
- Generally, the power flow analysis gives the actual operating condition of the network components like generation , transmission system, transformers and loads operations
- This can be achieved in online system by carrying numerous load flow solution techniques under a variety of conditions.

Introduction

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- Accordingly, the power flow also known as “Load Flow” solution is used for:
- Planning, operating and controlling the system
- The expansion of existing systems
- Knowing the effect of interconnection, adding new loads, new generation, lines, used to select size and location of VAR equipment's
- Generally, the load flow gives the real operating condition the network and planning future demands based on the steady-state load as presented in Fig.1

Introduction

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- Figure 1 shows the actual operating condition of the weekly load variations as per the customer requirements.

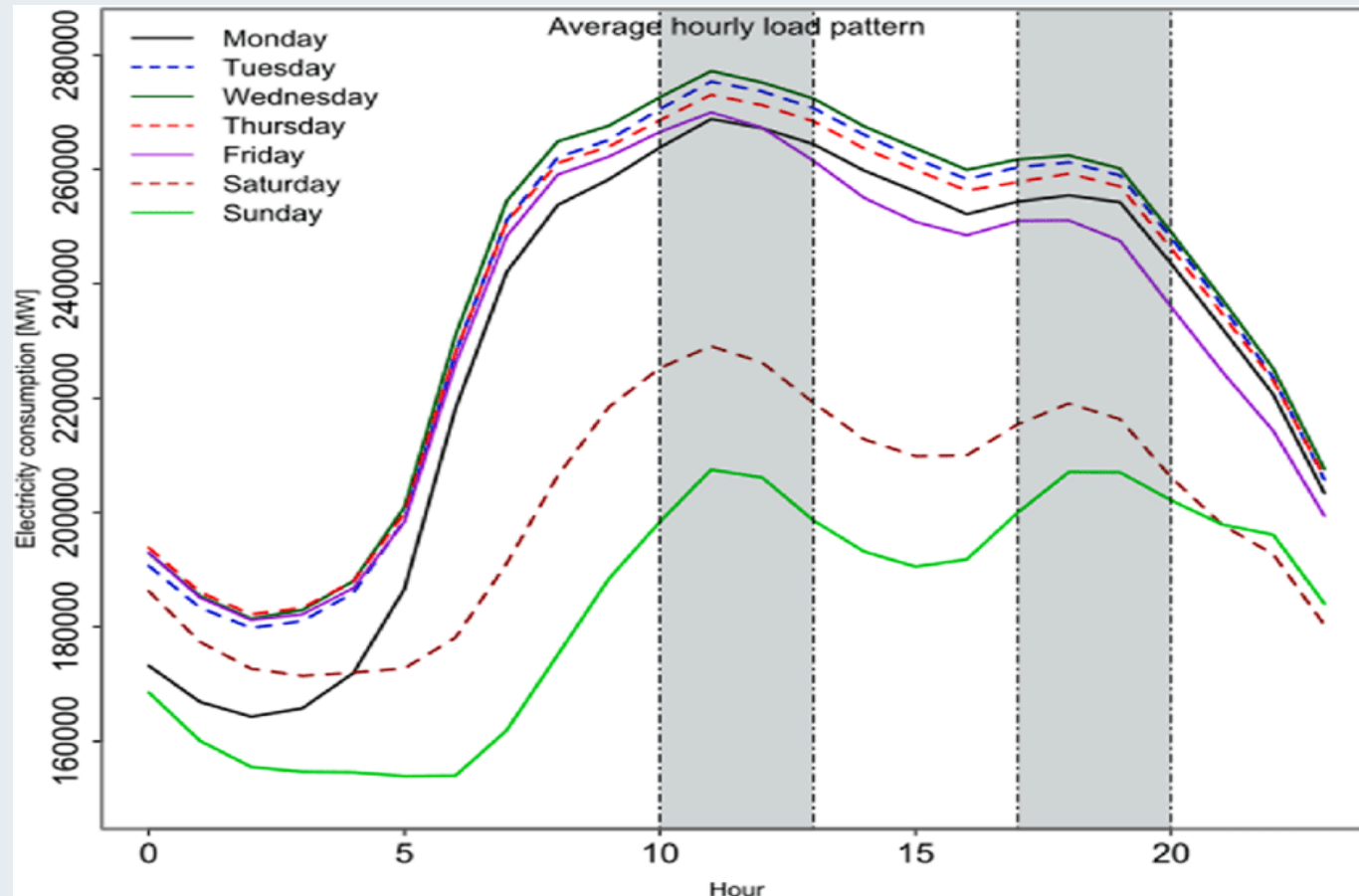


Figure 1. The average hourly load change through time.

https://www.researchgate.net/figure/Day-of-the-week-and-hourly-pattern-of-electricity-demand-Notes-The-shaded-areas_fig2_347597852

2. Objectives of Power Flow Analysis(OPFA)

- To find out the voltage magnitude and its phase angle at each bus
- To determine the active and reactive power flow in each line
- Thus, each bus has four state variables[2]:
 - voltage magnitude
 - voltage phase angle
 - real power injection
 - reactive power injection
- In order to perform the analysis, two parameters out of four state variables should be defined or given

OPFA

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- **For the successful operation of static power flow analysis ;**
 - Generation must supplies demand (load) and loss.
 - Node voltage magnitudes must be remain close to rated values.
 - Generator must operates within specified real and reactive power limits.
 - lines and transformers should not be overloaded
 - Finally, **to apply power flow analysis the** knowledge(Modeling) of power network, admittance matrix formulation and understanding the types of network buses are very important.

3. Power System Network Model(PSNM)

- Power flow analysis begins with understanding of power network structures.
- The network modeling for power flow analysis includes **creating a mathematical representation of a** network to analyze and simulate the load flow under numerous conditions.
- **These helps in determining the network bus** voltage magnitudes, phase angles, and power flows

Common components of Power System Network Modeling are[3] :

- Generator modeling
- Buses: represents modeling of the points where the electrical components like generators, loads, and transformers are connected.
- Transmission Lines: Represent the network of power transmission.

1. Generator Modeling:

- A crucial component for simulating and examining the behavior of power networks is **generator** modeling for power system analysis.
- The kind of **generator and the degree of information needed for the** investigation determine the modeling strategy.
- The following categories of generator models are frequently used in power system analysis:

1.1 Synchronous Generator model:

- Power systems frequently use synchronous generators, which are commonly represented as follows:

- i. **Constant Power Simple Output Model:** A generator can be thought of a **continuous power source**, with a fixed output power and **variable reactive power or voltage source** behind **synchronous reactance** based on the state of the system.
 - This model is frequently employed **in load flow analysis** or for simple power flow investigations where steady-state operation is the main emphasis.
- ii. **Detailed Model :** The excitation system, turbine-governor dynamics, and the generator's voltage regulation like AVR, dynamics are all included thorough models.
 - Dynamic **simulations and transient stability** require these models.

iii. The Swing Equation

- The rotor dynamics of a synchronous machine are described by eqn.(1).
- It is commonly applied in research of transient stability and symbolizes the balance between electrical and mechanical power as presented in eqn.(1):

$$\frac{\partial^2 \delta}{\partial t^2} = \frac{P_m - P_e}{M} \quad \text{eqn.(1)}$$

- Where, P_m is the input power or mechanical power, P_e is the output electrical power, M is the machine's inertia constant and δ is the angle of the rotor.

1.2 Induction Generator Model

- Typically, induction generators are found in industrial settings or in wind turbines.
- Since these generators are asynchronous devices, modeling them is easier.
- Usually, the slip or the difference between synchronous and rotor speeds controls their behavior.
- Equation (2) for power balance and rotor dynamics forms the foundation of the basic model.

$$P_e = \frac{V^2}{X_s} \text{Sin}(\delta)$$

eqn.(2)

1.3 Excitation System Modeling of Generators[4]:

- Excitation system **modifies the field current**, which regulates the rotor's magnetic field and, ultimately, the generator's voltage output.

Excitation system models includes:

- The simplified voltage control model modifies the field current through a feedback loop
- The detailed excitation system model contains dynamic equations for the stabilizer, exciter, AVR, and other parts as presented in Fig.2.

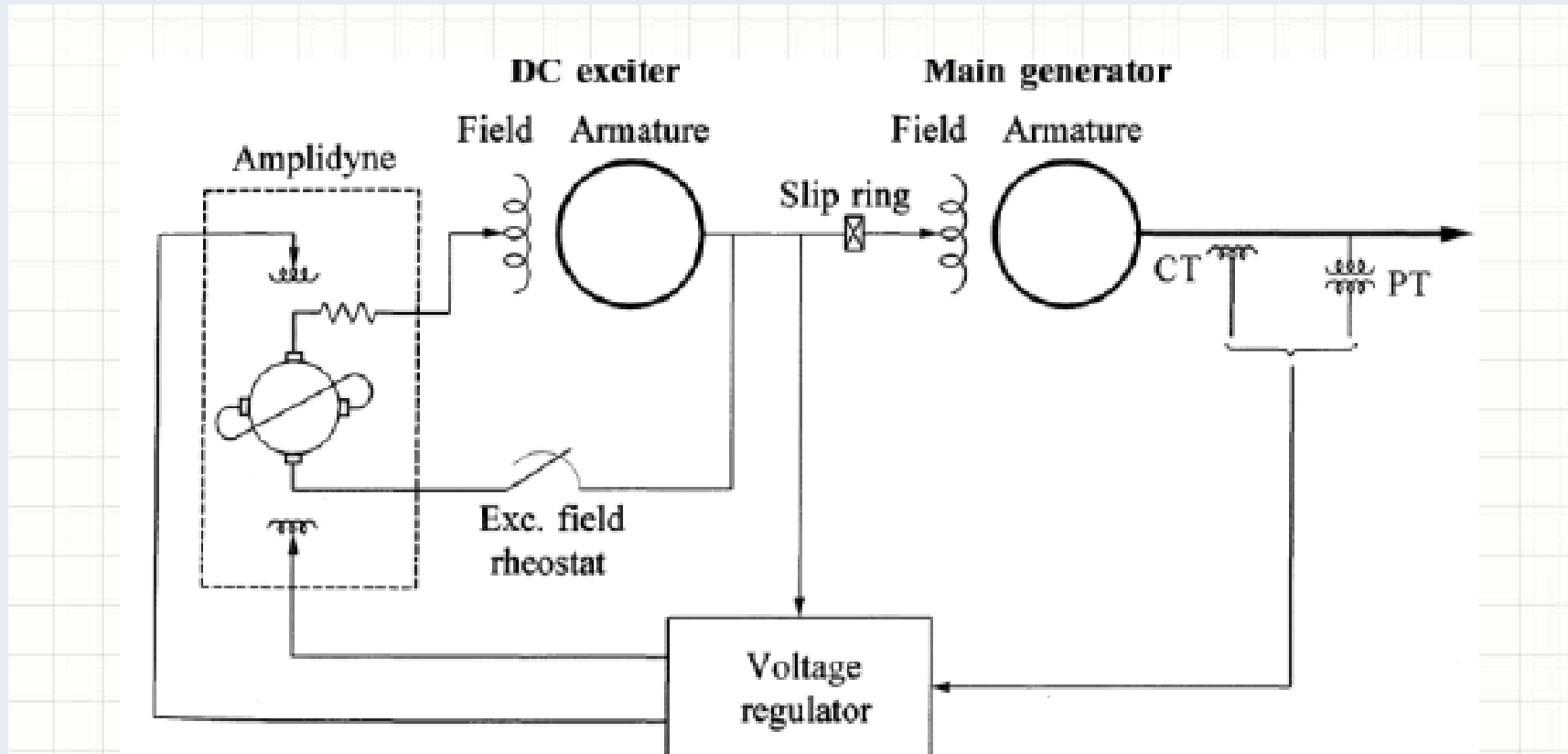


Figure 2. Generator excitation system model.

Url: <https://eepowerschool.com/wp-content/uploads/2018/06/DC-excitation-system-with-amplidyne-voltage-regulators.png>

1.4 Power System Stabilizer Model(PSSs)[5]:

- In **order to increase system stability**, PSSs are frequently incorporated into generator models.
- They provide damping by adjusting the generator's excitation system, which **suppresses** oscillations in the power system.
- For dynamic stability analysis, PSS models and generator models are typically used together.
- Figure 3 presents the power system stabilizer connection

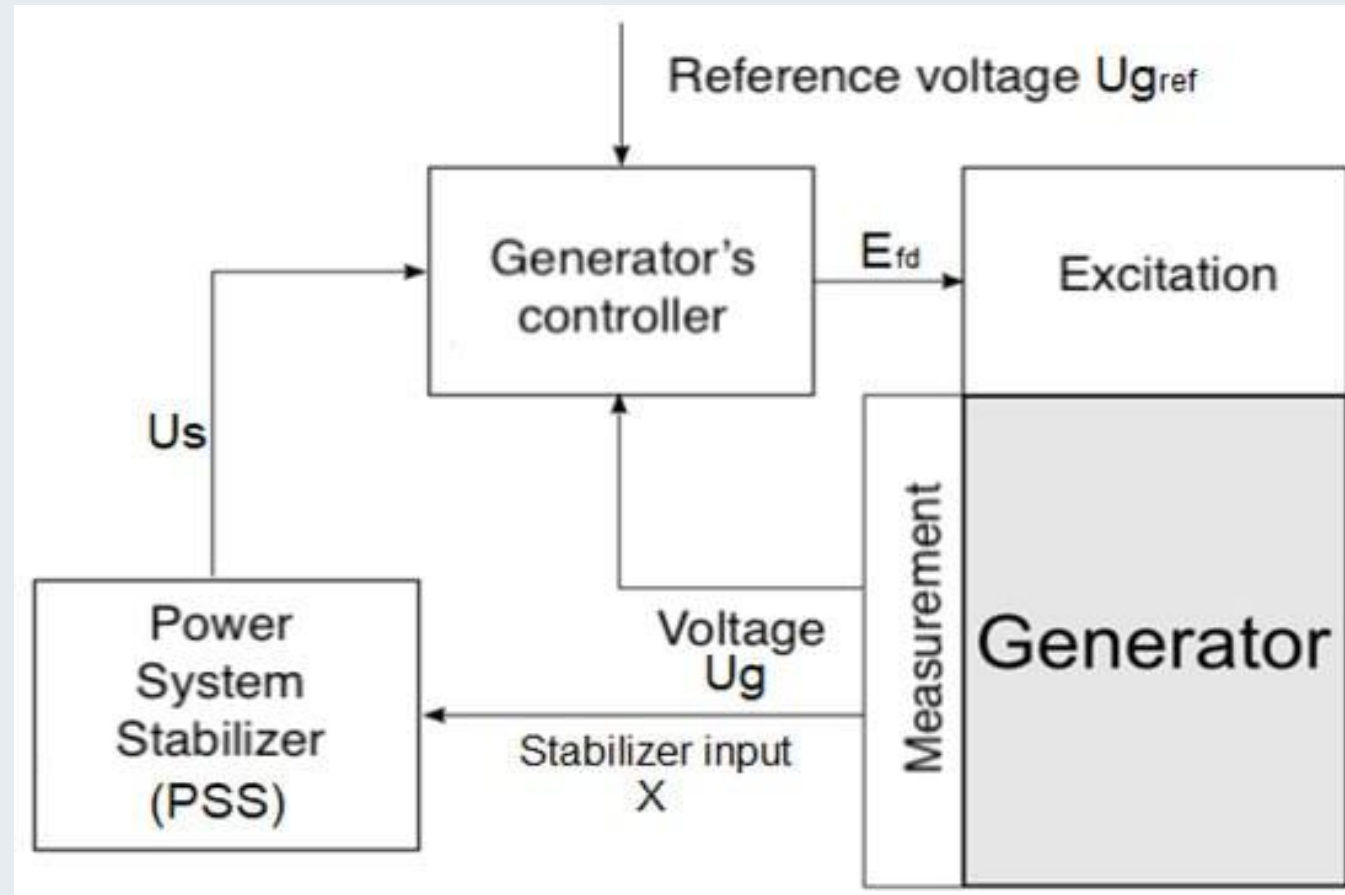


Figure 3. Power system Stabilizer block diagram.

https://pub.mdpi-res.com/energies/energies-14-06631/article_deploy/html/images/energies-14-06631-g001-550.jpg?1634285799

1.5 Time Domain Simulations Model:

- Among the **extensive dynamic equations** used to simulate generators in time-domain simulations are the rotor dynamics, excitation system, turbine-governor dynamics, and load models.
- Fault analysis, post-fault recovery, and transient stability analysis all depend on these models.

1.6 Short Circuits Analysis Models: Summary of Circuits Models are essential for simulating how a generator would react to a malfunction.

- These studies use the machine's transient characteristics and reactance to simulate the behavior of generators.

1.7 Voltage and Frequency control model: Crucial to regulate the frequency and voltage of generators in a networked system.

- The governor dynamics manage the generator's speed and, in turn, frequency, while the AVR controls the voltage.
- Due to the numerous interactions between the electricity system and these two subsystems, accurate modeling is required for stability analysis.

2. Transmission lines model

- The transmission line is modeled with its series impedance (resistance and reactance) and may include shunt **admittance for more detailed long transmission line analysis.**

3. **Transformers:** Transformers are used for voltage regulation

- It is also important in the **power flow model, they** are typically represented by their impedance and transformation ratio.

4. **Loads:** Represent the demand for power, real and reactive power load.

- These are typically modeled as PQ bus where the real and reactive power is specified.
- There are **two types of load in** power system, frequency independent and frequency dependent loads.

- **Generally, for the power system analysis**, the knowledge of the **following four parameters** are very important.
- The network structure based on the detail model of each component
- Energy conservation principles
- Bus admittance matrix formulation based on the types of transmission line and
- The types of power network buses and their functions
- The five bus network structure with detail model of each component is presented in Fig.4

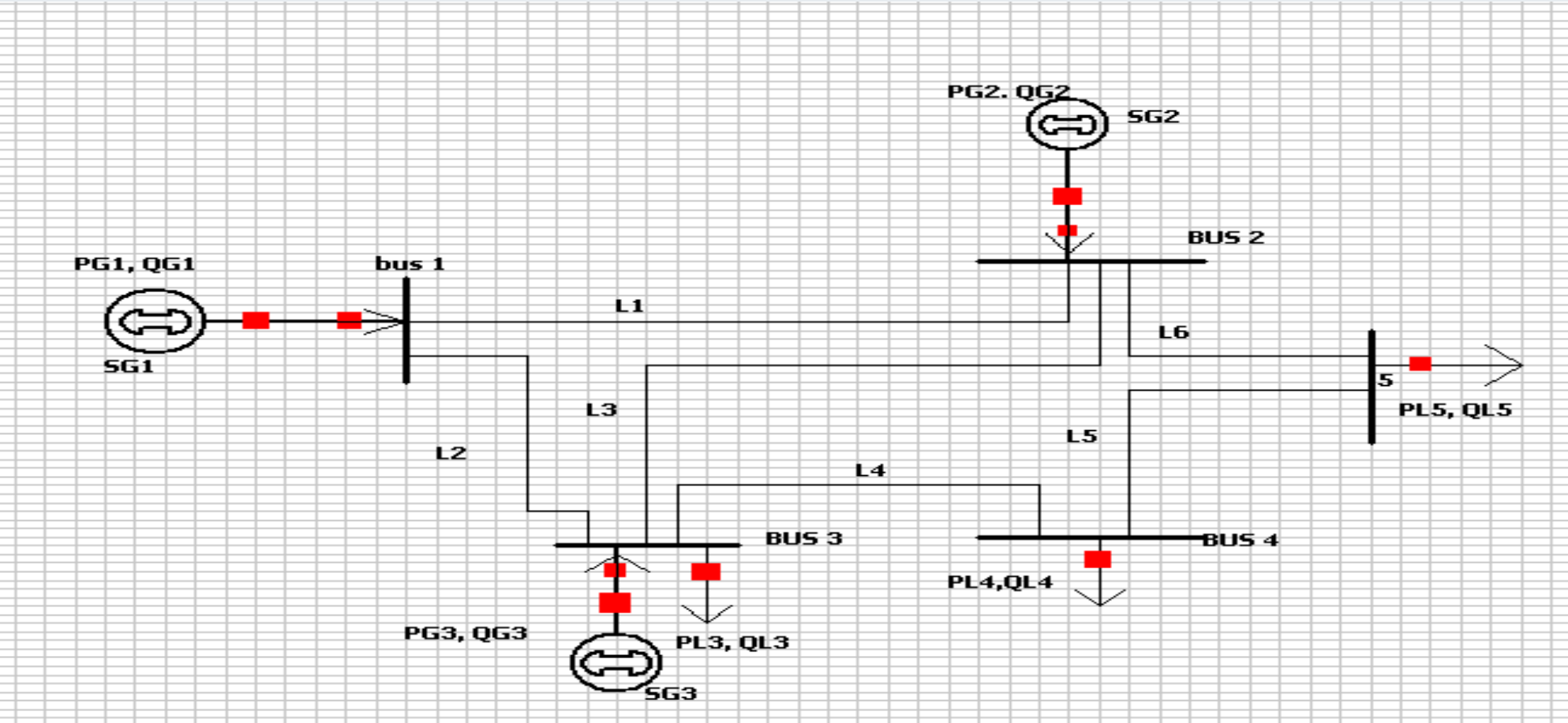


Figure 4. Five bus Power network single line diagram representation

PSNM

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- Figure 4 operates on the premise of energy conservation at all times.
- In power flow, energy conservation refers to the idea that, under ideal circumstances the amount of **energy entering a system** must equal the total amount of energy exiting the system, assuming no losses or outside energy sources.
- In electrical power systems, this idea is essential, especially when studying power flow analysis.
- The process of figuring out an electrical power system's steady-state operating conditions is known as power flow analysis, or load flow analysis

PSNM

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- It **entails** figuring out the power flows on transmission lines, the voltages at different buses (nodes), and the system's load and generation conditions.
- Since the power entering the system must balance the power generated and spent within the system, energy conservation is essential to this process.

Energy conservation comprises:

- Balance between Generation and Consumption: The total active power (real power) generated must match the sum of the active power losses in the system and the active power consumed by loads.

- Reactive **power generation also needs** to balance the reactive power that system supplies
- The power that performs **useful tasks**, such as heating, lighting, and mechanical labor, is known as active power (P).
- It needs to **be balanced throughout** the system. The system's stability will be impacted by any surplus or shortfall
- Reactive Power (Q): Reactive power is essential for sustaining system voltage levels and enables voltage regulation.

PSNM

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- It needs to be balanced, just like active power. Voltage instability can be brought on by inadequate reactive power.
- **Losses:** In actuality, resistance in transmission lines and other parts (such transformers and generators) causes losses.
- **Transmission Lines and Resistance to Motion:** Heat losses may result from the impedance introduced by transmission cables.
- With the belief that power loss is proportional to the square of the current (I^2R losses), power flow mode is account for these losses.

- Mathematical, the real ,reactive power and apparent power at each node, for instances at bus 'k' based on Fig.5 is given by:

$$S_{Gi} = V_i * I_i^*$$

$$P_K = \sum_{i=1}^n P_{ki} + P_L$$

$$Q_K = \sum_{i=1}^n Q_{ki} + Q_L$$

$$S_{G\min} \leq S_{Gi} \leq S_{G\max}$$

$$P_{G\min} \leq P_{Gi} \leq P_{G\max}$$

$$Q_{G\min} \leq Q_{Gi} \leq Q_{G\max}$$

eqn.(3)

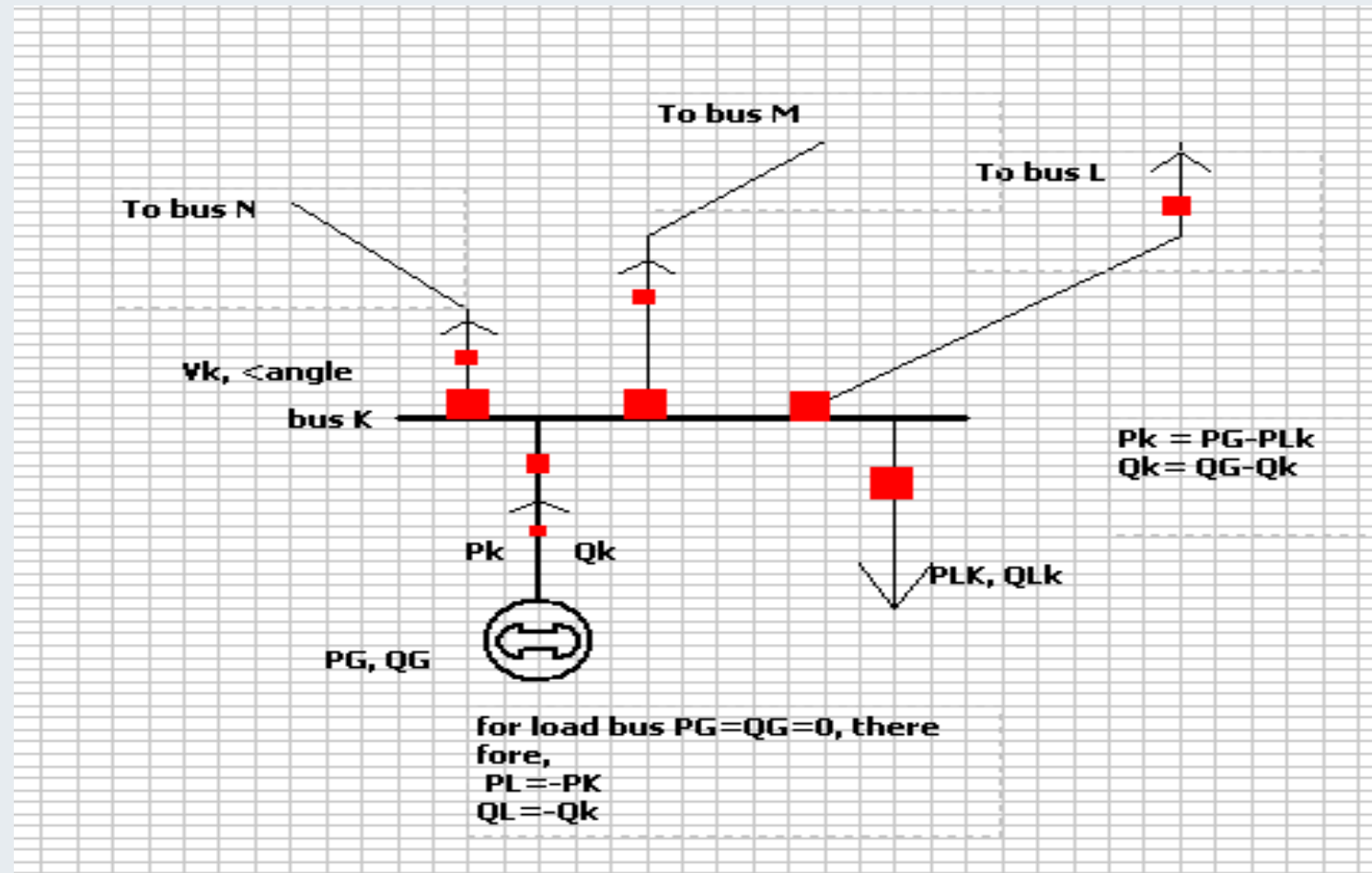


Figure 5. The power balance expression at bus 'k'.

4. Bus Admittance Matrix Formulation(BAMF)

- Formulation of bus admittance matrix is another important parameter needed to determined for power flow analysis.
- The power network should be represented in circuit form , for instances the four bus is given in Fig.6

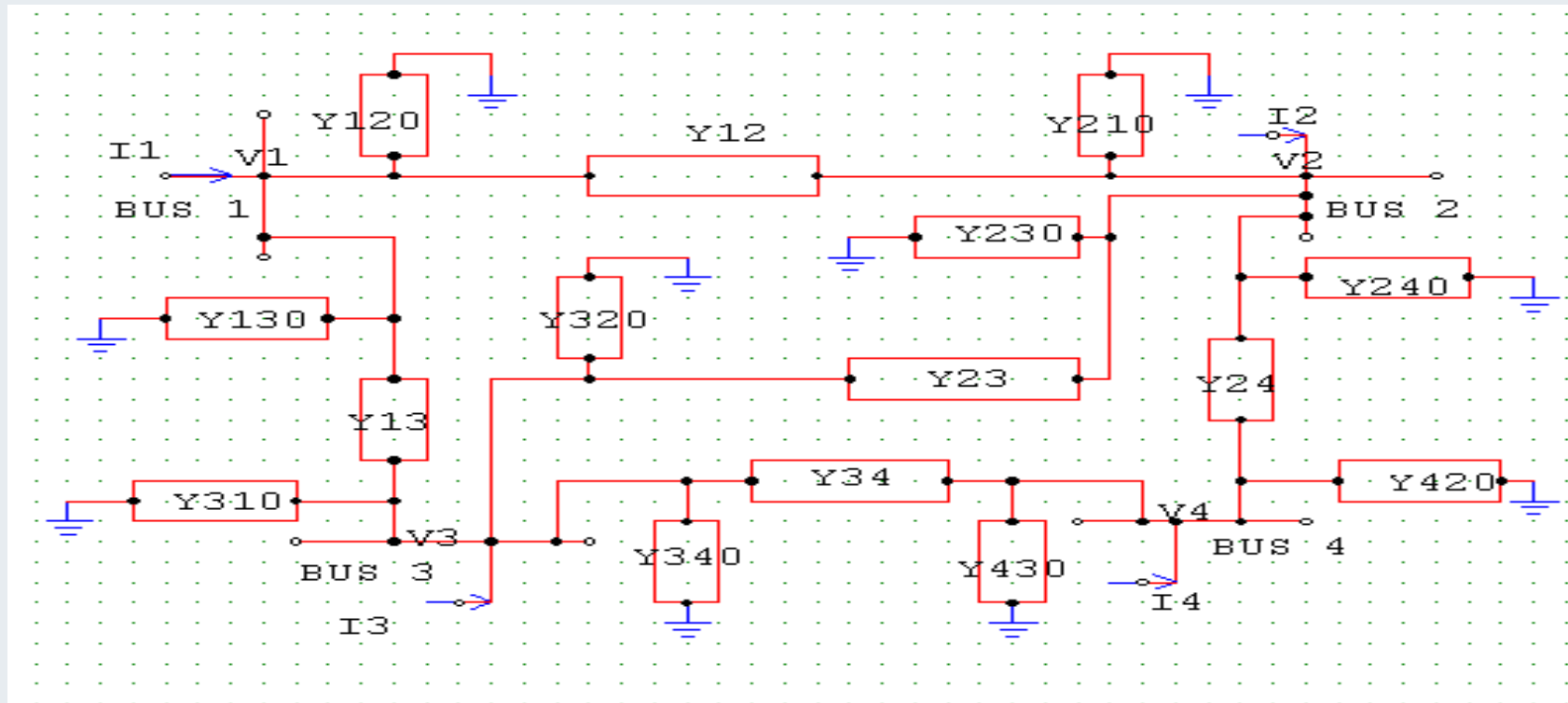


Figure 6. The π -model long transmission line representation of four bus system

BAMF

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- To find out the current 'I' flowing into bus i; apply KCL at each bus and currents are determined by:

$$I_1 = V_1 (Y_{120} + Y_{130} + Y_{12} + Y_{13}) - V_2 * Y_{12} - V_3 * Y_{13}$$

$$I_2 = V_2 (Y_{210} + Y_{230} + Y_{240} + Y_{12} + Y_{23} + Y_{24}) - V_1 * Y_{12} - V_3 * Y_{23} - V_4 * Y_{24}$$

eqn.(4)

$$I_3 = V_3 (Y_{310} + Y_{320} + Y_{340} + Y_{31} + Y_{23} + Y_{34}) - V_1 * Y_{13} - V_2 * Y_{23} - V_4 * Y_{34}$$

$$I_4 = V_4 (Y_{420} + Y_{430} + Y_{43} + Y_{42}) - V_3 * Y_{43} - V_2 * Y_{42}$$

BAMF

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- The current I in matrix form will be given as;

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

eqn.(5)

$$I = YV \Rightarrow I_i = \sum_{i,j=1}^n Y_{ij} V_j$$

- Then, the admittance matrix is given by:

$$\begin{vmatrix} Y_{11} & Y_{12} & Y_{13} & Y_{14} \\ Y_{21} & Y_{22} & Y_{23} & Y_{24} \\ Y_{31} & Y_{32} & Y_{33} & Y_{34} \\ Y_{41} & Y_{42} & Y_{43} & Y_{44} \end{vmatrix}$$

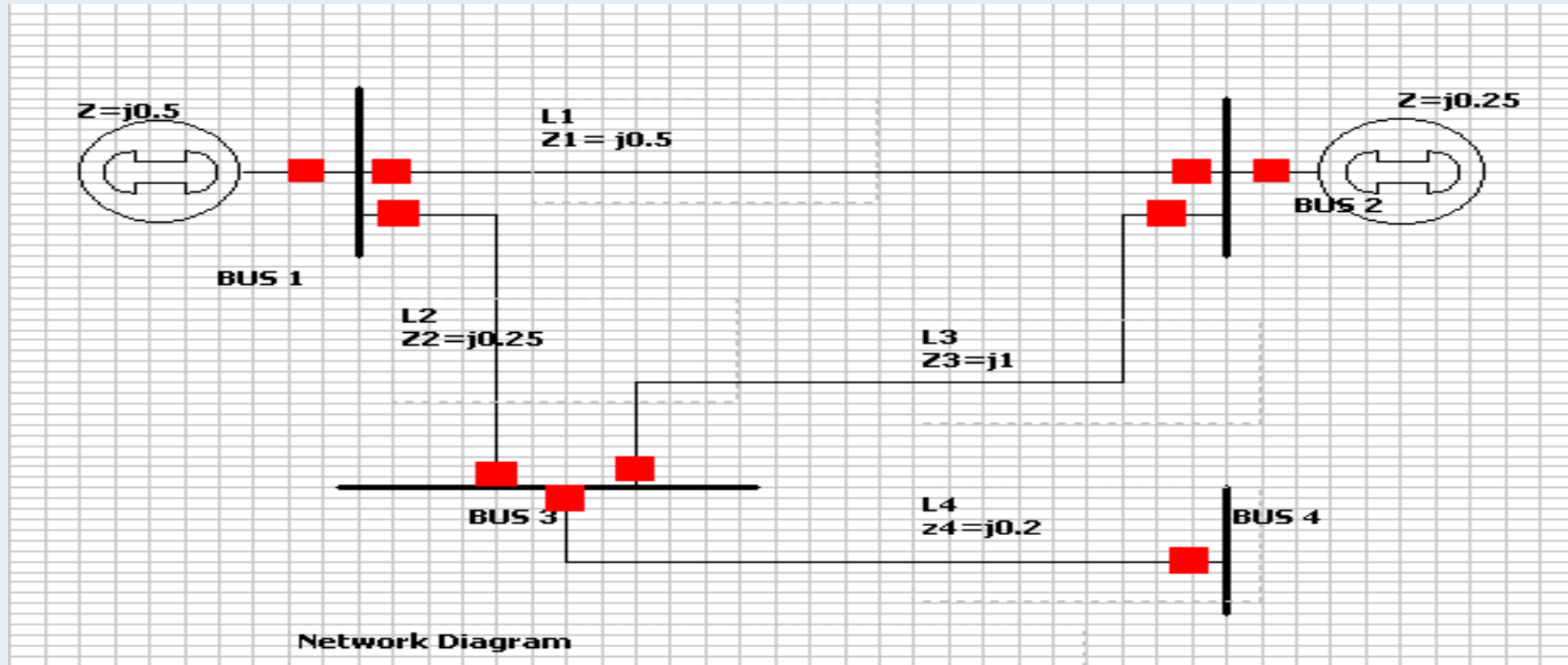
eqn.(6)

- The diagonal element Y_{11} , Y_{22} , Y_{33} and Y_{44} are called self (driving point) admittance
- Which is the **sum** of all admittances connected to the node identified by the repeated subscripts
- The other admittances are called mutual (transfer) admittance of the nodes, which is negative of admittances connected directly between two nodes.
- The admittance matrix for N-bus system can be easily determined using the above formula.

Characteristics of Y-bus matrix are:

- $N \times N$ matrix
- Sparse where as Z matrix is full matrix
- Symmetric matrix
- Diagonal elements of Y-bus matrix is the summation of all elements connected to bus-i
- Off-diagonal elements of Y bus matrix is simply obtained as negative of the magnitude of admittance connected between i and j

Example; Determine the Y-bus matrix for the four bus network given below



Summary

- The load flow analysis and its importance in the power network analysis is discussed in this lecture
- Thus, the significance of load flow analysis in terms supporting the countries GDPs, power system planning and operation is also discussed.
- It is observed that the aim of load flow analysis is to determine the network bus voltage, its angle, line real and reactive power flows during steady state operating conditions, which are very important for the power utility companies as well as the customers
- Besides this, important parameters for load flow analysis such as the knowledge of network modeling , the importance of energy conservation , bus admittance matrix formulation and types of network buses are well discussed.

References

- [1]. E.,Fergany. "A.A. Reviews on Load Flow Methods in Electric Distribution Networks". Arch Computed Methods Eng. 2024. Doi: <https://doi.org/10.1007/s11831-024-10191-7>.
- [2]. C., Enes; Y., Cemal;Y., Ercan and K.,Hamdi. 'Importance of Power Flow and Load Analysis in Pre-Installation Power Systems". 2019 3rd International Symposium on Multidisciplinary Studies and Innovative Technologies (ISMSIT). Pp.1-5, 2019. DOI:10.1109/ISM SIT.2019.8932900.
- [3]. B., Babak and E., Zia. "Power System Dynamic Modeling and Analysis in Evolving Networks". Springer NATURE.2024. <https://link.springer.com/referencework/10.1007/978-3-031-47821-5>
- [4]. P., Pan; H., Shi; G., Chen and etl.: "Modeling and Operating Characteristics of Excitation System for Variable Speed Pumped Storage Unit with Full-Size Converter". Electronics. V.13(505). 2024 . <https://doi.org/10.3390/electronics13030505>.
- [5]. M., Honarvar; G., Shahgholian; H., Mahmoodian and etl.: "Reviewing Power System Stabilizer (PSS) Parameters Optimization Using Evolutionary Meta-Heuristic Algorithms for Power System Stability". IEEE 21st Jubilee International Symposium on Intelligent Systems and Informatics (SISY). 2023. pp. 000481-000486. Doi: 10.1109/SISY60376.2023.10417875.

Thank you !