POWER DISTRIBUTION SYSTEM
2014 - 2015

4th Year's Lectures

Lecture – 1
Introduction

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Syllabus

- **Distribution System Configuration**

  Various distribution system circuit components, representation and parameters, radial, ring, spike, spindle, and interconnected systems.

- **Electrical Design of Distribution Systems**.
- Voltage level, selecting various system components, transformers, cables, overhead lines, switching and protective gear, voltage drop & power loss calculations, economical considerations.

- **Distribution Inside Large Buildings**
- Single rising mains, individual floor supply, ring supply, double feed and grouped supply, vertical and horizontal supply systems, main, sub-main, and final distribution boards.

- **Industrial Power Distribution**
- Special features, equipment layout, cable trenches, cable trays, earthing, emergency power supply.

- **Reactive Power Control in Distribution Systems**
- Individual, grouped, and centralized compensation, advantages, size and location of reactive power control equipment.

- **Electrical Load Management**
- Objectives, devices controlled, various methods of load control, practical implementation problems.

- **Renewable Energy Plants**
- Types of renewable plants, selection the size and location of embedded renewable plants, applications.
- **Recommended Textbooks**

1. Turan Gonen, Electric Power Distribution System Engineering, McGraw-Hill 1986.
2. Gunter G. Seip, Electrical Installation Handbook, John Wiley, 3rd Ed, 2000.
3. Robert B. Hickey, P.E., Electrical Engineer's Portable Handbook McGraw-Hill 2001.
4. T. L. Short, Electric Power Distribution Handbook, CRC Press, 2004.
5. William H. Kersting, Distribution System Modeling and Analysis. CRC Press, 2002.

Lecture Outline

1. Introduction \ DS Configuration
2. DS Schemes
3. DS parameters
4. Voltage Drop calculation

Introduction

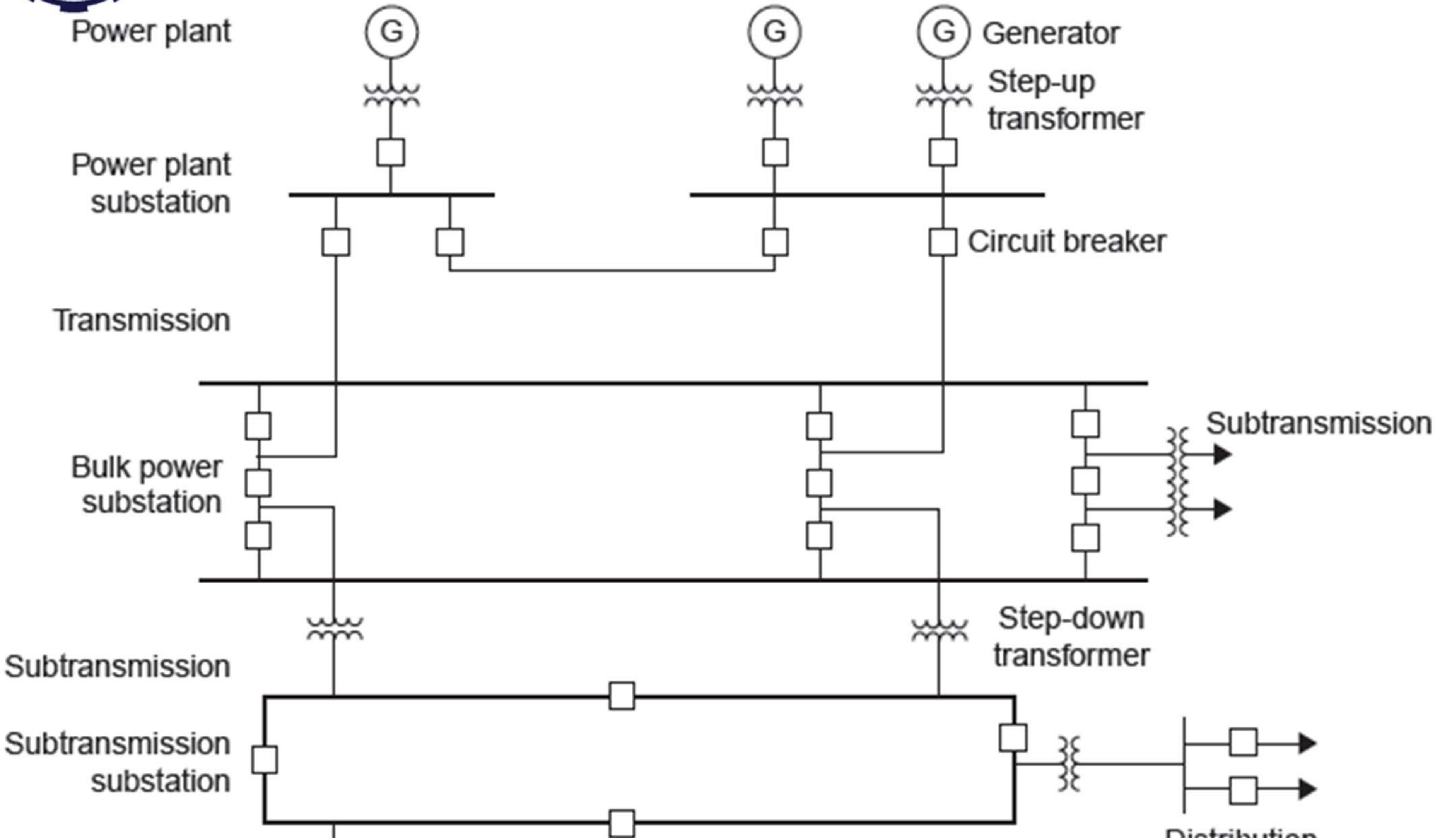
Utility
(Tension side)

Customer
(Relaxed side)

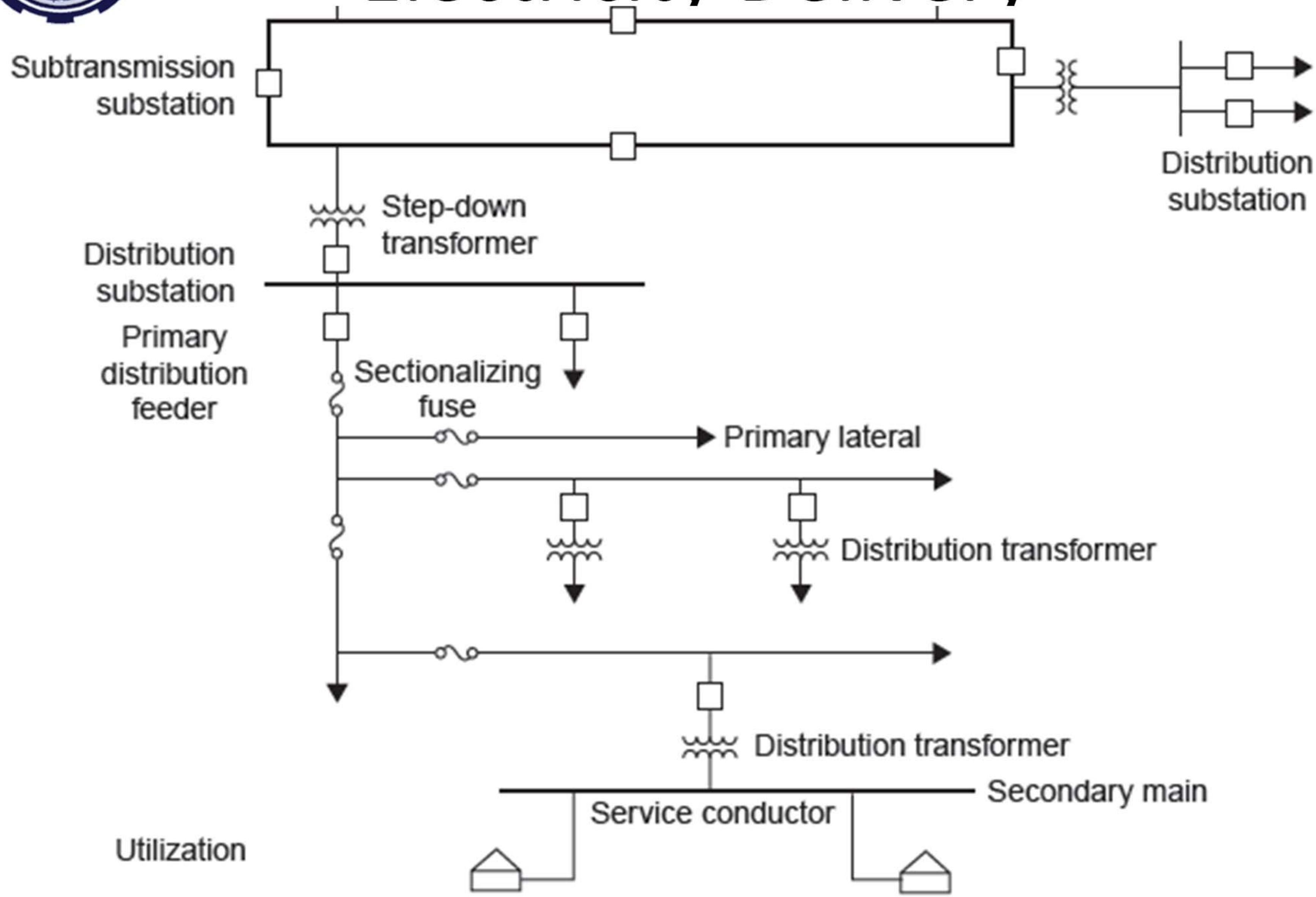
Electricity Delivery

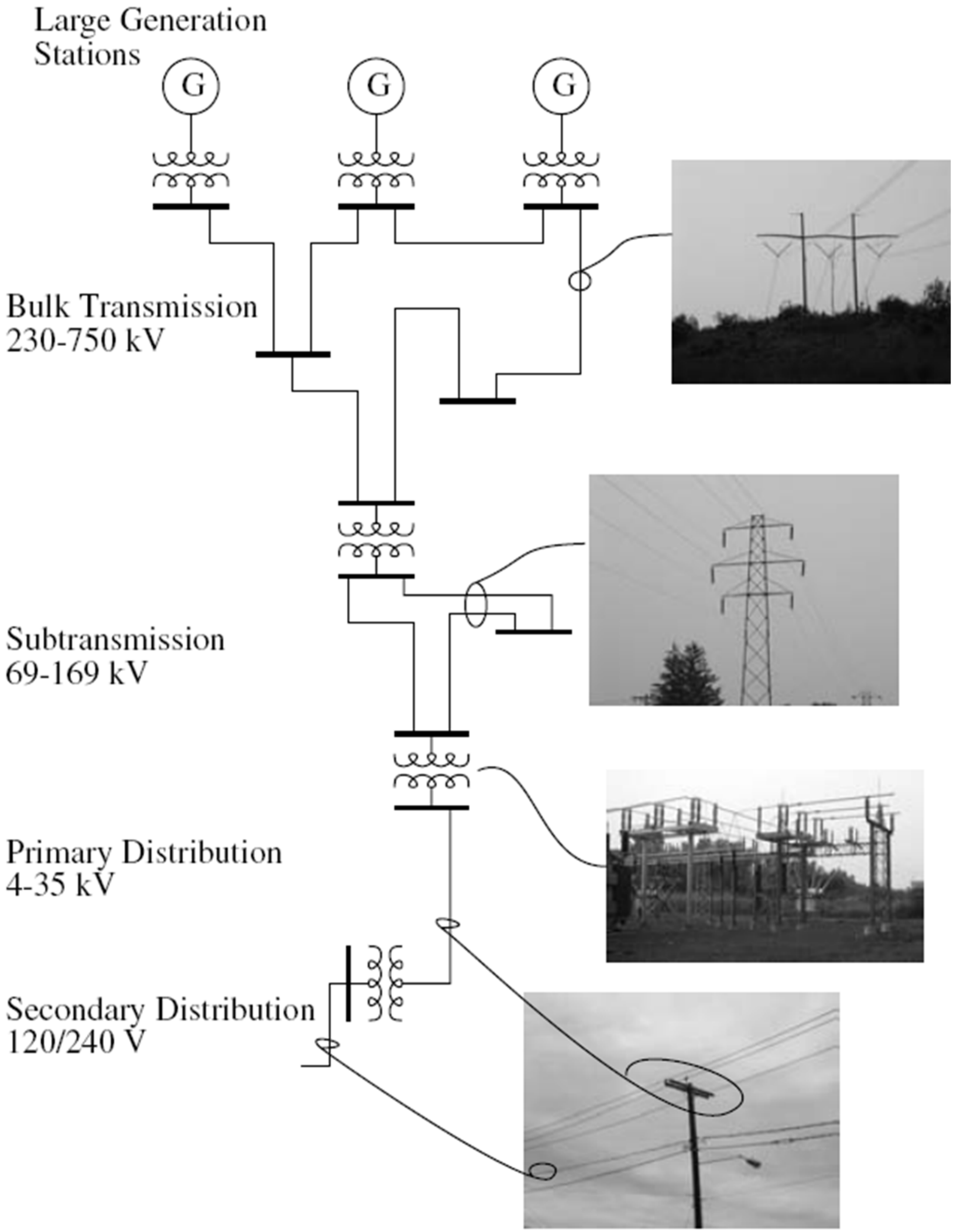
- Generation: 50-1300MVA, up to 20kV
- Transmission: 400MVA @ 230kV up to 4000MVA @ 765kV
  - Can include: HVDC, ac-dc links
- Sub-transmission: 69-138kV
  - Can include: taps for large single customer
- Primary distribution substations: 15-200MVA, 2.2-46kV
  - Can include: LTC (load tap changers), capacitor banks, reclosers
- Distribution feeders: 4MVA @ 4.16kV up to 30MVA @ 34.5kV
- Secondary distribution: 5-5000kVA, 120-480V
- Meters

Electricity Delivery



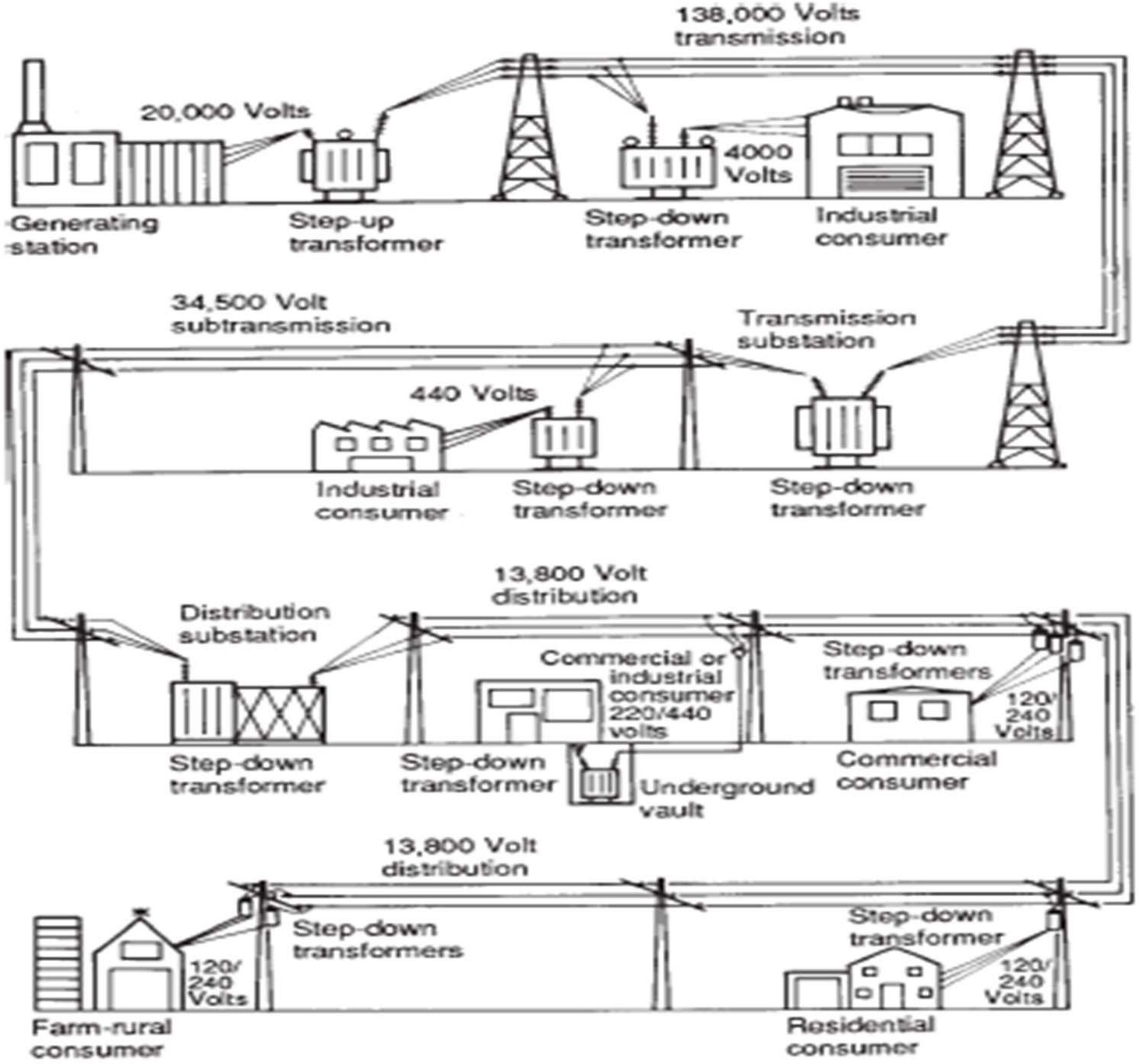
Electricity Delivery

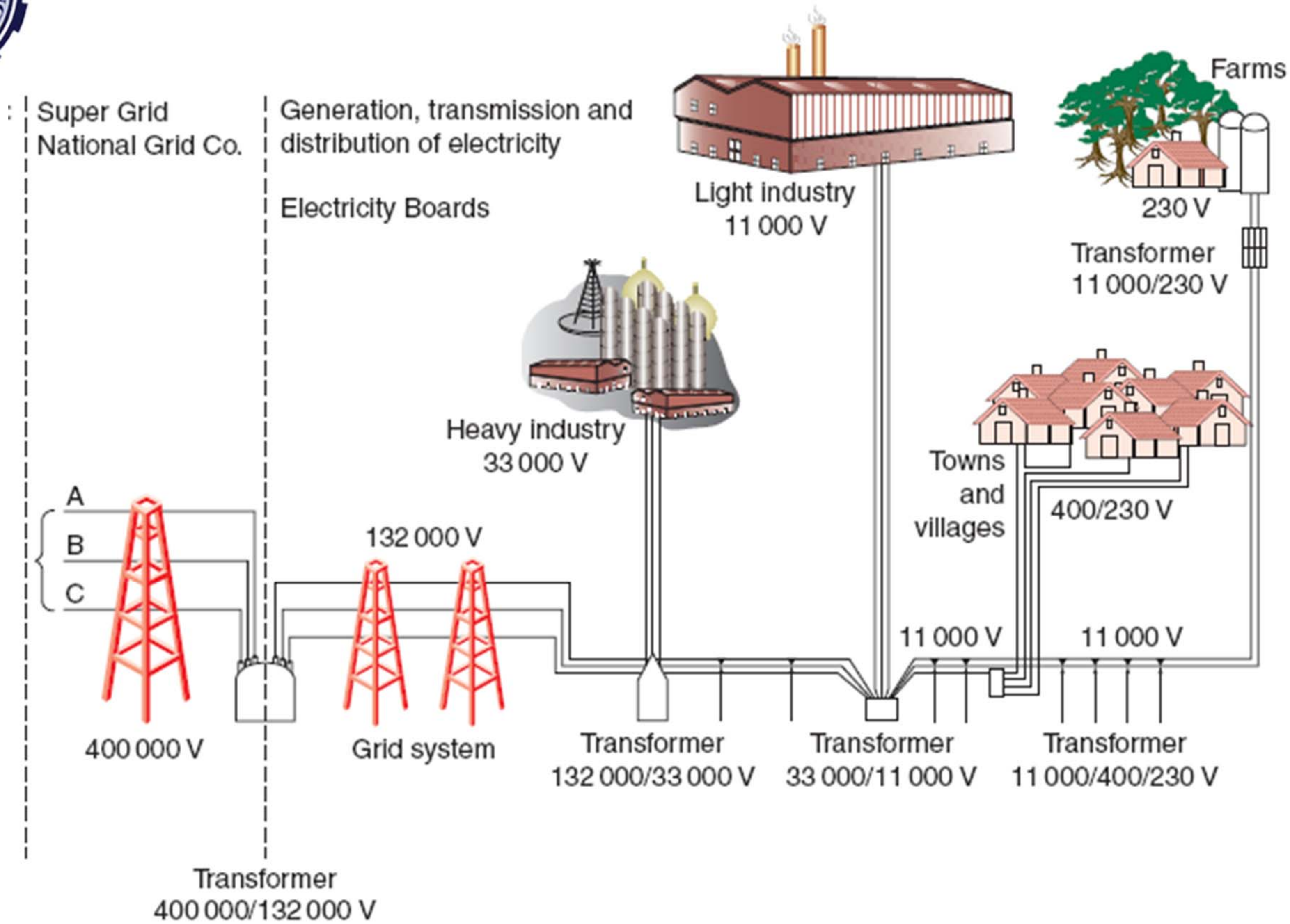




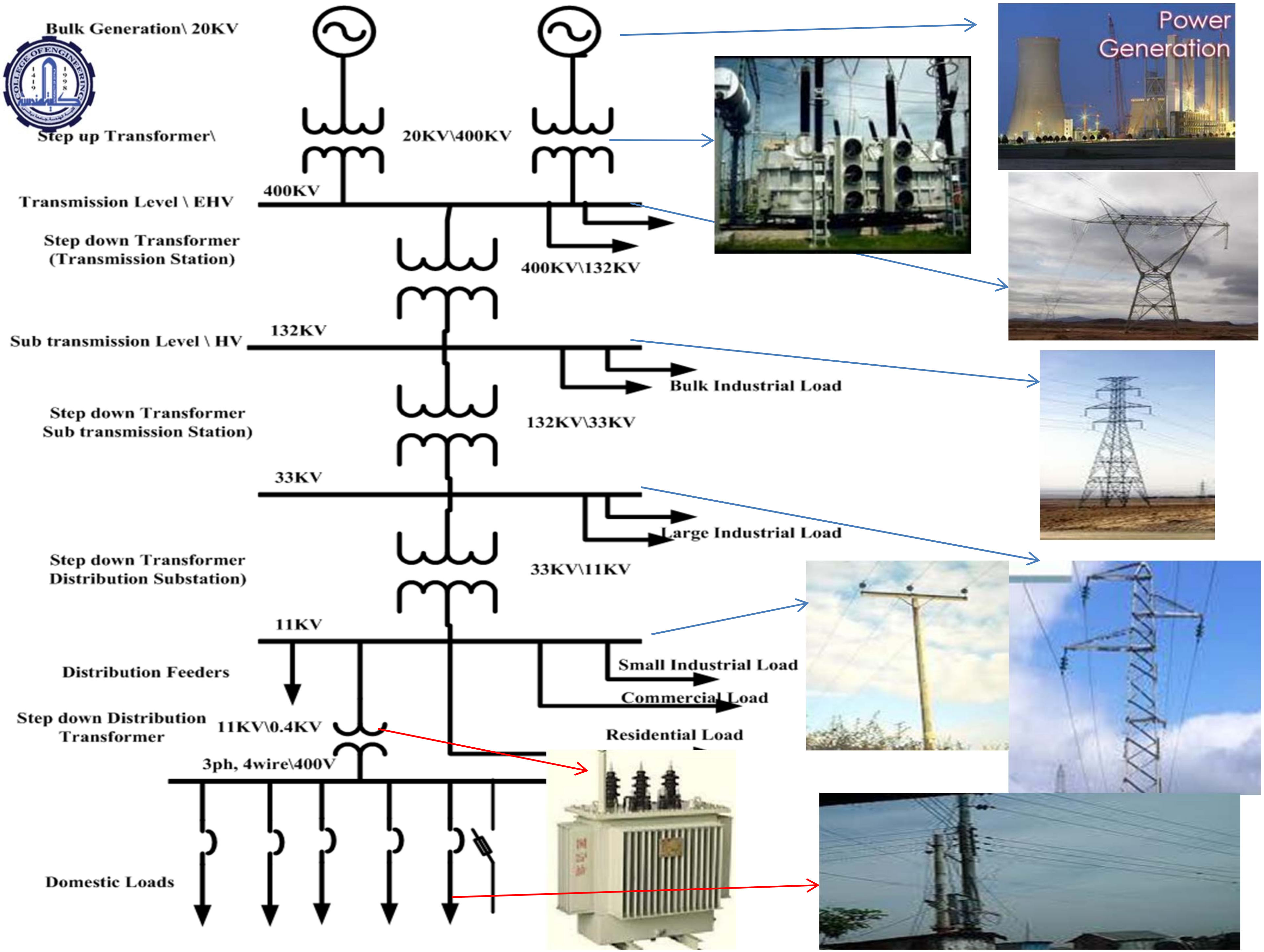
Large Generation Stations
G
G
G
Bulk Transmission 230-750 kV
Subtransmission 69-169 kV
Primary Distribution 4-35 kV
Secondary Distribution 120/240 V

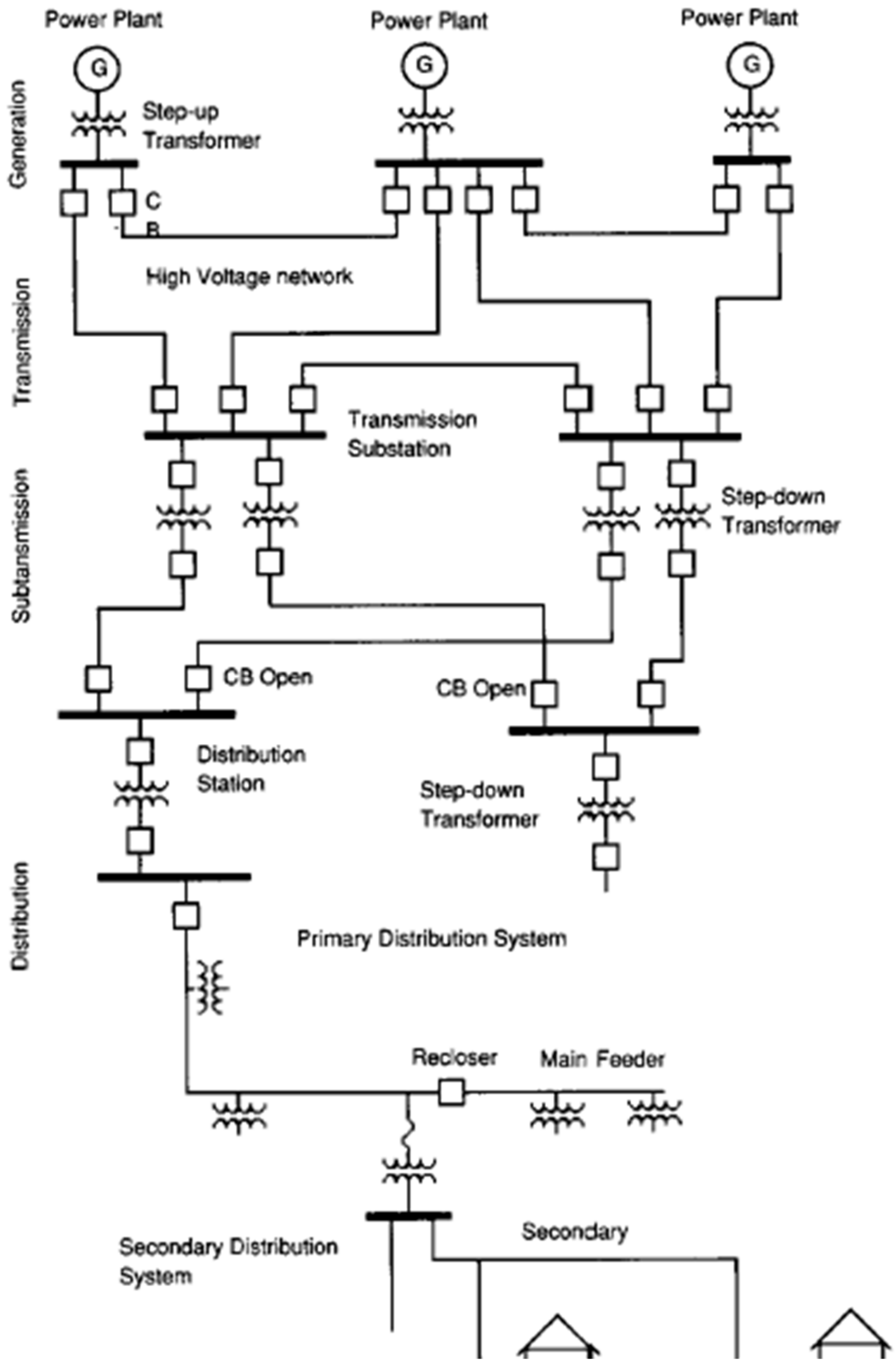
Power System Configuration





Super Grid
National Grid Co.
Generation, transmission and
distribution of electricity
Electricity Boards
Light industry
11 000 V
Farms
230 V
Transformer
11 000/230 V
Heavy industry
33 000 V
Towns
and
villages
400/230 V
A
B
C
132 000 V
11 000 V
11 000 V
400 000 V
Grid system
Transformer
132 000/33 000 V
Transformer
33 000/11 000 V
Transformer
11 000/400/230 V
Transformer
400 000/132 000 V


Bulk Generation\ 20KV
Step up Transformer\
20KV\400KV
Power
Generation
400KV
Transmission Level \ EHV
Step down Transformer
(Transmission Station)
400KV\132KV
132KV
Sub transmission Level \ HV
Bulk Industrial Load
Step down Transformer
Sub transmission Station)
132KV\33KV
33KV
Large Industrial Load
Step down Transformer
Distribution Substation)
33KV\11KV
11KV
Distribution Feeders
Small Industrial Load
Commercial Load
Step down Distribution
Transformer
11KV\0.4KV
Residential Load
3ph, 4wire\400V
Domestic Loads



Power Plant
Power Plant
Power Plant
G
G
G
Step-up Transformer
C B
Generation
High Voltage network
Transmission
Transmission Substation
Subtansmission
Step-down Transformer
CB Open
CB Open
Distribution Station
Step-down Transformer
Distribution
Primary Distribution System
Recloser
Main Feeder
Secondary
Secondary Distribution System

Introduction

Distribution networks deliver electrical power from main substations sited within areas of load, to secondary substations within lower voltage level and then to individual consumers. These networks may have limited spread, but are characterized by their density and complexity. These factors distinguish them from HV and EHV networks which carry the power from generating centers, frequently over long distances to the areas of load.

- Within the concept “ Distribution Network” all systems up to 33KV are included. In densely loaded areas a network operating at voltage up to 132KV may be incorporated.
- In the design and development of distribution systems, the configurations schemes are selected and compared using the following principles:

i. The circuit should be reliable (a fault in one part should not affect other healthy parts)

ii. The circuit should be economical.

iii. It should be simple in operation and maintenance.

iv. It should be capable to meet future expansions without large financial costs.

v. It should have reasonable short circuit level.

vi. Also consumer type and importance is considered.

Consumer Types

1. *First category: These consumers must be supplied from at least two independent sources, because any supply interruption might cause losses in human lives, e.g. the operating theaters in hospitals, intensive care units,… etc.*
2. *Second category: These consumers must also be supplied from two independent sources, because the supply interruption event might cause high financial losses, e.g. the large industrial plants.*
3. *Third category: These consumers accept short time power interruption as it does not cause damages mentioned above.*

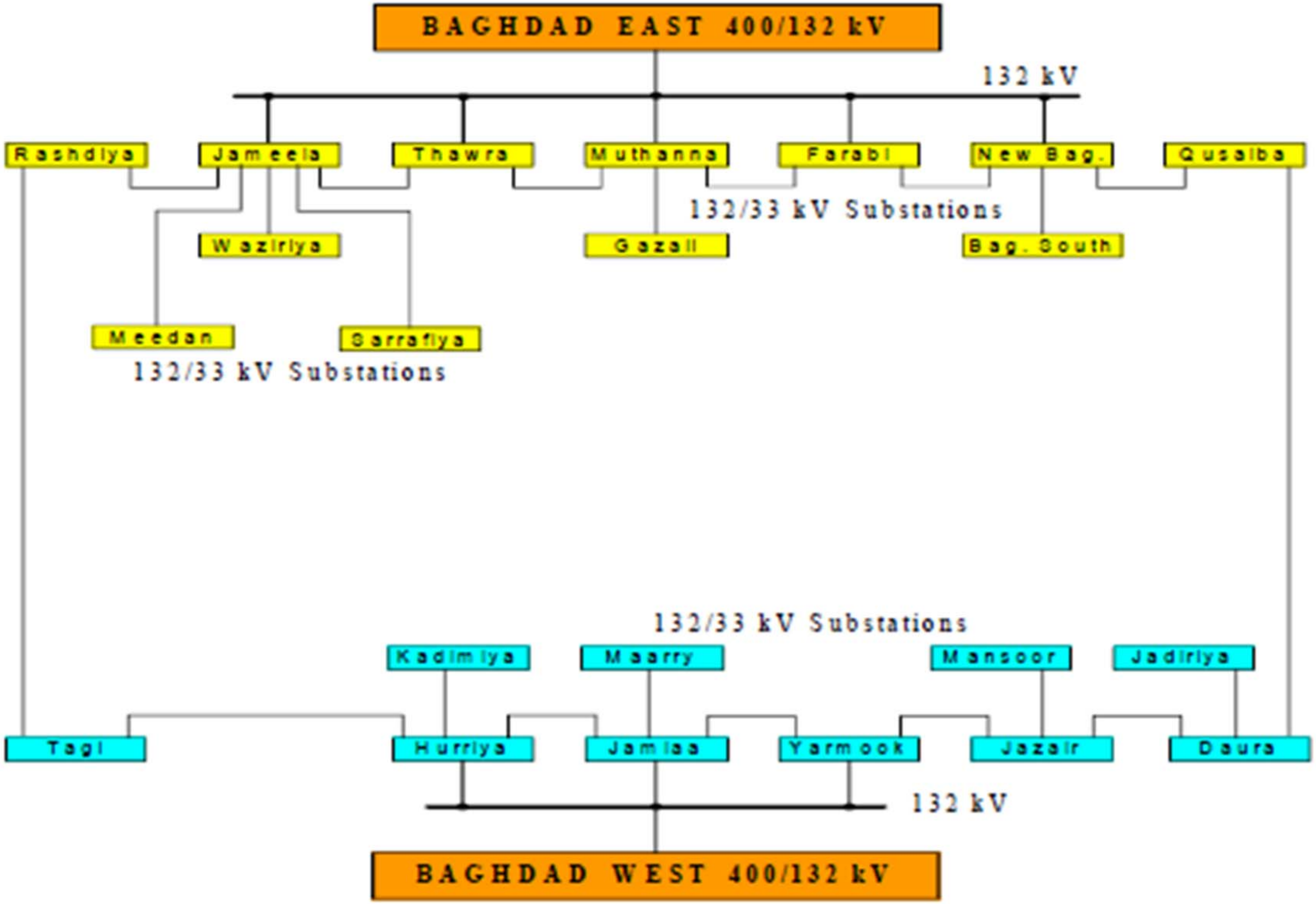


Fig.1 BAGHDAD CITY POWER SUPPLY STRUCTURE

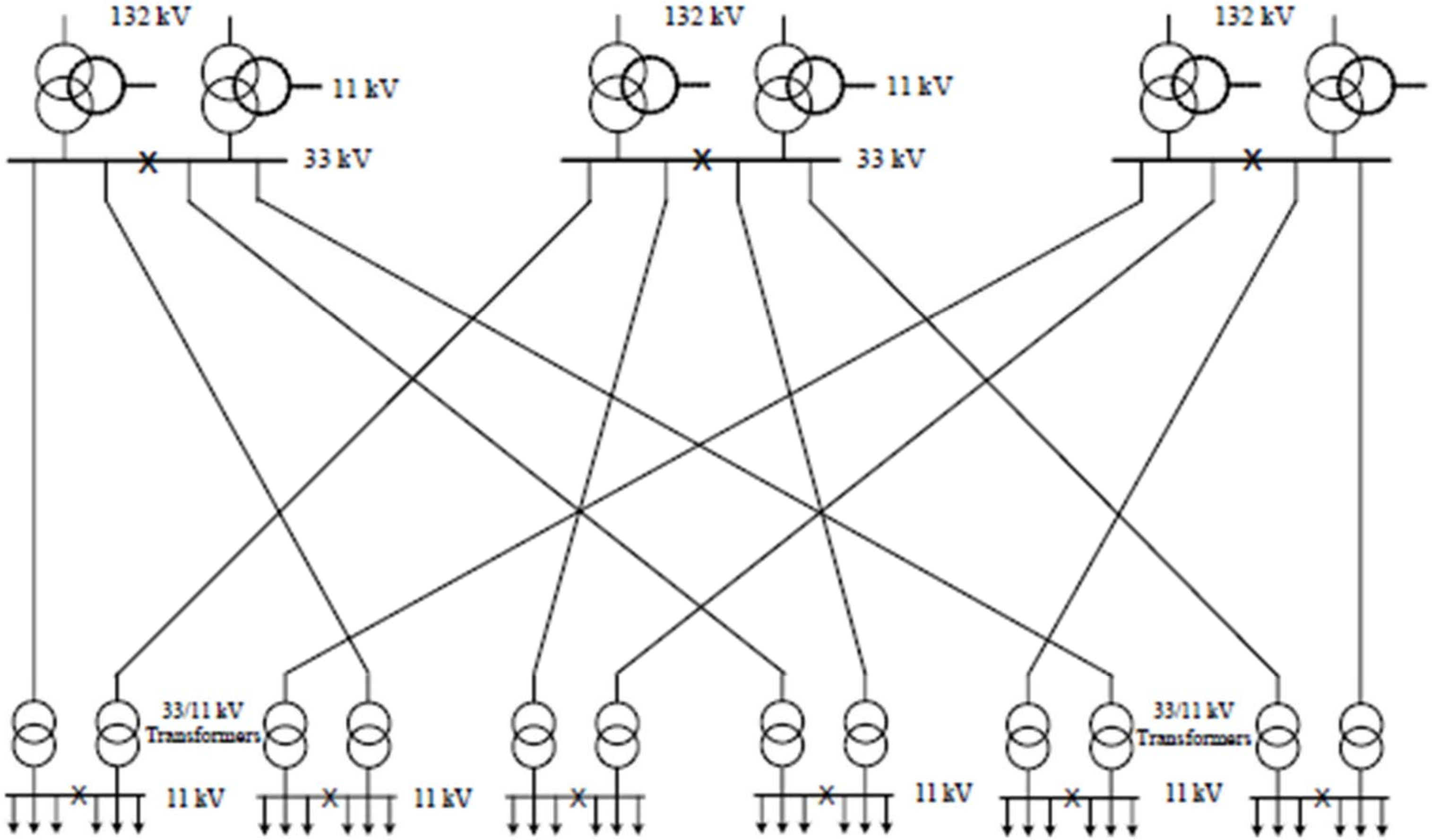


Fig.2. Power Supply Structure to 33/11 kV Substations from Main Satellite Substations

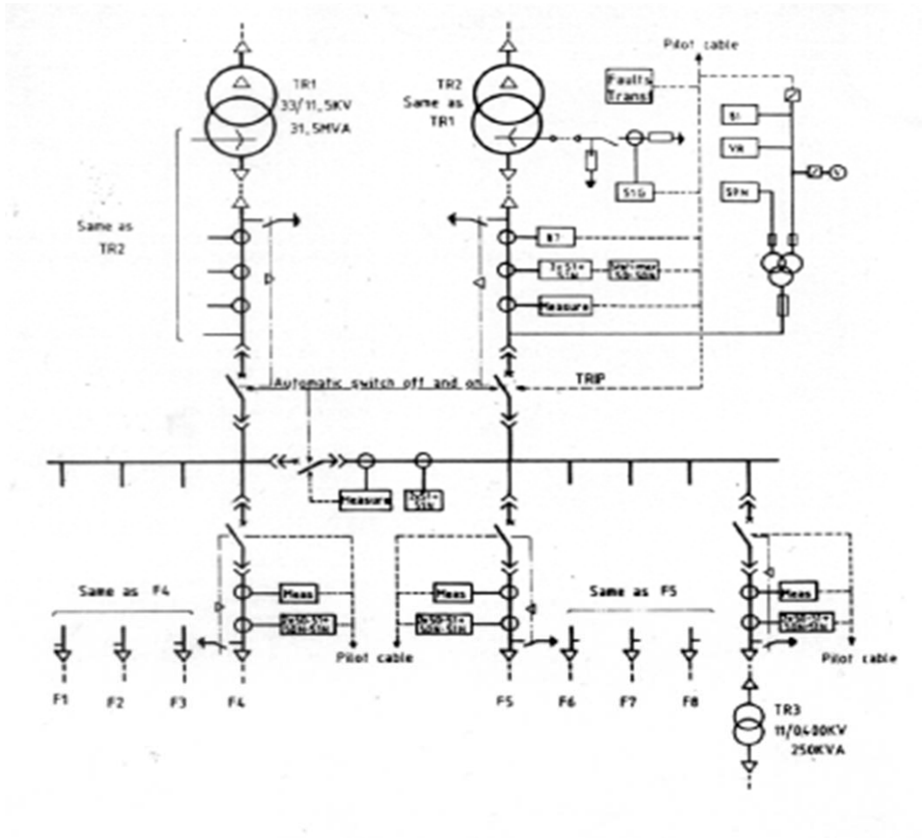


Fig.3 Single line Diagram of a Typical 33/11 kV Substation

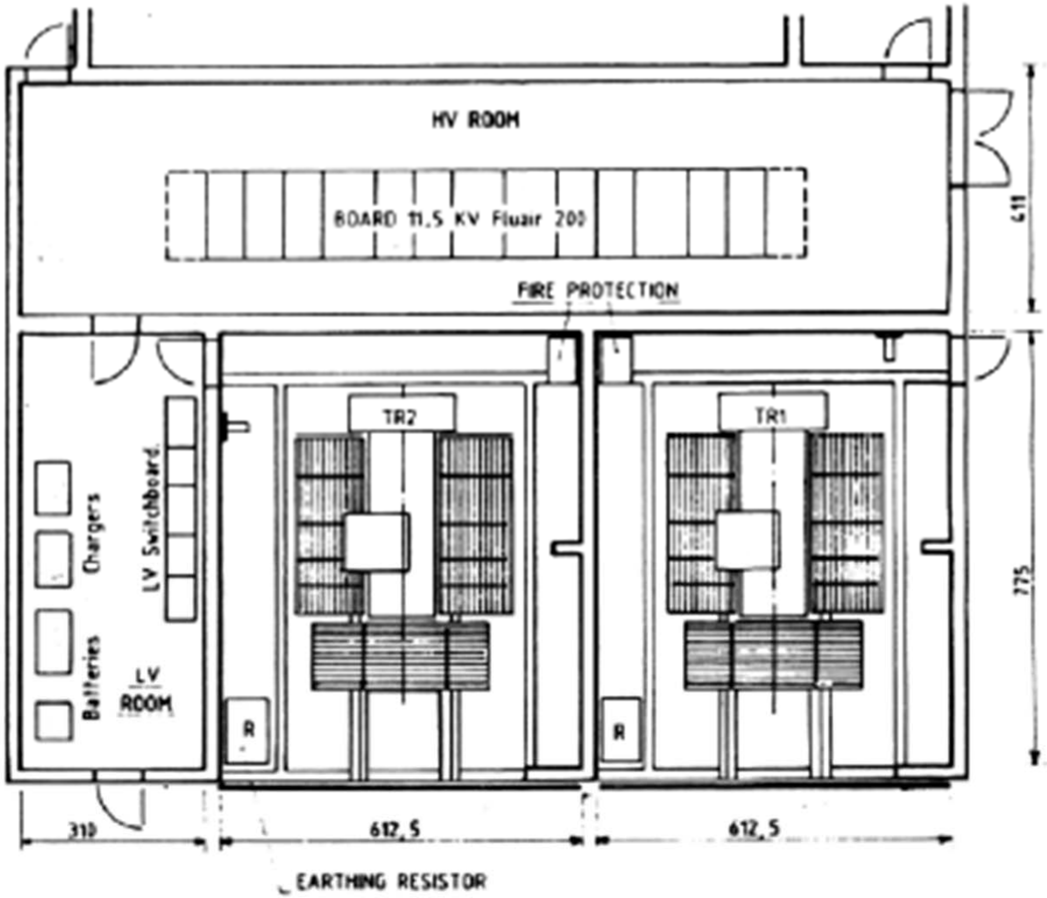


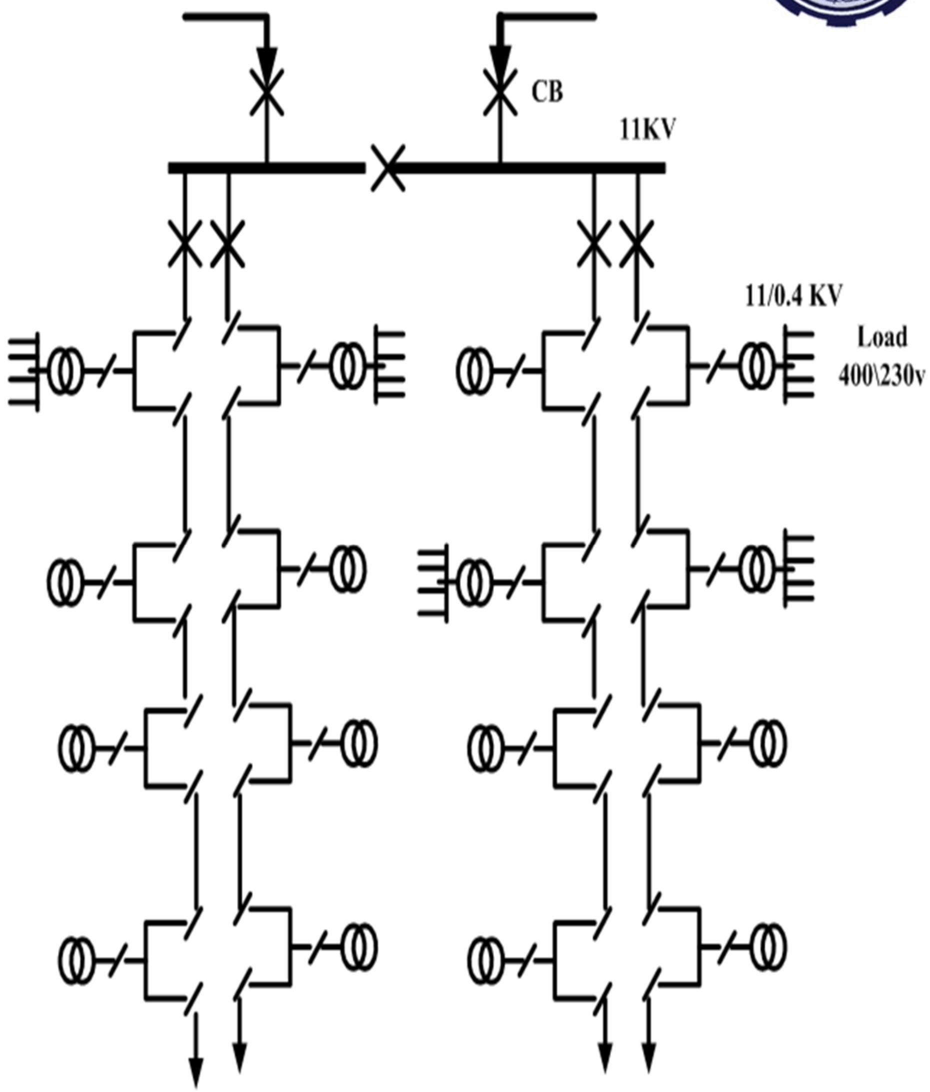
Fig.4. Equipment Layout of a Typical 33/11 kV Substation

Distribution system Schemes

1- Radial System

In this system ,separate feeders are radiated from a single substation and feed distribution transformers from one end only.
It is the simplest circuit and has the lowest initial cost but it the following drawbacks:

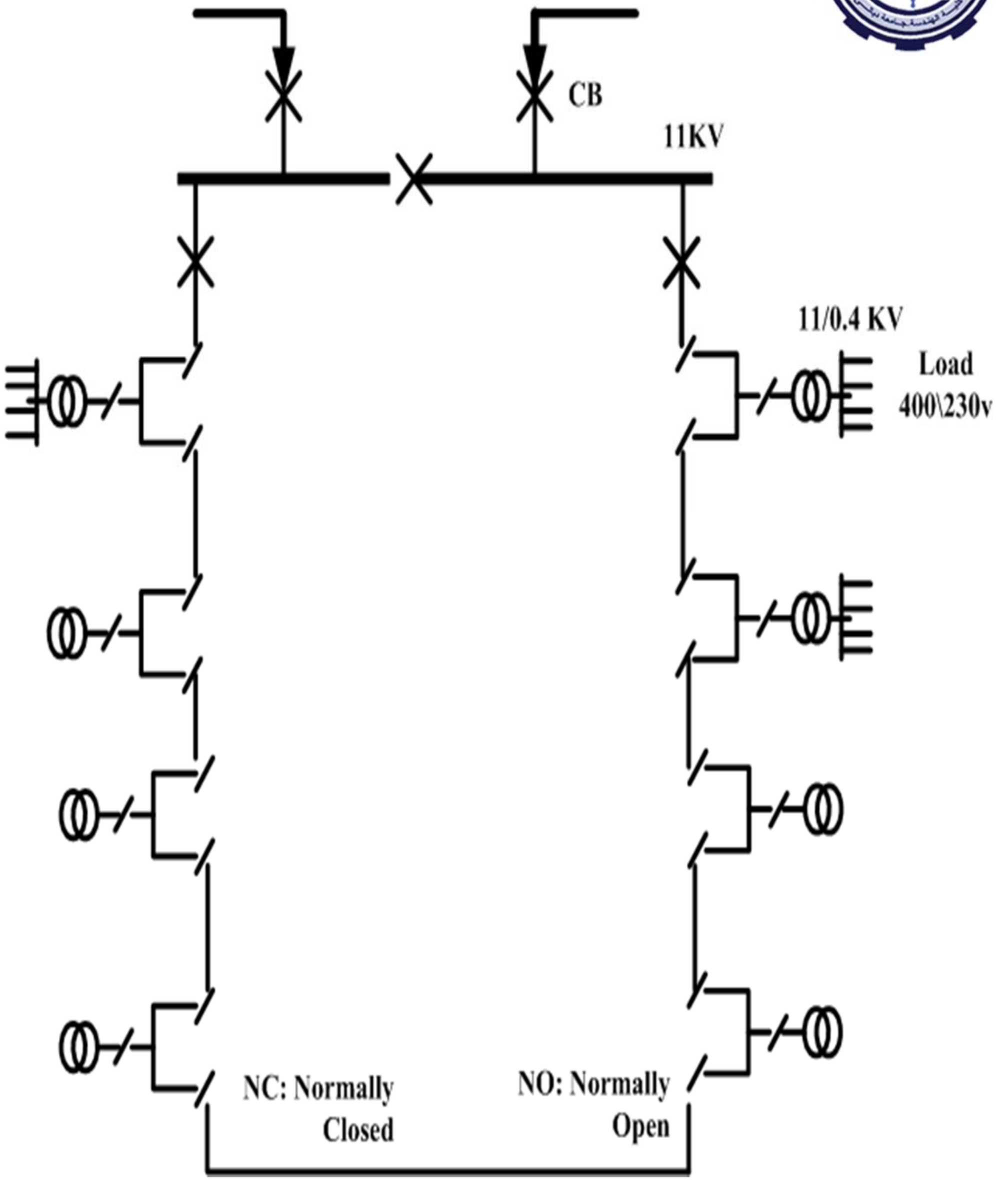
1. This circuit is not very reliable as in case of a fault in any feeder section, the supply to consumers who are in the side of fault a way from the substation are interrupted.
2. Feeder end nearest to the substation will be heavily loaded.
3. The consumers at the distant end of the feeder would be subjected to voltage fluctuations when the load on the feeder is changed.



2- Ring System

In this system the primaries of distribution transformers forms a loop . The loop circuit start from the substation bus-bar, makes a loop through areas to be served and returns to the substation as in figure.

This circuit is very reliable but has a larger cost. Also each side of the ring should not be loaded more than 50% of its rating to be able to accept the load of the other side in the case of fault.

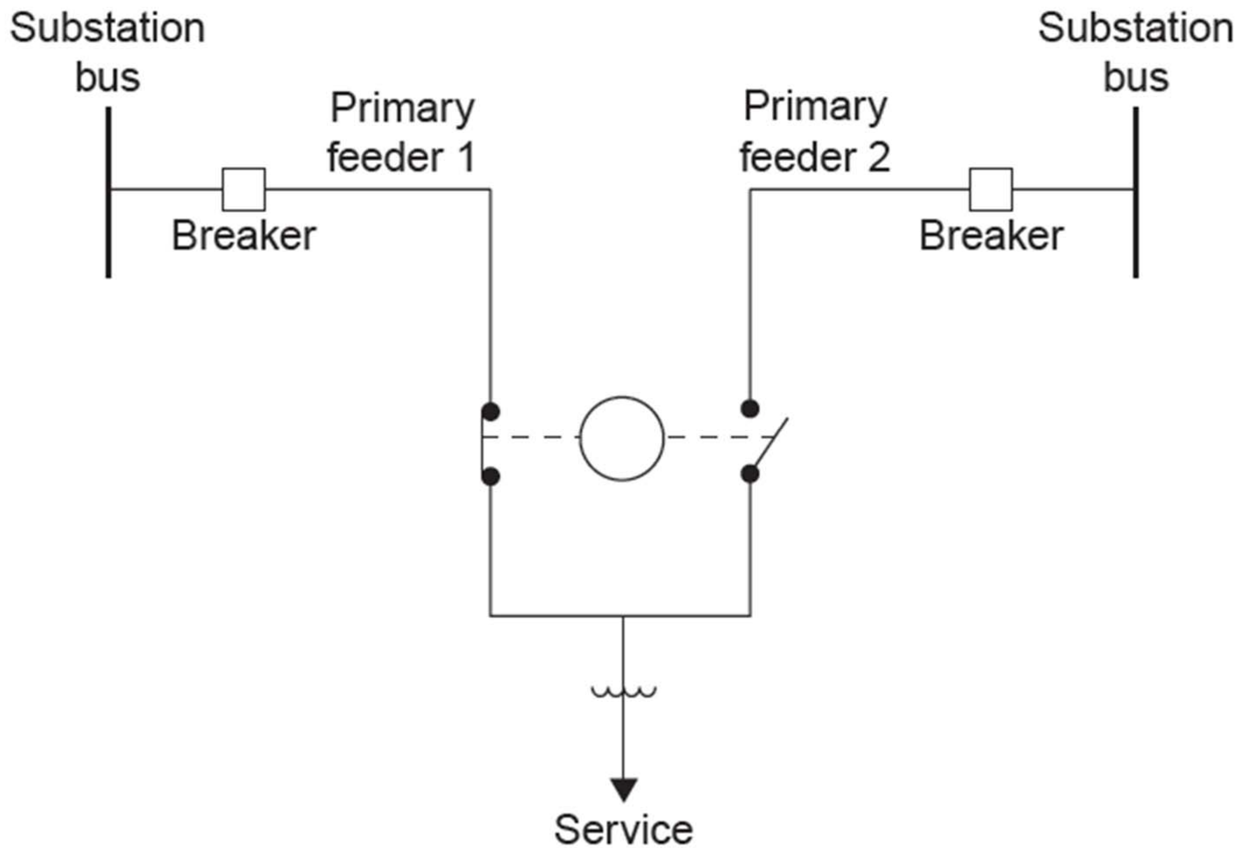


Ring System

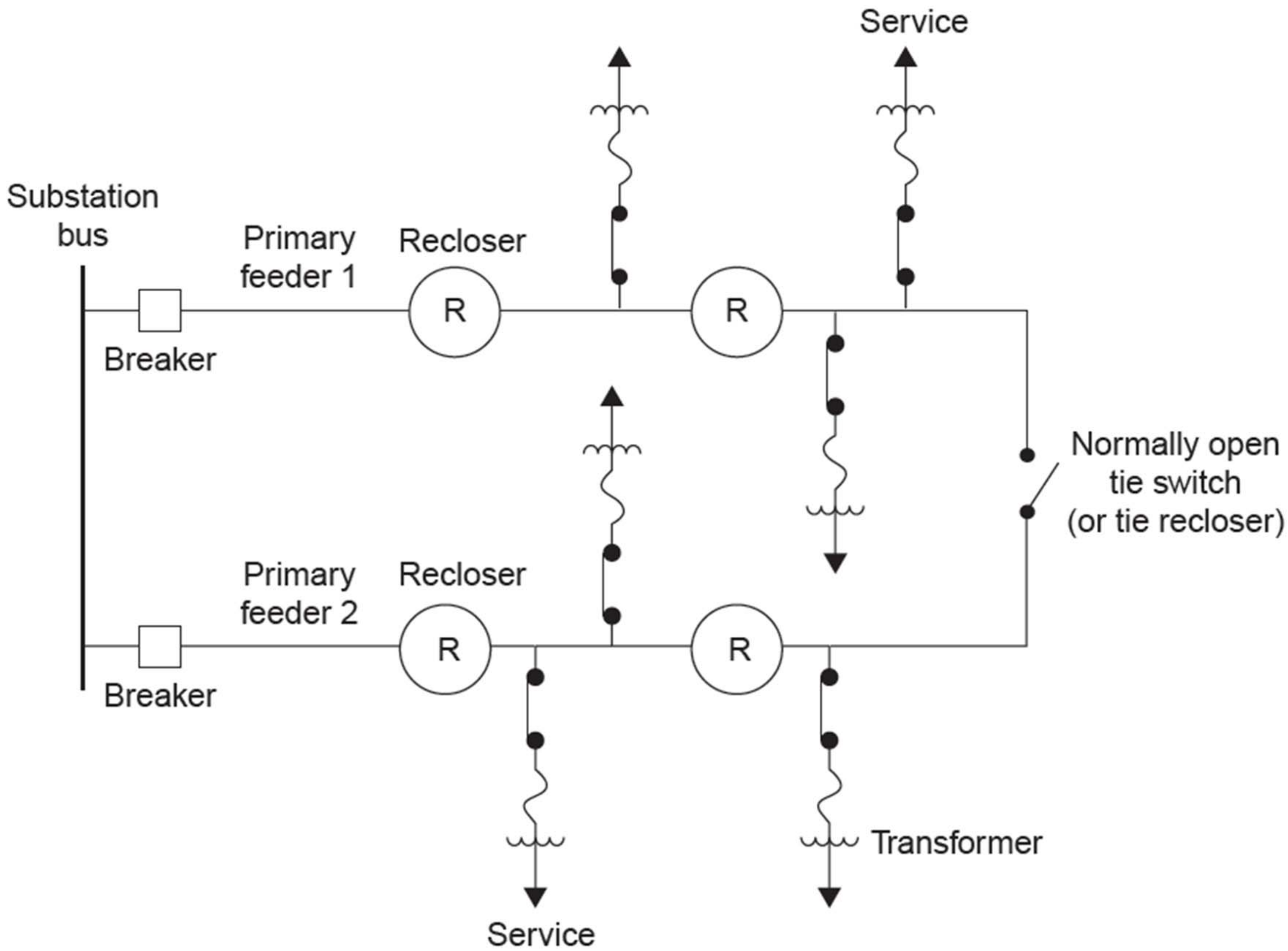
- Used where higher service reliability is required
- Generally more expensive than radial systems
- Feeder conductors are sized to feed entire loop
- Loop systems can be used in underground residential distribution (URD), where faults are infrequent but are usually permanent

Ring System

- Primary selective systems can be used as backup for critical loads such as hospitals

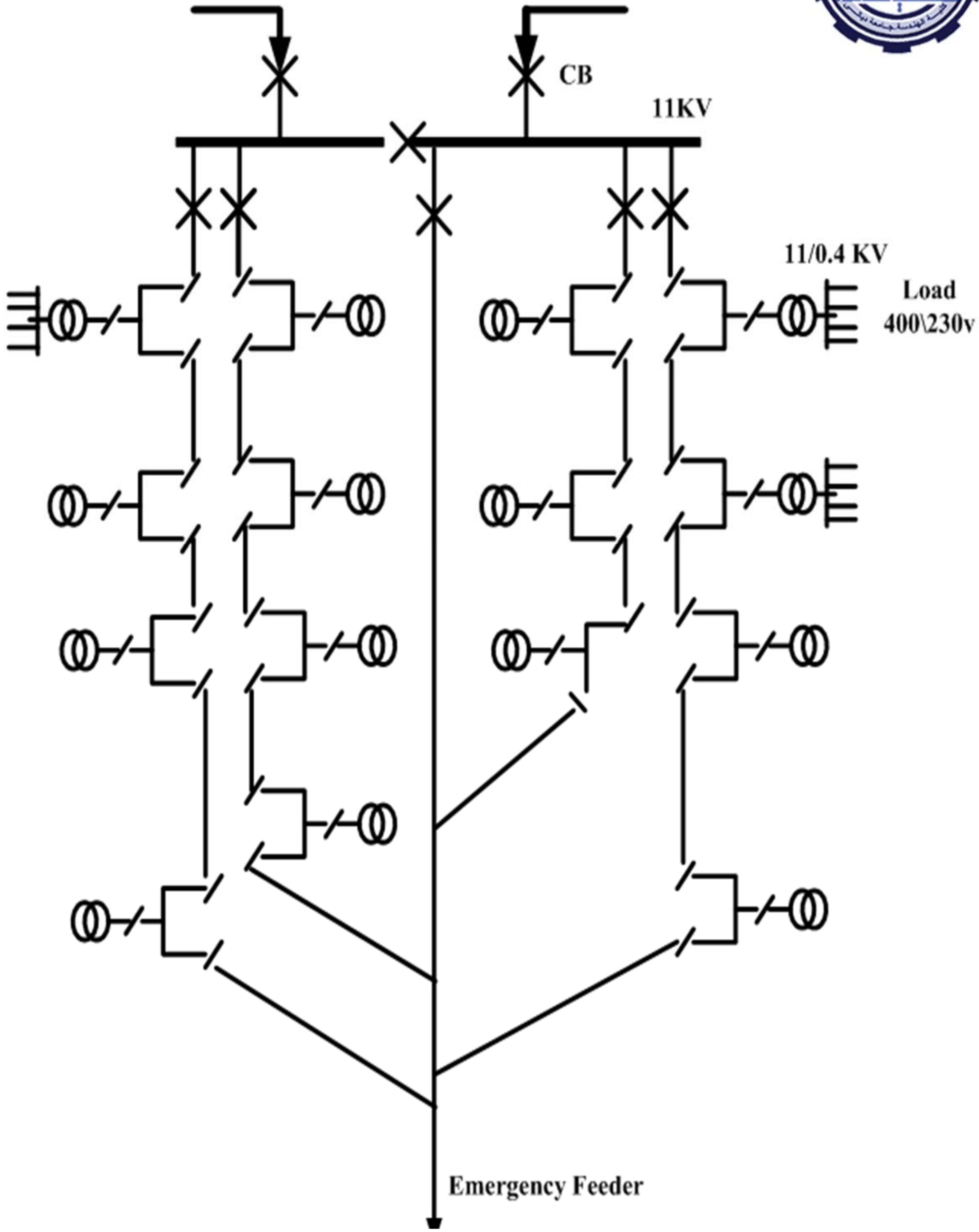


Ring System


Service
Substation
bus
Primary
feeder 1
Recloser
R
R
Breaker
Normally open
tie switch
(or tie recloser)
Primary
feeder 2
Recloser
R
R
Breaker
Transformer
Service

3- Spike System

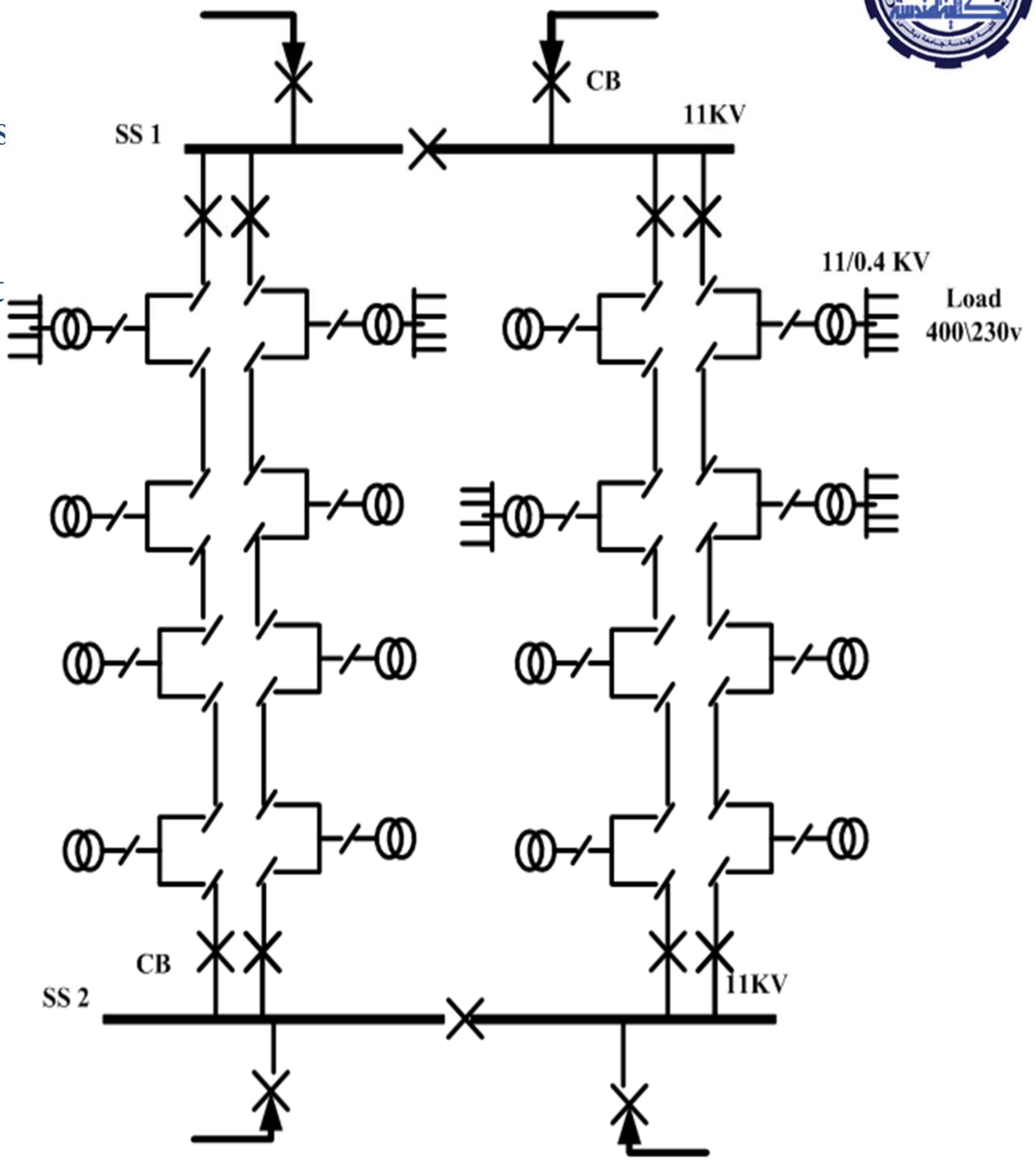
In this system, all secondary substation are supplied by using radial feeders. In addition a separate feeder is provided for emergency (to provide power supply in the case of fault in the main feeder) . This system type is reliable and widely used.



Distribution system Schemes

4- Spindle System

In this system, all secondary substations (distribution transformers) are supplied by using radial feeders. In addition a switching station is provided to connect the supply to the feeder with faulty section . This circuit is more expensive but reliable.

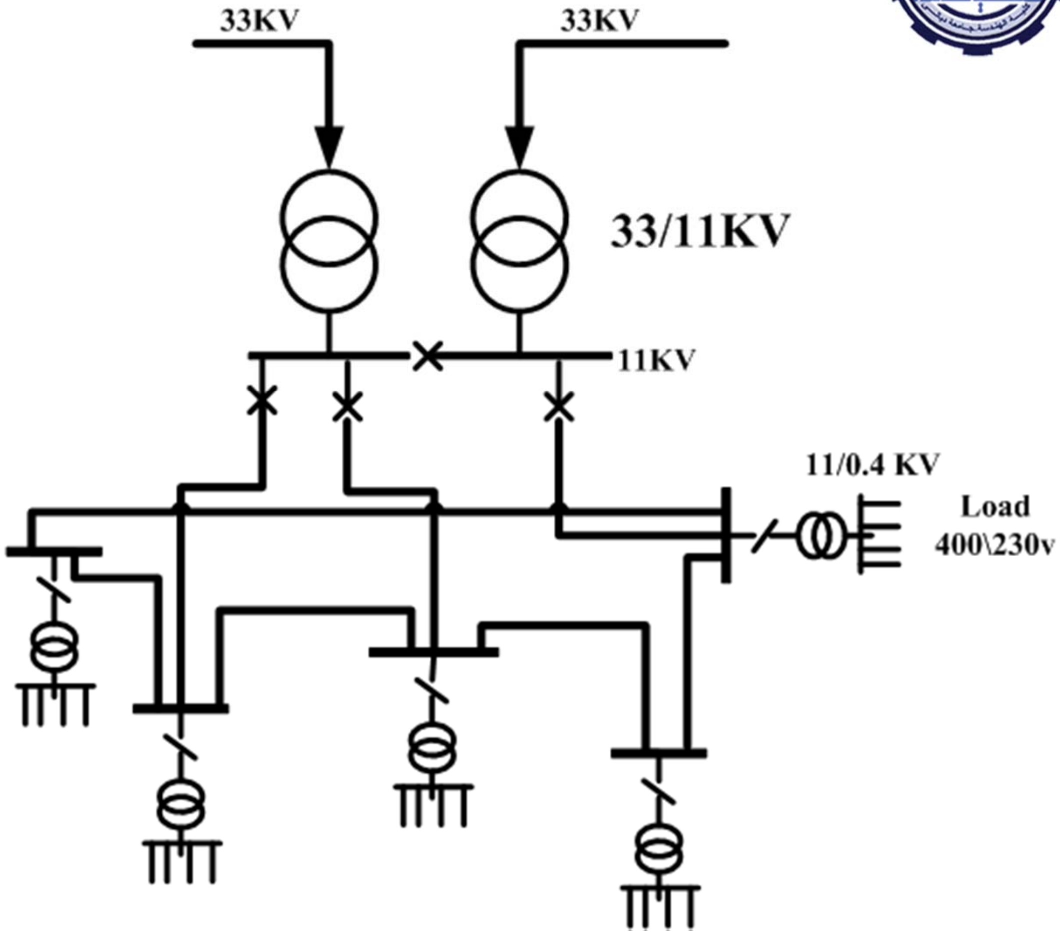


Distribution system Schemes

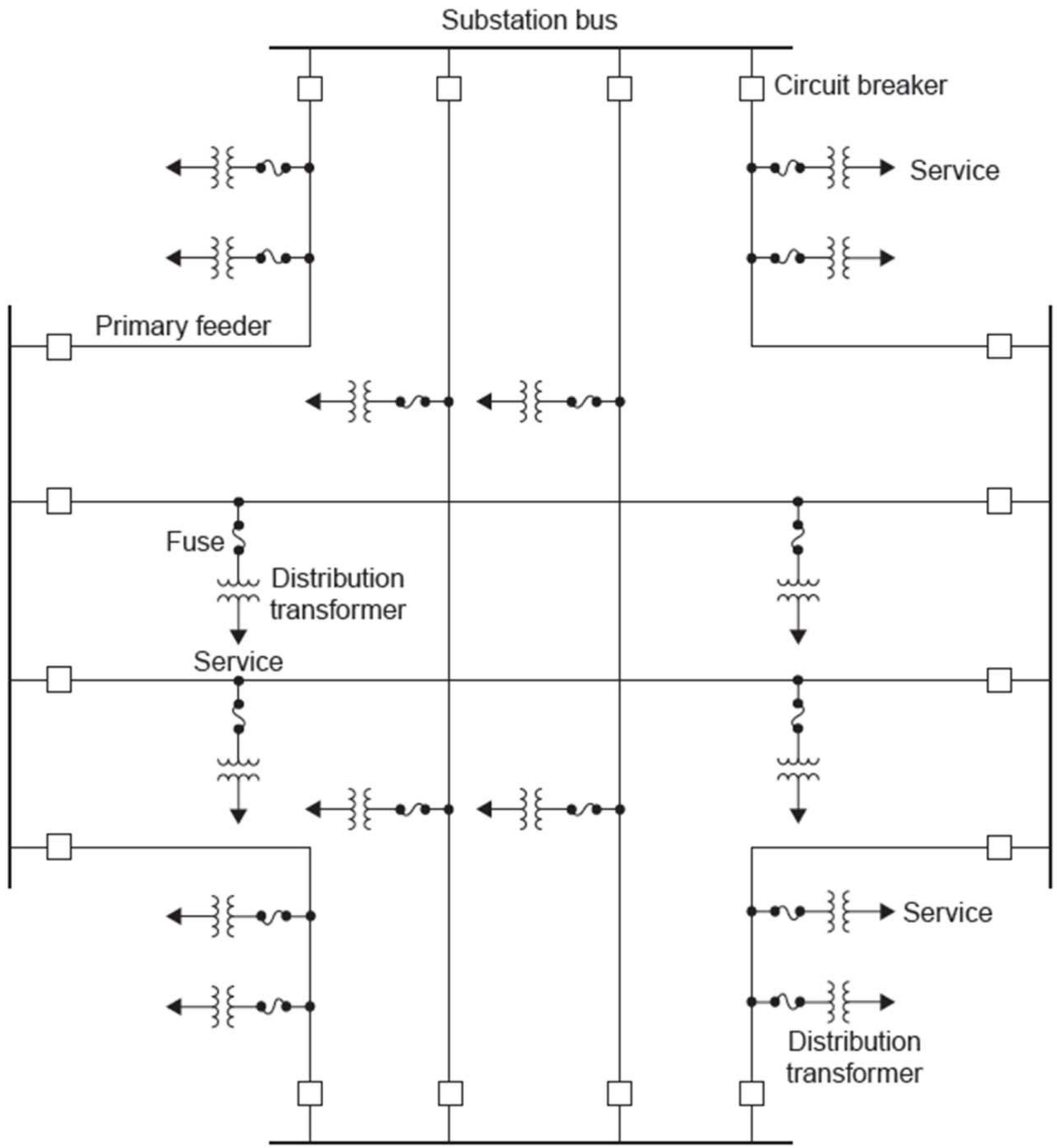
5-Grid system

This type is applicable in large distribution areas with large loads and where the system has to made more reliable for continuity of supply. This is true for primary distribution systems as well as on some applications to secondary distribution systems . the primary network is a system of interconnected primary feeders supplied by two or more main substations through several secondary distribution substation located at intersection points of the interconnected feeders . This type is specified as in following points

1. It is used where loads are heavy as in small crowded commercial areas .
2. It gives the maximum possible flexibility.
3. High reliability in continuity of service.
4. The best use of the advantage of diversity between loads.
5. It gives better voltage regulation.
6. The size of substation required is smaller to that required in redial system.
7. It use smaller length of feeders.
8. It accept any growth its circuit compared with other types ..



Primary Network Systems



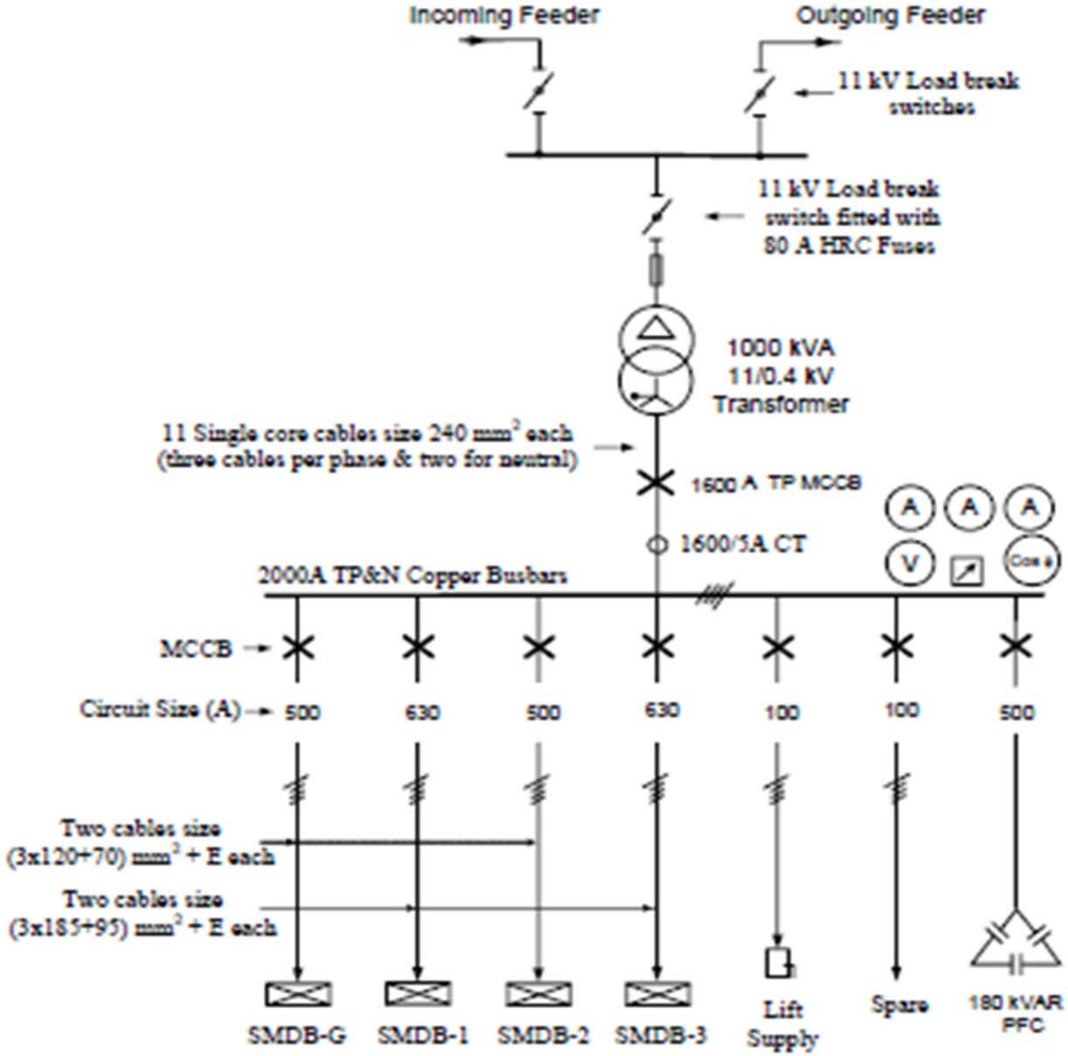


Fig.6 Single Line Diagram of a Typical 11/0.4 kV Substation

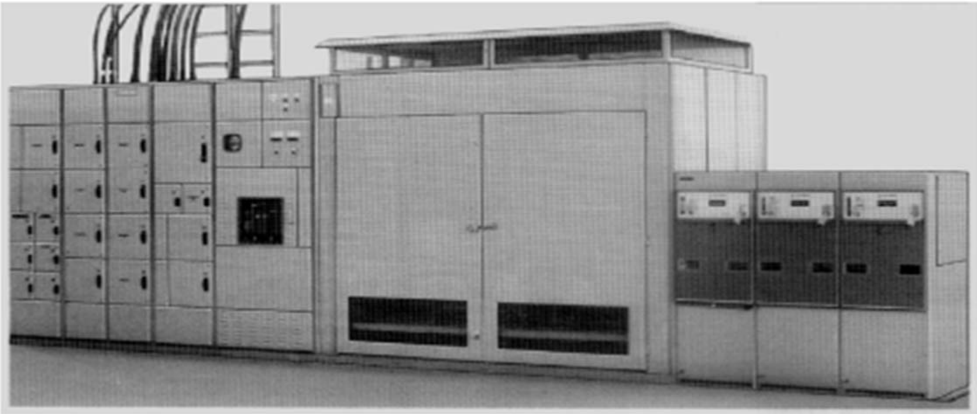


Fig.8 External View of a Privately Owned Substation

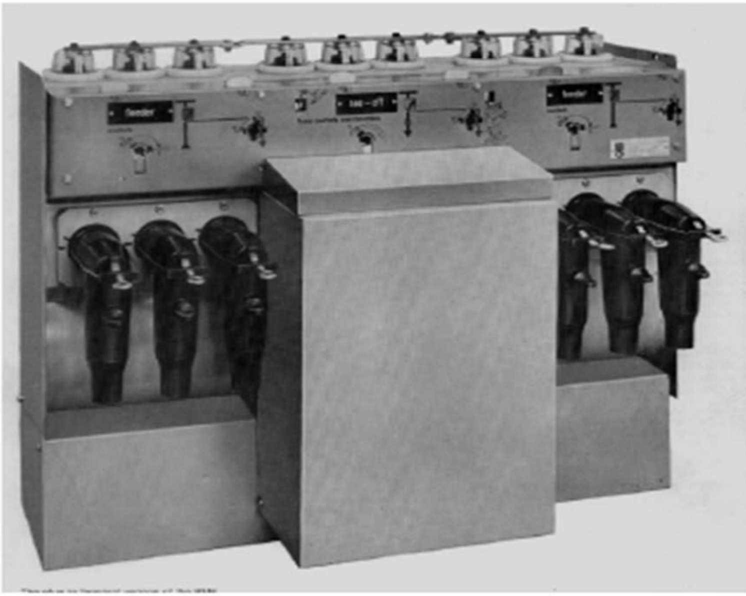
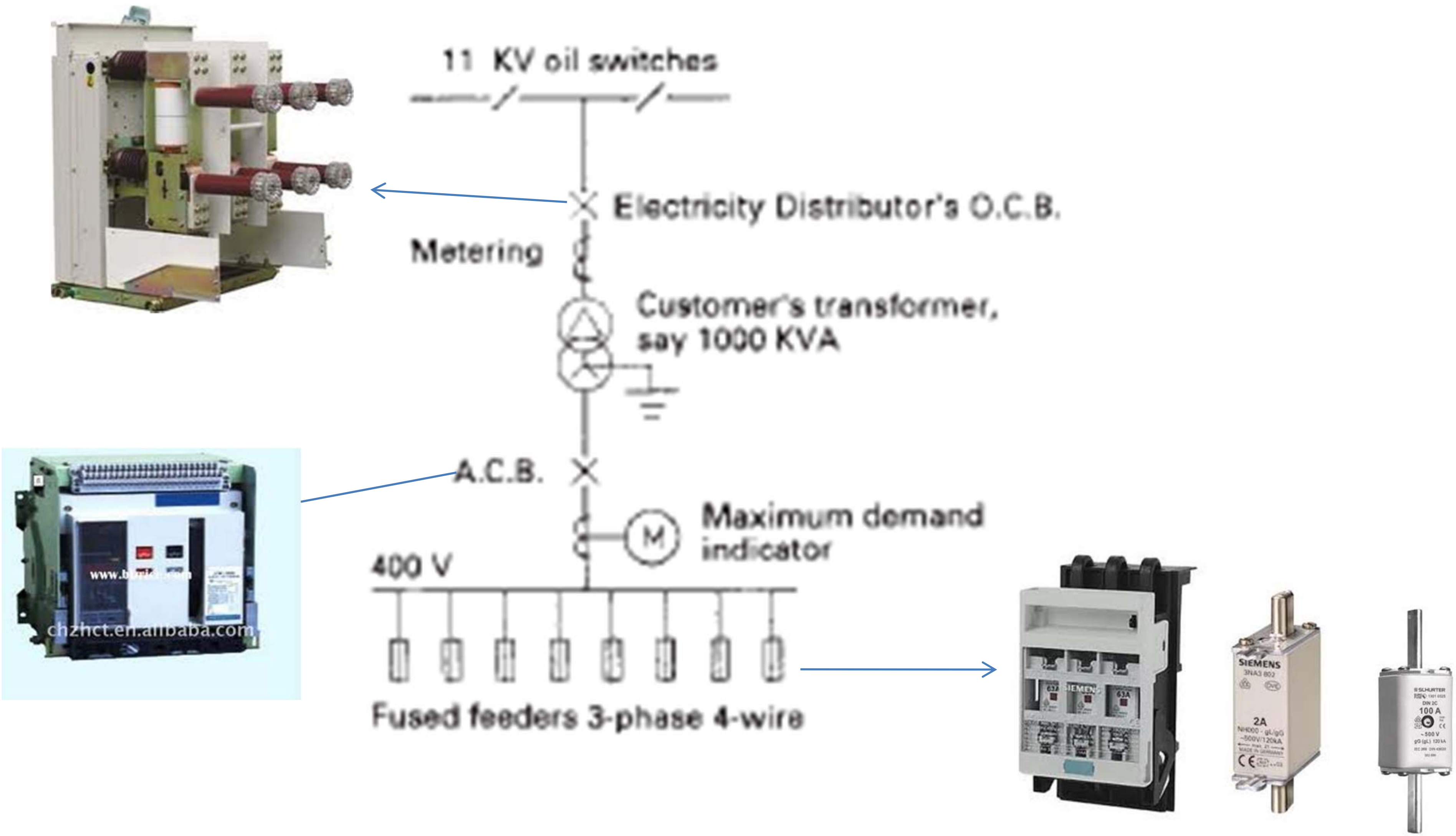


Fig.9 External View of the 11 kV Ring Main Unit

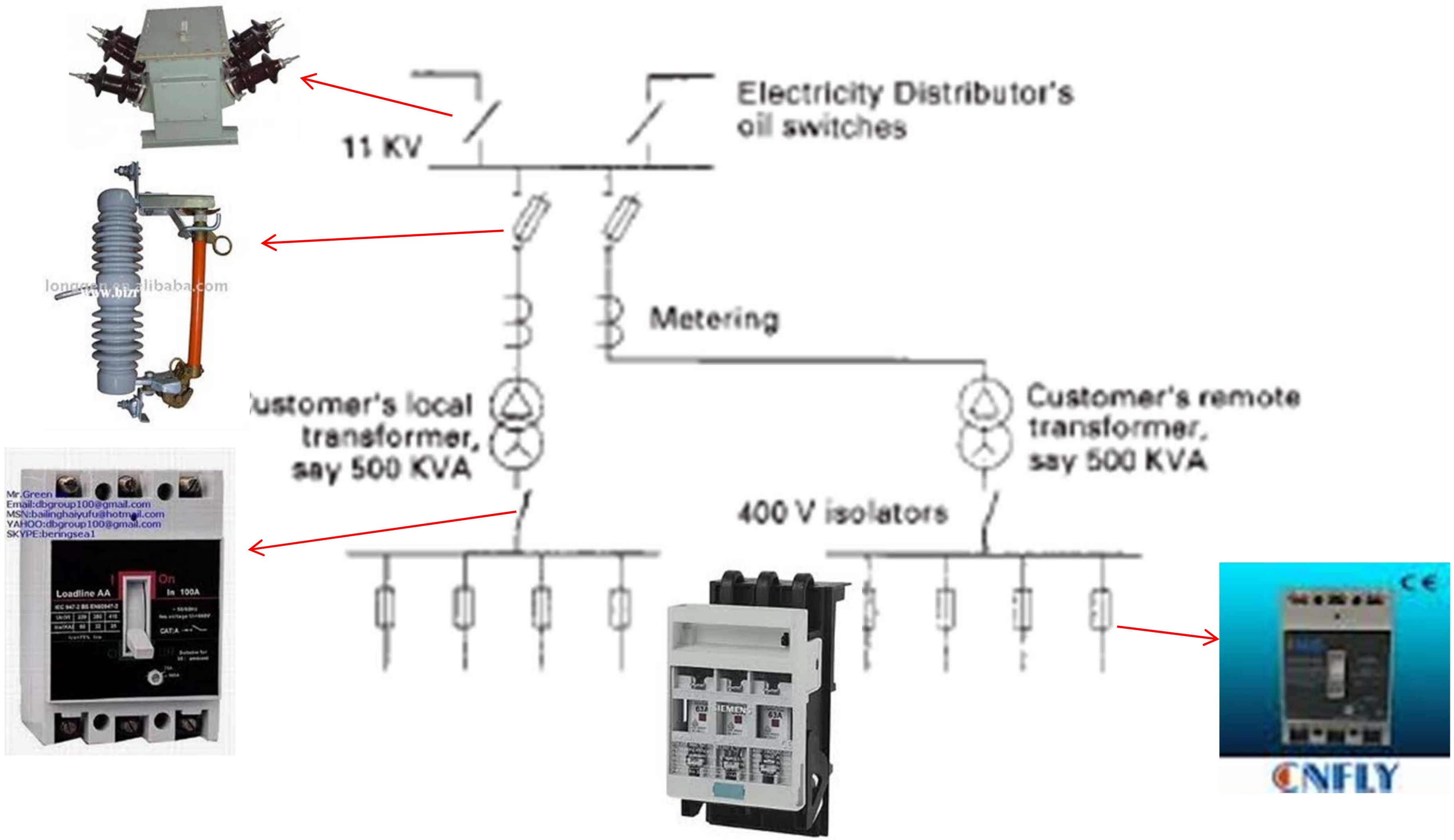
Distribution Substation

A typical ring-main unit incorporating a circuit-breaker in the tee-off circuit

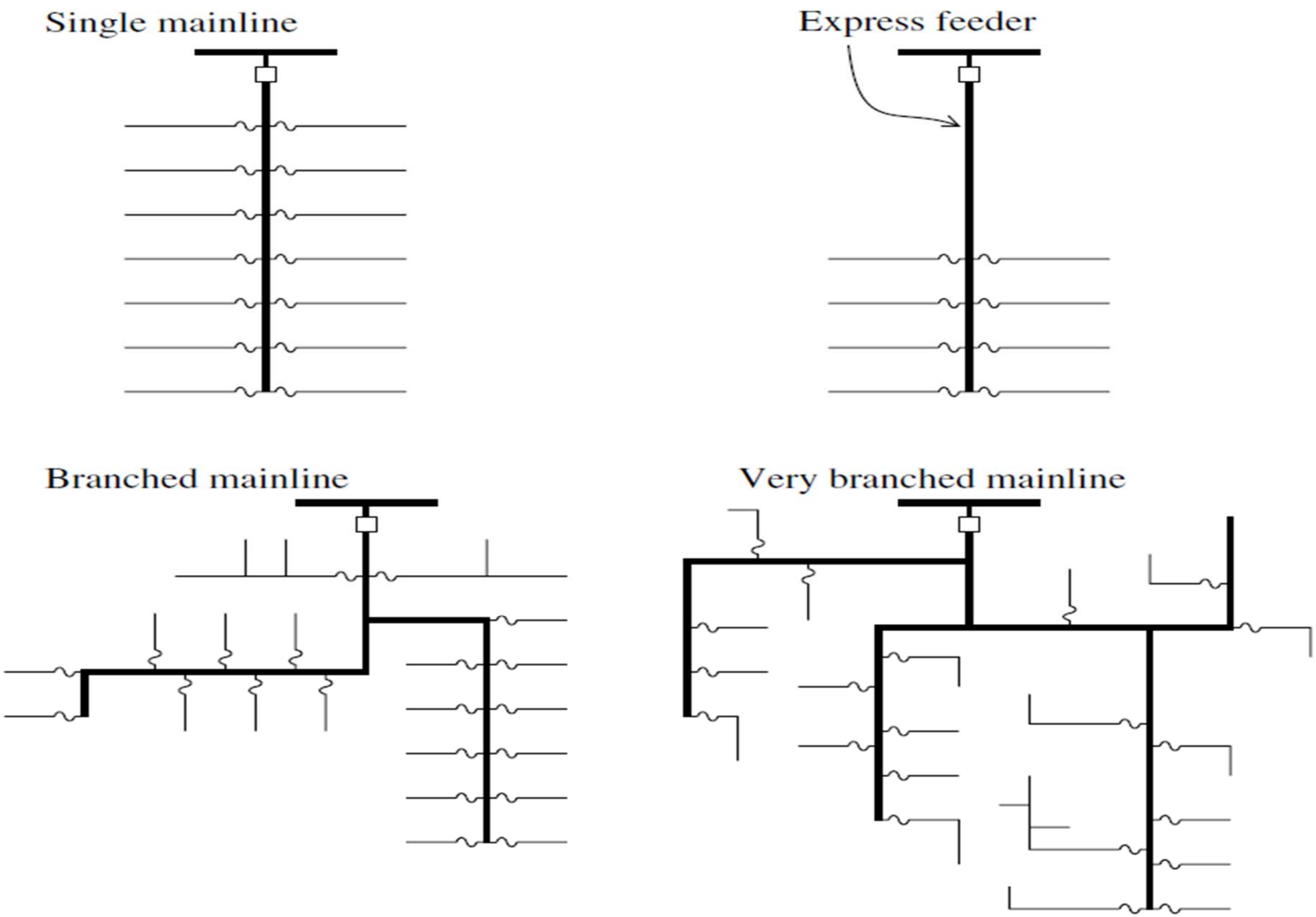


Distribution Substation

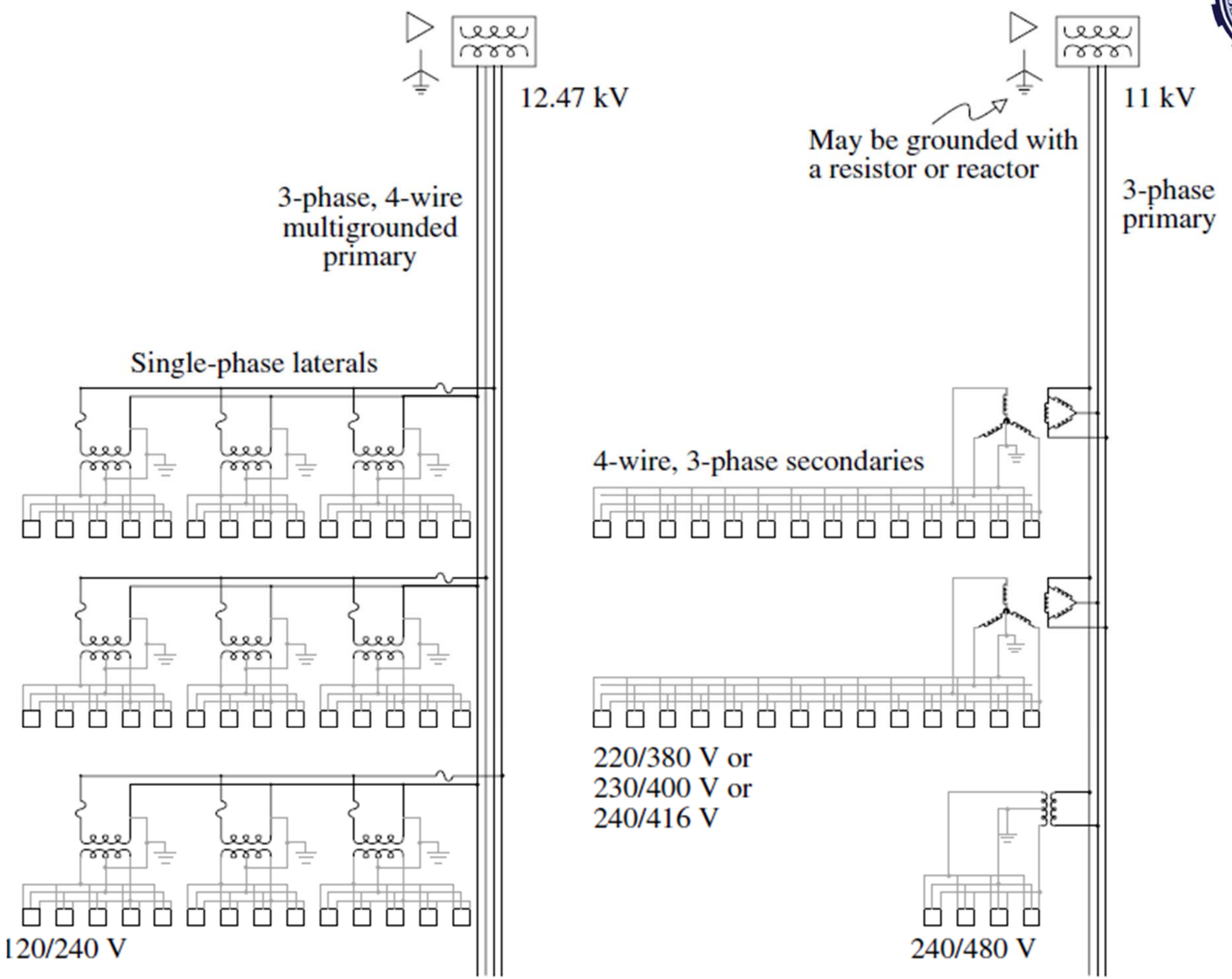
A typical ring-main unit incorporating a fuse-switch in the tee-off circuit



Common distribution primary arrangements.



North American Layout European Layout

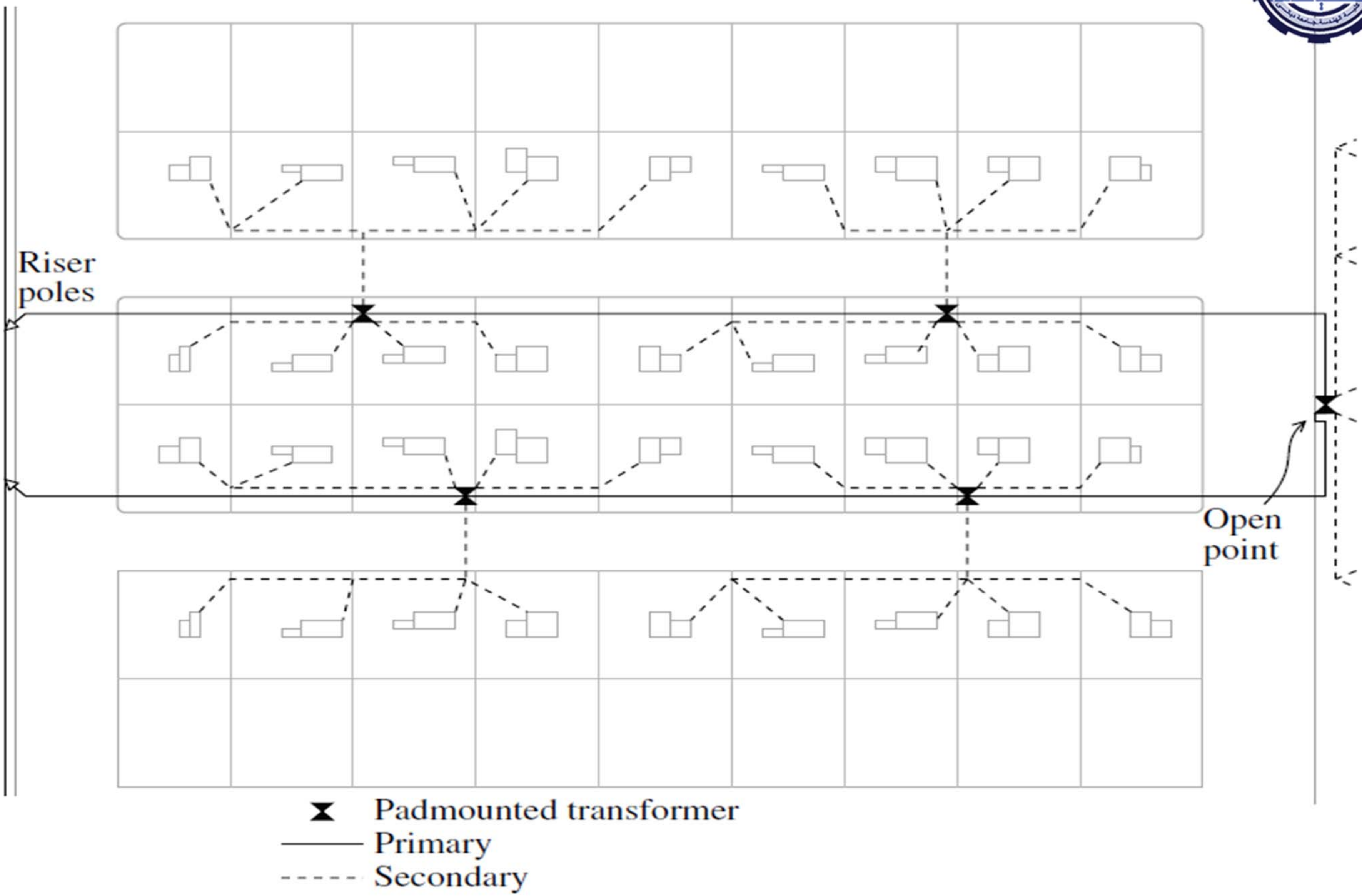


Underground Distribution

One of the main applications of underground circuits is for underground residential distribution (URD), underground branches or loops supplying residential neighborhoods. A classic underground residential distribution circuit is an underground circuit in a loop arrangement fed at each end from an overhead circuit .The loop arrangement allows utilities to restore customers more quickly; after crews find the faulted section, they can reconfigure the loop and isolate any failed section of cable. This returns power to all customers. Overhead and Underground Distribution

Overhead	**Underground**
Cost — Overhead's number one advantage. Significantly less cost, especially initial cost. *Longer life* — 30 to 50 years vs. 20 to 40 for new underground works. *Reliability* — Shorter outage durations because of faster fault finding and faster repair. *Loading* — Overhead circuits can more readily withstand overloads.	*Aesthetics* — Underground's number one advantage. Much less visual clutter. *Safety* — Less chance for public contact. *Reliability* — Significantly fewer short and long-duration interruptions. *Operation & Maintenance* — Notably lower maintenance costs (no tree trimming). *Longer reach* — Less voltage drop because reactance is lower

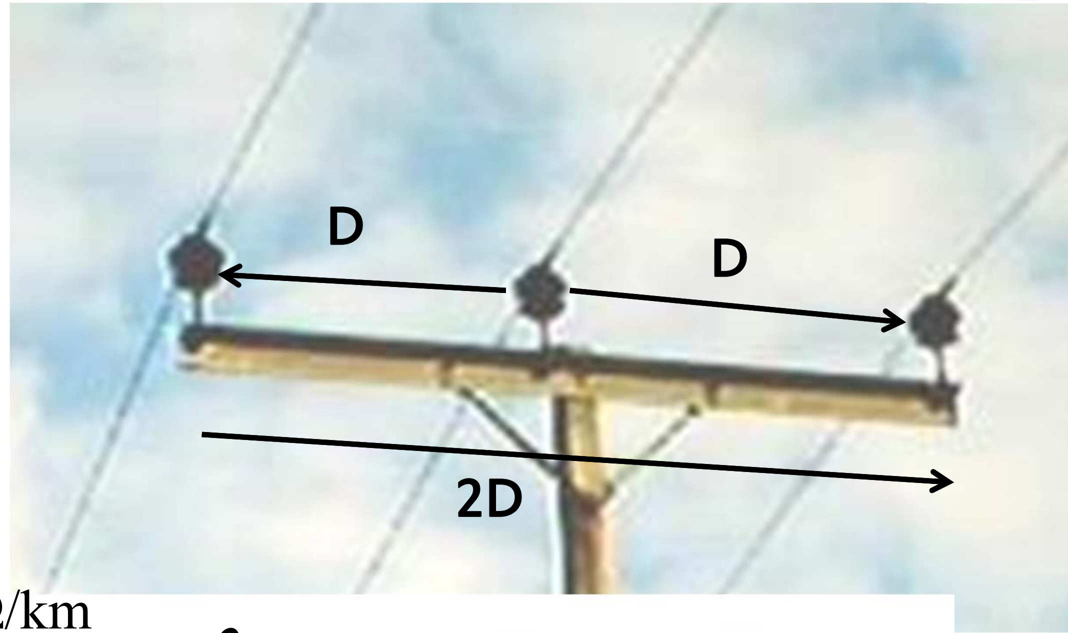
Under Ground Residential Distribution



An example front-lot underground residential distribution (URD) system

Distribution System parameters

Distribution network parameters are used in voltage drop and power losses calculations . The active resistance per unit length (Ro) depends on conductor size and its material and could be found from the corresponding tables of lines and cables. The reactance per unit length (xo) for lines and cables depends mainly on their geometry and could be found from the following equation :



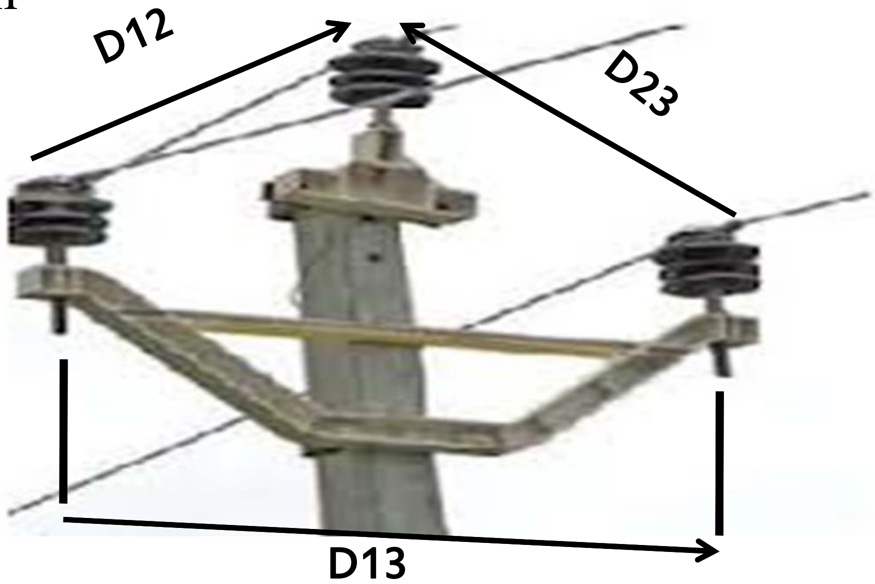
$$X_o = 0.144 \log_{10} \frac{D_{avg}}{GMR} + 0.0157 \ \Omega/\text{km}$$

D_{avg} = average spacing between conductors

GMR = Geometric Mean Radius

$$D_{avg} = \sqrt[3]{2D.D.D} = D.\sqrt[3]{2}$$

$$D_{avg} = \sqrt[3]{D_{12} D_{23} D_{13}}$$



Conductor Data

- For 60 Hz and output units of Ω/1000 ft, GMR, D_{avg} in ft

$$X_o = 0.0529 \ell og_{10} \frac{D_{avg}}{GMR} \quad \Omega/1000\text{ft}$$

- *AAC — all-aluminum conductor:* has the highest conductivity-to-weight ratio of all overhead conductors
- *ACSR — aluminum conductor, steel reinforced*

Because of its high mechanical strength-to-weight ratio, ACSR has equivalent or higher ampacity for the same size conductor

- *AAAC — all-aluminum alloy conductor*
- *ACAR — aluminum conductor, alloy reinforced*
- Copper — has very low resistivity and is widely used as a power conductor, although use as an overhead conductor has become rare because copper is heavier and more expensive than aluminum.

Reading conductors data from Tables (American Std)

- Different sizes of conductors are specified with gage numbers or area in circular mils. Smaller wires are normally referred to using the American wire gage (AWG) system. The gage is a numbering scheme that progresses geometrically. A number 36 solid wire has a defined diameter of 0.005 in. (0.0127cm), and the largest size, a number 0000 (referred to as 4/0 and pronounced
- “four-ought”) solid wire has a 0.46-in. (1.17-cm) diameter. The larger gage sizes in sequence of increasing conductor size are:
- 4, 3, 2, 1, 0 (1/0), 00 (2/ 0), 000 (3/0), 0000 (4/0). Going to the next bigger size (smaller gage number)
- increases the diameter by 1.1229. Some other useful rules are:
- An increase of three gage sizes doubles the area and weight and halves the dc resistance.
- An increase of six gage sizes doubles the diameter.

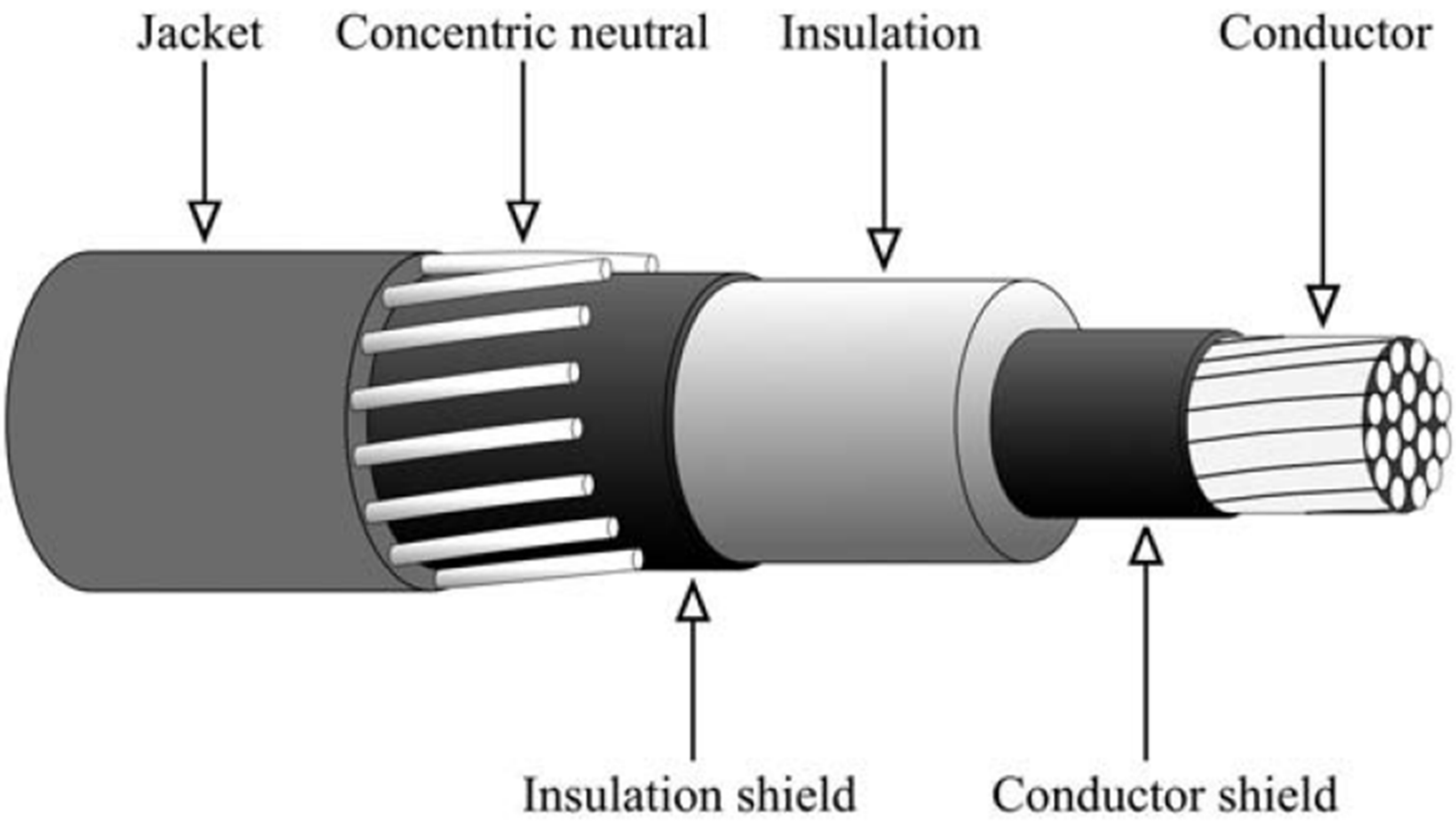
Conductor size in AWG

- Larger conductors are specified in circular mils of cross-sectional area. One circular mil is the area of a circle with a diameter of one mil (one mil is one thousandth of an inch). Conductor sizes are often given in kcmil, thousands of circular mils. By definition, a solid 1000-kcmil wire has a diameter of 1 in. The diameter of a solid wire in mils is related to the area in circular mils by
- Outside of America, most conductors are specified in mm^2. Some useful conversion relationships are:

$$1\,\text{kcmil} = 1000\,\text{cmil} = 785.4 \times 10^{-6}\,\text{in} = 0.5067\text{mm}^2$$

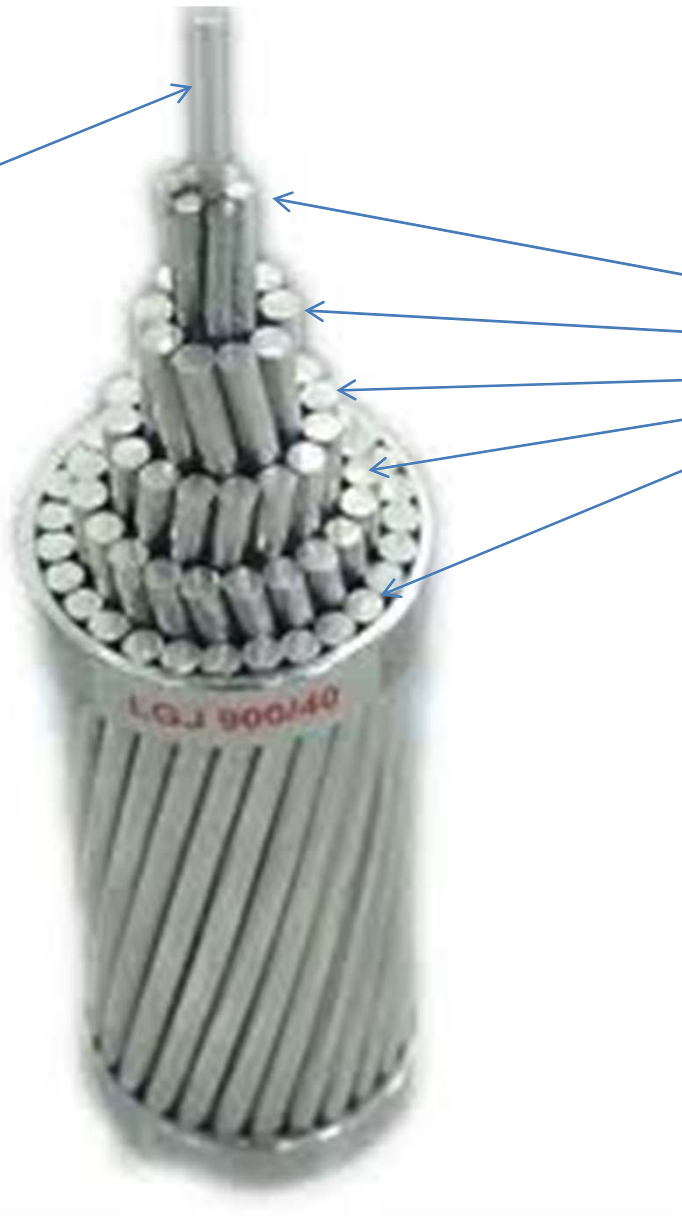
Stranded conductors increase flexibility. A two-layer arrangement has seven wires; a three-layer arrangement has 19 wires, and a four-layer arrangement has 37 wires. The cross-sectional area of a stranded conductor is the cross-sectional area of the metal, so a stranded conductor has a larger diameter than a solid conductor of the same area.

CABLE



Jacket
Concentric neutral
Insulation
Conductor
Insulation shield
Conductor shield

Stranded Conductor



$$\text{No. Strands} = 3n^2 + 3n + 1$$

n = No. of Layers

$$\text{Diameter} = d(2n+1)$$

d = Strand diameter

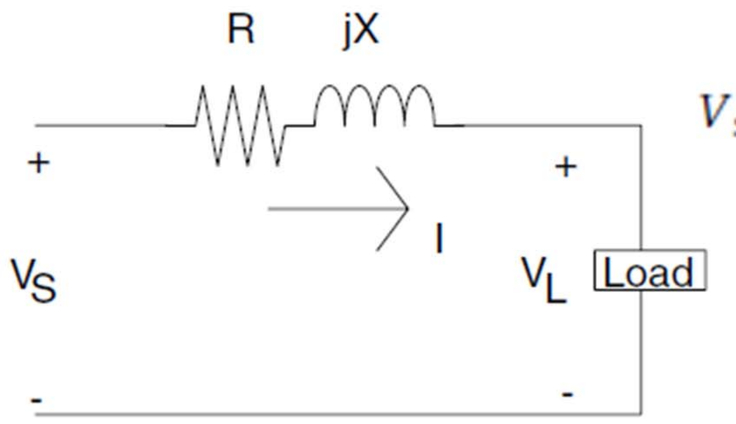
Temperature and Frequency Effect on Resistance

- Temperature and frequency — these change the resistance of a conductor.
- A hotter conductor provides more resistance to the flow of current.
- A higher frequency increases the internal magnetic fields. Current has a difficult time flowing in the center of a conductor at high frequency, as it is being opposed by the magnetic field generated by current flowing on all sides of it. Current flows more easily near the edges. This *skin effect* forces the current to flow in a smaller area of the conductor.
- Resistance changes with temperature as

$$R_{t2} = R_{t2}\frac{M+t_2}{M+t_1},$$

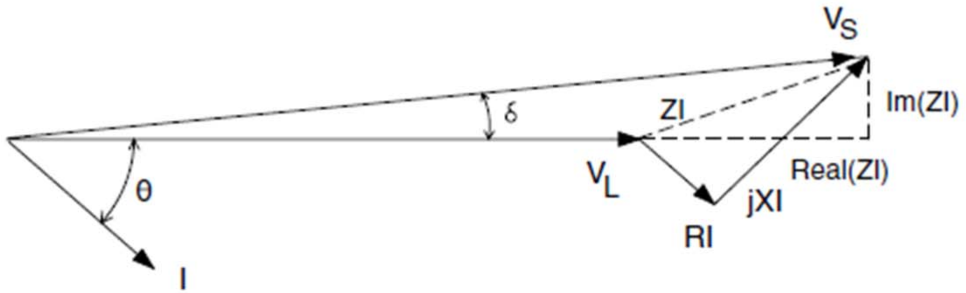
- Rt2= resistance at temperature *t2* given in ℃
- Rt1= resistance at temperature *t1* given in ℃
- *M*= a temperature coefficient for the given material ,
- M = 228.1 for aluminum
- M= 241.5 for annealed hard-drawn copper
- For most distribution power-frequency applications, we can
- ignore *skin effects* (and they are included in ac resistance tables).

Voltage Drop Calculations



$$V_S = V_L + (R + jX) \cdot I = V_L + R \cdot I + jX \cdot I$$

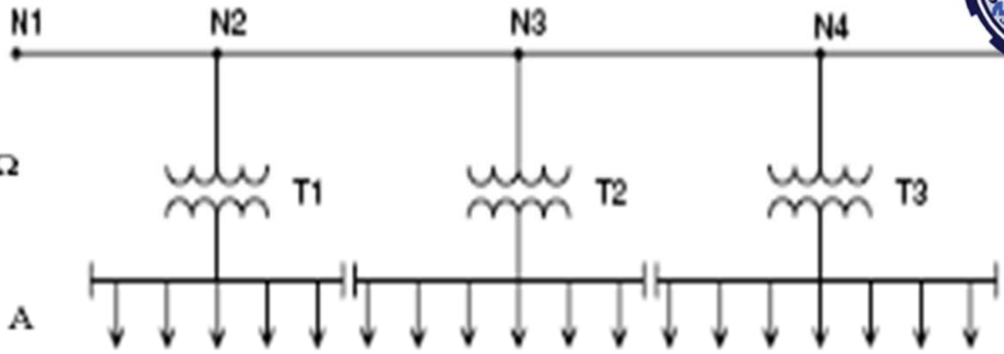
$$V_{drop} = |V_S| - |V_L|$$



The angle between the source voltage and the load voltage (δ) is very small. Because of that, the voltage drop between the source and load voltage is approximately equal to the real part of the impedance drop. That is :- =======> $V_{drop} \equiv \mathrm{Re}(Z \cdot I)$

For the purposes of drop calculation, this equation will be used as the definition of voltage drop.

Example:



$$Z_{12} = 0.2841 + j0.5682\ \Omega$$

The current flowing through the line segment is

$$I_{12} = 43.0093\underline{/-25.8419}\ \text{A}$$

The voltage at node N1 is

$$V_1 = 2400\underline{/0.0}\ \text{V}$$

The exact voltage at node N2 is computed to be

$$V_2 = 2400\underline{/0.0} - (0.2841 + j0.5682)\cdot 43.0093\underline{/-25.8419}$$
$$= 2378.4098\underline{/-0.4015}\ \text{V}$$

The voltage drop between the nodes is then:

$$V_{drop} = 2400.0000 - 2378.4098 = 21.5902\ \text{V}$$

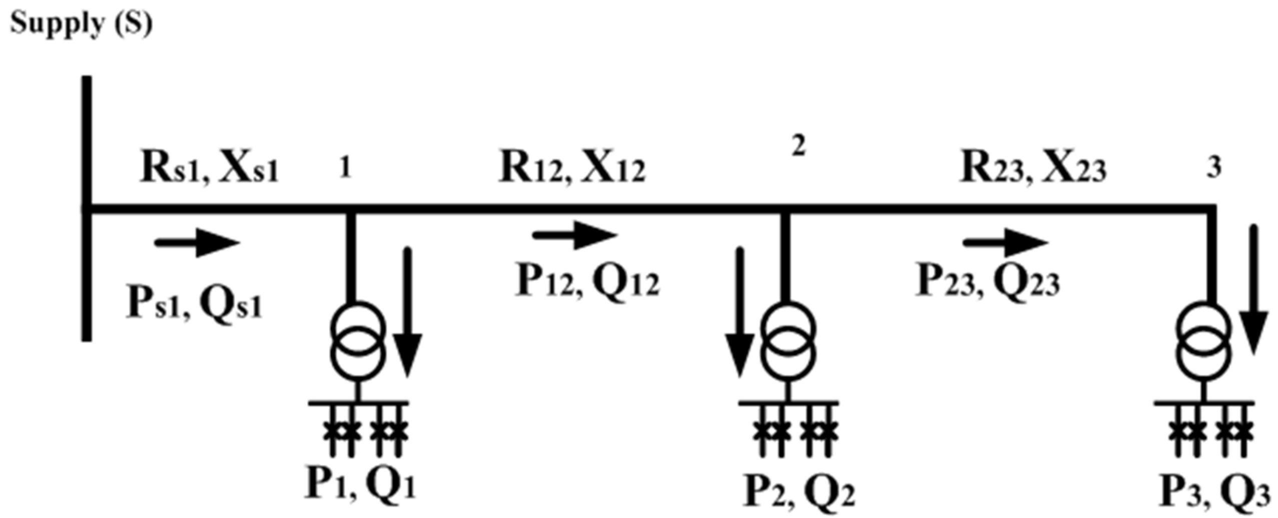
$$V_{drop} = \text{Re}[(0.2841 + j0.5682)\cdot 43.0093\underline{/-25.8419}] = 21.6486\ \text{V}$$

$$\text{Error} = \frac{21.5902 - 21.6486}{21.5902}\cdot 100 = -0.27\%$$

Voltage Drop Calculations

Voltage drop for each section could be calculated by approximated method, where the imaginary part can be neglected as:

$$\Delta V = \frac{P.R + Q.X}{V_{rat}}$$



Voltage drop for section S =>1 could be found as:

$$\Delta V_{s1} = \frac{P_{s1}.R_{s1} + Q_{s1}.X_{s1}}{V_{rat}}$$

$$P_{s1} = P_1 + P_2 + P_3$$

$$Q_{s1} = Q_1 + Q_2 + Q_3$$

$$\Delta V_{12} = \frac{P_{12}.R_{12} + Q_{12}.X_{12}}{V_{rat}}, \qquad P_{12} = P_2 + P_3, \quad Q_{12} = Q_2 + Q_3$$

$$\Delta V_{23} = \frac{P_{23}.R_{23} + Q_{23}.X_{23}}{V_{rat}}, \qquad P_{23} = P_3, \quad Q_{23} = Q_3$$

Voltage drop at the end of the feeder could be found as:

$$\Delta V = \Delta V_{s1} + \Delta V_{12} + \Delta V_{23}$$

Distribution System Losses Calculations

- **Transformer losses**
- **It** could be found from the following equation

$$\Delta P = \Delta P_i + \Delta P_c \left(\frac{S}{S_{rat}}\right)^2 \ \text{KW}$$

- ΔP: Total transformer losses
- ΔPi: Iron transformer losses (Independent of load)
- ΔPc: Copper transformer losses (Load losses)
- S_{rat}: The nameplate rated power of transformer
- S: The transformer actual load
- For n number of parallel operating transformers

$$\Delta P = n\Delta P_i + \frac{1}{n}\Delta P_c \left(\frac{S}{S_{rat}}\right)^2 \ \text{KW}$$

- S_{rat}: The nameplate rated power of one transformer of group
- S: The total load on all transformers
- Daily and annual losses can be found by

$$\Delta E = \sum \Delta P \times \Delta t \ \text{KWh}$$

- **Line and cable losses**

$$\Delta P = 3I^2R, \ I = \frac{s}{\sqrt{3}V}$$

$$\Delta P = 3\frac{S^2}{3V^2}R = \frac{P^2 + Q^2}{V^2}\text{R} \quad \text{KW}$$

Factors Affecting Distribution-System Losses:

- Inadequate Size of Conductor.
- Feeder Length.
- Location of Distribution Transformers.
- Low Voltage.
- Use of Over-Rated Distribution Transformers.
- Low Power Factor.

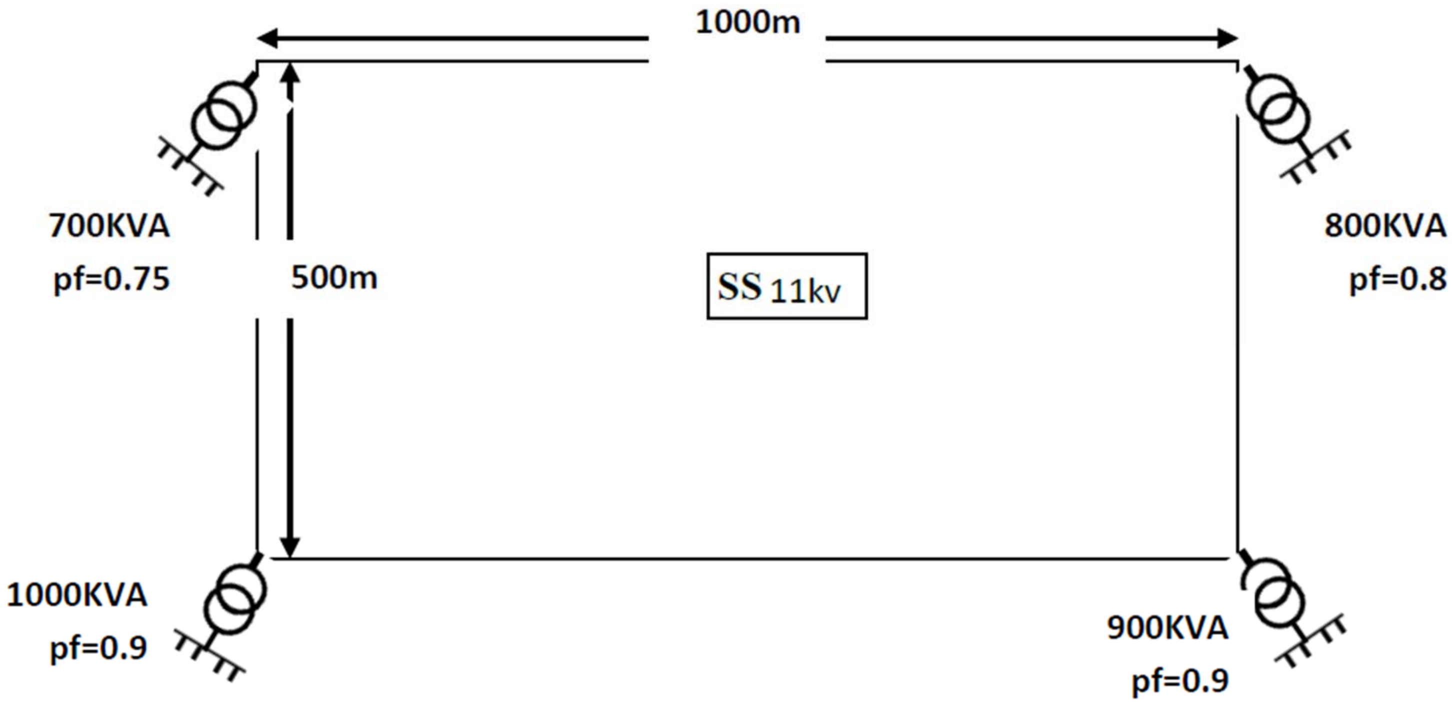
Problem1

For the load area shown in the Fig. 1,

a. Design a reliable distribution system scheme to supply all four loads by the substation (SS.11kv) located in the center. Consider tie switches for emergencies.

b. Select the suitable size and length of each piece of 11kv XLPE cable used in the design.

c. Calculate the maximum expected voltage drop in the system.



Methods For The Reduction Of Line Losses:

1. HV Distribution System.
2. Feeder Reconfiguration.
3. Reinforcement Of The Feeder.
4. Grading Of Conductor.
5. Construction Of New Substation.
6. Reactive Power Compensation.

Economic Number of Transformers

- In the case of daily and annual load variation and when several transformers are operating in parallel, it is more economical to switch transformers ON and OFF in accordance with the load curve

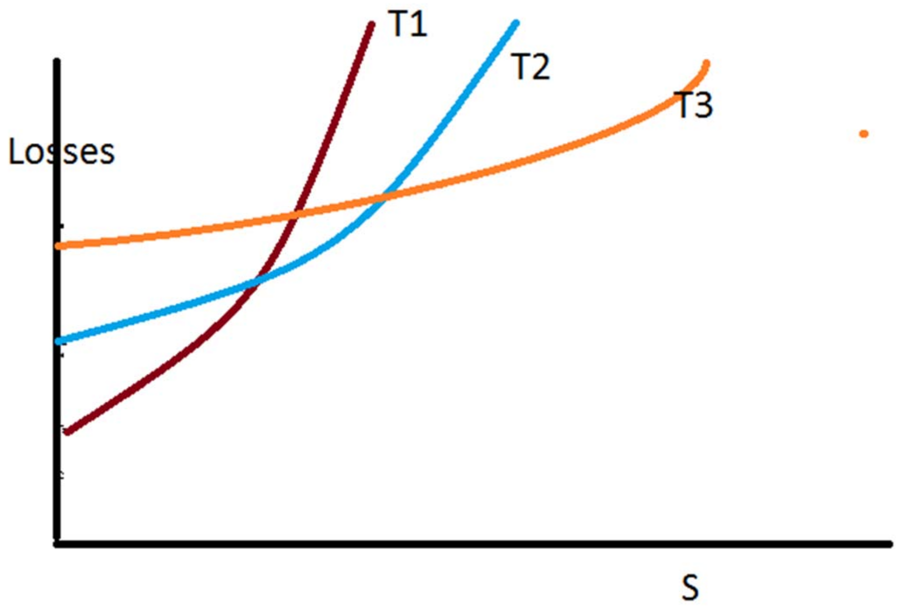
$$\Delta P_n = n\Delta P_i + \frac{1}{n}\Delta P_c\left(\frac{S}{S_{rat}}\right)^2 \text{ KW}$$

$$\Delta P_{n+1} = (n+1)\Delta P_i + \frac{1}{n+1}\Delta P_c\left(\frac{S}{S_{rat}}\right)^2 \text{ KW}$$

$$\Delta P_n = \Delta P_{n+1}$$

$$S = S_{rat}\sqrt{\frac{\Delta P_i}{\Delta P_c}.n(n+1)}$$

$$n(n+1) = \frac{\Delta P_c}{\Delta P_i}\left(\frac{S}{S_{rat}}\right)^2$$



- By solving the above equation the economical number of transformers can be determined for the specified demand