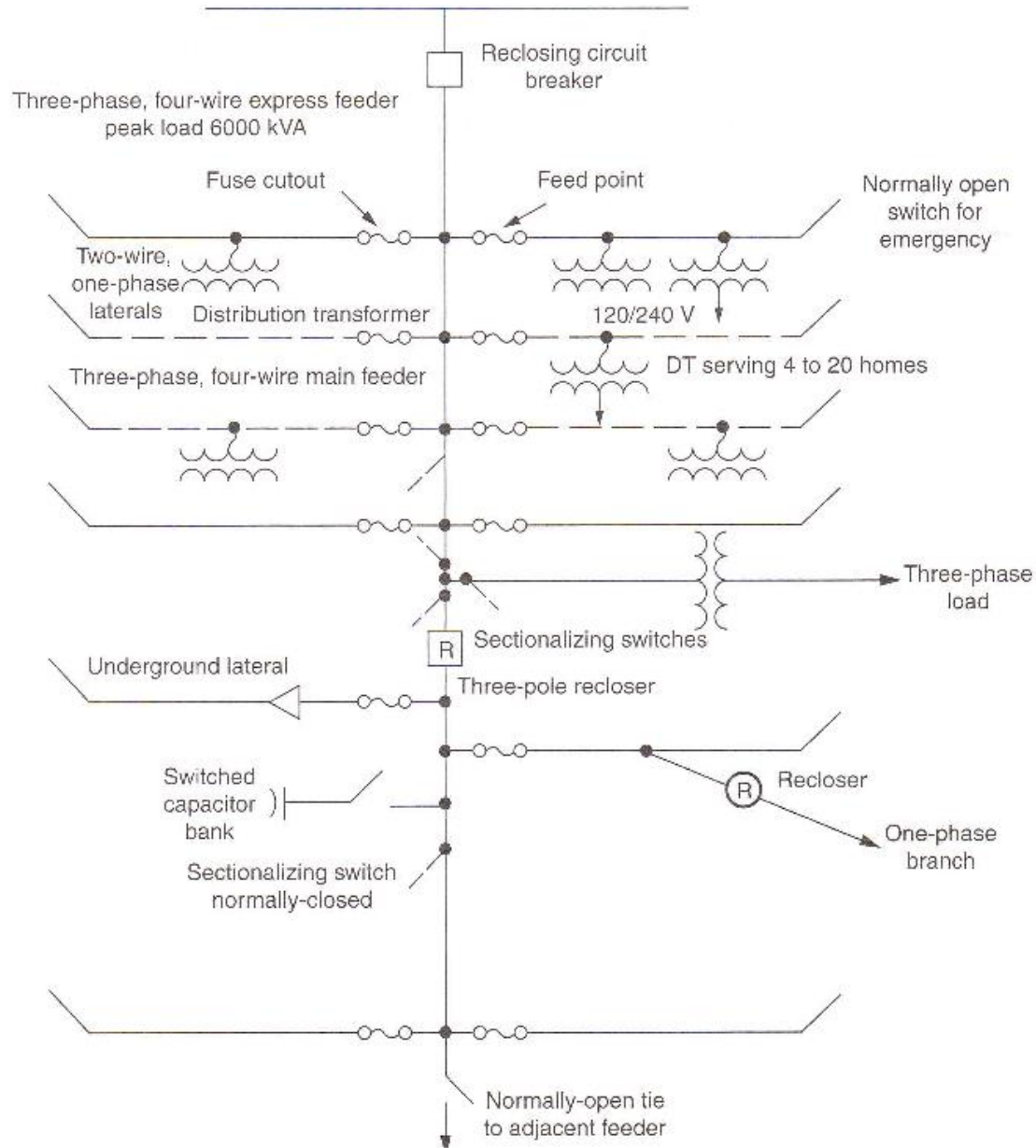


EE 741

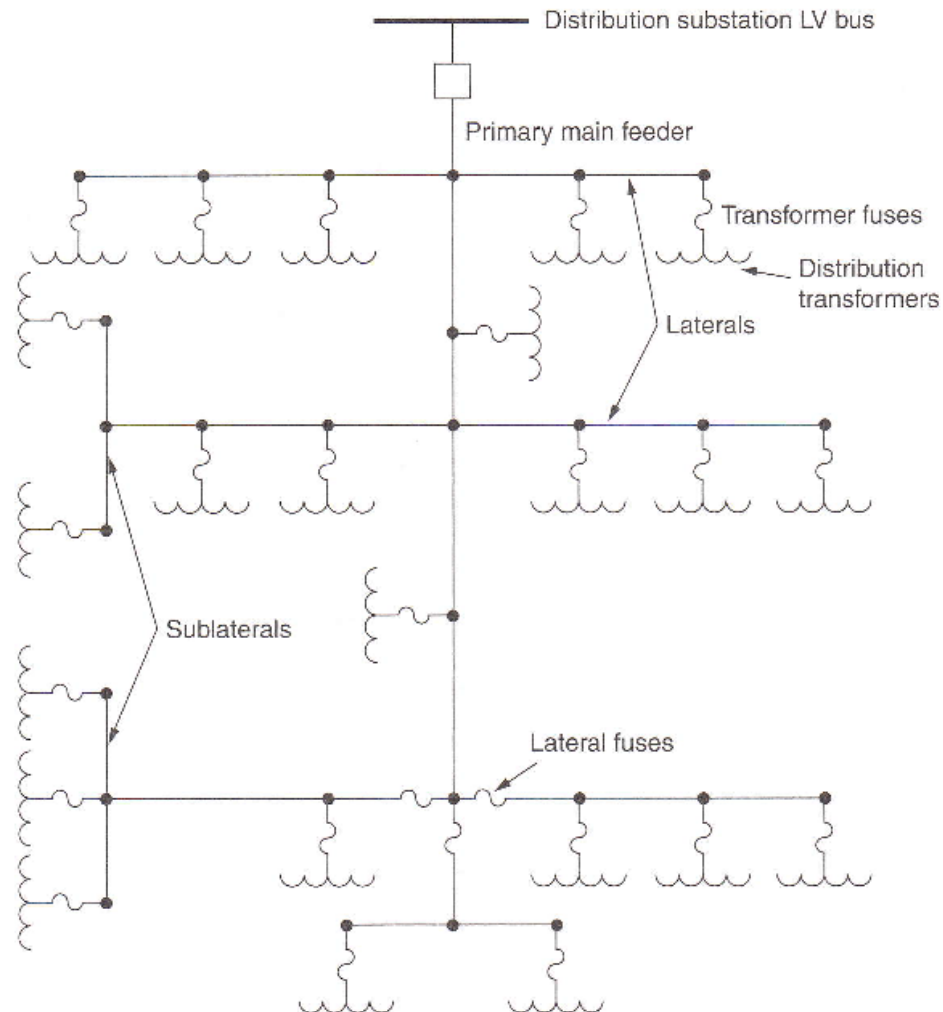
Primary and Secondary Distribution System

One-Line Diagram of Typical Primary Distribution System



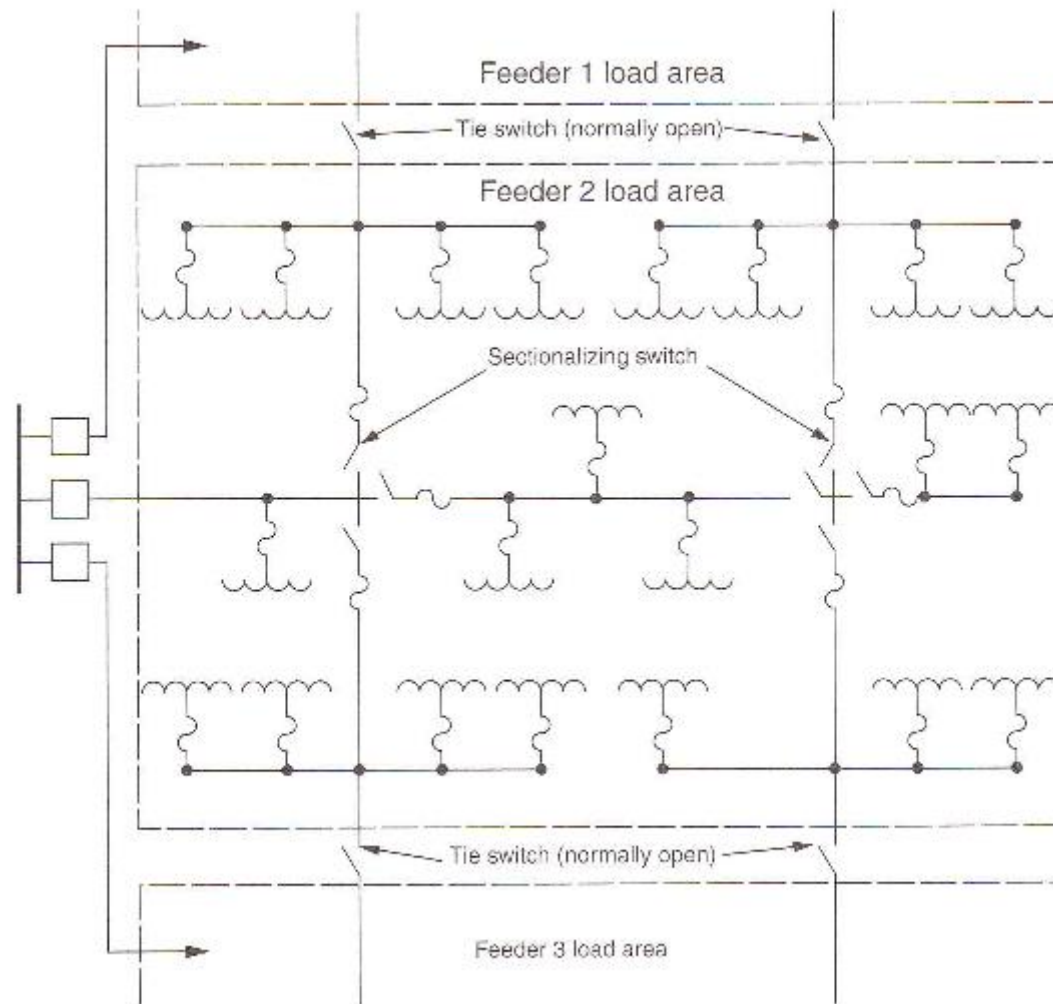
Radial-Type Primary Feeder

- Most common, simplest and lowest cost

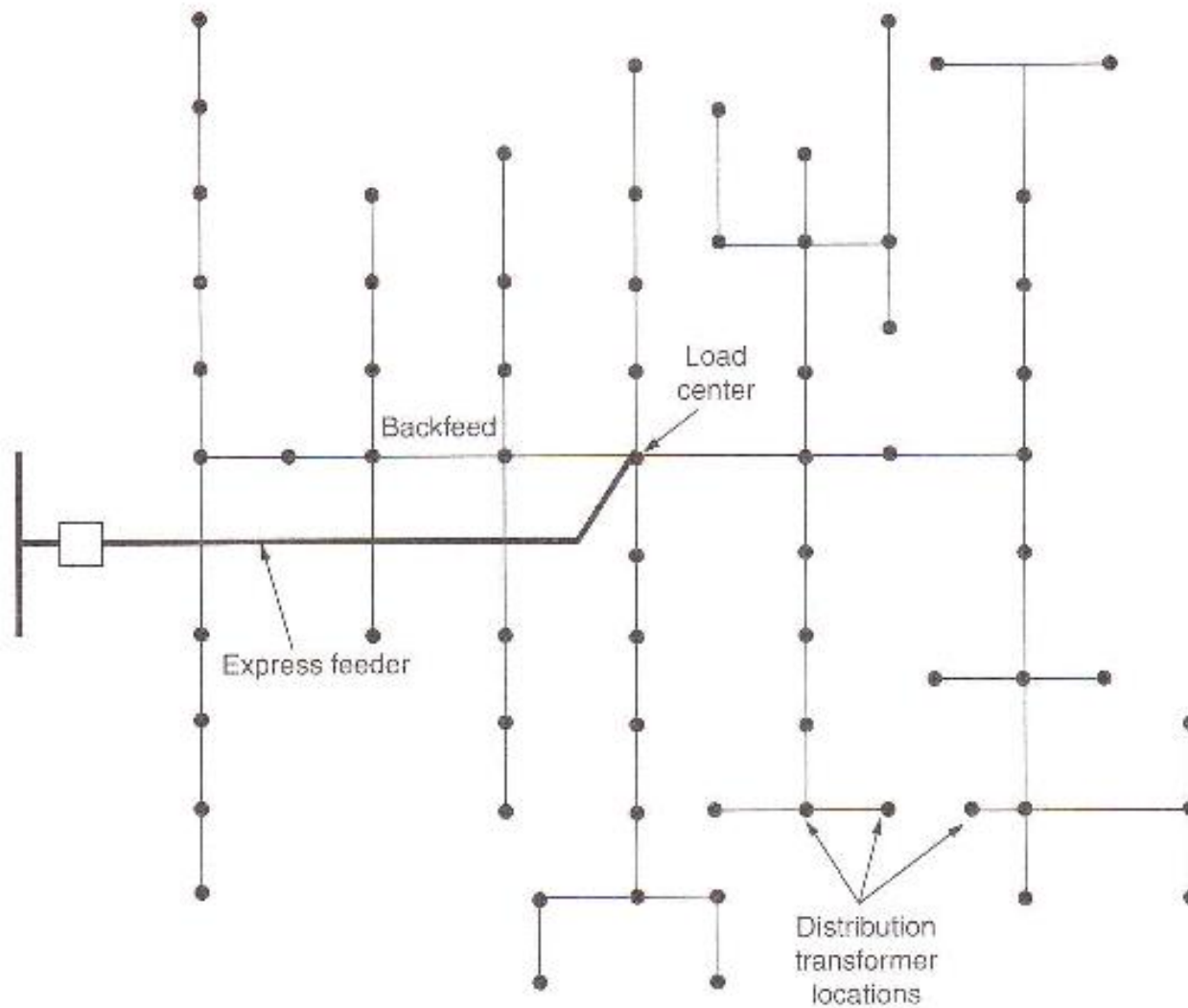


Radial-Type Primary Feeder with Tie and Sectionalizing Switches

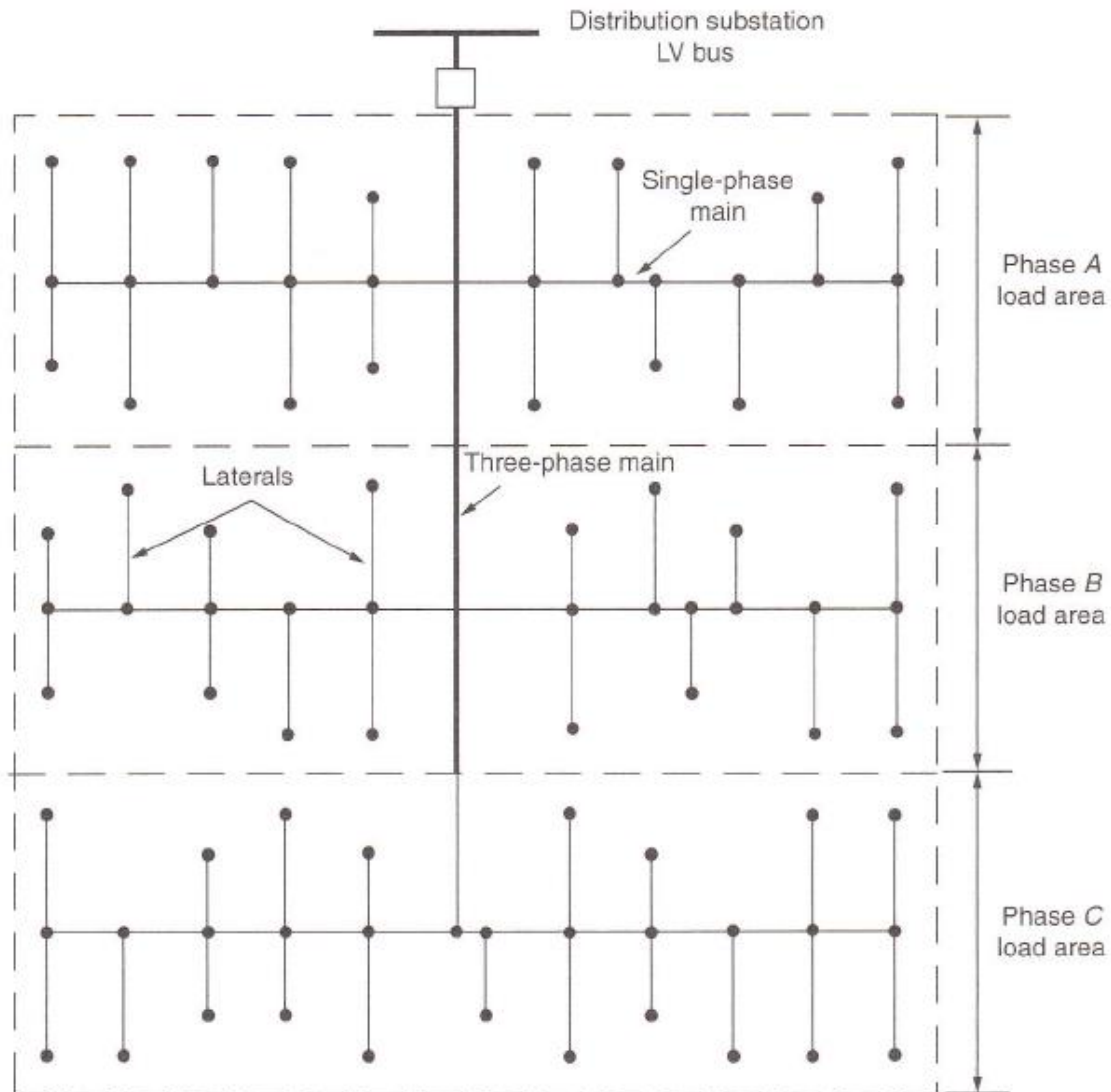
- Higher service reliability
- Fast restoration of service by switching un-faulted sections of the feeder to adjacent primary feeders



Radial-Type Primary with Express Feeder

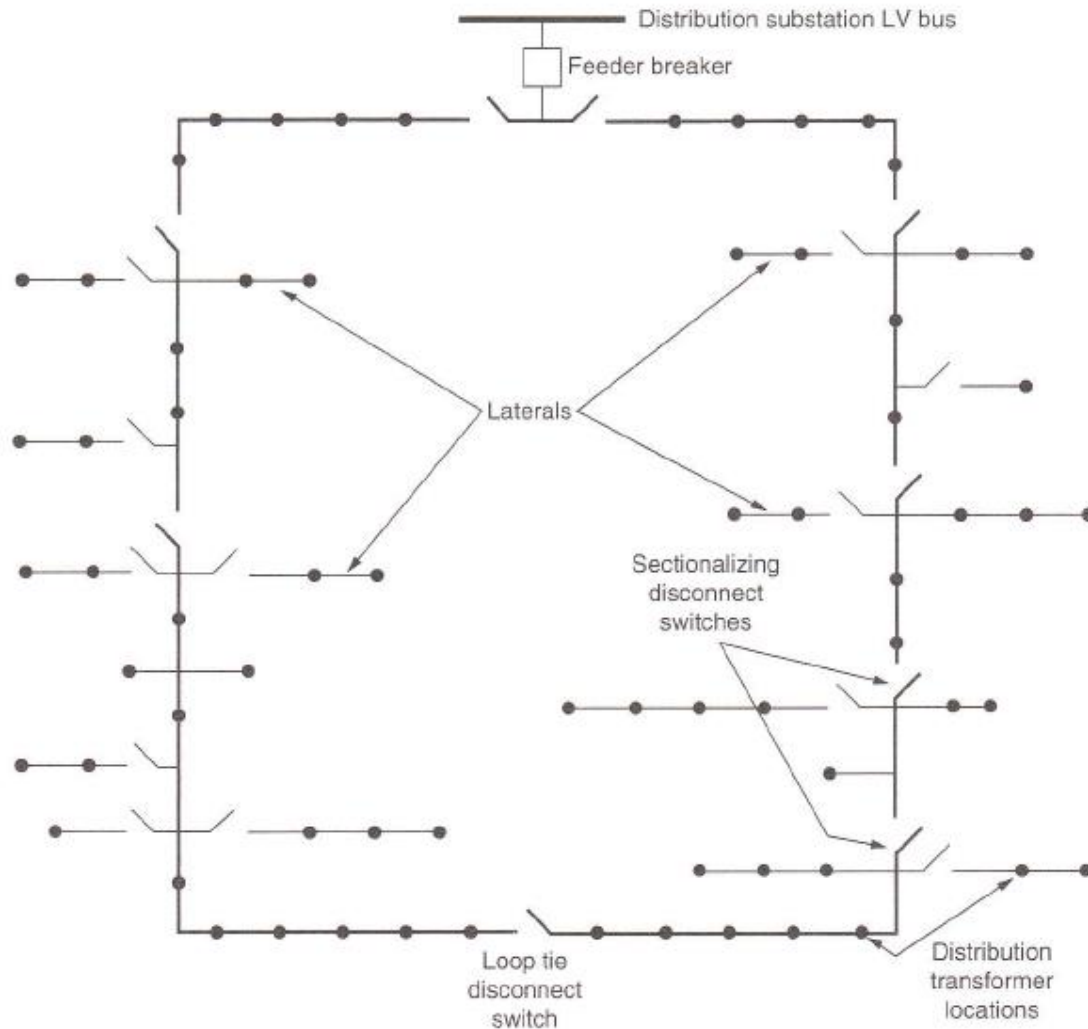


Radial-Type Phase Area Feeder



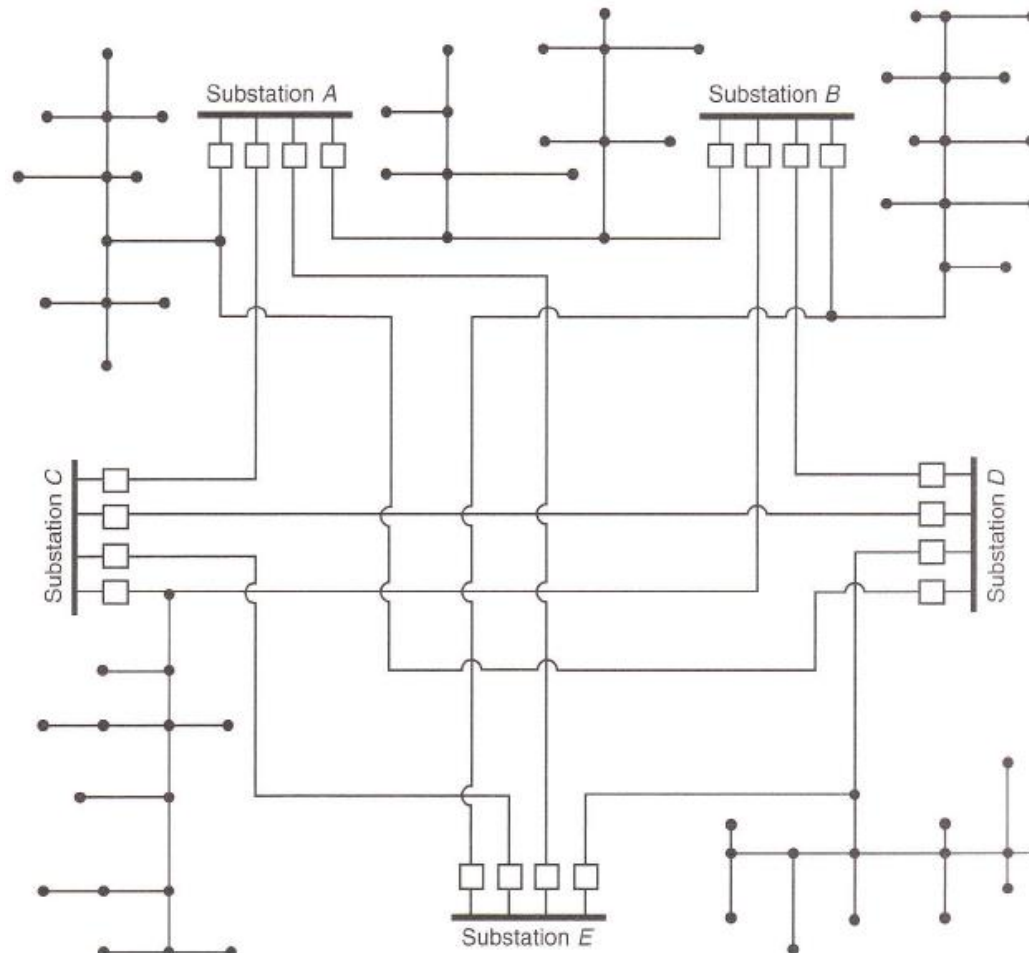
Loop Type Primary Feeder

- Loop tie disconnect switch normally open or normally closed

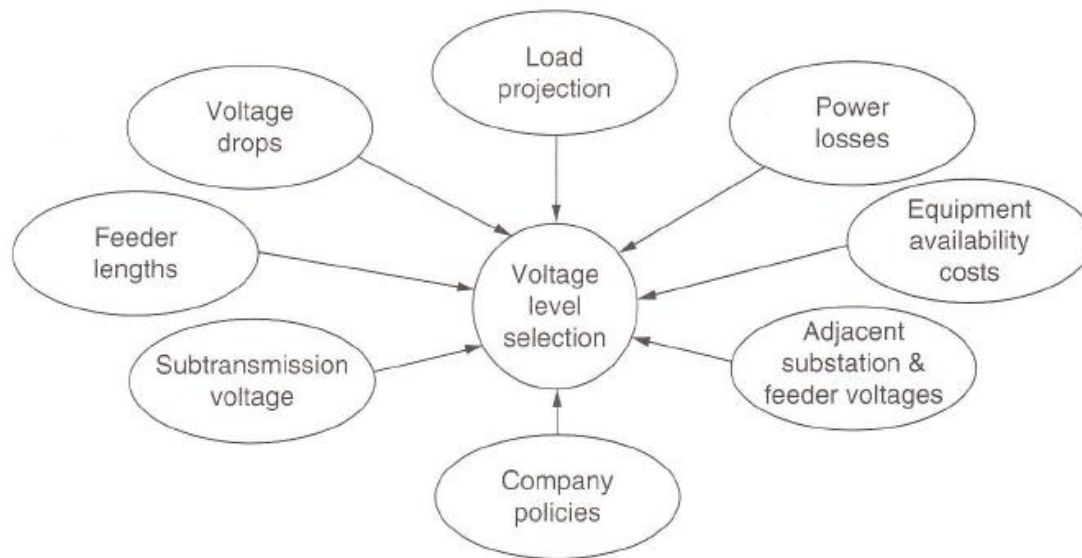


Primary Network

- Supplied by multiple substations
- Load supplied from multiple directions
- Highest reliability but more difficult to operate



Primary Voltage Levels & Factors Affecting Selection



Typical Primary Voltage Levels

Class		3 ϕ Voltage
2.5 kV	2300	3W- Δ
	2400*	3 W- Δ
5.0 kV	4000	3W- Δ or 3W-Y
	4160*	4W-Y
	4330	3W- Δ
	4400	3W- Δ
	4600	3W- Δ
	4800	3W- Δ
	6600	3W- Δ
8.66 kV	6900	3W- Δ or 4W-Y
	7200*	3W- Δ or 4W-Y
	7500	4W-Y
	8320	4W-Y
15 kV	11000	3W- Δ
	11500	3W- Δ
	12000	3W- Δ or 4W-Y
	12470*	4W-Y
	13200*	3W- Δ or 4W-Y
	13800*	3W- Δ
	14400	3W- Δ
25 kV	22900*	4W-Y
	24940*	4W-Y
34.5 kV	34500*	4W-Y

* Most common voltage in the individual classes.

Voltage Square Rule

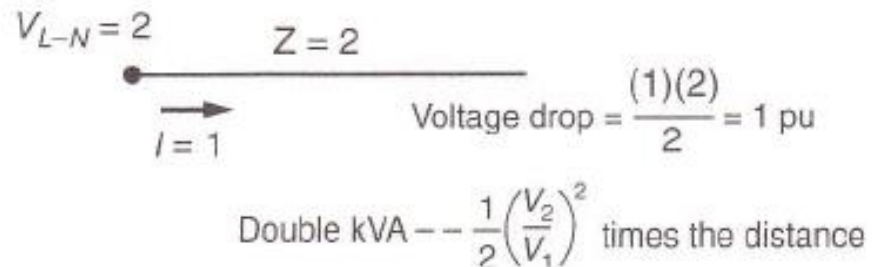
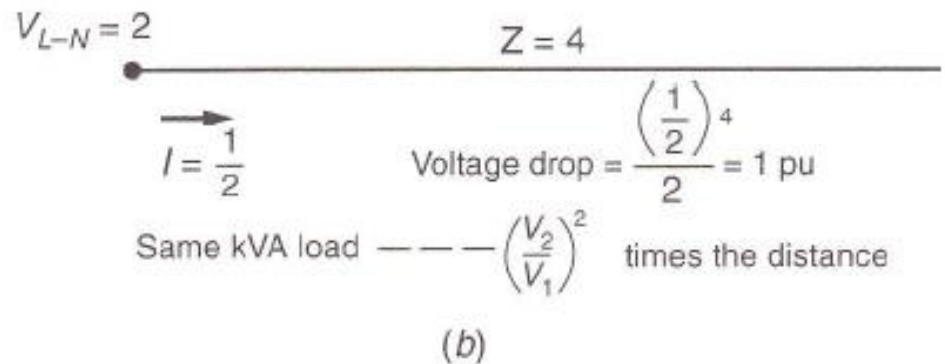
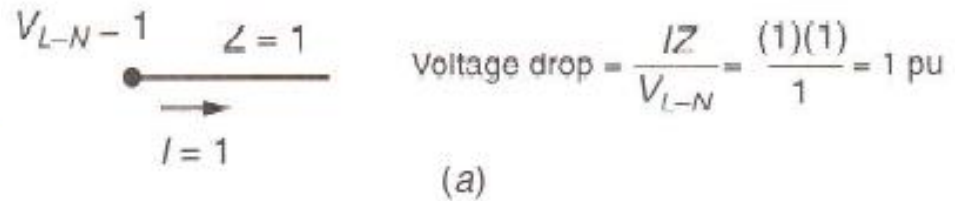
(for same voltage drop)

$$\text{Voltage-square factor} = \left(\frac{V_{L-N, \text{new}}}{V_{L-N, \text{old}}} \right)^2$$

Distance ratio $\times$ load ratio = voltage-square factor

$$\text{Distance ratio} = \frac{\text{new distance}}{\text{old distance}}$$

$$\text{Load ratio} = \frac{\text{new feeder loading}}{\text{old feeder loading}}$$



Feeder Area Coverage Principle

(if both dimensions of feeder service area change by the same proportion)

$$\left[\left(\frac{V_{L-N, \text{ new}}}{V_{L-N, \text{ old}}} \right)^2 \right]^{2/3}$$

$V_{L-N} = 1$ Load area



Per unit VD = 1
Area served = 1
Load = 1

(a)

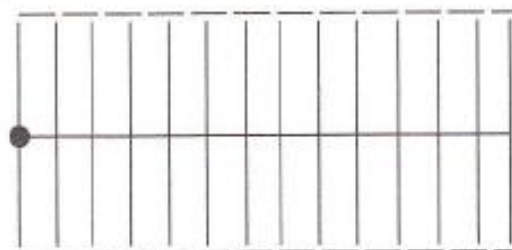
$V_{L-N} = 2$



VD = 1
Area served = 2
Load = 2

(b)

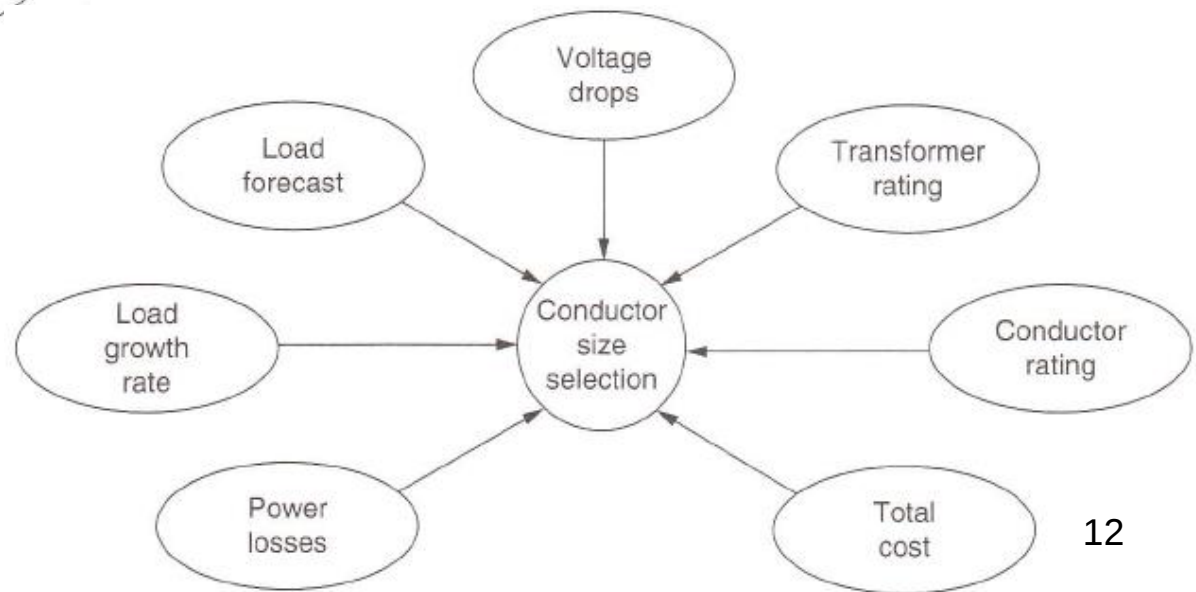
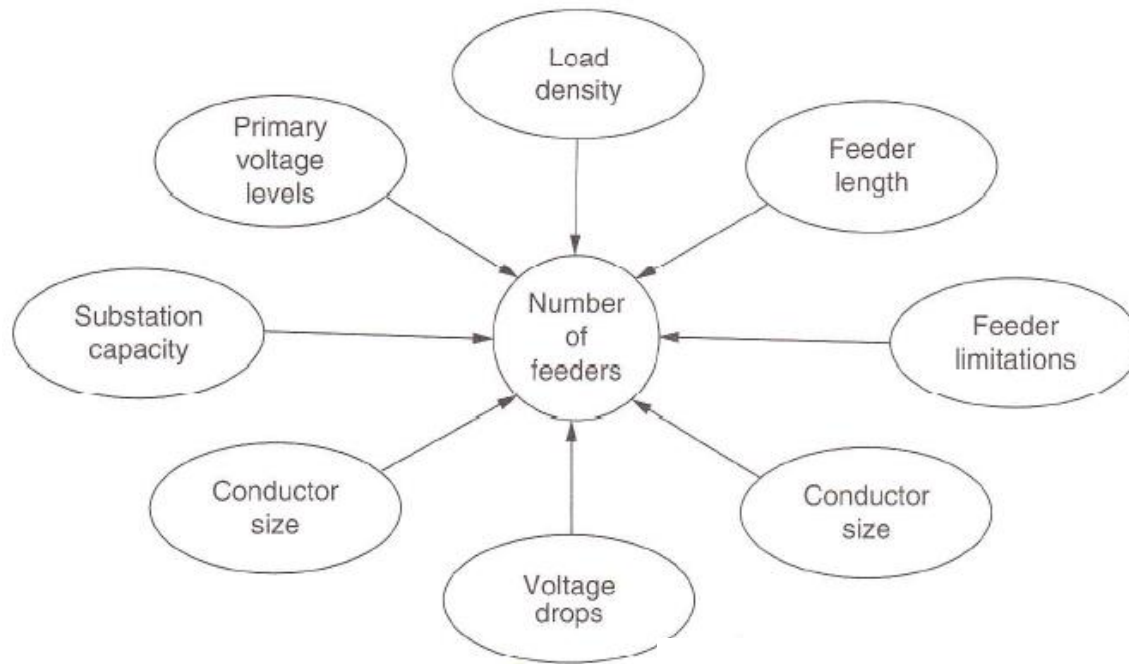
$V_{L-N} = 2$



VD = 1
Area served = 2.52
Load = 2.52

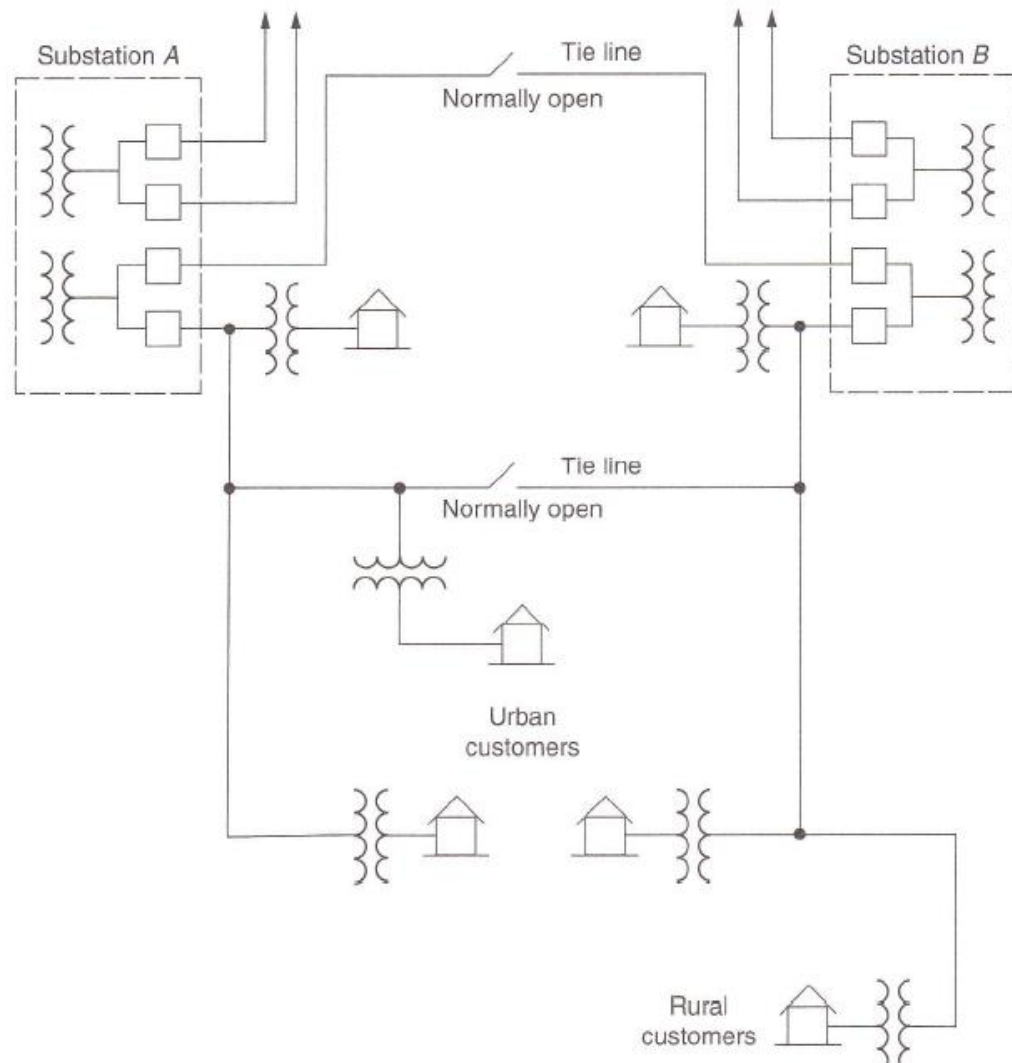
(c)

Factor Affecting Number of Feeders and Conductor Size Selection

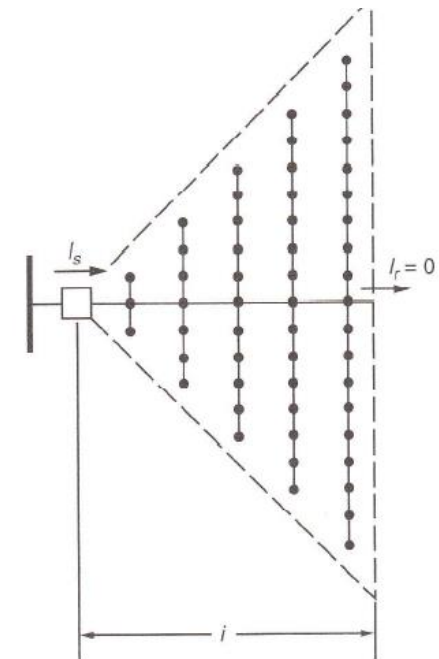
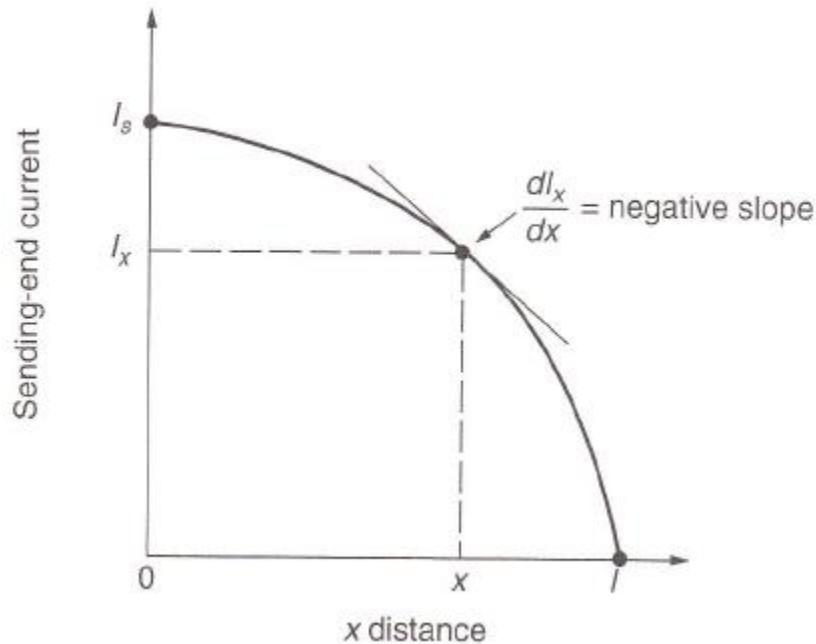
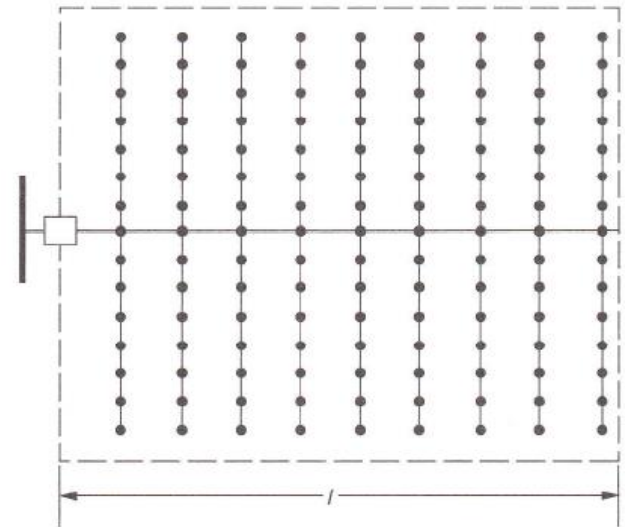
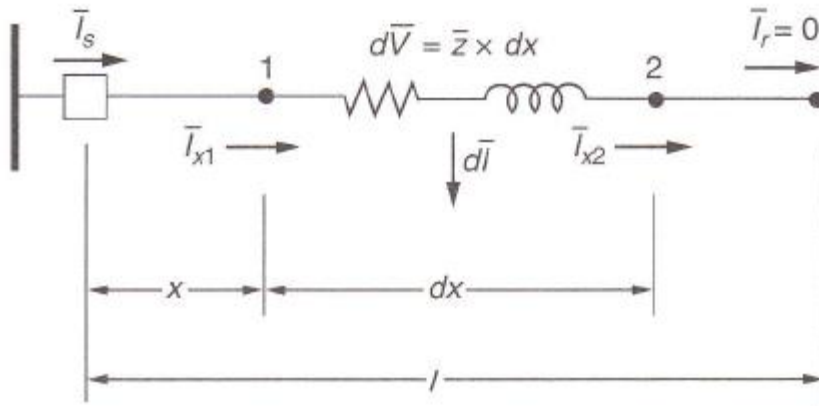


Tie Lines

- Provides emergency service from an adjacent feeder to customers thereby reducing outage time.



Voltage drop and Power Loss in Radial Feeder with Uniformly Distributed Load and Uniformly Increasing Load



Voltage drop and Power Loss in Radial Feeder with Uniformly Distributed Load and Uniformly Increasing Load

Uniformly Distributed Load:

$$VD = \frac{1}{2} z l I_s$$

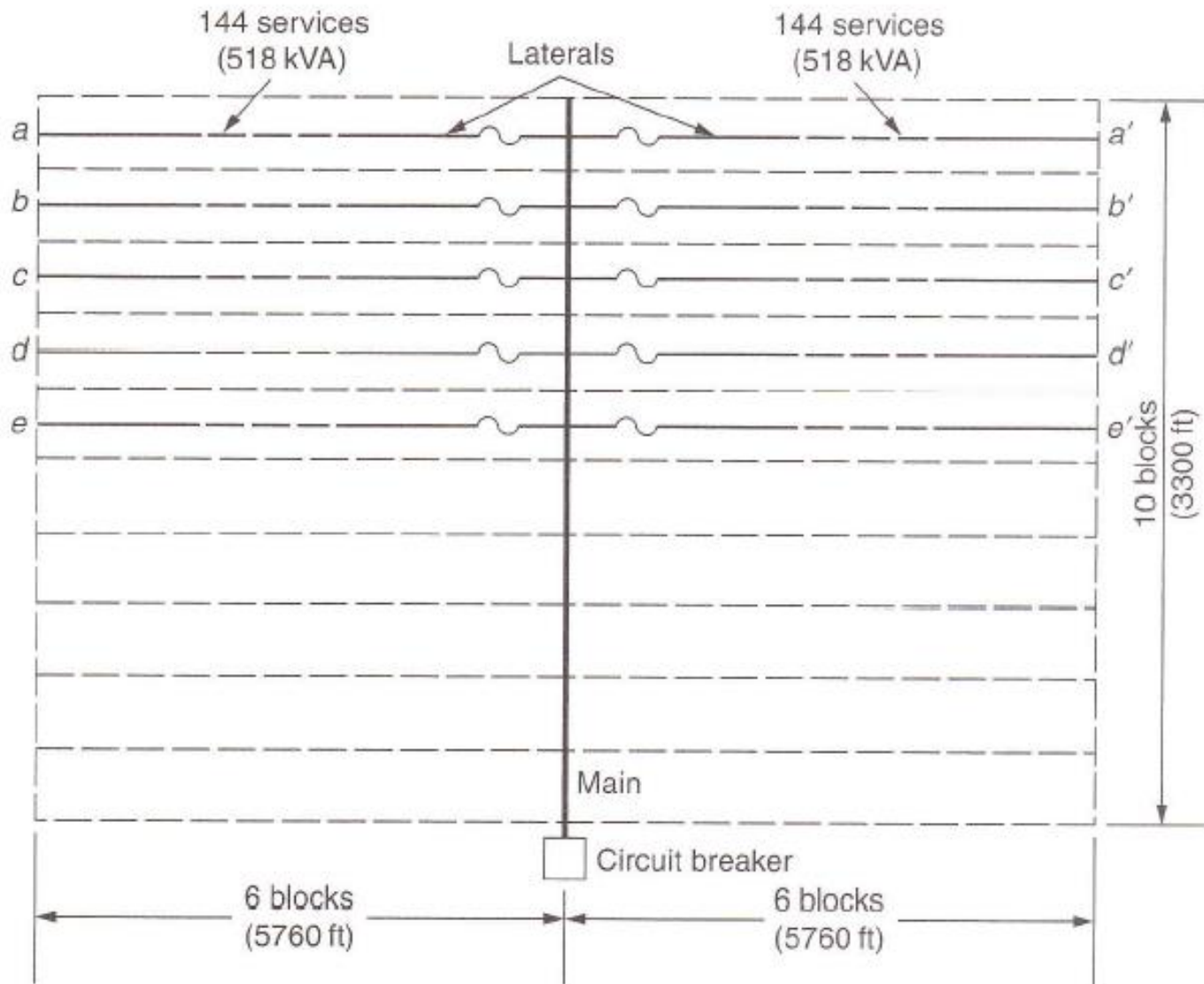
$$P_{loss} = \frac{1}{3} r l I_s^2$$

Uniformly Increasing Load:

$$VD = \frac{2}{3} z l I_s$$

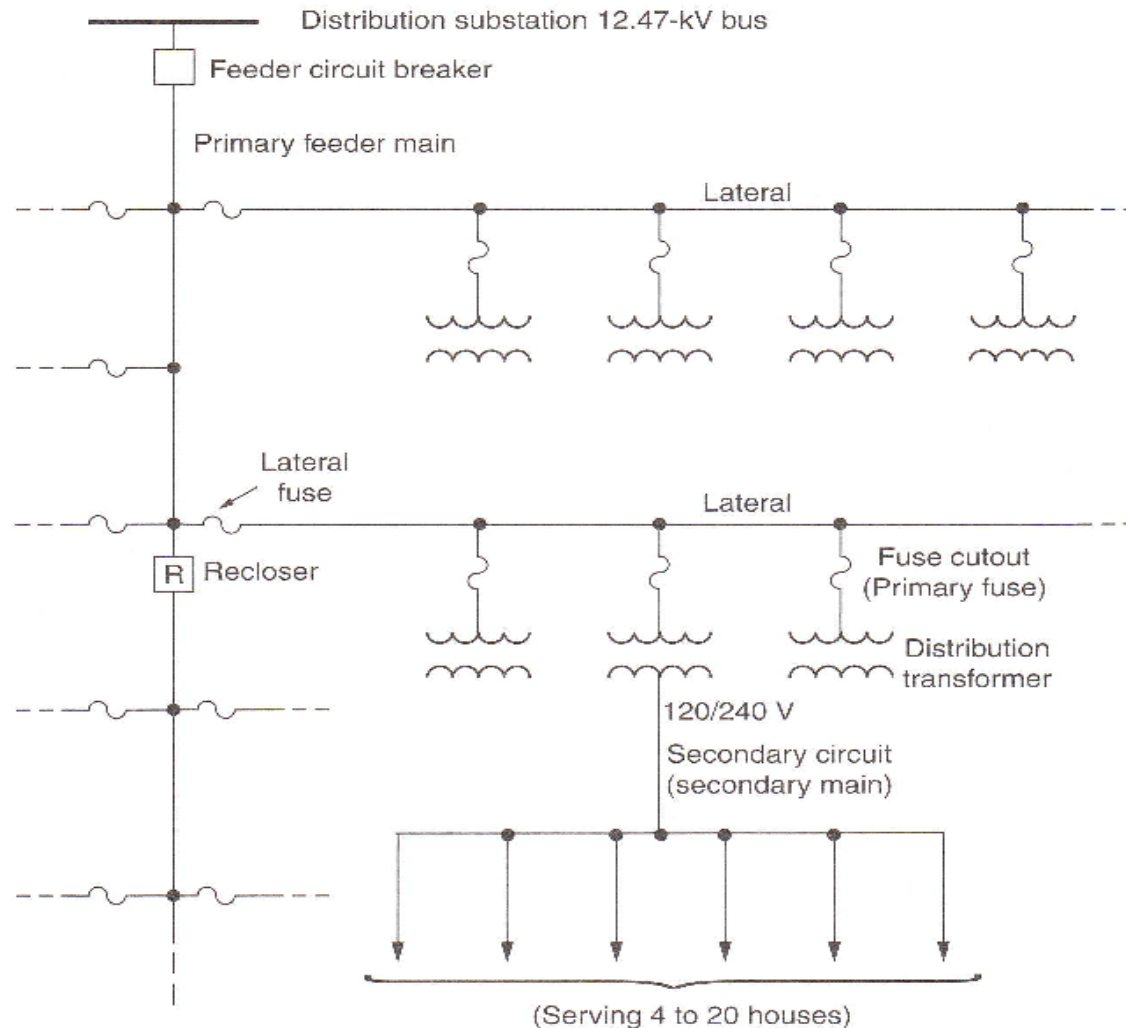
$$P_{loss} = \frac{8}{15} r l I_s^2$$

Example of Overhead Primary Feeder Layout



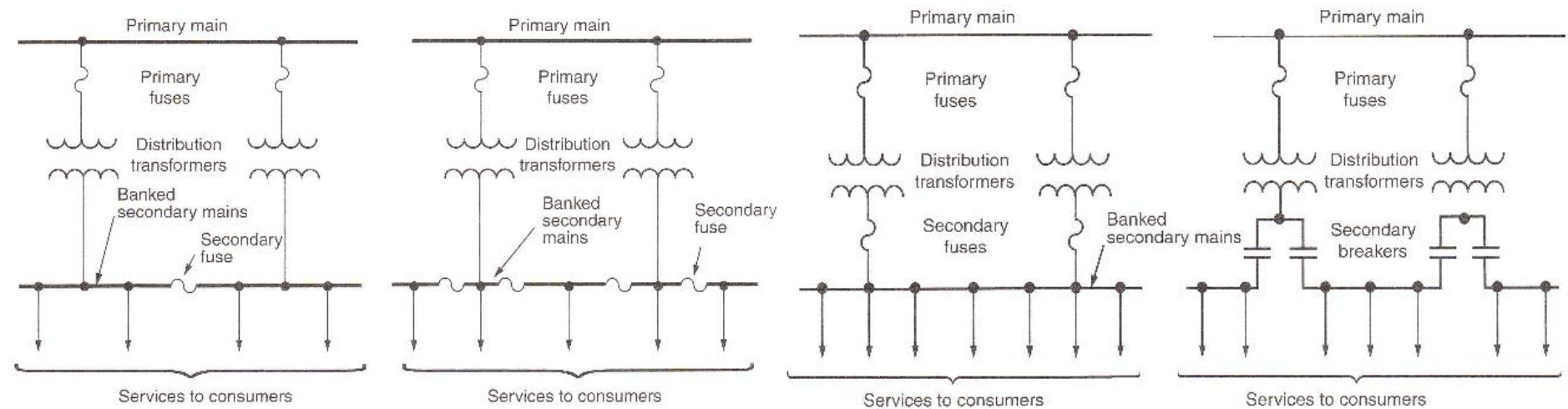
Radial Secondary Distribution System

- Common secondary main feeding a group of customers,
- In rural areas, a distribution transformer serves one customer.



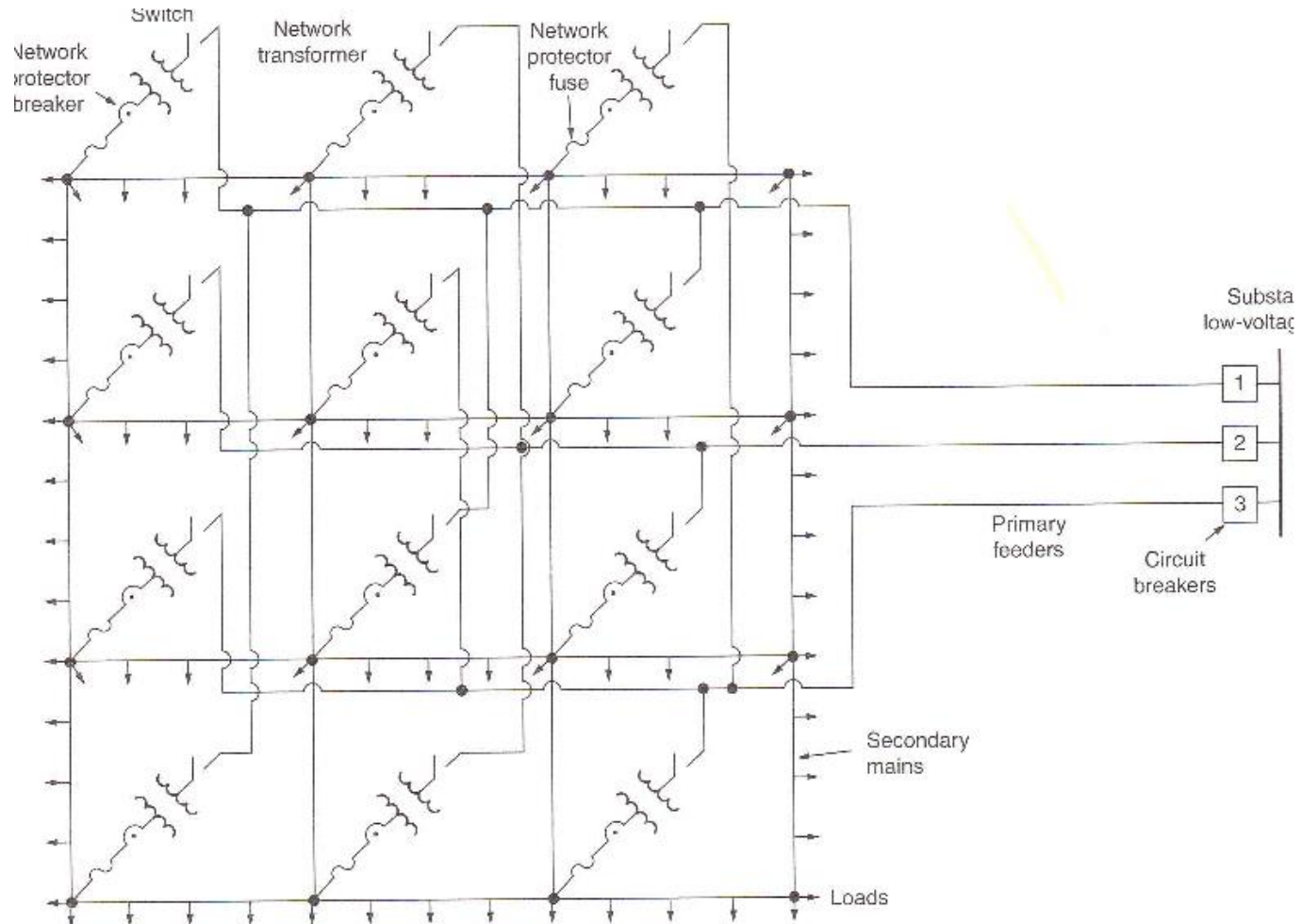
Secondary Banking

- Secondary main served by multiple transformers (in parallel) that are fed from the same primary feeder.
- Improved voltage regulation and service reliability, reduced voltage dip



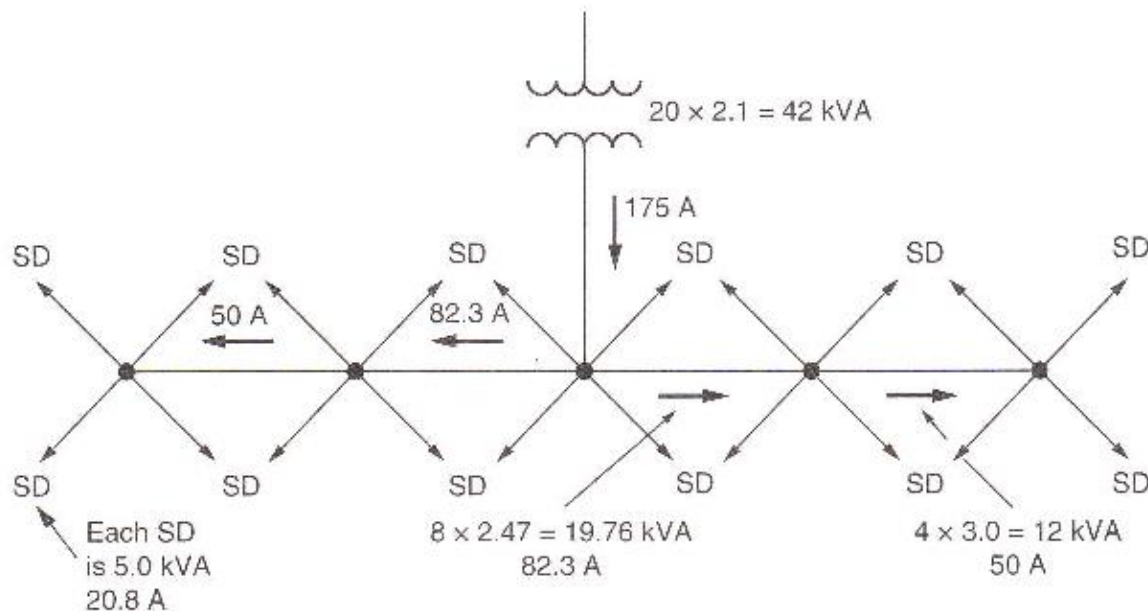
Secondary Network

- Meshed network that is powered by multiple feeders, through network-type transformers
- Fault current limiters, network protectors (i.e., air circuit breakers) with back-up fuses are used for secondary network protection.



Economic Design of Secondary Circuits

- Total Annual Cost (TAC) = annual installed cost of transformer, secondary cable and hardware + annual operating cost of transformer (excitation current, core and copper loss) and cable.



No. of Customer Being Diversified	Annual Maximum Demand, kVA/Customer
1	5.0
2	3.8
4	3.0
8	2.47
10	2.2
20	2.1
30	2.0
100	1.8

Series impedance of transmission lines

- Consists of the resistance of the conductors and the self and mutual inductive reactances resulting from the magnetic field surrounding the conductors.
- In the transmission system, the lines are often transposed and equally loaded. Hence the self and mutual reactances can be combined to form the phase reactance.
- In a 60 Hz system,

Series impedance:
$$z_i = r_i + j \cdot 0.12134 \cdot \ln \frac{D_{eq}}{GMR_i} \text{ } \Omega/\text{mile}$$

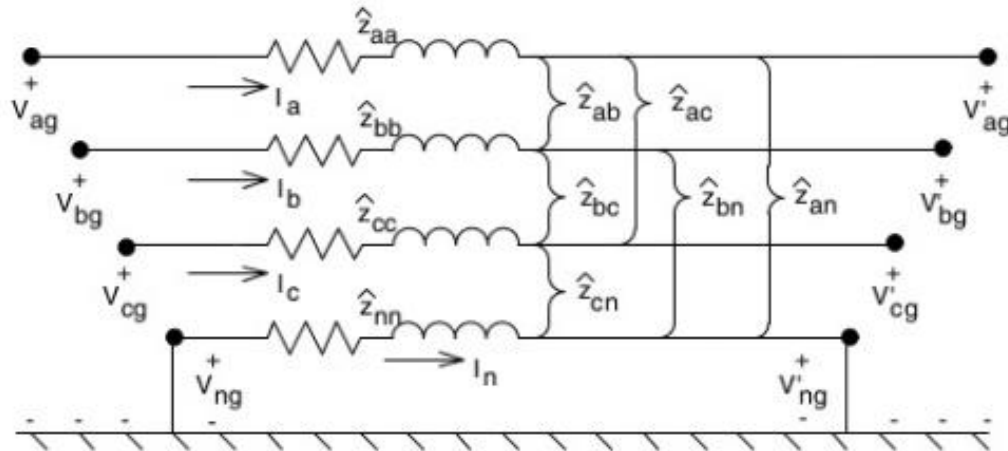
Series impedance of distribution lines

- Distribution lines are rarely if ever transposed. Additionally, the load is often unbalanced. Hence, it is necessary to retain the identity of the self and mutual reactances and take into account the ground return path of the unbalanced currents.
- In a 60 Hz system, with earth resistivity of 100 Ω -m, the self and mutual impedance of conductor i are approximated using the modified Carson's equations.

$$\hat{z}_{ii} = r_i + 0.09530 + j0.12134 \left(\ln \frac{1}{\text{GMR}_i} + 7.93402 \right) \Omega/\text{mile}$$

$$\hat{z}_{ij} = 0.09530 + j0.12134 \left(\ln \frac{1}{D_{ij}} + 7.93402 \right) \Omega/\text{mile}.$$

Phase impedance matrix of overhead lines



$$\begin{bmatrix} V_{ag} \\ V_{bg} \\ V_{cg} \\ V_{ng} \end{bmatrix} = \begin{bmatrix} V'_{ag} \\ V'_{bg} \\ V'_{cg} \\ V'_{ng} \end{bmatrix} + \begin{bmatrix} \hat{z}_{aa} & \hat{z}_{ab} & \hat{z}_{ac} & \hat{z}_{an} \\ \hat{z}_{ba} & \hat{z}_{bb} & \hat{z}_{bc} & \hat{z}_{bn} \\ \hat{z}_{ca} & \hat{z}_{cb} & \hat{z}_{cc} & \hat{z}_{cn} \\ \hat{z}_{na} & \hat{z}_{nb} & \hat{z}_{nc} & \hat{z}_{nn} \end{bmatrix} \cdot \begin{bmatrix} I_a \\ I_b \\ I_c \\ I_n \end{bmatrix}$$

- Partitioned form

$$\begin{bmatrix} [V_{abc}] \\ [V_{ng}] \end{bmatrix} = \begin{bmatrix} [V'_{abc}] \\ [V'_{ng}] \end{bmatrix} + \begin{bmatrix} [\widehat{z}_{ij}] & [\widehat{z}_{in}] \\ [\widehat{z}_{nj}] & [\widehat{z}_{nn}] \end{bmatrix} \cdot \begin{bmatrix} [I_{abc}] \\ [I_n] \end{bmatrix}$$

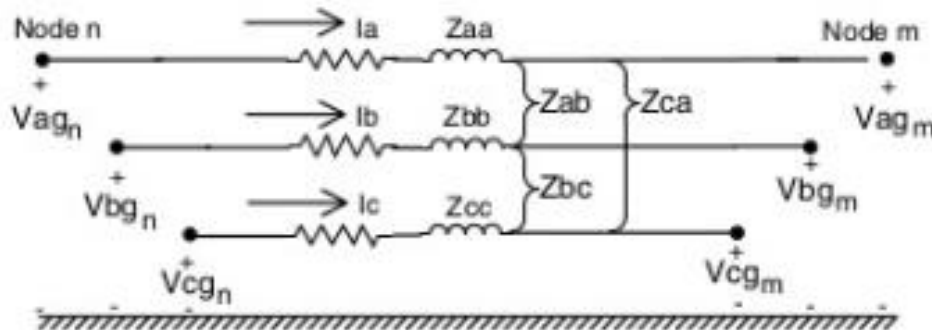
Continued

- Neutral to ground voltages are equal to zero. Kron reduction leads to

$$[V_{abc}] = [V'_{abc}] + ([\hat{z}_{ij}] - [\hat{z}_{in}] \cdot [\hat{z}_{nn}]^{-1} \cdot [\hat{z}_{nj}]) \cdot [I_{abc}]$$

$$[V_{abc}] = [V'_{abc}] + [z_{abc}] \cdot [I_{abc}]$$

$$[z_{abc}] = [\hat{z}_{ij}] - [\hat{z}_{in}] \cdot [\hat{z}_{nn}]^{-1} \cdot [\hat{z}_{nj}]$$



$$[z_{abc}] = \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} \end{bmatrix} \Omega/\text{mile}$$

Continued

- For a V-phase lines consisting of phases “a” and “c”,

$$[Z_{abc}] = \begin{bmatrix} Z_{ab} & 0 & Z_{ac} \\ 0 & 0 & 0 \\ Z_{ca} & 0 & Z_{cc} \end{bmatrix} \Omega/\text{mile}$$

- For a single-phase “b” line,

$$[Z_{abc}] = \begin{bmatrix} 0 & 0 & 0 \\ 0 & Z_{bb} & 0 \\ 0 & 0 & 0 \end{bmatrix} \Omega/\text{mile}$$

Sequence Impedance

$$[VLG_{abc}] = [A_s] \cdot [VLG_{012}]$$

$$[A_s] = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a_s^2 & a_s \\ 1 & a_s & a_s^2 \end{bmatrix}$$

where $a_s = 1.0 / \underline{120}$.

$$[VLG_{012}]_n = [VLG_{012}]_m + [Z_{012}] \cdot [I_{012}]$$

where

$$[Z_{012}] = [A_s]^{-1} \cdot [Z_{abc}] \cdot [A_s] = \begin{bmatrix} Z_{00} & Z_{01} & Z_{02} \\ Z_{10} & Z_{11} & Z_{12} \\ Z_{20} & Z_{21} & Z_{22} \end{bmatrix}$$

Continued

- In transmission (transposed) lines, the diagonal terms of the phase impedance matrix are equal, and so are the off-diagonal terms,

$$[Z_{abc}] = \begin{bmatrix} Z_s & Z_m & Z_m \\ Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_s \end{bmatrix} \Omega/\text{mile}$$

- The resulting the off diagonal terms of the sequence impedance matrix are zero, and the diagonal terms are

$$Z_{00} = Z_s + 2 \cdot Z_m \quad \Omega/\text{mile}$$

$$Z_{11} = Z_{22} = Z_s - Z_m \quad \Omega/\text{mile}$$

Shunt Admittance of overhead lines

- The shunt admittance consists of the conductance which is often very small, hence ignored, and the capacitance as a result of the potential difference between conductors.
- Using the method of conductors and their images,

$$[y_{abc}] = 0 + j \cdot \omega \cdot [C_{abc}] \mu\text{S/mile}$$

- Where

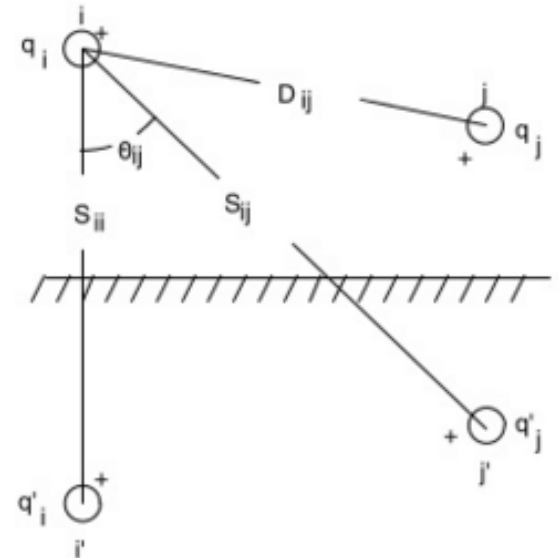
$$[C_{abc}] = [P_{abc}]^{-1}$$

$$[P_{abc}] = [\hat{P}_{ij}] - [\hat{P}_{in}] \cdot [\hat{P}_{nn}]^{-1} \cdot [\hat{P}_{nj}]$$

- Self and mutual potential coefficients:

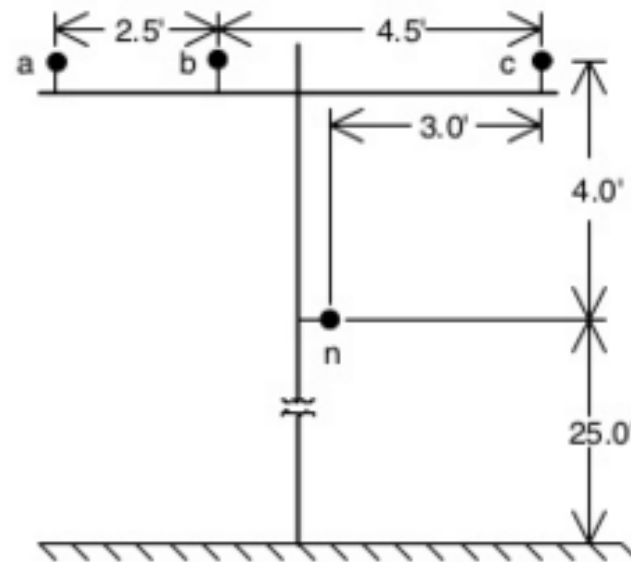
$$\hat{P}_{ii} = 11.17689 \cdot \ln \frac{S_{ii}}{RD_i} \text{ mile}/\mu\text{F}$$

$$\hat{P}_{ij} = 11.17689 \cdot \ln \frac{S_{ij}}{D_{ij}} \text{ mile}/\mu\text{F}$$



Example

- Determine the series impedance and shunt admittance matrices of the line to the right.
- Phase conductors:
 - ACSR 336,400
 - GMR = 0.0244 ft,
 - $r = 0.306 \Omega/\text{mile}$,
 - RD = 0.0304 ft
- Neutral conductor:
 - ACSR 4/0
 - GMR = 0.00814 ft,
 - $r = 0.592 \Omega/\text{mile}$,
 - RD = 0.02346 ft



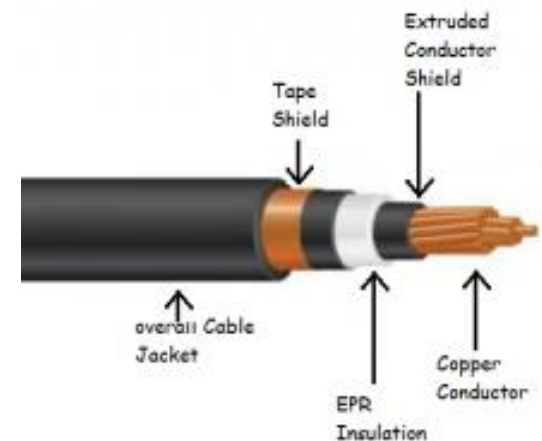
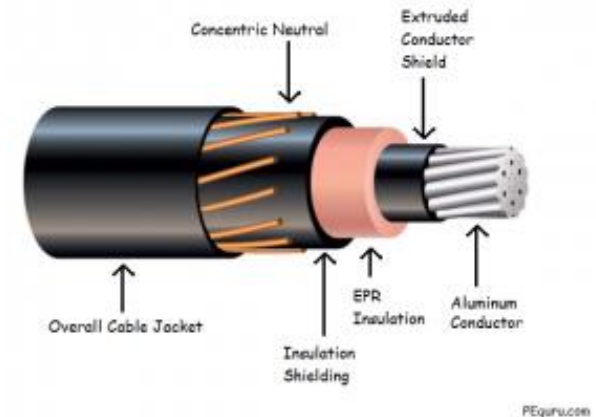
Answer:

$$[z_{abc}] = \begin{bmatrix} 0.4576 + j1.0780 & 0.1560 + j.5017 & 0.1535 + j0.3849 \\ 0.1560 + j0.5017 & 0.4666 + j1.0482 & 0.1580 + j0.4236 \\ 0.1535 + j0.3849 & 0.1580 + j0.4236 & 0.4615 + j1.0651 \end{bmatrix} \Omega/\text{mile}$$

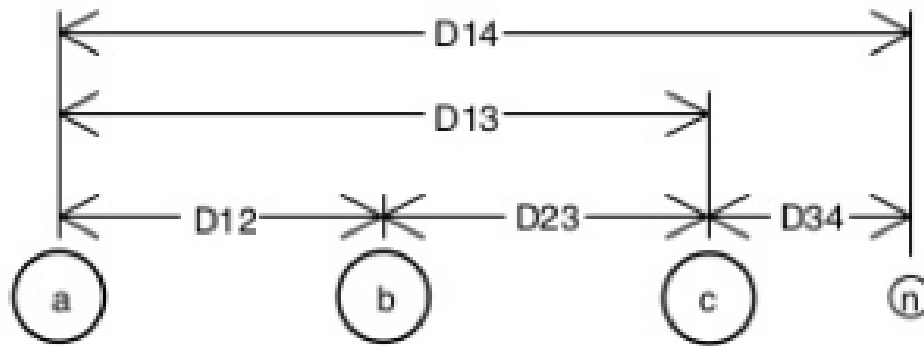
$$[y_{abc}] = j \cdot 376.9911 \cdot [C_{abc}] = \begin{bmatrix} j5.6712 & -j1.8362 & -j0.7034 \\ -j1.8362 & j5.9774 & -j1.169 \\ -j0.7034 & -j1.169 & j5.3911 \end{bmatrix} \mu\text{S}/\text{mile}$$

Series impedance & shunt admittance of underground cables

- Power cable with concentric neutral
 - For utility power distribution
 - Expensive to manufacture
 - Neutral carries residual current
 - Neutral grounded at both ends
- Power cable with tape shield
 - For industrial power distribution
 - Cheaper to manufacture
 - The tape is not designed to carry current
 - A dedicated neural wire is required
- The purpose of the tape is to distribute the electric field evenly around the conductor. The electric field is confined to the insulation material.



Underground cables

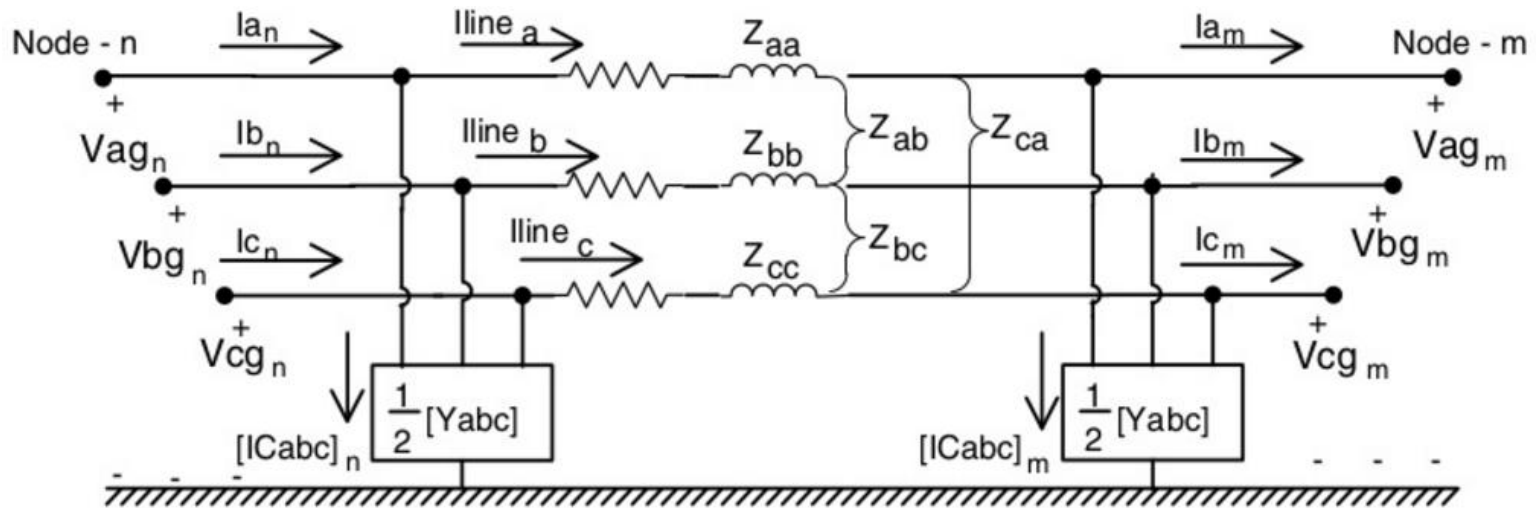


- Apply same procedure as in overhead lines
- The GMR of the tape shield is equal to the radius R of the circle passing through the middle of the shield.
- Equivalent GMR of concentric neutral computed using the equation of GMR in bundled conductors in transmission lines: $GMR_{cn} = \sqrt[k]{GMR_s \cdot k \cdot R^{k-1}}$
- Relative permittivity of various materials used range between 2 to 8.
- Shunt admittance of concentric neutral and tape shielded cables are as follows: ($\epsilon_r = 2.3$, R_b = radius of circle passing through concentric neutral or shield, k = # strands in concentric neutral, RD_c = radius of phase conductor, RD_s = radius of neutral strand). Mutual admittances = 0.

$$y_{ag} = 0 + j \frac{77.3619}{\ln \frac{R_b}{RD_c} - \frac{1}{k} \ln \frac{k \cdot RD_s}{R_b}} \mu\text{S/mile}$$

$$y_{ag} = 0 + j \frac{77.3619}{\ln \frac{R_b}{RD_c}} \mu\text{S/mile}$$

Distribution feeder model



$$\begin{bmatrix} [VLG_{abc}]_n \\ [I_{abc}]_n \end{bmatrix} = \begin{bmatrix} [a] & [b] \\ [c] & [d] \end{bmatrix} \cdot \begin{bmatrix} [VLG_{abc}]_m \\ [I_{abc}]_m \end{bmatrix}$$

$$[U] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$[a] = [d] = [U] + \frac{1}{2} \cdot [Z_{abc}] \cdot [Y_{abc}]$$

$$[c] = [Y_{abc}] + \frac{1}{4} \cdot [Y_{abc}] \cdot [Z_{abc}] \cdot [Y_{abc}]$$

$$[b] = [Z_{abc}]$$

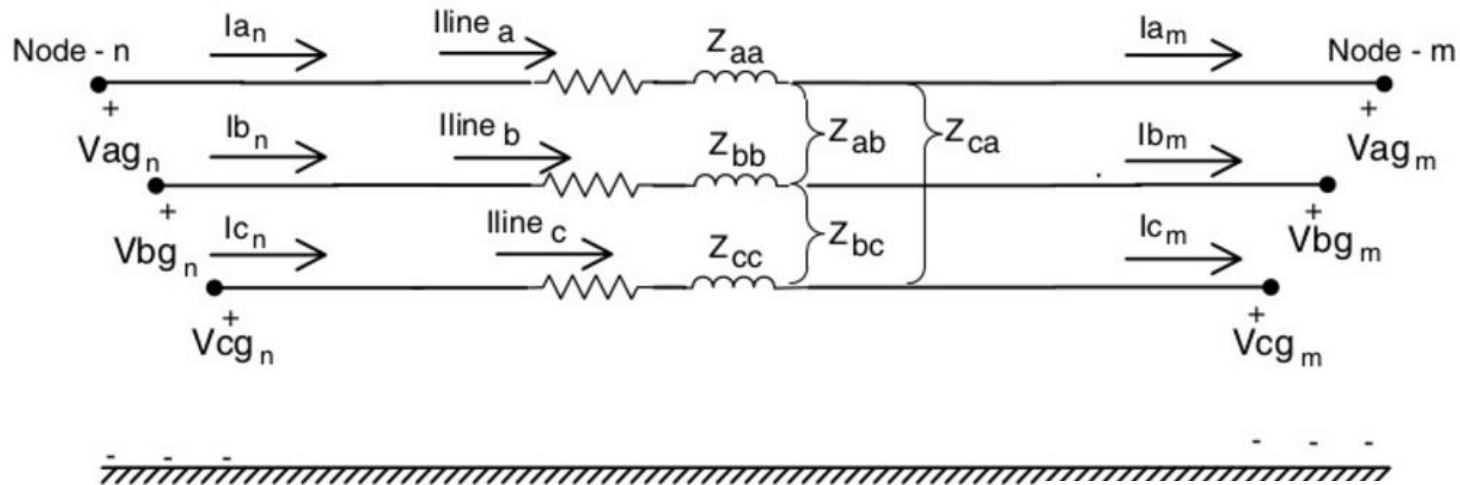
$$\begin{bmatrix} [VLG_{abc}]_m \\ [I_{abc}]_m \end{bmatrix} = \begin{bmatrix} [d] & -[b] \\ -[c] & [a] \end{bmatrix} \cdot \begin{bmatrix} [VLG_{abc}]_n \\ [I_{abc}]_n \end{bmatrix}^{32}$$

Distribution feeder model

- Voltage unbalance (NEMA definition):

$$V_{\text{unbalance}} = \frac{|\text{Maximum deviation from average}|}{|V_{\text{average}}|} \cdot 100\%$$

- Motor derating when voltage unbalance exceeds 1%.
- Simplified model (for short overhead lines with negligible shunt admittance)



$$[a] = [d] = [U] \quad [b] = [Z_{abc}] \quad [c] = [0]$$

Assignment # 2

Problem A:

Derive the voltage drop and power loss formulas in slide # 15.

Problem B:

Consider the line configuration in the example describe in slide # 29. The line length is 4 miles, and it serves a balanced 3 –phase load of 10 MVA @ 0.85 PF (lag). The voltages at the load are balanced and equal to 13.2 kV.

- 1) Compute the line-to neutral voltages at the source end.
- 2) Compute the voltage unbalance at the source end.
- 3) Compute the real and reactive power supplied by the source and the total power loss in the line.