EE 741

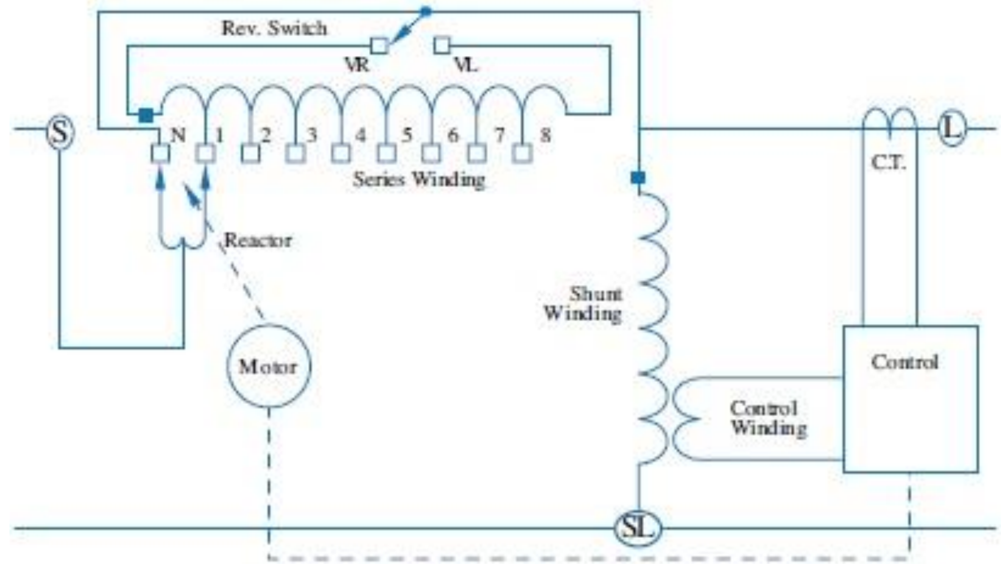
Voltage Regulators
and Shunt Capacitors

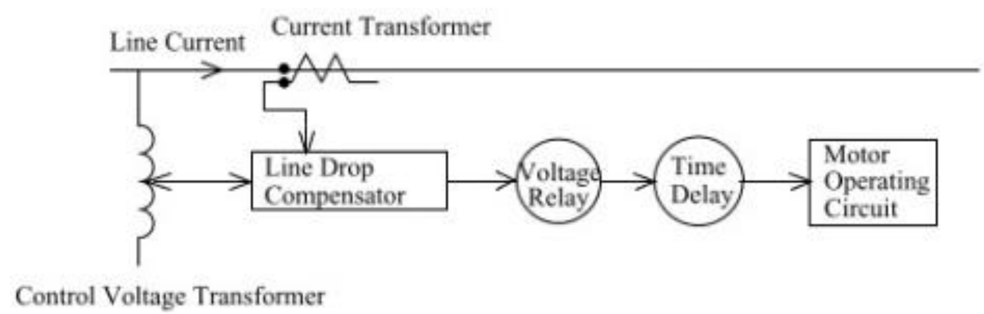
Standard Voltage Range (ANSI)

- Range A (normal)
  - 110 V ≤ utilization voltage ≤ 126 V
  - 114 V ≤ service voltage ≤ 126 V
- Range B (emergency)
  - 107 V ≤ utilization voltage ≤ 127 V
  - 110 V ≤ service voltage ≤ 127 V
- Voltage unbalance (at revenue meter)
  - $V_{imbalance} \le 3\%$

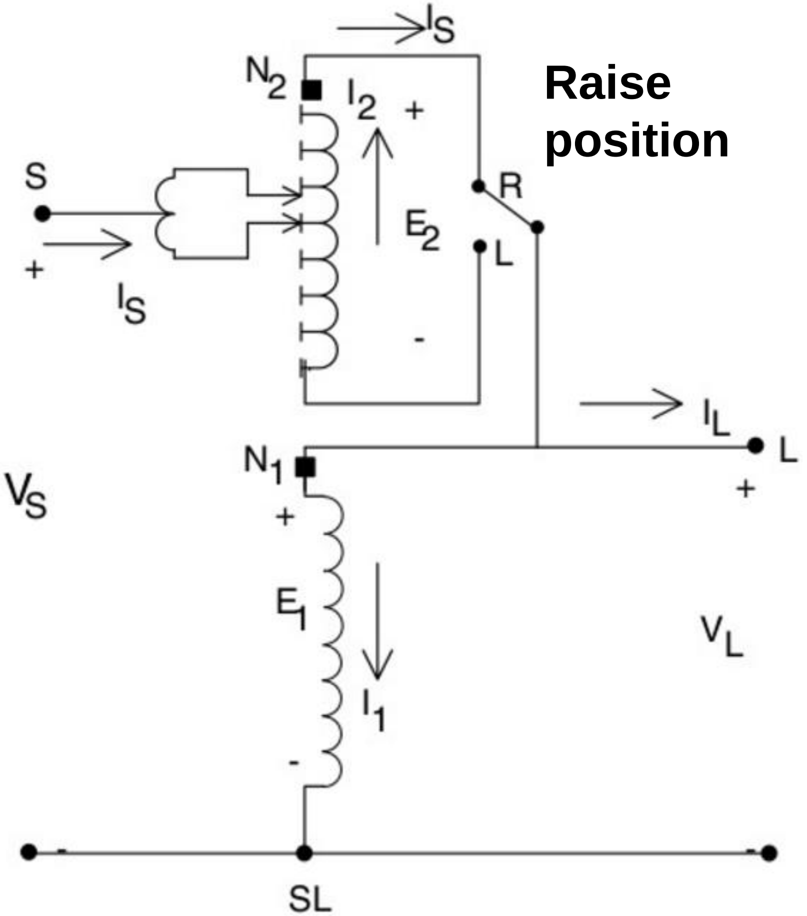
Step-voltage regulator

- Autotransformer with tap change mechanism.
- Reversing switch allows ± 10% regulator change.
- Typical # of steps: 32
  - 5/8% voltage change per step change.
- Tap position determined by a control circuit .
- Control settings:
  - Desired voltage
  - Bandwidth
  - Time delay
  - Line drop compensator.



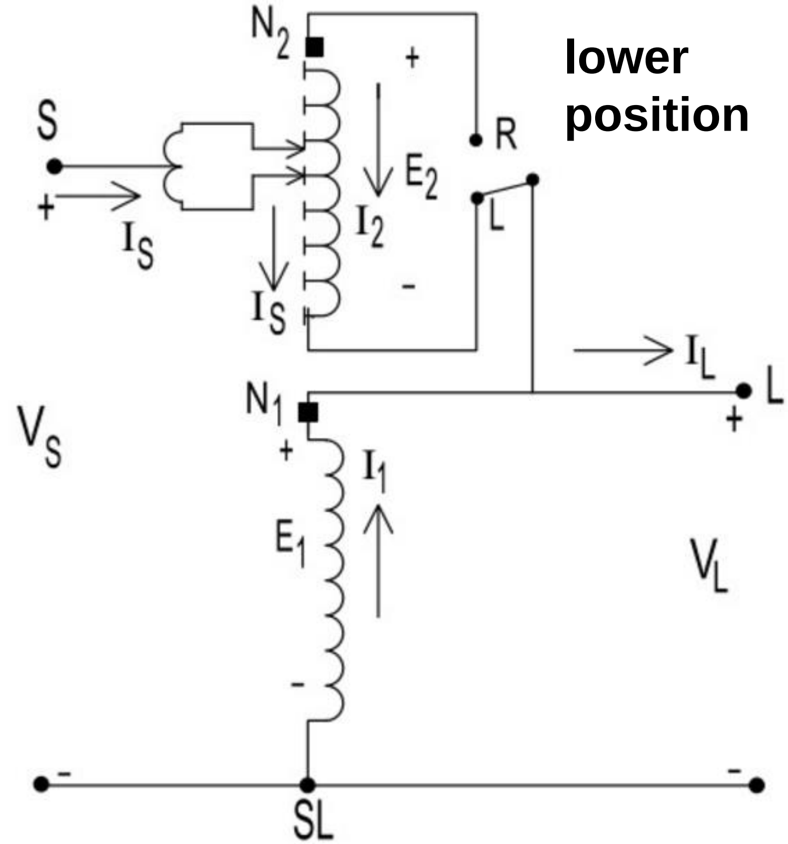


Voltage and current relations
(neglect series impedance and shunt admittance)



$$V_S = a_R \cdot V_L \qquad I_L = a_R \cdot I_S$$

$$a_R = 1 - \frac{N_2}{N_1}$$



$$V_S = a_R \cdot V_L \qquad I_L = a_R \cdot I_S$$

$$a_R = 1 + \frac{N_2}{N_1}$$

Step-voltage regulators

- Effective regulator ratio (knowing the Tap position):

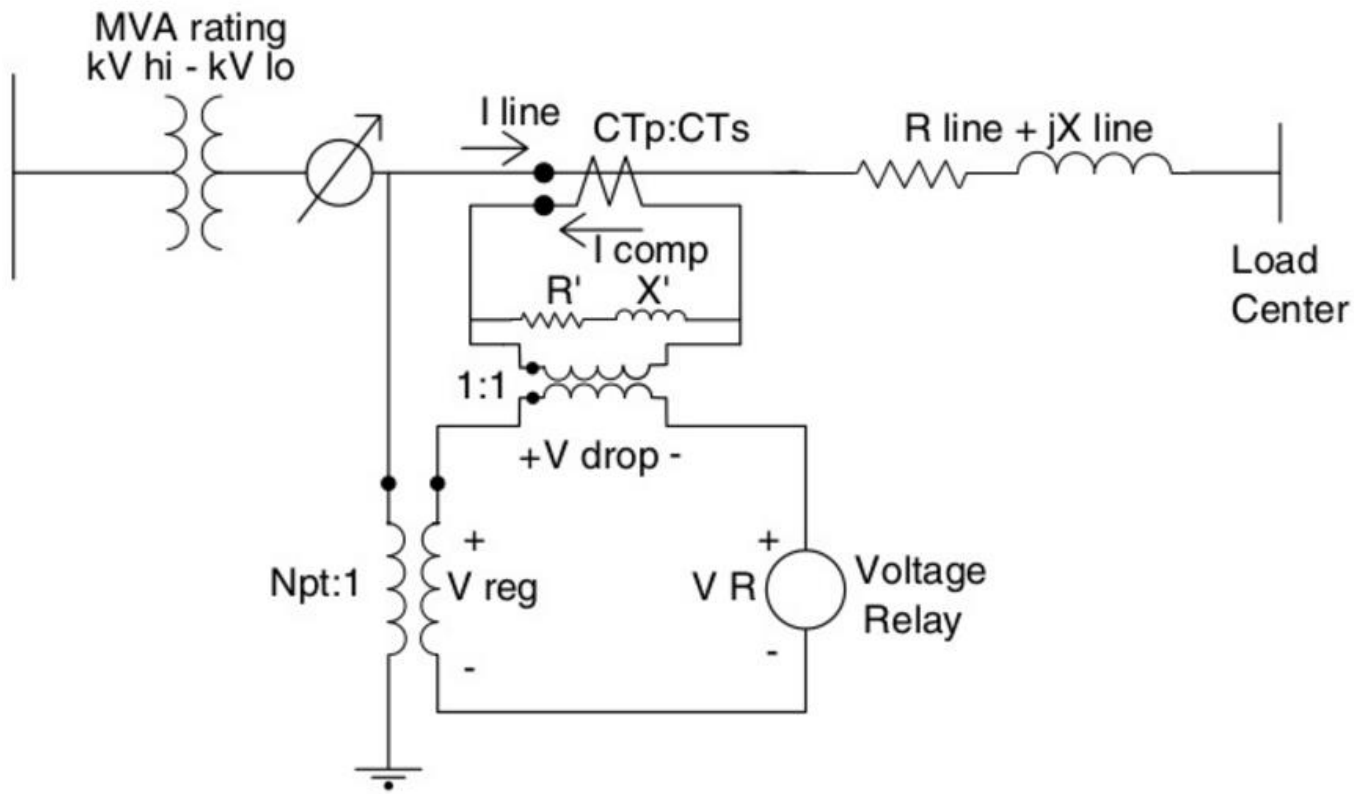
$$a_R = 1 \mp 0.00625 \cdot Tap$$

- Generalized abcd constants:

$$a = a_R \qquad b = 0 \qquad c = 0 \qquad d = \frac{1}{a_R}$$

- Regulator current rating = line current rating
- Regulator voltage rating: 10% of line voltage rating
- Regulator apparent power rating: 10% of line rating

Line Drop Compensator (LDC)



- Purpose: model the distribution line segment between the voltage regulator and load center.
- The compensator is an analog circuit that is a scale model of the line circuit

$$Rcomp_{\Omega} + jXcomp_{\Omega} = (Rline_{\Omega} + jXline_{\Omega}) \cdot \frac{CT_P}{N_{PT} \cdot CT_S} \quad \Omega$$

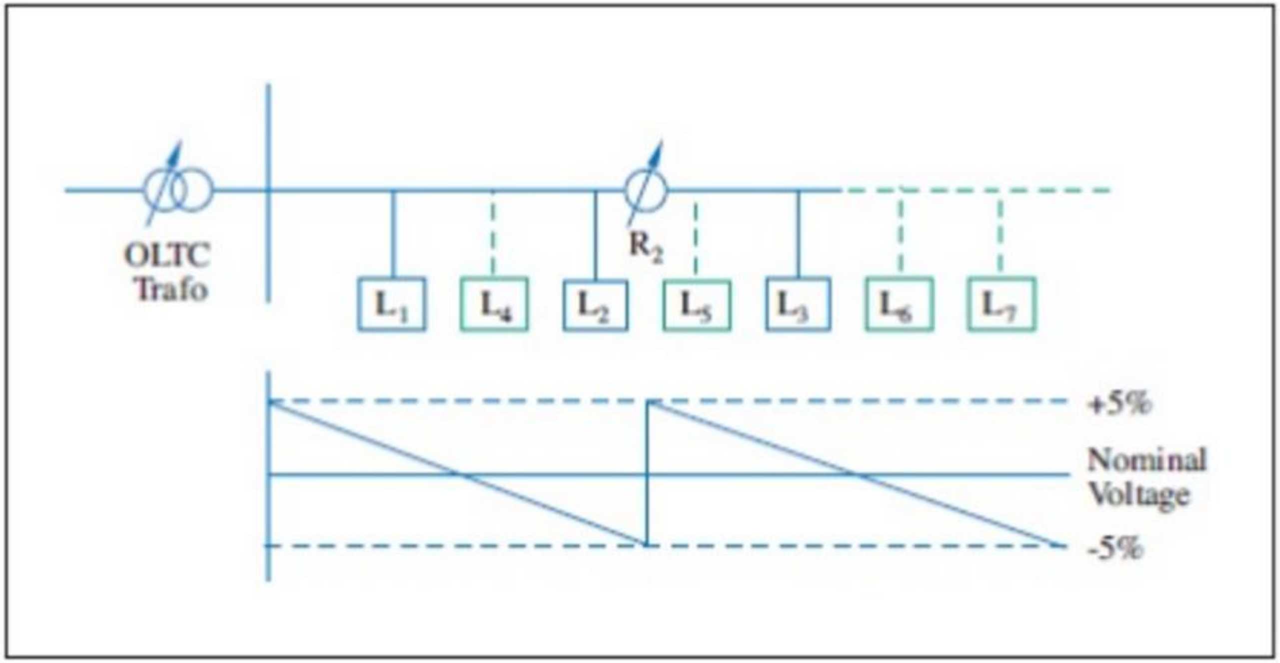
Example

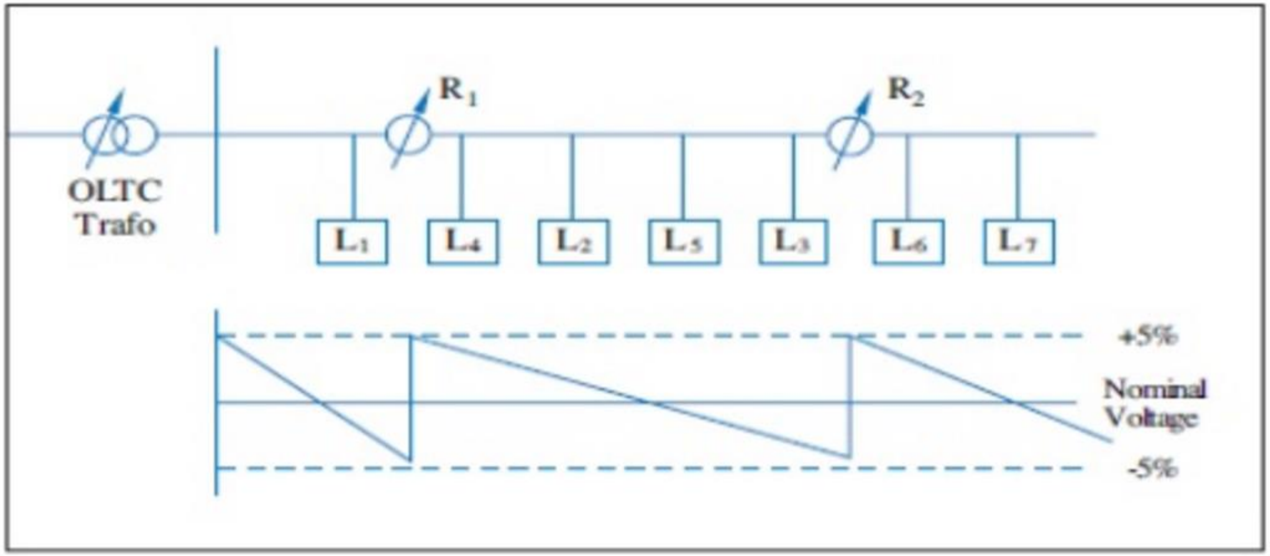
Assume substation transformer: 5 MVA, 115kV (Delta) /4.16kV (Y-grounded). R line + jX line = 0.3 +j0.9 Ω. Substation supplies 2.5 MVA at rated voltage and 0.9 PF. Find the following: a)Potential transformer turn ratio for LDC, b) Current transformer, c) R and X settings (in Ohms), e) It is desired to maintain 119 V at load center. What is the tap position?

Answer:

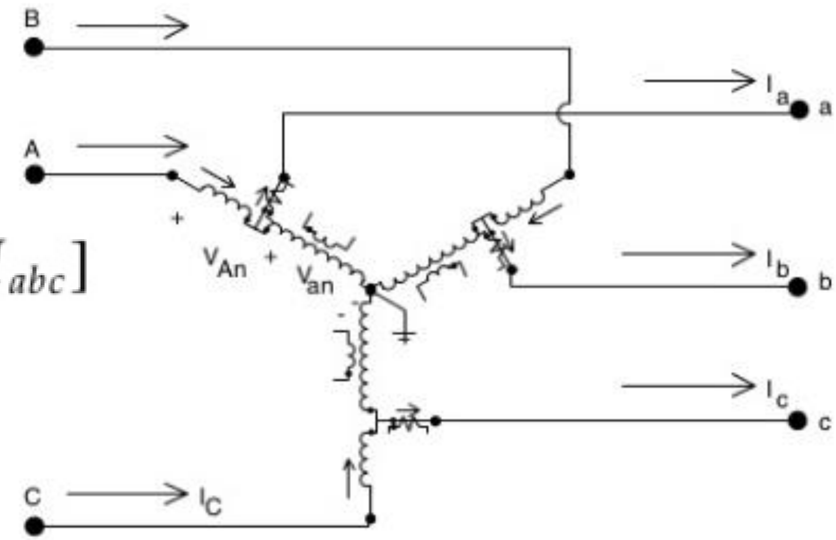
a) Vphase = 2,400 V, desire 120 V, then N_{PT} = 20
b) rated current of substation transformer 694 A (select a rating of 700 A), desire to reduce to 5 A, then CT_p/CT_s = 140.
c) 2.1 +j6.3 Ω.
d) Input voltage to compensator: 120 V, line current: 347 A @- 26 deg, current in compensator: 2.48 A @ -26 deg, voltage drop in compensator circuit: 16.46 V @ 45.7 deg, voltage across voltage relay: 109.25 V @ -6.2 deg, tap position: (118-109.25)/0.625 = +14

Voltage Regulator Effect on Feeder Voltage





3-phase voltage regulators (Y-connection)



$$[VLN_{ABC}] = [a] \cdot [VLN_{abc}] + [b] \cdot [I_{abc}]$$

$$[I_{ABC}] = [c] \cdot [VLG_{abc}] + [d][I_{abc}]$$

$$[a] = \begin{bmatrix} a_{Ra} & 0 & 0 \\ 0 & a_{Rb} & 0 \\ 0 & 0 & a_{Rc} \end{bmatrix} \qquad [c] = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$[b] = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \qquad [d] = \begin{bmatrix} \frac{1}{a_{Ra}} & 0 & 0 \\ 0 & \frac{1}{a_{Rb}} & 0 \\ 0 & 0 & \frac{1}{a_{Rc}} \end{bmatrix}$$

Independent operation
if 3 single phase regulators.

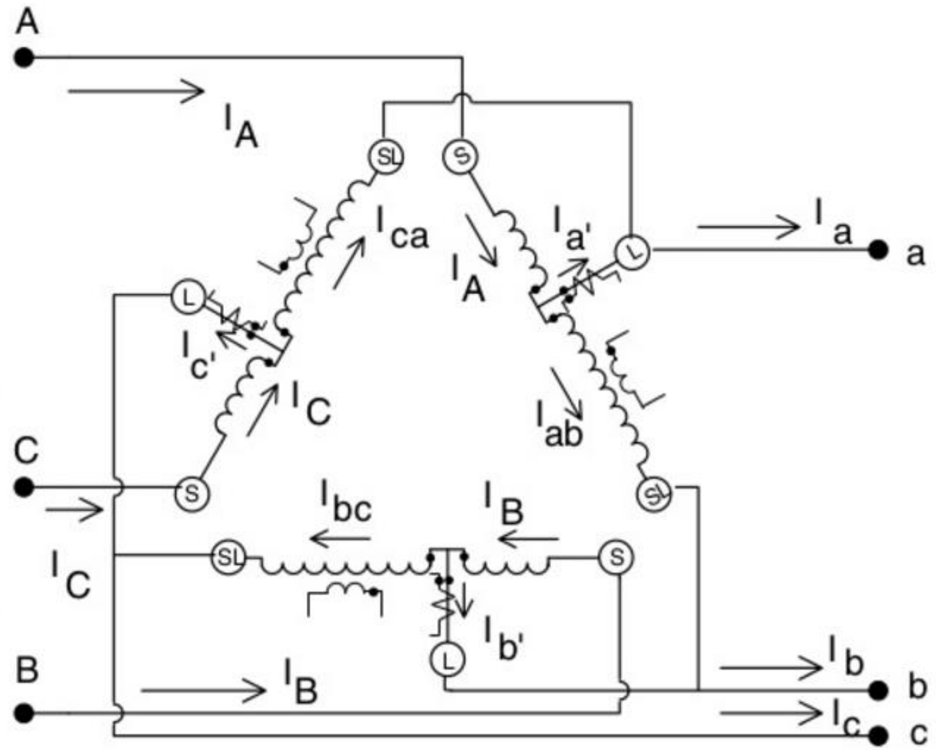
In 3-phase regulator, the voltage and current is sampled in only one phase, and all 3 phases change by the same tap number.

3-phase voltage regulators (closed delta)

$$\begin{bmatrix} V_{AB} \\ V_{BC} \\ V_{CA} \end{bmatrix} = \begin{bmatrix} a_{R\,ab} & 1-a_{R\,bc} & 0 \\ 0 & a_{R\,bc} & 1-a_{R\,ca} \\ 1-a_{R\,ab} & 0 & a_{R\,ca} \end{bmatrix} \cdot \begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix}$$

$$\begin{bmatrix} I_{a} \\ I_{b} \\ I_{c} \end{bmatrix} = \begin{bmatrix} a_{R\,ab} & 0 & 1-a_{R\,ca} \\ 1-a_{R\,ab} & a_{R\,bc} & 0 \\ 0 & 1-a_{R\,bc} & a_{R\,ca} \end{bmatrix} \cdot \begin{bmatrix} I_{A} \\ I_{B} \\ I_{C} \end{bmatrix}$$

$[d]^{-1}$



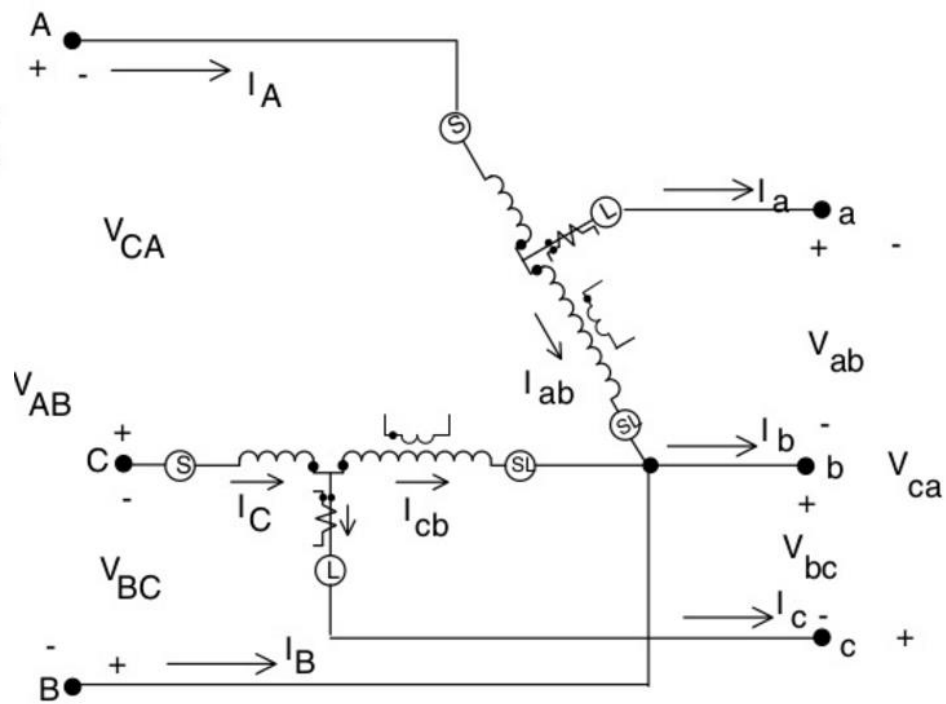
$$[c] = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \qquad [b] = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

Difficult to apply as change of tap in one regulator will affect the others.

3-phase voltage regulators (open delta)

$$[VLL_{ABC}] = [a_{LL}] \cdot [VLL_{abc}] + [b_{LL}] \cdot [I_{abc}]$$

$$[a_{LL}] = \begin{bmatrix} a_{Rab} & 0 & 0 \\ 0 & a_{Rcb} & 0 \\ -a_{Rab} & -a_{Rcb} & 0 \end{bmatrix}$$



$$[I_{ABC}] = [c_{LL}] \cdot [VLL_{ABC}] + [d_{LL}] \cdot [I_{abc}]$$

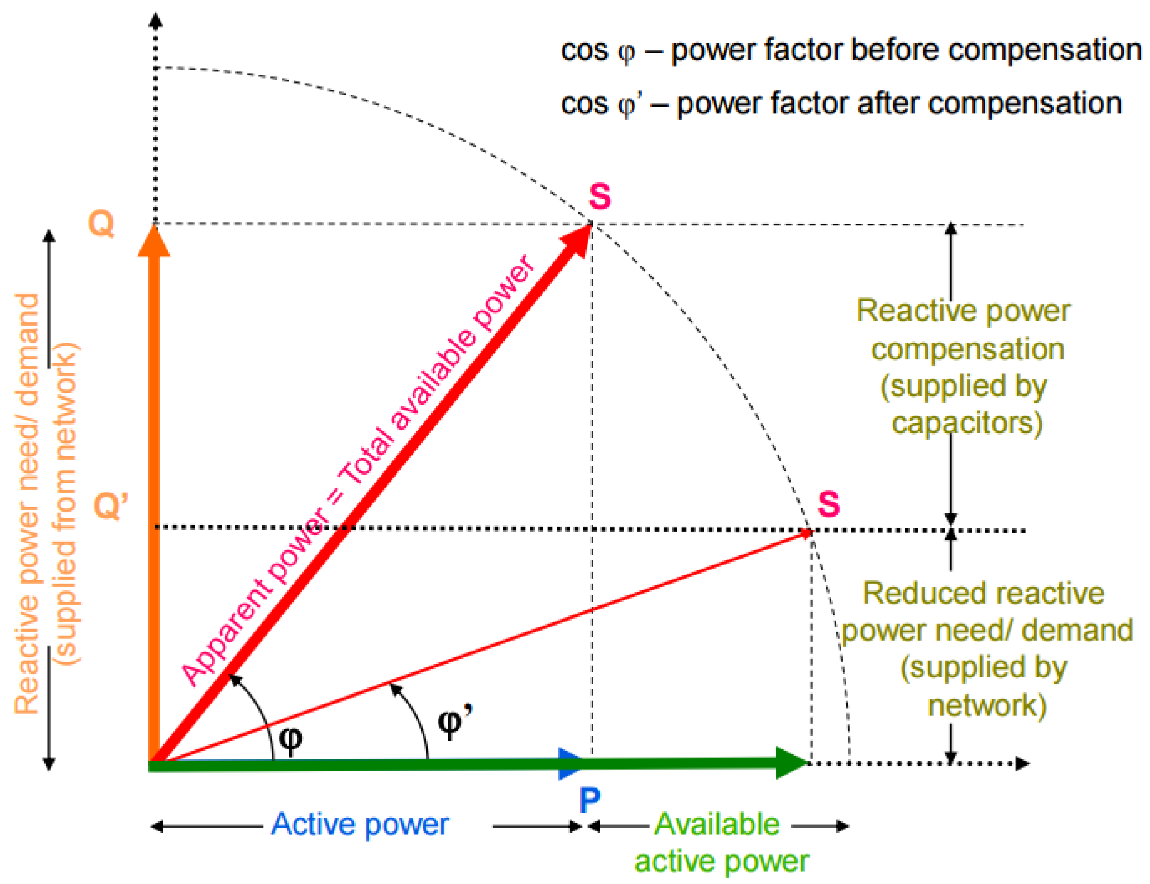
$$[d_{LL}] = \begin{bmatrix} \frac{1}{a_{Rab}} & 0 & 0 \\ -\frac{1}{a_{Rab}} & 0 & -\frac{1}{a_{Rcb}} \\ 0 & 0 & \frac{1}{a_{Rcb}} \end{bmatrix}$$

$$[c] = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \qquad [b] = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

Shunt Capacitors

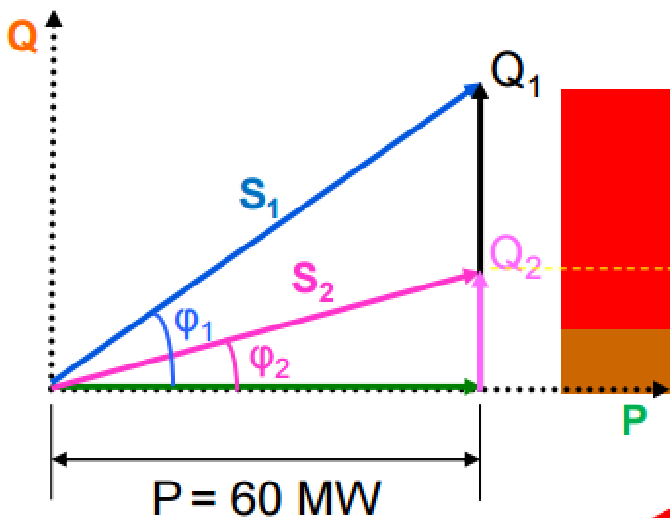
Reactive Power Compensation

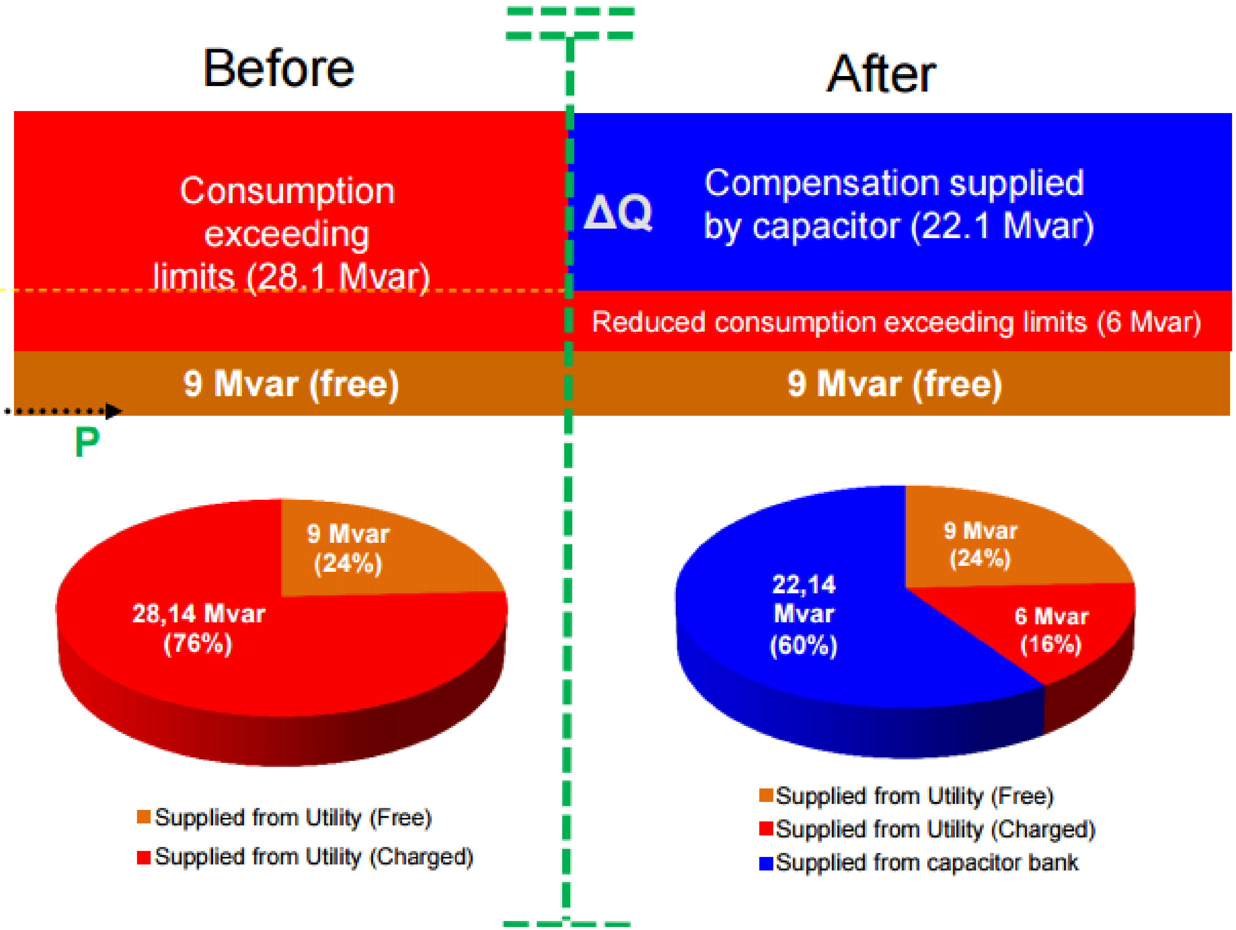
Electric loads generally draw reactive power in addition to real power. Distribution transformers and feeders also consume reactive power due to their inherent inductances.



Reactive power compensation @ customer site - an illustration

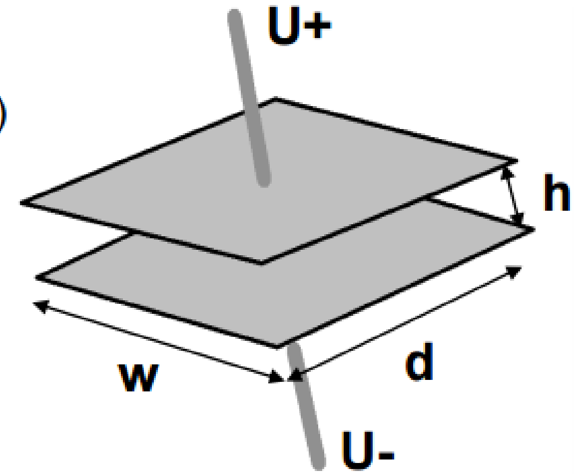
Q_{free} = X % x P according to tariff/utility regulation ⇨ Max. Q_{free} allowed from utility= 0,15 * 60 = 9 Mvar





Before	After
Cos φ_1= 0,85	Cos φ_2= 0,97
P= 60 MW	
S_1= 70,59 MVA	S_2= 61,86 MVA
Q_1= 37,19 Mvar	Q_2= 15,04 Mvar
ΔQ= 22,1 Mvar (cap. Bank power)	

Capacitors – basic definition



Capacitor

Two conductor layers separated by a insulating layer (dielectric)

Capacitance

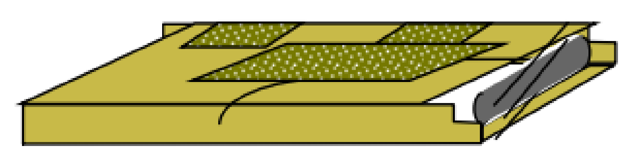
$$C = \varepsilon * \frac{A}{h}$$

- Area of the plates = w x d
- Distance between the plates (thickness of the dielectric)
- Permittivity of the insulating material (dielectric) or Dielectric constant

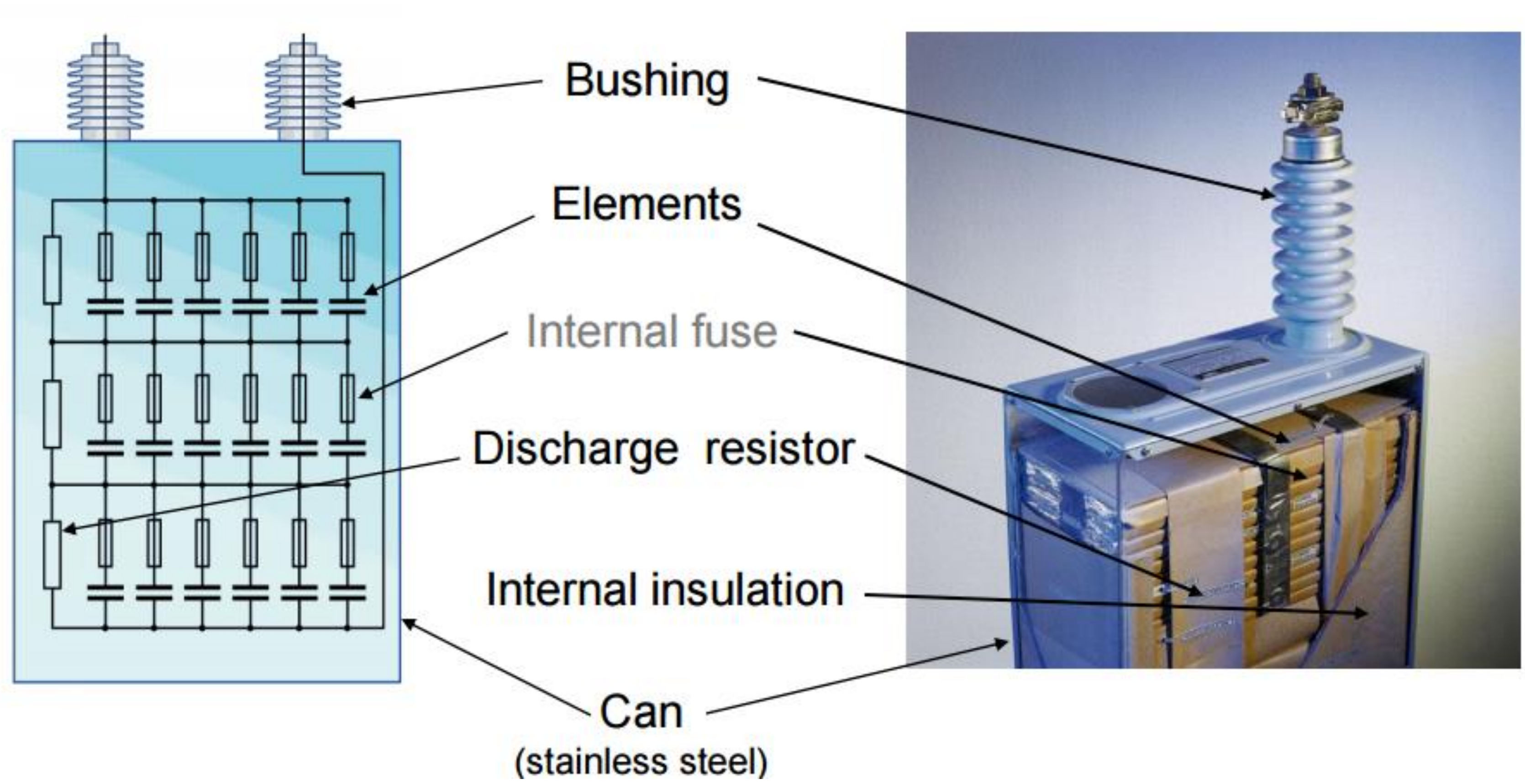
Reactive Power

$$Q = 2\pi f \times U^2 \times C$$

- Capacitance
- Voltage
- Frequency



Component of a capacitor unit



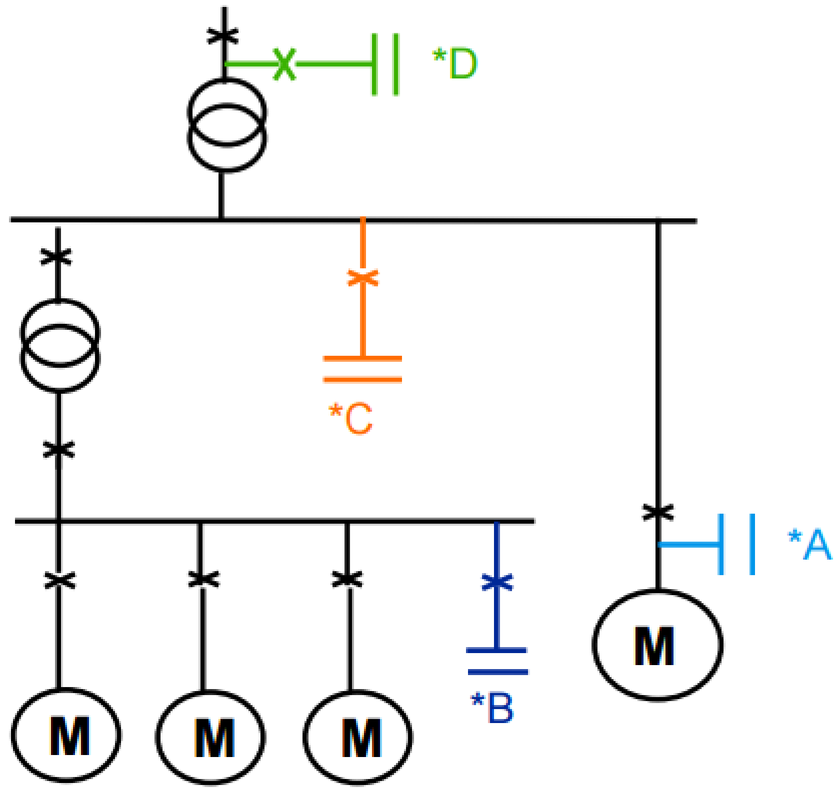
Capacitor Placement

Shunt compensation of reactive power can be employed either at load level, substation level or at transmission level.

Compensation should be provided as close as possible to the consumption point to avoid having to distribute this power in the other part of network.

Location is primarily determined by the reason for compensation.

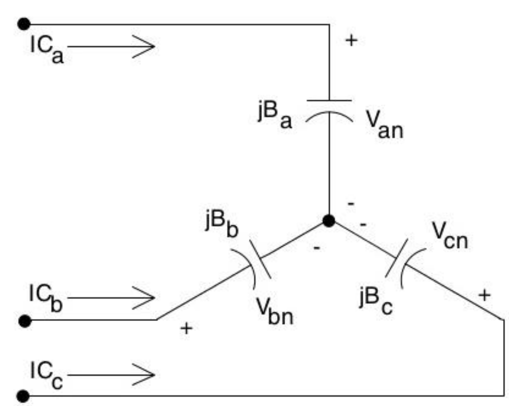
- *A : Direct Compensation
- *B : Group Compensation
- *C : Central Compensation at LV side
- *D : Central Compensation at HV side



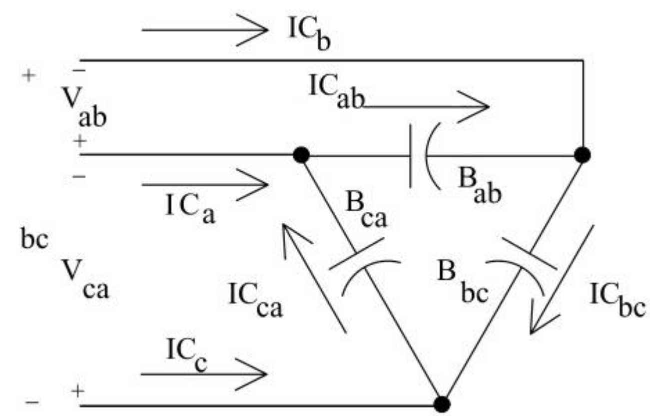
Capacitor application in distribution systems

- Capacitors a primarily used for voltage regulation and reactive power support.Other benefits include:
  - Power loss reduction ..
  - Capacity release at all levels
- A capacitor is modeled as constant susceptance, with a specified kVAR and kV rating

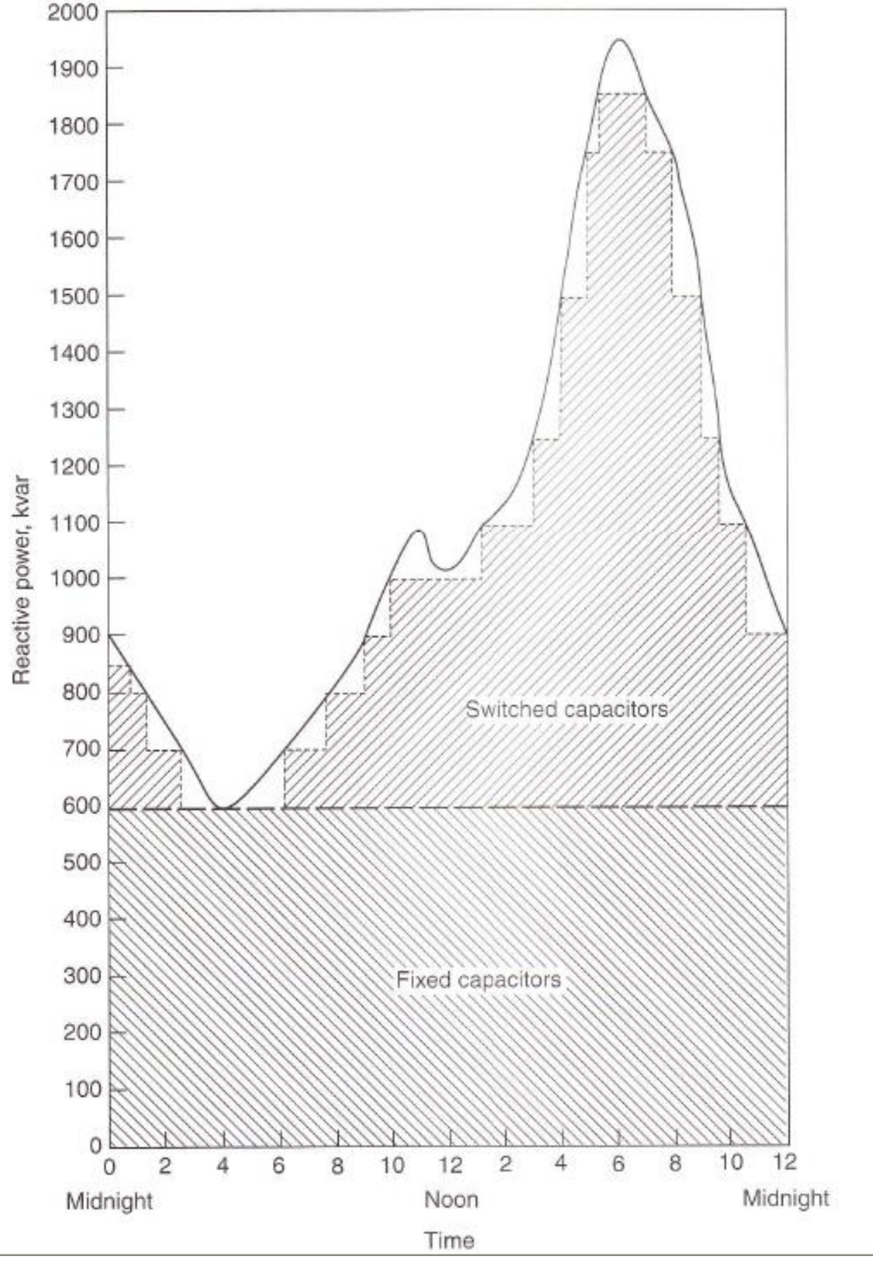
$$B_c = \frac{kvar}{kV_{LN}^2 \cdot 1000} \text{ S}$$



$$B_c = \frac{kvar}{kV_{LL}^2 \cdot 1000} \text{ S}$$



Fixed and Switched Capacitors



Types of capacitor controls

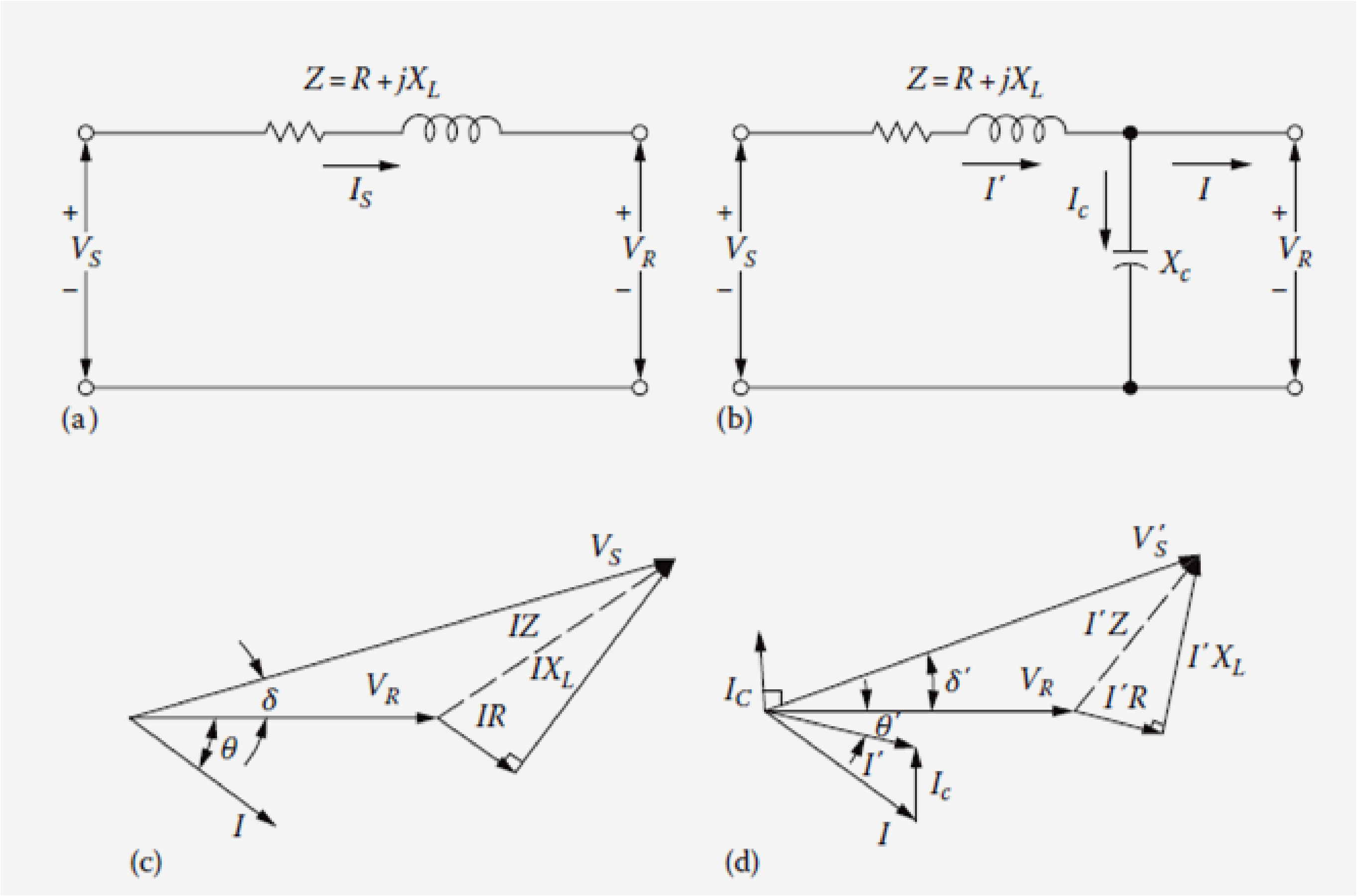
- **VAR control** is the natural means to control capacitors because the latter adds a fixed amount of leading VArs to the line regardless of other conditions. VAr controls require current sensors.
- **Current control** is not as efficient as VAr control because it responds to total line current, and assumptions must be made about the load power factor.
- **Voltage control** is used to regulate voltage profiles, however it may actually increase losses. Voltage control requires no current sensors.
- **Temperature control** is based on assumptions about load characteristics. Control effectiveness depends on how well load characteristics are know. Temperature control does not require any current sensors.
- **Time control** is based on assumptions about load characteristics. Time control does not require any current sensors.
- **Power factor control** is not the best way to control capacitor banks because power factor by itself is not a measure of reactive current. Current sensors are needed.
- **Combination control** using various above methods is usually the best choice. If enough current, and/or other sensors are available, a centrally managed computerized capacitor control system taking into account the variety of available input parameters can be most effective, though expensive to implement.

Economic Justification of Capacitors

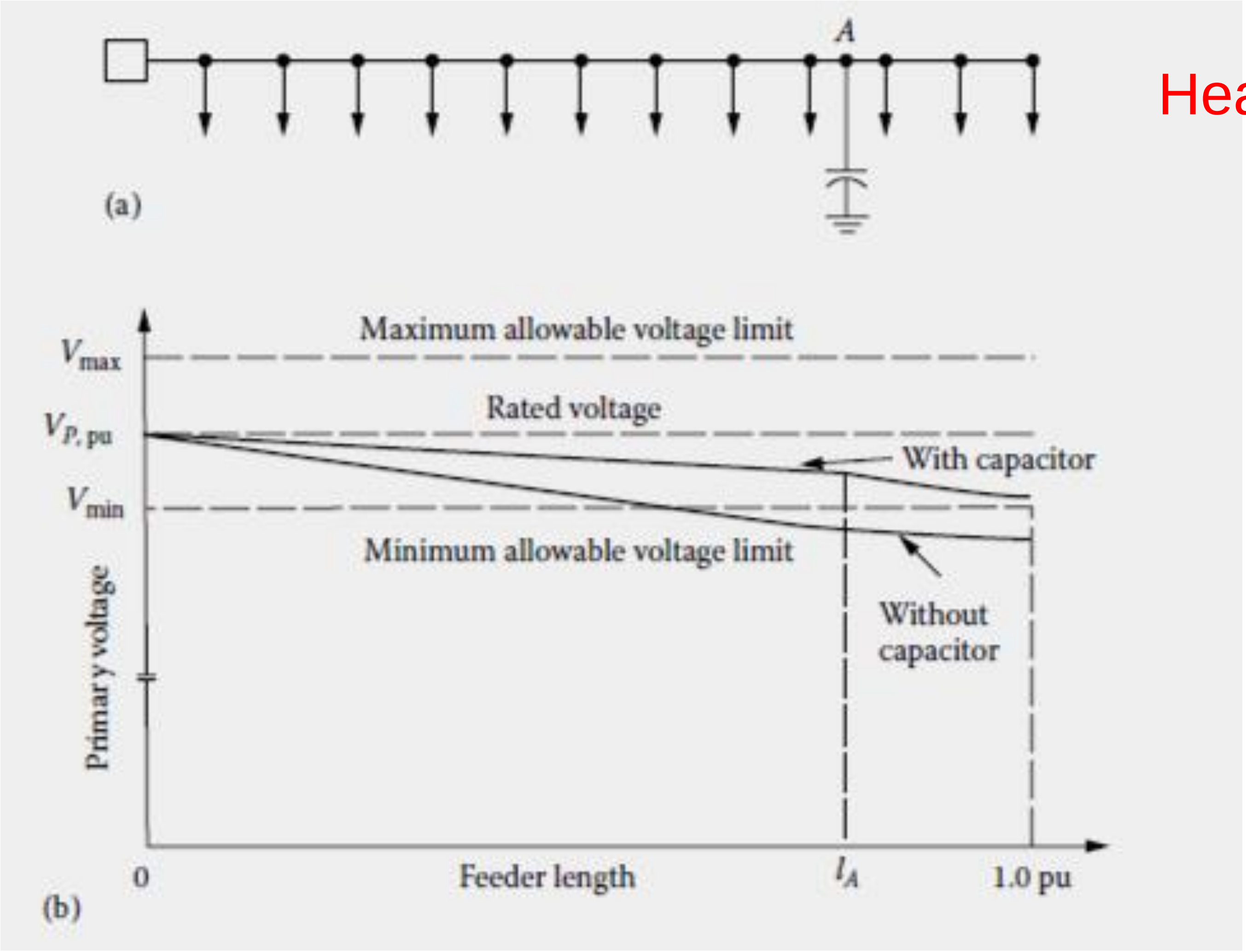
- Benefits:
  - Benefits due to released generation capacity
  - Benefits due to released transmission capacity
  - Benefits due to released distribution substation capacity
  - Benefits due to released feeder capacity
  - Benefits due to reduced energy loss
  - Benefits due to reduced voltage drop
  - Benefits due to voltage improvement
- Total benefits should be compared against the annual equivalent of the total cost of the installed capacitor bank

Shunt Capacitors

- Supply reactive power, reduce current, release capacity, correct the power factor, regulate the voltage …

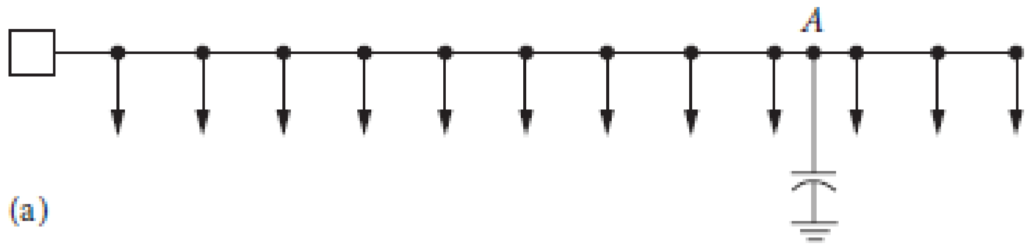


Effect of Capacitor on Voltage Profile

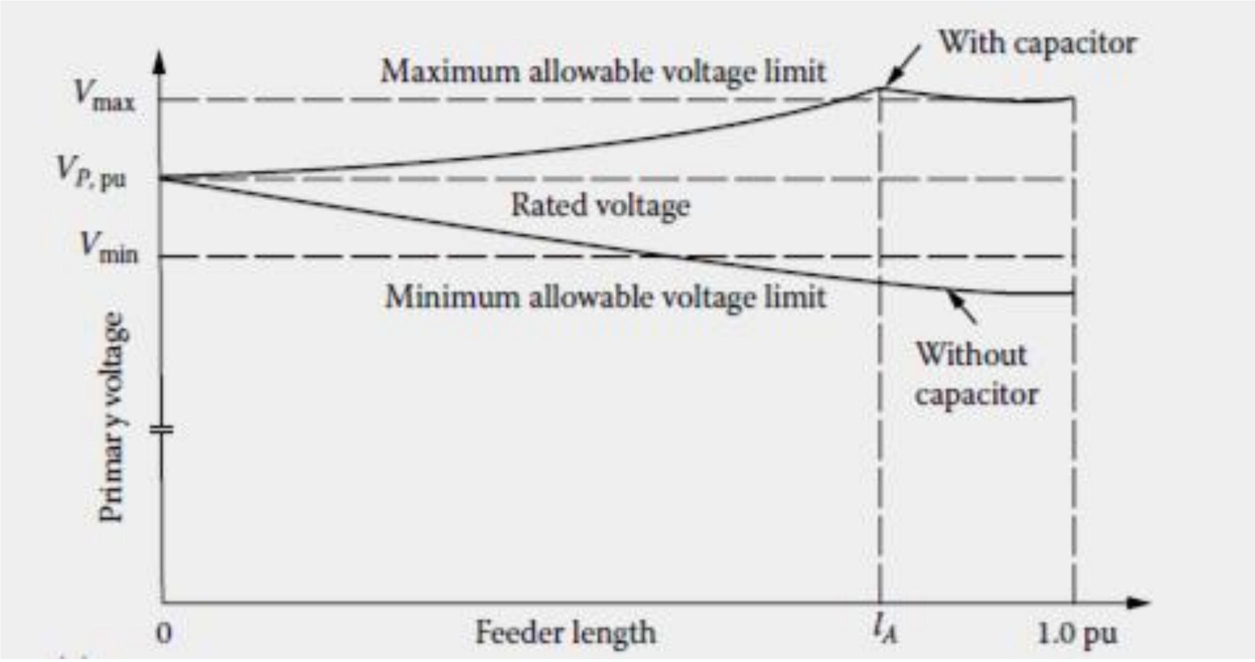


Heavy load

Effect of Capacitor on Voltage Profile

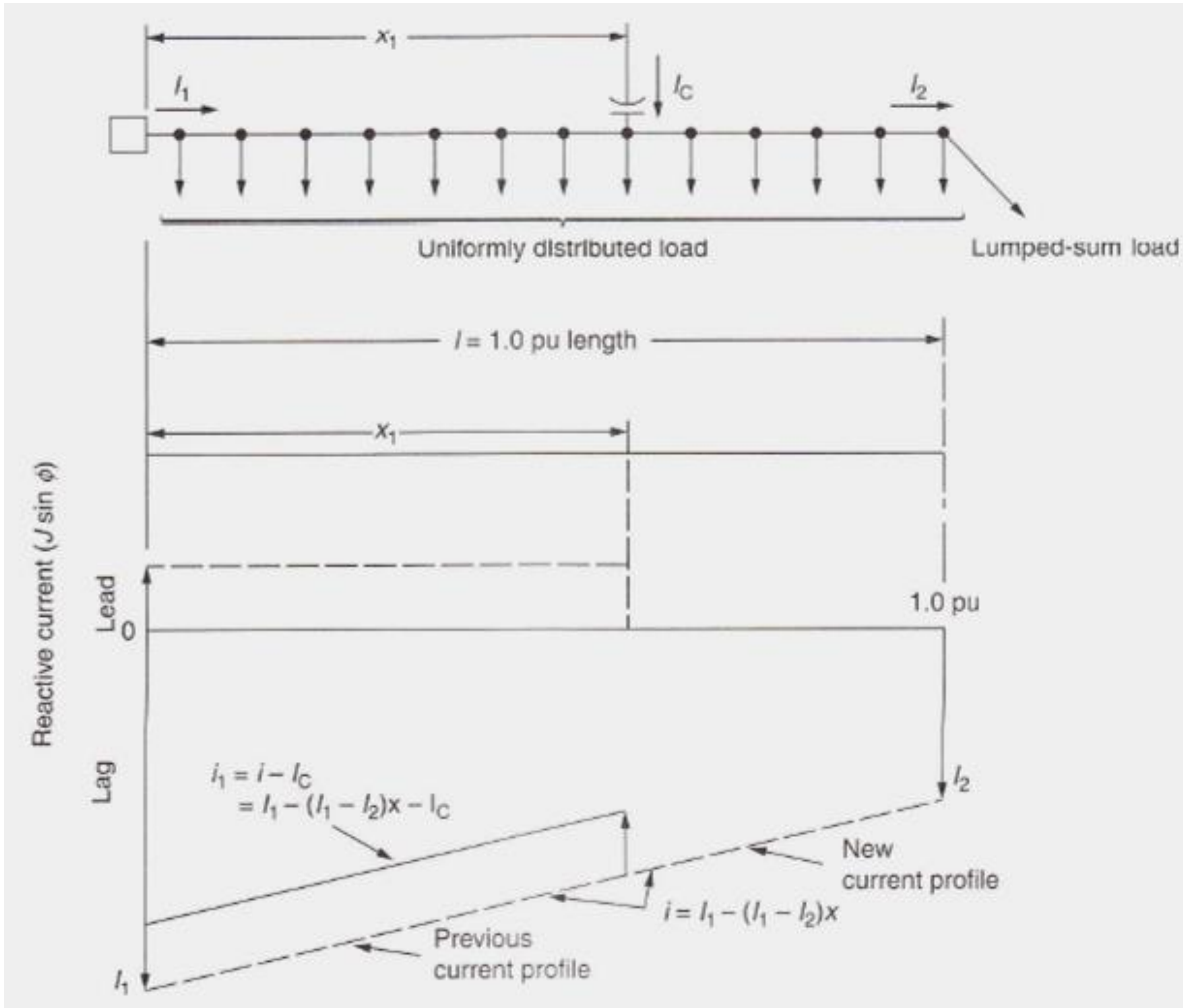


Light load



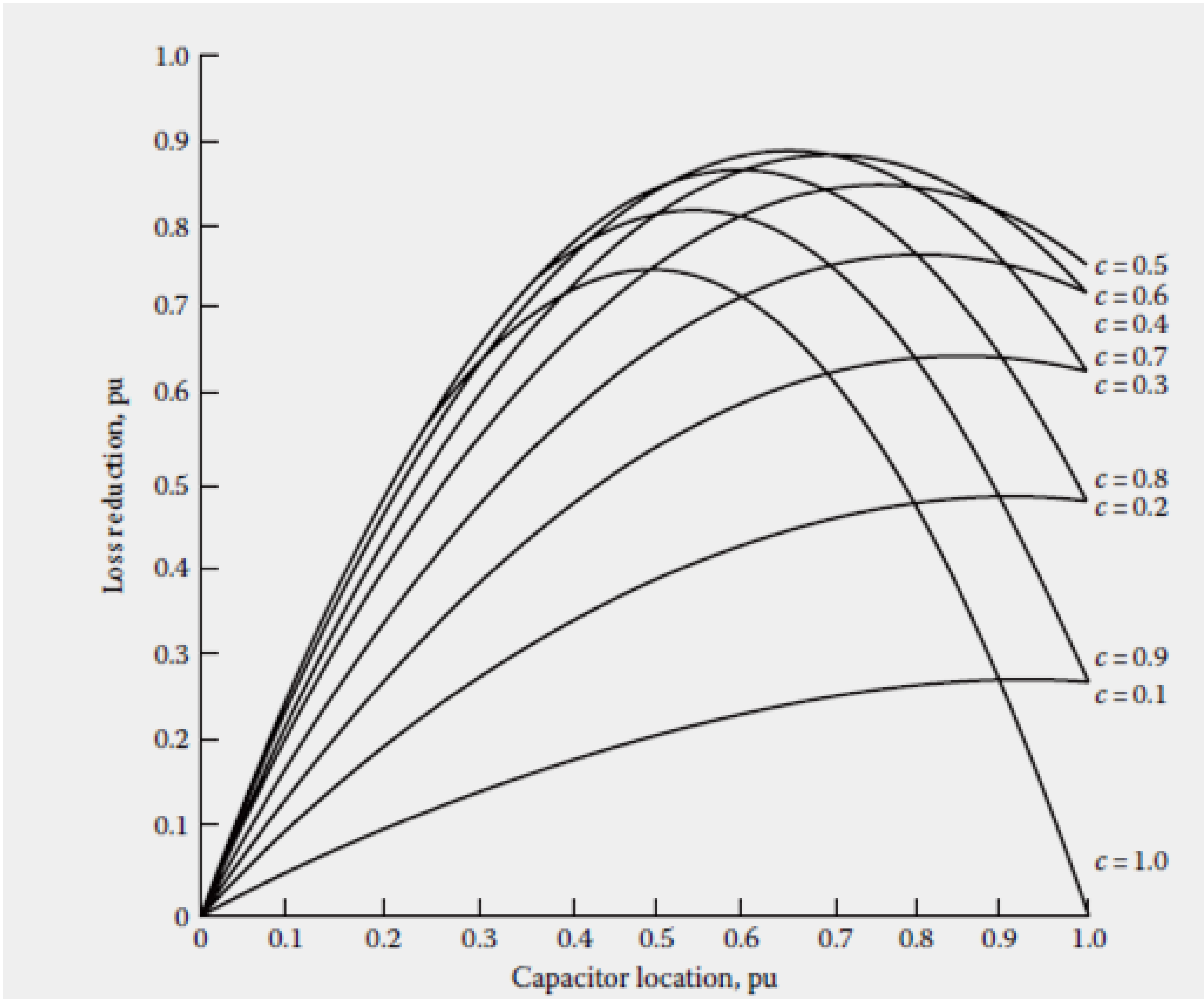
Power loss reduction of one capacitor bank on a feeder with uniformly distributed load

$\lambda = I_2/I_1$



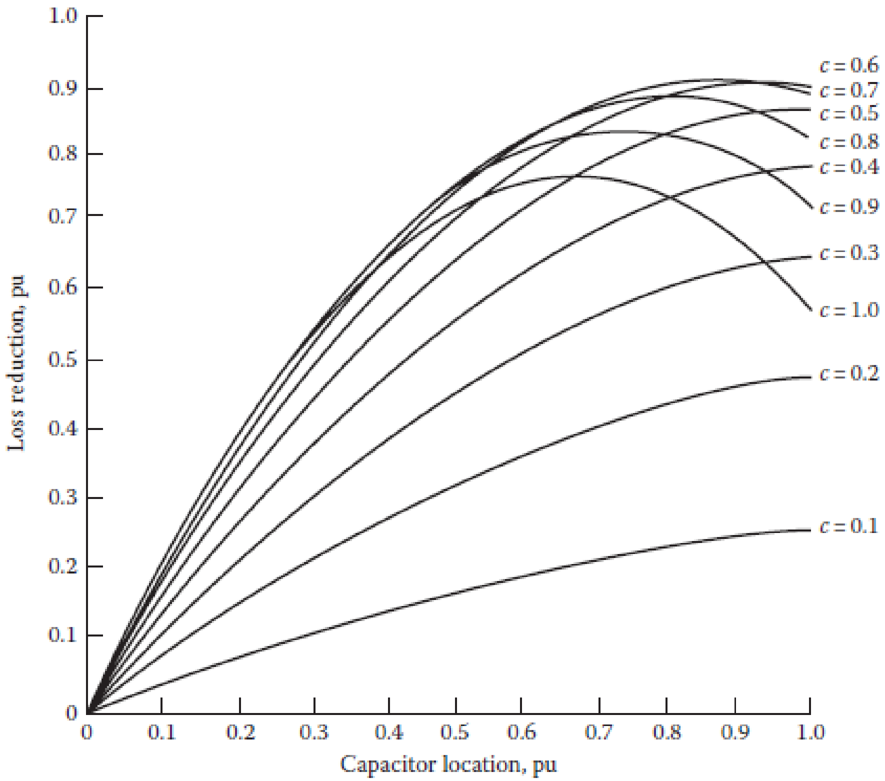
c: capacitor compensation ratio = I_c/I_1

Power loss reduction of one capacitor bank on a feeder with uniformly distributed load

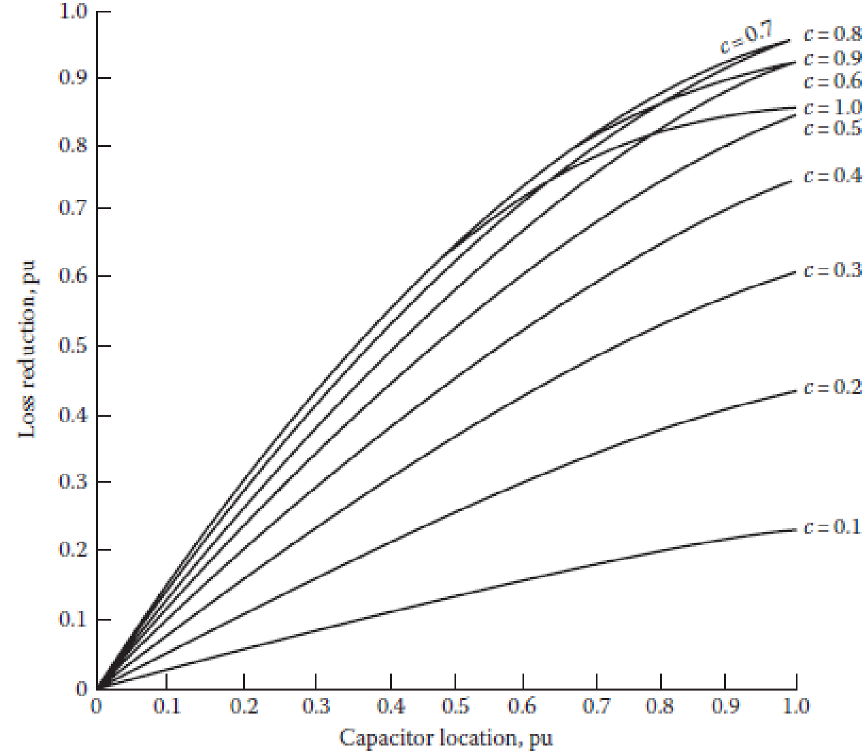


$\lambda = 0$

Power loss reduction of one capacitor bank on a feeder with uniformly distributed load

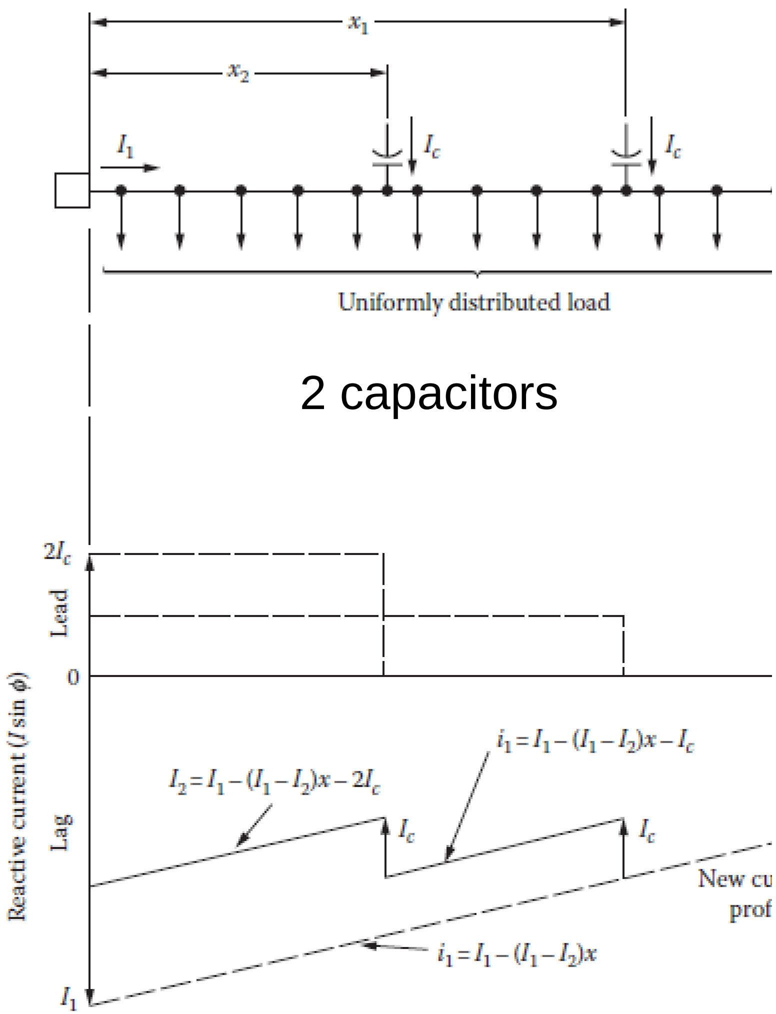


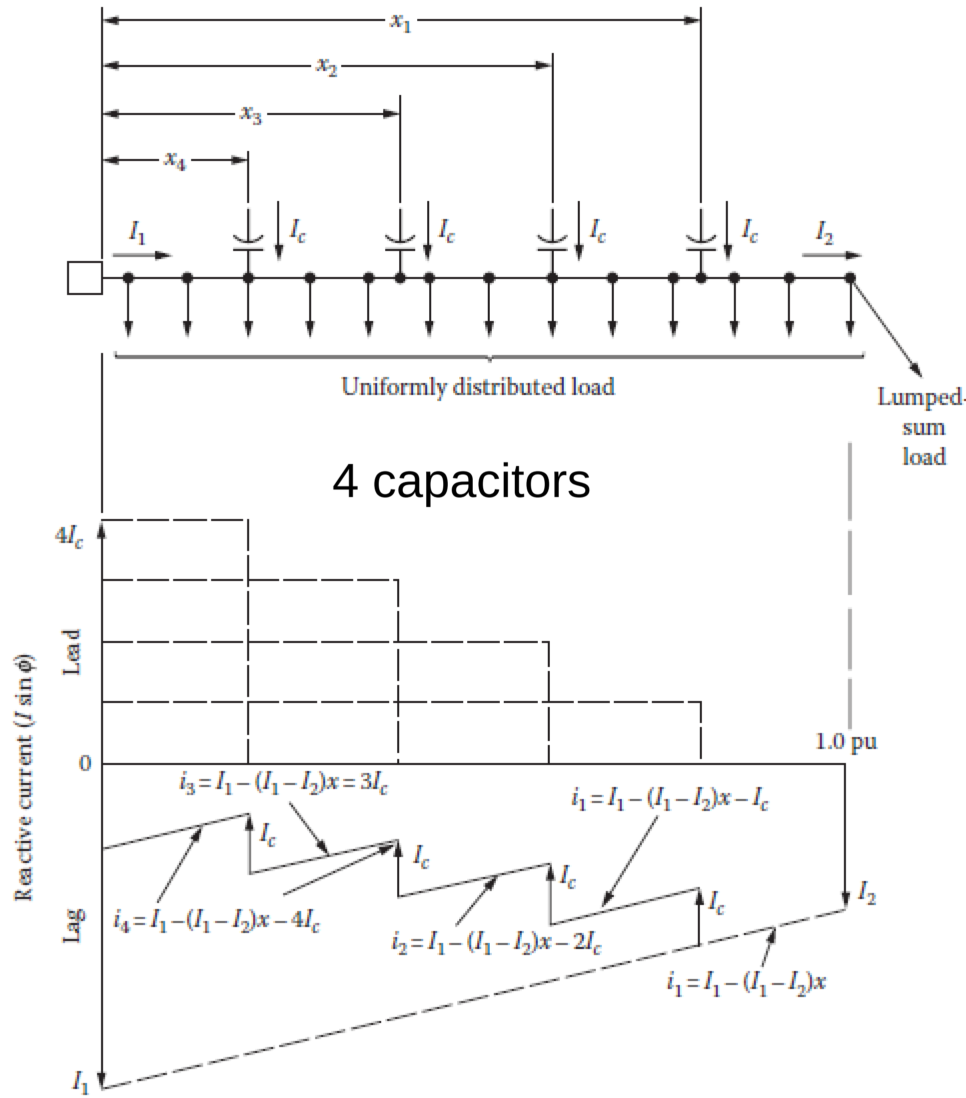
λ= 1/4



λ= 1/2

Multiple capacitor installations

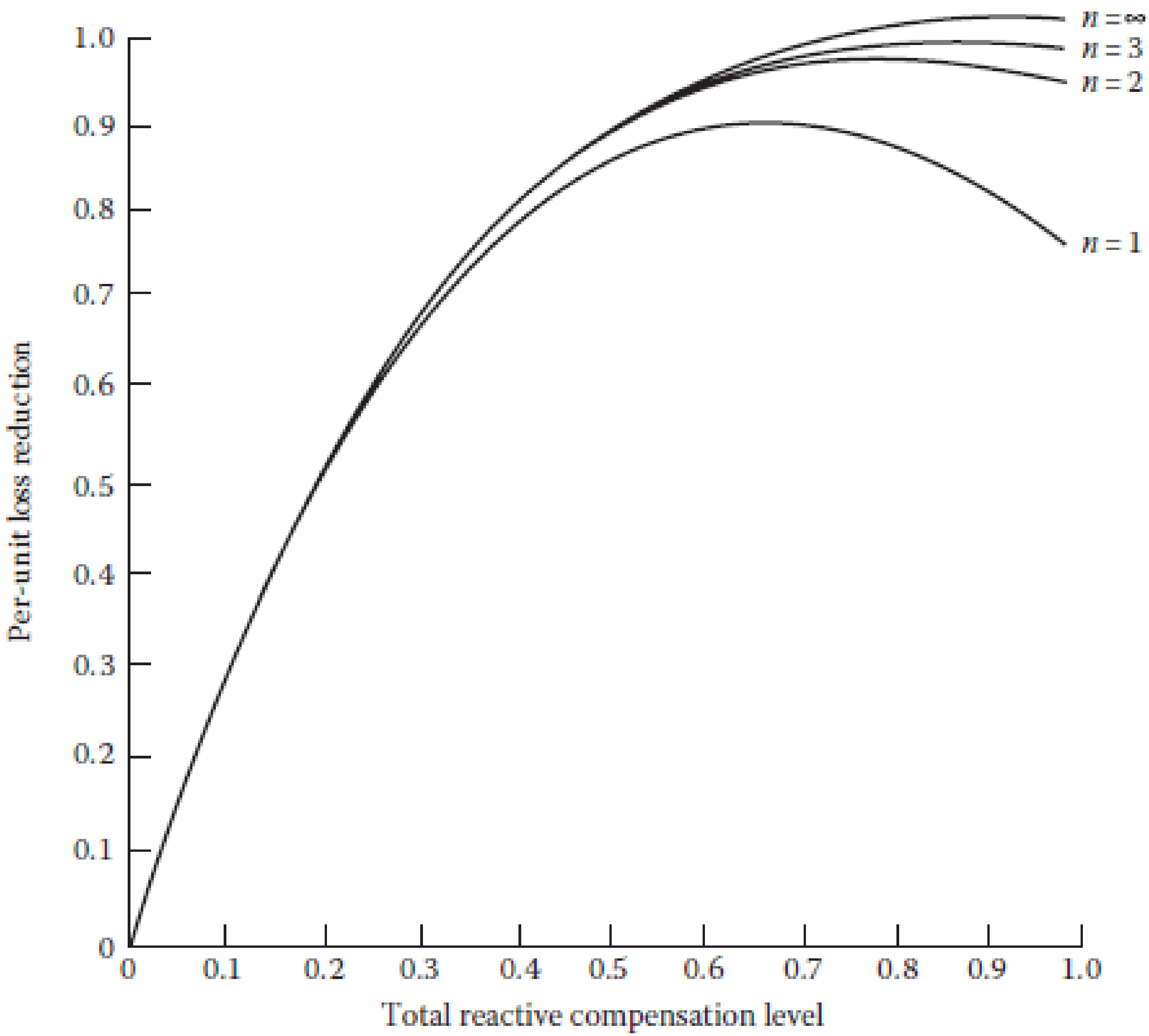




Optimal Solution

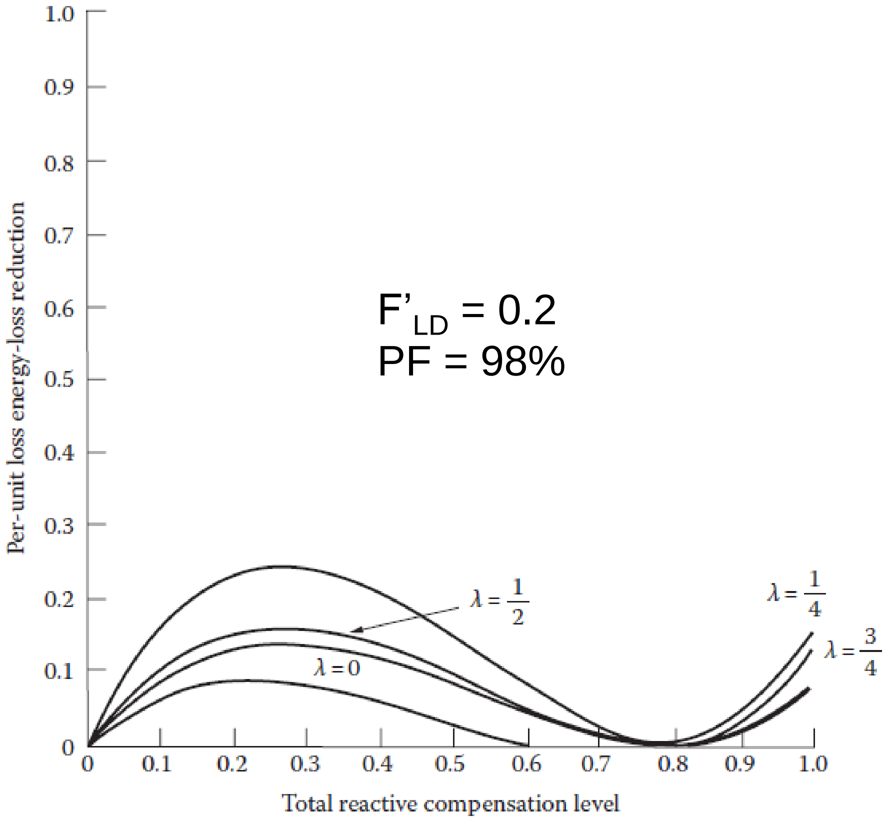
- Capacitor size: $$c = \frac{2}{2n+1}$$
- Optimal location: $$x_i = \frac{1}{1-\lambda} - \frac{(2i-1)c}{2(1-\lambda)}$$
- Optimal loss reduction: $$\Delta P_{loss} = \frac{3\alpha c}{1-\lambda}\left(n - cn^2 + \frac{c^2 n(4n^2-1)}{12}\right),$$
$$\alpha = \frac{1}{1+\lambda+\lambda^2}$$
- Special case: $n=1, \quad \lambda=0, \quad c=\frac{2}{3}\,pu, \quad x=\frac{2}{3}\,pu, \quad \Delta P_{loss}=\frac{8}{9}\,pu$

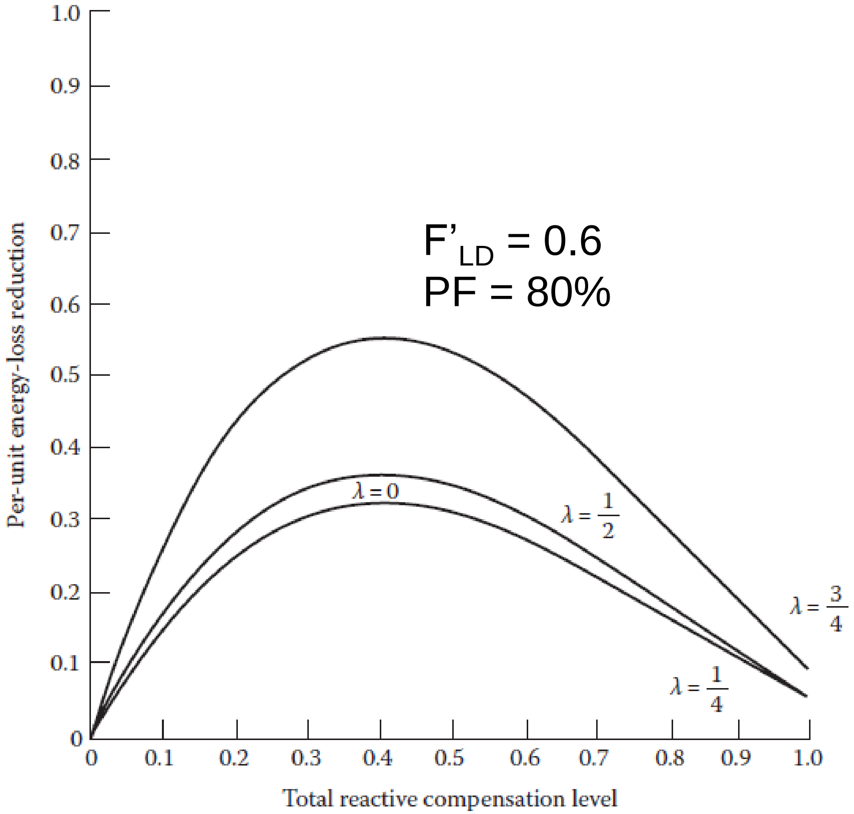
Comparison of loss reduction ($\lambda = 0$)



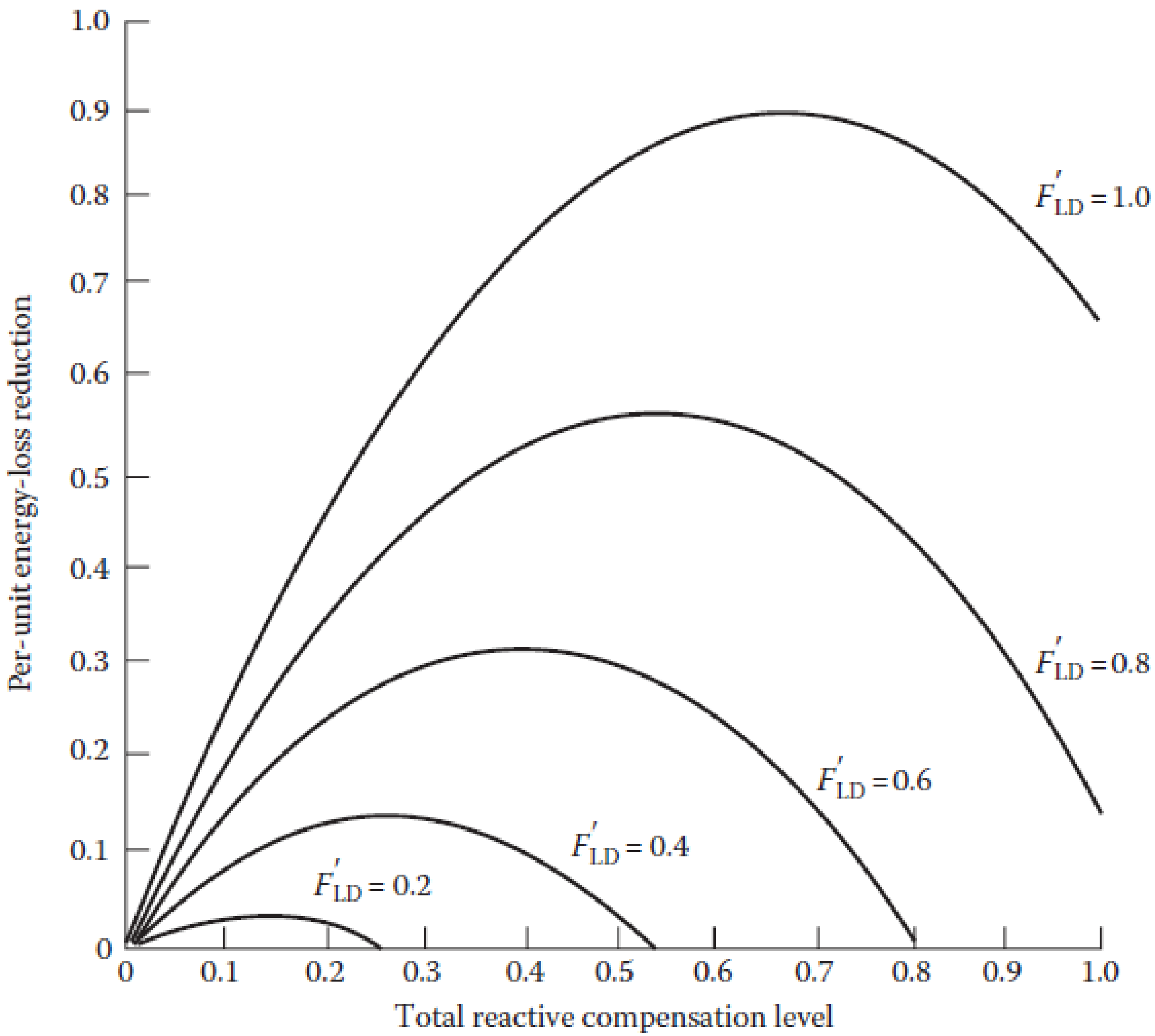
Total Power Loss Reduction

- Depends on how large is the reactive current (I_1) when compared to the total current – or how large is the reactive load factor $F'_{LD} = Q/S$





Effect of Reactive Load Factor on Total Power Loss (λ = 0)



Assignment # 2

- Consider a 5-mile long 12.47 kV distribution feeder with a uniformly distributed load of 10 MVA with 0.85 power factor. Assume the feeder is balanced and has a series impedance of 0.5 +j1 Ω/mile. The voltage at the substation is maintained at 1.05 p.u.
  - Derive and plot the voltage change along the feeder. Calculate the total power loss
  - Determine the size and location of a shunt capacitor that will result in a voltage within ± 0.05 p.u. of the nominal value. Plot the new voltage profile and calculate the new power loss
  - Determine the capacitor size and location that will minimize the power loss. Plot the new voltage profile.