

Reactive Power Compensation of Distribution Systems with Shunt Capacitors

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What is reactive power compensation?

- Reactive power compensation is an approach to locally supply the reactive power demand to the consumer. This results in:
 - Reduction of power loss
 - Improvement of bus voltage profile
 - power factor correction

This is also called volt/var control...

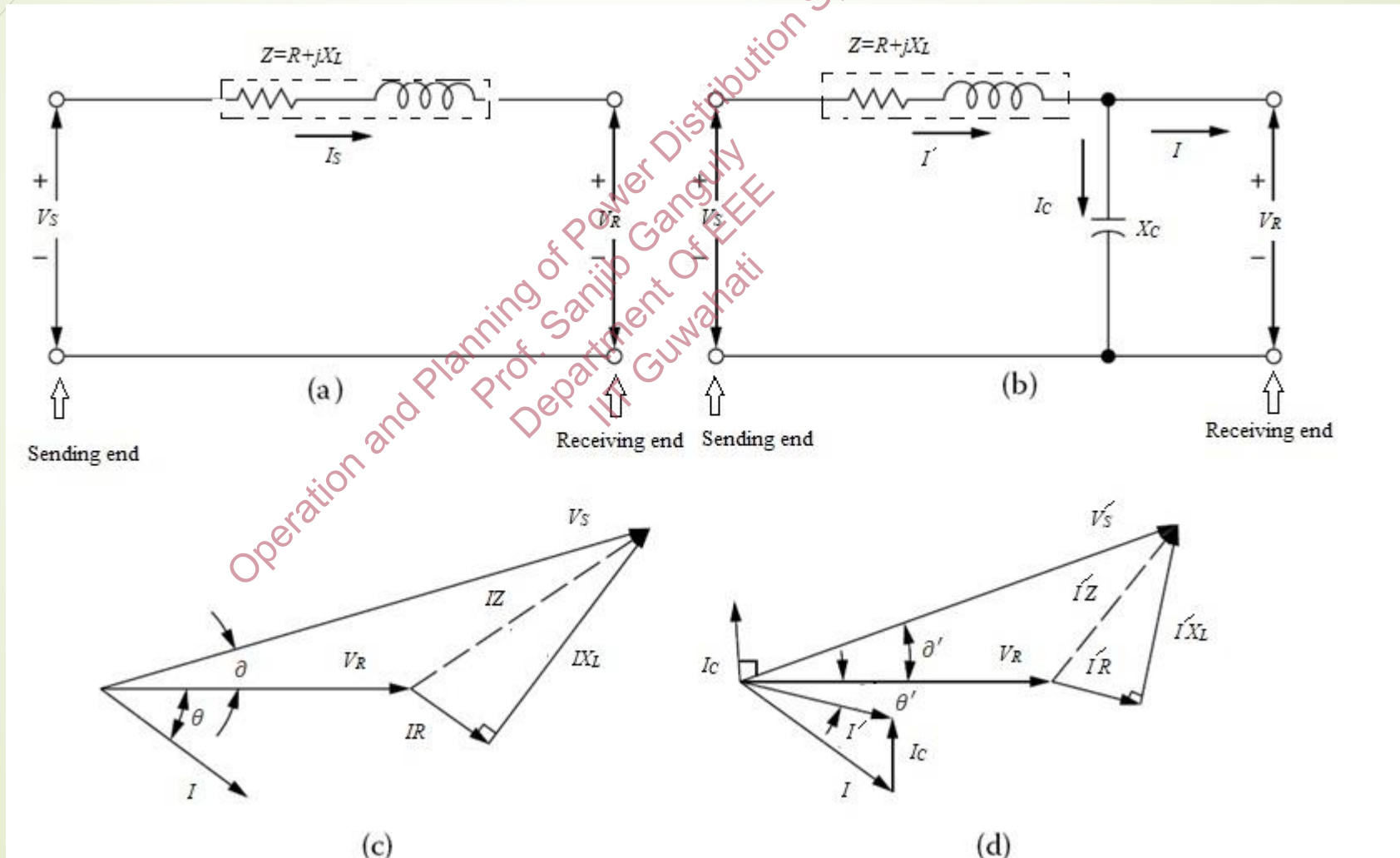
Different reactive power compensation techniques for distribution networks

- Capacitor
- Synchronous condenser
- Custom power devices
- Distributed generation units

Shunt Capacitor placement

- *Shunt capacitors, that is, capacitors connected in parallel with lines, are used extensively in distribution systems.*
- Shunt capacitors modify the characteristic of an inductive load by drawing a leading current.
- With shunt capacitor placement to a feeder, the magnitude of the source current can be reduced, the power factor can be improved, and consequently the voltage drop between the sending end and the load is also reduced.

Phasor diagram for a feeder section with and without capacitor placement



Voltage drop computation with capacitor placement

- ▶ Voltage drop in feeders, or in short transmission lines, with lagging power factor can be approximated as:

$$VD = I_R R + I_X X_L$$

where,

R is the total resistance of the feeder circuit, Ω

X_L is the total inductive reactance of the feeder circuit, Ω

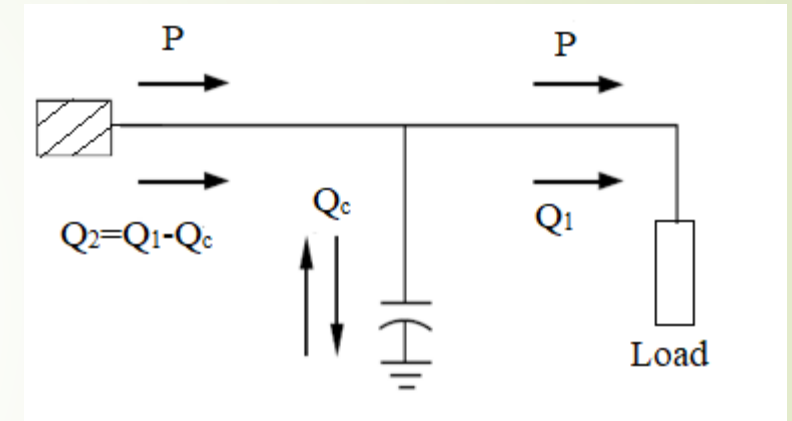
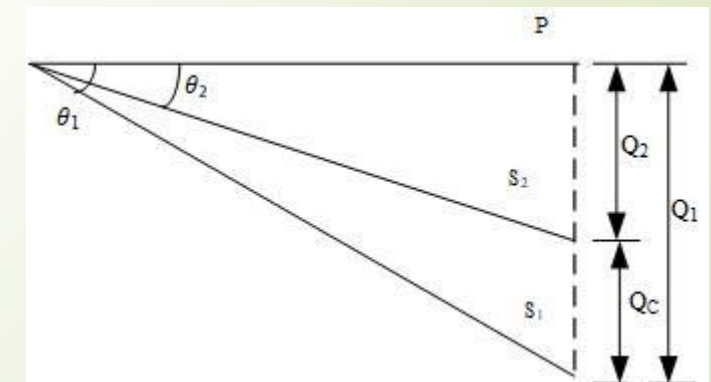
I_R is the real power (or in-phase) component of the current, A

I_X is the reactive power (or out-of-phase) component of the current lagging the voltage by 90° , A

Capacitor placement for the power factor correction: Power Triangle

- by adding the capacitors, the reactive power component Q of the apparent power S of the load can be reduced or totally suppressed.
- Assume that a load is supplied with a real power P , lagging reactive power Q_1 , and apparent power S_1 at a lagging power factor of

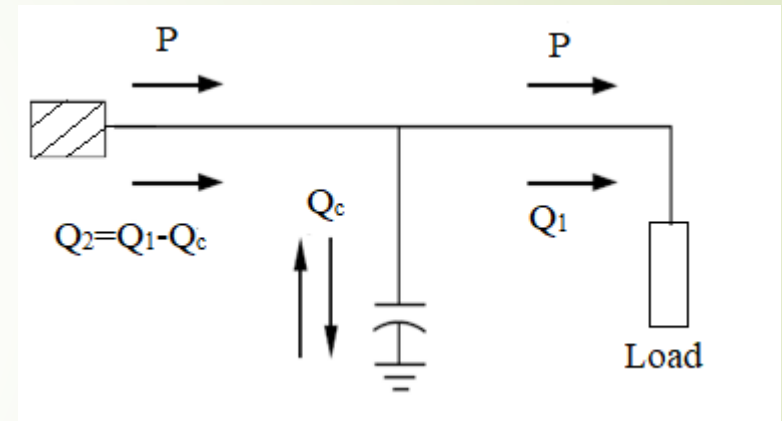
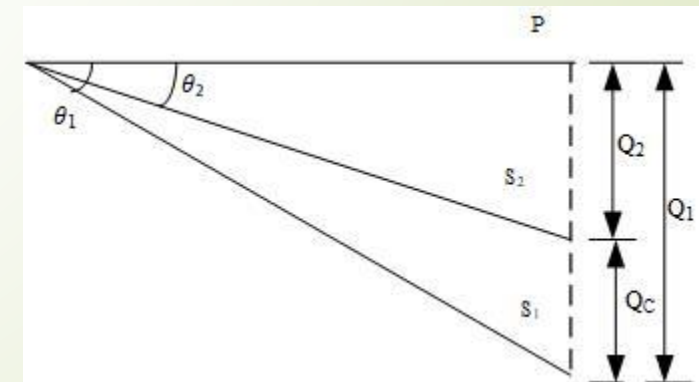
$$\cos\theta_1 = \frac{P}{S_1} = \frac{P}{(P^2 + Q_1^2)^{1/2}}$$



Capacitor placement for the power factor correction: Power Triangle

- When a shunt capacitor of Q_c kVA is installed at the load, the power factor can be improved from $\cos \theta_1$ to $\cos \theta_2$, where,

$$\cos \theta_2 = \frac{P}{S_2} = \frac{P}{(P^2 + Q_2^2)^{1/2}} = \frac{P}{[P^2 + (Q_1 - Q_c)^2]^{1/2}}$$



Power factor correction

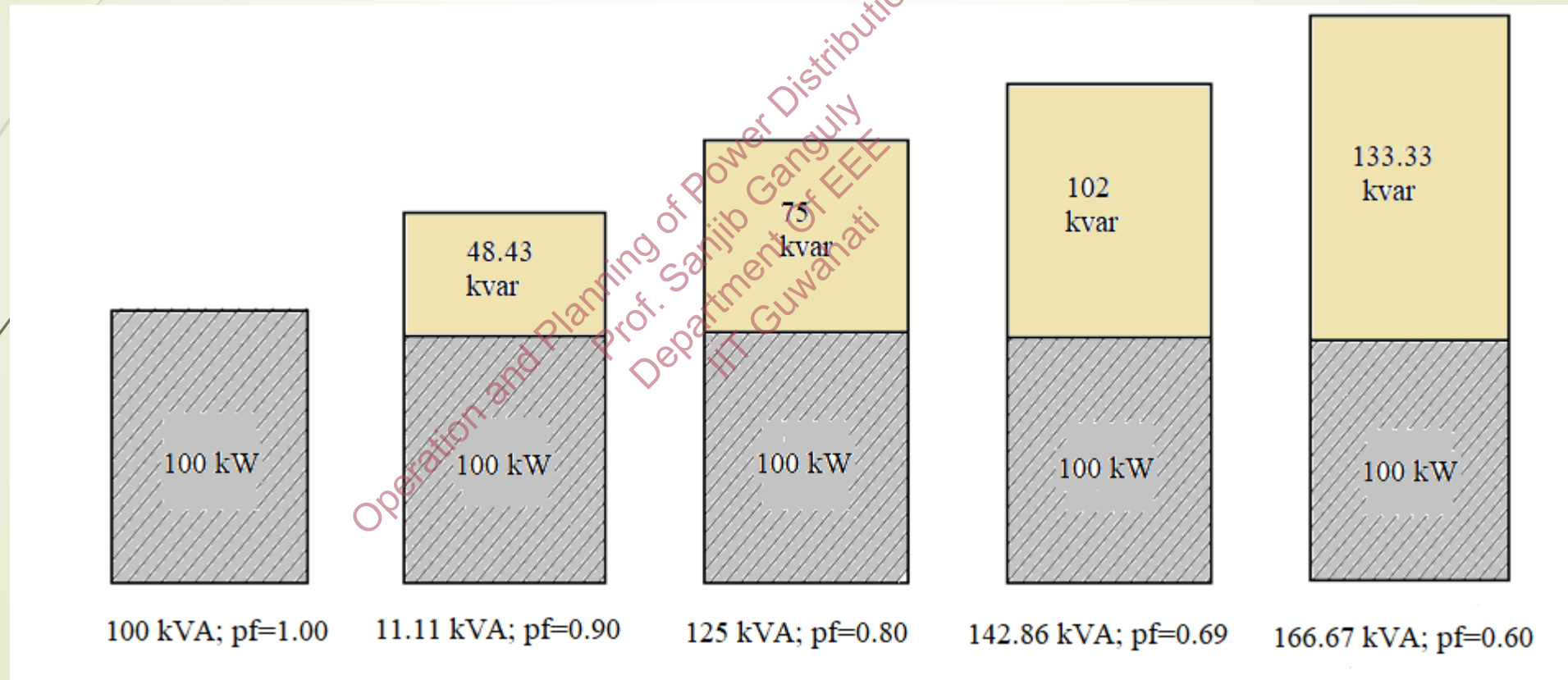
- It gives a multiplier to determine the kVAr requirement. It is based on the following formula:

$$Q = P(\tan\theta_{orig} - \tan\theta_{new}) = P \left\{ \sqrt{\frac{1}{PF_{orig}^2} - 1} - \sqrt{\frac{1}{PF_{new}^2} - 1} \right\}$$

where,

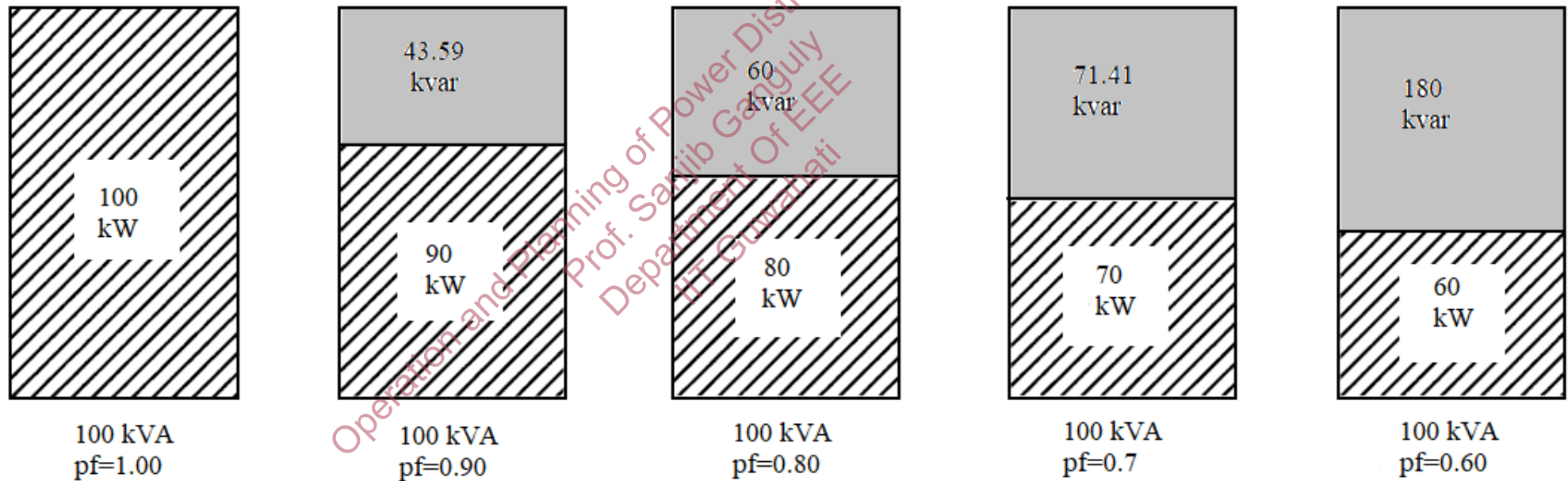
- Q is the required compensation in kVAr
- P is the real power kW
- PF_{orig} is the original power factor
- PF_{new} is the desired power factor

Illustrative example of the effect of reactive power on power factor



Ref. T. Gonen. *Electric Power Distribution System Engineering*

Illustrative example of the effect of reactive power on power factor



Concepts of leading and lagging power factor

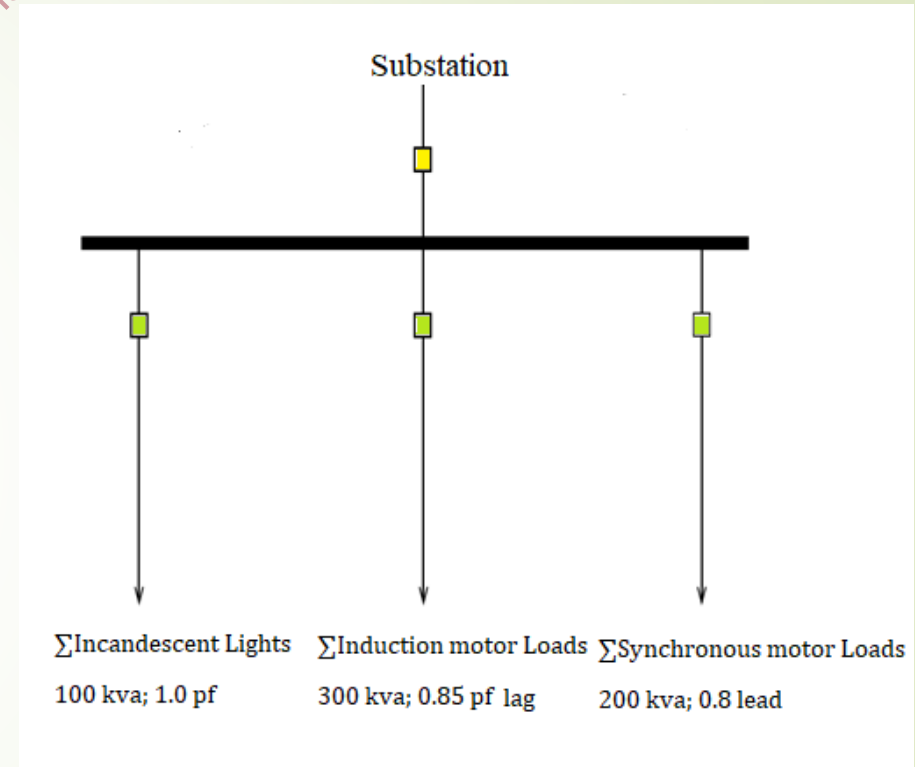
- The concept of “lagging” and “leading” power factors depends on the directions of the flows of real and reactive powers.
- For a given load, the power factor is *lagging* if the load consumes reactive power. It is *leading* if the load supplies reactive power.
- An induction motor has a lagging power factor, since it consumes reactive power from the source to meet its magnetizing requirements. But a capacitor (or an overexcited synchronous motor) supplies reactive power and thus has a leading power factor,

Economy in power factor correction: Concept of economic power factor

- Since the capacitor can compensate the reactive current drawn by the load, it results in a reduced total current, which in turn causes less power losses.
- Thus, the power factor correction produces economic savings in capital expenditures and fuel expenses through a release of kilovolt-amp capacity.
- The economic power factor is the point at which the economic benefits of adding shunt capacitors just equal the cost of the capacitors.

Example...

- Assume that a substation supplies three different kinds of loads, i.e., incandescent lights, induction motors, and synchronous motors, as shown in Figure. Based on the given data in Figure, determine the following:
 - a. The apparent, real, and kVAr's of each load
 - b. The total apparent, real, and reactive powers of the power that should be supplied by the substation
 - c. The total power factor of the substation



Solution...

❑ Since incandescent lights are basically a unity power factor load, hence, $S_1 = P_1 = 100 \text{ kW}$ and reactive power $Q_1 = 0$.

❑ For induction motor loads operating power factor of 0.85 lagging, $S_2 = 300 \text{ kVA}$

Real power consumption $P_2 = 300 \times 0.85 = 255 \text{ kW}$

❑ For synchronous motor load, the apparent power $S_3 = 200 \text{ kVA}$.
Thus, the real power consumption, $P_3 = (200 \text{ kVA}) \cos \theta$
 $= 200 \times 0.8 = 160 \text{ kW}$

Solution...

- ❖ Reactive power consumption (Q_2) of the induction motor

load is, $Q_2 = \sqrt{(300)^2 - (255)^2} = \sqrt{90,000 - 65,025} \cong 158 \text{ kVAr}$

- ❖ Reactive power consumption (Q_3) of the synchronous

motors is $Q_3 = -\sqrt{(200 \text{ kVA})^2 - (160 \text{ kW})^2}$

$$= -\sqrt{40,000 - 25,600}$$

$$= -\sqrt{14,400}$$

$$= -120 \text{ kVAr}$$

Solution...

At the substation, the total real power consumption is

$$\begin{aligned}P_{total} &= P_1 + P_2 + P_3 \\&= 100 + 255 + 160 \\&= 515 \text{ kW}\end{aligned}$$

Total Reactive power consumption is:

$$\begin{aligned}Q_{total} &= Q_1 + Q_2 + Q_3 \\&= 0 + 158 - 120 \\&= 38 \text{ kVAr}\end{aligned}$$

Reactive power

- Induction motor load required = 158 kVAr
- Synchronous motor supplied = 120 kVAr
- Substation must supply = 38 kVAr

Solution...

The kVA of the substation is $S_{total} = \sqrt{P_{tot}^2 + Q_{tot}^2}$

$$\begin{aligned} &= \sqrt{515^2 + 38^2} \\ &= \sqrt{266,669} \\ &= 516.4 \text{ kVA} \end{aligned}$$

The power factor of the substation is,

$$\begin{aligned} &= \frac{515 \text{ kW}}{516.4 \text{ kVA}} \\ &= 0.997 \text{ lagging} \end{aligned}$$

Example...

- A synchronous generator is rated 1250 kVA. It is operating at a rated load of 1250 kVA at 0.85 power factor lagging. An additional load of 150 kW at 0.85 power factor is to be added. Determine the value of capacitors needed in order not to overload the generator.

Solution:

- ❖ The generator provides real power $P = 1250 \times 0.85 = 1062.5 \text{ kW}$
- ❖ The generator provides reactive power $Q = \sqrt{1250^2 - 1062.5^2} = 658.48 \text{ kVAr}$

Solution...

- ❖ With an additional load of 150 kW, the generator needs to supply $P_{new} = 1062.5 + 150 = 1212.5$ kW
- ❖ Since the generator is rated 1250 kVA, with the additional load it can provide $Q_{new} = \sqrt{1250^2 - 1212.5^2} = 303.88$ kVAr
- ❖ The additional load demands the reactive power of $Q_{add} = \sqrt{\left(\frac{150}{0.85}\right)^2 - 150^2} = 92.96$ kVAr
- ❖ The total reactive power demand is $Q_d = Q + Q_{add} = 658.48 + 92.96 = 751.44$ kVAr
- ❖ However, the generator can only provide 303.88 kVAr
- ❖ Therefore, the capacitor rating should be $Q_c = 751.44 - 303.88 = 447.56$ kVAr

Exercise 1...

- Assume that a load consumes 80 kW and 60 kVAr lagging. It is required that its power factor is to be improved to 0.9 using capacitor bank so that the real power consumption of the load remains same. Determine the size of the capacitor bank.

Computerized method to determine the economic power factor

- Firstly, a load flow digital computer program can be employed to determine the kVA, kV, and kVAr at annual peak level for the whole system.
- Shunt capacitors are applied to a particular bus for correcting to an initial power factor, for example, 0.8.
- Then, a load flow run is performed to determine the total system losses.
- Additional capacitors are applied to the bus to increase the power factor by 0.01, and another load flow run is made.
- This process of iteration is repeated until the power factor becomes unity.

Computerized method to determine the economic power factor

- After determining the economic power factor, the additional capacitor size required can be calculated as:

$$\Delta Q_c = P_{PK} (\tan \phi - \tan \theta)$$

Where

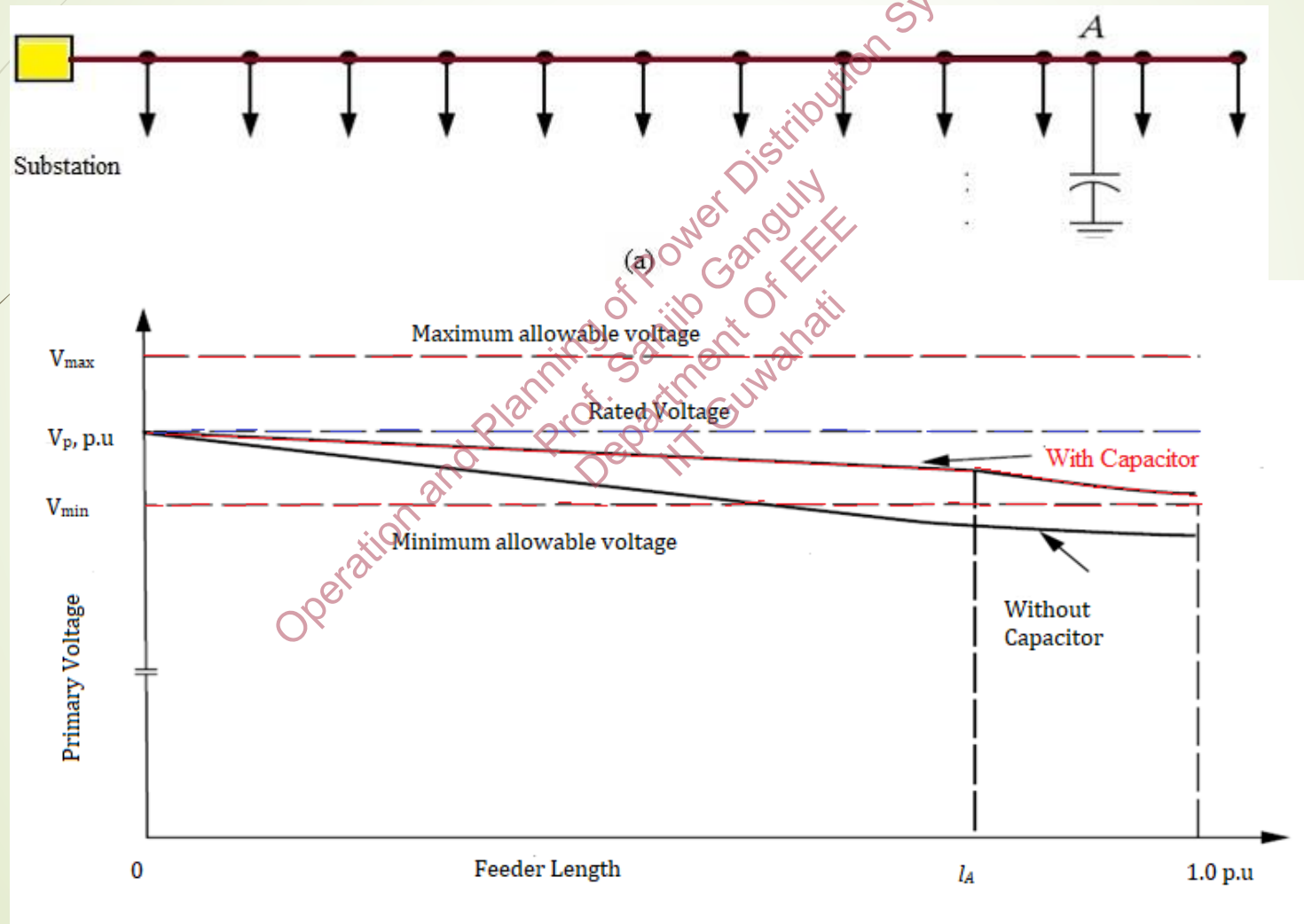
ΔQ_c is the required capacitor size, kVAr

P_{PK} is the system demand at annual peak, kW

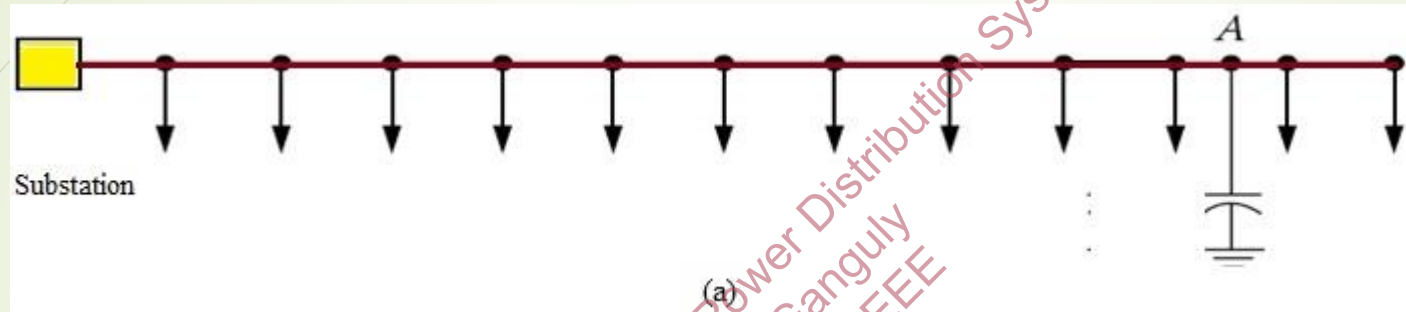
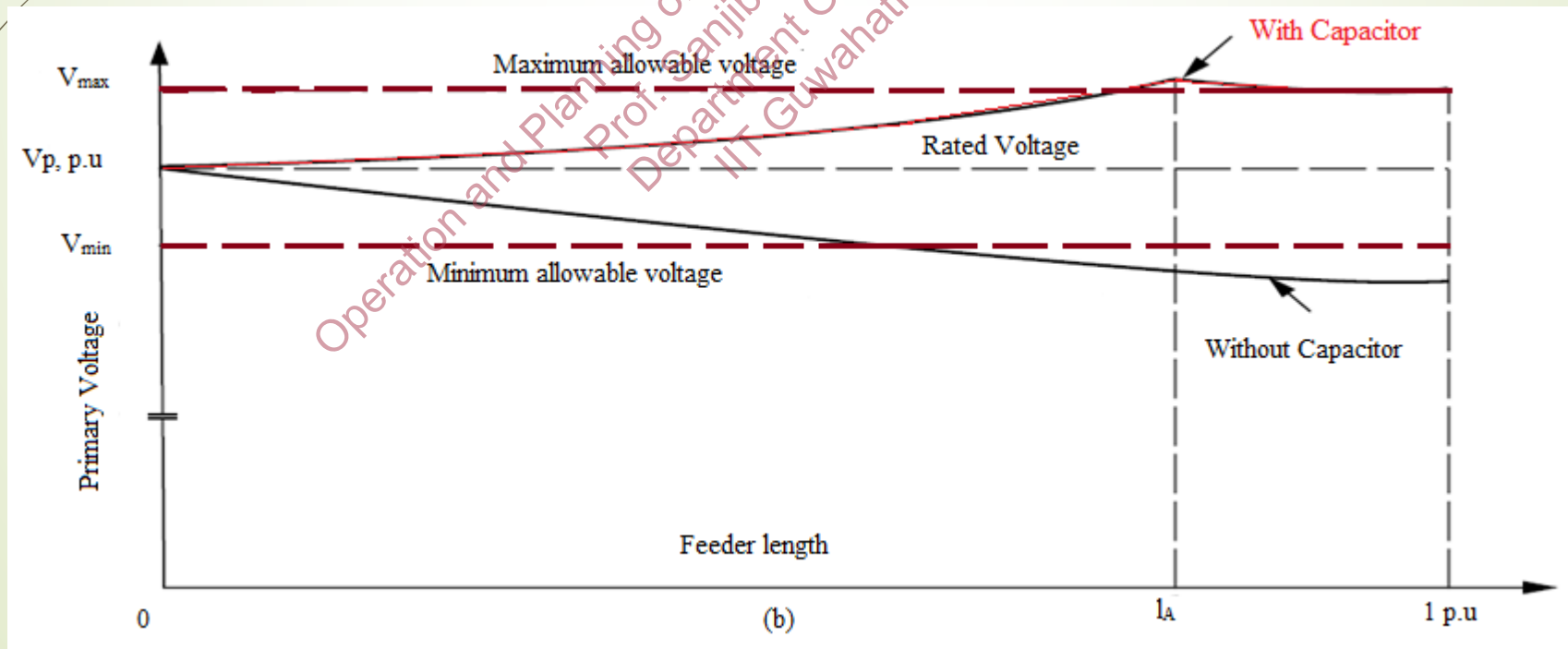
$\tan \phi$ is the tangent of original power factor angle

$\tan \theta$ is the tangent of economic power factor angle

Effect of Capacitor placement on the voltage profile of distribution feeder line at rated load



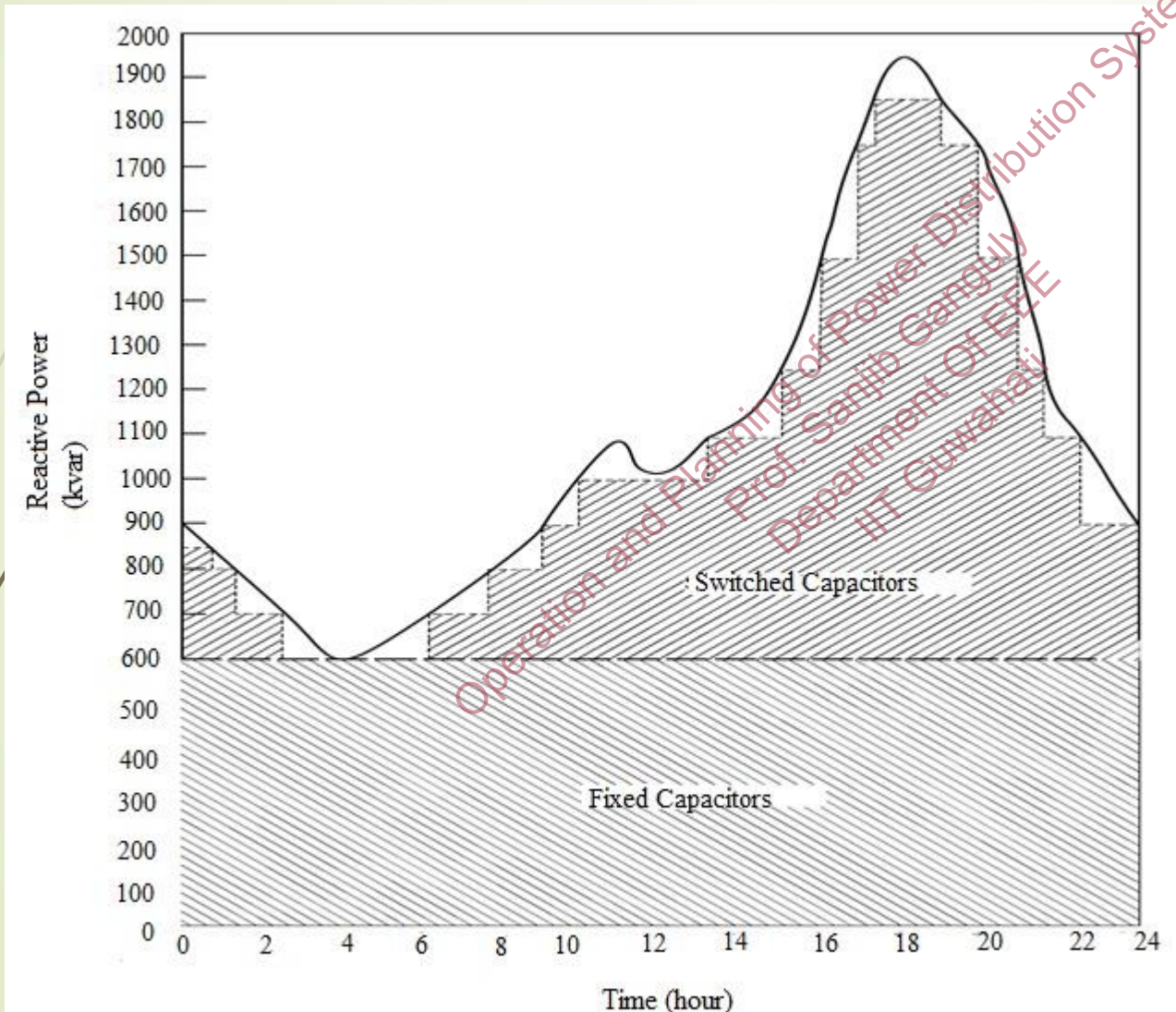
Effect of Capacitor placement on the voltage profile of distribution feeder line at light load



Effect of Capacitor placement on the voltage profile of distribution feeder line

- If only fixed-type capacitors are installed, there will be voltage rise problem during light load conditions.
- Therefore, some of the capacitors are installed as *switched capacitor banks* so they can be switched off *during light-load conditions*.
- Thus, the *fixed capacitors* are sized so that their presence would not cause voltage rise at light loading.

Switched capacitor bank



- However, in practice, the number of steps or blocks is selected to be much less than the ones shown in the figure due to the additional expenses involved in the installation of the required switchgear and control equipment.

Capacitor sizing

- Many utilities apply the following rule of thumb to determine the size of the switched capacitors:

$$\frac{kVAr \text{ from (switched + fixed) capacitors}}{kVAr \text{ of peak reactive feeder load}} \geq 0.70$$

Some utilities use the following rule of thumb: *The total amount of fixed and switched capacitors for a feeder is the amount necessary to raise the receiving-end feeder voltage to maximum at 50% of the peak feeder load.*

Economic benefits of capacitor placement for distribution networks

- Released distribution substation capacity
- Reduced energy losses
- Reduced voltage drop and consequently improved voltage regulation
- Released capacity of feeder and associated apparatus
- Postponement or elimination of capital expenditure due to system improvements and/or expansions
- Revenue increase due to voltage improvements

Total financial benefits of capacitor placement

- Therefore, the total benefits due to the installation of capacitor banks can be summarized as:

$$\begin{aligned}\sum \Delta\$ &= (\text{Demand reduction}) + (\text{Energy reduction}) + (\text{Revenue increase}) \\ &= (\Delta\$_G + \Delta\$_T + \Delta\$_S + \Delta\$_F) + \Delta\$_{ACE} + \Delta\$_{BEC}\end{aligned}$$

$\Delta\$_G$ is the released generation capacity beyond maximum generation capacity at original power factor, kVA

$\Delta\$_T$ is the released transmission capacity beyond maximum transmission capacity at original power factor, kVA

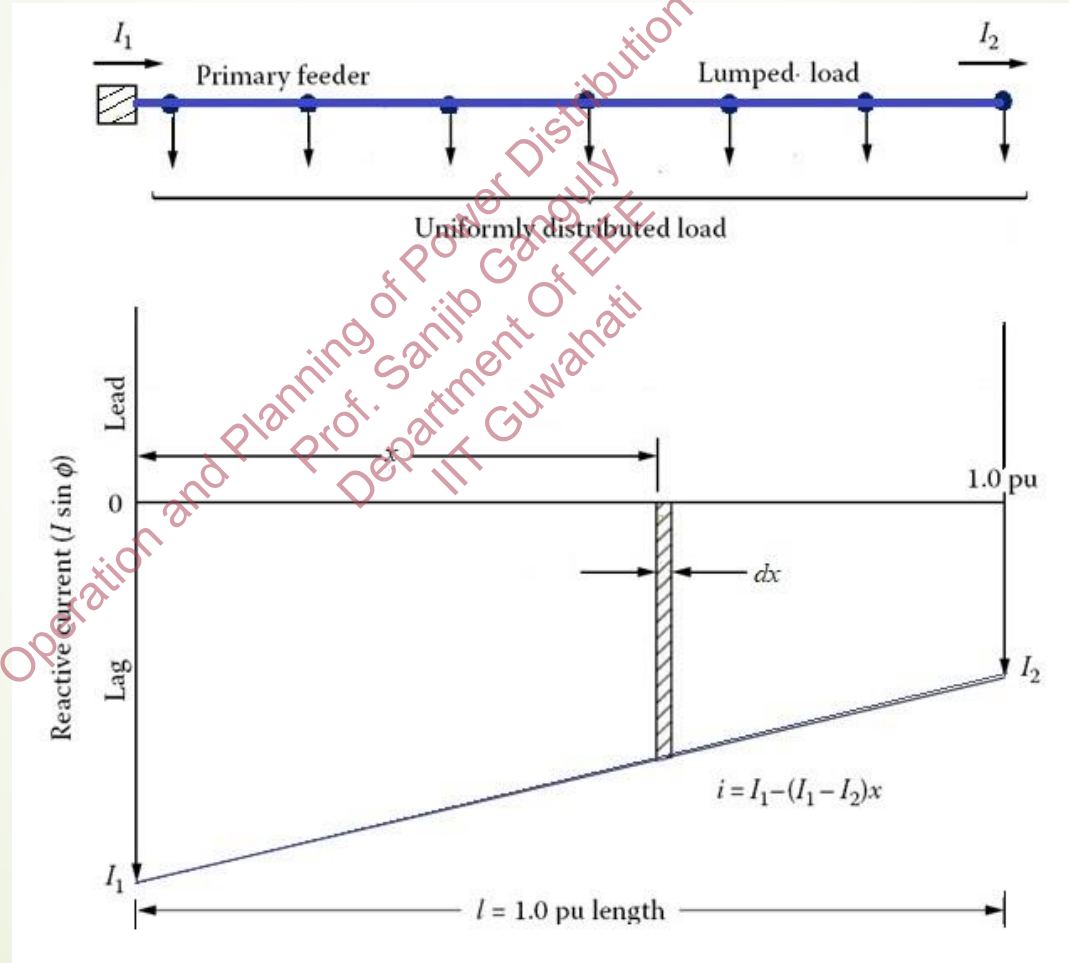
$\Delta\$_S$ is the released distribution substation capacity beyond maximum substation capacity at original power factor, kVA

$\Delta\$_F$ is the annual benefits due to released feeder capacity, \$/year

Analytical method to determine the optimum location for capacitor

- A realistic representation of a feeder that contains a number of line segments with a combination of concentrated (or lumped-sum) and uniformly distributed loads is considered.
- Each line segment represents a part of the feeder between sectionalizing devices, voltage regulators, and other points of significance.
- For the sake of convenience, the load or line current and the resulting power loss can be assumed to have two components, namely, (1) those due to the in-phase or active component of current and (2) those due to the out-of-phase or reactive component of current.

Analytical method to determine the optimum location for capacitor



Analytical method to determine the optimum location for capacitor

- Assume that the power losses are caused by a lagging line current I flowing through the circuit resistance R . Therefore, it can be shown that:

$$I^2 R = (I \cos \phi)^2 R + (I \sin \phi)^2 R$$

- After adding a shunt capacitor with current I_c , the resultants are a new line current I_1 and a new power loss. Hence,

$$I_1^2 R = (I \cos \phi)^2 R + (I \sin \phi - I_c)^2 R$$

Analytical method to determine the optimum location for capacitor

- Therefore, the loss reduction as a result of the capacitor addition can be found as:

$$\Delta P_{LS} = I^2 R - I_1^2 R$$
$$\Delta P_{LS} = 2(I \sin \phi) I_C R - I_C^2 R$$

- Thus, only the out-of-phase or reactive component of line current, that is, $I \sin \theta$, should be taken into account for power loss reduction as a result of a capacitor addition.

Analytical method to determine the optimum location for capacitor

- Assume that the length of a feeder segment is 1.0 pu length, as shown in Figure. The current profile of the line current at any given point on the feeder is a function of the distance of that point from the beginning of the feeder. Therefore, the differential power loss of a dx differential segment located at a distance x can be expressed as:

$$dP_{LS} = 3[I_1 - (I_1 - I_2)x]^2 R dx$$

Analytical method to determine the optimum location for capacitor

- Therefore, the total power loss of the feeder can be found

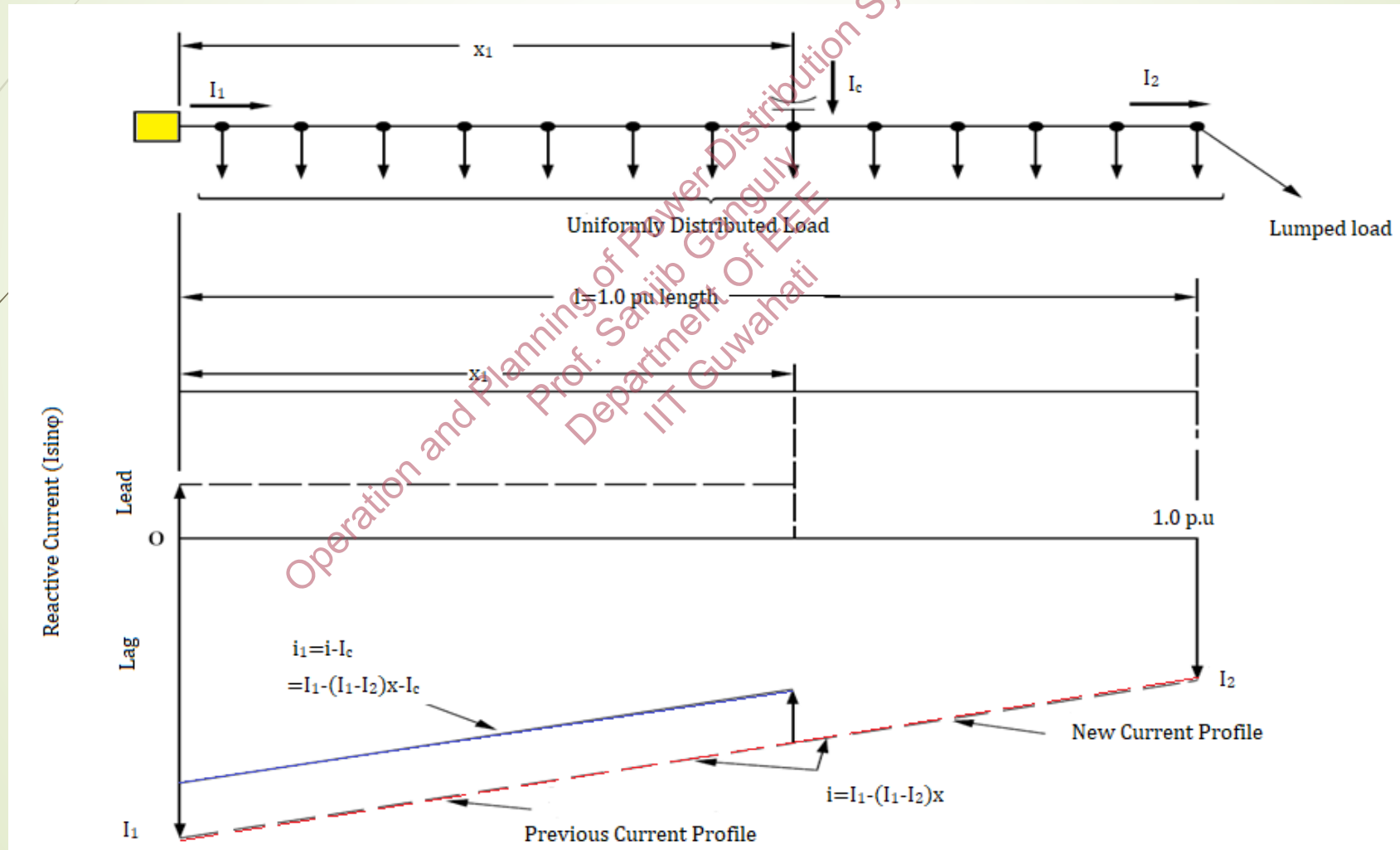
$$\text{as: } P_{LS} = \int_{x=0}^{1.0} dP_{LS} = 3 \int_{x=0}^{1.0} [I_1 - (I_1 - I_2)x]^2 R dx$$

$$= (I_1^2 + I_1 I_2 + I_2^2) R$$

where,

- P_{LS} is the total I^2R loss of the feeder before adding the capacitor
- I_1 is the reactive current at the beginning of the feeder segment
- I_2 is the reactive current at the end of the feeder segment
- R is the total resistance of the feeder segment
- X is the per unit distance from the beginning of the feeder segment

Analytical method for capacitor placement: Single capacitor bank



Analytical method for capacitor placement: Single capacitor bank

- The insertion of one capacitor bank on the primary feeder causes a break in the continuity of the reactive load profile, modifies the reactive current profile, and consequently reduces the loss, as shown in Figure.
- Therefore, the loss equation after adding one capacitor bank can be found as before:

$$P'_{LS} = 3 \int_{x=0}^{x_1} [I_1 - (I_1 - I_2)x - I_c]^2 R dx + 3 \int_{x=x_1}^{1.0} [I_1 - (I_1 - I_2)x]^2 R dx$$

$$P'_{LS} = (I_1^2 + I_1 I_2 + I_2^2) + 3x_1[(x_1 - 2)I_1 I_c - x_1 I_2 I_c + I_c^2]R$$

Analytical method for capacitor placement: Single capacitor bank

- Thus, the per unit power loss reduction as a result of adding one capacitor bank can be found from:

$$\Delta P_{LS} = \frac{P_{LS} - P'_{LS}}{P_{LS}}$$

$$\Delta P_{LS} = \frac{-3x_1[(x_1 - 2)I_1I_c - x_1I_2I_c + I_c^2]R}{(I_1^2 + I_1I_2 + I_2^2)R}$$

$$\Delta P_{LS} = \frac{3x_1}{1 + (I_2/I_1) + (I_2/I_1)^2} \left[(2 - x_1) \left(\frac{I_c}{I_1} \right) + x_1 \left(\frac{I_2}{I_1} \right) \left(\frac{I_c}{I_1} \right) - \left(\frac{I_c}{I_1} \right)^2 \right]$$

Analytical method for capacitor placement: Single capacitor bank

- If c is defined as the ratio of the capacitive kVA (kVA) of the capacitor bank to the total reactive load, that is,

$$c = \frac{\text{kVA of capacitor installed}}{\text{Total reactive load}}, \text{ then } c = \frac{I_c}{I_1}$$

- If λ is defined as the ratio of the reactive current at the end of the line segment to the reactive current at the beginning of the line segment, that is,

$$\lambda = \frac{\text{Reactive current at the end of line segment}}{\text{Reactive current at the beginning of line segment}}, \text{ then } \lambda = \frac{I_2}{I_1}$$

Analytical method for capacitor placement: Single capacitor bank

- Therefore, the per unit power loss reduction can be found as:

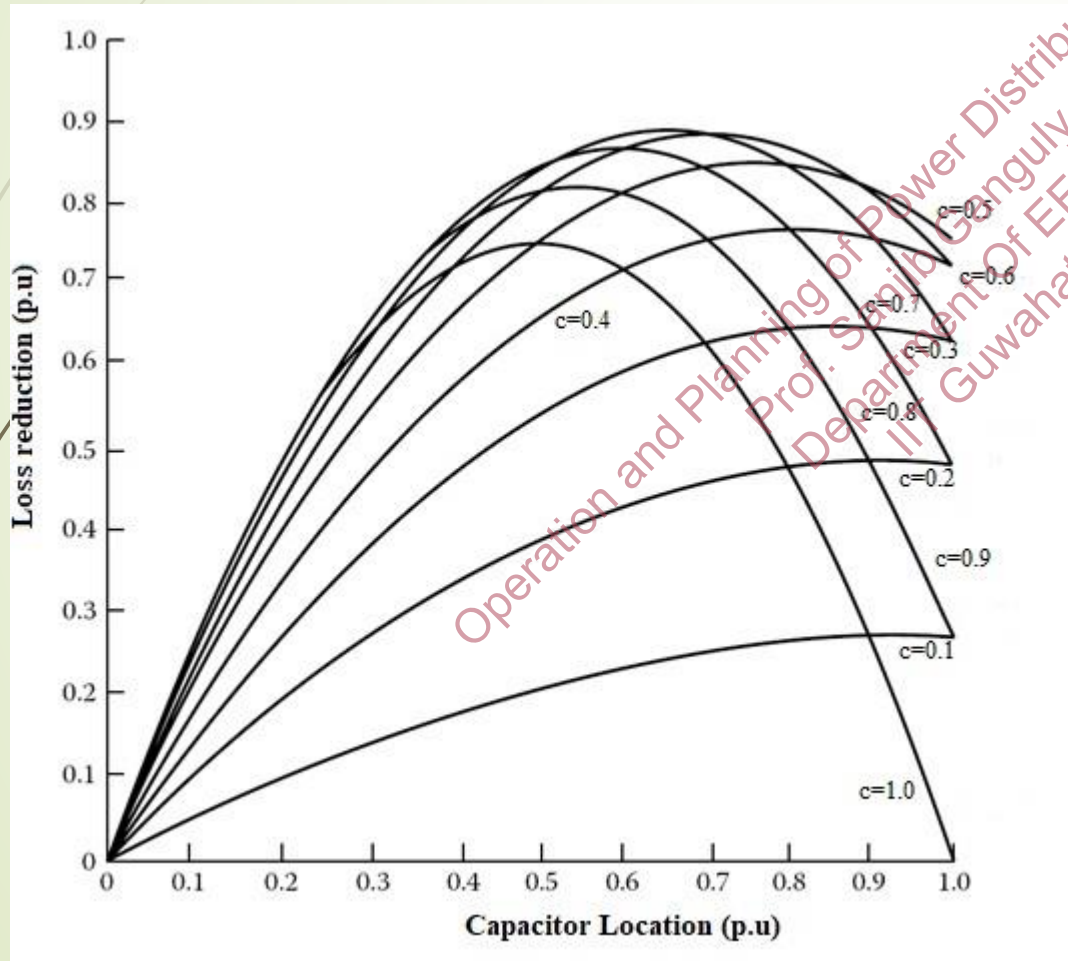
$$\Delta P_{LS} = \frac{3cx_1}{1+\lambda+\lambda^2} [(2-x_1) + \lambda x_1 - c]$$

- where x_1 is the per unit distance of the capacitor-bank location from the beginning of the feeder segment (between 0 and 1.0 p.u.).

If α is defined as the reciprocal of $1+\lambda+\lambda^2$, that is, $\alpha = \frac{1}{1+\lambda+\lambda^2}$

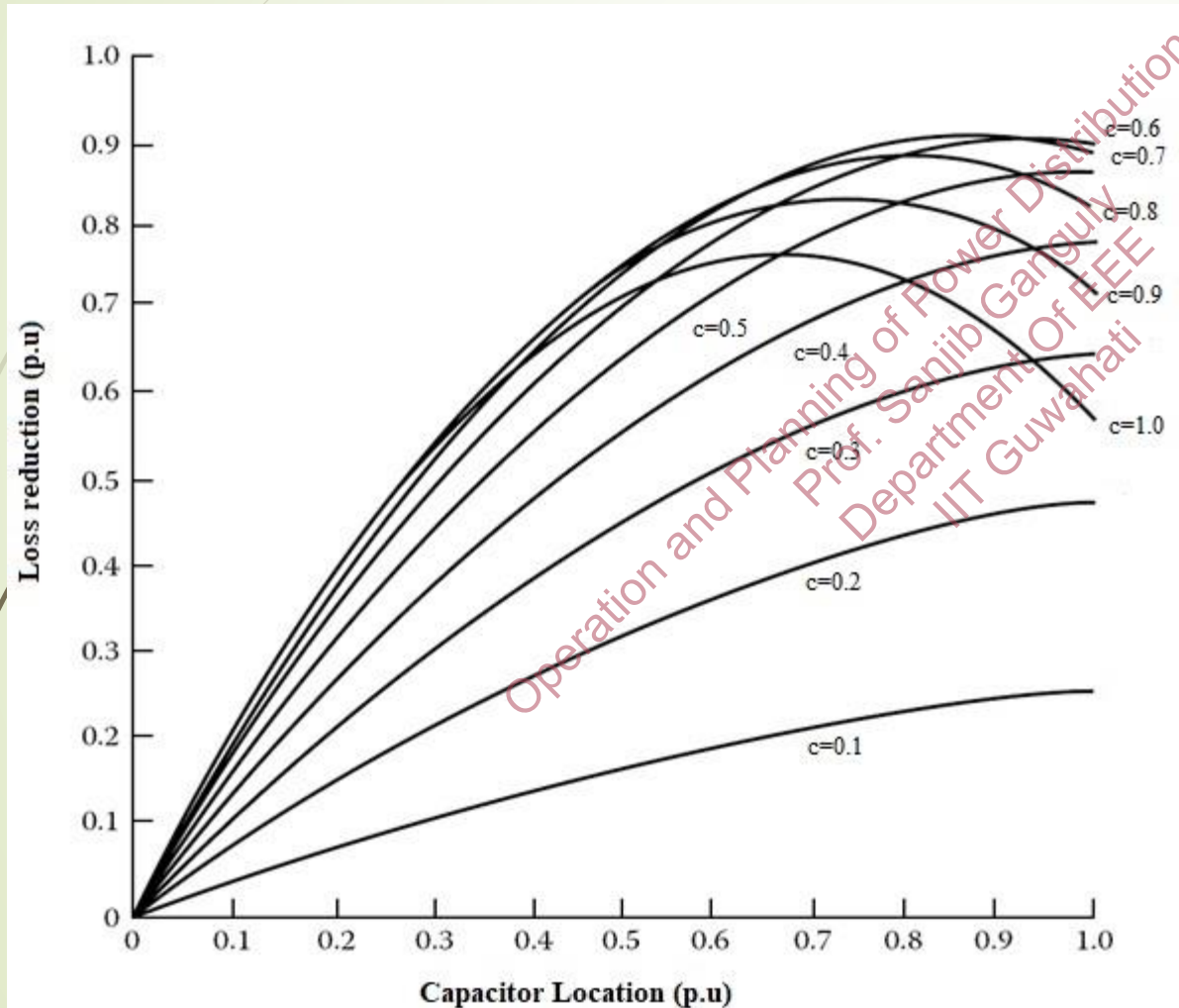
$$\Delta P_{LS} = 3\alpha cx_1 [(2-x_1) + \lambda x_1 - c]$$

Analytical method for capacitor placement: Single capacitor bank



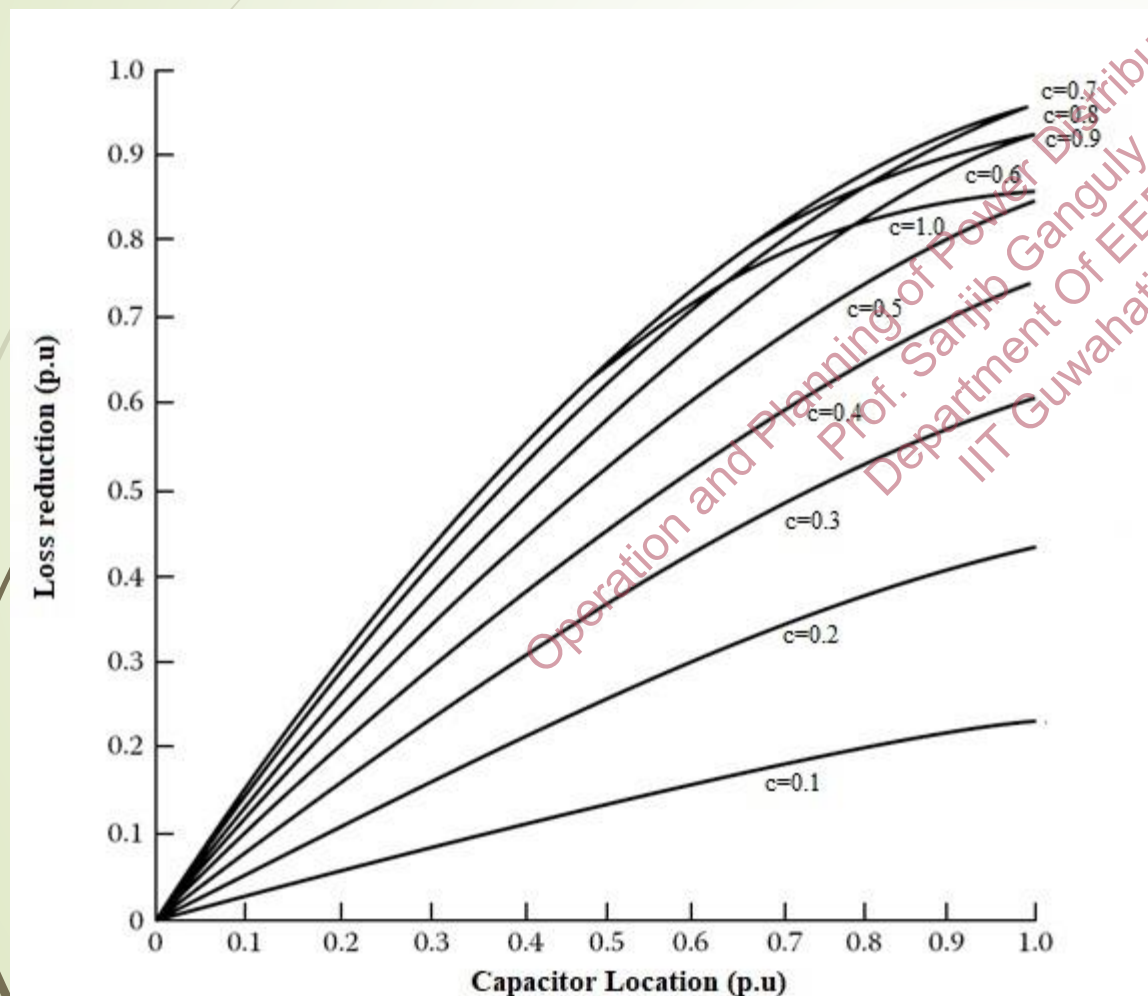
Loss reduction as a function of the capacitor-bank location and capacitor compensation ratio for a line segment with uniformly distributed loads ($\lambda = 0$).

Analytical method for capacitor placement: Single capacitor bank



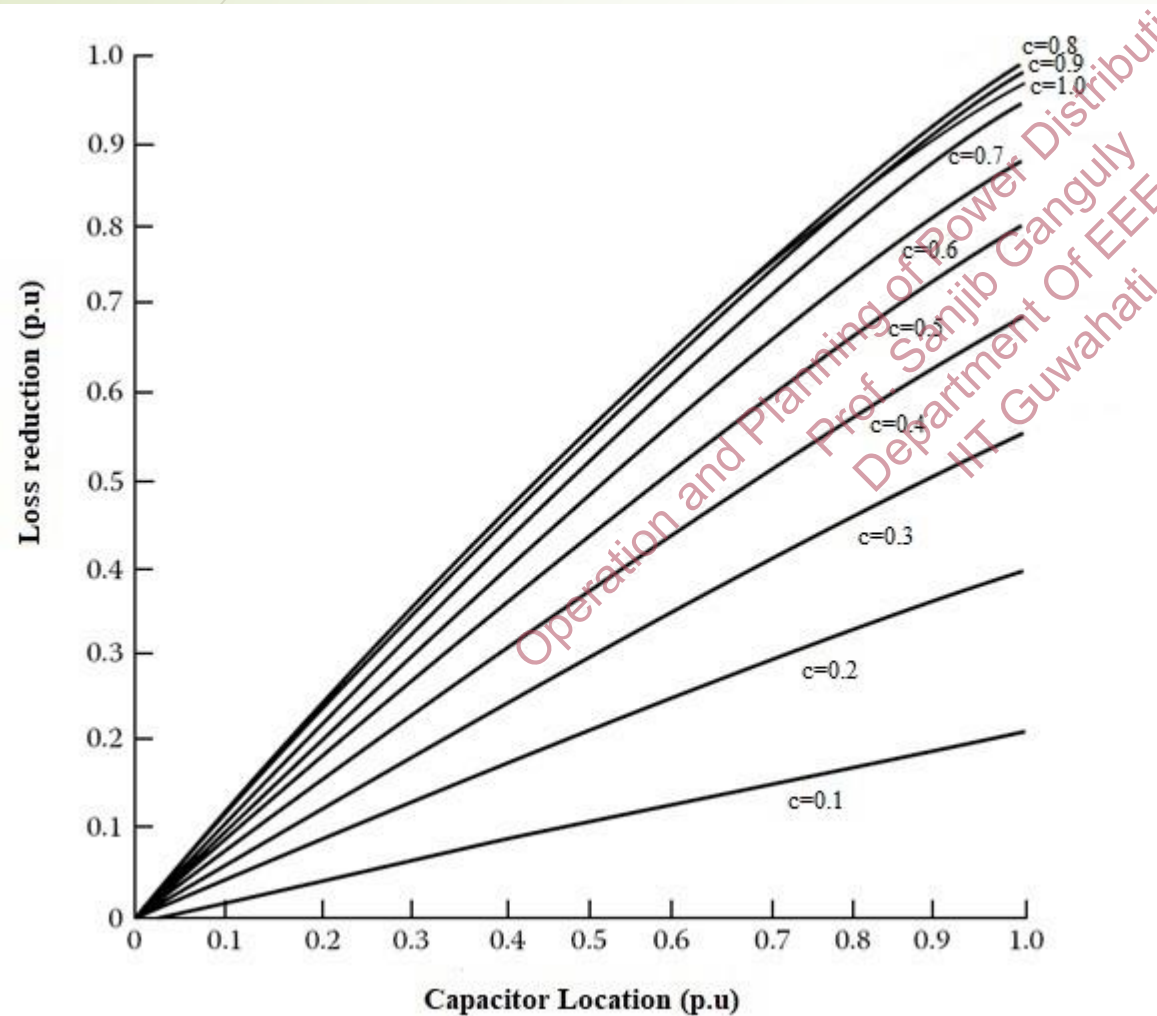
Loss reduction as a function of the capacitor-bank location and capacitor compensation ratio for a line segment with a combination of concentrated and uniformly distributed loads ($\lambda = 1/4$).

Analytical method for capacitor placement: Single capacitor bank



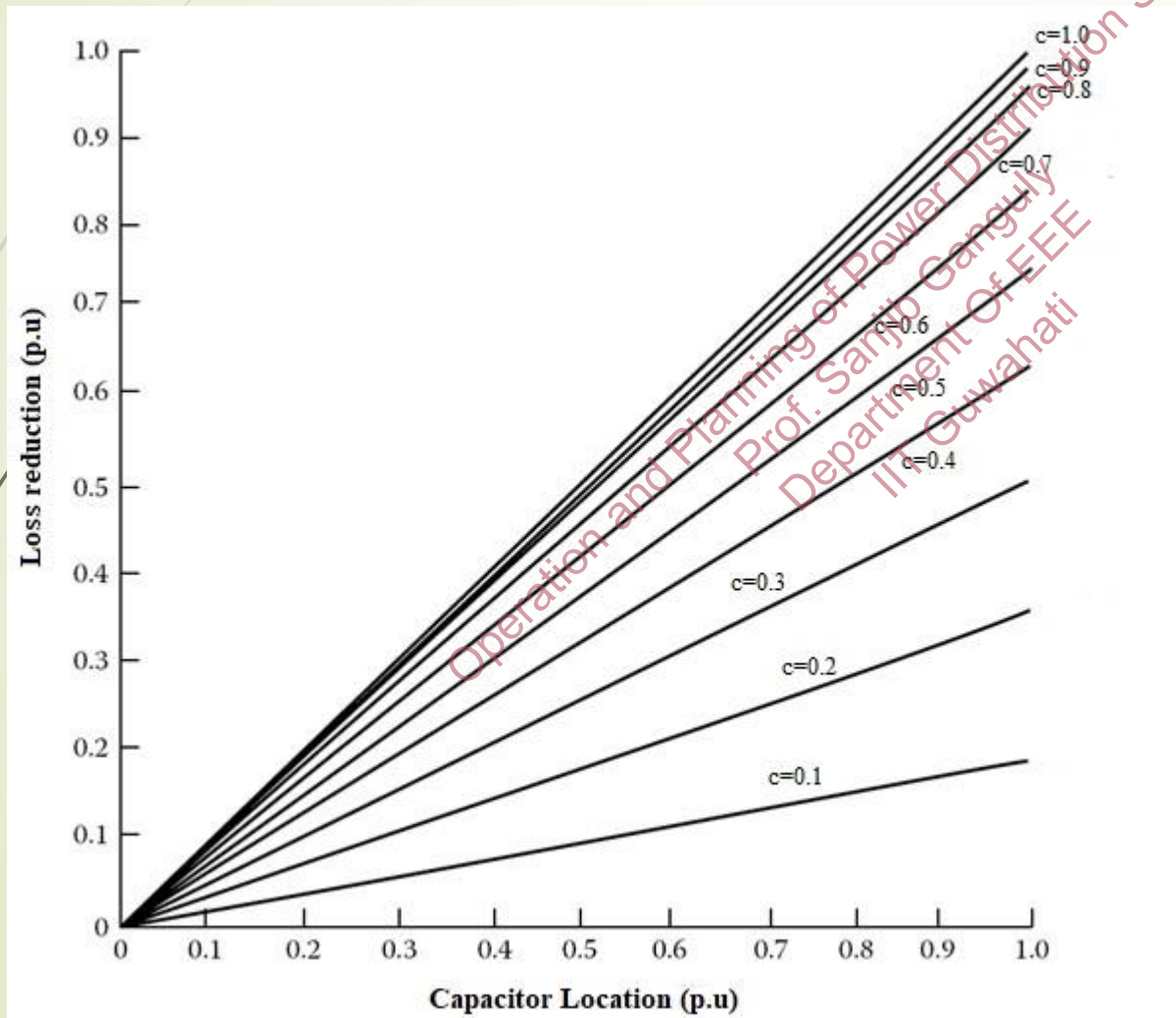
Loss reduction as a function of the capacitor-bank location and capacitor compensation ratio for a line segment with a combination of concentrated and uniformly distributed loads ($\lambda = 1/2$).

Analytical method for capacitor placement: Single capacitor bank



Loss reduction as a function of the capacitor-bank location and capacitor compensation ratio for a line segment with a combination of concentrated and uniformly distributed loads ($\lambda = 3/4$).

Analytical method for capacitor placement: Single capacitor bank



Loss reduction as a function of the capacitor-bank location and capacitor compensation ratio for a line segment with concentrated loads ($\lambda = 1$).

Analytical method for capacitor placement: Single capacitor bank

Optimum Location and Optimum Loss Reduction		
Capacitor Bank rating, p.u	Optimum Location, p.u	Optimum Loss reduction, %
0.0	1.0	0
0.1	0.95	27
0.2	0.90	49
0.3	0.85	65
0.4	0.80	77
0.5	0.75	84
0.6	0.70	88
0.7	0.65	89
0.8	0.60	86
0.9	0.55	82
1.0	0.50	75

Analytical method for capacitor placement: Two capacitor banks

- Let us assume that, two capacitor banks of same size are located at distances of x_1 and x_2 from the substation. The power loss reduction will be,

$$= 3 \int_{x=0}^{x_1} [I_1 - (I_1 - I_2)x - 2I_c]^2 R dx + 3 \int_{x_1}^{x_2} [I_1 - (I_1 - I_2)x - I_c]^2 R dx + 3 \int_{x_2}^1 [I_1 - (I_1 - I_2)x - I_c]^2 R dx$$

$$= 3\alpha c x_1 [(2 - x_1) + \lambda x_1 - 3c] + 3\alpha c x_2 [(2 - x_2) + \lambda x_2 - c]$$

Analytical method for capacitor placement: Three capacitor banks

- For two capacitor banks of same size are located at distances of x_1 , x_2 , x_3 from the substation. The power loss reduction will be,

$$= 3\alpha cx_1[(2 - x_1) + \lambda x_1 - 5c] + 3\alpha cx_2[(2 - x_2) +$$

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Analytical method for capacitor placement: n capacitor banks

- For n capacitor banks of same size are located at distances of $x_1, x_2, \dots, x_n$ from the substation. The power loss reduction will be,

$$= 3\alpha c \sum_{i=1}^n x_i [(2 - x_i) + \lambda x_i - (2i - 1)c]$$

- The optimum locations for the capacitor banks can be obtained by taking first order derivative with respect to x_i and equates it with zero. This yields,

$$(x_i)_{optimal} = \frac{1}{1 - \lambda} - \frac{c}{2} \left(\frac{2i - 1}{1 - \lambda} \right)$$

Analytical method for capacitor placement: n capacitor banks

- The optimal loss reduction with n -capacitor banks will be,

$$= 3\alpha c \sum_{i=1}^n \left\{ \frac{1}{1-\lambda} - c \left(\frac{2i-1}{1-\lambda} \right) + \left(\frac{i^2 c^2}{1-\lambda} \right) - \frac{1}{4} \left(\frac{c^2}{1-\lambda} \right) - \left(\frac{ic^2}{1-\lambda} \right) \right\}$$

- With algebraic reduction, we get the expression for the optimal power loss reduction,

$$= \frac{3\alpha c}{1-\lambda} \left[n - cn^2 + \frac{c^2 n(4n^2-1)}{12} \right]$$

Analytical method for capacitor placement: $n=1$

- For $n=1$, we get the power loss reduction expression as, $\Delta P_{LS} = \frac{3\alpha}{1-\lambda} \left[c - c^2 + \frac{c^3}{4} \right]$
- Differentiating with respect to c and by equating it to zero, we get the optimal value of $c = \frac{2}{3}$ and $x_1 = \frac{2}{3} \left(\frac{1}{1-\lambda} \right)$
- The power loss reduction will be $\Delta P_{LS} = \frac{3\alpha}{1-\lambda} \left(\frac{8}{27} \right) = \frac{8}{9} \left(\frac{\alpha}{1-\lambda} \right)$
- For $\lambda = 0$, i.e., uniformly distributed load, the power loss reduction will be $\Delta P_{LS} = \frac{8}{9}$ p.u., for the capacitor placed at $x_1 = \frac{2}{3}$ p.u. distance with $c = \frac{2}{3}$ p.u. size. **This is well used $\left(\frac{2}{3}\right)$ thumb-rule for capacitor placement.**

Reference

- T. Gonen. *Electric Power Distribution System Engineering*; CRC Press, 3rd Edition, 2014.

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Thank You...

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