$$Z_L = [Z_{Ldm}] \tag{33}$$

$$I(L) = [I_{dm}(L)] \tag{34}$$

For CM current propagation model:

$$V(0) = \begin{bmatrix} V_{cm1}(0) \\ V_{cm2}(0) \end{bmatrix} \tag{35}$$

$$V_S = \begin{bmatrix} V_{cm1} \\ V_{cm2} \end{bmatrix} = \begin{bmatrix} V_{cm} \\ V_{cm} \end{bmatrix} \tag{36}$$

$$Z_S = \begin{bmatrix} 2Z_{Scm-E} + Z_{Scm-L} & 0 \\ 0 & 2Z_{Scm-E} + Z_{Scm-N} \end{bmatrix} \tag{37}$$

$$I(0) = \begin{bmatrix} I_{cm1}(0) \\ I_{cm2}(0) \end{bmatrix} = \begin{bmatrix} I_{cm}(0) \\ I_{cm}(0) \end{bmatrix} \tag{38}$$

$$V(L) = \begin{bmatrix} V_{cm1}(L) \\ V_{cm2}(L) \end{bmatrix} \tag{39}$$

$$V_L = \begin{bmatrix} V_{L1} \\ V_{L2} \end{bmatrix} = \begin{bmatrix} I_{cm1}(L) \cdot 2Z_{Lcm-E} \\ I_{cm2}(L) \cdot 2Z_{Lcm-E} \end{bmatrix} \tag{40}$$

$$Z_L = \begin{bmatrix} Z_{Lcm-L} & 0 \\ 0 & Z_{Lcm-N} \end{bmatrix} \tag{41}$$

$$I(L) = \begin{bmatrix} I_{cm1}(L) \\ I_{cm2}(L) \end{bmatrix} = \begin{bmatrix} I_{cm}(L) \\ I_{cm}(L) \end{bmatrix} \tag{42}$$

III. Determination of Line Parameters

The per-unit-length matrices of the power line cable need to be derived first in order to obtain the chain parameter matrix.

A. Resistance

When a high frequency current flows in the power line cable, we need to consider the skin effect when computing the per-unit-length resistance. We assume that the current flows only within the skin depth of the wire. The skin depth δ is given by [4]

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \tag{43}$$

where μ is the permeability of the metal wire and σ is its conductivity. The high frequency per-unit-length resistance for a cable of radius r_{cable} in a homogeneous medium can be approximated by

$$R_{cable} = \frac{1}{2\pi r_{cable} \sigma \delta} \tag{44}$$

The above equation is valid only if the complete circular conductor. In the case for stranded conductor cables, corrections need to be accounted for the gaps at the circumference of the conductor strands. This can be shown in Fig. 7 in which δ is the skin depth, and the shaded area indicates the area of current flow. To compute the resistance, the ratio of the effective current flow area of the whole cable and the stranded conductor needs to be determined.

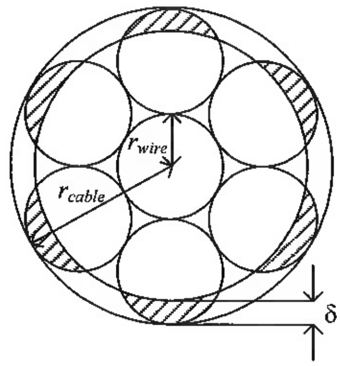


Fig. 7. The area of the current flow on the skin depth of the power line cable.

The current flow area for the whole cable is given by

$$\begin{aligned} A_{cable} &= \pi r_{cable}^2 - \pi (r_{cable} - \delta)^2 \\ &= \pi (2 r_{cable} \delta - \delta^2) \end{aligned} \tag{45}$$

In order to calculate the total shaded area, we need to consider the area of current flow on one stranded conductor. The area of the shaded area, A_{shaded}, in Fig. 8 can be obtained by subtracting the area of triangle OIG and the area of the crescent shape IHGJ from the area of the circular sector OIDG.

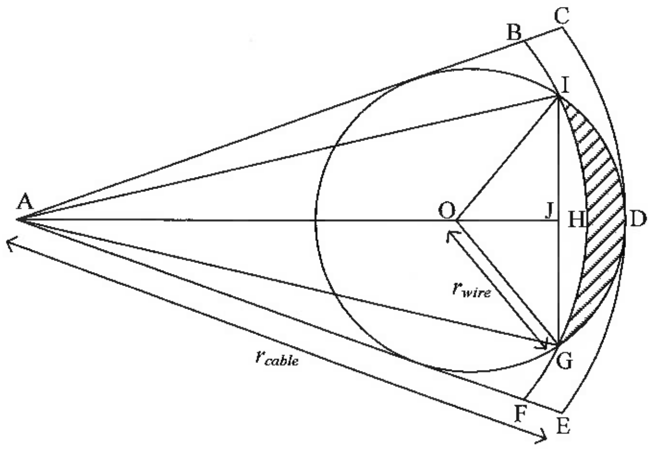


Fig. 8. The area of the current flow on a single stranded wire.

The total area current flow on the outer surface of the stranded conductor is given by

$$A_{stranded} = N A_{shaded} \tag{46}$$

where N is the number of the surface wires of the stranded conductor. The correction factor is given by

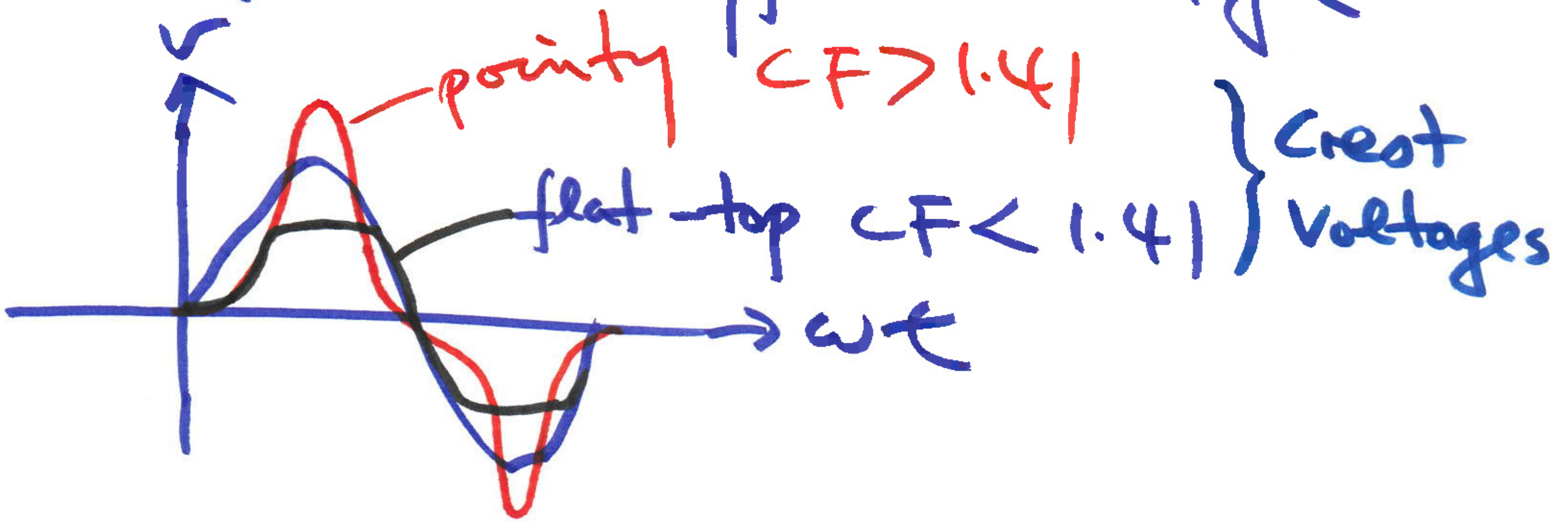
$$X_{corr} = \frac{A_{stranded}}{A_{cable}} \tag{47}$$

With this correction factor, the final resistance for the stranded cable is

$$R_{cable-corr} = X_{corr} R_{cable} \tag{48}$$

$$\text{Crest factor} = \frac{\text{Peak voltage}}{\text{Effective voltage}} = 1.41$$

$$\text{Peak Voltage} = \sqrt{2} \times \text{Effective voltage}$$



Effect of harmonics on transformers

- Additional heat generated by the losses caused by harmonics
  - Presence of harmonic voltages increases $\underbrace{\text{hysteresis and eddy current losses}}_{\text{Iron losses or Core losses}}$ in the lamination and stresses the insulation
  - Flow of harmonic currents increases copper losses
  - Converter transformers do not benefit from the presence of filters
    - Extra rating is necessary
    - Often develop unexpected hot spots in the tank
  - Delta winding overloaded by circulation of triplen frequency zero-sequence current, unless these extra currents are considered in the design
    - Additional heating in tanks, core clamps caused by zero-sequence harmonic fluxes
    - Derating factor,
      - I_R is fundamental rms current under rated load conditions
      - P_{EC-R} is the ratio of eddy-current loss to rated I^2R loss

$$K = \sqrt{\frac{\sum_h \left(I_h^2 h^2\right)}{\sum_h I_h^2}} \Rightarrow I_{\max} = \sqrt{\frac{1+P_{EC-R}}{1+KP_{EC-R}}}\left(I_R\right)$$

stray loss factor due to harmonics or K factor

derated current or max allowed current

derating factor

- Other effects on transformer
  - Possible resonances between transformer inductance and system capacitance
  - Mechanical insulation stress (winding and lamination) due to temperature cycle
  - Possible small core vibrations

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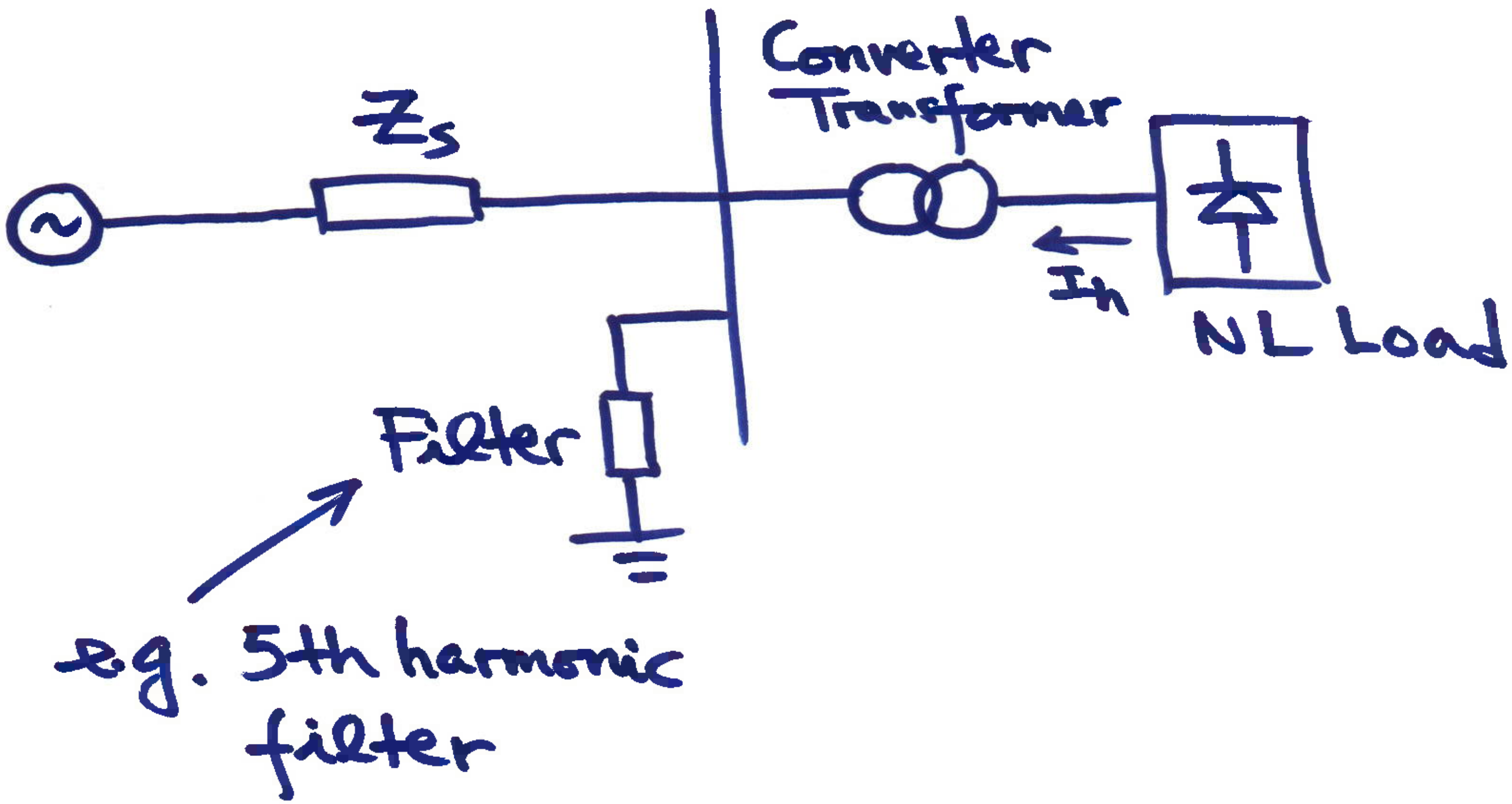
n: 1.5 – 2.5 for common core materials

$\uparrow P_h = k_h B_m^n \, h\!\uparrow\! f$ Hysteresis Loss

$\uparrow P_e = k_e B_m^2 (h\!\uparrow\! f)^2 \uparrow$ Eddy Current Loss

<u>Core Loss</u>

$\uparrow P_c = \uparrow P_h + \uparrow P_e$



Z_s
Converter Transformer
I_h
NL Load
Filter
e.g. 5th harmonic filter

K factor is a property of the distorted current and not of the transformer. It indicates the potential heating effect when the distorted current flows in a transformer. For this reason, some transformers are designed with a specific *K* factor to indicate the level of distortion they can tolerate without overheating.

$$K = \frac{\sqrt{I_F^2 + 3^2 I_3^2 + 5^2 I_5^2 + \cdots}}{\sqrt{I_F^2 + I_3^2 + I_5^2 + \cdots}}$$

$= 1$ (undistorted current)

> 1 (distorted current)

Effect of harmonics on capacitor banks

- Presence of voltage distortion increases the dielectric loss in capacitors

total loss $\sum_{n=1}^{\infty} C(\tan\delta)\,\omega_n V_n^2$

  - $\tan(\delta) = R/(1/\omega C)$ is the loss factor
  - $\omega_n = 2\pi f n$
  - V_n is the r.m.s. voltage of the nth harmonic
  - The additional thermal stress can be assessed approximately with the help of a special capacitor weighted THD factor,

$$THD_C = \frac{\sqrt{\sum_{n=1}^{N}\left(n \cdot V_n^2\right)}}{V_1}$$

- Series and parallel resonances with the rest of system
  - Overvoltages and high currents result in increased losses and overheating, thus leading to capacitor destruction
  - PF correction capacitor often tuned to about 3rd or 5th by adding a small series inductance (about 9% or 4% respectively) to make it look inductive above these frequencies and thus avoids parallel resonance

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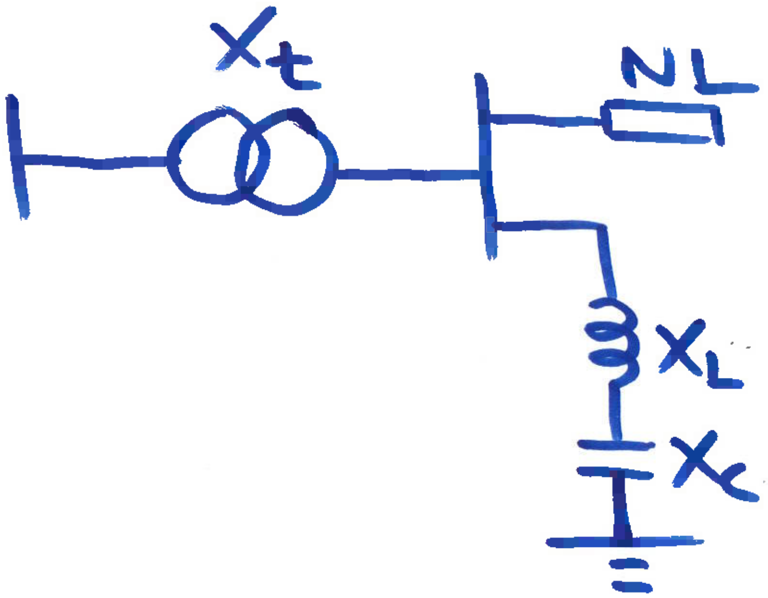


Tuned at 3rd harmonic

$X_L = X_c$ $\Rightarrow$ no capacitive reactance

$\Rightarrow$ no parallel resonance

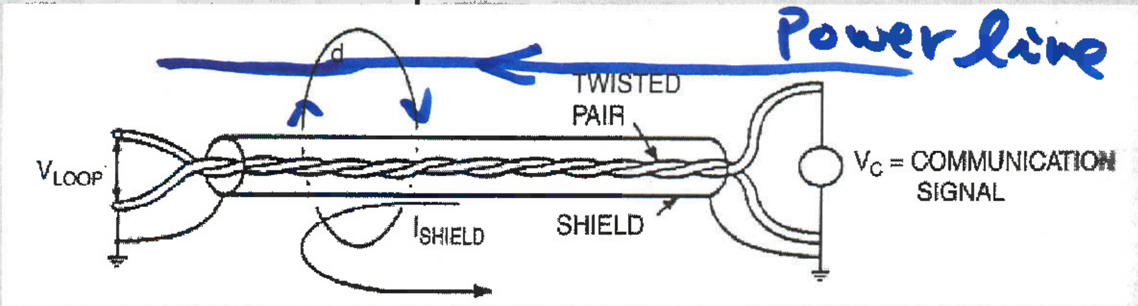
At 5th harmonic

$X_L \uparrow$, $X_c \downarrow$ $\Rightarrow$ look inductive

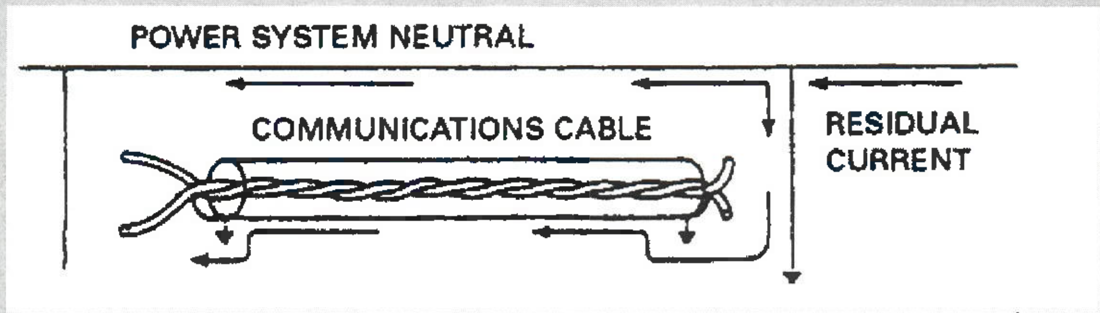
$\Rightarrow$ no parallel resonance

Harmonic currents flowing in the shield

- Even with shielded twisted-pair conductors for telephone circuit, inductive coupling can still be a problem
  - High harmonic current induced in the shield surrounding telephone conductors, resulting in IR voltage drop, which leads to potential difference in the ground references at ends of the telephone cable



- Direct conduction can also cause harmonic current flowing in the shield
  - Shield in parallel with power system ground path
  - High shield IR drop causes potential difference in ground references



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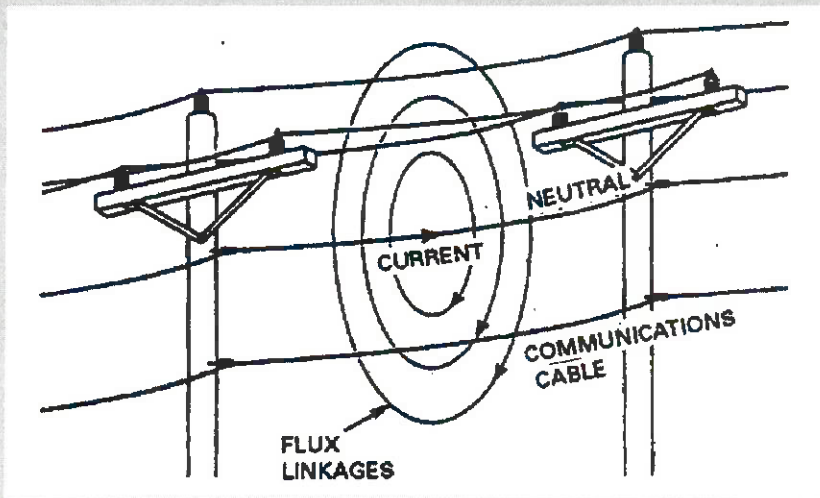
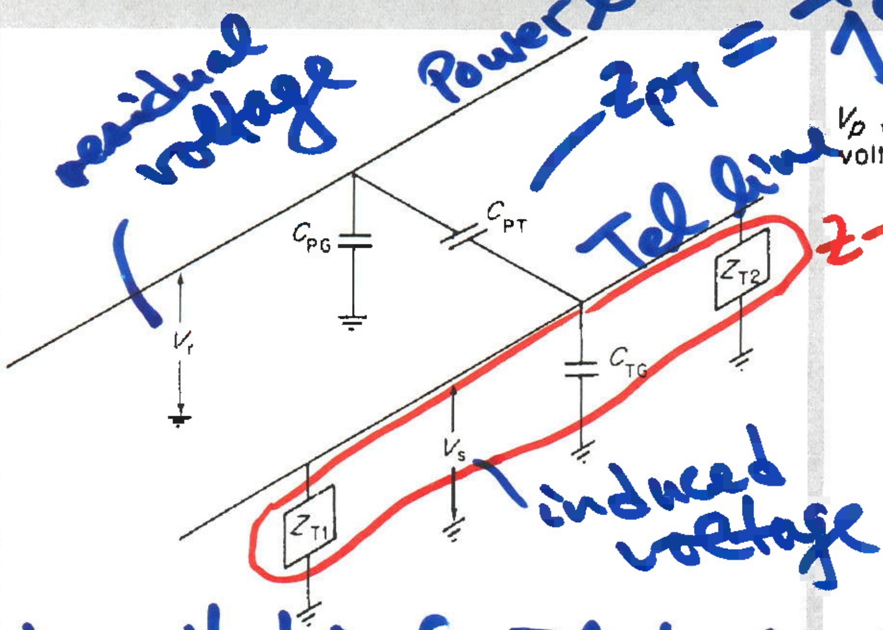
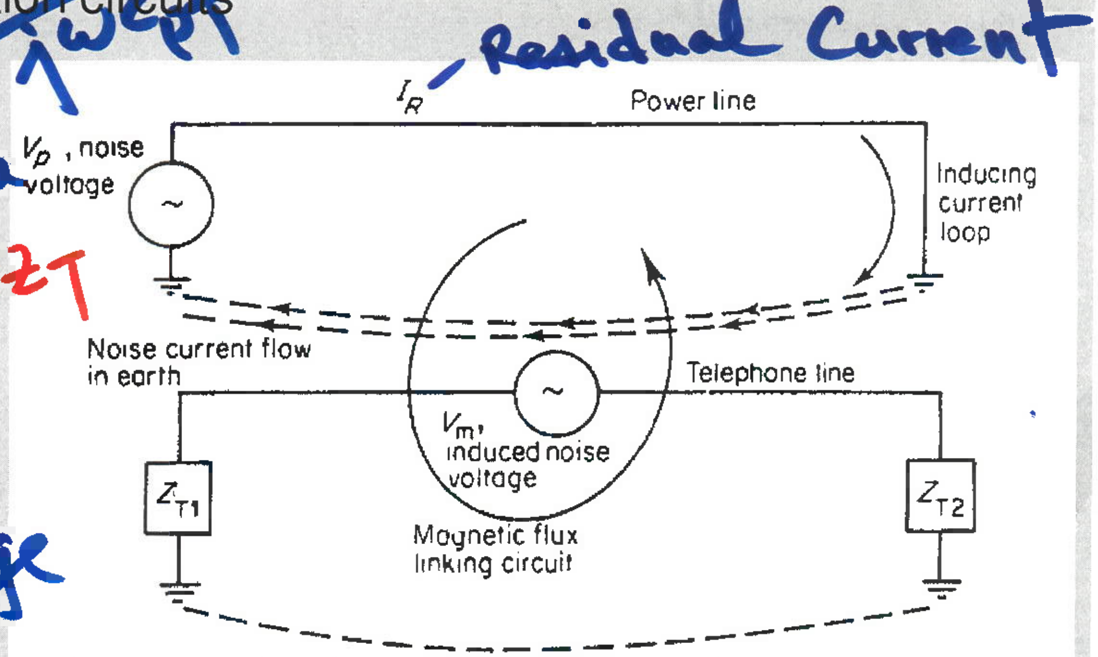
Telecommunication interference

- Residual voltages
  - electrostatic induction
- Residual currents
  - electromagnetic induction
- Important factors
  - Influence of power systems
  - Coupling to communication circuits
  - Susceptiveness of communication circuits







Longitudinal Electrostatic induction

Longitudinal Electromagnetic Induction

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$$\frac{1}{Z_T} = \frac{1}{Z_{T_1}} + \frac{1}{\frac{1}{j\omega C_{TG}}} + \frac{1}{Z_{T_2}}$$

$$V_s = V_r \times \frac{Z_T}{Z_{pT} + Z_T}$$

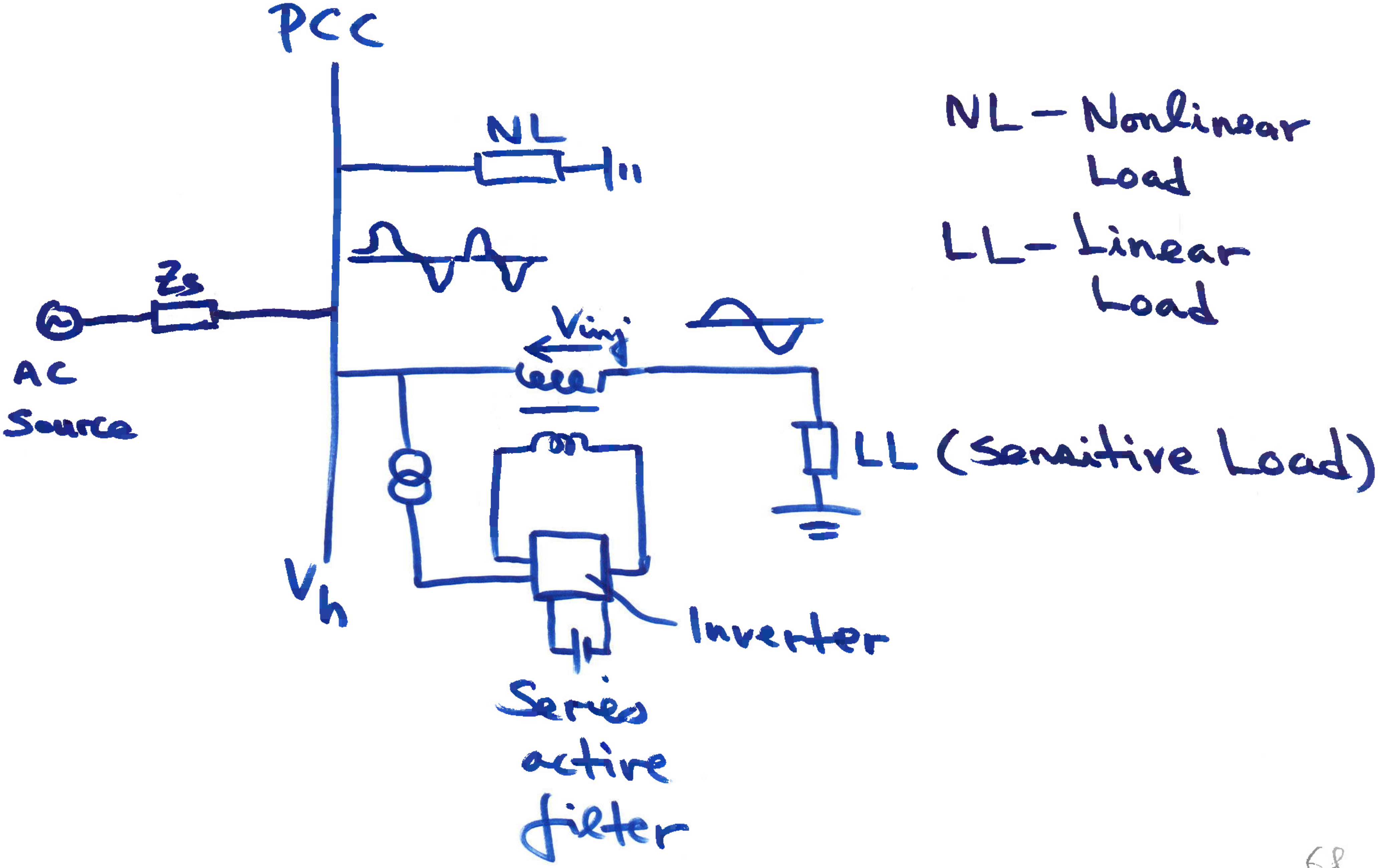
1 2 2

$$\frac{1}{j\omega C_{pT}}$$

two lines are very close together

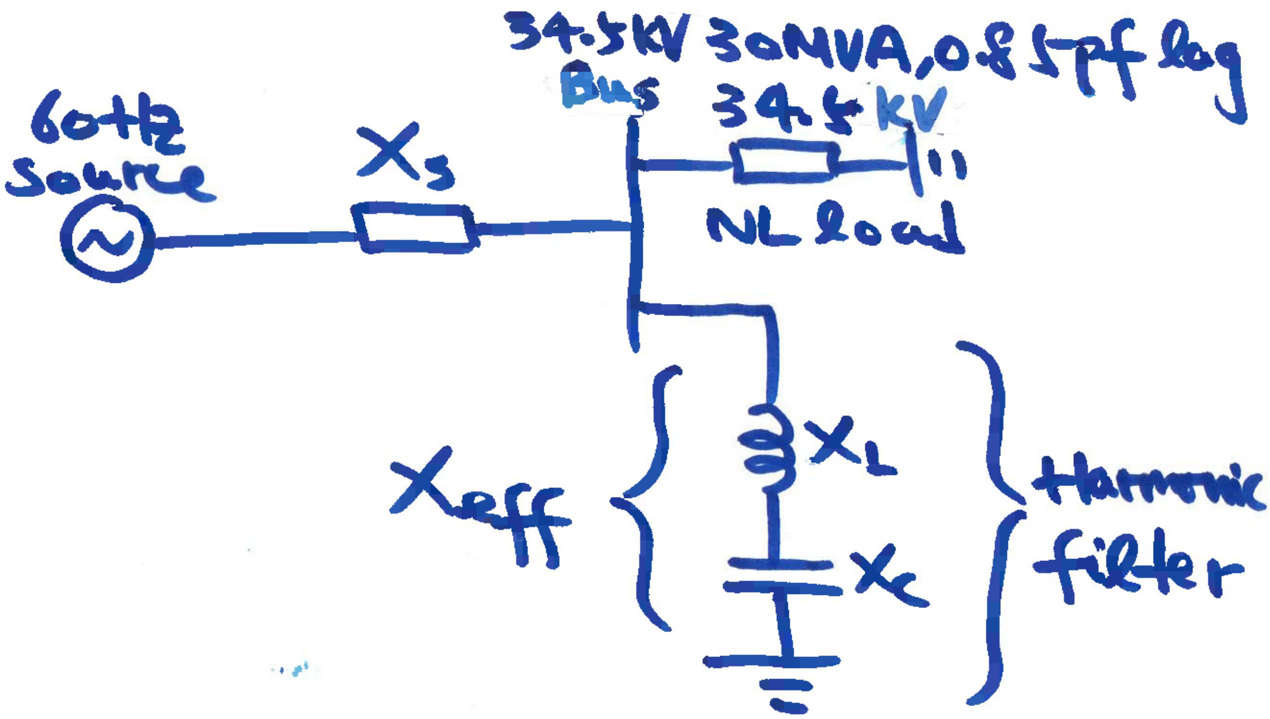
V_r = Residual Voltage

V_s = Induced Voltage



NL – Nonlinear Load

LL – Linear Load



Pf lag : 0.85 ⟶ 0.95

Q_{eff} : 7.42 MVAr

↑

harmonic
filter

X_L : filter reactor

X_C : filter capacitor

Without **With**

$P = 25.5\,MW \rightarrow 25.5\,MW$

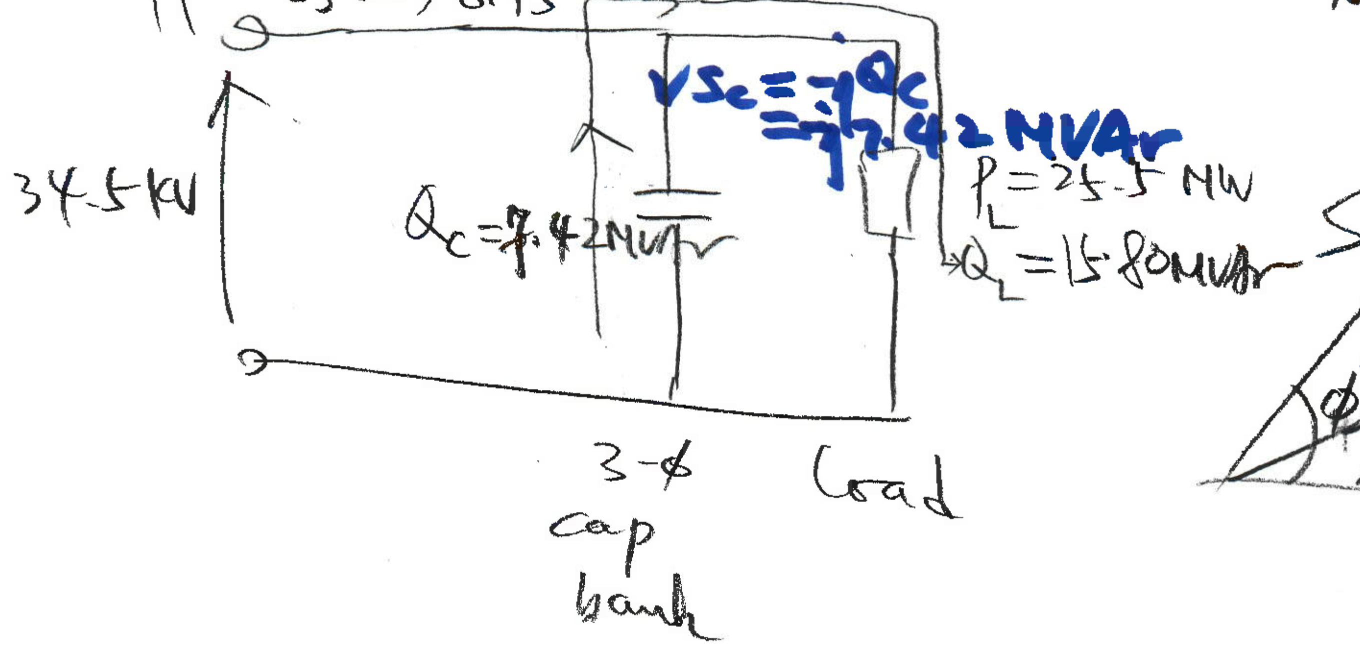
$Q = 15.8\,MVAr \rightarrow 8.38\,MVAr$

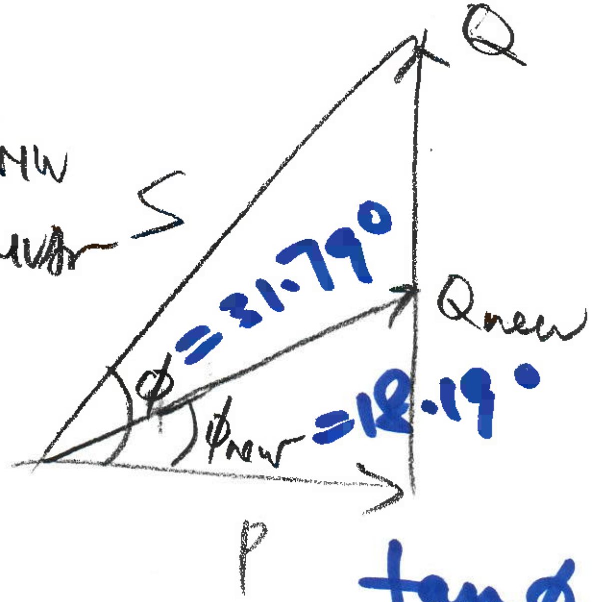
$pf = 0.85 \rightarrow 0.95$

$\cos\phi = pf = 0.85$

$\phi = \cos^{-1} 0.85 = 31.79^\circ$

$\phi_{new} = \cos^{-1} 0.95 = 18.19^\circ$





$\tan\phi_{new} = \frac{Q_{new}}{P}$

$P = 30 \times 0.85 = 25.5\,MW$

$Q = P\tan\phi = 15.8\,MVAr$

$\tan\phi = \frac{Q}{P}$

$Q_{new} = P\tan\phi_{new}$

$= 25.5 \times \tan 18.19^\circ$

$= 8.38\,MVAr$

$P = 25.5\,MW \rightarrow 25.5\,MW$

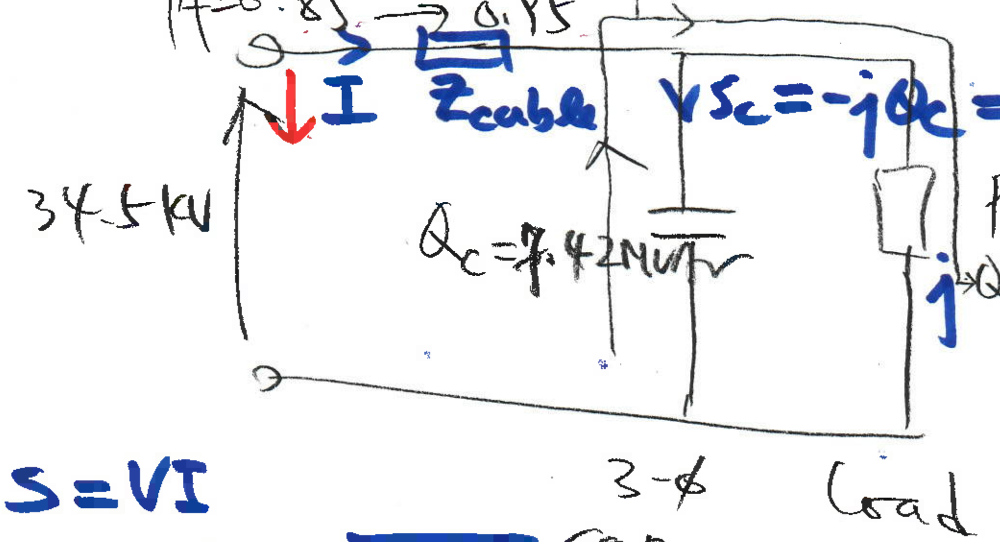
$Q = 15.8\,MVAr \rightarrow 8.38\,MVAr$

$pf = 0.85 \rightarrow 0.95$

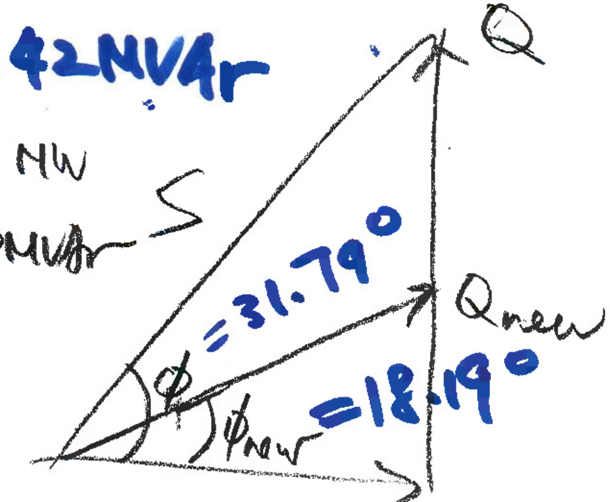
$\cos\phi = pf = 0.85$

$\phi = \cos^{-1} 0.85 = 31.79^\circ$

$\phi_{new} = \cos^{-1} 0.95 = 18.19^\circ$



$VS_c = -jQ_c = -j7.42\,MVAr$



$S = VI$

$\downarrow I = \frac{S}{V} = \frac{\sqrt{P^2+Q^2}}{V} \downarrow$

① Reduce line losses; ② Reduce line drop

③ $pf \geq 0.85$ lagging — Supply Regulation

$P = 30 \times 0.85 = 25.5\,MW$

$Q = P\tan\phi = 15.8\,MVAr$

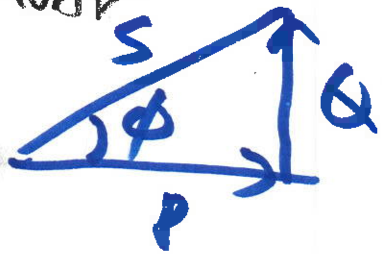
$Q_{new} = P\tan\phi_{new}$

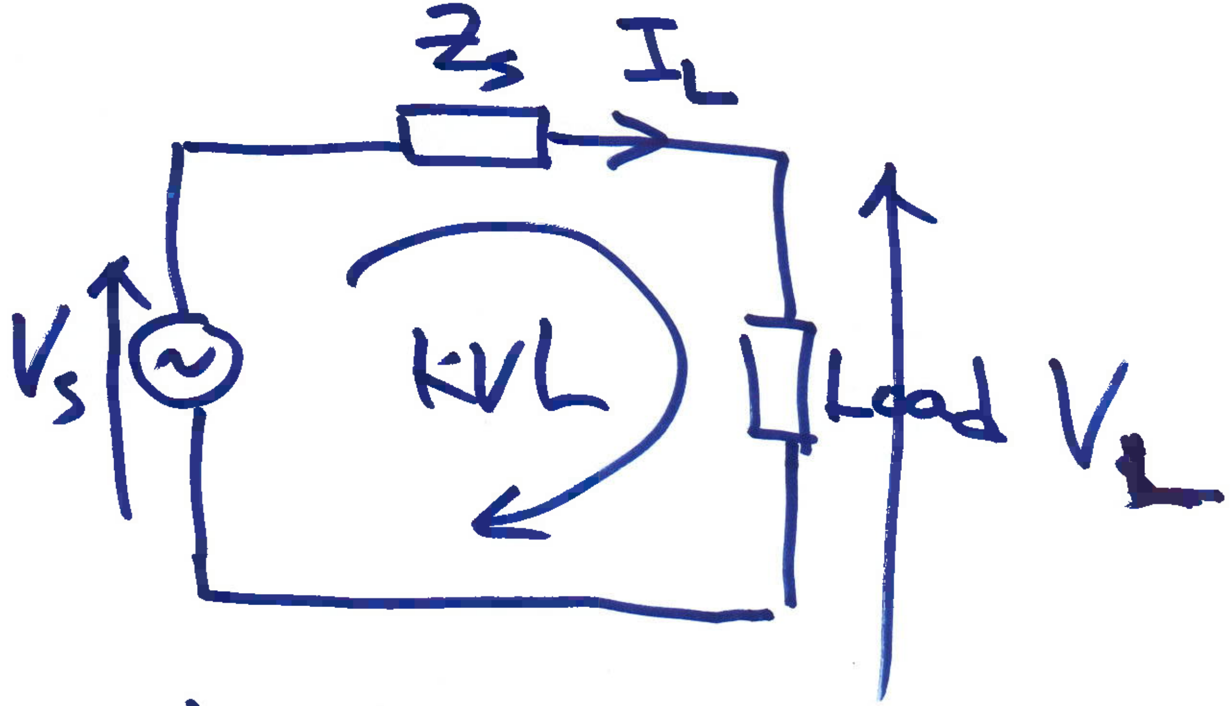
$= 25.5 \times \tan 18.19^\circ$

$= 8.38\,MVAr$

$\tan\phi = \frac{Q}{P}$

$Q = P\tan\phi$



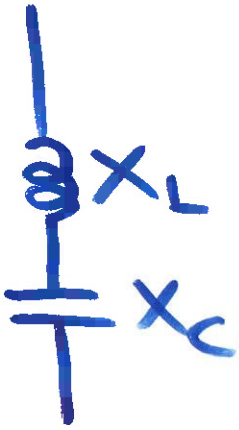


$$\underset{\text{constant}}{V_s} = \underbrace{Z_s I_L \downarrow}_{\text{reduce}} + V_L \uparrow$$

Voltage Regulation

Tuned at 5th harmonic frequency (i.e. 250 Hz)

$$X_L = X_C$$



At frequency lower than tuned frequency (e.g. 200 Hz)

$$\downarrow f \rightarrow \uparrow X_C = \frac{1}{2\pi f \downarrow C}, \; \downarrow X_L = 2\pi f \downarrow L$$

$\rightarrow$ look capacitive

$$X_C = \frac{V_L^2}{Q_{C,3\text{-}\phi}}$$

$$= \frac{(\sqrt{3}\,V_P)^2}{3\,Q_{C,1\text{-}\phi}}$$

$$= \frac{V_P^2}{Q_{C,1\text{-}\phi}}$$

$$X_{eff} = X_C - X_L \implies X_C = \left(\frac{h^2}{h^2-1}\right) X_{eff}$$

$$hX_L = \frac{X_C}{h}$$

Substitue

$$X_L = \frac{X_C}{h^2}$$