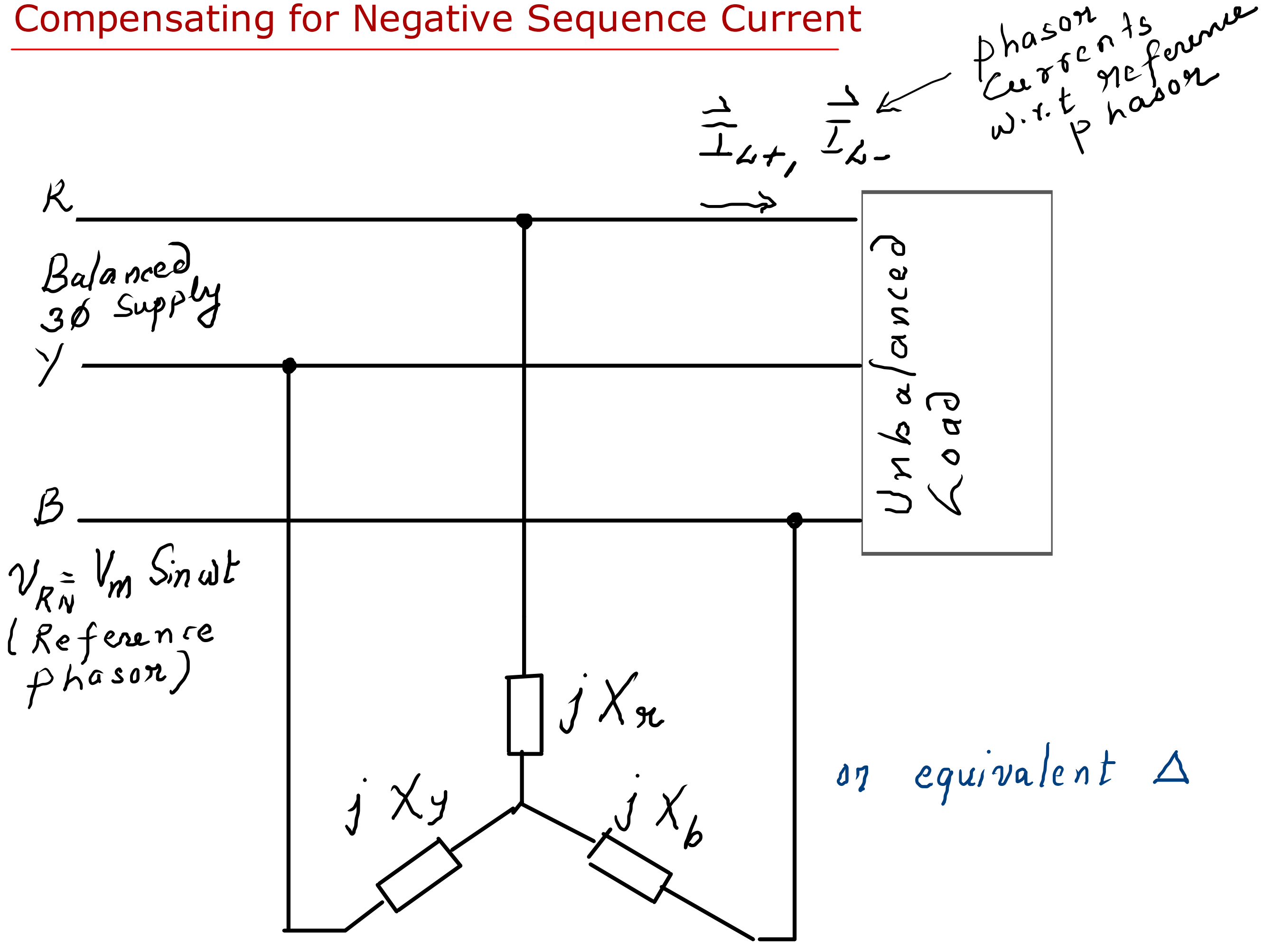
Load Compensation - Compensating for Negative Sequence and Zero Sequence Currents in a 3-Phase 4-Wire System

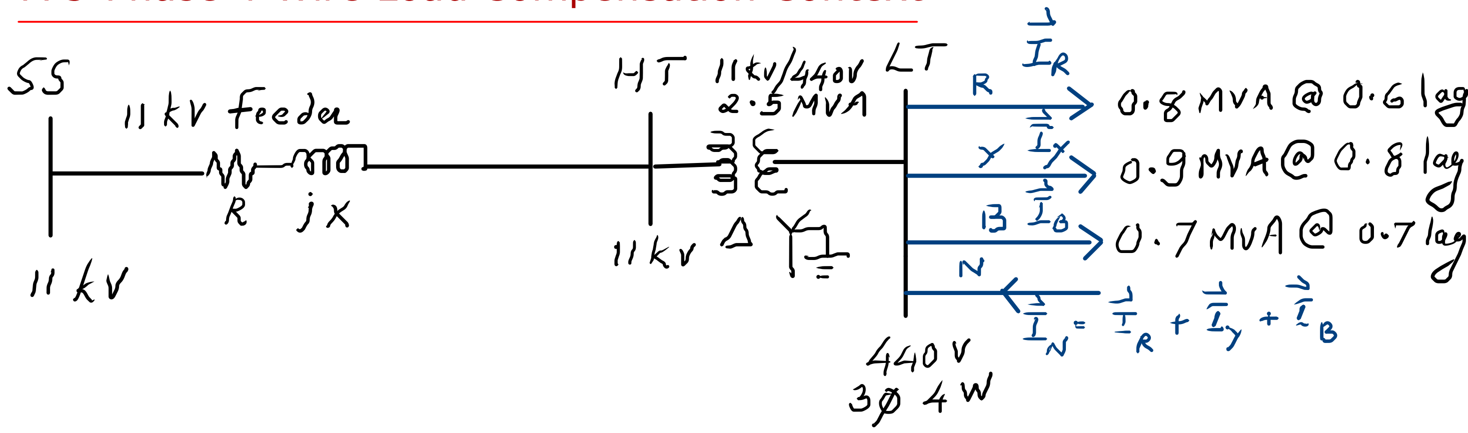
Compensating for Negative Sequence Current



$$X_r + X_y + X_b = 0 \quad \text{—— (1)}$$

$$X_r + a^2 X_y + a X_b = \frac{\frac{3 V_m}{\sqrt{2}} \angle 0}{j(-\vec{I}_{L-})} \quad \text{—— (2)}$$

A 3-Phase 4-Wire Load Compensation Context



Assumptions:
1) The loads on R, Y, B phases behave as constant power loads
2) After -ve seq & 0-seq Compensation the LT bus voltage is at nominal voltage of 440V (l-l) and is balanced.

Zero Sequence current flows in secondary windings and circulates in delta windings of primary. There is no zero-seq current in 11 kV Feeder. If zero-seq current is compensated at LT Bus, transformer losses will come down and transformer capacity will be released.

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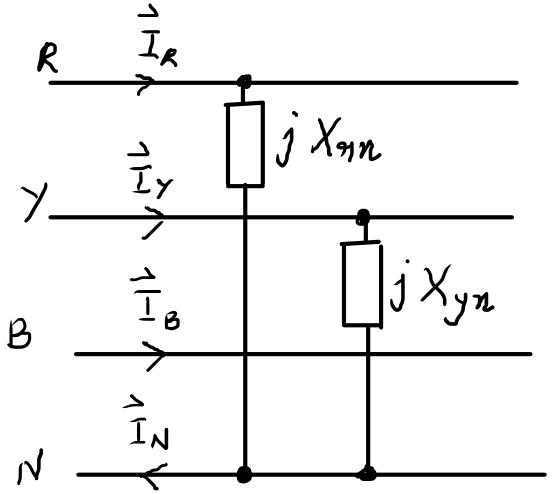
If −ve sequence load current is compensated at LT bus (i) transformer losses go down (ii) transformer capacity is released (iii) feeder losses go down (iv) feeder capacity is released and (v) HT Bus voltage becomes balanced.

If both −ve seq & 0-seq currents are compensated at LT bus, then LT Bus Voltage also becomes balanced.

If +ve seq reactive component is also compensated at LT bus, transformer and feeder losses go down further, further release of trf and feeder capacity takes place and feeder voltage regulation improves.

How can we compensate for zero-seq current at LT Bus?

Consider the following arrangement using two reactances.



$$\vec{I}_R = \frac{-jV}{X_{rn}} \quad \text{where } V = \frac{V_m}{\sqrt{2}}$$

$$\vec{I}_y = \frac{-j a^2 V}{X_{yn}} \; ; \; a^2 = 1\angle -120^\circ$$

$$\vec{I}_B = 0$$

Zero Sequence Current $= \vec{I}_0$

$$\vec{I}_0 = \frac{1}{3}\left(\vec{I}_R + \vec{I}_y + \vec{I}_B\right) = \frac{\vec{I}_N}{3}$$

$$= \frac{1}{3}\left(-j\frac{V}{X_{rn}} - j a^2 \frac{V}{X_{yn}}\right)$$

$$= \frac{1}{3}\left(-j\frac{V}{X_{rn}} - 1\angle -30 \frac{V}{X_{yn}}\right)$$

$$= \frac{1}{3}\left(-j\frac{V}{X_{rn}} - \frac{\sqrt{3}}{2}\frac{V}{X_{yn}} + j\frac{1}{2}\frac{V}{X_{yn}}\right)$$

$$\therefore \vec{I}_N = -\frac{\sqrt{3}}{2}\frac{V}{X_{yn}} - j\left(\frac{V}{X_{rn}} - \frac{V}{2X_{yn}}\right)$$

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Let $\vec{I}_N = I_{aN} + j\, I_{rn}$. Then

$$I_{aN} = -\frac{\sqrt{3}}{2}\frac{V}{X_{yn}} \rightarrow \boxed{X_{yn} = \frac{-\sqrt{3}\,V}{2\, I_{aN}}}$$

$$I_{rN} = -\left(\frac{V}{X_{rn}} - \frac{V}{2X_{yn}}\right)$$

$$= -\left(\frac{V}{X_{rn}} + \frac{I_{aN}}{\sqrt{3}}\right)$$

$$\therefore \boxed{X_{rn} = \frac{-\sqrt{3}\,V}{I_{aN} + \sqrt{3}\, I_{rn}}}$$

*Note: $\sqrt{3}\,V$ is line to line RMS volts

Expressing required X_{rn} & X_{yn} in terms of neutral current of load $I_{NL} = I_{aNL} + j\, I_{rNL}$,

$$X_{rn} = \frac{\sqrt{3}\,V}{I_{aNL} + \sqrt{3}\, I_{rNL}}$$

$$X_{yn} = \frac{\sqrt{3}\,V}{2\, I_{aNL}}$$

But this zero-sequence compensator will now draw +ve and -ve sequence currents too.

$$\vec{I}_R = -j\,\frac{I_{aNL} + \sqrt{3}\, I_{rNL}}{\sqrt{3}}$$

$$\vec{I}_Y = -j\, a^2 \frac{2}{\sqrt{3}} I_{aNL} \quad (a^2 \text{ for } 1\angle -120^\circ)$$

$$\vec{I}_+ = \frac{1}{3}\left(\vec{I}_R + a\vec{I}_Y + a^2 \vec{I}_B\right)$$

$$= -j\,\frac{\left(\sqrt{3}\, I_{aNL} + I_{rNL}\right)}{3};$$

* a pure reactive current

$$\vec{I}_- = \frac{1}{3}\left(\vec{I}_R + a^2 I_Y + a\vec{I}_B\right)$$

$$= \frac{I_{aNL}}{3} - j\,\frac{I_{rNL}}{3}$$

These two currents have to be added to corresponding components drawn by load before -ve sequence current compensator and +ve sequence reactive compensator are calculated.

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Numerical Solution for the Example System

Assuming that the LT Bus is at $\frac{440}{\sqrt{3}}\angle 0$ in R Phase to Neutral, the line currents and neutral current of load are worked out from the power data as

$$\vec{I}_R = 3.1492 \angle -53.13^\circ \text{ kA}$$

$$\vec{I}_Y = 3.5428\, a^2 \angle -36.87^\circ \text{ kA}$$

$$\vec{I}_B = 2.7555\, a \angle -45.57^\circ \text{ kA}$$

$$\vec{I}_{NL} = -0.6287 - j1.2568 \text{ kA}$$

∴ Zero Sequence compensator elements are

$$X_{rn} = \frac{\sqrt{3}\,V}{I_{aNL} + \sqrt{3}\, I_{rNL}} = \frac{0.440}{(-0.6287 - 1.2568 \times \sqrt{3})}$$

$$= -0.1568\ \Omega$$

$$X_{yn} = \frac{\sqrt{3}\,V}{2\, I_{aNL}} = \frac{0.44}{-2 \times 0.6287}$$

$$= -0.35\ \Omega$$

Both are Capacitive reactance

Now positive and negative sequence currents drawn by this zero-sequence compensator are to be calculated. They are

$$\vec{I}_+ = -j\,\frac{\sqrt{3}\, I_{aNL} + I_{rNL}}{3} = j\,0.7819 \text{ kA}$$

(capacitive)

$$\vec{I}_- = \frac{I_{aNL}}{3} - j\,\frac{I_{rNL}}{3} = (-0.2095 + j0.419) \text{ kA}$$

These have to be added to corresponding components drawn by load.

We calculate the +ve seq and −ve seq currents drawn by load as

$$\vec{I}_{L+} = (\vec{I}_R + a\,\vec{I}_Y + a^2\,\vec{I}_B)/3$$

$$= \frac{1}{3}(3.1492 \angle -53.13^\circ + 3.5428 \angle -36.87^\circ + 2.7555 \angle -45.57^\circ)$$

$$= 2.2205 - j\,2.2043 \text{ kA}.$$

$$\vec{I}_{L-} = \frac{1}{3}(\vec{I}_R + a^2\,\vec{I}_Y + a\,\vec{I}_B)$$

$$= \frac{1}{3}(3.1492 \angle -53.13^\circ + 3.5428 \angle 83.13^\circ + 2.7555 \angle 194.43^\circ)$$

$$= -0.1184 + j\,0.1038 \text{ kA}.$$

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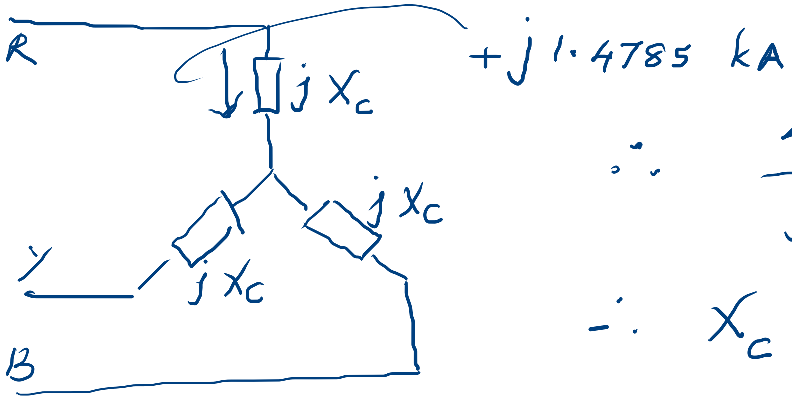
$\therefore$ Total +ve Sequence current drawn by load + zero sequence compensator $\Big\} = (2.2205 - j\,1.4785)$ kA

Total −ve sequence current drawn by load + zero sequence compensator $\Big\} = (-0.328 + j\,0.5228)$ kA

We calculate the +ve sequence reactive power compensator as

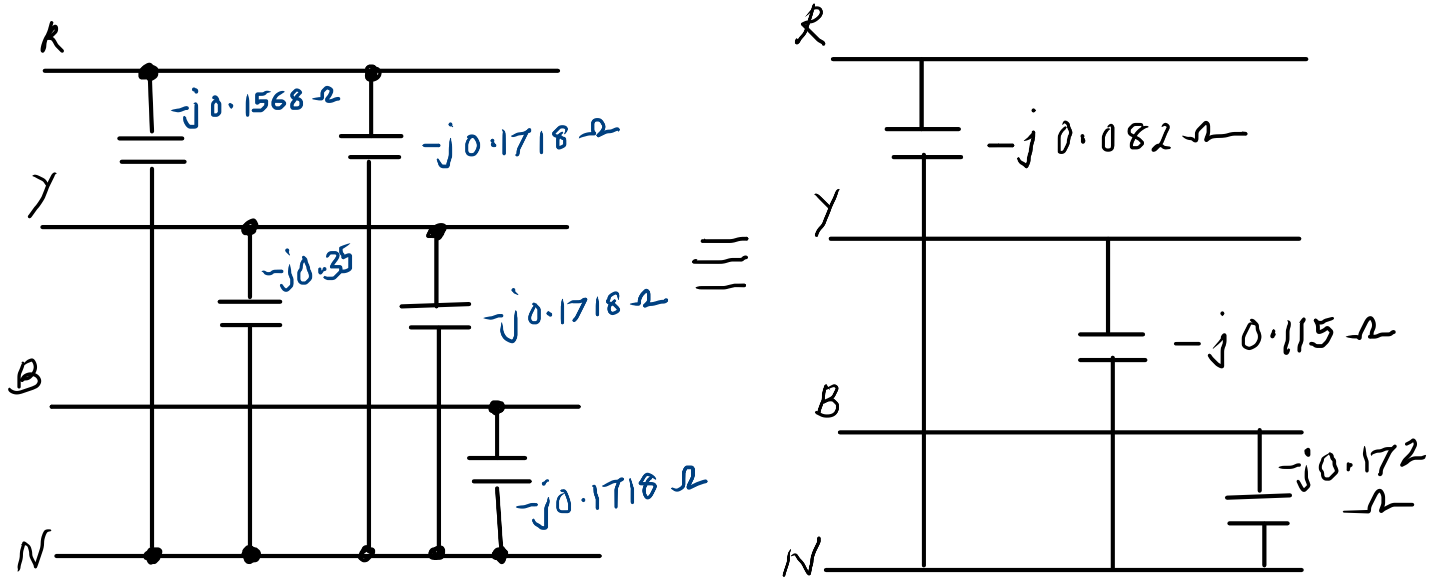


$$\therefore \frac{400/\sqrt{3}}{jX_c} = j\,1.4785 \text{ kA}$$

$$\therefore X_c = -0.1718\ \Omega$$

$\therefore$ The reactance is capacitive.

This is a balanced impedance and so its neutral will be at zero potential w.r.t to source neutral. So its neutral can be connected to source neutral if so desired. That makes it possible to combine zero-sequence compensator and +ve seq Reactive compensator into a single star-connected reactive network.



Load Compensation - Compensating for Negative Sequence and Zero Sequence Currents in a 3-Phase 4-Wire System

Now we calculate the −ve Sequence Compensator.

$$X_r + X_y + X_b = 0$$

$$X_r + a^2 X_y + a X_b = \frac{3 \times \frac{440}{\sqrt{3}} \angle 0}{j\,\underbrace{(328 - j522.8)}_{\text{−ve of negative sequence current drawn by load + zero seq compensator}}}$$

$$= 0.95854 - j0.60861$$

$$X_r + 1\angle{-120^\circ}\, X_y + 1\angle{120}\, X_b = \quad ''$$

$$X_r - \frac{1}{2}(X_y + X_b) = 0.95854$$

$$\frac{\sqrt{3}}{2}(X_b - X_y) = -0.60861$$

$$X_r + X_y + X_b = 0$$

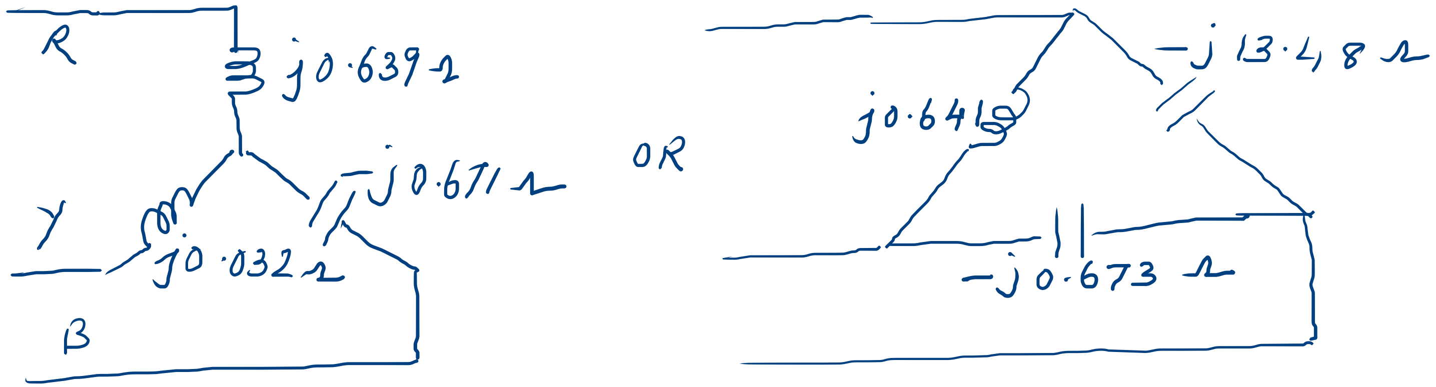
Solving

$X_r = 0.639\,\Omega$ (Inductive)

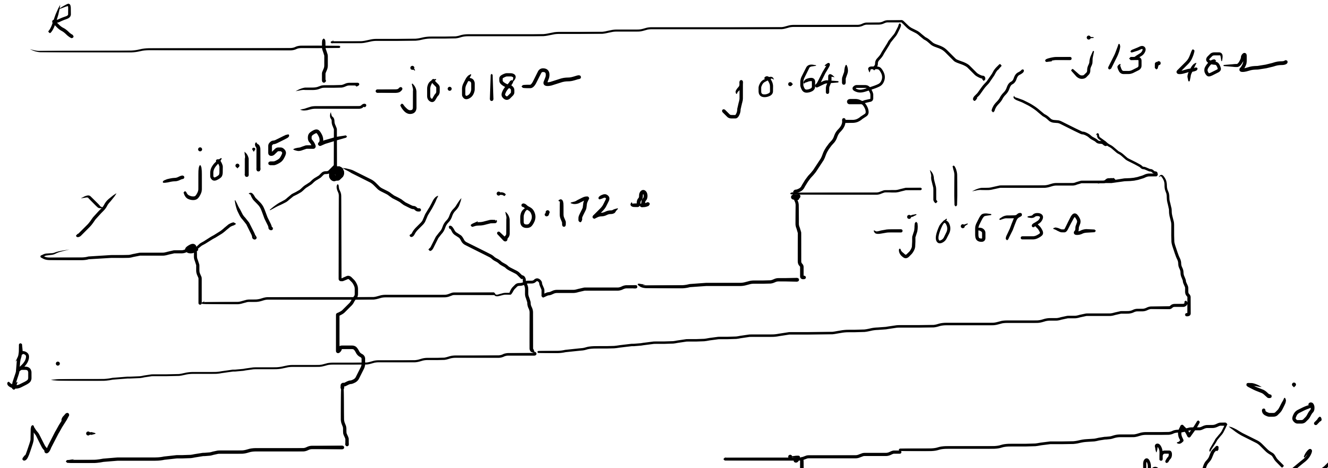
$X_y = 0.032\,\Omega$ ('')

$X_b = -0.671\,\Omega$ (Capacitive)

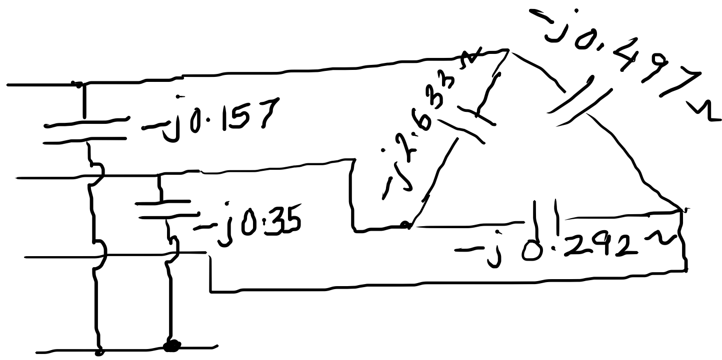
So the −ve Sequence Compensator is



Total Compensation System.

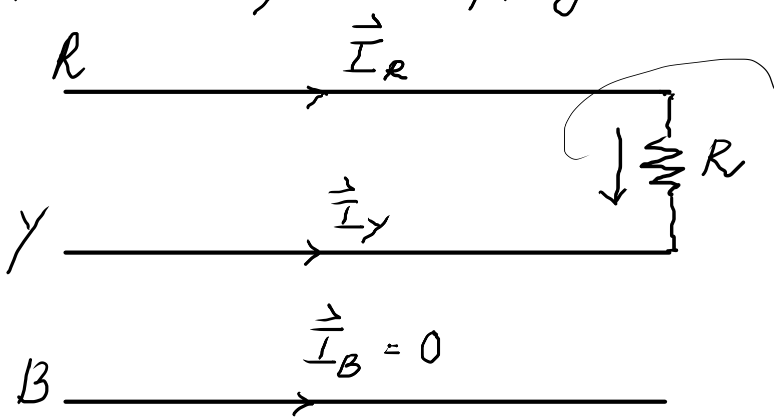


Another Option.



Compensation for Single Phase Load - The Steinmetz Circuit

Consider a Resistive Load connected between two lines (say between R & Y) of a balanced 3ϕ supply.



Note: RN voltage is taken as $V_m \sin \omega t$ and as phasor reference

Obviously $\vec{I}_R = \sqrt{3}\,V\angle 30^\circ$, $\vec{I}_Y = -\sqrt{3}\,V\angle 30^\circ$, $\vec{I}_B = 0$

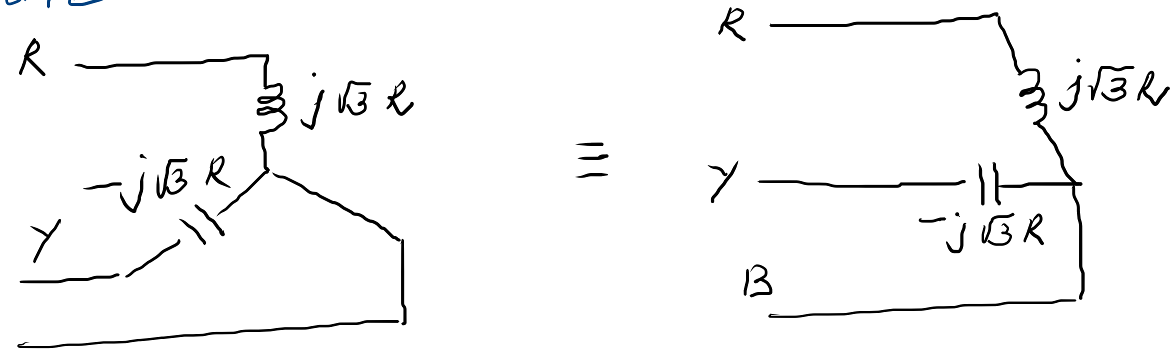
So
$$\vec{I}_0 = \frac{1}{3}(\vec{I}_R + \vec{I}_Y + \vec{I}_B) = 0$$
$$\vec{I}_+ = \frac{1}{3}(\vec{I}_R + a\vec{I}_Y + a^2\vec{I}_B)$$
$$= \frac{1}{3}(\sqrt{3}\,V\angle 30^\circ - \sqrt{3}\,V\angle 150^\circ)$$
$$= \frac{1}{3}(\sqrt{3}\,V\angle 30^\circ + \sqrt{3}\,V\angle -30)$$
$$= \frac{V}{R}$$
$$\vec{I}_- = \frac{1}{3}(\vec{I}_R + a^2\vec{I}_Y + a\vec{I}_B) = \frac{V}{R}\left(\frac{1}{2} + j\frac{\sqrt{3}}{2}\right)$$

Let us find the 3ϕ Star-connected reactive ckt that will compensate for this $-$ve sequence current.

$$X_r + X_y + X_b = 0$$
$$X_r + a^2 X_y + a X_b = \frac{3V\angle 0}{j\left(-\frac{V}{R}\left(\frac{1}{2} + j\frac{\sqrt{3}}{2}\right)\right)}$$
$$= 3R\angle 30^\circ$$
$$\therefore \left[X_r - \frac{1}{2}(X_y + X_b)\right] + j\frac{\sqrt{3}}{2}(X_b - X_y) = \frac{3\sqrt{3}}{2}R + j\frac{3}{2}R$$
$$\therefore X_r - \frac{1}{2}(X_y + X_b) = \frac{3\sqrt{3}R}{2}$$
$$\frac{\sqrt{3}}{2}(X_b - X_y) = \frac{3}{2}R$$

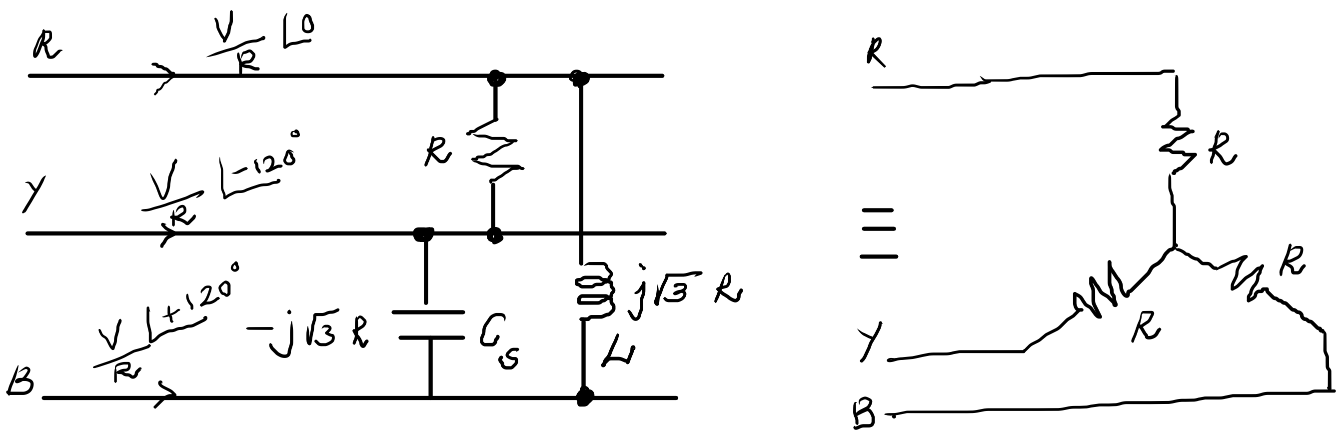
Solving $X_r = \sqrt{3}R$, $X_y = -\sqrt{3}R$, $X_b = 0$

So the required network and its Δ equivalent are

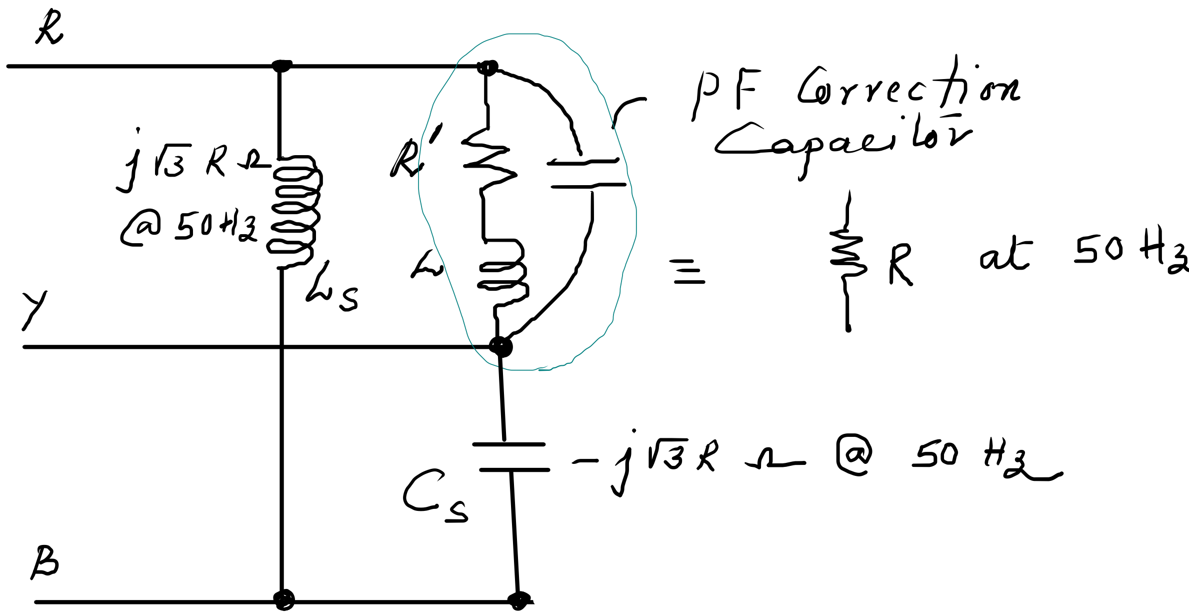


Compensation for Single Phase Load - The Steinmetz Circuit

So the load alongwith the compensator that will make it appear as a balanced load is as below.



If the single phase load is not resistive but inductive, a power factor correction capacitor that makes it a UPF load can be put across it and then the -ve sequence current compensator may be calculated.



L_s & C_s are called the Steinmetz Compensator for a single phase resistive load connected across line voltage.

Application Areas : Induction Furnaces,
Electric Arc Furnaces
Electric Welding Units
Railway Electrification
Resistance Welding Units