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MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY

3. Three-phase electric power distribution, power factor correction

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3.1 Origin and advantages of three-phase system

The most of the AC power is produced by generators in the power stations and distributed to the consumers as the three-phase power (G. Rizzoni: Fundamentals of electrical engineering). The reason is that the three-phase system has advantages as follows:

- creates rotational magnetic field
- higher power and economy of generators, transformers and motors
- more economic electric power transmission in our country
- constant three-phase power in time

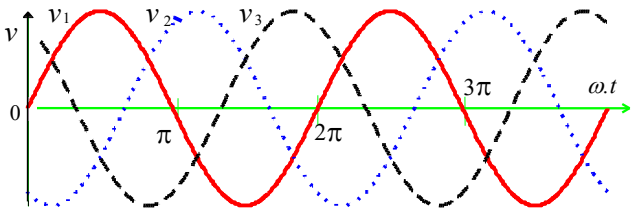
As stated above the three-phase power is generated by the generators in the power stations (https://en.wikipedia.org/wiki/Power_station). The electric generator produces sinusoidal symmetrical (balanced) three-phase voltages defined as:

$$v_1 = V_m \cdot \sin(\omega t)$$

$$v_2 = V_m \cdot \sin\left(\omega t - \frac{2\pi}{3}\right)$$

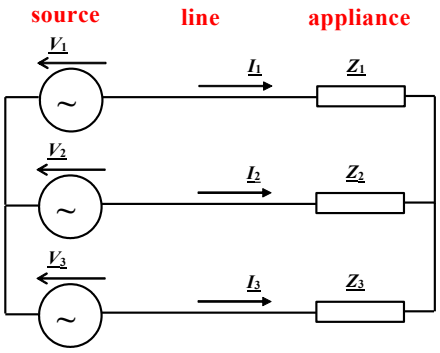
$$v_3 = V_m \cdot \sin\left(\omega t - \frac{4\pi}{3}\right) = V_m \cdot \sin\left(\omega t + \frac{2\pi}{3}\right)$$

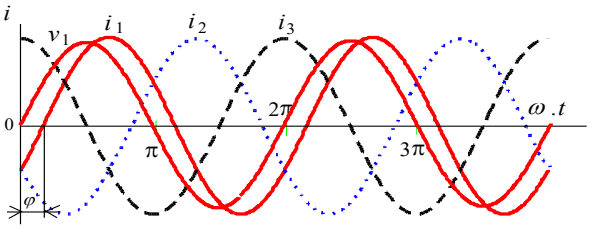
$$v_1 + v_2 + v_3 = 0$$



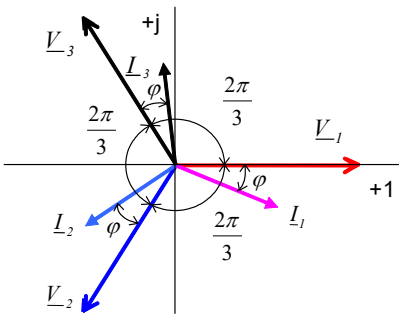
When a balanced three-phase linear load is connected, so a three-phase circuit is also symmetrical with sinusoidal currents. Their shifts are the same as defined at the voltages. The balanced load is characterized by its phase impedances:

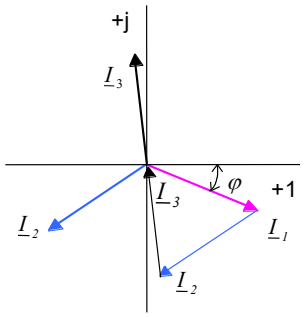
$$\underline{Z}_1 = \underline{Z}_2 = \underline{Z}_3 \quad (Z_1 = Z_2 = Z_3 = Z, \varphi_1 = \varphi_2 = \varphi_3 = \varphi)$$





The phasor diagram of the voltage and current rms values is in the figure.





$$I_1 = I_2 = I_3 = I$$

$$I = \frac{V}{Z}$$

The sum of the phase currents is equal to zero:

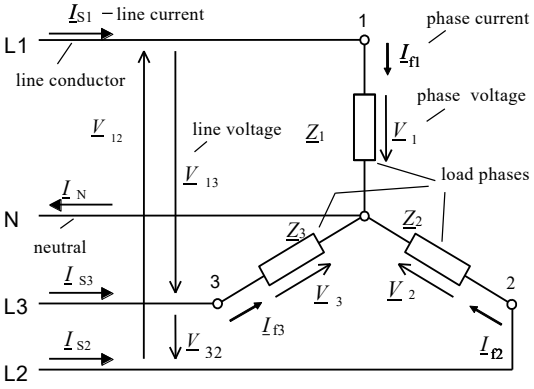
$$\underline{I}_1 + \underline{I}_2 + \underline{I}_3 = 0$$

The balanced three-phase loads are e.g. electrical machines (generators, transformers, induction motors….), electric heaters or boilers, furnaces (https://en.wikipedia.org/wiki/Three-phase).

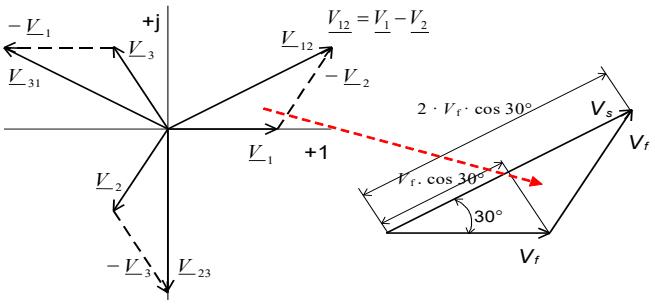
3.2 Star and delta connections

Three-phase devices can be connected into two basic configurations: star or wye (Y) and delta (Δ or D). For the three-phase system the line and phase current is defined (in the case of the star connection the neutral current in the neutral wire) and the line and phase voltage (https://en.wikipedia.org/wiki/Three-phase_electric_power).

3.2.1 The star connection of the symmetrical system



Voltages and currents in the star connection are defined as:



$$V_1 = V_2 = V_3 = V_f$$
$$V_{12} = V_{23} = V_{31} = V_S$$
$$V_S = 2\cdot V_f\cdot\cos 30^0 \rightarrow V_S = \sqrt{3}\cdot V_f$$
$$I_{f1} = I_{f2} = I_{f3} = I_f \ , \ I_f = I_S$$

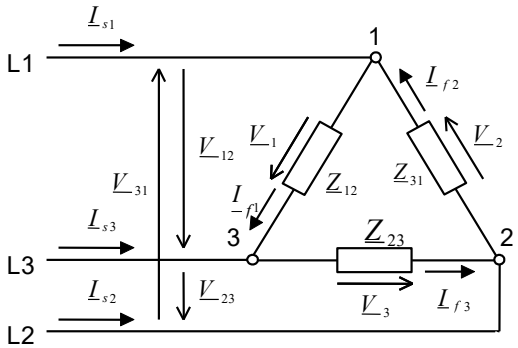
The current in the neutral wire is equal to zero (I_N=0). The total real power consumed by the balanced load is equal to the sum of real power of each phase:

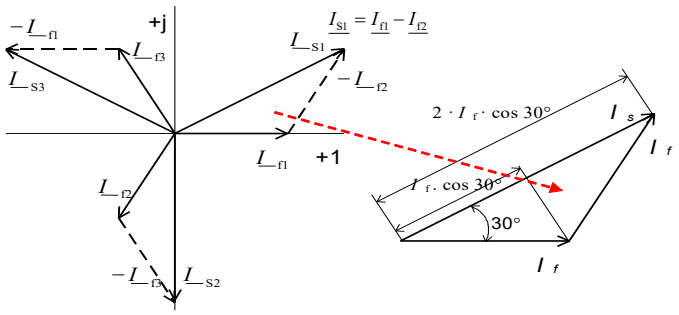
$$P = P_1 + P_2 + P_3 = V_{f1}\cdot I_{f1}\cdot\cos\varphi_1 + V_{f2}\cdot I_{f2}\cdot\cos\varphi_2 + V_{f3}\cdot I_{f3}\cdot\cos\varphi_3$$

$$P = 3\cdot V_f\cdot I_f\cdot\cos\varphi = 3\cdot\frac{V_S}{\sqrt{3}}\cdot I_S\cdot\cos\varphi = \sqrt{3}\cdot V_S\cdot I_S\cdot\cos\varphi$$

Similarly, the reactive and the apparent power can be calculated (G. Rizzoni: Fundamentals of electrical engineering).

3.2.2 The delta connection of the symmetrical system





$$I_{f1} = I_{f2} = I_{f3} = I_f$$
$$I_{S1} = I_{S2} = I_{S3} = I_S$$
$$I_S = 2\cdot I_f\cdot\cos 30^0 \rightarrow I_S = \sqrt{3}\cdot I_f$$
$$U_S = U_f$$

The total real power consumed by the balanced load is equal to the sum of real power of each phase:

$$P = P_1 + P_2 + P_3 = V_{f1} \cdot I_{f1} \cdot \cos\varphi_1 + V_{f2} \cdot I_{f2} \cdot \cos\varphi_2 + V_{f3} \cdot I_{f3} \cdot \cos\varphi_3$$

$$P = 3 \cdot V_f \cdot I_f \cdot \cos\varphi = 3 \cdot V_S \frac{I_S}{\sqrt{3}} \cdot \cos\varphi = \sqrt{3} \cdot V_S \cdot I_S \cdot \cos\varphi$$

Similarly, the reactive and the apparent power can be calculated (G. Rizzoni: Fundamentals of electrical engineering).

The electrical power distribution of the low voltage is mostly realized as 3x 400/230V, which means the three-phase system with line voltage (between two line conductors) of 400V, and with phase voltage (between the line and neutral conductor) of 230V.

3.3 Non-symmetrical three-phase system

The non-symmetrical (or unbalanced) system is characterized by loads with different impedances in their phases. This unbalanced loading causes different currents flowing in the line or phase conductors causing a current in the neutral conductor if it is connected. The unbalanced loading is caused by the single-phase appliances connected into the three-phase network.

$$\underline{Z_1} \neq \underline{Z_2} \neq \underline{Z_3} \quad (Z_1 \neq Z_2 \neq Z_3 \neq Z, \varphi_1 \neq \varphi_2 \neq \varphi_3 \neq \varphi)$$

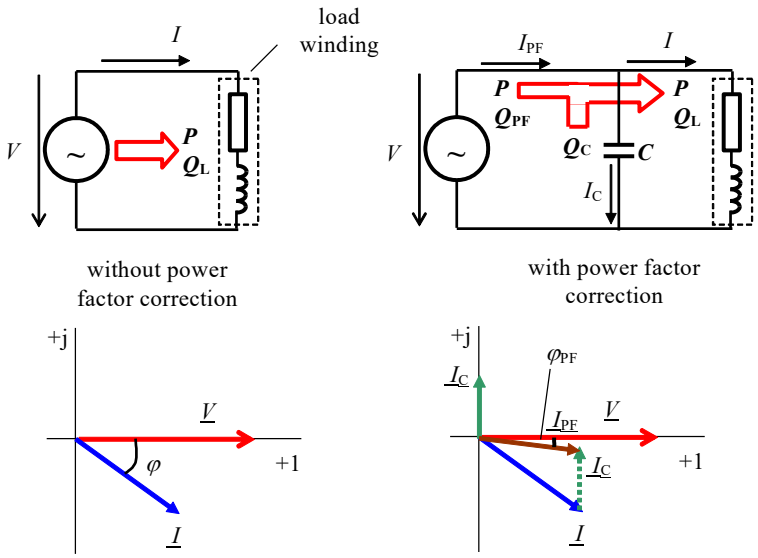
$$P = P_1 + P_2 + P_3 = V_{f1} \cdot I_{f1} \cdot \cos\varphi_1 + V_{f2} \cdot I_{f2} \cdot \cos\varphi_2 + V_{f3} \cdot I_{f3} \cdot \cos\varphi_3$$

$$S = S_1 + S_2 + S_3 = V_{f1} \cdot I_{f1} + V_{f2} \cdot I_{f2} + V_{f3} \cdot I_{f3}$$

$$\underline{I_{f1}} + \underline{I_{f2}} + \underline{I_{f3}} = \underline{I_N} \neq 0$$

3.4 Power factor correction, methods and benefits

A lot of loads connected to the network consume reactive power, which is necessary for their operation (motors, transformers, induction heating, contactors, etc…). It causes a lower power factor in the network (e.g. commonly used induction motor has its power factor equal to c. 0.8), than stated by the standard (equal to 0.95). The higher power factor is desirable to reduce losses in the power line and increasing load carrying capabilities (https://en.wikipedia.org/wiki/Power_factor). The principle is shown in the picture.



The most common device for power factor correction is a unit, which consists of a number of capacitors, which supplies the demand reactive power to the device. The reactive power of a power-factor capacitor is defined:

$$Q_L = Q_{PF} + Q_C$$

$$Q_C = Q_L - Q_{PF} = P \cdot (\mathrm{tg}\varphi - \mathrm{tg}\varphi_{PF})$$

The capacitance of power-factor capacitor:

$$C = \frac{Q_C}{V^2 \cdot \omega}$$

Besides a bank of capacitors an unloaded synchronous motor or power electronic devices can be used.