

7 Polyphase Networks and Power in AC Circuits

Student Group

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7 Polyphase Networks and Power in AC Circuits

emphasizing the importance of power considerations

- three-phase four-wire systems

7.0 Recap of complex two-terminal networks

In the last semester, AC current, AC voltage, and their effects have been considered on a circuit that had simply included an AC voltage source.

These circuits can be now understood as.

- the sinusoidal alternating voltage is produced by the rotation of a coil in a homogeneous magnetic field, and
- the sinusoidal alternating current is formed by a connected load (or complex impedance).

are formed.

This will be briefly illustrated here. In [figure 1](#) a coil with w windings is seen in a magnetic field with a magnetic flux density \vec{B} . The coil rotates - starting from φ_0 with angular velocity ω . The rotation changes the chained flux Ψ through the coil and thus a voltage $u(t)$ is induced.

Fig. 1: voltage generation in generator



For the rotation angle φ holds:
$$\varphi(t) = \omega t + \varphi_0$$

Thus, the induced voltage $u(t)$ is given by:
$$u(t) = -\frac{d\Psi}{dt} = -N \frac{d\Phi}{dt} = -NB \frac{d}{dt} \cos(\omega t + \varphi_0) = \omega \hat{\Psi} \sin(\omega t + \varphi_0) = \hat{U} \sin(\omega t + \varphi_0)$$

Such single-phase systems are therefore alternating current systems, which use one outgoing line and one return line each for the current conduction.

Out of the last formula we derived the following instantaneous voltage $u(t)$
$$u(t) = \hat{U} \sin(\omega t + \varphi_0) = \sqrt{2} U \sin(\omega t + \varphi_0)$$

7.1 Power in AC

Learning Objectives

By the end of this section, you will be able to:

1. Know the formula of the instantaneous power of the resistor, inductor, and capacitor and be able to determine its values.

In the first chapter, we mainly focussed on the power given by $P = U \cdot I$. This is however only valid for DC circuits. For AC circuits we have to consider the instantaneous power $p(t)$. The instantaneous power is given by:

$$p(t) = u(t) \cdot i(t)$$

Ideal Ohmic resistance R

The simplest component to look at for the instantaneous power is the resistor. For this, we start with the basic definition of the instantaneous voltage $u_R(t)$ (which was given in the last semester) as

$$u_R(t) = \sqrt{2} U \sin(\omega t + \varphi_u)$$

With the defining formula for the resistor, we get:

$$u_R(t) = R \cdot i(t) \implies i(t) = \frac{u_R(t)}{R} = \frac{\sqrt{2} U}{R} \sin(\omega t + \varphi_u)$$

This leads to an instantaneous power $p_R(t)$ of
$$p_R(t) = u_R(t) \cdot i_R(t) = 2 \cdot \frac{U^2}{R} \sin^2(\omega t + \varphi_u) = \frac{U^2}{R} (1 - \cos(2(\omega t + \varphi_u)))$$

For the last step the [Double-angle formula](#) " $\cos(2x) = 1 - 2 \sin^2(x)$ " was used.

This result is interesting in the following ways:

1. The part $\cos(2 \cdot (\omega t + \varphi_u))$ is always non-negative and a shifted sinusoidal function between $0 \dots 2$. The average value of this part is 1 .
2. The average value of $p_R(t)$ is then: $P_R = \frac{U^2}{R}$
3. The use of the $\sqrt{2}$ in the definition $u_R(t) = \sqrt{2} U \sin(\omega t + \varphi_u)$ leads to the average power as $P_R = \frac{U^2}{R}$. This formula for the power is exactly like the formula for the power in pure DC situations.

Ideal Inductivity L

A similar approach is done for the ideal inductivity. We again start with the basic definition of the instantaneous voltage

$$u_L(t) = \sqrt{2} U \sin(\omega t + \varphi_u)$$

With the defining formula for inductivity, we get:
$$u_L(t) = L \frac{di_L(t)}{dt} \implies i_L(t) = \frac{1}{L} \int u_L(t) dt = -\frac{\sqrt{2}}{\omega L} U \cos(\omega t + \varphi_u)$$

This leads to an instantaneous power $p_L(t)$ of

$$p_L(t) = u_L(t) \cdot i_L(t) = -2 \frac{U^2}{\omega L} \sin(\omega t + \varphi_u) \cos(\omega t + \varphi_u) = -\frac{U^2}{\omega L} \sin(2 \cdot (\omega t + \varphi_u))$$

Again a trigonometric identity ([Double-angle formula](#) “ $\sin(2x) = 2 \sin(x) \cos(x)$ ”) was used.

Also, this result is interesting:

1. The part $\sin(2 \cdot (\omega t + \varphi_u))$ has an average value of 0 .
2. Therefore, the average value of $p_L(t) = 0$

Ideal Capacity C

Also here, we start with the basic definition of the instantaneous voltage

$$u_C(t) = \sqrt{2} U \sin(\omega t + \varphi_u)$$

With the defining formula for the capacity, we get:
$$i_C(t) = C \frac{du_C(t)}{dt} = \sqrt{2} U \omega C \cos(\omega t + \varphi_u)$$

This leads to an instantaneous power $p_C(t)$ of

$$p_C(t) = u_C(t) \cdot i_C(t) = 2 U^2 \omega C \sin(\omega t + \varphi_u) \cos(\omega t + \varphi_u) = + U^2 \omega C \sin(2 \cdot (\omega t + \varphi_u))$$

Again this result leads to:

1. The part $\sin(2 \cdot (\omega t + \varphi_u))$ has an average value of 0 .
2. Therefore, also the average value of $p_C(t) = 0$

- Instantaneous values of power at R , L , C
- Active, reactive, apparent, and complex power

This effect can also be seen in the following simulation: The simulation shows three loads, all with an impedance of $|Z| = 1 \text{ k}\Omega$. The diagram on top of each circuit shows the instantaneous **voltage**, **current** and **power**.

1. Ohmic load: The instantaneous voltage is in phase with the instantaneous current. The instantaneous power is always non-negative. The average power is $P = U^2/R = \frac{1}{2} \hat{U}^2/R = \frac{1}{2} (6V)^2/1 \text{ k}\Omega = 18 \text{ mW}$
2. Inductive load: The voltage is ahead of the current. The phase angle is $+90^\circ$ (which also reflects the $+j$ in the inductive impedance $+j\omega L$). The instantaneous is half positive, half negative; the average power is zero (in the simulation not completely visible).
3. Capacitive load: The voltage is lagging the current. The phase angle is -90° (which also reflects the $-j$ in the capacitive impedance $\frac{1}{j\omega C}$). The instantaneous is again half positive, half negative; the average power is zero (in the simulation not completely visible).

arbitrary two-terminal Component

For an arbitrary component, we do not have any defining formula. But, the $u(t)$ and $i(t)$ can generally be defined as:

$$\begin{aligned} \color{blue}{u(t)} &= \sqrt{2}U \sin(\omega t + \varphi_u) \\ \color{red}{i(t)} &= \sqrt{2}I \sin(\omega t + \varphi_i) \end{aligned}$$

This leads to an instantaneous power $p(t)$ of

$$p(t) = \color{blue}{u(t)} \cdot \color{red}{i(t)} = 2UI \sin(\omega t + \varphi_u) \sin(\omega t + \varphi_i)$$

The formula can be further simplified with the help of the following equations

- $\varphi = \varphi_u - \varphi_i \quad \rightarrow \quad \varphi_i = \varphi_u - \varphi$
- $\sin(\Box - \varphi) = \sin(\Box) \cos \varphi - \cos(\Box) \sin \varphi$
- $2 \sin \Box \sin \Box = 1 - \cos(2\Box)$
- $2 \sin \Box \cos \Box = \sin(2\Box)$

$$p(t) = UI \left(\cos \varphi \left(1 - \cos(2(\omega t + \varphi_u)) \right) - \sin \varphi \sin(2(\omega t + \varphi_u)) \right)$$

This result is twofold:

1. The part $\cos \varphi \left(1 - \cos(2(\omega t + \varphi_u)) \right)$ results into a non-zero average - explicitly this part is 1 in average. On average the first part of the formula results in $UI \cos \varphi$.
2. The part $-\sin \varphi \sin(2(\omega t + \varphi_u))$ is zero on average, so the second part of the formula results in zero. The amplitude of the second part is $UI \sin \varphi$

Notice:

A distinction is now made between:

- An **active power** (alternatively real or true power, in German: *Wirkleistung*): $P = UI \cos \varphi$
 - The active power represents a pulsed energy drain out of the electrical system (commonly by an ohmic resistor).
 - The active power transforms the electric energy permanently into thermal or mechanical energy
 - Therefore, the unit of the active power is Watt .
- A **reactive power** (in German: *Blindleistung*): $Q = UI \sin \varphi$
 - The reactive power describes the “sloshing back and forth” of the energy into the electric and/or magnetic fields.
 - The reactive power is completely regained by the electric circuit.
 - To distinguish the values, the unit of the reactive power is VAr (or Var) for **V**olta **r**eactive.
- An **apparent power** (in German *Scheinleistung*): $S = UI$
 - The apparent power is the simple multiplication of the RMS values from the current and the voltage.
 - The apparent power shows only what seems to be a value of power, but can deviate from usable power when inductors or capacitors are used in the circuit.
 - The unit of the apparent power is VA for **V**olta**a**mpere

Similarly, the currents and voltages can be separated into active, reactive, and apparent values.

Based on the given formulas the three types of power are connected with each other. Since the apparent power is given by $S = U \cdot I$, the active power $P = U \cdot I \cdot \cos \varphi = S \cdot \cos \varphi$ and the reactive power $Q = S \cdot \sin \varphi$, the relationship can be shown in a triangle (see [figure 2](#)).

Fig. 2: Power Triangle of active, reactive and apparent power

Generally, the apparent power can also be interpreted as a complex value:

$$\underline{S} = S \cdot e^{j\varphi} = U \cdot I \cdot e^{j\varphi}$$

Based on the definition of the phase angle $\varphi = \varphi_U - \varphi_I$, this can be divided into:

$$\underline{S} = U \cdot I \cdot e^{j(\varphi_U - \varphi_I)} = \underbrace{U \cdot e^{j\varphi_U}}_{\underline{U}} \cdot \underbrace{I \cdot e^{-j\varphi_I}}_{\underline{I}^*}$$

where \underline{I}^* is the complex conjugated value of \underline{I} .

Notice:

The apparent power \underline{S} is given by:

- $\underline{S} = UI \cos \varphi$
- $\underline{S} = UI (\cos \varphi + j \sin \varphi)$
- $\underline{S} = P + jQ$
- $\underline{S} = \underline{U} \cdot \underline{I}^*$

The following simulation shows three ohmic-inductive loads, all with an impedance of $|Z| = 1 \text{ k}\Omega$, however with different phase angles φ . The diagram on top of each circuit shows the instantaneous **voltage**, **current** and **power**. Similar to the last simulation, a pure ohmic resistance would consume an average power of $P = U^2/R = \frac{1}{2} \hat{U}^2/R = \frac{1}{2} (6 \text{ V})^2/1 \text{ k}\Omega = 18 \text{ mW}$. The three diagrams shall be discussed shortly.

1. Phase angle $\varphi = 10^\circ$: Nearly all of the impedance is given by the resistance and therefore the real part of the impedance. The instantaneous voltage is nearly in phase with the current. The instantaneous power is almost always larger than zero. The average power with 17.47 mW is about the same as for an ohmic impedance.
2. Phase angle $\varphi = 60^\circ$: It is clearly visible, that instantaneous voltage and current are out of phase. The instantaneous power is often lower than zero. The ohmic resistor has $500 \text{ }\Omega = \frac{1}{2}|Z|$, but does not show half of the voltage! This is because the addition has to respect the complex behavior of the values. The complex part is 90° perpendicular to the real part - so they generate a right-angled triangle. The average power with 9 mW is exactly half of the power for an ohmic impedance since only the resistance provides a way for consuming power permanently.
3. Phase angle $\varphi = 84.28^\circ$: The phase angle is calculated in such a way, that the resistance is only 10% of the amplitude of the impedance $|Z|$. In this case, the load is nearly pure inductive. The instantaneous power is consequently almost half of the time lower than zero. The average power here is also only 10% of the power for a pure ohmic impedance.

The next simulation enables us to play around with the phase angle of an impedance. The circuit on the left side is a bit harder to understand but consists of a resistive (real) impedance and a complex impedance, which are driven by an AC voltage source. All of these components are parameterizable in such a way that the phase angle can be manipulated by the slider on the right side.

In the middle part reflects the time course of:

- The instantaneous power p of the **real part (active power)**, the **imaginary part (reactive power)** and **overall power**.
- The instantaneous **voltage** and **current**.

On the right-hand side, the impedance Phasor is shown (lower diagram). The upper diagram depicts the u - i -diagram, which would be a perfect line for a pure ohmic resistance (since $u_R = R \cdot i_R$) and a circle for a pure complex impedance (since the phase angle of $\pm 90^\circ$ between $u_{L, C}$ and $i_{L, C}$). The simulation is in this part not completely perfect: The pure line and circle are sometimes not reachable.

The following questions can be solved with this simulation:

1. How does the amplitude of the active and reactive instantaneous power change, when the phase angle is changed between $-90^\circ \dots +90^\circ$?
2. What is the phase shift between the active and reactive instantaneous power?

1)

Also, the last simulation shows the relation between the phase angle (here: α) and instantaneous values, like power, voltage, and current.

Fig. 3: Simulation of instantaneous power as a function of phase

Change the phase angle with the slider under α
 press here for the animation

7.1.3 Applications

Power Factor Correction

Cables and components have to conduct the sum of active and reactive currents, but only the active current is used outside of the circuit. Therefore, a common goal is to minimize the reactive part. The technical way to represent this is the **power factor** pf is used.

Notice:

The power factor is given by:

$$\text{pf} = \cos \varphi = \frac{P}{\underline{S}}$$

The power factor shows how much real power one gets out of the needed apparent power.

How does the power factor show the problematic effects? For this one can investigate the situation of an ohmic-inductive load \underline{Z}_L which is connected to a voltage \underline{U}_0 source with a wire R_{wire} . This circuit is shown in [figure 4](#).

Fig. 4: Power Factor of a Power Line



The usable output power is $P_L = U_{\text{L}} \cdot I \cdot \cos \varphi$. Based on this, the current \underline{I} is:

$$I = \frac{P_L}{U_{\text{L}} \cdot \cos \varphi}$$

The power loss of the wire P_{wire} is therefore:

$$P_{\text{wire}} = R_{\text{wire}} \cdot I^2 = R_{\text{wire}} \cdot \frac{P_L^2}{U_{\text{L}}^2 \cdot \cos^2 \varphi}$$

This means: As smaller, the power factor $\cos \varphi$, as more power losses P_{wire} will be generated. More power losses P_{wire} lead to more heat up to or even beyond the maximum temperature. To compensate for this, the cross-section of the wire has to be increased, which means more copper.

Alternatively, a bad power factor can be compensated with a counteracting complex impedance. This compensating impedance has to provide enough power with the opposite sign to cancel out the unwanted reactive power. The following simulation shows an uncompensated circuit and a circuit with power factor correction. In the latter, the voltage on the load resistor is the same, but the current provided by the power supply is smaller.

Another explanation of the power factor can be seen here:



Impedance matching

not covered in this course

7.2 Polyphase Networks

To transfer power over long distances alternating current and explicitly rotary current are used. Rotary current is the common name for a three-phase current. The first three-phase high voltage power transfer worldwide started in the August of 1891 for the “[International Electrotechnical Exhibition](#)”. The power plant in Lauffen (see [figure 5](#)) - about \$10 \sim \text{km}\$ away from the university Heilbronn - was therefore the first modern three-phase generator and started the three-phase transmission networks, which are the power backbone throughout the world.

Fig. 5: Worldwide first three-phase High Voltage Power Transfer



In the following, the way to polyphase networks and explicitly three-phase systems will be described. Be aware, that the term “phase” is used in two different meanings: In the first usage, the phase shift φ between voltage and current on a single component is commonly called “phase”. The second usage of “phase” is for a single circuit of a “multi-circuit” setup, called a polyphase network.

The ladder terminology will be explained in the following in more detail.

7.2.1 Technical terms of the Polyphase Networks

General

Various general technical terms in the polyphase system (in German: Mehrphasensystem) will now be briefly discussed.

1. A **m -phase system** describes a circuit in which m sinusoidal voltages transport the power. The general term for these systems is polyphase systems.

The voltages are generated by a homogenous magnetic field containing m rotating windings, which are arranged with a fixed offset to each other (see [figure 6](#)). The induced voltages exhibit the same frequency f .

Fig. 6: Visible Representations of a m -phase System



2. An m -phase system is **symmetrical** when the voltages of the individual windings exhibit the same amplitude and are offset at the same angle to each other ($\varphi = 2\pi/m$).

Thus, the voltage phasors $\underline{U}_1 \dots \underline{U}_m$ form a symmetrical star.

Example: A 3-phase system is symmetrical for $\varphi = 360^\circ/3 = 120^\circ$ between the voltages of the windings: $\underline{U}_1 = \sqrt{2} \cdot U \cdot e^{j(\omega t + 0^\circ)}$, $\underline{U}_2 = \sqrt{2} \cdot U \cdot e^{j(\omega t - 120^\circ)}$, $\underline{U}_3 = \sqrt{2} \cdot U \cdot e^{j(\omega t - 240^\circ)}$

Fig. 7: Visible Representations of the a symmetric and asymmetric System



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3. The windings can be concatenated (=linked) in different ways. The most important ways of **concatenation** are:
1. All windings are independently connected to a load. This phase system is called **non-interlinked** (in German: *nicht verkettet*).
 2. All windings are connected to each other, then the phase system is called **interlinked**.

With interlinking, fewer wires are needed. Star or ring circuits can be used for daisy chaining. The two simulations in [figure 8](#) show a non-interlinked and an interlinked circuit with generator and load in star shape.

Fig. 8: Comparison of non-interlinked and interlinked circuits

To show the simulations: click on Edit » Center Circuit

To view the simulations: click here!

1. The instantaneous power $p_i(t)$ of a winding i is variable in time. For the instantaneous power $p(t)$ of the m -phase system one has to consider all single instantaneous powers of the windings. When this instantaneous power $p(t)$ does not change with time, the polyphase system is called **balanced**.

If a balanced load is used, then polyphase systems are balanced with $m \geq 3$.

For $m \geq 3$ and symmetrical load, the following is obtained for the instantaneous power:

$$p = m \cdot U \cdot I \cdot \cos\varphi = P$$

Fig. 9: Visible Representations of a balanced System



The following simulation shows the power in the different phases of a symmetrical and balanced system. The instantaneous power of each phase is a non-negative sinusoidal function shifted by 0° , 120° , and 240° .

Balanced polyphase networks have the lowest wiring costs.

The structure of a polyphase network can also represent a ring interlinking (also called ring connection, see next simulation).

The often used (and also here used) term of three-phase current or alternating current has not to be

taken literally: If no load is connected, there is no three-phase AC network, but a three-phase **voltage** network.

7.2.2 Three-Phase System

See also: [MATHWORKS Onramp Video: What is 3-phase power?](#)

The most commonly used polyphase system is the three-phase system. The three-phase system has advantages over a DC system or single-phase AC system:

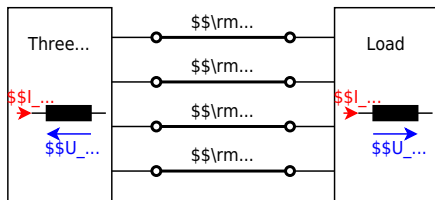
- Simple three-phase machines can be used for generation.
- Rotary field machines (e.g. synchronous motors or induction motors) can also be simply connected to a load, converting the electrical energy into mechanical energy.
- When a symmetrical load can be assumed, the energy flow is constant in time.
- For energy transport, the voltage can be up-transformed and thus the AC current, as well as the associated power loss (= waste heat), can be reduced.

To understand the three-phase system, we have to investigate the different voltages and currents in this system.

For this the three-phase system will be separated into three parts:

1. Three-phase generator(s)
2. Line conductors
3. Loads

Fig. 10: Three-Phase System



Three-phase generator

- The windings of a three-phase generator are called U , V , W ; the winding connections are correspondingly called: $U1$, $U2$, $V1$, $V2$, $W1$, $W2$ (see [figure 11](#)).

Fig. 11: Motor Terminal



- The typical **winding connections** in a three-phase generator are called **Delta connection** (for ring connection) and **Wye connection** (for star connection). This winding connection can simply be changed by reconnecting the motor terminal. In figure 12 the two types of winding connections are shown. For the Wye connection, is often the star configuration shown, and for the Delta connection the ring configuration. For the Wye connection, it is also possible to have the star point on a separate terminal.

Fig. 12: Motor Terminal Setup for the two Connections



- The **phase voltages** are given by:

$$\begin{aligned}
 & \color{RoyalBlue}{u_{\text{U}}} \ \& \ \color{RoyalBlue}{=} \ \sqrt{2} \ U \ \color{RoyalBlue}{\cos(\omega t + \alpha - 0)} \ \color{Green}{u_{\text{V}}} \ \& \ \color{Green}{=} \ \sqrt{2} \ U \ \color{Green}{\cos(\omega t + \alpha - \frac{2}{3}\pi)} \ \color{DarkOrchid}{u_{\text{W}}} \ \& \\
 & \color{DarkOrchid}{=} \ \sqrt{2} \ U \ \color{DarkOrchid}{\cos(\omega t + \alpha - \frac{4}{3}\pi)} \ \color{RoyalBlue}{u_{\text{U}}} \ \color{Green}{u_{\text{V}}} \ \color{DarkOrchid}{u_{\text{W}}} \ \& \ = \ 0 \ \color{RoyalBlue}{\end{aligned}}
 \end{aligned}$$

- The **direction of rotation** is given by the arrangement of the windings:
 - The three-phase generator with clockwise direction (CW, mathematically negative orientation) shows the phase sequence: u_{U} , u_{V} , u_{W} . Therefore, u_{V} is 120° lagging to u_{U} .

This is the common setup for generators.

- The three-phase generator with counter-clockwise direction (CCW, mathematically positive orientation) shows the phase sequence: u_{U} , u_{W} , u_{V} . Therefore, u_{V} is 120° ahead of u_{U} .
- The direction can be changed simply by switching two of the three phases (it does not need to be u_{V} with u_{W} !).

Fig. 13: Direction of Rotation



Line Conductors

The lines connected to the generator / load terminals U_1 , V_1 , W_1 are often called L_1 , L_2 , L_3 (L for **L**ine or **L**ive = active) outside of the generator or load. It is important to distinguish between the different types of voltages and currents, which depend on the point of view (either onto a three-phase generator/load or the external conductors).

- **String voltages/currents** U_{S} , I_{S} (alternatively: winding voltages/currents, in German: *Strangspannungen/Strangströme*):

The string voltages/currents are the values measured on the windings - independent of the winding connection.

These voltages are shown in the previous images as u_{U} , u_{V} , and u_{W} .

- **Phase voltages/currents** U_{L} , I_{L} (alternatively: phase-to-phase voltages/currents, line-to-line voltages/currents, external conductor voltages/currents, in German: *Außenleiterspannungen/Außenleiterströme*):

The phase voltages are measured differentially between the lines. The phase voltages are therefore given as U_{12} , U_{23} , U_{31} .

The phase currents are given as the currents through a single line: I_1 , I_2 , I_3 .

The potential of the star point is called **neutral** N

- **Star Voltages** U_{Y} (alternatively: phase-to-neutral voltages, line-to-neutral voltages, in German: *Sternspannungen*): the voltages of the lines can be also measured or used referring to the neutral potential.

Fig. 14: Example of an Three-Phase System



The setup with $L1$, $L2$, $L3$ and N is called **three-phase four-wire system**. When only a Delta connection without neutral is connected it is called a **three-phase three-wire system**. The star and phase voltages are given by

$$U_{\text{S}} = + U_{\text{L}}$$

$$U_{\text{L}} = + U_{\text{S}}$$

$$U_{\text{L}} = - U_{\text{S}}$$

A phasor diagram can be constructed based on the given voltages. Be aware, that commonly the phasor is shown as a vector (i.e. as an arrow starting from the origin or zero). In contrast to this, the voltage in a circuit is shown as an arrow pointing towards the zero potential.

Fig. 15: Phasor-Diagram with Phase- and Star-Voltages

ssl...

For the yellow triangle in [figure 15](#) applies:

$$\begin{aligned} \frac{1}{2} U_{31} &= U_{\text{LN}} \cdot \cos 30^\circ \quad \&= U_{\text{LN}} \cdot \frac{\sqrt{3}}{2} \\ U_{31} &= \sqrt{3} \cdot U_{\text{LN}} \end{aligned} \quad \boxed{U_L = \sqrt{3} \cdot U_Y}$$

The phase voltages are $\sqrt{3}$ larger than the star-voltage. In Europe, the low-voltage network of electric power distribution is defined by the RMS value of a star-voltage of 400~V .

The phase voltage is therefore $\frac{1}{\sqrt{3}} \cdot 400\text{~V} \approx 230\text{~V}$. The following two simulations show these voltages.

7.2.3 Load and Power in Three-Phase Systems

Fig. 15: CEE Connector

To understand the load in three-phase systems, the power at different types of loads will be investigated:

- Load in Wye connection with the three-phase four-wire system
- Load in Wye connection with the three-phase three-wire system
- Load in Delta connection

An example circuit is chosen for each investigation.

Load in Wye connection (Four-Wire System)

The four-wire wiring is one of the most common ways to connect three-phase systems. The [IEC 60309](#) connector (in German commonly known as *CEE Stecker*) is often used for this connection. The connector has an additional pin PE , besides the explained phases L1 , L2 , L3 , and the neutral line N . **PE** stand for protective earth and is part of the [Earthing System](#). In short: PE provides a reference potential, which is everywhere available, due to the fact, that the power plant provides it to the soil ground.

For the four-wire system, the four pins L1 , L2 , L3 , and the neutral line N are used for power transfer. This is for example applied for loads in a star configuration, e.g. three-phase motors in Wye connection or three single-phase loads, where each load is connected to a single phase.

Example

The example in the following simulation shows a 50 Hz / 231 V three-phase four-wire

system with an unbalanced load in the Wye connection, with the given impedances.

- Calculate the phase currents I_1 , I_2 , I_3 , the neutral current I_N
- Calculate the true power, apparent power, and reactive power.

Voltages - Currents - True Power - Apparent and Reactive Power

The following “path”: calculate voltages \rightarrow calculate currents \rightarrow calculate true power \rightarrow calculate apparent and reactive power is the best way to get to all wanted values.

1. **Voltages:** It is obvious, that the phase voltages (\underline{U}_{12} , \underline{U}_{23} , \underline{U}_{31}) and star-voltages (\underline{U}_{1N} , \underline{U}_{2N} , \underline{U}_{3N}) are applied by the three-phase network independently of the load.
2. **Currents:** For the phase currents it applies that: $\underline{I}_1 + \underline{I}_2 + \underline{I}_3 = \underline{I}_N$ (be aware, that the voltage given in the simulation is only the RMS value without the phase shift).

The phase currents are given by the phase impedances and the star-voltages:

$$\begin{aligned} \underline{I}_1 &= \frac{\underline{U}_{1N}}{\underline{Z}_1} \quad , \quad \underline{I}_2 = \frac{\underline{U}_{2N}}{\underline{Z}_2} \quad , \quad \underline{I}_3 = \frac{\underline{U}_{3N}}{\underline{Z}_3} \\ \end{aligned}$$

3. The **true power** P_x for each string is given by the apparent power S_x of the string times the individual phase angle φ_x of the string:

$$P_x = S_x \cdot \cos \varphi_x = U_x \cdot I_x \cdot \cos \varphi_x$$

Therefore, the resulting true power for the full load is:

$$P = U_{1N} \cdot (I_1 \cdot \cos \varphi_1 + I_2 \cdot \cos \varphi_2 + I_3 \cdot \cos \varphi_3)$$

The angle φ here is given by $\varphi = \varphi_u - \varphi_i$, and hence:

$$P = U_{1N} \cdot \left(I_1 \cdot \cos (\varphi_{u,1} - \varphi_{i,1}) + I_2 \cdot \cos (\varphi_{u,2} - \varphi_{i,2}) + I_3 \cdot \cos (\varphi_{u,3} - \varphi_{i,3}) \right)$$

4. For the **apparent power** one could think of S_x for each string is given by the string voltage and the current through the string $S_x = U_x \cdot I_x$. However, this misses out on the apparent power of the neutral line!

Even when considering all four lines a simple addition of all the apparent powers per phase would be problematic: The apparent power can be either positive or negative. There is the possibility to cancel each other out in the calculation, even when there is an unbalanced impedance given. It is better to use a definition, which can consider all of the phase apparent powers.

By DIN 40110 the **collective apparent power** S_{Σ} can be assumed as

$$S_{\Sigma} = \sqrt{\sum_x U_x^2 + \underbrace{U_{\Sigma}^2}_{=0}} \cdot \sqrt{\sum_x I_x^2 + I_{\Sigma}^2} \quad \text{and} \quad \sqrt{3} \cdot U_{\Sigma} \cdot \sqrt{I_1^2 + I_2^2 + I_3^2 + I_{\Sigma}^2}$$

5. Given the collective apparent power the **collective reactive power** Q_{Σ} is given by

$$Q_{\Sigma} = \sqrt{S_{\Sigma}^2 - P^2}$$

Example

In the example, this leads to:

- The star-voltages and the phase voltages are given as

$$U_{\Sigma} = 231 \text{ V} = U_{1N} = U_{2N} = U_{3N} \quad U_L = \sqrt{3} \cdot 231 \text{ V} = 400 \text{ V} = U_{12} = U_{23} = U_{31}$$

The phasors of the star-voltages are given as:

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- Based on the star-voltages and the given impedances the phase currents are:

$$\begin{aligned} \underline{I}_1 &= \frac{\underline{U}_{1N}}{\underline{Z}_1} = \frac{231 \text{ V}}{10 \text{ } \Omega + j \cdot 2\pi \cdot 50 \text{ Hz} \cdot 1 \text{ mH}} = 23.08 \text{ A} \cdot e^{-j1.8^\circ} \\ \underline{I}_2 &= \frac{\underline{U}_{2N}}{\underline{Z}_2} = \frac{231 \text{ V}}{\left(-\frac{1}{2} - j \cdot \frac{1}{2} \sqrt{3} \right) \cdot 50 \text{ } \Omega + j \cdot 2\pi \cdot 50 \text{ Hz} \cdot 100 \text{ } \mu\text{F}} = 5.58 \text{ A} \cdot e^{-j38.9^\circ} \\ \underline{I}_3 &= \frac{\underline{U}_{3N}}{\underline{Z}_3} = \frac{231 \text{ V}}{\left(-\frac{1}{2} + j \cdot \frac{1}{2} \sqrt{3} \right) \cdot 20 \text{ } \Omega} = 5.78 \text{ A} \cdot e^{+j38.9^\circ} \\ \underline{I}_{\Sigma} &= \underline{I}_1 + \underline{I}_2 + \underline{I}_3 = 22.88 \text{ A} \cdot e^{+j11.8^\circ} \end{aligned}$$

- The true power is calculated by:

$$P = 231 \text{ V} \cdot \left(23.09 \text{ A} \cdot \cos(0^\circ - (-1.8^\circ)) + 7.17 \text{ A} \cdot \cos(-120^\circ - (-38.9^\circ)) + 11.55 \text{ A} \cdot \cos(-240^\circ - (-240^\circ)) \right) = 8.26 \text{ kW}$$

{~\rm kW} \end{align*}

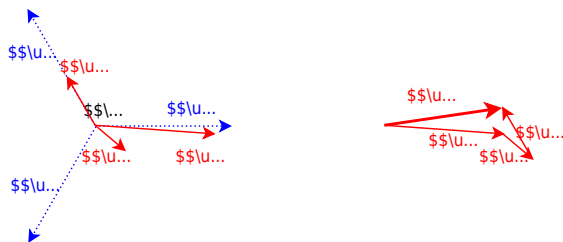
4. The collective apparent power is:

$$\begin{aligned} S_{\Sigma} &= \sqrt{3} \cdot 231 \text{ \rm V} \cdot \sqrt{(23.09 \text{ \rm A})^2 + (7.17 \text{ \rm A})^2 + (11.55 \text{ \rm A})^2} = 14.23 \text{ \rm kVA} \end{aligned}$$

5. The collective reactive power is:

$$\begin{aligned} Q_{\Sigma} &= \sqrt{(14.23 \text{ \rm kVA})^2 - (8.26 \text{ \rm kW})^2} = 11.58 \text{ \rm kVar} \end{aligned}$$

Fig. 17: Load in Wye connection (Four-Wire System)



For Symmetric Load

In the case of a symmetric load, the situation and the formulas get much simpler:

1. The **phase-voltages** U_{L} and star-voltages $U_{\text{Y}} = U_{\text{S}}$ are related by: $U_{\text{L}} = \sqrt{3} \cdot U_{\text{S}}$ (equal to the asymmetric load).
2. For equal impedances the absolute value of all **phase currents** I_x are the same: $|\underline{I}_x| = |\underline{I}_{\text{S}}| = \left| \frac{\underline{U}_{\text{S}}}{\underline{Z}_{\text{S}}} \right|$.

Since the phase currents have the same absolute value and have the same φ , they will add up to zero. Therefore there is no current on the neutral line: $I_{\text{N}} = 0$

3. The **true power** is three times the true power of a single phase: $P = 3 \cdot U_{\text{S}} \cdot I_{\text{S}} \cdot \cos \varphi$.

Based on the line voltages U_{L} , the formula is $P = \sqrt{3} \cdot U_{\text{L}} \cdot I_{\text{S}} \cdot \cos \varphi$

4. The **(collective) apparent power** - given the formula above - is: $S_{\Sigma} = \sqrt{3} \cdot U_{\text{S}} \cdot \sqrt{3 \cdot I_{\text{S}}^2} = 3 \cdot U_{\text{S}} \cdot I_{\text{S}}$.

This corresponds to three times the apparent power of a single phase.

5. The **reactive power** leads to: $Q_{\Sigma} = \sqrt{S_{\Sigma}^2 - P^2} = 3 \cdot U_{\text{S}} \cdot I_{\text{S}} \cdot \sin \varphi$.

Load in Wye connection with (Three-Wire System)

The three-wire system is used the four pins L_1 , L_2 , L_3 , and the neutral line N is used for power transfer. Sometimes the load does not provide a neutral connection, even when it is in a Wye connection - the star point can for example only be provided for measurement with a thin cable. Additionally, the neutral connection of a load in a Wye connection can break and lead to a three-wire system.

In the case of a three-wire system, only the potentials L_1 , L_2 , and L_3 are provided and used for power transfer.

Example

The example in the following simulation shows a 50 Hz / 231 V three-phase three-wire system with an unbalanced load in the Wye connection, with the given impedances.

- Calculate the phase currents I_1 , I_2 , I_3 , the neutral current I_{N}
- Calculate the true power, apparent power, and reactive power.

The following simulation has the same impedances in the load, but the load does not provide a neutral connection.

Voltages - Currents - True Power - Apparent and Reactive Power

The simulation differs in the following:

- The network star-voltages $\underline{U}_{1\text{N}}$, $\underline{U}_{2\text{N}}$,

$\underline{U}_{\text{3N}}$ related to the neutral potential \underline{U}_{N} , and the load string voltages (= load star-voltages) $\underline{U}_{\text{1S}}$, $\underline{U}_{\text{2S}}$, $\underline{U}_{\text{3S}}$ related to the star potential of the load are separated.

- The star point voltage $\underline{U}_{\text{SN}}$ from the potential of node S star point to N neutral is shown.
- With the switch S , the star potential can short-circuited to the neutral potential; so set $\underline{U}_{\text{SN}}=0$. This enables a comparison with the previous four-wire three-phase system.

Also here, the “path”: calculate voltages \rightarrow calculate currents \rightarrow calculate true power \rightarrow calculate apparent and reactive power is the best way to get to all wanted values.

1. **Voltages:** Here, only the phase voltages ($\underline{U}_{\text{12}}$, $\underline{U}_{\text{23}}$, $\underline{U}_{\text{31}}$) are applied by the three-phase net, independently of the load. The star-voltages of the load $\underline{U}_{\text{xS}}$ are not given by the network anymore since the neutral potential is not provided. The network star-voltages and the load star-voltages can be connected in the following way: The calculation of the star-voltage $\underline{U}_{\text{SN}}$ is explained after investigating the currents.

$$\begin{aligned} \underline{U}_{\text{1S}} &= \underline{U}_{\text{1N}} - \underline{U}_{\text{SN}} \\ \underline{U}_{\text{2S}} &= \underline{U}_{\text{2N}} - \underline{U}_{\text{SN}} \\ \underline{U}_{\text{3S}} &= \underline{U}_{\text{3N}} - \underline{U}_{\text{SN}} \end{aligned}$$

2. **Currents:** For the phase currents it applies that: $\underline{I}_1 + \underline{I}_2 + \underline{I}_3 = 0$ (again, voltages given in the simulation are only the RMS value without the phase shift).

The phase currents are given by the phase impedances and the star-voltages:

$$\begin{aligned} \underline{I}_1 &= \frac{\underline{U}_{\text{1S}}}{\underline{Z}_1} \quad , \quad \underline{I}_2 = \frac{\underline{U}_{\text{2S}}}{\underline{Z}_2} \quad , \quad \underline{I}_3 = \frac{\underline{U}_{\text{3S}}}{\underline{Z}_3} \end{aligned}$$

To get $\underline{U}_{\text{SN}}$, one has to combine the individual formulas for \underline{I}_x , $\underline{U}_{\text{xS}}$ and that the $\sum_x \underline{I}_x = 0$. This leads to

$$\underline{U}_{\text{SN}} = \left(\sum_x \frac{\underline{U}_{\text{xS}}}{\underline{Z}_x} \right) \cdot \left(\sum_x \frac{1}{\underline{Z}_x} \right)^{-1}$$

3. Also here, the **true power** P_x for each string is given by:

$$P_x = S_x \cdot \cos \varphi_x = U_{\text{S}} \cdot I_x \cdot \cos \varphi_x$$

Also here, the resulting true power for the full load is (with U_{S} as the RMS value of the network star-voltage):

$$P = U_{\text{S}} \cdot (I_1 \cdot \cos \varphi_1 + I_2 \cdot \cos \varphi_2 + I_3 \cdot \cos \varphi_3)$$

$$+ I_3 \cdot \cos(\varphi_3) \quad \text{\&= } U_{\text{S}} \cdot \left(I_1 \cdot \cos(\varphi_{u,1} - \varphi_{i,1}) + I_2 \cdot \cos(\varphi_{u,2} - \varphi_{i,2}) + I_3 \cdot \cos(\varphi_{u,3} - \varphi_{i,3}) \right) \text{\end{align*}}$$

4. Since the three-wire system has no current out of the network star point, the **apparent power** \underline{S}_x for each string is given by the string voltage and the current through the string $\underline{S}_x = U_x \cdot \underline{I}_x$. This leads to an overall apparent power \underline{S} of

$$\underline{S} = P + jQ = \sum_x \underline{S}_x = \sum_x \left(\underline{U}_x \cdot \underline{I}_x \right)$$

In order to simplify the calculation, it would be better to have a formula based on the network star-voltages:

$$\underline{S} = \sum_x \left(\underline{U}_x \cdot \underline{I}_x \right) + \underline{U}_x \cdot \underline{I}_x \quad \text{\&= } \sum_x \left(\underline{U}_x \cdot \underline{I}_x \right) \quad \text{\&= } \sum_x \left(\underline{U}_x \cdot \underline{I}_x \right) \quad \text{\&= } \sum_x \left(\underline{U}_x \cdot \underline{I}_x \right)$$

Given that $\sum_x \underline{I}_x = 0$, it is also true, that $\sum_x \underline{I}_x = 0$ and so $\underline{I}_3 = -\underline{I}_1 - \underline{I}_2$.

By this, one can further simplify the calculation for the apparent power down to

$$\underline{S} = \underline{U}_{12} \cdot \underline{I}_1 + \underline{U}_{23} \cdot \underline{I}_2 \quad \text{\&= } \underline{U}_{12} \cdot \underline{I}_1 + \underline{U}_{23} \cdot \underline{I}_2 \quad \text{\&= } \underline{U}_{12} \cdot \underline{I}_1 + \underline{U}_{23} \cdot \underline{I}_2$$

For the phase voltages it applies that: $\underline{U}_{12} = -\underline{U}_{21}$, $\underline{U}_{23} = -\underline{U}_{32}$, $\underline{U}_{31} = -\underline{U}_{13}$. For the **collective apparent power**, S_Σ the formula differs in the definition (to consider the reactive part more for an unbalanced generator). Since we consider here a given balanced network the definition leads to a similar result as based on the four-wire connection:

$$S_\Sigma = \sqrt{\frac{1}{2}} \cdot (U_{12}^2 + U_{23}^2 + U_{31}^2) \cdot \sqrt{\sum_x I_x^2} = \sqrt{3} \cdot U_{\text{S}} \cdot \sqrt{\sum_x I_x^2}$$

5. The absolute **reactive power** Q can be calculated by the apparent power:

$$jQ = \underline{S} - P$$

the **collective reactive power** Q_Σ is given by the collective apparent power:

$$Q = \sqrt{S_\Sigma^2 - P^2}$$

Example

In the example, this leads to:

- The phase voltages are given as $U_{\text{L}} = \sqrt{3} \cdot 231 \text{ V} = 400 \text{ V} = U_{12} = U_{23} = U_{31}$
The phasors of the star-voltages of the network are again given as

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2. Based on the star-voltages of the network and the given impedances the star-voltage $\underline{U}_{\text{SN}}$ of the load can be calculated with:

$$\underline{U}_{\text{SN}} = \frac{\sum_x \left(\frac{1}{\underline{Z}_x} \cdot \underline{U}_x \right)}{\sum_x \left(\frac{1}{\underline{Z}_x} \right)}$$

Once investigating the numerator $\sum_x \left(\frac{1}{\underline{Z}_x} \cdot \underline{U}_x \right)$, once can see, that it just equals the sum of the phase currents of the four-wire system. So, the numerator equals the (in the three-wire system: fictive) current on the neutral line.

The numerator is therefore: $22.88 \text{ A} + j \cdot 4.77 \text{ A}$ (see calculation for the four-wire system).

The denominator is:

$$\sum_x \left(\frac{1}{\underline{Z}_x} \right) = \frac{1}{10 \text{ } \Omega + j \cdot 2\pi \cdot 50 \text{ Hz} \cdot 1 \text{ mH}} + \frac{1}{5 \text{ } \Omega + j \cdot 2\pi \cdot 50 \text{ Hz} \cdot 100 \text{ } \mu\text{F}} + \frac{1}{20 \text{ } \Omega} = 0.1547 \text{ } \Omega^{-1} + j \cdot 0.02752 \text{ } \Omega^{-1}$$

The star-voltage $\underline{U}_{\text{SN}}$ of the load is:
$$\underline{U}_{\text{SN}} = \frac{22.88 \text{ A} + j \cdot 4.77 \text{ A}}{0.1547 \text{ } \Omega^{-1} + j \cdot 0.02752 \text{ } \Omega^{-1}} = 148.7 \text{ V} + j \cdot 4.41 \text{ V}$$

Given this star-voltage $\underline{U}_{\text{SN}}$ of the load, the phase currents are:

$$\begin{aligned} \underline{I}_1 &= \frac{\underline{U}_{1N} - \underline{U}_{\text{SN}}}{\underline{Z}_1} = \frac{231 \text{ V} - 148.7 \text{ V} - j \cdot 4.41 \text{ V}}{10 \text{ } \Omega + j \cdot 2\pi \cdot 50 \text{ Hz} \cdot 1 \text{ mH}} = 8.21 \text{ A} - j \cdot 0.70 \text{ A} = 8.24 \text{ A} \angle -4.9^\circ \\ \underline{I}_2 &= \frac{\underline{U}_{2N} - \underline{U}_{\text{SN}}}{\underline{Z}_2} = \frac{231 \text{ V} \cdot \left(-\frac{1}{2} - j \cdot \frac{1}{2} \sqrt{3} \right) - 148.7 \text{ V} - j \cdot 4.41 \text{ V}}{5 \text{ } \Omega + j \cdot 2\pi \cdot 50 \text{ Hz} \cdot 100 \text{ } \mu\text{F}} = 5.00 \text{ A} + j \cdot 9.08 \text{ A} = 10.36 \text{ A} \angle -61.2^\circ \\ \underline{I}_3 &= \frac{\underline{U}_{3N} - \underline{U}_{\text{SN}}}{\underline{Z}_3} = \frac{231 \text{ V} \cdot \left(-\frac{1}{2} + j \cdot \frac{1}{2} \sqrt{3} \right) - 148.7 \text{ V} - j \cdot 4.41 \text{ V}}{20 \text{ } \Omega} = -13.21 \text{ A} + j \cdot 9.78 \text{ A} = 16.44 \text{ A} \angle +143.5^\circ \end{aligned}$$

3. The true power is calculated by:

$$P = 231 \text{ V} \cdot \left(8.24 \text{ A} \cdot \cos(0^\circ - (-4.9^\circ)) + 10.36 \text{ A} \cdot \cos(-120^\circ - (-61.2^\circ)) + 16.44 \text{ A} \cdot \cos(-240^\circ - (+143.5^\circ)) \right) = 6.62 \text{ kW}$$

$\{\sim\mathrm{kW}\} \end{align*}$

4. The apparent power \underline{S} is:

$$\begin{aligned} \underline{S} &= \underline{U}_{13} \cdot \underline{I}_1^* + \underline{U}_{23} \cdot \underline{I}_2^* = 400\{\sim\mathrm{V}\} \cdot (-\{\mathrm{j}\} \cdot \mathrm{e}^{-\{\mathrm{j}\}} \cdot \frac{7}{6} \pi) \cdot (8.21\{\sim\mathrm{A}\} + \{\mathrm{j}\} \cdot 0.70\{\sim\mathrm{A}\}) + \{\mathrm{e}\}^{-\{\mathrm{j}\}} \cdot \frac{3}{6} \pi \cdot (5.00\{\sim\mathrm{A}\} - \{\mathrm{j}\} \cdot 9.08\{\sim\mathrm{A}\}) = 6.62\{\sim\mathrm{kW}\} - \{\mathrm{j}\} \cdot 3.40\{\sim\mathrm{kVAr}\} \\ &= \underline{U}_{12} \cdot \underline{I}_1^* + \underline{U}_{32} \cdot \underline{I}_3^* = 400\{\sim\mathrm{V}\} \cdot (\{\mathrm{e}\}^{\{\mathrm{j}\}} \cdot \frac{1}{6} \pi \cdot (8.21\{\sim\mathrm{A}\} + \{\mathrm{j}\} \cdot 0.70\{\sim\mathrm{A}\}) - \{\mathrm{e}\}^{-\{\mathrm{j}\}} \cdot \frac{3}{6} \pi \cdot (-13.21\{\sim\mathrm{A}\} - \{\mathrm{j}\} \cdot 9.78\{\sim\mathrm{A}\})) + 400\{\sim\mathrm{V}\} \cdot (-\{\mathrm{j}\} \cdot \frac{1}{6} \pi \cdot (5.00\{\sim\mathrm{A}\} - \{\mathrm{j}\} \cdot 9.08\{\sim\mathrm{A}\}) + \{\mathrm{e}\}^{-\{\mathrm{j}\}} \cdot \frac{7}{6} \pi \cdot (-13.21\{\sim\mathrm{A}\} - \{\mathrm{j}\} \cdot 9.78\{\sim\mathrm{A}\})) = 6.62\{\sim\mathrm{kW}\} - \{\mathrm{j}\} \cdot 3.40\{\sim\mathrm{kVAr}\} \quad \& = 7.44\{\sim\mathrm{kVA}\} \quad \angle -27.2^\circ \end{aligned}$$

The collective apparent power is:

$$S_{\Sigma} = \sqrt{3} \cdot U_{\mathrm{S}} \cdot \sqrt{\sum_x |I_x|^2} = \sqrt{3} \cdot 231\{\sim\mathrm{V}\} \cdot \sqrt{(8.24\{\sim\mathrm{A}\})^2 + (10.36\{\sim\mathrm{A}\})^2 + (16.44\mathrm{A})^2} = 8.45\{\sim\mathrm{kVA}\}$$

5. The reactive power is:

$$Q = -\{\mathrm{j}\} \cdot (\underline{S} - P) = -3.40\{\sim\mathrm{kVAr}\}$$

The collective reactive power is:

$$Q_{\Sigma} = \sqrt{(8.44\{\sim\mathrm{kVA}\})^2 - (6.62\{\sim\mathrm{kW}\})^2} = 5.24\{\sim\mathrm{kVAr}\}$$

Fig. 18: Load in Wye connection (Three-Wire System)



For Symmetric Load

The case of a symmetric load in a three-wire system equals the symmetric load in a four-wire system since the symmetric four-wire system also does not show a current on the neutral line.

Load in Delta connection

The delta connection uses also a three-wire system like the Wye connection without the neutral line. Internally, the load is now connected in a triangular shape. Therefore the individual string currents differ from the individual phase currents. This setup is for the example given for motors when higher torque is needed. In this connection, each string sees $U_{\text{L}} = \sqrt{3} \cdot U_{\text{S}}$ and can therefore produce more current and more power.

In the case of a delta connection, also only the potentials L1 , L2 , and L3 are provided and used for power transfer.

Example

The example in the following simulation shows a 50 Hz / 231 V three-phase three-wire system with an unbalanced load in delta connection, with the given impedances.

- Calculate the phase currents I_1 , I_2 , I_3 , the neutral current I_{N}
- Calculate the true power, apparent power, and reactive power.

The following simulation has the same impedances in the load, but the load does not provide a neutral connection.

Voltages - Currents - True Power - Apparent and Reactive Power

The simulation differs in the following:

- The strings of the load are now connected to two phases and not to a star point anymore.
- The network phase voltages \underline{U}_{12} , \underline{U}_{23} , \underline{U}_{31} equals to the string voltages of the load.
- The star point that the voltages are toward is in this case not relevant, and cannot be connected in any way to the strings.

Again here the “path”: calculate voltages \rightarrow calculate currents \rightarrow calculate true power \rightarrow calculate apparent and reactive power is the best way to get to all wanted values.

1. **Voltages:** Here, the string voltages of the load are applied by the three-phase net:

$$\begin{aligned} \underline{U}_{12} &= U_{\text{L}} \cdot e^{j\omega t} \\ \underline{U}_{23} &= U_{\text{L}} \cdot e^{j(\omega t - 120^\circ)} \\ \underline{U}_{31} &= U_{\text{L}} \cdot e^{j(\omega t - 240^\circ)} \end{aligned}$$

2. **Currents:** For the phase currents one can focus on the nodes between the phase lines

and the strings. An incoming single-phase current onto a node divides into two string currents:

$$\begin{aligned} \underline{I}_1 &= \underline{I}_{12} - \underline{I}_{31} \\ \underline{I}_2 &= \underline{I}_{23} - \underline{I}_{12} \\ \underline{I}_3 &= \underline{I}_{31} - \underline{I}_{23} \end{aligned}$$

The string currents can be calculated by the string voltages and the impedances:

$$\begin{aligned} \underline{I}_{12} &= \frac{\underline{U}_{12}}{\underline{Z}_{12}} \quad , \quad \underline{I}_{23} = \frac{\underline{U}_{23}}{\underline{Z}_{23}} \quad , \quad \underline{I}_{31} = \frac{\underline{U}_{31}}{\underline{Z}_{31}} \end{aligned}$$

- Also here, the **true power** can be calculated by adding up the true power of each phase. The faster way (as shown before) is to add up the (complex) apparent power.
- The **apparent power** \underline{S}_x here is again the sum the (complex) apparent power for each string:

$$\underline{S} = \underline{U}_{12} \cdot \underline{I}_{12}^* + \underline{U}_{23} \cdot \underline{I}_{23}^* + \underline{U}_{31} \cdot \underline{I}_{31}^*$$

Since \underline{U}_{12} , \underline{U}_{23} , and \underline{U}_{31} are given by the three-phase network, a further simplification lead to:

$$\underline{S} = P + j \cdot Q = U_{\text{L}}^2 \cdot \left(\frac{1}{\underline{Z}_{12}^*} + \frac{1}{\underline{Z}_{23}^*} + \frac{1}{\underline{Z}_{31}^*} \right)$$

The **collective apparent power** \underline{S}_{Σ} here is the same as for the three-wire or four-wire connection.

In the Delta connection the phase currents I_x have to be calculated since the formula only applies to them:

$$\underline{S}_{\Sigma} = \sqrt{\frac{1}{3}} (U_{12}^2 + U_{23}^2 + U_{31}^2) \cdot \sqrt{\sum_x I_x^2} = U_{\text{L}} \cdot \sqrt{\sum_x I_x^2}$$

- The absolute **reactive power** Q can be calculated by the apparent power:

$$j \cdot Q = \underline{S} - P$$

the **collective reactive power** Q_{Σ} is given by the collective apparent power:

$$Q = \sqrt{\underline{S}_{\Sigma}^2 - P^2}$$

Example

In the example, this leads to:

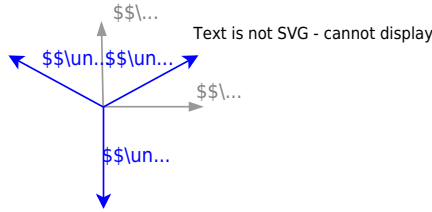
- The phase voltages are given as

$$U_{\text{L}} = \sqrt{3} \cdot 231 \text{ V} = 400 \text{ V} = U_{12} = U_{23} =$$

U_{31}

The phasors of the string voltages of the network are given as

U_{L}



- Based on the string voltages of the network and the given impedances the string currents I_{12} , I_{23} , I_{31} of the load can be calculated:

$$\begin{aligned}
 I_{12} &= \frac{400 \text{ V}}{10 \sqrt{3} + j(2\pi \cdot 50 \cdot 1 \text{ mH})} = 35.24 \text{ A} + j18.90 \text{ A} = 40 \text{ A} \angle 28.2^\circ \\
 I_{23} &= \frac{400 \text{ V}}{5 + j(2\pi \cdot 50 \cdot 100 \mu\text{F})} = 12.27 \text{ A} - j1.93 \text{ A} = 12.42 \text{ A} \angle -8.9^\circ \\
 I_{31} &= \frac{400 \text{ V}}{20 \sqrt{3} + j(2\pi \cdot 50 \cdot 100 \mu\text{F})} = -17.33 \text{ A} + j10.00 \text{ A} = 20.01 \text{ A} \angle 150^\circ
 \end{aligned}$$

By these voltages the phase currents I_x can be calculated:

$$\begin{aligned}
 I_1 &= (35.24 \text{ A} + j18.90 \text{ A}) - (-17.33 \text{ A} + j10.00 \text{ A}) = 52.57 \text{ A} + j8.90 \text{ A} = 53.32 \text{ A} \angle 9.6^\circ \\
 I_2 &= (12.27 \text{ A} - j1.93 \text{ A}) - (35.24 \text{ A} + j18.90 \text{ A}) = -22.98 \text{ A} - j20.83 \text{ A} = 31.01 \text{ A} \angle -137.8^\circ \\
 I_3 &= (-17.33 \text{ A} + j10.00 \text{ A}) - (12.27 \text{ A} - j1.93 \text{ A}) = -29.59 \text{ A} + j11.93 \text{ A} = 31.90 \text{ A} \angle 158.0^\circ
 \end{aligned}$$

- The true power is calculated by:

$$P = 231 \text{ V} \cdot (53.32 \text{ A} \cdot \cos(0^\circ - 9.6^\circ) - 31.01 \text{ A} \cdot \cos(-120^\circ - (-137.8^\circ)) + 31.90 \text{ A} \cdot \cos(-240^\circ - (+158.0^\circ))) = 24.77 \text{ kW}$$

- The apparent power S is:

$$\begin{aligned}
 S &= U_{13} \cdot I_1^* + U_{23} \cdot I_2^* + U_{32} \cdot I_3^* \\
 &= 400 \text{ V} \cdot (-j8.90 \text{ A}) + 400 \text{ V} \cdot (j20.83 \text{ A}) + 400 \text{ V} \cdot (j11.93 \text{ A}) \\
 &= -j3568 \text{ VA} + j8332 \text{ VA} + j4772 \text{ VA} = j9436 \text{ VA} = 9.44 \text{ kVAR}
 \end{aligned}$$

$$\begin{aligned} & \cdot (-29.59 \text{ A} - j \cdot 11.93 \text{ A})) = 24.77 \text{ kW} - j \cdot 4.41 \text{ kVAR} \\ & \underline{U}_{21} \cdot \underline{I}_2^* + \underline{U}_{31} \cdot \underline{I}_3^* = 400 \text{ V} \cdot (-j \cdot \frac{1}{6} \pi \cdot (-22.98 \text{ A} + j \cdot 20.83 \text{ A}) + e^{-j \cdot \frac{7}{6} \pi} \cdot (-29.59 \text{ A} - j \cdot 11.93 \text{ A})) = 24.77 \text{ kW} - j \cdot 4.41 \text{ kVAR} \end{aligned}$$

The collective apparent power is:

$$\begin{aligned} S_{\Sigma} &= U_L \cdot \sqrt{\sum_x I_x^2} = \sqrt{3} \cdot 231 \text{ V} \cdot \sqrt{(53.32 \text{ A})^2 + (31.01 \text{ A})^2 + (31.90 \text{ A})^2} = 27.78 \text{ kVA} \end{aligned}$$

5. The reactive power is:

$$Q = \underline{S} - P = -4.41 \text{ kVAR}$$

The collective reactive power is:

$$Q_{\Sigma} = \sqrt{(27.78 \text{ kVA})^2 - (24.77 \text{ kW})^2} = 12.59 \text{ kVAR}$$

Fig. 19: Load in Delta connection



Overview of the Power in different Connections

Fig. 20: Overview of the Power in different Connections

$$\frac{1}{R_s + j \cdot X_{Ls}} \parallel \frac{1}{R_p - j} \\ \frac{1}{X_{Lp}} = \frac{R_s - j \cdot X_{Ls}}{R_s^2 + X_{Ls}^2} \parallel \\ \frac{Z \cdot \cos \varphi - j \cdot Z \cdot \sin \varphi}{Z^2} \parallel \frac{\cos \varphi - j \cdot \sin \varphi}{Z} \parallel \end{align*}$$

Therefore

Now, the real and imaginary part is analyzed individually. First the real part:

$$\begin{align*} \frac{1}{R_p} = \frac{\cos \varphi}{Z} \parallel \rightarrow R_p \\ = \frac{Z}{\cos \varphi} = \frac{46 \text{ } \sim \Omega}{\cos 60^\circ} \end{align*}$$

$$\begin{align*} \frac{1}{X_{Lp}} = \frac{\sin \varphi}{Z} \parallel \rightarrow X_{Lp} \\ = \frac{Z}{\sin \varphi} = \frac{46 \text{ } \sim \Omega}{\sin 60^\circ} \parallel \rightarrow L_p \\ = \frac{46 \text{ } \sim \Omega}{2\pi \cdot 50 \text{ } \sim \text{Hz} \cdot \sin 60^\circ} \end{align*}$$

Exercise 7.1.2 Power and Power Factor II

A magnetic coil shows at a frequency of $f=50.0 \text{ } \sim \text{Hz}$ the voltage of $U=115 \text{ } \sim \text{V}$ and the current $I=2.60 \text{ } \sim \text{A}$ with a power factor of $\cos \varphi = 0.30$

1. Calculate the real power, the reactive power, and the apparent power.
2. Draw the equivalent parallel circuit. Calculate the active and reactive part of the current.
3. Draw the equivalent series circuit. Calculate the ohmic and inductive impedance and the value of the inductivity.

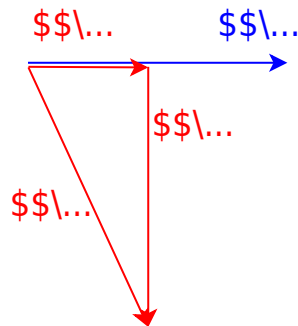
Result for 1.

$$\begin{align*} \text{The real power is } P &= U \cdot I \cdot \cos \varphi \parallel = 115 \text{ } \sim \text{V} \cdot \\ &2.6 \text{ } \sim \text{A} \cdot 0.3 \parallel = 89.7 \text{ } \sim \text{W} \end{align*}$$

$$\begin{align*} \text{The reactive power is } Q &= U \cdot I \cdot \sin \varphi \parallel = 115 \text{ } \sim \text{V} \\ &\cdot 2.6 \text{ } \sim \text{V} \cdot \sqrt{1 - 0.3^2} \parallel = 285 \text{ } \sim \text{Var} \end{align*}$$

$$\begin{align*} \text{The apparent power is } S &= U \cdot I \parallel = 115 \text{ } \sim \text{V} \cdot 2.6 \text{ } \sim \text{A} \parallel \\ &= 299 \text{ } \sim \text{VA} \end{align*}$$

Result for 2.



The complex current \underline{I} is given as:

$$\underline{I} = I_R + j I_L \quad \text{and} \quad I = I \cos \varphi - j I \sin \varphi$$

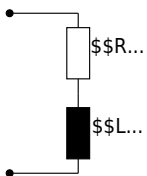
The active and reactive part of the current is therefore:

$$I_R = 2.60 \text{ A} \cdot 0.30 = 0.78 \text{ A} \quad \text{and} \quad I_L = -2.60 \text{ A} \cdot \sqrt{1 - 0.30^2} = 2.48 \text{ A}$$

Result for 3.

Important: The cosine function is ambiguous! Based on $\cos \varphi = 0.30$ it is unclear, whether φ is positive or negative.

Therefore, only based on the power factor it is unclear whether the circuit is ohmic-inductive or ohmic-capacitive! However, this is explicitly given in the problem definition.



$$Z_s = \frac{U}{I} = \frac{115 \text{ V}}{2.60 \text{ A}} = 44.2 \text{ } \Omega \quad R_s = \frac{U}{I} \cos \varphi = \frac{115 \text{ V}}{2.60 \text{ A}} \cdot 0.30 = 13.3 \text{ } \Omega \quad X_{Ls} = \frac{U}{I} \sin \varphi = \frac{115 \text{ V}}{2.60 \text{ A}} \cdot \sqrt{1 - 0.30^2} = 42.2 \text{ } \Omega \quad L_s = 134 \text{ mH}$$

Exercise 7.1.3 Power and Power Factor III

A consumer is connected to a $220\text{ V} / 50\text{ Hz}$ network. A current of 20.0 A and a power of 1800 W is measured.

1. What is the value of the active power, the reactive power, and the power factor?
2. Assume that the consumer is a parallel circuit.
 1. Calculate the resistance and reactance.
 2. Calculate the necessary inductance/capacitance.
3. Assume that the consumer is a series circuit.
 1. Calculate the resistance and reactance.
 2. Calculate the necessary inductance/capacitance.

Result for 1.

The active power is $P = 1.80\text{ kW}$.

The apparent power is $S = U \cdot I = 220\text{ V} \cdot 20\text{ A} = 4.40\text{ kVA}$.

The reactive power is $Q = \sqrt{S^2 - P^2} = \sqrt{(4.40\text{ kVA})^2 - (1.80\text{ kW})^2} = 4.01\text{ kVar}$

The power factor is $\cos \varphi = \frac{P}{S} = \frac{1.80\text{ kW}}{4.40\text{ kVA}} = 0.41$.

Result for 2.

Important: The cosine function is ambiguous! Based on $\cos \varphi = 0.30$ it is unclear, whether φ is positive or negative.

Therefore, only based on the power factor it is unclear whether the circuit is ohmic-inductive or ohmic-capacitive!

The consumer is a parallel circuit of the resistance $R\text{ }\Omega$ and the reactance $X\text{ }\Omega$ on the voltage U . Both values can be calculated based on the real and reactive power:

$$\begin{aligned} P &= \frac{U^2}{R\text{ }\Omega} \rightarrow R_p = \frac{U^2}{P} = 26.9\text{ }\Omega \\ Q &= \frac{U^2}{X\text{ }\Omega} \rightarrow X_p = \frac{U^2}{Q} = 12.1\text{ }\Omega \end{aligned}$$

The respective values for inductance/capacitance are: $L = \frac{X_p}{2\pi \cdot f} = 38.4\text{ mH}$ $C = \frac{1}{2\pi \cdot f \cdot X_p} = 263\text{ }\mu\text{F}$

Result for 3.

The consumer is a series circuit of the resistance $R\text{ }\Omega$ and the reactance $X\text{ }\Omega$ with the current I . Both values can be calculated based on the real and reactive power:

$$\begin{aligned} P &= I^2 \cdot R_{\text{ }\Omega} \rightarrow R_{\text{ }\Omega} = \frac{P}{I^2} = 4.50\text{ }\Omega \\ Q &= I^2 \cdot X_{\text{ }\Omega} \rightarrow X_{\text{ }\Omega} = \frac{Q}{I^2} = 10.0\text{ }\Omega \end{aligned}$$

The respective values for inductance/capacitance are: $L = \frac{X_{\text{ }\Omega}}{2\pi \cdot f} = 31.9\text{ mH}$ $C = \frac{1}{2\pi \cdot f \cdot X_{\text{ }\Omega}} = 318\text{ }\mu\text{F}$

Exercise 7.1.4 Power and Power Factor IV

An uncompensated ohmic-inductive series circuit shows at $U=230\text{ V}$, $f=50\text{ Hz}$ the current $I_{RL}=7\text{ A}$, $P_{RL}=1.3\text{ kW}$

The power factor shall be compensated to $\cos\varphi = 1$ via a parallel compensation.

1. Calculate the apparent power, the reactive power, the phase angle, and the power factor before the compensation.
2. Calculate the capacity C which has to be connected in parallel to get $\cos\varphi=1$.

Solution

$$S = U \cdot I_{RL} \quad Q = \sqrt{S^2 - P_{RL}^2} \quad \varphi = \arctan\left(\frac{Q}{P}\right) = \arccos\left(\frac{P}{S}\right)$$

The inductor L creates the reactive power $Q = Q_L$. To compensate for a equivalent reactive power $|Q_C| = |Q_L|$ has to be given by a capacitor. The reactive power is given by: $Q = \operatorname{Re}(U) \cdot \operatorname{Im}(I) = U \cdot \frac{U}{X} = \frac{U^2}{X}$

$$X_C = \frac{U^2}{Q_L} = \frac{1}{\omega C} \quad \rightarrow \quad C = \frac{1}{\omega U^2}$$

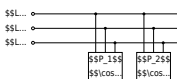
Result

$$S = 1.62\text{ kVA} \quad Q = 0.95\text{ kVAR} \quad \varphi = +36^\circ \quad C = 57.2\text{ }\mu\text{F}$$

Exercise 7.2.1 Three-Phase Load

A three-phase power net with a phase voltage of 400 V has two symmetrical ohmic-inductive loads connected to it. The true power and the power factor are given as follows:

Fig. 21: Three-Phase Net with Two Loads



- Load 1: $P_1 = 2.7\text{ kW}$, $\cos\varphi_1 = 0.89$
- Load 2: $P_2 = 3.8\text{ kW}$, $\cos\varphi_2 = 0.76$

1. Calculate the reactive power Q_1 and Q_2 .

Solution

First, calculate the apparent power:
$$\begin{aligned} P_1 &= S_1 \cos \varphi_1 \quad \rightarrow S_1 = \frac{1}{\cos \varphi_1} \cdot P_1 = \frac{1}{0.89} \cdot 2.7 \text{ kW} = 3.0 \text{ kVA} \\ P_2 &= S_2 \cos \varphi_2 \quad \rightarrow S_2 = \frac{1}{\cos \varphi_2} \cdot P_2 = \frac{1}{0.76} \cdot 3.8 \text{ kW} = 5.0 \text{ kVA} \end{aligned}$$

For calculating the reactive power, $\sin \varphi_{1,2}$ are needed. There are different ways to get this:

- One way would be to calculate $\varphi_{1,2}$ first from $\arccos(\cos \varphi_{1,2})$
- Another way is to use the formula $1^2 = \sin^2 \varphi_{1,2} + \cos^2 \varphi_{1,2}$.

$$\begin{aligned} Q_1 &= S_1 \sqrt{1 - \cos^2 \varphi_1} = 3.0 \text{ kVA} \sqrt{1 - 0.89^2} = 1.4 \text{ kVAr} \\ Q_2 &= S_2 \sqrt{1 - \cos^2 \varphi_2} = 5.0 \text{ kVA} \sqrt{1 - 0.76^2} = 3.2 \text{ kVAr} \end{aligned}$$

Result

$$Q_1 = 1.4 \text{ kVAr} \quad Q_2 = 3.2 \text{ kVAr}$$

2. Which (complex) apparent power does the net have to provide for both loads combined?
Solution

$$\begin{aligned} \underline{S}_{\text{net}} &= \underline{S}_1 + \underline{S}_2 = (P_1 + jQ_1) + (P_2 + jQ_2) = (2.7 \text{ kW} + 3.8 \text{ kW}) + j(1.4 \text{ kVAr} + 3.2 \text{ kVAr}) \\ &= 6.5 \text{ kW} + j4.6 \text{ kVAr} = P_{\text{net}} + jQ_{\text{net}} \end{aligned}$$

As a complex value in Euler representation:
$$\begin{aligned} \underline{S}_{\text{net}} &= \sqrt{P_{\text{net}}^2 + Q_{\text{net}}^2} \cdot e^{j \arctan\left(\frac{Q_{\text{net}}}{P_{\text{net}}}\right)} \\ &= \sqrt{(6.5 \text{ kW})^2 + (4.6 \text{ kVAr})^2} \cdot e^{j \arctan\left(\frac{4.6}{6.5}\right)} = 8.0 \text{ kVA} \cdot e^{j 35^\circ} \end{aligned}$$

Result

$$\underline{S}_{\text{net}} = 6.5 \text{ kW} + j4.6 \text{ kVAr} = 8.0 \text{ kVA} \cdot e^{j 35^\circ}$$

3. Calculate the RMS value of the single-phase current I which the power net has to provide.

Solution

The apparent power S_{net} is given by $S_{\text{net}} = 3 \cdot U \cdot I$, with U as

the star-voltage $U_Y = \frac{1}{\sqrt{3}} \cdot U_{\text{L}}$.

Therefore, the single-phase current I can be calculated from S_{net} :
$$S_{\text{net}} = 3 \cdot U \cdot I = \sqrt{3} \cdot U_{\text{L}} \cdot I$$

The current is:
$$I = \frac{S_{\text{net}}}{\sqrt{3} \cdot U_{\text{L}}} = \frac{8.0 \text{ kVA}}{\sqrt{3} \cdot 400 \text{ V}} = 12 \text{ A}$$

Result

$$I = 12 \text{ A}$$

4. What is the overall power factor $\cos\varphi_{\text{net}}$ of the power net?

Solution

The overall power factor can be calculated from the apparent power and its angle φ_{net} (see the Euler representation in task 2).

$$\cos\varphi_{\text{net}} = \cos(35^\circ) = 0.82$$

Result

$$\cos\varphi_{\text{net}} = 0.82$$

Exercise E7.2.2 Motor on 3-Phase System I

A three-phase motor is connected to an artificial three-phase system and can be configured in wye or delta configuration.

- The voltage measured on a single coil shall always be 230 V .
- The current measured on a single coil shall always be 10 A .
- The phase shift for every string is 25°

1. The motor shall be in wye configuration.

Write down the string voltage, phase voltage, string current, phase current, and active power

2. The motor shall be in delta configuration.

Write down the string voltage, phase voltage, string current, phase current, and active power

3. Compare the results

Exercise E7.2.3 Heater on 3-Phase System

A three-phase heater with given resistors is connected to the $230 \text{ V}/400 \text{ V}$ three-phase system. The heater shows purely ohmic behavior and can be configured in wye

or delta configuration.

1. The heater is configured in a delta configuration and provides a constant heating power of 6 kW .
 1. Calculate the resistor value of a single string in the heater
 2. Calculate the RMS values of the string currents and phase currents.
2. The heater with the same resistors as in 1. is now configured in a wye configuration.
 1. Calculate the RMS values of the string currents and phase currents.
 2. Compare the heating power in delta configuration (1.) and wye configuration (2.)

Exercise E7.2.4 Motor on 3-Phase System II

A three-phase motor is connected to a three-phase system with a phase voltage of 400 V . The phase current is 16 A and the power factor 0.9 . Calculate the active power, reactive power, and apparent power.

Exercise E7.2.5 Motor on 3-Phase System III

A symmetrical and balanced three-phase motor of a production line shall be configured in a star configuration and provide a power of 17 kW with a power factor of 0.75 . The voltage on a single string is measured to be 135 V . Calculate the string current.

Related Links

- [IPES ETHZ](#): interactive display on the field in the motor
- [interactive example of the time course of current, voltage and power](#) in Falstad

1)

For further development: [CalcImpedances](#) [VarResistor](#) [varLC](#) [SineGenerator](#) [full simu](#)

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