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MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY

9. Transformers

9.1 Principle of operation and construction of single-phase transformer

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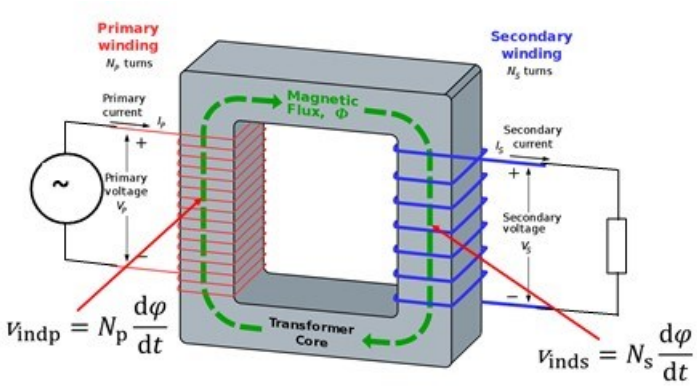
9.3 Three-phase transformers: design, examples of connection, application

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9.1. Principle of operation and construction of single-phase transformer

9.1.1. Principle of operation



The transformer is an electrical device that transfers electrical energy between two circuits through electromagnetic induction. A varying current in the primary winding (connected to the alternating voltage source) of the transformer produces a varying magnetic field (magnetic flux) in the transformer core, which in turn induces a varying electromotive force (emf) or voltage in the secondary winding (connected to the load). Power is transferred without a metallic connection between the two windings. The ideal transformer has core of infinitely high magnetic permeability so that all of the magnetic flux passes through both the primary and secondary windings (https://en.wikipedia.org/wiki/Transformer).

RMS values can be derived from instantaneous induced primary and secondary voltages as:

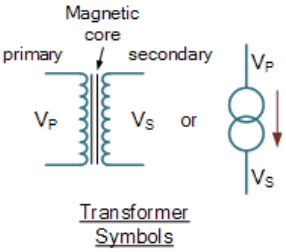
$$V_{\mathrm{indp}} = 4{,}44 f_{\mathrm{p}} N_{\mathrm{p}} \varphi_m \quad \text{and} \quad V_{\mathrm{inds}} = 4{,}44 f_{\mathrm{s}} N_{\mathrm{s}} \varphi_m$$

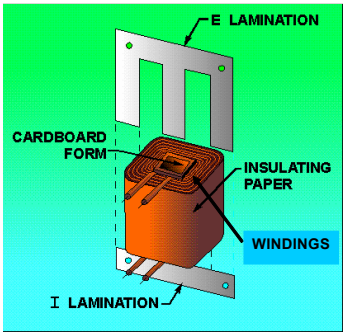
where f is frequency, N number of winding turns, φ_{m} peak value of magnetic flux. Transformer ratio is defined for no-load connection (secondary winding open) as:

$$\frac{V_{\mathrm{indp}}}{V_{\mathrm{inds}}} = \frac{N_{\mathrm{p}}}{N_{\mathrm{s}}} = K$$, for secondary winding closed as: $$S_{\mathrm{p}} = S_{\mathrm{s}} = V_{\mathrm{p}} I_{\mathrm{p}} = V_{\mathrm{s}} I_{\mathrm{s}} = \frac{V_{\mathrm{p}}}{V_{\mathrm{s}}} = \frac{I_{\mathrm{s}}}{I_{\mathrm{p}}} = K$$

The formulas are valid for the ideal transformer when the transformer losses are neglected (G. Rizzoni: Fundamentals of electrical engineering).

9.1.2. Construction of single-phase transformer





Transformer has the core made of high permeability silicon steel. The steel has a permeability many times that of free space and the core confines the flux to a path which closely couples the windings. The core is designed as a laminated made from interleaved stacks of E- and I-shaped steel sheets. The purpose of the lamination is to reduce losses in the magnetic core (hysteresis and eddy-current losses). Windings made from copper varnished conductors (so that each turn of the winding is insulated from every other turn) are usually arranged concentrically to minimize flux leakage. The primary and secondary winding is insulated each other (sheet, paper, cloth...). The complete winding is covered with an insulating paper on its surface. Small transformers are self-cooled by air natural convection (https://en.wikipedia.org/wiki/Transformer).

9.2. Transformer operating conditions

9.2.1. Transformer under no-load

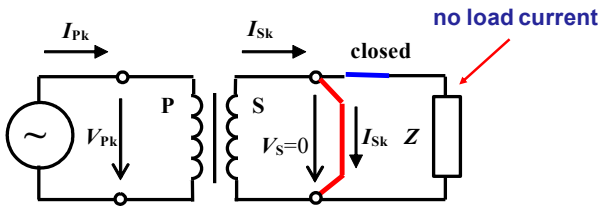
The secondary winding is disconnected. The transformer does not deliver any power to the load. Power withdrawn from the source mainly dissipates in the magnetic core of the transformer where so-called iron losses arises (consists of hysteresis and eddy-current losses). This no-load current is very small and because the copper loss

$$P_{\mathrm{P0}} = \Delta P_{\mathrm{fe}} + R_{\mathrm{P}} I_{\mathrm{P0}}^2 \cong \Delta P_{\mathrm{fe}}$$
$$P_{\mathrm{S}} = 0$$

in the primary is proportional to the square of this current, it is negligible. There is no copper loss in the secondary because there is no secondary current (https://en.wikipedia.org/wiki/Open-circuit_test).

9.2.2. Transformer short-circuit test

The secondary winding is short-circuited. The transformer does not deliver any power to the load. Power withdrawn from the source mainly dissipates in the transformer windings where so called copper losses arises. A short-circuit test for determination of transformer impedance and losses in windings is carried out with winding currents equal to the nominal ones. As the primary voltage applied for the nominal (full load) current in short circuit test on transformer is quite small compared to the rated primary voltage of the transformer, the iron losses in transformer can be taken as negligible. Also the additional losses are negligible (https://en.wikipedia.org/wiki/Short-circuit_test).



$$I_{Pk} = I_{Pn} \rightarrow V_P = V_{Pk}$$

percentage impedance

$$P_K = \Delta P_j + \Delta P_d \cong \Delta P_j$$

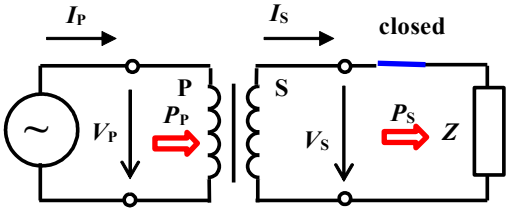
losses in windings

$$\Delta P_{jn} = R_P I_{Pn}^2 + R_S I_{Sn}^2$$

$$z_{pu} = \frac{V_{Pk}}{V_{Pn}} \cdot 100 = \frac{I_{Pn}}{I_{PSC}} \cdot 100$$

9.2.3. Transformer under load

Power is delivered from the transformer secondary winding to the load. Transformer efficiency of the power transmission from the primary side (from the connected source) to the secondary side (to the connected load) is given by the formula as follows:



$$\eta = \frac{P_S}{P_P}$$

$$\Delta P = P_P - P_S \rightarrow \eta = \frac{P_P - \Delta P}{P_P}$$

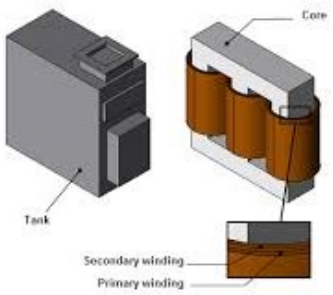
$$\Delta P = \Delta P_{fe} + \Delta P_j$$

$$P_P = V_P I_P \cos\varphi_P$$

where P_p is power withdrawn from the source (on the primary side), P_s power delivered to the load (on the secondary side), ΔP the total losses in the transformer, ΔP_{fe} iron losses, ΔP_j copper losses.

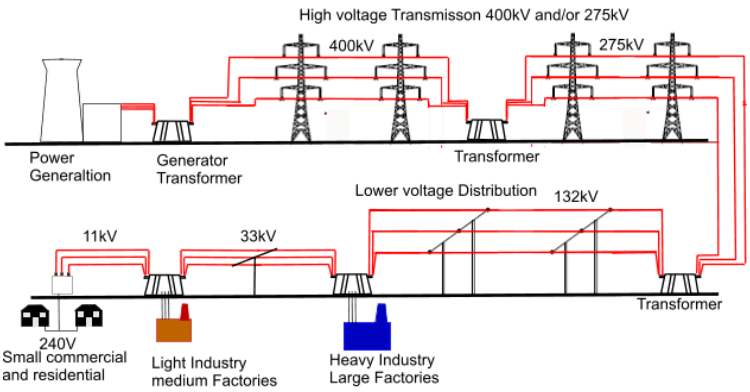
9.3. Three-phase transformers: design, examples of connection, application

A design of the three-phase transformer can be seen from the pictures. Transformers are often cooled by forced-air cooling, forced-oil cooling, water-cooling, or combinations of these. Large transformers are filled with transformer oil that both cools and insulates the windings. The tank of liquid filled transformers often has





radiators through which the liquid coolant circulates by natural convection or fins. Some large transformers employ electric fans or pumps for forced-air cooling. Transformers are provided with high-voltage insulated bushings made of polymers or porcelain. The three-phase windings can be connected into delta, wye (star) for HV and LV side, or zigzag (only for LV side) (https://en.wikipedia.org/wiki/Zigzag_transformer).



Primary winding: HV (delta: D, wye (star): Y)

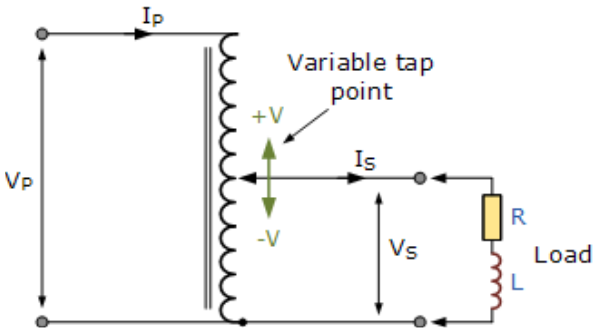
Secondary winding: LV (delta: d, wye (star): y, zigzag: z)

Often used connection: Yy0, Yz1, Dy1, Yd1

9.4. Autotransformer, instrument transformer

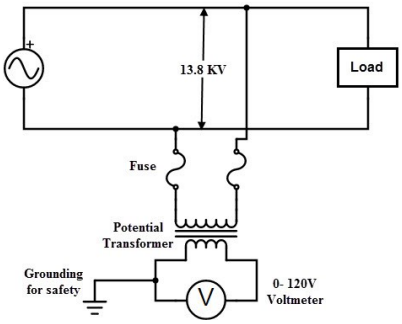
9.4.1. Autotransformer

Autotransformers are often used to step up, or step down voltages (LV to LV, HV to HV). It has one winding (smaller, more economic, cheaper, infinitely adjustable output voltage than ordinary transformer). An autotransformer does not provide electrical isolation between its windings as an ordinary transformer does; a failure of the isolation of the windings of an autotransformer can result in full input voltage applied to the output (https://en.wikipedia.org/wiki/Autotransformer).

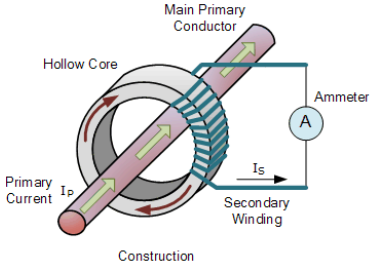


9.4.2. Instrument transformer

Instrument transformers are used to isolate or transform voltage or current levels. The most common usage of instrument transformers is to operate instruments or metering from high voltage or high current circuits, safely isolating secondary control circuitry from the high voltages or currents. The primary winding of the transformer is connected to the high voltage or high current circuit, and the meter or relay is connected to the secondary circuit (https://en.wikipedia.org/wiki/Instrument_transformer).



The voltage (=potential) transformer is used for measuring in HV circuits with output voltage of 100 V or 110 V. It is described by its voltage ratio from primary to secondary. A 1000:110 voltage transformer will provide an output voltage of 110 V when 1000 V are impressed across its primary winding.



The current transformer is used for measuring high currents in LV circuits or in HV circuits with output current 5 A or 1 A. It is often constructed by passing a single primary turn (either an insulated cable or an uninsulated bus bar) through a well-insulated toroidal core wrapped with many turns of wire. A current clamp uses a current transformer with a split core that can be easily wrapped around a conductor in a circuit. This is a common method used in power installations, which cannot be disconnected (an ordinary ammeter cannot be used). It is typically described by its current ratio from primary to secondary. A 1000:5 current transformer will provide an output current of 5 A when 1000 A are flowing through its primary winding.