ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE

Faculty of Electrical Engineering

Power Engineering Department

Power Transformers in Electrical Transmission and Distribution Grids

Bachelor's Thesis

Study programme: Electrical Engineering, Power Engineering and Management

Specialisaion: Applied Electrical Engineering

Supervisor: Ing. Jan Svec, Ph.D.

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Czech Technical University in Prague
Faculty of Electrical Engineering

Department of Electrical Power Engineering

BACHELOR PROJECT ASSIGNMENT

Student: **Aidana Ibatullayeva**

Study programme: Electrical Engineering, Power Engineering and Management
Specialisation: Applied Electrical Engineering

Title of Bachelor Project: **Power Transformers in Electrical Transmission and Distribution Grids**

Guidelines:

Work up the following items to fulfil the assignment:

1. Explain the theory of transformers function and their electrical parameters.
2. Describe transformers construction (materials, components, accessories).
3. Explain basic calculations during transformers operation in ES.
4. Describe special transformer types, their principles and using in ES.

Bibliography/Sources:

[1] Weedy, B.M. et al.: Electric Power Systems. 5th ed. Wiley, 2012. ISBN 978-0-470-68268-5
[2] Electric Power Transformer Engineering. CRC Press, 2004. ISBN 0-8493-1704-5
[3] Beaty, H.W.: Handbook of Electric Power Calculations. McGraw-Hill, 2001. ISBN 0-07-136298-3

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Valid until the end of the summer semester of academic year 2017/2018

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Prague, February 20, 2017

Declaration

I hereby declare that this thesis is the result of my own work and all the sources I used are in the list of references, in accordance with the Methodological Instructions of Ethical Principle in the Preparation of University Thesis.

In Prague, 26.05.2017 Signature……………………..

Acknowledgement

I would like to thank my thesis advisor Ing. Jan Svec who has coordinated me since the beginning and doc. Dr. Ing. Jan Kyncl for guiding and supporting me during the thesis.

I wish to express my sincere gratitude to my parents for their endless love and encouragement through the duration of my studies.

Abstract

This Bachelor thesis is about the basics of Power Transformers, such as construction, electrical parameters, special types and their usage, brief explanation of technical aspects and practical problems in utilization. In the end of work basic calculations during their operation in ES are presented.

Key words

Transformer, construction, transformer cooling, parallel operation, transformer losses.

Abstrakt

Tato bakalářská práce se zabývá základy výkonových transformátorů, jako konstrukce, elektrické parametry, speciální typy a jejich využití, stručné vysvětlení technických aspektů a praktické problémy využití. Na závěr práce jsou prezentovány základní výpočty během jejich provozu .

Klíčová slova

Transformátor , konstrukce, chlazení transformátoru, paralelní provoz, ztráty transformátoru.

Table of contents

1. Introduction

Transformers are important component in our current life and they make large power systems possible. To effectively transfer hundreds of megawatts of power over long distances, very high line voltages are required - in the range of 161 to 1000 kV. However, the highest practical design voltage for large generators is about 25 kV. How can electrical power be generated at 25 kV and transmitted at a much higher voltage? Transformers can provide the solution to this problem. They can step voltages up or down with a very small loss of power. Connecting a step-up transformer between the generator and a transmission line allows the creation of a practical design voltage for the generator and at the same time an effective transmission line voltage. With step-down transformers connected between the transmission line and the various electrical loads connected to it, it is allowed to use the transmitted power at a safe voltage. Without them, it would be impossible to develop large power systems that exist today.

In ideal case, a transformer should not make any changes to the power factor and should have zero internal power loss. If P_1 is the input power for a three-phase transformer and P_2 its output power, the following relationship must be satisfied for an ideal three-phase transformer:

$$\sqrt{3}V_{L1}I_{L1}cos\theta_{\emptyset} = P_1 = P_2 = \sqrt{3}V_{L2}I_{L2}cos\theta_{\emptyset} \quad (1)$$

where,

V_{L1} - line-to-line voltage at the input terminals of the transformer, [V]

I_{L1} - input line current, [A]

V_{L2} - line voltage at the output terminals, [V]

I_{L2} - output line current, [A]

$\theta_{\emptyset}$ - angle between phase current and phase voltage (The angle between phase current and phase voltage is assumed to be unchanged between input and output)

$cos\theta_{\emptyset}$ - power factor.

Then, solving Equation 1 for the current ratio,

$$\frac{I_{L1}}{I_{L2}} = \frac{V_{L2}}{V_{L1}} \quad (2)$$

It is clear that, when the transformer steps up the voltage, it proportionately reduces the current. Since the losses in transmission lines are proportional to square of the line current (I^2R), it is obvious that the high transmission line voltages, which can be obtained with the help of transformers, increase the efficiency of the power system by reducing the line currents.

2. General description of transformer

A transformer is a four-terminal device that transforms an AC input voltage into a higher or lower AC output voltage. It transforms power from a particular circuit to another with no frequency changes regardless of the voltage levels. The transformer consists of three main components: primary winding, which acts as an input, the second coil secondary winding, which acts as the output, and the iron core, which serves to strengthen the magnetic field generated.

Transformer has no internal moving parts, and it transfers energy from one circuit to another by electromagnetic induction. External cooling may include heat exchangers, radiators, fans, and oil pumps. Transformers typically used because a change in voltage is needed. Power transformers are defined as transformers rated 500 kVA and larger (In figure 1 is shown typical power transformer).

Figure 1. Power transformer

Transformers transfer electrical energy between circuits completely insulated from each other and this allows using very high (stepped-up) voltages for transmission lines, resulting in a lower (stepped-down) current. Higher voltage and lower current reduce the required size and cost of transmission lines and reduce transmission losses.

They do not require, as much attention as most other devices; nevertheless, the care and maintenance, which they really require, is absolutely necessary. Because of their reliability, maintenance is sometimes ignored, which reduces service life and sometimes outright failure.

2.1. Principle of operation

The function of the transformer is based on the principle that electrical energy is transferred efficiently by magnetic induction from one circuit to another. When one winding of the transformer is energized from an AC source, an alternating magnetic field is installed in the transformer core. Alternating magnetic lines of force, which circulate through the core, are called "flux". With a second winding around the same core, voltage is induced by the alternating flux lines. A circuit, connected to the terminals of the second winding, results in current flow.

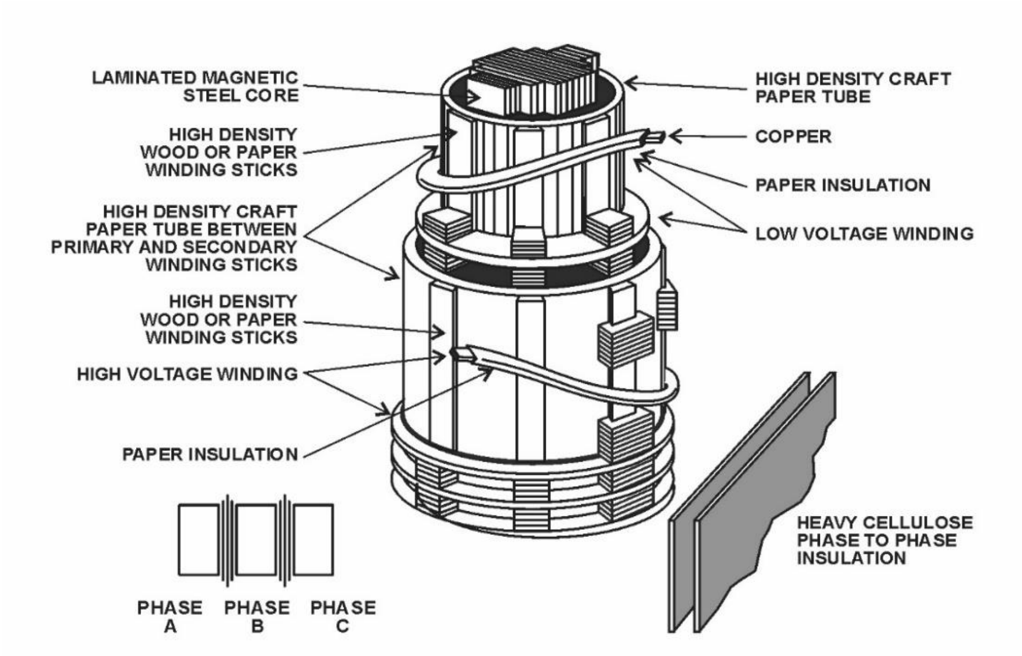


Figure 2. Transformer Construction

Each phase of a transformer consists of two separate coil windings, wound on a common core. The low-voltage winding is located closer to the core; the high-voltage winding is then placed around the low voltage winding and core. We can see from figure 2 internal construction of one phase. The core is usually made from very thin steel laminations, each of which is covered with insulation. Isolation between individual laminations reduces losses. The steel core provides a low resistance path for magnetic flux. High-voltage and low-voltage windings are isolated from the core and from each other, and leads are brought out through insulating bushings. A three-phase transformer typically has a core with three legs and has around each leg both high-voltage and low-voltage windings. For insulation and internal structural support are used special paper and wood.

2.2. Principle of working

Basically, a transformer is very simple static (or stationary) electro-magnetic passive electrical device that works on the principle of Faraday's law of induction by converting electrical energy from one value to another. Actually, mutual induction between two or more winding is responsible for transformation action in an electrical transformer. **Faraday's Laws of Electromagnetic Induction (second law)** states that the magnitude of emf (E) induced in the coil is equal to the rate of change of flux that linkages with the coil. The flux linkage of the coil is the product of number of turns in the coil and flux associated with the coil.

$$-E = U = \frac{d\psi}{dt} = N\frac{d\phi}{dt} \qquad (3)$$

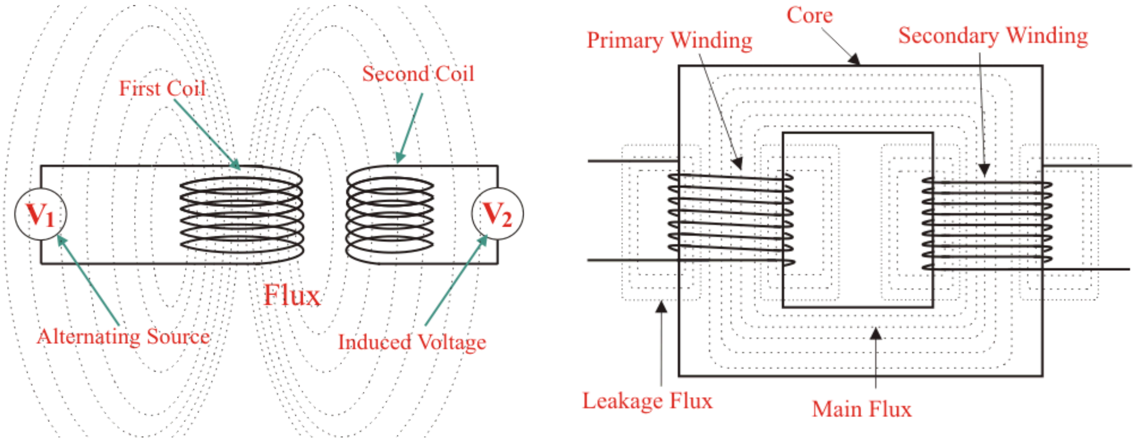


Figure 3. Topology of induction coils and real transformers

As we said before, transformer has three main parts, which are:

- **Primary winding of transformer** - produces magnetic flux when it is connected to electrical source.
- **Secondary winding of transformer** – output winding. The flux, produced by primary winding, passes through the core and will link with the secondary winding.
- **Magnetic Core of transformer** - the flux produced by the primary winding, that will pass through this low reluctance path linked with secondary winding and create a closed magnetic circuit.

2.3. Operation of transformer

2.3.1. Equivalent circuit of a transformer

The equivalent circuit is used to simplify circuit analysis and helpful in predetermining the behavior of the transformer under the various conditions of operation.

In figure below are full description of a transformer:

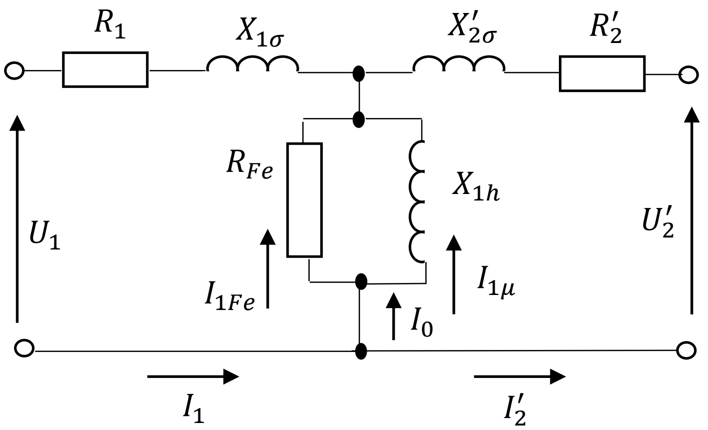


Figure 4. Equivalent circuit of transformer.

where:

R_1 and R'_2 - the primary and secondary winding resistances (denoted respectively).

The resistances cause voltage drops as I_1R_1 and I_2R_2 and also copper losses $I_1^2R_1$ and $I_2^2R_2$.

$X_{1\sigma}, X'_{2\sigma} -$ leakage flux in both primary and secondary side give rise to leakage reactance at both side (denoted respectively).

R_{Fe} – the iron-core resistance having the value corresponding to power loss in the magnetic circuit:

$$\Delta P = \Delta P_{Fe} = R_{Fe} I_{1Fe}^2 \tag{4}$$

X_{1h} – magnetizing reactance of primary circuit corresponding to mutual flux and representing primary Electromotive force (emf- described later).

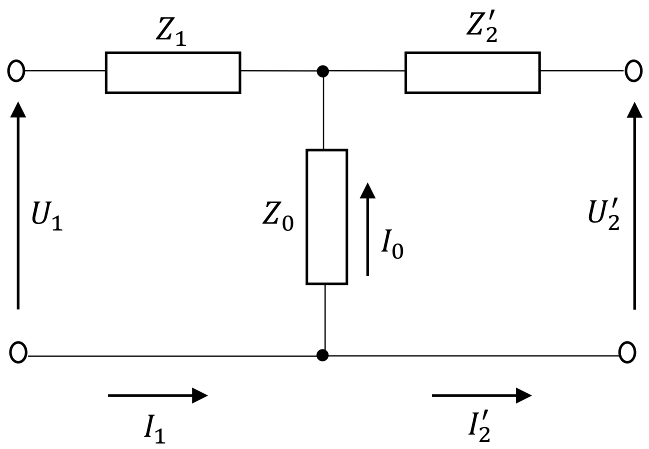


Figure 5. Concise equivalent circuit of transformer

Figure 5 is a reduced version from circuit above (figure 4), it represents the impedance Z which is combined from reactance and resistance of transformer. From this reduced circuit we can easily describe the operation of transformer by following equations:

$$Z_0 = \frac{R_{Fe}.jX_{1h}}{R_{Fe}+jX_{1h}} \tag{5}$$

$$Z_1 = R_1 + jX_{1\sigma} \tag{6}$$

$$Z'_2 = R'_2 + jX'_{2\sigma} \tag{7}$$

$$U_1 = Z_1 I_1 + Z_0 I_0 \tag{8}$$

$$U'_2 = -Z'_2 I'_2 + Z_0 I_0 \tag{9}$$

Z- All values are denoted as impedances for primary, iron-core, secondary winding (respectively).

$U_1 -$ Voltage on primary winding; $U'_2 -$ Voltage on secondary winding.

Note: All equations above are represented in phasor form.

2.3.2. *Electromotive force in windings*

EMF Equation of transformer can be determined very simple. In fact, in power transformer, one alternating electrical source is applied to the primary winding and due to this, magnetizing current flowing through the primary winding, which produces alternating flux in the core of transformer. However, this flux links with both primary and secondary windings. Since this flux is alternating in nature, there must be a rate of change of flux. This phenomenal is related to Faraday’s law and can be described by following equations:

$$U_i = N\frac{d\phi}{dt} \quad (10)$$

where ϕ is the instantaneous alternating flux and it can be represented as:

$$\phi = \phi_{hm} sin\omega t \quad (11)$$

Using equation 11 we`ll find U_i

$$U_i = N\phi_{hm}\omega \cdot cos\omega t \quad (12)$$

RMS value of induced emf in whole primary winding U_{i1} is:

$$U_{i1} = 4{,}44 f N_1 \phi_{\mu max} \quad (13)$$

Similarly, RMS induced emf in secondary winding (U_{i2}) can be given as:

$$U_{i2} = 4{,}44 f N_2 \phi_{\mu max} \quad (14)$$

where:

U_{i1}, U_{i2}- Voltages generated by EMF in primary and secondary windings (denoted respectively)

f – frequency of applied AC source

N_1, N_2 – Number of turn of coils in primary and secondary windings (denoted respectively)

$\phi_{\mu max}$– The maximum rate change in flux generated by magnetic circuit.

Note: The convention of U_i in all equations are effective values!

Finally, from the above equations 13 and 14 we have general equation of electromotive force for transformer.

$$p = \frac{N_1}{N_2} = \frac{U_{i1}}{U_{i2}} \quad (15)$$

This constant (p) is called **transformation ratio of transformer**.

- If $N_2 > N_1$, i.e. $p > 1$, then the transformer is step up transformer.
- If $N_2 < N_1$, i.e. $p < 1$, then the transformer is step down transformer.

2.4. *Short-circuit state and short-circuit test*

Short circuit test on transformer is used to determine copper loss in transformer at full load and parameters of approximate equivalent circuit of transformer. At short circuit, the secondary terminals of transformer are short-circuited. U_2=0 and I_2 and I_1 can be very high (depending on voltage). They are much higher than Io, therefore, after assuming Io≈0 the equivalent circuit can be simplified:

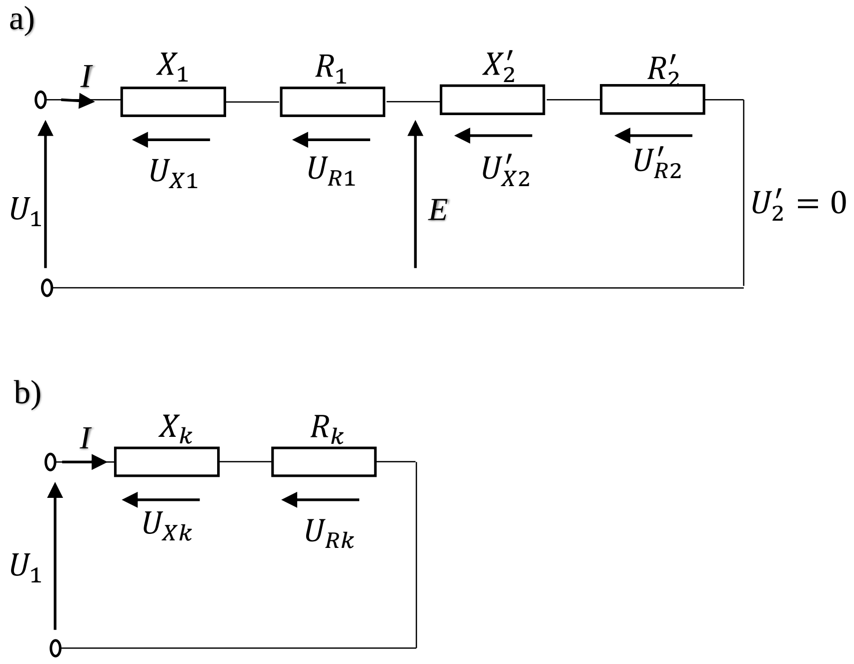


Figure 6. Equivalent short-circuit of transformer

We determine the following parameters:

short-circuit resistance and reactance

$$R_k = R_1 + R_2' \text{ and } X_k = X_1 + X_2' \tag{16}$$

then, short-circuit impedance, sometimes called as *equivalent impedance of transformer*

$$Z_k = R_k + jX_k \tag{17}$$

$$Z_k = \frac{U_1}{I} \tag{18}$$

In laboratory or during field tests the short-circuit tests are very often performed. For the voltage changes from zero up to the value providing the current flow not too much higher than I_N (nominated current), P_1,I_1,$cos\varphi$ are measured and their characteristics drawn as:

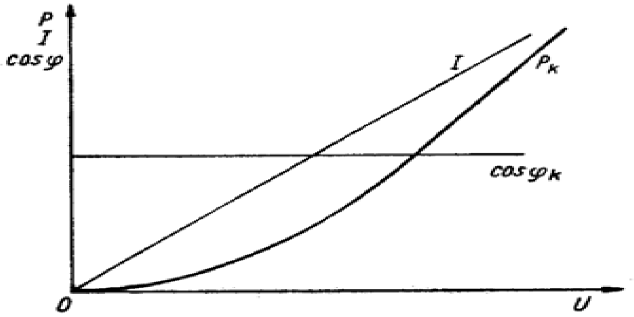


Figure 7. Characteristics of P_1,I_1,$cos\varphi$

For I_1=I_N we determine and specify:

U=U_k – short-circuit voltage (having two components: U_{Rk} andU_{Xk});

P_1=P_k – short-circuit power;

$cos\varphi$= cos φ_k – short-circuit power factor.

<u>Short-circuit voltage</u> is the value of supplying voltage in short-circuited transformer that provides a flow of rated currents (I_2 and I_1). Its value is always shown in ratings of transformers or nameplates (usually in p.u. or in %).

Typical percent value of short-circuit voltage is:

- several % for small and medium power transformers,
- 10 to 20% for large power transformers (hundreds of MVA).

Short-circuit power, i.e. the power absorbed by short-circuited transformer is totally "lost" in the transformer (the output power P_2=0). The iron losses in such transformer are much smaller when compared to copper loss and can be neglected.

2.5. No-load operation and no-load test

At no-load state, the secondary circuit of the transformer is opened:

I_2=0 and I_1=I_N (I_N- nominated current)

No-load test of the transformer is easy to be made in laboratory or even in a substation:

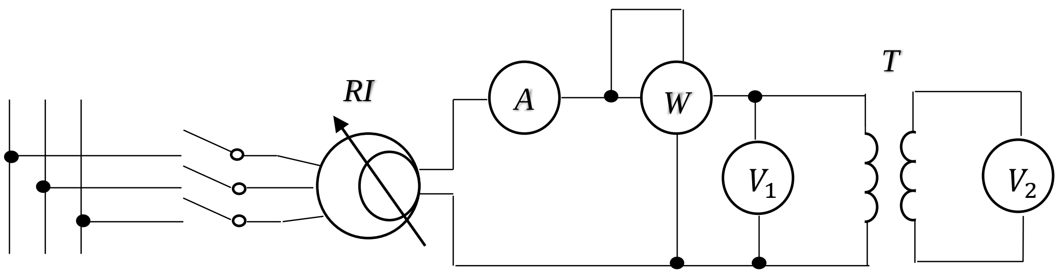


Figure 8. Measuring circuit diagram.

*RI – induction regulator (voltage source of variable output),

A – ammeter,

V – voltmeter,

W – wattmeter.

During the test, the supplying voltage is varied from 0 up to U_N (sometimes more). The following quantities are measured: U_1; U_2 ; I_0 ; P_{1o} .

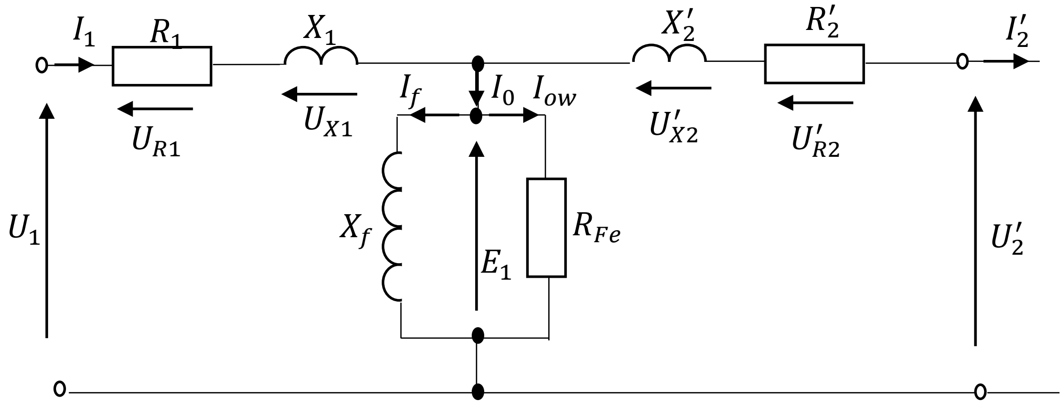


Figure 9a. Equivalent circuit of two-winding transformer

where ,

I_0 – no-load current

I_f – magnetizing current (reactive component of no-load current)

I_{ow} – active component of no-load current

Appropriate characteristics are drawn in the function of primary voltage:

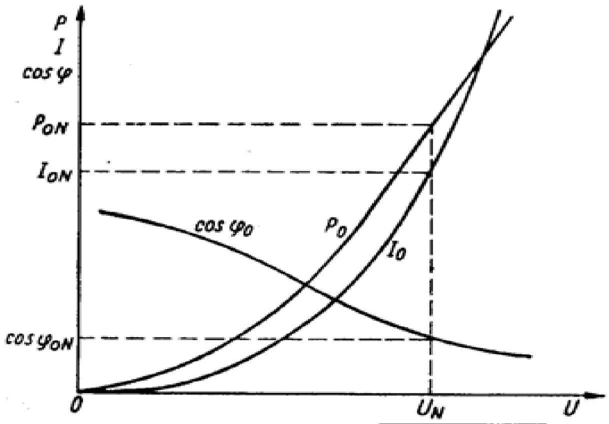


Figure 9b. Basic no-load characteristics

From the no-load test results, we can determine some parameters of the transformer being tested or its equivalent circuit:

$$cos\varphi = \frac{P_{1o}}{U_1 I_0} \ , \qquad I_{ow} = I_0 cos\varphi_0 \ , \qquad I_f = I_0 sin\varphi_0 \tag{19}$$

$$R_{Fe} = \frac{\Delta P_0}{I_{ow}^2} \approx \frac{U_1^2}{\Delta P_0} = \frac{U_1^2}{\Delta P_{Fe}} \ , \qquad X_f = \frac{U_1}{I_f} \tag{20}$$

Rated no-load current (i.e. the value of no-load current at rated voltage) expressed in p.u. or in percent

$$I_{oN\%} = \frac{I_{oN}}{I_N} \times 100\% \tag{21}$$

is rather of small value: from a few % in large power transformers to 20-30% in small transformers.

2.6. Under load state

For simplified consideration of the transformer operation under load we can apply its simplified equivalent circuit.

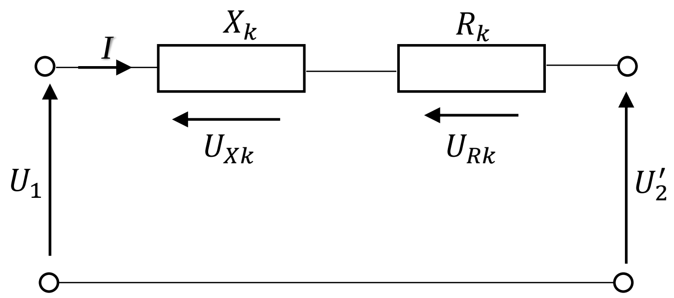


Figure 10. Simplified equivalent circuit

Simplification of equivalent circuit (EC) leads to some error – much lower when I_0 is smaller in comparison to I_1 or I_2 currents. Hence, we can use such equivalent circuit (EC) for discussing power transformers fully loaded.

Using such this model, we can consider the problem of output voltage variation for different value and character of the load current. Let us consider the following problem:

transformer is supplied with constant primary voltage U_1 and the loading current I_2 varies. The character of load current is given by its phase angle φ_2 varying at closed interval [-90°, +90°].

For I_2'=I=0 the output voltage U'_{2o}=U_1. For I>0 and some φ_2

*U2o is no-load output voltage for U1 ≠ U1N

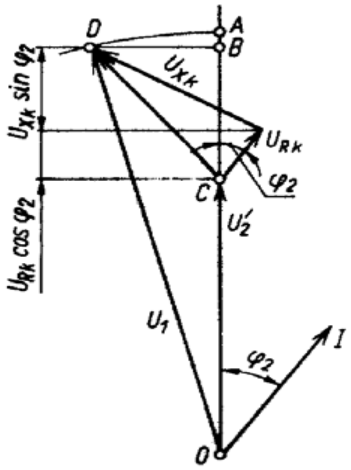


Figure 11. Voltage drops triangle

We observe the voltage drop ΔU (difference in voltage values)

$$\Delta U = U_1 - U_2' = U_{2o}' - U_2' = IR_k cos\varphi_2 + IX_k sin\varphi_2 \quad , \tag{22}$$

Assuming $U_1 = U_{1N}$ and expressing ΔU in in per units

$$\Delta U_r = \frac{U_{2oN}' - U_2'}{U_{2oN}'} = \frac{I}{I_N}(R_{kr}cos\varphi_2 + X_{kr}sin\varphi_2), \tag{23}$$

and for $I = I_N$: (where $U_{Rkr} = R_{kr}$ and $U_{Xkr} = X_{kr}$)

$$\Delta U_{rN} = R_{kr}cos\varphi_2 + X_{kr}sin\varphi_2 = U_{Rkr}cos\varphi_2 + U_{Xkr}sin\varphi_2 \, , \tag{24}$$

The function $\Delta U = f(cos\varphi_2)$ for $I = I_N$ is shown in following figure

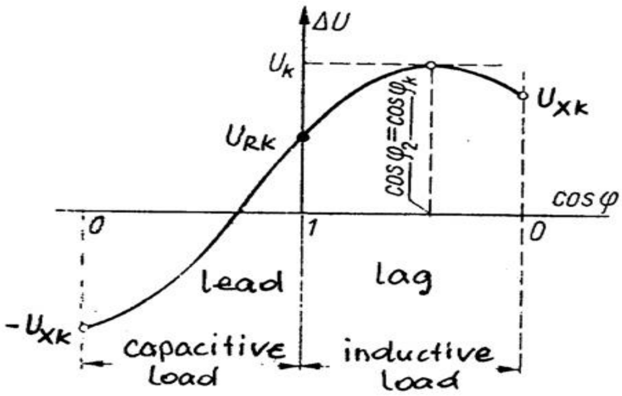


Figure 12. Dependence of ΔU on $cos\varphi_2$

It is seen that max(ΔU) = U_k occurs at $cos\varphi_2 = cos\varphi_k$ i.e. for very special value being a known parameter of the transformer (short-circuit power factor).

*lead = leading character of the current, i.e. the current of capacitive character, or current phasor leads the voltage phasor;

*lag= lagging character of the load, inductive load, current phasor lags the voltage phasor.

3. Types of Transformers

In this part, we are not discussing in detail about each type of transformer, so I described in general types of transformer according to their usages, shapes, use etc..

- Step up Transformer & Step down Transformer - They are used for stepping up and down the voltage level of power in transmission and distribution power system network.
- Three Phase Transformer & Single Phase Transformer - Former, as a rule, is used in three-phase power system, as it is more cost effective than later. However, when size matters, it is preferable to use a bank of three single-phase transformer, as it is easier to transport than one single three-phase transformer unit.
- Electrical Power Transformer, Distribution Transformer – *Power Transformer* is transferring energy between high voltage and very high voltage systems, i.e. between generators and transmission systems and between transmission systems and distribution systems. Also, they are used in transmission network for stepping up or down the voltage level. It operates mainly during high or peak loads and has maximum efficiency at or near full load.
  Distribution transformer steps down the voltage for distribution purpose to domestic or commercial users. It has good voltage regulation and operates 24 hours a day with maximum efficiency at 50% of full load.
- Indoor Transformer & Outdoor Transformer - Transformers that are designed for installing at indoor are *indoor transformers* and transformers designed for installing at outdoor are *outdoor transformers*.
- Oil Cooled & Dry Type Transformer - In *oil cooled transformer* the cooling medium is transformer oil whereas in *dry type transformers* air is used as the cooling medium instead of oil.
- Phase-Shifting Transformer- A *phase-shifting transformer* is a device for controlling the power flow through specific lines in a complex power transmission network.
  Purposes of *Phase-Shifting transformers*:
  a) To control the power flow between two large independent power systems;
  b) To change the effective phase displacement between the input voltage and the output voltage of a transmission line, thus controlling the amount of active power that can flow in the line.

3.1. *Transformers in Power Systems (Transmission and Distribution systems)*

Transmission refers to the bulk transfer of power by high-voltage links between central generation and load centres. Distribution, on the other hand, describes the conveyance of this power to consumers by means of lower voltage networks.

Modern transformers used in transmission and distribution systems have very high efficiencies up to 90%-99%. This means that they can transmit up to 90%-99% of the electrical energy input to them when stepping up or stepping down the voltage.

Transmission: Generators usually produce voltages in the range 11–25kV, which is increased by transformers to the main transmission voltage. At substations, the connections between the various components of the system, such as lines and transformers, are made and the switching of these components is carried out. Large amounts of power are transmitted from the generating stations to the load-centre substations, for example at 400kV and 275kV in Britain, and at 765, 500 and 345kV in the USA.

Distribution Systems: Distribution networks differ from transmission networks in several ways, quite apart from their voltage levels. The number of branches and sources is much higher in distribution networks and the general structure or topology is different. A typical system consists of a step-down (e.g. 132/11kV) on-load tap-changing transformer at a bulk supply point feeding a number of circuits which can vary in length from a few hundred metres to several kilometres. A series of step-down three-phase transformers, for example, 11kV/433V in Britain or 4.16kV/220V in the USA, are spaced along the route and from these are supplied the consumer three-phase, four-wire networks which give 240V, or, in the USA, 110V, single-phase supplies to houses and similar loads.

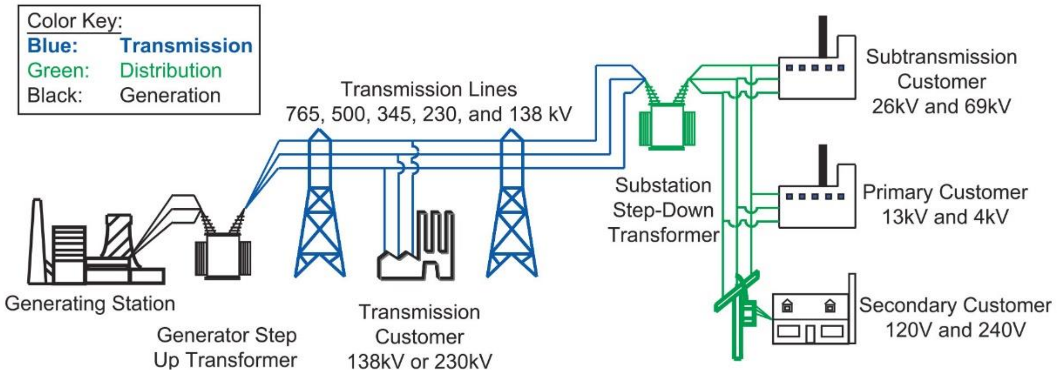


Figure 13. Electric Power system

A large number of transformers of different classes and sizes are needed in the transmission and distribution network, with a wide range of operating voltages. The last transformation step into the consumer mains voltage (in Europe 400/230V) is done by the distribution transformer. Distribution transformers operated and owned by electricity distribution companies are responsible for supplying about 70% of low voltage electricity to final users. Voltage levels are classified as:

- Extra high voltage: transmission grid(>150kV) typically 220–400kV(ultra high>400kV)
- High voltage >70 kV up to 150 kV
- Medium voltage >1 kV up to 70 kV (typically up to 36 kV)
- Low voltage < 1kV (e.g. 110V, 240V, 690 V).

3.2. Special types of transformers

3.2.1. Instrument transformers

Instrument transformer is an electrical device used to transform current as well as voltage level. Sometimes, they are also called as isolation transformers. Instrument transformers are commonly used to safely isolate the secondary winding when the primary has high current supply and high voltage so that the measuring instrument relays or energy meters, which are connected to the secondary side of the transformer will not get damaged. The instrument transformer is divided into two types: Current Transformer (CT) and Potential Transformer (PT)

- ***Current Transformer (CT)***

The CT is used for measuring and for the protection. The primary of a current transformer typically has only one turn, it never has more than a very few turns, while the secondary can have a great many turns, depending upon how much the current must be stepped down. In a lot of cases, the primary of a current transformer is a single wire or bus bar, and the secondary is wound on a laminated magnetic core, placed around the conductor in which the current needs to be measured (see figure 14).

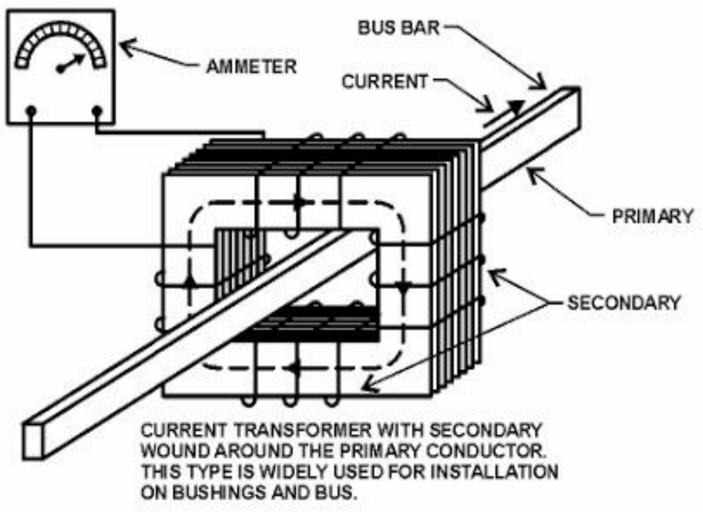


Figure 14. Current transformer

The CT is typically described by its current ratio from primary to secondary, for example, if its ratio is 2000:5, it means a CT has an output current of 5 amperes when 2000 amperes are flowing through its primary winding. They are used with ammeters, wattmeters, power factor meters, watt-hour meters, compensators, protective and regulating relays, and trip coils of circuit breakers. Actually, one current transformer can be used to operate several instruments, provided the combined loads of the instruments do not exceed that for which the CT is rated. Secondary windings are usually rated at 5 amperes.

- ***Potential Transformers (PT)***

The potential transformer is also called as the voltage transformer. The main function of the Potential transformer (PT) is to step down the voltage level to a safe limit or value. They are used with voltmeters, wattmeters, watt-hour meters, power-factor meters, frequency meters, synchronizing apparatus, protective and regulating relays, and under voltage and overvoltage trip coils of circuit breakers. One potential transformer may be used for a number of instruments if the total current required by the instruments connected to the secondary winding does not exceed the transformer rating.

Figure 15. Potential or voltage transformer.

3.2.2. Autotransformers

An Autotransformer is a transformer with only one winding wound on a laminated core. They are less costly and smaller for small voltage changes than standard transformers. Autotransformers transfer much of the power directly through a wire connection. Moreover, less current flows through the shunt winding, whereas most of the current passes through the lower-voltage series winding at the top.

This type of transformers have two main applications on distribution systems:

- *Voltage regulators*: The regulator is an autotransformer with adjustable taps, which, as a rule, is able to regulate the voltage by ± 10%.
- *Step banks*: Generally, autotransformers are often used instead of traditional transformers on step banks and even substation transformers, where the relative voltage change is moderate.

Autotransformer with an equivalent circuit is shown in figures 16a, b below.

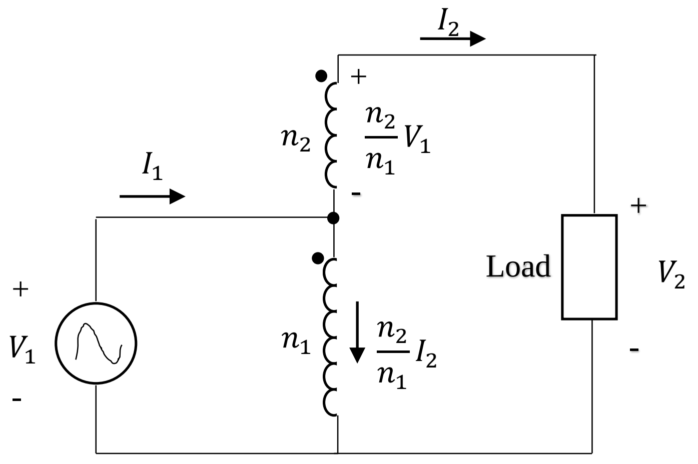


Figure 16a. Autotransformer with an equivalent circuit

$$I_2 = \frac{n_1}{n_1 + n_2} I_1 = \frac{I_1}{b}\,, \tag{25}$$

$$V_2 = V_1 + \frac{n_2}{n_1} V_1 = bV_1\,, \tag{26}$$

Where,

b- Voltage change ratio, in per unit and it is equal to:

$$b = \frac{n_1 + n_2}{n_1}\,, \tag{27}$$

$$\frac{n_2}{n_1} = b - 1\,, \tag{28}$$

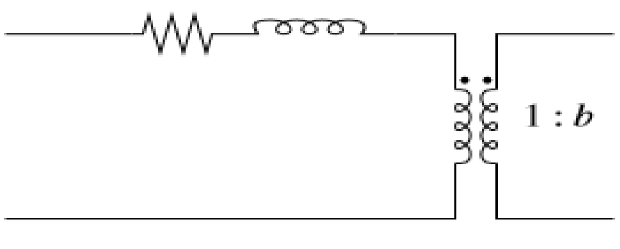


Figure 16b. Equivalent model

The required rating of the autotransformer depends on the voltage change between the primary and secondary windings. The rating of each winding as a percentage of the load is defined as:

$$S = \frac{b-1}{b} \tag{29}$$

To obtain a 10% voltage change (b = 1.1), an autotransformer only has to be rated at 9% of the load kVA. For a 2:1 voltage change (b= 2), an autotransformer has to be rated at 50% of the load kVA. By comparison, a standard transformer must have a kVA rating equal to the load kVA.

The series impedance of autotransformers is less than an equivalent standard transformer. And the equivalent series impedance of the autotransformer is defined as:

$$Z_{auto} = (\frac{b-1}{b})^2 Z \tag{30}$$

Where, Z - impedance across the entire winding (see fig 16b).

3.2.3. Transformer Taps

Most power transformers have taps on the primary or secondary windings to change the number of turns and, consequently, the output voltage. The percentage of voltage variation, above or below normal, between different tap positions varies in different transformers.Taps on oil-cooled transformers are brought to an oil-filled tap changer, which is externally located or brought to a tap changer, located under the oil inside the tank. Taps on dry-type transformers are brought to insulated terminal boards, which is located inside the metal housing, accessible by removing a panel.

Tap changers connected to the primary or secondary side windings of the transformer depending on:

- Current rating of the transformer;
- Insulation levels present;
- Type of winding within the transformer (eg. Star, delta or autotransformer);
- Position of tap changer in the winding;
- Cost;
- Physical size.

Tap changers are divided into two types:

- On-load (OLTC)
- Off-load/de-energized (DECT).

Off-load tap-changing (manual tap changing) mechanisms require the transformer to be isolated before its tap settings can be adjusted, and is normally the case with smaller distribution transformers. However, since the off-load tap changer causes interruption in the supply on-load tap changers are more preferred today in power system.

The on-load tap-changer (automatic changing) allows to select the ratio change when the transformer is in service. This means that the transformer ratio may be changed while the power (current) is still flowing through it. On-load tap changers generally consist of a diverter switch and a selector switch operating as a unit to effect transfer current from one voltage tap to the next. The resistors in the diverter switch are typically a few ohms.

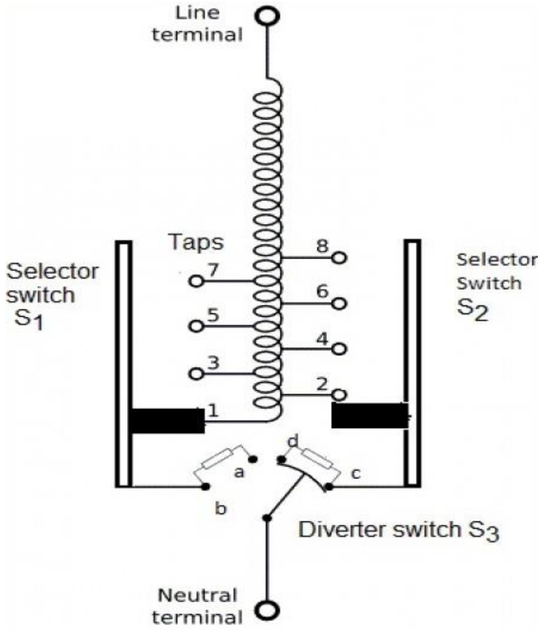


Figure 17. Typical on-load tap changer

4. Transformer connections

4.1. Three-phase transformer connections

Three-phase connections can be made either by using three single-phase transformers or by using a three-phase transformer. Advantages of the three-phase transformer are:

- it costs less;
- the weight is less;
- it requires less floor space;
- has lower losses than three single-phase transformers.

The methods of connecting windings will be the same, whether using the one three-phase transformer or three separate single-phase transformers. The two general methods of connecting three-phase transformers are shown in figure 18.

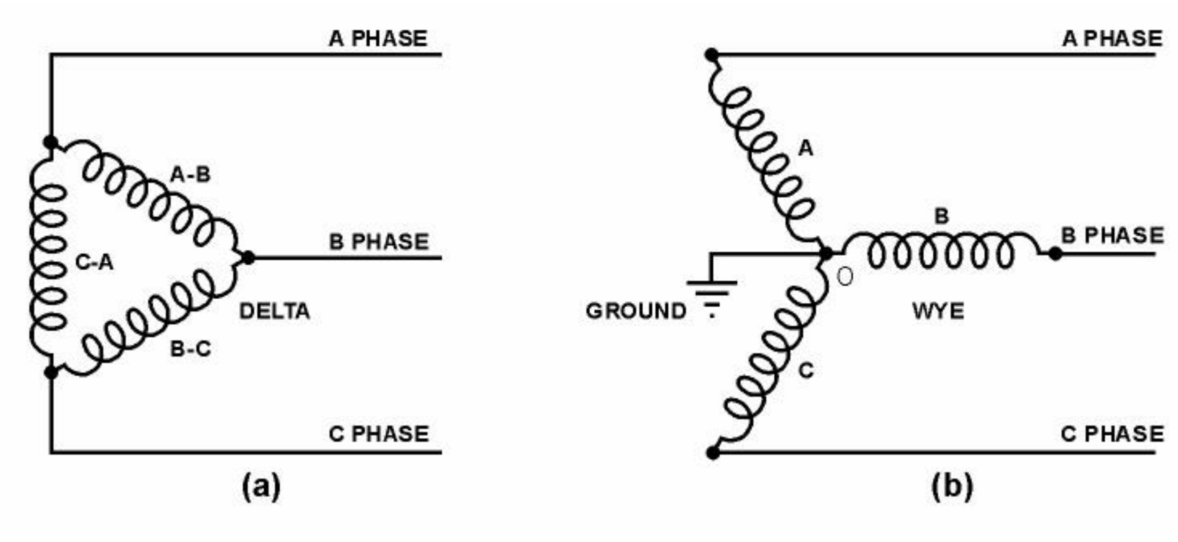


Figure 18. Three-phase transformer connections

The method shown in at figure 18a is known as a delta connection and figure 18b as the star or wye connection. Differences between wye and delta connection in that wye connection has two phases in series. And the common point “O” of the three windings is called the neutral because equal voltages exist between this point and any of the three phases.

- *Wye–Wye Connections of Transformer*

For high-voltage transmission systems, the use of the wye-connected transformer is more economical because the voltage across the phase of each winding is a factor of 1.73 less than the voltage between the lines. If the neutral point is grounded, there is no need to insulate it for the line voltage.

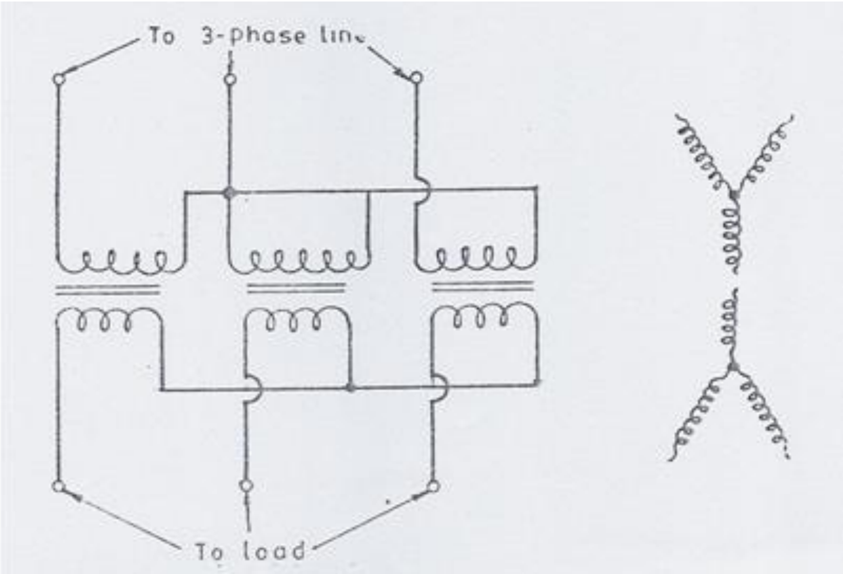


Figure 19. The Y-Y connection of transformer.

Figure 19 shows a bank of three transformers connected in Y on both the primary and secondary sides. If the ratio of transformation of each transformer is K, then the same ratio will exist between the line voltages on the both sides. This connection will give satisfactory service only if the three-phase load is balanced; when the load is unbalanced, the electrical neutral will shift from its exact center to a point that will make the line to neutral voltages unequal.

<u>Advantages of the Y-Y connection:</u>

- The primary and secondary circuits are in phase; i.e., there are no phase angle displacements introduced by the Y-Y connection. This is an important advantage when transformers are used to interconnect systems of different voltages in a cascading manner. For example, suppose there are four systems operating at 500, 230, 138, and 69kV that need to be interconnected. Substations can be constructed using Y-Y transformer connections to interconnect any two of these voltages. The 500 kV system can be tied with the 69 kV system through a single 500 to 69 kV transformation or through a series of cascading transformations at 230, 138, and 69 kV.

- If the neutral end of a Y-connected winding is grounded, then it is possible to use reduced levels of insulation at the neutral end of the winding. A winding, which is connected across the phases, requires full insulation throughout the winding.

Disadvantages of the Y-Y connection:

- The presence of third (and other zero-sequence) harmonics at an ungrounded neutral can cause overvoltage conditions at light load. When constructing a Y-Y transformer using single-phase transformers connected in a bank, the measured line-to-neutral voltages are not 57.7% of the system phase-to-phase voltage at no load but are about 68% and very quickly decrease as the bank is loaded. The effective values of voltages at different frequencies combine by taking the square root of the sum of the voltages squared. With sinusoidal phase-to-phase voltage, the third-harmonic component of the phase-to-neutral voltage is about 60%, so the effective voltage across the winding is calculated as follows:

$$E = \sqrt{[0.577^2 + (0.6 \times 0.577)^2} = 68\%. \quad (31)$$

- *Delta–Delta Connection*

The delta–delta connection has an economic advantage over the wye–wye connection for low-voltage, high-current requirements because the winding current is reduced by a factor of 1.73 to 58% of that in the wye–wye connection. Another advantage of this connection, if composed of three single-phase transformers, is that one transformer can be removed and the remaining two phases operated at 86.6% of their rating in the open delta(if one transformer fails it may switched out of the line and operation continued at a reduced power level) connection.

The principle disadvantage of the delta–delta connection is that the neutral is not available. As a result, the phases cannot be grounded except at the corners. The insulation design is more costly because this type of three-phase transformer connection has higher ground voltages during system fault or transient voltages. Supplying an artificial neutral to the system with a grounding transformer can help to control these voltages. The delta-connection insulation costs increase with increasing voltage. Therefore, this type of connection is usually limited to a maximum system voltage of 345 kV.

In figure 20 is shown a bank of transformers connected in delta on both the primary and secondary sides.

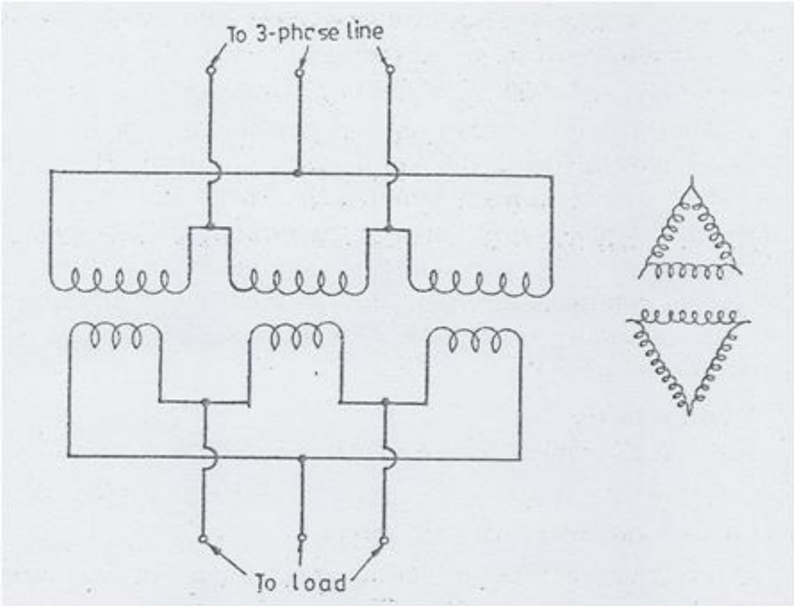


Figure 20. The delta-delta connection of transformer.

- *Wye–Delta and Delta–Wye Connections*

The wye-delta or delta-wye connections have less objectionable features than any other connections. In general, these combine most of the advantages of the wye–wye and delta–delta connections. Complete voltage and current symmetry is maintained by the presence of the delta. The exciting third-harmonic current circulates within the delta winding, and no third-harmonic voltage appears in the phase voltages on the wye side. The high-voltage windings can be connected wye, and the neutral can be brought out for grounding to minimize the cost of the insulation.

Differences in magnetizing current, voltage ratio, or impedance between the single-phase units are regulated by a small circulating current in the delta. All of these factors result in unbalanced phase voltages on the delta, which causes a current to circulate within the delta.

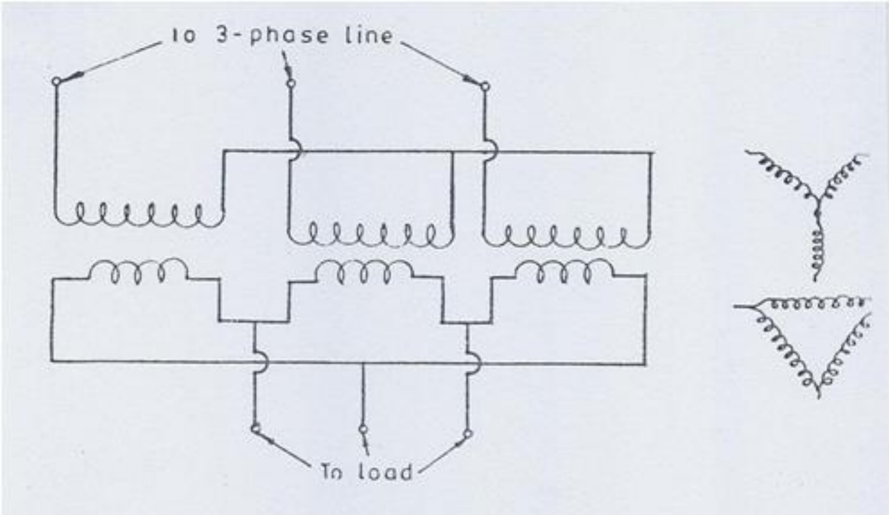


Figure 21. The Wye-delta connection.

Although the delta–wye connection has most of the advantages of the wye–wye and delta–delta, it still has several disadvantages. This connection introduces a 30r phase shift between the primary and secondary windings, which must be matched for a parallel operation. A delta–wye bank cannot be operated with only two phases in an emergency. If the delta is on the primary side and should accidentally open, the unexcited leg on the wye side can resonate with the line capacitance.

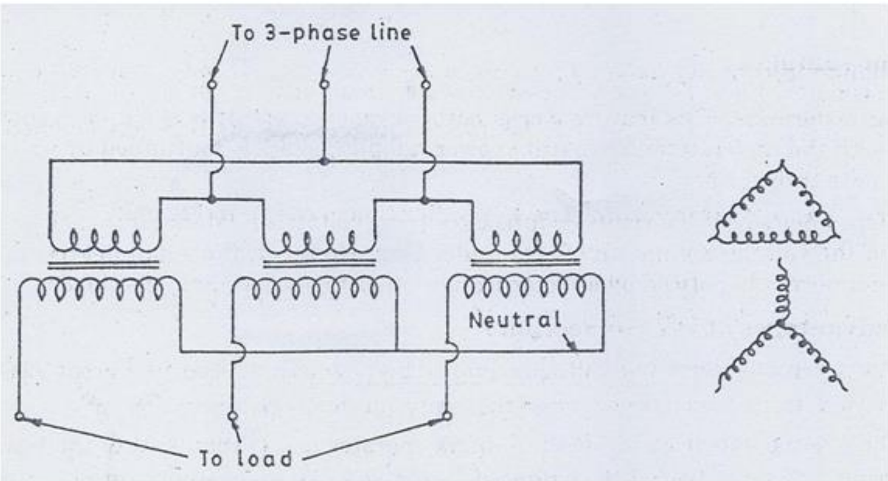


Figure 22. The Delta-Wye connection of transformer.

The three-phase Delta-Wye connections are shown in Figure 22 above. This type of connections is used where it is necessary to step up the voltage, as for example, at the beginning of a high-tension transmission system.

5. Technical aspects of transformers

5.1. Transformer cooling

Usually the efficiency of power transformers is more than 99% and because of this the input and output powers are almost the same. Because of the small amount of inefficiency, losses occur inside the transformer. These losses are losses such as losses in conductors, losses in electrical steel due to the changing flux, which is carried, and losses in metallic tank walls and other metallic structures cause by the stray time varying flux. These losses lead to temperatures increases, which must be controlled by cooling. The primary cooling media for transformers are oil and air.

In oil-cooled transformers, the coils and core are immersed in an oil-filled tank. The oil is then circulated through radiators or other types of heat exchanger so that the ultimate cooling medium is the surrounding air or possibly water for some types of heat exchangers. In small distribution transformers, the tank surface in contact with the air provides enough cooling surface so that radiators are not needed. Some time in these units, the tank surface area is augmented by means of fins or corrugations.

Figure 23. Oil transformer with air convection cooled heat exchangers

The cooling medium in contact with the coils and core must provide adequate dielectric strength to prevent electrical breakdown or discharge between components at different voltage levels. For this reason, oil immersion is common in higher voltage transformers since oil has a higher breakdown than air. Often one can rely on the natural convection of oil though the windings, driven by buoyancy effects, to provide adequate cooling so that pumping is not necessary. Air is a more efficient cooling medium when it is blown by means of fans through the windings for air-cooled units.

In some applications, the choice of oil or air is dictated by safety considerations such as the possibility of fires. For units inside buildings, air-cooling is common because of the reduced fire hazard. While transformer oil is combustible, there is usually tittle danger of fire since the transformer tank is often sealed from the outside air or the oil surface is blanketed with an inert gas such as nitrogen. Although the flash point of oils is quite high, if excessive heating or sparking occurs inside an oil-filled tank, combustible gasses could be released.

Environment also plays a big role in the choice of coolants. Mineral oil used in transformers is known to be detrimental to the environment if there is an accident. For transformers such as those used on planes or trains or units designed to be transportable for emergency use, air-cooling is preferred. For units that are not so restricted, oil is the preferred cooling medium, in general oil cooled transformers are used in everyday units, from large generator or substation units to distribution units on telephone poles.

There are other cooling media, which find limited use in certain application, such as sulfur hexafluoride gas, which is usually pressurized. This is a relatively inert gas and it has a higher breakdown strength than air, it is generally used in high-voltage units where oil cannot be used and where air does not provide enough dielectric strength. Usually, the standard transformer oil is used in oil-cooled transformers. Nevertheless, there are other types of oil are also used for specialized usage. For example, silicon oil. It can be used at a higher temperature than the standard transformer oil and at a reduced fired hazard.

5.1.1. Transformer Cooling Methods

- Dry type transformers

This method can be divided in two types:

- ✓ Air Natural (AN)

Air natural or self-air cooled transformer is generally used for small ratings transformers up to 3 MVA. Basically, this method uses the natural air flow surrounding the transformer as cooling medium.

- ✓ Air forced (AF)

Natural air-cooling method is adequate to use for transformers rated more than 3 MVA. Therefore, blowers or fans are required to force the air towards the core and windings so, hot air is gained cooled due to the outside natural conventional air. However, the air forced must be filtered to prevent the accumulation of dust particles in ventilation ducts. This method can be used for transformers up to 15 MVA. In figure below, we can see the example of forced air-cooled transformer.

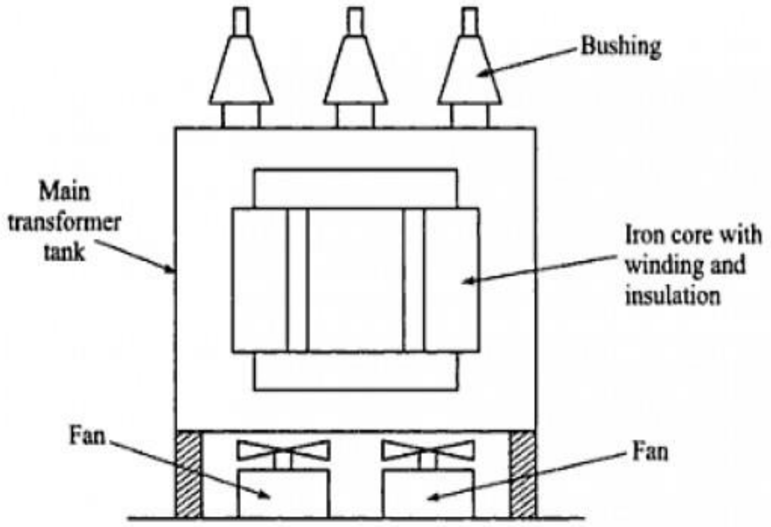


Figure 24. Forced air-cooled transformer

- <u>Oil immersed transformers</u>

Generally, the transformer winding and core are immersed in the mineral oil, which has good electrical insulating property to block the current flow through the oil and high thermal conductivity.

This method can be divided into four types:

- ✓ Oil Natural Air Natural (ONAN)

This cooling method may be used for transformers up to about 30MVA. In this method, the heat generated in the core and winding is transferred to the oil. The heated oil moves in the upward direction and flows from the upper portion of the transformer tank according to the principle of convection. The heat from the oil will dissipate in the atmosphere due to the natural air flow around the transformer. In this case, the oil in transformer will keep circulating because of natural convection and will dissipate heat in atmosphere due to natural conduction. In figure below is shown an example of oil natural air natural cooling of transformer.

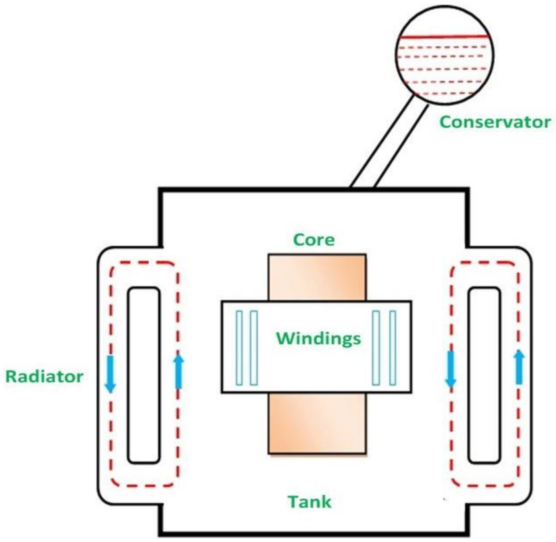


Figure 25. Oil Natural Air Natural (ONAN) cooling of Transformer.

- ✓ Oil Natural Air Forced (ONAF)

Generally, this method of transformer cooling is useful for large transformers up to about 60 MVA. The heat dissipation can be improved by applying forced air on the dissipating surface. Heat dissipation rate is faster and more in ONAF transformer cooling method than ONAN cooling system. In this manner, fans are mounted near to the radiator and can be provided with an automatic starting arrangement, which turns on when temperature increases beyond certain value.

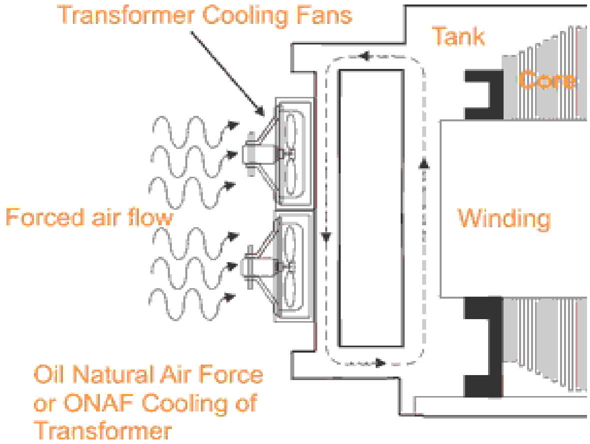


Figure 26. Oil Natural Air Forced (ONAF) cooling of Transformer.

✓ Oil Forced Air Forced (OFAF).

Oil Forced Air Forced (OFAF) cooling method is provided for higher rating transformers at substations or power stations. In this method, oil is circulated with the help of a pump, and then compressed air is forced to pass on the heat exchanger with the help of high-speed fans. Furthermore, the heat exchangers can be mounted separately from the transformer tank and connected through pipes at top and bottom as shown in the figure below.

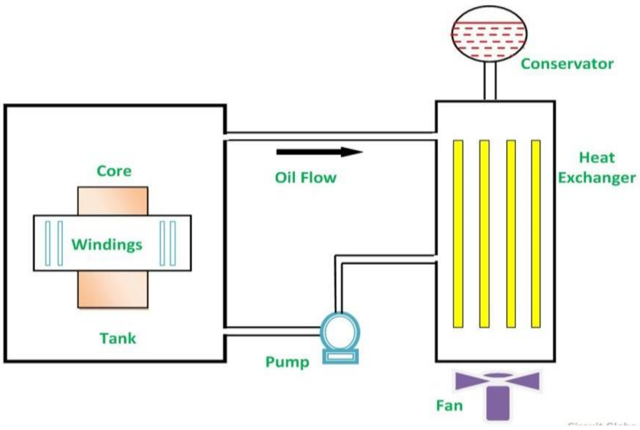


Figure 27. Oil Forced Air Forced (OFAF) cooling of transformer.

✓ Oil Forced Water Forced (OFWF).

We know that ambient temperature of water is much less than the atmospheric air in same weather condition. Thus, water may be used as better heat exchanger medium than air. The oil is forced to flow through the heat exchanger with the help of a pump, where the heat is dissipated in the water, which is also forced to flow. The heated water is taken away to cool in separate coolers. Generally, this type of cooling is used for very large transformers with very high power rating above 500 MVA.

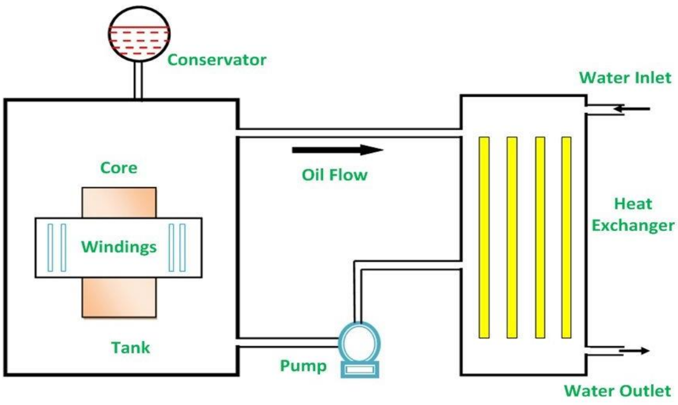


Figure 28. Oil Forced Water Forced (OFWF) cooling of transformer.

5.2. *Losses in transformers*

Like every existing machine, transformers also can`t work without energy losses. The transformer has no moving parts and therefore the mechanical losses are absent in it. Transformer losses are classified as no-load losses and load losses. These types of losses are common to all types of transformers, regardless of transformer application or power rating. However, there are two other types of losses: extra losses created by the non-ideal quality of power and auxiliary (or cooling) losses, which may apply particularly to larger transformers, caused by the use of cooling equipment such as fans and pumps.

5.2.1. *No-load losses*

No-load losses (also called iron loss or core loss) are constant and occur 24 hours a day, 365 days a year, regardless of the load, from this the term no-load losses. They present in the transformer core whenever the transformer is energized. They are categorized as shown below:

- Hysteresis losses caused by the frictional movement of magnetic domains in the core laminations being magnetized and demagnetized by alternation of the magnetic field. These losses are responsible for 50% to 80% of total no-load losses and depend on the type of material used to build a core. Silicon steel has much lower hysteresis than normal steel but amorphous metal has much better performance than silicon steel. Hysteresis losses can be reduced by material processing such as cold rolling, laser treatment or grain orientation.
- Eddy current losses caused by varying magnetic fields inducing eddy currents in the laminations and thus generating heat and usually they are responsible for 20–50% of total no-load losses. Eddy current losses can be reduced by building the core from thin laminated sheets insulated from each other by a thin varnish layer to reduce eddy currents.
- Less significant stray and dielectric losses occur in the transformer core and these losses usually account for no more than 1% of total no-load losses.

5.2.2. *Load losses*

Load losses (also called copper losses or short-circuit losses) occur in the resistance of the winding of the transformer when it carries the load current. The total loss of copper in the transformer is obtained by adding both primary and secondary copper losses.Load losses vary according to the transformer loading. These losses include:

- Ohmic heat loss (sometimes called as copper loss) occurs in transformer windings and caused by the resistance of the conductor. The magnitude of this loss increases with the square of the load current (I_{load}^2) and is proportional to the resistance of the winding ($R_{winding}$).
  Ohmic heat loss can be reduced by increasing the cross-sectional area of the conductor or by reducing the winding length of conductor (R=$\frac{\rho l}{S}$).
- Conductor eddy current losses caused by alternating current and occur in the windings (due to magnetic fields). Eddy currents can be reduced by reducing the cross-section of the conductor, so stranded conductors with the separate strands isolated against each other are used to achieve the required low resistance while controlling eddy current loss.

5.2.3. Extra losses

Extra losses caused by unbalanced harmonics and reactive power.

- Harmonics: Non-linear loads, such as power electronic devices, such as variable speed drives on motor systems, computers, UPS systems, TV sets and compact fluorescent lamps, cause harmonic currents on the network. Harmonic voltages are generated in the impedance of the network by the harmonic load currents. Harmonics increase both load and no-load losses due to increased skin effect, eddy current, stray and hysteresis losses.
- Unbalance: Transformers subject to negative sequence voltage transform them in the same way as positive sequence voltages. The behavior with respect to homo-polar voltages depends on the primary and secondary connections and, more particularly, the presence of a neutral conductor. If, for example, one side has a three-phase four-wire connection, neutral current can flow. If at the other side of the winding is delta-connection, the homo-polar current is transformed into a circulating (and heat-causing) current in the delta. The associated homo-polar magnetic flux passes through constructional parts of the transformer causing by parasitic losses in parts such as the tank, sometimes requiring an additional derating.
- Extra losses due to current distortion: The most important of these losses is that due to eddy current losses in the winding, it can be very large and consequently most calculation models ignore the other harmonic-induced losses. The precise impact of a harmonic current on load loss depends on the harmonic frequency and the way the transformer is designed. In general, the eddy current loss increases by the square of the frequency and the square of the load

current. So, if the load current contains 20% fifth harmonic, the eddy current loss due to the harmonic current component would be $5^{2}*0.2^{2}$ multiplied by the eddy current loss at the fundamental frequency, meaning that the eddy current loss would have doubled.

To avoid excessive heating in transformer supplying harmonic currents, two approaches are used:

a) Reducing the maximum apparent power transferred by the transformer, often called de-rating. To estimate the required de-rating of the transformer, the load's de-rating factor can be calculated. This method, used commonly in Europe, is to estimate by how much a standard transformer should be de-rated so that the total loss on harmonic load does not exceed the fundamental design loss. This de-rating parameter is known as "factor K".

The transformer de-rating factor is calculated according to the formula:

$$K = \left[1 + \frac{e}{1+e}\left(\frac{I_h}{I}\right)^2 \sum_{n=2}^{n=N}\left(n^q\left(\frac{I_n}{I_1}\right)^2\right)\right]^{0.5} , \qquad (32)$$

where

e - the eddy current loss at the fundamental frequency divided by the loss due to a DC current equal to the RMS value of the sinusoidal current, both at reference temperature;

n - the harmonic order;

I - the RMS value of the sinusoidal current including all harmonics given by

$$I = (\sum_{n=1}^{n=N}(I_n)^2)^{0.5} = I_1(\sum_{n=1}^{n=N}(\frac{I_n}{I_1})^2)^{0.5} , \qquad (33)$$

Where

I_n - the magnitude of the *n*th harmonic;

I_1 - the magnitude of the fundamental current;

q - exponential constant that is dependent on the type of winding and frequency. Typical values are 1.7 for transformers with round rectangular cross-section conductors in both winding and 1.5 for those with foil low voltage windings.

b) Developing special transformer design rated for non-sinusoidal load currents. This process requires analysis and minimizing of the eddy loss in the windings, calculation of the hot sport temperature rise, individual insulation of laminations, increasing the size of core or winding.

Each manufacturer will use any or all of these technique according to labour rates, production volume and capability of his plant and equipment. These products are sold as “K rated” transformers. During the transformer selection process, the designer should estimate the K factor of the load and select a transformer with the same or higher K factor, defined as:

$$K = \sum_{n=1}^{n=n_{max}} I_n^2 n^2 \quad , \qquad (34)$$

- <u>Extra losses due to voltage distortion</u>: The common approach presented above assumes that although the magnetizing current does include harmonics, these are extremely small compared with the load current and their effect on the losses in minimal.

  When not ignoring extra harmonic losses from voltage harmonics and also those generated in the transformer core, the full formula to calculate losses in transformers due to harmonics, is as follows:

$$P_T = 3\sum_n I_n^2 \cdot R_n + P_{Fe}\sum (\frac{V_n}{V_1})^m \cdot \frac{1}{n^{2.6}} \quad , \qquad (35)$$

where

P_T - losses of transformer due harmonic distortion;

P_{Fe} - fundamental frequency iron losses;

R_n - equivalent copper loss resistance of transformer at the *n*th order;

V_1- fundamental component voltage;

V_n - harmonic voltage of order *n*;

I_n- harmonic current of order *n*;

n - order of harmonic;

m - exponent empiric value (assumed to be the value 2).

The second component in the above equation represents losses in the transformer core caused by voltage distortion. This is a partly empiric formula that may still underestimate core harmonic losses caused by current distortion.

5.2.4. Auxiliary Losses

Auxiliary losses are caused by using energy to run cooling fans or pumps, which help to cool larger transformer.

6. Materials for manufacturing of transformers

Thanks to advanced data processing with mathematical tools and models, it is now possible to design a transformer using the finite-element method with the provision of electrical and mechanical strengths, heat transfer and dynamic properties, including short-circuit conditions. As a practical result, two-dimensional or three-dimensional field plots are used to help design different elements of transformer and save losses at desired levels with an optimal balance between costs and efficiency. In practice, it is to minimize the influence of an out of proportion increase of one of the cost components, either the conductor, insulant, or core material for the purpose of loss optimization at the design stage. Material and material processing technology developments have the largest influence on losses. Without evolution in material technologies, the progress in improving the efficiency of transformers would be impossible on so large a scale.

Fabrication technics may include some improvements; better stacking, precision in manufacturing, insulating and shielding against stray magnetic flux add smaller but still significant loss reductions.

6.1. Materials for magnetic core

Working of primary, secondary windings and also tertiary winding depends on the flux that is produced between these windings. Magnetic cores are used in transformers, which serve as the pathway of the flux. These cores are magnetic materials with high magnetic permeability, used to direct magnetic fields in transformers and other devices. There are many materials that can be used to manufacture magnetic cores, the most common ones are:

- <u>Laminated steel:</u>

Laminated magnetic cores feature thin iron sheets covered with an insulating layer that lie parallel to the lines of magnetic flux. These insulating layers prevent the eddy current, and restrict them to narrow loops within each layer of lamination. From this, it can be seen that the thinner the layers, the lower will be the eddy currents. They are most frequently used for small to high-powered transformers.

- <u>Amorphous steel:</u>

These cores are made from several paper-thin metallic tapes, which help to reduce the flow of eddy currents. Amorphous steel cores have fewer losses than other magnetic cores, and they can easily operate at high temperatures than standard lamination stacks. They are most commonly used in high efficiency transformers that operate at medium frequencies.

- Ferrite ceramics:

The magnetic cores made from ferrite ceramics are commonly used in high-frequency applications. Ferrite ceramics are made from iron oxide, and one or multiple metallic elements. These ceramic materials serve as efficient insulators, and help decrease eddy currents, although losses such as hysteresis losses can still occur.

- Silicon steel:

Silicon steel has high electrical resistivity and it has high permeability, also low losses, which allows the use of cores made of silicon steel in high-performance applications. Silicon steel offers high saturation flux density.

- Vitreous Metal:

Amorphous metals are non-crystalline or glassy. These metals are used to create high-efficiency transformers and the materials have low conductivity, which helps reduce eddy currents.

- Solid iron core:

Solid iron cores provide magnetic flux, and helps retain high magnetic fields without iron saturation. However, solid iron is also a good conductor, allowing the magnetic field to produce large eddy currents. In turn, these eddy currents cause potentially massive inefficiency and heat generation at higher operating frequencies.

6.2.Materials for winding

While the transformer core serves the magnetic circuit, the windings form the electrical circuit of a transformer. The resistive losses are directly dependent on the resistance of primary and secondary windings. If the length and the cross-section of the windings decreases, then the losses will be lower. The length of the windings and the number of turns depends on the core geometry and properties of the core material.

Materials for windings:

- Copper
- Aluminum

Aluminum and copper are the main materials used as conductors in power-transformer windings. Although aluminum is lighter and generally cheaper than copper, it is necessary to use a larger cross section of an aluminum conductor for current transfer with the same characteristic as copper. Copper has a higher mechanical strength and is used almost exclusively in all but the smaller size ranges, where aluminum conductors may be perfectly acceptable. In cases where extreme forces occur, materials such as silver-bearing copper can be used for even greater strength. The conductors used in power transformers are typically stranded with a rectangular cross section, although some transformers at the lowest ratings can use sheet or foil conductors. Technical possibilities of usage in different types of transformers are very similar for both of these materials and because of this, the most important parameter is usually the final price.

The physical properties of copper and aluminum are shown in Table 1.

Physical property	Unit	Copper (Cu)	Aluminum (Al)
Density at 20 ℃	$kg \cdot dm^3$	8.96	2.698
Conductivity hard	$m\Omega \cdot mm^{-2}$	55	33
Conductivity half-hard	$m\Omega \cdot mm^{-2}$	56	35
Conductivity soft	$m\Omega \cdot mm^{-2}$	57	37
Temperature coefficient of resistance	$℃^{-1}$	0.00393	0.00377
Coefficient of linear expansion	$℃^{-1}$	$16.2\text{x}10^{-6}$	$23.9\text{x}10^{-6}$
Tensile strength (soft/hard)	$N \cdot mm^{-2}$	200/350	70/150
Elongation at rupture (soft/hard)	%	30/20	22/2
Modulus of elasticity	$N \cdot mm^{-2}$	125 000	72 000
Thermal conductivity	$W\ m^{-1}\ ℃^{-1}$	338 000	231 000
Specific heat	$Ws\ kg^{-1}\ ℃^{-1}$	385	920
Fusion point (melting temperature)	℃	1 083	659
Boiling point (boiling temperature)	℃	2 300	2 270
Specific heat of fusion	$Ws\ kg^{-1}$	209 000	355 000
Electrochemical potential	V	+0.35	-1.28

Table 1. Physical properties of copper and aluminum.

7. Practical problems in utilization of transformers

7.1. Parallel operation of transformers

To supply a load that exceeds the rated power of an existing transformer, two or more transformers may be connected in parallel with the existing transformer. Transformers are connected in parallel, when the load on one of the transformers exceeds its capacity. The reliability increases with parallel operation, than when using single large unit. The cost associated with maintaining the spares is less when two transformers are connected in parallel.

Usually it is economical to install in parallel another transformer instead of replacing an existing transformer by a single larger unit. In the case of two parallel transformers with the equal rating, the cost of the spare unit is also lower than the cost of one large transformer. Also for reliability reasons, it is preferable to have a parallel transformer.

Requirements for Parallel operation of Transformers:

- Same voltage Ratio & Turns Ratio (both primary and secondary Voltage Rating is same).
- Same Percentage Impedance and X/R ratio.
- Identical Position of Tap changer.
- Same KVA ratings.
- Same Phase angle shift (vector group are same).
- Same Frequency rating.
- Same Polarity.
- Same Phase sequence.

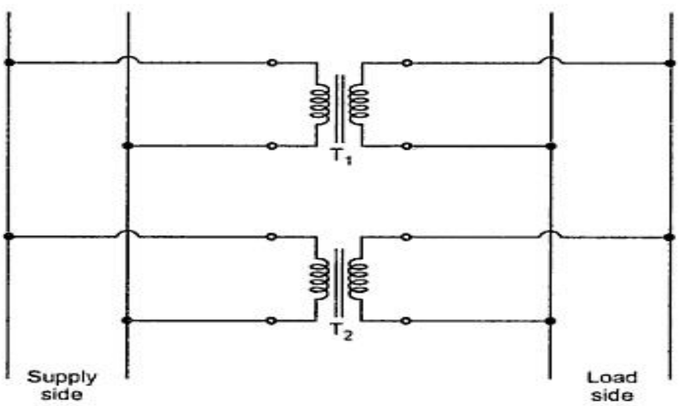


Figure 29. Parallel connection of transformers.

Purposes of using parallel connection:

- <u>To maximize electrical power system efficiency:</u>

Typically, a power transformer provides maximum efficiency at full load. If we run numbers of transformers in parallel, we can switch on only those transformers that will give the total demand, approaching its full load during this time. When the load increases, we can not switch any other transformer connected in parallel to fulfil the total demand. In this way, we can run the system with maximum efficiency.

- <u>To maximize electrical power system availability:</u>

If the numbers of transformers are running in parallel, we can shut down any of them for maintenance purposes and other parallel transformers in the system will serve the load without completely interrupting power.

- <u>To maximize power system reliability:</u>

In case of any one of the transformers run in parallel, is tripped due to fault of other parallel transformers is the system will share the load, consequently power supply cannot be interrupted if the shared loads do not make other transformers over loaded.

- <u>To maximize electrical power system flexibility:</u>

There is always a possibility of increasing or decreasing future demand of power system. If it is projected that the power demand will be increased in the future, it is necessary to connect the connecting transformers in the system in parallel to fulfil the extra demand, since it is economically inexpedient to install a more powerful rated single transformer by forecasting the increased future demand, as it is unnecessary investment of money. Also, if future demand decreases, parallel transformers can be removed from the system to balance the capital investment and its return.

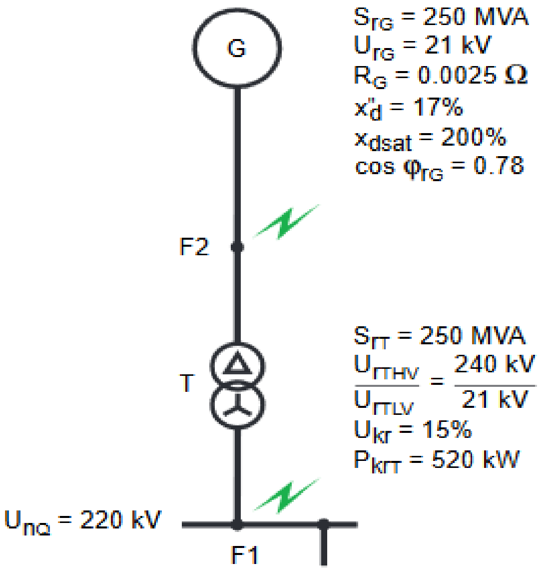
7.2. Calculation

7.2.1. Example for short-circuit level

A Power station Unit S comprises a generator G and a transformer T with an on-load tap-changer.

Calculate: The initial short-circuit power at F1 and F2

Impedances of the Transformer and Generator.



Solution:

1) Three-phase fault at F1

Impedance of the Transformer:

$$Z_{THV} = \frac{u_{kr}}{100} \times \frac{U_{rTHV}^2}{S_{rT}} = \frac{15}{100} \times \frac{240^2}{250} = 34.56\ \Omega$$

$$R_{THV} = P_{krT}\frac{U_{rTHV}^2}{S_{rT}^2} = 0.52 \times \frac{240^2}{250^2} = 0.479\ \Omega$$

We know that

$$Z_{THV} = \sqrt{X_{THV}^2 + R_{THV}^2}$$

And using this formula we can calculate reactance

$$X_{THV} = \sqrt{Z_{THV}^2 - R_{THV}^2} = \sqrt{34.56^2 - 0.479^2} = 34.557\ \Omega$$

Impedance of the Generator:

$$X_d'' = \frac{x_d''}{100} \times \frac{U_{rG}^2}{S_{rG}} = \frac{17}{100} \times \frac{21^2}{250} = 0.2999\ \Omega$$

$$Z_G = R_G + jX_d'' = 0.0025 + j0.2999$$
$$|Z_G| = 0.2999\ \Omega$$

Z_G- Impedance of the Generator

2) Three-phase fault at F2

Initial short-circuit power at F2:

$$S_{kG}'' = \frac{S_{rG}}{x_d''} = \frac{250}{0.17} = 1470\ MVA$$

And initial short-circuit power at F1 is calculated as:

$$S_{kT}'' = \frac{S_{rT}}{x_k''} = \frac{S_{rT}}{x_d'' + x_T''} = \frac{250}{0.15 + 0.17} = 781.25\ MVA$$

From the result we see that initial short-circuit power at F1 is 781.25 MVA and at F2 is 1470 MVA.

7.2.2. Voltage drop calculation

Three-phase transformer:

Load 150 kVA, PF (power factor) =0.8=$cos\theta$,$\theta = 36°$, $sin\theta = 0.6$

From Manufacturer: $\%R$ 1.08% Resistance

$\%X$ 1.63% Reactance

120/280 V, 3phase - Secondary Voltage

Find: Voltage Drop (V_d)

1) First, we will find actual Resistance and actual Reactance, using these formulas:

$$R_\Omega actual = \frac{10(\%R)(KV\ Secondary)^2}{KVA\ \ Transformer}$$

$$X_\Omega actual = \frac{10(\%X)(KV\ Secondary)^2}{KVA\ \ Transformer}$$

$$R_{\Omega}actual = \frac{10(1.08\%)(0.280\ KV)^2}{150\ KVA} = 0.0056\ \Omega$$

$$X_{\Omega}actual = \frac{10(1.63\%)(0.280\ KV)^2}{150\ KVA} = 0.0085\ \Omega$$

And the result is:

R=0.0056 Ω and X=0.0085 Ω

2) Then, we have to find actual load current:

$$I = \frac{KVA}{KV\sqrt{3}} = \frac{150\ KVA}{0.28\ KV\ \sqrt{3}} = 309\ A$$

3) Using values, which we found above , we can calculate voltage drop:

$$V_d = \sqrt{3}\ I\ [\ Rcos\theta + X\ sin\theta\ ]$$

$$V_d = \sqrt{3}(309A)[0.0056 \cdot (0.8) + 0.0085 \cdot (0.6)] = 5.12\ Volts\ drop$$

$$\%V_d = \frac{5.12\ V}{280} \times 100 = 1.82\%$$

Finally, Voltage drop (V_d) is about 1.82%.

8. Conclusion

In my thesis, I tried to introduce transformer as an electrical machine, explain its operation, technical aspects and practical problems in utilization. We know that no device can work without losses and transformer is no exception. All the losses in the transformer are losses of active power that occur in the magnetic system, windings and other parts of the transformer under various operating conditions. I also described advantages of using parallel connection of Transformers; we know that it is economical to install numbers of smaller rated transformers in parallel than installing a bigger rated power transformers. It is also preferable to have a parallel transformer also for reliability reasons.

The last part was about the basic calculations during transformers operation in ES. Short circuits or faults can and do occur on electric power and distribution systems. When a fault occurs on the load side of a transformer, the fault current will pass through the transformer and as components on these systems, transformers need to be able to withstand these fault currents. These fault currents flowing through transformers are much higher than the rated currents of the transformers. From the calculation for short-circuit level we could see how transformer changes the short-circuit level i.e. SC power if the fault is on different Transformer sides.

Next example was for voltage drop to show a percentage voltage change if Transformer loaded e.g. by the rated power. And from this example we can see that in case of Transformers there is also voltage drop and we should compensate it by voltage control or tap changing.

At the end of my thesis I would like to tell about importance of transformers in power system. We know that energy is lost in the process of transmitting electricity long distances, for example, during the journey from a power plant to our home. Less energy is lost if the voltage is very high, so electrical utilities use high voltage in long-distance transmission wires. However, this high voltage is too dangerous for home use. Because of this electrical utilities use transformers to change the voltage of electricity. First, the voltage of electricity coming from the power plant is "stepped up" using transformers to the right level for long-distance transmission and then again using transformers the voltage is stepped down before it enters our home. I decided to research transformers, because they have become an essential part of our day-to-day life. I tried to describe basics of Transformers in my thesis and I believe the result might be useful.

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