Basic principles and operation of a transformer

Seminar paper for course Distribution and industrial networks

Andrea Ljubljanac

Mentor: professor Grega Bizjak

Ljubljana, March 2018
# TABLE OF CONTENTS

1  INTRODUCTION .................................................................................................................. 1

2  STANDARDS AND PRINCIPLES .......................................................................................... 2
   2.1 Basic transformer action ................................................................................................. 2
   2.2 Transformer equivalent circuit ....................................................................................... 3
   2.3 Voltage and current distribution and transformer impedance representation .................. 4
   2.4 Tap changers .................................................................................................................. 6

3  VOLTAGE, IMPEDANCE AND POWER RATING ................................................................. 9
   3.1 Voltage drop and impedance ......................................................................................... 9
   3.2 Voltage ratio and tappings ............................................................................................ 9
   3.3 Vector groups and neutral earthing .............................................................................. 10

4  THERMAL DESIGN ............................................................................................................. 12
   4.1 Temperature rise .......................................................................................................... 12
   4.2 Loss of life expectancy with temperature .................................................................... 12
   4.3 Ambient temperature .................................................................................................. 13
   4.4 Solar heating ................................................................................................................. 13
   4.5 Transformer cooling classifications ............................................................................. 13
   4.6 Selection of cooling classification ............................................................................... 16
   4.7 Capitalization of losses ............................................................................................... 16

5  CONSTRUCTIONAL ASPECTS ............................................................................................ 17
   5.1 Cores ........................................................................................................................... 17
   5.2 Windings ....................................................................................................................... 17
   5.3 Tanks and enclosures ................................................................................................... 18
   5.4 Low fire risk types ...................................................................................................... 19
   5.5 Underground transformers .......................................................................................... 19

6  ACCESSORIES .................................................................................................................... 20
   6.1 Buchholz relay .............................................................................................................. 20
   6.2 Sudden pressure relay and gas analyzer relay .............................................................. 20
   6.3 Pressure relief devices .................................................................................................. 20
   6.4 Temperature monitoring .............................................................................................. 21
   6.5 Breathers ..................................................................................................................... 21

7  CONCLUSION ....................................................................................................................... 22

8  QUESTIONS .......................................................................................................................... 23
A power transformer is a passive electromagnetic device that transfers energy from one circuit to another circuit by means of inductive coupling. Power transformers differ from other transformer types in that they are designed to comply with regulatory requirements for mains power interfacing, working at mains voltages and relatively high currents. The most important specification of a power transformer is its primary to secondary transformer galvanic isolation, which is usually specified in kV. This is a fundamental safety aspect in protecting humans from potentially lethal earth fault conditions.

Power transformers typically have a single primary (mains side) winding and one or more secondary windings. The secondary winding may be tapped at different points to generate multiple voltage outputs. A power transformer operates according to Faraday's Law of Induction. Transformers are extremely efficient when operating within their design specifications.

Core type is an important consideration. Typical power transformer supplies include laminated core. Laminations can be important as they help prevent eddy currents flowing in the core that cause loss of efficiency. The maximum output current is specified at the point where the core is saturated, or the windings current rating is exceeded. Power transformers are found in any application that requires mains power.

Power transformers play an important and significant role in the power system to connecting the subsystems and delivering the electricity to the consumers. They are one of the most expensive elements in the power system, which is why focusing on their status of parameters is the primary task. This seminar paper will focus on highlighting certain important aspects of voltage selection and thermal aspects.

Voltage selection goes for determining and calculating transformer voltage ratio, the specification of insulation levels, examples of voltage regulation, rating, tap ranges and impedance calculations.

Thermal aspects go for specification of temperature rise and ambient conditions. Also, constructional features of different types of a transformer in common use together with the purpose and selection of accessories.
2 STANDARDS AND PRINCIPLES

2.1 Basic transformer action

First, we will observe the phasor diagram for a single-phase transformer with a 1:1 turns ratio supplying an inductive load of power factor $\cos \phi_2$.

![Figure 1: Phasor diagram for a single-phase transformer with a 1:1 turns ratio supplying an inductive load of power factor $\cos \phi_2$.](image)

$I_0$ – no-load primary current
$I_m$ – primary magnetizing current
$I_c$ – primary core loss current (iron loss component; consists of hysteresis and eddy current components)
$I_1 R_1$ – primary resistance voltage drop
$I_1 X_1$ – primary reactance voltage drop
$I_1 Z_1$ – primary impedance voltage drop
$I_1$ – total primary current ($I_0 + I_2'$)
$I_2$ – secondary load current

$I_1'$ – load component of total primary current (reflected secondary current)
$\phi_m$ – maximum peak value of magnetic flux (linkage and leakage flux)
$V_1 (U_1)$ – primary terminal voltage
$E_1$ – primary induced emf
$V_2 (U_2)$ – secondary terminal voltage
$E_2$ – secondary induced emf
$\cos \theta_1$ – primary total load power factor
$\cos \theta_2$ – secondary load power factor

The construction of certain values is seen in Figure 1. It is important to emphasize that no-load current ($I_0$) is almost equal to $I_m$ in power transformers.

The whole magnetic field created by the primary is attracted into the steel core and is encircled by the secondary winding. The actual field strength, if is considered common to both primary and secondary transformer winding, becomes of no importance. Therefore, only following four variables of voltage and coil winding turns remain giving the
Basic principles and operation of transformer

The fundamental transformer expression:

\[ \frac{U_1}{U_2} \sim \frac{N_1}{N_2} \]

When a transformer is loaded, the voltage induced in the secondary winding coil drives a current into the load. Also, the secondary current produces its own magnetic field which is reducing (opposing) the existing field, which is why the field in the primary is reduced. More current flows until a turns balance is reached. The final outcome is that the magnetic field is left unchanged, comparing to the state before adding load to the secondary coil (\(I_1\) and \(I_2\) produce equal and opposite magnetic fields). This is why we get the second equation:

\[ N_1 \cdot I_1 = N_2 \cdot I_2 \]

The magnetic flux levels in the core do not rise in proportion to the load current. Combining previous two equations we get:

\[ U_1 \cdot I_1 = U_2 \cdot I_2 \]

### 2.2 Transformer equivalent circuit

Transformer equivalent circuit is the essential basis for different calculations including voltage drop or regulation under various load conditions. In Figure 2, the magnetizing circuit is taken as a shunt-connected impedance. The magnetizing current is rich in harmonics which must be kept in check. This is done by keeping the flux density within specified limits. When the transformer is being energized, the transient current inrush rich in second harmonic will result. A mentioned effect can be uncovered using transformer protection relays in a way that they control the existence of the second harmonic component, so that the anomalous tripping is avoided.

![Figure 2: Transformer equivalent circuit](image)

- \(V_1\) (\(U_1\)) – primary terminal voltage
- \(E_1\) – primary induced emf (theoretical)
- \(V_2\) (\(U_2\)) – secondary terminal voltage
- \(E_2\) – secondary induced emf (theoretical)
- \(I_0\) – vector sum of primary magnetizing and core loss currents
- \(I_1\) – total primary current (\(I_0 + I_2\))
- \(I_2\) – secondary load current
- \(I_2'\) – load component of total primary current (reflected secondary current)
- \(X_0\) & \(R_0\) – magnetizing and core loss reactive and resistive components
- \(X_1\) & \(R_1\) – primary winding reactive leakage and coil resistance
- \(X_2\) & \(R_2\) – secondary winding reactance and resistance
- \(N_1\) – primary coil number of turns
- \(N_2\) – secondary coil number of turns
2.3 Voltage and current distribution and transformer impedance representation

To illustrate the relationship between voltage and currents in transformer windings, vector representation, as shown in Figure 3 for Dy11 vector group transformer connection, is being used. Usually, the arrowheads are pointing away from the source of the generation towards the load.

![Winding Arrangement](image)

**Figure 3: Transformer phase relationships - Dyn11 connections**

Basic equations:

\[ K = \frac{\text{Primary phase-to-phase voltage}}{\text{Secondary phase-to-phase voltage}} \]

\[ I'_R = \frac{(I_r - I_b)}{\sqrt{3}K} \]

\[ I'_Y = \frac{(I_y - I_r)}{\sqrt{3}K} \]

\[ I'_B = \frac{(I_b - I_y)}{\sqrt{3}K} \]

Positive sequence: \[ I'_{R1} = I_{r1} \left( \frac{\sqrt{3}}{2} - j0.5 \right) \]

Negative sequence: \[ I'_{R2} = I_{r2} \left( \frac{\sqrt{3}}{2} - j0.5 \right) \]
Basic principles and operation of transformer

In load flow and fault studies, transformers are represented in the network diagrams by their equivalent impedances. For two winding power transformers, these impedances are usually represented as percentage reactance on the base of the transformer rating. Three winding transformers can be represented in an impedance network by three impedances, rather than a single. Both two winding and three winding transformers have equivalent positive and negative sequence impedances.

Transformer zero sequence impedances depend on winding vector grouping and neutral point earthing of both transformers and/or source generators within the system. Turns balance is normally produced within the transformer windings. Nevertheless, under fault conditions, the zero sequence impedance results in the extent to which the configuration allows the zero sequence current in one winding to be balanced by equivalent ampere-turns in another winding.

Two examples are given in Figures 4 and 5.

![Figure 4: Star/star (YNyn) transformer vector grouping with primary and secondary star points together with source generator solidly earthed](image)

$$Z_0 = Z_1 = Z_2$$

In Figure 4, primary and secondary ampere-turns are balanced. The transformer primary star point and the source generator are solidly earthed such that zero sequence currents arising from a fault on the secondary side of the transformer may flow in the primary circuit. The overall zero sequence impedance is that of the transformer and generator transferred to the same MVA or voltage base.

![Figure 5: Star/star (Yyn) transformer vector grouping with secondary star point and source generator solidly earthed](image)

$$Z_0 >> Z_1$$

In Figure 5, without primary star point earthing there is no path for zero sequence currents on the primary side of the transformer. Therefore, zero sequence fault currents on the secondary side are relatively small. The transformer connection approximates to an open circuit for zero sequence components. The actual value for $Z_0$ depends upon the transformer magnetic circuit arising from three or five limb constructions.
2.4 Tap changers

A tap changer is a mechanism in transformers which allows for variable turn ratios to be selected in discrete steps. Transformers with this mechanism obtain this variable turn ratio by connecting to several access points known as taps along either the primary or secondary winding.

Tap changers switches may be mounted separately on the side of the tank with their own separate oil insulation, or in the main transformer tank in order to reduce costs and result in a compact transformer design. Tap changers may be motor driven or manually operated by a switch.

Types of tap changers:

1. **Off-circuit** – The condition for this type of tap change is that the transformer is not energized. Off-circuit tap changers are usually switches which are located close to the winding tapings and they are operated by a handle or a wheel.

2. **Off-load** – The condition is that the circuit may be energized, but the operation is not happening when the circuit is drawing load current.

3. **On-load** – The tap changer may be operated under load conditions, which means they can change tapping position with transformer load current flowing. Some of the manufacturer’s requirements for this type of tap changer are: reliability, lowest cost, minimal maintenance, dielectric strength, electrical and mechanical life expectancy, overload and fault current capability.

Three basic tapping arrangements are shown in Figure 6.

![Tap changer arrangements](Figure 6: Basic arrangements of tapped windings)

*Linear arrangement* is mostly used for smaller tapping ranges and results in a simple tap changer. *Reversing arrangement* is commonly used for larger tapping ranges. The *coarse/fine arrangement* contains some of the advantages of the reversing arrangement but displays lower copper losses on the minimum tap position.

The most common and economical electrical connection for double wound
Basic principles and operation of transformer

 Transformers to the main winding is at the neutral end of star connected HV windings, though it is also possible to connect it to the delta-connected windings. For auto-transformers, the ideal position for the tapping is at the neutral end. As with double wound transformers, this has the advantage of a smaller, lower cost tap changer. However, it is also possible for auto-transformers to be positioned at the line-end taps. The line-end connection has the advantage to constant flux density and therefore constant tertiary voltage over the tapping range.

![Figure 7: Operating sequence of tap selector and diverter switch](image)

In Figure 7 the switching sequence of the tap changer selector and diverter switch is illustrated. The duty of the tap changer is to transfer connection from the selected tap to a preselected neighboring tapping without interrupting the power supply to the load. While the transfer switch is moving from contact M1 to contact M2, the load is carried by the transition impedance (RT), which is usually a resistor. The main contacts M1 and M2 are carrying the full load current continuously. The diverter switch contacts T1 and T2 must be capable of sustaining arc erosion and
Basic principles and operation of transformer

mechanical duty resulting from making and breaking full load current. The arcing of these contacts produces gases which saturate the neighboring oil and a barrier must be provided to separate this oil from the main transformer oil. *In-tank tap changers* have tapping winding peaks connected to the selector contacts (maintenance free) within the main transformer oil, while diverter switches (maintained) are enclosed in an oil-filled insulating cylinder which is piped to its own conservator. *Bolt-on tap changers* are divided into two main types:

1. *Double-compartment type* has a construction of separated selector contacts from the diverter switch, in which way two main compartments are formed. Now, they can be operated separately. Larger transformers build in the UK prefer this type.

2. *Single-compartment type* is used for the lower ratings. This type of tap changer uses selector switches which combine the function of selection and transfer in one mechanical device.

It is notable to mention the main standard reference for power transformers, which is IEC 60076.
3 VOLTAGE, IMPEDANCE AND POWER RATING

3.1 Voltage drop and impedance

Voltage drop happens in a transformer under secondary load conditions, due to the leakage reactance and the winding resistance. It is most commonly expressed as a percentage value referred to the kVA (or MVA) rating of the transformer. Regulation of the transformer is the change in transformer terminal voltage from no load to full load. This change matches with the volt drop appearing at the full load. Most commonly used formula is following:

\[ \Delta U = \sqrt{(R \cdot p)^2 + (X \cdot q)^2} \times 100\% \]

- \( X \) - leakage reactance (%)
- \( R \) - winding resistance (%)
- \( p \) - power factor, \( \cos \phi \) (%)
- \( q \) - \( \sin \phi \) (%)
- \( \Delta U \) - % volt drop at full load

The main parameter for a transformer is the short circuit (internal) impedance. The lowest value is limited by the minimum physical distance between windings, while the highest is limited by the effects of the associated high leakage flux. This means that extreme values are limited by design factor.

Three phase systems consider zero sequence impedance as well, as it determines the magnitude of fault currents flowing between the neutral of a star-connected winding and earth during phase-to-earth faults. This impedance depends on the core configuration (whether it is 3 or 5 limb core) and whether or not a delta-connected auxiliary winding is fitted.

3.2 Voltage ratio and tappings

It is always advisable to think twice before deciding on the voltage ratio for the transformer. For example, if there is a transformer with values 132kV connecting to the 20kV system, this does not mean that the voltage ratio is 132/20kV since we need to take into account:

1. The 132kv voltage is not constant and may vary as much as \( \pm 10\% \) from the nominal value
2. Volt drop on load will lower the voltage at the 20kV terminals.

Every practical transformer will need tappings to allow selection of different voltage ratios to suit different circumstances.

Off-circuit (off-load) tappings are used in situations when the transformer regulation and the primary voltage variations are small, which means that change from one tapping to another will be very rare in the transformer life. These are usually used in domestic and industrial distribution systems. The voltage ratio is usually chosen to give approximately nominal secondary voltage at full load. Therefore, a ratio of 11 kV to 433 V is usually chosen to feed a 415 V system. Distribution transformer off-circuit tappings giving -5.0%, -2.5%, 0%, +2.5% and +5.0% variation in ratio are conventionally specified and will be adequate for the
Basic principles and operation of transformer

majority of situations. The middle tap of a transformer is referred to as the 'principal tap'.
*On-load* tappings are used for frequent changes in tapping without removing the transformer from service. They are used in most of transmission system applications. However, the procedure for defining voltage ratio and tapping range often causes problems. In the standard IEC 60076-1 are defined categories of voltage variation for transformers with tappings.

### 3.3 Vector groups and neutral earthing

Three configurations in which three phase windings of the transformer are usually connected are *delta, a star or an interconnected star (zig-zag)*. The configurations are shown in Figure 8. How the vectors are grouped and how the phase relationship nomenclature is used are defined as follows:

- Capital letters for primary winding vector group designation
- Small letters for secondary winding group designation
- D or d represents a primary or a secondary delta winding
- Y or y represents a primary or secondary star winding
- Z or z represents a primary or secondary interconnected star winding
- N or n indicates primary or secondary winding with an earth connection to the star point
- Numbers represent phase relationship between the primary and the secondary windings. The secondary to primary voltage displacement angles are given in accordance with the position of the “hands” on a clock relative to the mid-day or twelve o’clock position (this means: 1 is -30°, 3 is -90°, 11 is +30° and so on).

![Figure 8: Winding arrangements](image)
Example on defining Dy1 vector grouping is given in Figure 8. In this case, it is noticeable that the secondary star voltage is at the one o’clock position, meaning that it is lagging the primary delta voltage vector by 30°.

![Figure 8: Determination of Dy1 vector grouping](image)

In Figure 9, there is another example of defining Dyn5 vector grouping. It is clear that the secondary star voltage is at the 5 o’clock position, meaning that it is lagging the primary delta voltage vector by $5 \cdot 30^\circ = 150^\circ$.

Mostly the system designers are the one to decide which vector grouping arrangement is required for each voltage level in the network, though there are many factors influencing the decision. Important aspects from user’s point of view are:

- Vector displacement between the systems connected to each winding of the transformer and ability to achieve parallel operation
- Provision of a neutral earth point or points, where the neutral is referred to earth either directly or through an impedance
- The practicality of transformer design and cost associated with insulation requirements
- The Z winding reduces voltage unbalance in systems where the load is not equally distributed between phases and permits neutral current loading with inherently low zero-sequence impedance. Therefore, it is often used for earthing transformers.
4 THERMAL DESIGN

There are several ways of producing heat in a transformer. Most significant ones are the heat produced in a transformer due to the flow of load current through the resistance of the winding conductor, where load loss exists, and due to the heat production in the magnetic core, where there is no load loss. Some other sources of heat include dielectric heating of insulating materials, eddy current heating in conductors and support steel structures. Thermal design of a transformer aims to remove this heat economically and effectively, in a way to avoid any unwanted deterioration of components.

4.1 Temperature rise

The heat is produced in the windings of the conductor. Windings are insulated with a paper type wound around them. It is saturated with oil, since the winding is located in the oil inside of the transformer tank, so this insulation is good for protecting (insulating) from the earthed parts and other windings. Heat from the conductor moves through the paper type insulation, then in the bulk of oil and it is finally conducted away from the winding, which results in dissipation of the heat into the air. To prevent damage of the conductor, the maximum temperature is determined, which is on average 98°C. Generally, not all the parts of a winding are the same temperature. The warmest part is called the "hot spot", which location is not always known, but it can be determined with the infrared imaging technique. Besides hot spot, also "average winding temperature" is determined. From the researches, it is known that the "hot spot" temperature is about 13°C above the average winding temperature. However, when the transformer is unloaded the conductor temperature is practically the same as the ambient temperature. From these conclusions, follows the formula for the temperature of the hot spot:

\[ \text{hot spot temperature} = \text{ambient temperature} + \text{average winding temperature rise} + \text{hot spot differential} \]

Based on the IEC specification and conclusions written above, following can be said:

\[ 98°C \geq 20°C + \text{average winding temperature rise} + 13°C \]

Which means that the average winding temperature rise should be ≤65°C, which is a basis of the IEC specification.

4.2 Loss of life expectancy with temperature

In the previous segment, it was mentioned that the insulating materials are determined by the maximum temperature, which does not mean that immediate insulation failure would happen, but that the insulation would have shortened lifespan. The estimated lifespan is determined by the law due to Arrhenius:

\[ \text{Loss of life expectancy} = A + B/T \]

A and B are empirical constants for a given material
T is the absolute temperature in °C

The Arrhenius effect equalizes the periods of operation with the insulation above
the “normal life” temperature with the periods of the lower temperature, where the life is above normal. The good example is the ambient temperature of insulator during winter and summer, which significantly changes, but after all the lifespan is equalized.

4.3 Ambient temperature

Ambient temperature is not the same everywhere around the world. That means that the average winding temperature rise would drop (or rise) if the ambient temperature is higher (lower).

Nevertheless, the IEC reference ambient temperature is given in four components as follows:
- Maximum: 40°C
- Maximum average over a 24-hour period: 30°C
- Annual average: 20°C
- Minimum -25°C

The correct annual average temperature to use when specifying transformers is a “weighted” value given as follows:

$$T_{a^1} = 20 \log_{10} \left( \frac{1}{N} \sum_{1}^{N} 10^{T_a/20} \right)$$

$T_{a^1}$ – weighted annual ambient temperature
$T_a$ – monthly average temperature
$N$ – month number

The weighted value is designed to take proper account of the Arrhenius law.

4.4 Solar heating

In tropical climates, it is important to include solar heating of transformers into account. In these cases, the additional typical rise of the oil in the transformer is small, about 2°C to 3°C. However, the transformers which has a large surface compared to the volume (like pole-mounted units) can get higher temperature rise, between 5°C and 10°C. This means that much should be subtracted from the permitted winding temperature rise at full load.

4.5 Transformer cooling classifications

Previously, one method of cooling the transformer has been mentioned, where the heat is conducted to the oil from the windings and core, after which is transmitted to the surrounding air at the tank surface. Practically, only the smallest pole-mounted distribution transformers have enough tank surface to dissipate the internal heat effectively (Figure 10.a). With larger transformers, the surface area for heat dissipation is deliberately increased by attaching radiators to the tank. A 1000kVA hermetically sealed transformer with radiators is shown in Figure 10.b.
Figure 10: Cooling arrangements: a) Tank surface only and b) Radiators on a tank

With even larger transformers, separate cooler banks are used as indicated in Figure 11.

Figure 11: Cooling arrangement: separate cooler banks

The only mentioned and first described method of cooling has no moving parts. It functions in a way when the oil is warmed inside the tank it raises up (to the tops of the radiators) and as the oil cools down it falls to the bottom of the radiator and then back into the bottom of the tank. This is called natural circulation of cooling oil and it repeats itself.
Basic principles and operation of transformer

There are several ways to increase cooling efficiency, like adding fans to the radiators to blow cooling air across the radiator surfaces. This method is shown in Figure 12.

![Figure 12: Cooling arrangement: fans attached to the radiators](image)

Another possible increase in efficiency is achieved by pumping the oil around the cooling circuit, and in that way boosting the natural circulation. The classification done in the terms of IEC cooling classification codes gives the user codes which indicate the primary cooling medium (the medium extracting the heat from the windings and core) and the secondary cooling medium (the medium which removes the heat from the primary cooling medium). The following codes are used:

<table>
<thead>
<tr>
<th>KIND OF COOLING MEDIUM</th>
<th>CODE</th>
</tr>
</thead>
<tbody>
<tr>
<td>MINERAL OIL</td>
<td>O</td>
</tr>
<tr>
<td>WATER</td>
<td>W</td>
</tr>
<tr>
<td>AIR</td>
<td>A</td>
</tr>
<tr>
<td>NON-FLAMMABLE OIL</td>
<td>L</td>
</tr>
<tr>
<td>KIND OF CIRCULATION</td>
<td></td>
</tr>
<tr>
<td>NATURAL</td>
<td>N</td>
</tr>
<tr>
<td>FORCED</td>
<td>F</td>
</tr>
<tr>
<td>FORCED DIRECTED LIQUID</td>
<td>D</td>
</tr>
</tbody>
</table>

Table 1: Coding method

With coding method it is possible to choose kind of primary cooling medium and it’s type of circulation and kind of secondary cooling medium and it’s type of circulation (i.e. an oil-immersed transformer with natural oil circulation to radiators dissipating heat naturally to surrounding air is coded as ONAN, while adding fans makes it ONAF; dry type transformer uses only two-letter code, AN).
4.6 Selection of cooling classification

It is hard to choose the most appropriate method of cooling for a particular application, but the following guidance for mineral oil-immersed transformers may help. The basic questions to consider are related to capital cost, maintenance procedure, use of the transformer (on its own or parallel), how critical is physical size.

ONAN
This type of cooling requires zero to minimum maintenance, as it has no mechanical moving parts. Numerous developing countries prefer this type of cooling because of the reliability, but there is an increasing cost penalty as sizes increase.

ONAF
This type has fans fitted to the radiators, and it has the rating between 15% and 33% greater than with the fans not in operation. Therefore, the transformer has an effective dual rating under ONAN and ONAF conditions. It can be specified as 20/25MVA ONAN/ONAF. However, it is not always desirable to use ONAN/ONAF transformers, as in the example of transformers working in parallel. In this case, fans would run very rarely and will produce a loud noise, which can be a problem in environmentally sensitive areas.

OFAF
Generator transformers and power station interbus transformers often use OFAF cooling. This cooling method is forcing the oil circulation and blowing air over the radiators. The maintenance burden is increased owing to the oil pumps, motors and radiator fans required. Good maintenance procedures are recommended.

ODAF/ODWF
These are special cooling categories where the oil is directed by pumps into the closest proximity possible to the winding conductors. The external cooling medium can be air or water. Because of the design, the operation of the oil pumps, cooling fans, or water pumps is crucial to the rating obtainable and such transformers may have rather poor naturally cooled (ONAN) ratings. Such directed and forced cooling results in a compact and economical design suitable for use in well-maintained environments.

4.7 Capitalization of losses

Lower investment in materials will result in initial lower costs, but a shorter life of transformer, when on the other side, investing a bit more initially in the transformer can pay off in a way of a longer lifetime of the transformer.

The total cost of the transformer is called the capital cost. In most cases, the consultant or electrical supply utility will specify separate capitalizing factors for the load and no-load losses and typical figures for UK transmission transformers are: no-load loss capitalization rate £4000/kW; load loss capitalization rate £650/kW.

The transformer manufacturer can then easily calculate the capitalized price following the formula:

\[
\text{Capitalized cost} = \text{selling cost} + 4000 \times \text{no-load losses (kW)} + 650 \times \text{load loss (kW)}
\]
5 CONSTRUCTIONAL ASPECTS

5.1 Cores

In order to enhance core’s magnetic properties, it is constructed from an iron and silicon mixture (alloy). The magnetic core consists of a few thin sheets (0.3 mm to 0.23 mm thick) of the core metal. Each of these sheets has a thin layer of insulation so that conduction between sheets is not possible. In this way, the eddy currents are minimized in the core metal. This type of core is called laminated core (Figure 13). Leading transformer manufacturers also use surface laser-etched 0.23 mm steels, which results in further 15% loss reduction and such treatment may be justified as a result of the electrical supply utility’s loss capitalization formulae. It is also important, for the transmission and distribution system engineer, to specify the flux density in conjunction with the manufacturer before ordering transformers. If the flux density is too high, the transformer may go into saturation at the most difficult tap setting.

By avoiding air gaps or non-magnetic components at joints, a continuous magnetic circuit is obtained.

![Laminated core of a transformer](image)

**Figure 13: Laminated core of a transformer**

5.2 Windings

- **Conductors and insulation**
  
  To reduce load losses, transmission and distribution oil-immersed power transformer windings are usually made of copper. In oil-immersed transformers is used a cellulose paper material as winding insulation. Aluminum has a higher specific resistance than copper, which is why it requires a larger cross-section for a given current rating. However, aluminum has certain advantages over copper when used as foil windings in a dry type cast resin distribution transformers. The short circuit thermal withstand time tends to be greater for aluminum than for the copper in an equivalent design. Also, aluminum foil eddy current losses are lower.

- **Two winding (double wound)**
  
  This is the basic transformer type with two windings connecting a higher voltage system to a lower voltage system. This type is the normal arrangement for step-down transformers in distribution and sub-transmission systems and for generator transformers.
Three winding

Third winding is added because a third voltage level is involved or for design reasons. A star/star transformer is often combined with third (delta-connected) winding. This can be for numerous of reasons:

- In order to reduce the transformer impedance to zero sequence currents, so that earth fault currents of sufficient magnitude can flow to operate the protection
- In order to suppress the third harmonics due to the no-load current in the earth connection when the neutral is earthed
- In order to stabilize the phase-to-phase voltages under unbalanced load conditions
- In order to enable overpotential testing of large high voltage transformers to be carried out by excitation at a relatively low voltage
- In order to provide an intermediate voltage level for supply to an auxiliary load where a tertiary winding offers a more economical solution than a separate transformer

Besides these advantages, there are still some disadvantages concerning three winding cores, as it increases costs of a transformer by 6% to 8% which follows also additional losses of 5%.

Auto-transformers

This type of transformer has only one winding. Prefix auto refers to the single coil acting alone (not to any kind of automatic mechanism). Portions of the same winding act as both the primary and the secondary sides of the transformer (if a tap is made part way down the winding). Since having just one winding, auto-transformers have advantages of often being smaller lighter and cheaper than typical two winding transformers. A disadvantage is not providing electrical insulation between primary and secondary circuits. Auto-transformers are usually star connected, which means that both high and low voltage systems have the same neutral. This is only desirable in transmission systems where solid earthing of neutrals is common at all voltage levels.

5.3 Tanks and enclosures

Oil preservation

The oil inside transformer tank acts as heat transfer medium and an insulation. The oil must be dry and free from contaminants, to keep good insulating properties. This is done by sealing the oil inside the tank so that there is no contact with the atmosphere. Also, there has to be left some free area to allow expansion in volume of oil because of temperature changes. Some of the methods to be used depending on the rating of the transformer, its location and the particular policy of the manufacturer are:

- **Sealed rigid tank** – The tank is not fully filled with oil. The free space above oil is filled with a dry gas, which has no chemical reaction with the oil. The tank should be strong because of the large pressure changes inside of it.
- **Sealed expandable tank** – Not all the transformers can use this technique. The tank is fully filled with oil, but the surfaces of the tank are flexible to allow the expansion of oil due to temperature changes.
- **Positive pressure nitrogen** – It is applied to the large transformers. It is similar to the sealed rigid tanks, just that it has venting for minimizing pressure changes.
- **Conservator (with breather)** – Applied to any size of transformers. The tank
Basic principles and operation of transformer

is filled with oil and changes in volume are allowed by an expansion tank (conservator) mounted above the main tank. A conservator has a vent to the atmosphere, in which an air-drying device is located.

- **Conservator (with diaphragm seal)** – The expansion tank contains a flexible synthetic rubber diaphragm which allows for oil expansion, but seals the oil from the atmosphere.

It is crucial that the quality of tank welding, gasketing, and painting is carefully specified and inspected prior to release from the manufacturer’s works, in order to avoid oil leakage.

- **Dry type transformer enclosures**

These types of transformers have physical protection around them to protect the core and windings from dust, water entry, condensation and to keep personnel away from live parts. Open steel mesh surround may be specified for indoor applications depending on the classification required.

5.4 **Low fire risk types**

The possible situations where a transformer may be involved in a fire fall in three categories:

- There has been an internal fault that leads to ignition and subsequent burning of the materials within the transformer. However, arcing faults should be cleared by overcurrent devices in short time.
- The transformer is located in the enclosed space involving materials such as wood, which could ignite the transformer.
- The transformer is located in an enclosure in which a fire involving hydrocarbon fuels or plastic materials occur taking the transformer in flames.

When comparing the dry type and non-flammable liquid-immersed types to the mineral oil-immersed units, the difference in cost is noticeable (latter are the cheapest).

The fire protection of transformers is usually done by controlling the oil spillage from a tank. For outdoor installations, additional protection exists, represented by a temperature sensor located above the transformer, which initiates water spray or foam system to extinguish the fire.

5.5 **Underground transformers**

Distribution transformers may be buried or installed in underground chambers. This is usually done in dense urban areas where substation sites are difficult to obtain. In Europe are typically directly buried small units up to 1 MVA, which are ON/AF types and in the USA, which are AN/AF types, both with air ducts leading to a radiator on the surface. Problem with these types of transformers is tank corrosion of directly buried units. Special care should include minimizing the effect of soil drying, which can be done by using the thermal backfill. Another type of underground transformers includes those of size 100 MVA, which are in underground substations and in fully accessible rooms.
Beside elementary assembly of transformers, there are also additional accessories which may or may not be obligatory for a transformer. Those are accessories for protection, safety purposes, and monitoring.

### 6.1 Buchholz relay

Buchholz relay is a protective device mounted on some oil-filled power transformers, equipped with an external overhead oil reservoir – conservator (Figure 14). They are mandatory for conservator type transformers. This type of relay is designed to detect free gas being slowly produced in the main tank, possibly as a result of partial discharging. It also detects sudden rush movement of oil, when an internal transform fault happens. Buchholz relay also provides a chamber for collection and later analysis of evolved gas, which can give maintenance staff and an indication as to the cause of the fault.

![Figure 14: Placement of Buchholz relay](image)

### 6.2 Sudden pressure relay and gas analyzer relay

Sudden pressure relays are usual accessories for sealed transformers, while gas analyzer devices are only used on large important transformers. Sudden pressure relay detects internal pressure rises due to falls, and gas devices can be used to detect an accumulation of gases.

### 6.3 Pressure relief devices

Pressure relief devise is used to give a controlled release of internal pressure, in order to avoid tank rupture resulting from the high pressure involved in an internal transformer fault. They should be an essential accessory for all oil-immersed transformers, while very large transformers may require even two of these devices. Transformers which are older may be equipped with a diaphragm, where the excess pressure breaks the diaphragm and oil is discharged. For this reason, it may be important to have pressure relief device.
6.4 Temperature monitoring

Oil and winding temperature is monitored in all but small (less than 200 kVA) distribution transformers. If a transformer is correctly loaded and specified, it should not produce excessive temperatures. Winding temperature indicator usually has a feature to initiate automatic switch-on and switch-off of cooling fans and oil circulation pumps. This is how ONAN/ONAF will automatically switch from ONAN to ONAF (and vice versa), according to the transformer loading conditions. Temperature monitoring can also help in detecting “hot spot” winding temperature. Oil temperature monitor is usually a capillary type thermometer with the sensor located near the hottest oil in the tank (i.e. at the top of the tank, before hot oil enters the radiators). Both oil and winding temperature monitors are fitted with contacts which can be set to operate at the desired temperature. These contacts are used for alarm and trip purposes.

6.5 Breathers

Breathers are places in the vent pipes of conservators as the volume of oil contracts on transformer cooling. They use the moisture absorbing crystals, which are replaced when the color of them changes (this means that they are saturated with moisture). The alternative way is to continuously separate moisture dissolved in the transformer oil by freezing the moisture out of the air by passing it over refrigerating elements and then evaporating it off to the atmosphere. Breather that uses this technique is called Drycol breather (Figure 15), which is commonly used in the UK. This technique improves the life-span of the transformers, as researchers state.

![Figure 15: Drycol breather](image)

Some other accessories used in the transformers are also core earth link, oil level gauge, tap changer accessories and oil sampling valve.
In this seminar, basic components, standards, and principles of a transformer have been described. When applying power transformer to the wanted part in the power network, it is important to follow requirements and specifications given, together with the use of essential monitoring, safety, and reliability accessories. Otherwise, significant damages may occur.

When choosing the transformer for one’s application, the geographical location should be taken into consideration too, as the thermal design is dependent on the average ambient temperature, which varies around the world. Accordingly, should the cooling systems be chosen and used.

Power transformers are a crucial part of the power systems. Considering this fact, continuous monitoring and diagnostics of transformers increase stability, reliability, and safety as well as their life-span. Also, non-obligatory, but desirable accessories may be used, such as Buchholz relay, sudden pressure relay, pressure relief devices, breathers.
8 QUESTIONS

1) What is the use of tap changer and how do we divide them?

The purpose of a tap changer is to regulate the output voltage of a transformer. It does this by altering the number of turns in one winding and thereby changing the turns ratio of the transformer.

Types of tap changers:
- Off-circuit
- Off-load
- On-load

2) When does a voltage drop in a transformer happen?

Voltage drop happens in a transformer under secondary load conditions, due to the leakage reactance and the winding resistance. It is most commonly expressed as a percentage value referred to the kVA (or MVA) rating of the transformer.

3) What is the “hot spot” and how do we calculate its temperature?

The warmest part of the winding is called the “hot spot”.

The formula for the temperature of the hot spot is:

\[
\text{hot spot temperature} = \text{ambient temperature} + \frac{1}{2} \left( \text{average winding temperature rise} + \text{hot spot differential} \right)
\]

4) How are transformers divided based on the number of windings?

They are divided into following types:
- two winding (double wound)
- three winding
- auto-transformers (one winding)
Basic principles and operation of transformer

**HOMEWORK**

a) Find the volt drop of the three-phase transformer with a leakage reactance of 6.6%, and resistance of 2.4%. The transformer has manufacturer rating given as follows:

\[ \frac{U_1}{U_2} = 12.7kV/0.23kV \]
\[ S = 150 \text{ kVA} \]
\[ P = 120 \text{ kW} \]
\[ R = 2.4\% \]
\[ X = 6.6\% \]

Solution:

We will use the following formula:

\[ \Delta U = \sqrt{(R \cdot p)^2 + (X \cdot q)^2} \]

Observing the formula, we realize that we need to calculate power factor \((cos\varphi = p)\).

\[ p = cos\varphi = \frac{P}{S} = \frac{120}{150} = 0.8 \]

Therefore, we can also get \(sin\varphi \ (q)\):

\[ q = sin\varphi = \sqrt{1 - cos^2\varphi} = \sqrt{1 - 0.8} = 0.6 \]

Finally, we have:

\[ \Delta U = \frac{\sqrt{(R \cdot p)^2 + (X \cdot q)^2}}{100\%} = \frac{\sqrt{(2.4 \cdot 80)^2 + (6.6 \cdot 60)^2}}{100\%} = 4.4\% \]

b) Draw a vector diagram of three-phase distribution transformer with vector grouping Yd7.

Solution:

![Vector diagram](image)
Basic principles and operation of transformer

10 LITERATURE

1) C. Bayliss, B. Hardy: Transmission and Distribution Electric Engineering
2) Vezir Rexhepi: An Analysis of Power Transformer Outages and Reliability Monitoring
3) https://en.wikipedia.org/wiki/ (date of use 06.03.2018)
4) Andrea Ljubljanac, notes from lectures and exercises from course Generators and Transformers