Basic Principles and Operation of Transformer

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.

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:

$$\text{Hotspot temperature} = \text{ambient temperature} + \text{average winding temperature rise} + \text{hot spot differential}$$

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.

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.

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

Transformer cooling classifications

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. 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.

Cooling arrangements: a) Tank surface only and b) Radiators on a tank

With even larger transformers, separate cooler banks are used as indicated. 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.
There are several ways to increase cooling efficiency, like adding fans to the radiators to blow cooling air across the radiator surfaces.

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>
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<tbody>
<tr>
<td>MINERAL OIL</td>
<td>O</td>
</tr>
<tr>
<td>WATER</td>
<td>W</td>
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<tr>
<td>AIR</td>
<td>A</td>
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<tr>
<td>NON-FLAMMABLE OIL</td>
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<tr>
<td>KIND OF CIRCULATION</td>
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<tr>
<td>NATURAL</td>
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<td>FORCED</td>
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<tr>
<td>FORCED DIRECTED LIQUID</td>
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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).

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 inter-bus 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.

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:

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

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To be continued........