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The influence of transformer loading to the ageing of the oil–paper insulation

Z. Radakovic[1], E. Cardillo[2] and K. Feser[2]
[1] University of Belgrade, Belgrade, Yugoslavia
[2] University of Stuttgart, Stuttgart, Germany

Abstract: The paper deals with the problem of degradation process of the mechanical and dielectric insulation system properties. Although there are many factors influencing this process in a real transformer operation, the only factor considered quantitatively is the temperature of the solid insulation. The intensity of thermal ageing is dependent on the hot-spot temperature. This temperature is neither easy to measure nor to calculate. An overview of calculating methods and generally of possible approaches is discussed in the paper. All parameters limiting a transformer loading are systematically exposed in the paper, followed by appropriate examples. Also, some considerations of thermal protection and monitoring systems, experienced by the authors, are contained in the paper.

1. Introduction

Power transformers should have proper insulation and mechanical properties matching rated voltages and expected mechanical stresses during short-circuit faults. During a transformer operation the insulating and mechanical properties of the solid winding insulation are degrading continuously. This change is the result of irreversible change in the structure of solid insulation material. The most expressive factor characterizing the structure change is the degree of polymerization (DP), which represents the average number of glucose rings in the molecule of cellulose. Three mechanisms contribute to the insulation degradation [1]: hydrolysis, oxidation and pyrolysis. The agents responsible for the respective mechanisms are water, oxygen and heat. Water and oxygen content can be controlled by the transformer oil preservation system, but heat can not be controlled and depends on the loading conditions. Some investigations, reviewed in [1], showed that the deterioration rate is directly proportional to the water content. In the case of a failure of the oil preservation system (loss of tank seal), the water and oxygen content change, which dramatically accelerates the insulation deterioration. Especially it is valid for the oxidation process where the products of oil oxidation (acids, esters and metallic soap) attack the cellulose insulation with vigor and tenacity. Supposing ideal conditions (moisture content of less than 0.5 % by weight and oil having an oxygen content of less than 500 ppm) the ageing of the insulation is usually considered as temperature dependent, i. e. transformer loading only.

The most intensive ageing process appears at the point of the highest insulation temperature (hot-spot temperature). Due to the fact that transformers are mainly loaded with different current and at different ambient temperature, the hot-spot temperature is not constant and there is a strong practical interest for the functional dependence of ageing from the hot-spot temperature. This function enables to calculate the ageing in every moment and after that a cumulative value for a longer period - usually for a period of a cyclic hot-spot temperature change (typically one year). Some explanations about laws of thermal ageing are exposed in the next section.

The value of the hot-spot temperature during a transformer loading is not important for the thermal ageing only. This temperature and also the top oil temperature must not exceed prescribed limits in order to avoid immediate fault. Although the current change does not produce instantaneously the change of temperatures, the highest current of a transformer is limited [1-3].

In a real time transformer operation, the loading strategy should be to keep the ageing under a desired limit, but obligatory to keep the maximal hot-spot and top oil temperatures and the current load under the allowed limits. The following limits are given in [2]: the current can be 30 % to 100 % (the amount depends on the transformer size and the operating conditions) above rated current of a transformer, the hot-spot temperature range stretches from 120 ^{0}C to 160 ^{0}C and the top oil temperature extends from 105 ^{0}C to 115 ^{0}C. For instant, for distribution transformers and normal cyclic load, the limits amount 1.5 p. u. for the load current, 140 ^{0}C for the hot-spot temperature and 105 ^{0}C for the top-oil temperature.

2. Laws of thermal ageing

Nowadays usually used laws are established on Arrhenius relation:

$$D=e^{\alpha+\beta/T} \qquad (1)$$

D is the expected transformer life, α and β are material constants and T is the absolute hot-spot temperature (K).

For the operating temperature level in transformers, Montsinger has proposed a somewhat simpler relation:

$$D = K\, e^{-p\vartheta}, \tag{2}$$

where K and p are the material constants and ϑ is the hot-spot temperature in ^{0}C.

Since there is no clear criteria of the insulation's end of life, it is not an easy task to define the constants in expressions (1) and (2). Especially this is valid for the constants α in (1) and K in (2), i. e. the constants β and p are more or less known. That is the main reason why relative ageing functions are introduced; the expected life is expressed as a per unit value to the expected life at "normal" (rated) temperature ϑ_n. In fact, instead of the relative expected life, commonly the inverse function is used; this function is conventionally called relative thermal ageing (V). In the case of using (1), it is equal to

$$V = e^{\beta/T_n - \beta/T} \tag{3}$$

and in the case of (2)

$$V = e^{\,p(\vartheta - \vartheta_n)} \tag{4}$$

i.e.

$$V = 2^{\frac{\vartheta - \vartheta_n}{\theta_i}} \tag{5}$$

The relations between constants p and θ_i can be derived from (2) using elementary mathematical operations.

The values of the constants used in literature are $\beta = 15000$ [1] and $\theta_i = 6$ K [3]. A very important question is how to define the rated temperature. In [1] the value of 110 ^{0}C is adopted and in [3] the value is specified to 98 ^{0}C. In [2] both of these values are present with the following explanation. Under ideal conditions the relative ageing rate 1.0 corresponds to a temperature of 110 ^{0}C for all types of paper insulation. However, during its service life, a transformer may have a higher moisture content and may contain oil having a higher oxygen content. Taking these factors into consideration, for non-thermally upgraded paper insulation, the relative ageing rate of 1.0 corresponds to the lower temperature of 98 ^{0}C (the difference between non-thermally upgraded and thermally upgraded paper as regards to the influence of moisture content is explained in [4]).

3. Practical application of the calculation

The cases of constant load and constant ambient temperatures can be considered as exemptions in a transformer loading practice. A "normal" practice of a transformer loading would be to have a unity ageing in a cyclic one year period. Owing to the periods with lower temperatures, when the ageing is smaller than the rated, it is allowed to apply temporarily loads and temperatures higher than the rated values. In periods of a transformer overloading, the allowed temperature and current limits must not be exceeded. Regarding to this, the type of overloading (normal cyclic, long-time emergency and short-time emergency) has to be defined in order to select a proper set of limits.

The calculations can be used twofold: to dimension a transformer for a known loading diagram or to determine the maximal load of an existing transformer. In both cases the loading diagrams are expressed in per unit values. The shapes of the diagrams have to be defined, as well as the shape of cooling medium temperature change. Details of the procedures are given in [5] and [6].

As an example for a "hypothetical" transformer with rated current of 400 A one of the daily diagrams in normal operation conditions is shown in Figure 1, and for a short-time emergency loading in Figure 2 (solid lines). These diagrams were measured at 10 kV feeder in a 110 kV / 10 kV transformer station and represents a cumulative load of a number of distribution transformers 10 kV / 0.4 kV of lower rated powers. That is why the load is quoted as the load of "hypothetical" transformer. The factors of maximal diagram scaling determined for these two diagrams were $F_N = 1.63$ and $F_E = 1.45$. As the critical limits maximal p. u. current has appeared. Since $F_N > F_E$, the emergency loading is more critical, i. e. maximal load in a normal operation has to be $(1.5 \cdot 400\text{ A}) \cdot (1.45 / 1.63) = 533$ A to avoid exceeding the limit of $1.8 \cdot 400 = 720$ A during short-time emergency loading. The p. u. current limit 1.5 and 1.8 are taken from [2], as ones valid for distribution transformers. The result can also be interpreted so that for the given loading diagrams the transformer of rated current $400 / 1.45 = 276$ A is sufficient. In concrete case, the emergency load was caused by drastic breaks in the power supply during the war years in Serbia due to the lack of energy. A detailed analysis is exposed in [6].

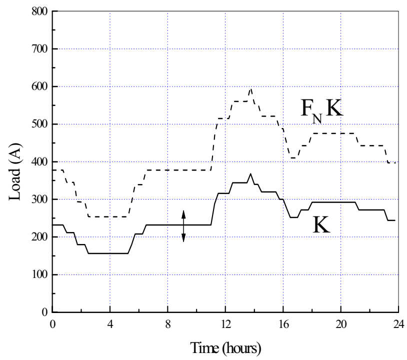

Figure 1: Daily diagrams in a normal operation.

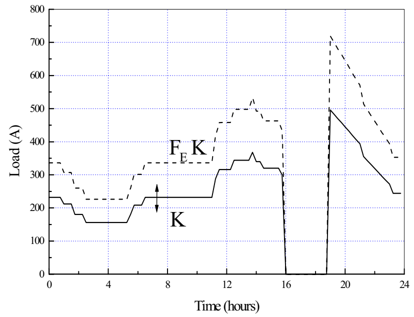

Figure 2: Daily diagrams in a short-time emergency loading.

An emergency load can also occur due to some faults causing lost of transformer consumer supply [7] or faults in the network causing the need that a transformer accepts additional power transfer.

4. Aspects of protection and monitoring systems

If the strategy decision is to overload a transformer to the maximum, a monitoring of all important parameters is necessary to avoid possible damage of a transformer. Three practical solutions can be met: 1. monitoring of two temperatures, current and the ageing, 2. monitoring of the temperatures and the current, 3. monitoring of the current. By the simplest solution 3 the reliability is the lowest. For example, in the case of loading diagrams given in Figure 1 and Figure 2, as a critical factor the maximum p. u. current in emergency conditions appeared. If the diagrams would not change their shapes, it would be sufficient to have only overcurrent protection set to 1.8 p. u. In the case of a proportional load increase the first factor indicating high load would be the reaction of the overcurrent protection in an emergency condition. The reliability of the protection is jeopardised by the prolongation of the maximal load, since in that case the maximal temperatures can appear as a critical limit. An example of such a load diagram change in normal operation is shown in Figure 3.

So, to keep reliable protection, it is necessary to monitor the temperatures. Further prolongation of maximal load after a certain amount leads to the ageing as a critical limit. Up-to date thermal digital relays have the possibility of ageing calculation.

Generally speaking, in many practical cases it is not expected that the shape of diagrams would change intensively. Especially it is expected on small transformer units with fixed consumers. In spite of that it seems too risky to protect a transformer only with overcurrent protection set-up to a high p. u. current value and simple contact thermometer for top oil temperature measurement. The authors experience with the staff in power utility companies is that nobody would accept transformer loading "at the edge" without having information about the hot-spot temperature and the ageing.

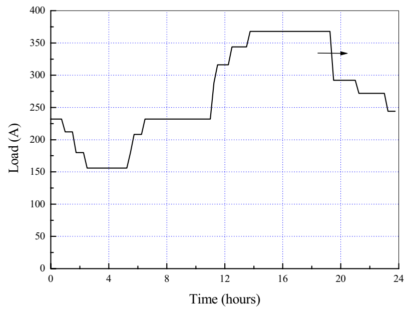

Figure 3: Change of the load shape influencing the needed type of the protection.

Monitoring systems basically give just additional comfort, but no essentially new content. A benefit is first of all the possibility for the on-line decisions in cases of some network faults. For example, the monitoring system can deliver in a clear form in every moment an overloading possibility of the transformer [8].

An essential problem in both thermal digital relays and monitoring systems is how to calculate the hot-spot temperature due to the complex heat transfer phenomena inside a transformer. The problem is discussed in the following section.

5. Hot-spot temperature

Possible approaches are to measure the hot-spot temperature (using fibre-optics technique) or to calculate it, using a thermal model of power transformers. Due to the complexity of heat transfer phenomena there exists no exact thermal model. A number of papers have been published proposing improvements of the thermal model from the valid IEC standard [3]. A thermal model can be created to deliver: a) the temperature distribution over the whole winding or b) the temperature values at the characteristic points. The approach with a complete temperature distribution requires the use of a heat flux winding network with exactly defined convection heat transfer coefficients over the whole winding surface. Such an approach is possible in transformers of a dry type [9] and in an oil filled transformers with directed oil flow and forced air flow (ODAF cooling type), used in high rated units [10]. In the cases of transformers of these two types the main convection heat transfer characteristics can be determined by heat transfer theory [11]. The problem appears when a transformer with natural oil flow (ON) is treated. The conditions of oil streaming in enclosure and return oil path through radiators disable us to use formulas from convection heat transfer theory. In the previous work of the authors the original thermal models for transformers with ON cooling system are established [12, 13]. The model takes into account the influence of non-linear thermal characteristics to transient thermal processes; instead of exponential functions and time constants, the numerical solution of differential equations is used. The model delivers hot-spot and bottom oil temperatures [13]. The parameters of the model can be precisely determined from inexpensive measurements in a short-circuit heating experiment.

6. Experiences with monitoring systems

A stand alone thermal monitoring system, inside a complex monitoring system developed at the University of Stuttgart, is installed on a 380 / 110 kV, 300 MVA ODAF transformer. The input data from the transformer are twenty temperatures (four at each of the four heat exchangers, three for the top oil and one for the ambient), states of the pumps and fans, the tap changer position and load currents in two phases. The system is described in detail in [10].

An extensive experience with practical load diagrams and limiting criteria was achieved through the analysis of the data recorded in a remote control system of the Power utility of Belgrade. The analysis has shown that for the widest class of transformers [6] as the critical parameter appears the maximal p. u. current load. Temperatures or ageing appear as critical values on transformers having maximal load during a longer period (in [6], examples of hospital and pump plant were given).

7. Conclusions

The paper contains a general outlook of the strategy of maximal transformer loading. The physical phenomena influencing the paper insulation ageing were discussed. The limiting factors of a transformer load are identified. In the widely adopted and applied approach, the only physical problem represents the hot-spot temperature calculation in real time operating conditions: the possible methods are also reviewed in the paper. The results of an analysis of some load diagrams and the need for a different functionality of protection and monitoring systems are also discussed.

8. References

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Author address: Enzo Cardillo
Institute of Power Transmission and High-Voltage Technology, University of Stuttgart,
Pfaffenwaldring 47, 70569 Stuttgart-Vaihingen, Germany
Email: cardillo@ieh.uni-stuttgart.de