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Theoretical Study on a Thermal Model for Large Power Transformer Units

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***Abstract*—**The paper analyzes the large power transformer unit regimes, indicating the criteria for the management of the voltage operating conditions, as well as the change in the operating conditions with the load connected to the secondary winding of the transformer unit. Further, the paper presents the software application for the evaluation of the transformer unit operation under different conditions. The software application was developed by means of virtual instrumentation.

***Keywords*—**Operating regimes, power transformer, overload, lifetime, virtual instrumentation.

I. Introduction

AT present, the admissible loading regimes of the large power transformers in service worldwide are given special attention. Until recently, it was considered necessary to limit the load, if the system condition allowed it, so that it never intentionally exceeded its rated power. This conception is no longer considered efficient, as, in case the peak load is limited to the rated power, the transformer unit should be under-loaded most of the time (because of the ambient temperature that usually surpasses 20°C). Short time overload, especially at lower ambient temperatures may not reduce transformer's lifetime too much. Therefore, considering the effects of overloading on transformer's lifetime, as well as on its economical operation and the quality of its operation (minimum secondary voltage limits at the secondary windings), respectively, guides for power transformer unit loading have been developed.

The loading guides have been developed on the basis of the following main principles and hypotheses:

- the transformer unit lifetime is tributary to the changes in the mechanical and dielectric properties of the winding cellulose insulation, caused by thermal ageing;

- temperature distribution is not uniform in most power transformers. Therefore, that part operating at the highest temperature is the one that has also got the fastest thermal ageing. Thus, the temperature which gives the overall ageing rate is the so called "hot-spot temperature (HST)[1)]";

- the effects of thermal aging are given by Arrhenius' equation for the chemical reaction speed, which states that the logarithm of the time necessary for a certain insulation physical property to reach its limit condition is a linear function depending on the insulation absolute temperature;

- thermal aging is linearly cumulative;

- loss of half of the insulation initial tensile strength represents the quantitative criterion for assessing the end of the insulation life. Usually, this also means the end of the transformer life, which generally occurs then, when the mechanical resistance of the conductors insulation can no longer withstand the mechanical forces caused by a short-circuit in the system, as the insulation destruction causes the electrical transformer failure.

Some of the users, who have actually performed power transformer overloading according to current standards have noticed that the loss of life calculated according to these standards is less than the loss of life determined as a result of a comprehensive insulation analysis after opening the transformer. Not so many power transformers have failed due to overloading. These observations made the users believe that the loading guides in these standards are too conservative.

The explanation of these observations is based on the following:

- only few transformers operate at an average ambient temperature equal to that taken as reference at the rated power, from the thermal point of view:

- maximum annual average ambient temperature: 20°C,

- maximum daily average ambient temperature: 30°C,

- maximum temperature for one hour: 40°C;

- most of the power transformers, except those from the power-plants, support cyclic loading with loading peaks that rarely causes temperatures to reach the limits prescribed in those standards;

- the way the loading guides are developed does not clearly distinguish between the load losses (RI^2) and the losses due to Foucault currents, occurring either in the winding or outside it, that are also related to load. As the temperature of a part heated by the Foucault currents increases, its electrical resistance increases in its turn, causing the current to decrease. Thus, the energy transformed into heat decreases with the load increase. On the other hand, as the temperature of the winding

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[1)] *Hot-spot temperature (HST) is the temperature of the hottest place (spot) of the winding.*

increases, the losses in the winding increase too, due to the resistance increase. So, the ratio between the load current and temperature is not only a function of the I^2;

- it is considered that then, when a transformer is overloaded, the maximum temperatures are instantaneously reached when the load is applied and remain constant during the entire loading time. The loss of life is calculated using this maximum temperature. Actually, the temperature reaches its maximum value with an exponential variation given by the thermal time constant of the transformer. Thus, the standards indicate greater lifetime consumption than the real one.

It is more difficult to establish the admissible loading regimes of the large power transformers (more than 100 MVA), than those of the small and medium ones out of the following reasons:

- the heating due to the leakage flux is difficult to control in the case of large power transformers;
- the research activity that has been carried out in the field of combined effects of thermal ageing and short-circuits stress on the dielectric strength has led to the conclusion that the loss of life is more important in the case of large power transformers;
- as the large power transformers have greater rated voltages they are subjected to greater dielectric stresses, so they require greater insulation volumes;
- deterioration of large power transformer units has a great impact on the maintenance and operation costs.

II. The Large Power Transformer Loading Possibilities with The Voltage Level

A transformer should be able to operate at the rated current, and at a voltage equal to 105% of its rated voltage. In special cases, the beneficiary may require that the transformer operate under specified conditions at 110% of its rated power. These provisions have been taken over from [1], [2], [3], [6] and [10] and aim at avoiding the magnetic core over-excitation and its corresponding deterioration. According to [10], the load current, I_s, should be reduced to zero (no-load operation) when the corresponding operating voltage of a voltage factor K_U [2)], of 1.1 is attained, in agreement with (1).

$$K_U = \frac{U}{U_n} = 1{,}1 - 0{,}05\left(\frac{I_s}{I_n}\right)^2 \quad (1)$$

Since the admissible over-excitation is determined by the magnetic flux density, which is proportional to the ratio between the applied voltage and the frequency (U/f), relation (1) can be written as:

$$\frac{U}{f} = \left[1{,}1 - 0{,}05\left(\frac{I_s}{I_n}\right)^2\right] \cdot \frac{U_n}{f_n} \quad (2)$$

[2)] The voltage coefficient K_U is the ratio between the voltage applied to the transformer unit and the rated voltage on the manufacturer plate.

where:

f – frequency of the applied voltage;

f_n – transformer rated frequency.

In order to reduce the risk of damaging the magnetic core the no-load operation voltage should be limited as value and time, as in [9], according to Fig. 1.

The transformers that are directly connected to the electric generators may be subjected to sudden load disconnections. Therefore, they should be able, according to [10], to withstand a voltage which is 1.4 times greater than the rated voltage, for 5s, at the winding terminals connected to the generator.

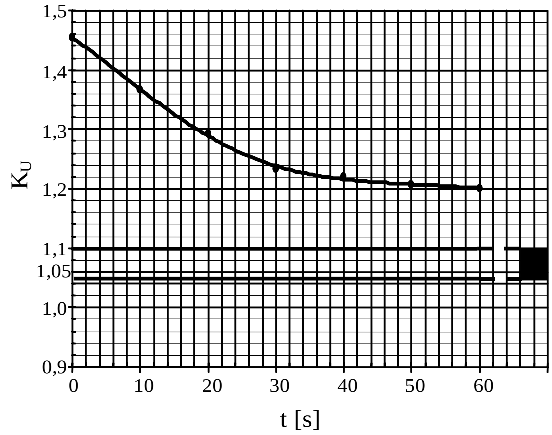

Fig. 1 KU coefficient with time

In this situation, the magnetic circuit will be entirely saturated and a great part of the magnetic flux will close on other paths, such as different metallic parts for mechanical support. This flux may cause important losses in these metallic parts, leading to the storage of the entire amount of heat, due to their thermal constant that is greater than the over-excitation time. Thus, the temperature rise is proportional to the over-excitation time. This time should be reduced in as much as possible to prevent the occurrence of very high temperatures that may damage the nearby insulation. This phenomenon cannot be considered during the design stage.

For the K_U, voltage factors, ranging between 1 and 1.05, the transformer unit should be able to operate at the rated power, requiring the corresponding load current reduction, while in the case of the voltage factors ranging between 1.05 and 1.1, the currents through the winding should be reduced according to (1), representing the black area in Fig. 1.

III. The Admissible Loads of the Large Transformer Units in Different Operation Regimes

Normal operation regime is the regime allowing the connection of loads that are higher than the nominal power of the transformer, either continuously, when the ambient temperature is low (below 20°C), or for a short period of time, (following after a relatively long period of time, when the load had been less than the nominal one), so that the hot spot temperature (HST) would not surpass 98°C, and the top oil temperature 55°C, respectively, for the ONAN and ONAF cooling, or 40°C for the OFAF and OFWF cooling[3)].

The emergency loading regime is the operation regime that occurs then, when the normal operation of the power system is interrupted due to one or more random causes, determining the transformer overloading for a short period of time (less than an hour in case of an event).

Among the factors influencing the regimes of the large power transformer units mention should be made of:

- the rated power, depending on the site altitude and the ambient temperature;
- the power in operation at the respective moment, considering the effective exploitation time of the power transformer units;
- admissible operating voltages and currents for the power transformer units;
- the admissible duration of the overloads for the power transformers units;
- the limit steps of the tap changer.

In all the transformer unit standards, the rated currents are defined for the following conditions:

- the altitude of the mounting place that should not surpass 1000 m above the sea level;
- the annual average temperature should not be greater than +20ºC;
- the air daily average temperature should not be greater than +30ºC;
- the maximum cooling agent temperature should not be greater than +40ºC (for the air-cooled transformers) and +25°C (for the water-cooled transformers).

According to [7], [8] and [9], the normal lifetime of large power transformer units is guaranteed if the HST does not surpass the standard value of 98ºC.

According to [9], this is not possible unless the loading factor, K_{24}[4)] (corresponding to a 24 hour loading time) takes the values indicated in Table I, depending on the ambient temperature.

To conclude with, the transformer units can be overloaded with loading coefficients ranging up to 1.31 in winter. Nevertheless, in summer, the loading coefficients should be lowered (up to 0.83, at +40ºC) in order to preserve their lifetime, thus performing a cyclic loading regime. This cyclic regime can be utilized within a day's time, considering the cyclic character of the load curves (higher values during daytime and lower during nighttime).

To this goal, the load curve is approximated as in Fig. 2.

The quantities in Fig. 1 are defined as follows:

K_1 – the lower loading coefficient (K_1 is less than 1), corresponding to the period of time when the transformer unit operates at loading current I_s, lower than the rated current, I_n;

K_2 – the higher loading coefficient (K_2 is greater than 1), corresponding to the period of time when the transformer unit operates at loading current I_s, greater than, I_n;

t_2 – the period of time when the unit operates at the load corresponding to K_2.

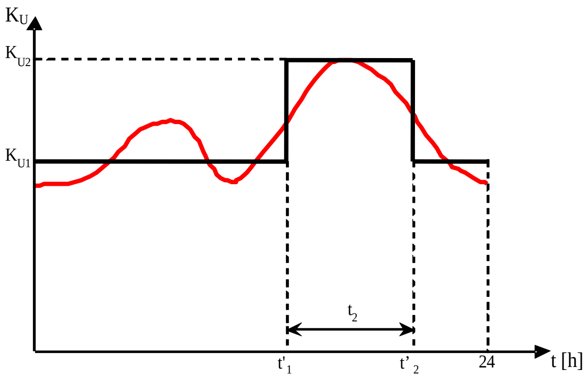

Fig. 2 Approximation of the daily load curve

HST is calculated according to [9], by means of the following relations:

- for ON cooling:

$$\theta_h = \theta_a + \Delta\theta_{or} \cdot \left[\frac{1 + R \cdot K^2}{1 + R}\right]^x + Hg_r \cdot K^y \qquad (3)$$

- for OF cooling:

$$\theta_h = \theta_a + \Delta\theta_{br} \cdot \left[\frac{1 + R \cdot K^2}{1 + R}\right]^x + 2 \cdot [\Delta\theta_{imr} - \Delta\theta_{br}] \cdot K^y + Hg_r \cdot K^y \qquad (4)$$

where:

K – the loading factor;

θ_h – hot spot temperature (HST), in °C;

θ_a – ambient temperature, in °C;

$\Delta\theta_{or}$ – rise of top oil temperature, at rated current, in K;

$\Delta\theta_{br}$ – rise of bottom oil temperature, at rated current, in K;

$\Delta\theta_{imr}$ – medium oil temperature, at the rated current, in K;

R – the ratio between the load-losses and no-load losses;

Hg_r – the difference between the HST and the top oil temperature, at rated current, in K;

x – oil exponent;

y – winding exponent;

[3)] *The cooling methods names are given by the cooling fluid circulation method:*
- *oil natural (ON): the oil flow is determined only by its temperature difference;*
- *oil forced (OF): the oil flow is given by circulation oil pumps;*
- *air natural (AN): the air flows naturally between cooling pipes;*
- *air forced (AF): the air is flowed between cooling pipes by fans;*
- *water forced (WF): the cooling pipes are "washed" by water, circulated by water pumps.*

[4)] *The loading factor K is the ratio between the actual current of the transformer unit and the rated current on the manufacturer's plate.*

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The relative thermal ageing rate is determined according to [9], with:

$$v = 2^{\frac{(\theta_h - 98)}{6}} \tag{5}$$

By means of these elements, a software application enabling the determination of the power transformer operating conditions, accepting supplementary life consumption, has been developed. The user interface is given in Fig. 3.

Fig. 3 The main window of the software application

Main input data:

- ambient temperature, in °C;
- K_1 and K_2, in relative units;
- transformer unit parameters, as defined in [9].

Main output data:

- initial oil temperature, in °C;
- final oil temperature, in °C;
- initial hot-spot temperature, in °C;
- final hot-spot temperature, in °C.

References [4], [5], [8], [9] recommend adoption of lower values of loading factors for large power transformer units in order to increase their reliability.

IV. Conclusion

The present paper analyzes the regimes of the large power transformer units (whose power is greater than 100MVA). It also presents the criteria lying at the basis of the regimes that may occur in operation, namely: the normal operation regime (long term) and the emergency regime (short term), from the loading point of view.

A software application enabling the study of the large transformer unit behavior operating in the two specified regimes, as well as the limits they can operate at, set by the national dispatcher in order to preserve their lifetime.

Based on the software output data, the national dispatcher will be able to coordinate the large power transformer unit loading possibilities more efficiently, considering the future interconnection of the national power system with UCTE (Union for the Coordination of Transmission of Electricity), leading to the increase in the power circulation in the national power grid.

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