METHODOLOGY FOR PREVENTIVE REPLACEMENT OF OVERLOAD DISTRIBUTION TRANSFORMERS BASED ON EXTERNAL TANK THERMOGRAPHY MEASUREMENTS

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ABSTRACT

This paper presents a new methodology for preventive replacement of overloaded distribution transformers based on external tank thermography measurements. To develop this methodology a large number of load cycles, measured in low-voltage distribution systems, were performed in laboratory to determine suitable criteria correlating the tank temperature of the distribution transformer with the load level at which the equipment is being submitted and the estimated daily loss of life. By performing this series of laboratory tests and also establishing the procedure for estimating the transformer loss of life was possible, considering some limitations, only with the knowledge of the loading conditions, the definition of external temperatures on the transformer tank that indicate the need for relocation the distribution transformer due to excessive overload.

INTRODUCTION

The National Electric Energy Agency (ANEEL) in Brazil regulates the Research and Development (R&D) program of the electricity sector. In this program, between the years 2010 and 2013 the Institutes Lactec conducted in partnership with the Electricity Utility of the State of Bahia (Coelba) the R&D project entitled "Reduced Failure Rate of Distribution Transformers of Classes 15 kV and 36, 2 kV in Coelba" [1, 2]. One of the project objectives was to develop a methodology for preventive replacement of overload distribution transformers based on external tank thermography measurements.

The transformers loading guides deliberate as a main factor of aging degradation due to heat the mechanical properties of the existing paper insulation between the windings and directly related the transformer useful life with the state of it isolation [3, 4]. Thus, the overload, sometimes imposed on distribution transformers, causing higher internal temperatures, contributes significantly to reduce the useful life and to the high failure annual rate observed in these devices, recently estimated at 30%, due to the excessive overload.

In order to reduce the failure rate of distribution transformers by excessive overload the Coelba Utility has been monitoring for some years the external temperature of the distribution transformer tanks, through the use of pyrometers and thermal imager cameras to prevent the excessive loading. The previously criteria used were empirical, but have indicated that the methodology could prevent transformer failure due to overload. So, in R&D project, by measuring the load cycles of some transformers at electrical power distribution system, which were subsequently removed from operation for performing laboratory tests simulating the measured load cycles, and comparing these measurements with the monitoring tank temperature of these ones with thermal imager devices, the methodology for preventive replacement of overload distribution transformers was developed.

DEVELOPMENT

<u>Laboratory tests in a distribution transformer with thermocouples placed into one of HV windings coils</u>

To establish a relationship of temperature on the external tank of distribution transformers with the load cycle applied to these, temperature rise tests were performed at Lactec High Voltage Laboratory in a distribution transformer (13.8-0.220/0.127 kV, 75 kVA, three-phase) with thermocouples inserted into one of its high voltage (HV) winding coils. In addition to the thermocouples placed inside the transformer, three thermocouples were externally added in the radiator fins, located on each phase of the transformer windings at usual height to the measuring points employed by Coelba and measurements were performed with thermal imaging camera, as shown in Figure 1.

Laboratory tests were performed with balanced and unbalanced load conditions and with different environment air flow conditions for the measurement of the external tank temperature of the distribution transformer.

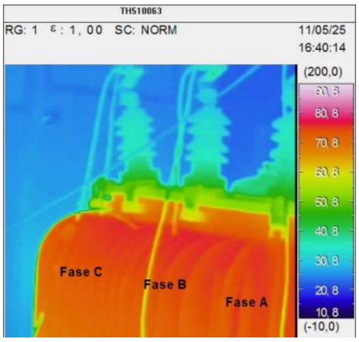

Figure 1. Thermal image of distribution transformer tank.

The results obtained showed that: even for unbalanced loads, external temperature measurements in the tank, for measuring points in the same height relative to the base of the tank, are very close, which indicates that with the measurement of tank temperature is not possible to identify load unbalanced. The results also showed that the height from the base of the measuring point from the external tank temperature with thermal imager is significant for the temperature reading. The load cycle in which the equipment operates is crucial in temperature rises that are measured in the external transformers tank, and a sudden rise loading is only observed from the external measurements after some delay. Environmental conditions, particularly in relation to air circulation, influence the temperature measurements in the transformer tank significantly.

Transformer tank temperature measurements in distribution system and laboratory tests

Were chosen six distribution transformers (two groups of three transformers with same features and factory lot) with overload operation signs to be monitored in the electrical power distribution system in which current and voltage monitoring equipment were installed, for an average period of a week, and, in addition, temperature measurements were made in transformer tank with the thermal imager, during the peak and out of the peak load. Two of these monitored distribution transformers were removed from operation and sent to Lactec Laboratory for simulation of real load cycles (measured). The simulation of some of loading cycles measured at electrical distribution system aimed to estimate the transformer loss of life for each load condition. For other load cycles was established procedure that even without laboratory simulation of the load cycle the loss of life could be estimated.

The determination or the estimated loss of life for different loading conditions aimed to correlate this parameter with the external transformer tank temperature and thereby establish methodology to indicate through the external temperature the loss of life for which the equipment is subject depending on the load to which it is exposed. Both for the simulation tests of the measured load cycles and established procedure for estimating the loss of life of distribution transformers, balanced loads were considered, that is, keeping constant the average effective value of the currents measured on the three phase HV winding terminals of the transformer for 1 h intervals (during 24 h) and unbalanced loads where current applied to each winding are equivalent to the average measurements current per phase in the distribution system.

Load cycles simulation tests

In Figure 2 it can be seen the measuring of the current in the three phases of low voltage winding of the monitored transformer (TR1 - 30 kVA, 15 kV) held between 05/16 and 05/25, 2012. The daily average current for each phase were calculated (A, B and C) and also the daily average of these currents. The average current of the three phases has been calculated, hour by hour, corresponding to 24 power levels of a daily cycle, which representing the measurement period of the transformer, in order to make possible a laboratory simulation tests.

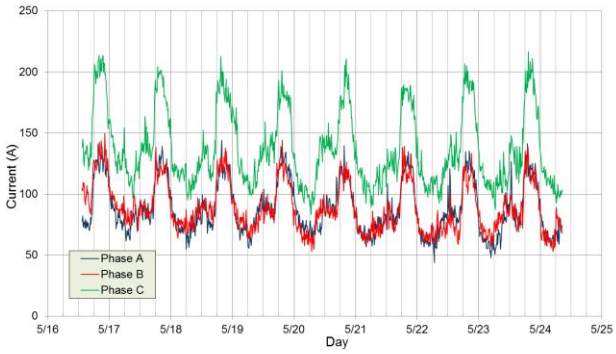

Figure 2. Measuring of the current in the three phases of the transformer (TR1 - 30 kVA, 15 kV).

The Figure 3 exemplifies a laboratory simulated load cycles in the TR1, for balanced loading conditions in three phases, maximum load of 186%, with testing room doors and windows closed to prevent the circulation air currents that would help cooling the transformer. This figure also shows the top oil temperature rise, measured with a thermocouple, and the tank temperature rise, externally measured at the height of low-voltage transformer bushings and that temperature measured before by Coelba in its system, with thermal imager and pyrometer. Additionally, are presented: the average windings temperature rise, estimated based on the instantaneous values of current and load losses; the temperature rise of the hottest spot estimated as procedure established by IEC 354/1991 [4]; as well as the accumulated loss of life (24 hours) for a simulated load cycle in the laboratory. The estimated cumulative loss of life was based on the procedure described in IEEE C57.91-1995 [3] that calculates the transformer daily loss of life due to the variation of its hotspot temperature.

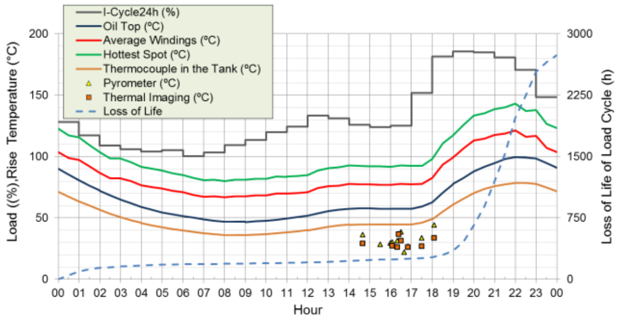

Figure 3. Residential simulated load cycle in TR1 in laboratory, with balanced load, 186% peak load, and without air circulation.

It could be noted from Figure 3 that for the simulated load cycle with typical residential characteristics, average peak load of 186% and duration of 5 hours, the average winding temperature rise reaches around 120°C (absolute temperature or 150°C, considering the average ambient temperature of 30°C at Salvador, Brazil), during peak load, imposing a severe operating condition to the transformer when there is no movement of air currents in the test room environment, hindering its cooling and accumulating a daily loss of life very significant of approximately 2800 hours.

The temperature rise measure in the tank, for this case, was significantly superior to measurements at Coelba's distribution system for the same load cycle, which leads to the conclusion that the condition imposed in the laboratory test was very critical and the air circulation conditions in the environment should be taken into consideration.

Therefore, for residential load cycle, considered typically in this study, were simulated in the laboratory other levels of loading (peak load) determined in proportion to the original load cycle, allowing the circulation of air in the test environment, so assess its influence on the transformer cooling system. These simulations show that the average windings temperature rise varies by a factor of proportionality, over daily load cycle, so approximately constantly in relation to the top oil rise temperature and by other factor of proportionality relative to external transformer tank temperature rise. However, these respective proportionality factors found depends on ambient air circulation conditions, confirming that the temperature rises (average winding, hotspot, top oil and external tank) are quite influenced by the air circulation conditions of ambient.

For natural air circulation near the transformer, the relationship between the temperatures of the top oil and the average winding presented a little variation in the simulated load cycle, with a value of approximately 0,68. In turn, the relationship between the temperatures of the external tank and the average windings approaches 0,49, throughout the simulated load cycle.

As the air flow conditions influence the transformer temperature rises, so that all simulated situations could be compared, was chosen to reference all of them to the natural air circulation (LN) condition. Thus, it can be said that a residential load cycle with peak of 186% without air circulation is equivalent to a load cycle with peak of 194,8% with natural air circulation. This same load cycle with peak of 186% with forced air circulation (installation of a fan located near the transformer radiator) amounts to a maximum of 158,8% load only with natural air circulation.

Figure 4 presents the transformer tank temperature rises for different load levels simulated in the laboratory (all proportional to the measured load cycle), referenced to condition the natural air circulation (LN) and the temperature rise measured at Coelba's distribution system with the thermal imager. It can be seen in Figure 4 that the temperature measurement in transformer tank at distribution system (thermal imager and pyrometer) are located between the loading cycles with peaks of 194,8% and 158,8% simulated in the laboratory, corresponding to an average maximum load of 186% differentiated only by imposed air flow condition. This result indicates that in the case of load measured in the system, probably the air circulation conditions were among the two situations simulated in the laboratory (much and little wind). It can also be seen from Figure 4 that for simulation of situations cycles with a maximum load of 140%, 156% and 158,8%, the temperature rise outside the transformer tank out of peak load cycle period are very similar. What differentiates these loading cycles are the temperatures rises that are achieved only during load peak periods. Therefore, for residential load cycles, the measurement of the external tank temperature rise outside the peak load period could not indicate the real load that is imposed upon the transformer to the peak load period. Furthermore, it can be seen in both simulations with balanced and unbalanced load maximum equivalent to 98%, the temperature rise in the transformer tank was very similar, which reinforces the statement that is not possible to identify unbalanced load conditions with measurements of the transformer tank temperature.

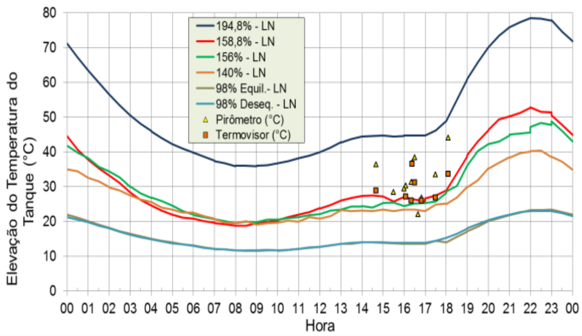

Figure 4. Temperature rises measured in transformer tank (TR1) for simulations and at Coleba's system.

For the load cycle simulations carried out on the transformer, beyond measures of temperature rises with thermocouple in the tank and on top oil, load losses were also measured for each equivalent load cycle. With the values of the load losses measured for each interval of 1 hour, the average windings temperature rises and the hotspot and also their loss of life were calculated. Then a curve was set depending on loss of life calculated for this transformer and has determined that for a daily loss of life of 24 hours should be obtained to a maximum load (balanced condition and LN) equivalent to 131,3%, resulting in average temperature rises in the transformer tank during the peak and out of peak periods, respectively, of 32,6°C and 19,6°C.

Estimate temperature rises and loss of life without laboratory load cycles simulations

In order to eliminate the need for load cycles simulations in laboratory to estimate the transformer temperature rises and consequently its loss of life, it was established a procedure in which these values are calculated only by knowing the variation of the amplitude of the load current.

The procedure adopted to estimate the temperature rises (hotspot, average windings, top oil and external tank) assumes estimated losses in transformer as function of load for each hour of the daily load cycle measured by the Coelba, considering a balanced load, determined by the arithmetic mean of the current in each phase as equation below:

$$W_{CARGA-EST} = W_{CARGA-75°C} \cdot \left(\frac{I_{MED}}{I_{NOM}} \right)^{2,18}$$

where WCARGA-75°C corresponds to the load loss measures in the standard test (rated current), referred to 75°C. For a given temperature condition, when the resistance value of the windings does not change, this kind of loss varies with the square of the current, however, for variable temperature conditions as those measured in the windings of a transformer during their daily load cycle, this variation occurs according to a power that depends on both the shape as the peak amplitude of the load curve. For distribution transformers operating in typical residential load cycles, it was found in tests carried out in LACTEC the exponent 2.18 is very reasonable.

Possessing the estimative values of load losses, it is possible to calculate the average windings temperature rise (balanced case) and the average overloaded phase temperature rise (unbalanced case). In the sequence, determine the hotspot temperature for each interval of the load cycle and estimate the transformer daily loss of life, considering both balanced and unbalanced loads. The method was used for all real load cycles measured in transformers at the distribution system.

In Figure 5 is presented the daily average current for each of the phases and the daily average of these currents referring to the current measurements in the three phases, performed at Coelba's distribution system (TR2 - 30 kVA, 15kV), between 10/15 and 10/30, 2012. The average current of the three phases has been evaluated, hour by hour, corresponding to 24 current levels of a daily load cycle that represents the measurement period. It can also be observed in figure the temperature rises measured in the transformer tank with the pyrometer and thermal imager and estimations of temperature rises to the top oil, to the transformer tank and losses of life, considering balanced loading and the real (unbalanced), determined by the above procedure.

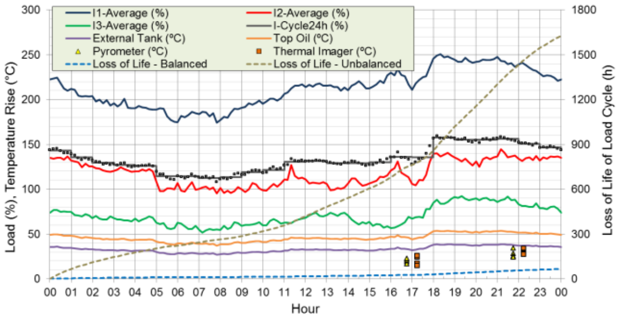

Figure 5. Average current for a period of 24 h, temperature rises measures at Coelba's system and estimates and loss of life of TR2.

It could be seen in Figure 5 that the estimated temperature rise for the TR2 tank is slightly higher than those measured at Coelba's system by using thermal imager or pyrometer. This difference is probably due to the imposed condition of natural air circulation (LN), considered in this estimation. The daily loss of life estimated for this transformer is approximately 66 hours on the balanced load condition, but is greater than 1700 hours by day when considering the real and unbalanced load at low voltage network, indicating the severity condition of operation of distribution transformer in these conditions.

Overall results

In Figure 6 is presented the daily loss of life estimated and measured in the laboratory for balanced and unbalanced loads with a fitted curve indicating the daily loss of life as function of average load during the peak load cycle, with a statistic confidence interval of 95% .

In Figure 7, it can be observed all mean temperature rises of the transformer tank, estimated and measured in the laboratory, as function of maximum load, both during the peak load cycle (18-23h) as out of the peak load (8-18h), with confidence interval of 95%, with an error bar with ± 20%. Thus, through the fitted curve, it is possible to identify the load level on the load peak period or out of this as a function of the external transformer tank temperature rise in these respective intervals.

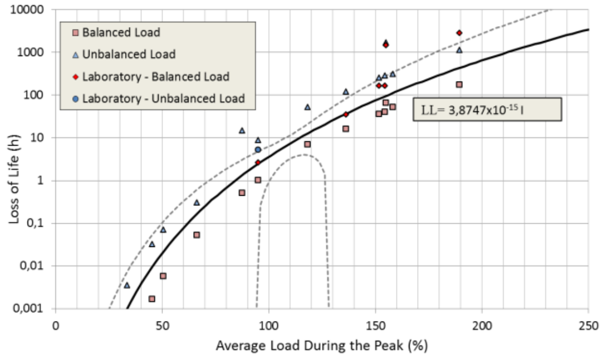

Figure 6. Daily loss of life depending on the maximum loading at the peak load (18-23h)

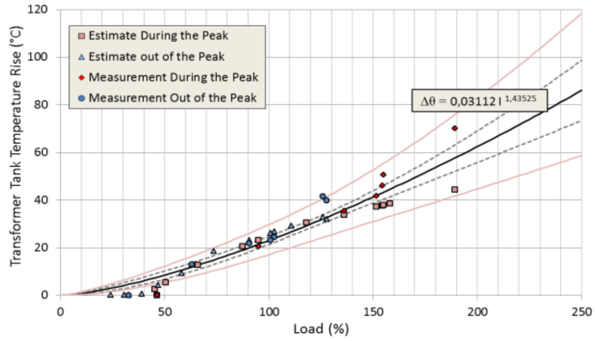

Figure 7. Transformer tank temperature rise due to the load imposed.

So, for residential loading cycles, with load factor (average load out of the peak / average load at the peak) close to 0,69, natural air circulation (LN) condition and transformers with copper winding, through the fitted curve in Figure 6, it can be seen that for a daily loss of life of 24 h the average load on the peak load must be approximately 128,7%, and for this load can be seen in the curve fitted in Figure 7 that the average temperature rise in transformer tank at the peak load period is approximately 35°C.

CONCLUSION

This paper presented a methodology for preventive replacement of overload distribution transformers through measurements of external tank temperature of this equipment with thermal imagers or pyrometers. With the development of this methodology can be said that, for all transformers that have load losses behavior and temperature rise similar to the transformers used in this study, maximum daily loss of life of 24 hours (service life of 20 years), load factor of around 0,7 and the duration of the peak load cycle of 5 hours (residential cycles), the measurements of the tank temperature rises with thermal imager are reliable and accurate. The environmental conditions favor the cooling of the transformer, in a situation resembling the natural air circulation (LN).

External tank temperature rises above 20°C when measured between 8 and 18 hours, and greater than 30°C when measured between 18 and 23 hours, are an important indicative that the distribution transformer monitored is in excessive overhead. For temperature rises close to these parameters, especially outside of the load peak period, the need for replacement of the transformer must be confirmed by measuring the real daily load. In addition, it can be stated that only with the measurements of external temperature of the tank is not possible to identify unbalanced loading phase.

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