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Investigation of Transformer Cooling Improvement Utilizing Online Monitoring System

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***Abstract*-Forced cooling have been utilized for many years to increase transformer loading capacity. Method of transformer cooling system control affects its thermal performance directly. So, it is possible to prevent from undesired operational conditions such as accelerated ageing and critical hot spot temperature to some extent by proper control of cooling system. In this paper, the method of transformer cooling control in online monitoring system is addressed. Also, advantages of this control scheme over traditional method are discussed and demonstrated by simulation results.**

I. INTRODUCTION

Transformer is one of the main components of electrical power system. Transformer loading is mainly restricted by its winding hot spot temperature. High hot spot temperature causes acceleration of transformer insulation ageing and may lead to premature failure of the transformer [1,2].

Transformer forced cooling (ONAF and OFAF cooling modes) increases its loading capability by reinforcement of heat dissipation from the transformer [1]. In the other words, forced cooled transformers can carry more load without appearance of critical hot spot temperature. Therefore, effective control of transformer cooling system is of great importance.

Transformer online monitoring system has some capabilities which may be applied to improve cooling system control. In the following sections, these capabilities are described and based on them the method of transformer cooling control by online monitoring system is discussed. Then, the advantages of this method over traditional control scheme are revealed by simulation.

This paper is one of the results of transformer online monitoring project which has been implemented by the authors in a substation in Tehran Regional Electric Company (TREC).

II. TRASFORMER ONLINE MONIYORING SYSTEM(TOMS)

In 1997, the first two power transformers have been equipped with online monitoring systems. The online monitoring system has been continuously improved during its 10 years of operation [3].

Usually, the load current and voltages at the high voltage bushings are measured. Using the measured tap-changer position, the actual load transmitted by the transformer can be determined easily [3].

Also, evaluation of the output signal of a gas-in-oil sensor allows conclusions about the condition of the insulation system. Furthermore, digital input values like the state of all fans and pumps are considered in online monitoring system [4].

The data acquisition device is mounted in a control cabinet and connected to a computer via a serial link (e.g. fiber optic) [3,4].

The computer archives all the measured data and performs further analysis on the measured data. When using this configuration there is no need to disconnect the configured data acquisition unit if the transformer has to be moved. Moreover, measurement and computer are galvanic decoupled and the data transmission cannot be influenced by electromagnetic fields. By choosing this architecture, a hardware exchange is very easy, because, no additional device is needed in the computer [4].

An additional monitoring function consists of a thermal model of the transformers windings. This model estimates transformer top oil and hot spot temperatures. These temperatures depend on the load and ambient conditions, etc. [4].

III. TRANSFORMER COOLING CONTROL SYSTEM

A. *Traditional Cooling System Control*

Traditionally, transformer cooling system has been controlled by winding (or top oil) temperature gauges. Conventional winding temperature indicator gauges use a capillary thermometer to measure top oil temperature, and have a small heater in a thermal well to simulate the temperature rise of the winding hot spot over the top oil temperature ("the gradient"). Current from one of the bushing CTs is passed through the heater, raising the measured temperature. The wattage output of the heater is calibrated using a resistor or other calibrating device [5].

Calibration of the heater is done based on the temperature rise tests, which measure the average winding and oil temperature rise. The difference is the average gradient, to which is added an allowance for additional rise of hot spot over average in accordance with the IEEE or IEC standards.

The winding gauge provides a typical accuracy of 3-4 °C and is known to deteriorate with time. Errors of 6-10 °C on site are not uncommon. To remain accurate, the system requires regular calibration and servicing.

The time constant of the simulated hot spot rise is determined by the sensor and thermal well design and is based on the amount of oil circulation near the thermal well (which will dissipate the heat generated by the resistor). The resulting time constant cannot be tuned or adjusted [5].

Transformer manufacturers are responsible for calibrating the heater to read correctly at full load. If the calculated gradient is accurate, the tuned system will provide good readings at full load under steady state conditions. The accuracy of the reading at loads greater and less than this will depend on the transformer design [6].

One of the most common complaints with traditional simulated winding hot spot gauge systems is the tendency of the gauge to stick. This problem has been noted on both new and old transformers and is a cause for concern, especially when the gauge is used for cooling control where a stuck gauge can cause excessive transformer aging or transformer failure [6].

B. TOMS-based Cooling System control

In online monitoring system, the hot spot temperature is calculated using a thermal model (e.g. IEEE thermal model [1]). Calculation of the hot spot temperature based on the thermal models is more accurate than using the winding temperature gauges [5]. Also, in online monitoring system top oil temperature is measured. So, the measured value can be used directly and there is no need to top oil calculation. It can improve the thermal model accuracy.

Furthermore, control of cooling system by online monitoring system offers some advantages over traditional method. These advantages may be classified in two categories as follows:

B.1 Operational Advantages

In this section, operational advantages of online monitoring system application in transformer cooling system control are described. These advantages improve the performance of the cooling system. The main advantages are as follows [6,7]:

B.1.1 More Accurate Hot spot Temperature Estimation

As mentioned earlier, application of thermal models for hot spot temperature estimation is more accurate than using winding temperature gauges which have been used in traditional cooling control method. So, cooling system may be controlled more effectively.

On the other hand, it is possible to use new thermal models (such as the models in [8] and [9]) to consider the effect of various operating condition such as over-excitation and harmonic loads on hot spot temperature increment. It leads to more accurate hot pot temperature estimation in this condition. It is obvious that this capability may not be achieved by traditional winding temperature gauges.

B.1.2 Smart Cooling (pre-cooling)

Smart cooling control system can turn on the transformer cooling in a predictive manner and cool off (pre-cool) the transformer before it gets hot. This can be accomplished based on the load or based on the calculated ultimate hot spot temperature taking into account load and ambient [6]. In the other words, when a step rise in the transformer load is observed or the control system recognizes that the hot spot temperature may reach one of the cooling system set points in the future (e.g. after 15 min), cooling system control activates that stage. For the pre-cooling based on the hot spot temperature, this temperature may be calculated for a time in future using the thermal model equations, assuming that the load and ambient temperature remain at present values.

B.2 Reliability Advantages

Reliability advantages of cooling system control by online monitoring system are related to cooling system reliability enhancement. These advantages are as follows [6]:

B.2.1 Fail-safe Cooling Control

Cooling control systems should be designed in such a manner that a control component failure does not cause the loss of the transformer cooling. So, the following capabilities are considered:

a. Utilizing the normally closed contacts on the cooling system contactors, the system shall be designed to turn on cooling if a temperature sensor fails.

b. The system shall turn on cooling if the power to the central processor (e. g. PLC) fails or if the control itself fails.

c. In the event of a cooling fan, pump, or contactor failure or if a breaker trips for one of the cooling stages, the cooling control shall resort to the second stage of cooling.

B.2.2 Detection of the System Problems

By monitoring the current draw of fans and pumps, the system confirms that all cooling components are operating and cooling contactors working properly. In the case of problem detection, an alarm is generated. Also, automatic exercise of cooling system provides early warning of cooling system problems [6].

A periodic, automatic exercise of the cooling system can provide early detection of fan, pump or contactor failures. Also, this feature prevents the fans from corroding in place and bird nesting [6,7].

In TOMS, it is possible to compare the calculated top oil temperature with the measured one. Typically, the calculated top oil temperature will differ from the measured top oil by only a few degrees. Large differences indicate one or more of the following potential problems [5,6]:

a. Cooling system valves are not open
b. Coolers are clogged
c. Oil level is below the radiator header pipes
d. Loss of fans or pumps

B.2.3 Cooling System Duty Leveling

Run hours are tallied for each stage of cooling. The system automatically staggers the use of each cooling stage to maintain even wear on the cooling system. In addition, the total run hours of each stage are indicated and can be used to trigger maintenance tasks on the coolers, pumps or fans.

IV. COMPARISON OF ONLINE AND TRADITIONAL COOLING SYSTEM CONTROL SCHEMMES

In this section, thermal performance of traditional and online monitoring-based cooling system control is compared. In the other words, "operational advantages" of the TOMS-based cooling control will be demonstrated. To do this, some simulation studies based on IEEE thermal model have been performed. The thermal model block diagram is shown in Fig.1 [10,11].

where

K : transformer load, per unit

θ_A : instantaneous ambient temperature, ^oC

R : rated load to no load loss ratio, dimensionless

$\Delta\theta_{H,R}$: rated hot spot temperature rise over top oil, ^oC

$\Delta\theta_{TO,R}$: rated top oil temperature rise over ambient, ^oC

T_{to} : top oil time constant, hours

T_w : hot spot time constant, hours

m :empirically derived exponent, dependent on the cooling method, dimensionless

n : empirically derived exponent, again dependent on the cooling method, dimensionless.

S : Laplace operator

For example, a power transformer with thermal parameters of Table I is considered. In this Table, n values of 0.7 and 0.9 are related to ONAN and ONAF cooling modes, respectively [9]. Transformer load and ambient temperature are assumed as Figs 2 and 3, respectively.

TABLEI
TRANSFORMER THERMAL MODEL PARAMETER

Transformer MVA	31.5
Cooling mode	ONAN / ONAF
$\Delta\theta_{TO,R}$	50.6
$\Delta\theta_{H,R}$	29.4
T_{to}	2.7
T_w	0.1
R	7.7
n	0.7 / 0.9
m	0.7 / 0.7

In traditional cooling control method, transformer fans are turned on and off at predetermined hot spot temperature set points. In this paper, these set points are assumed to be $70\,^oC$ and $58\,^oC$, respectively.

It is assumed that the TOMS-based cooling controller maintains these set points, but at the load step rise (about 0.2 pu rise with time constant less than winding time constant), it does not wait for hot spot to reach the activation set point and pre-cools the transformer until the load becomes less than the pre-step value or the hot spot temperature is decreased to a value less than fan activation set point. After that, transformer cooling system is controlled based on the considered set points.

Such a step rise is observed in load profile at the time of 1.17 hour and from 0.39 pu to 0.57 pu. Hot spot temperature reaches $70\,^oC$ at the time of 2.67 hour. So, TOMS-based and traditional cooling control systems activate the cooling system at times 1.17 and 2.67 hour, respectively.

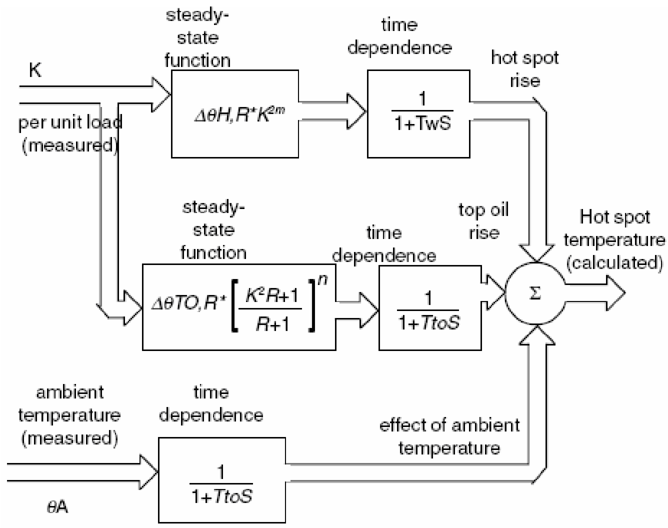

Fig. 1. Block diagram of IEEE thermal model

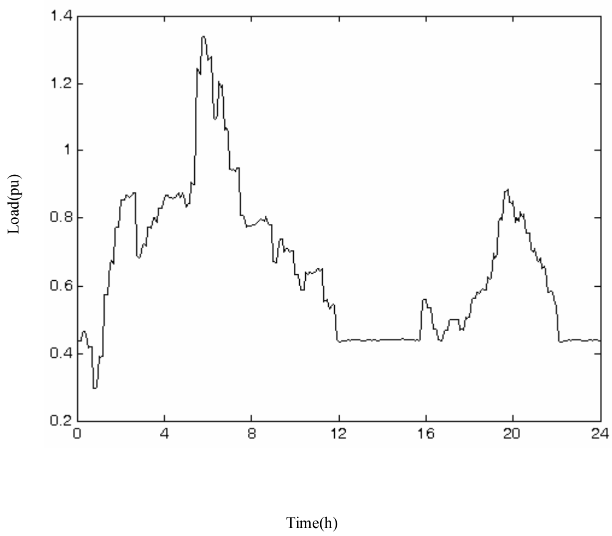

Fig. 2.Transformer load profile

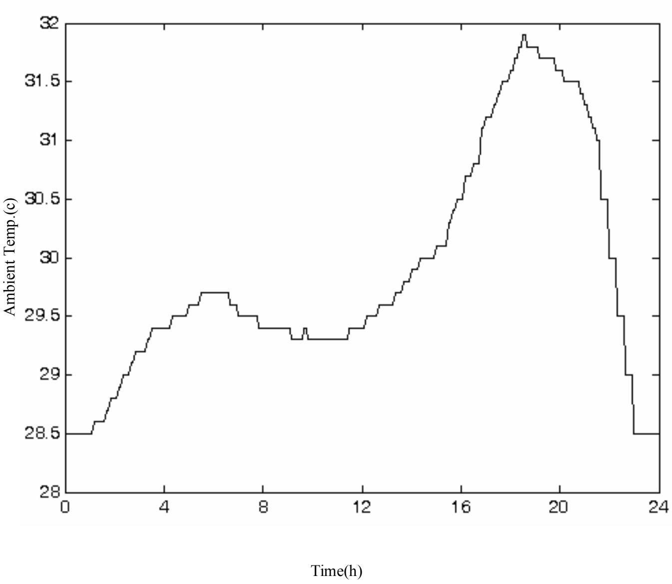

Fig. 3.Ambient temperature

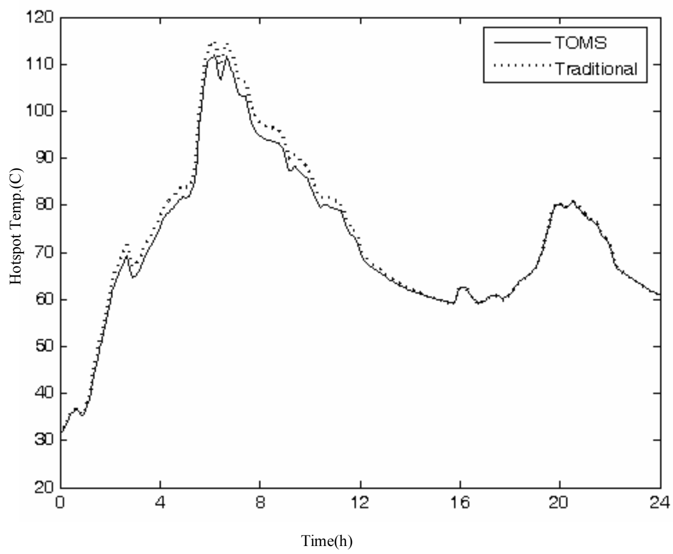

Fig. 4. Hot spot temperature

The resulted hot spot temperature profiles with traditional and TOMS-based cooling control are shown in Fig. 4. As seen, transformer operates cooler under TOMS-based control.

So, the cooling system state under two control schemes is as Fig 5.

Note that in the simulations it is assumed that the winding temperature gauge (used in traditional cooling control) estimates the same hot spot temperature profile as thermal model (used in TOMS-based cooling control). This assumption is made because of the random and unpredictable nature of the gauge hot spot estimation. In the other words, the first operational advantage of the TOMS-based control scheme (more accurate hot spot temperature estimation) is ignored in the simulations.

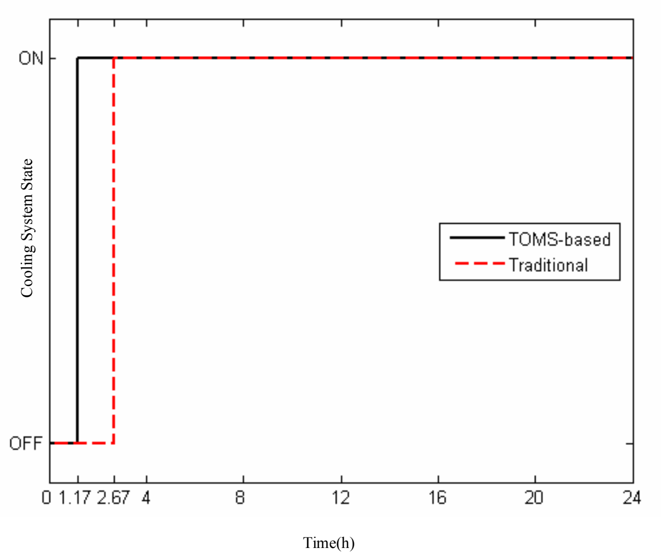

Fig. 5. Cooling system state

On the other hand, winding hot spot temperature is the most critical parameter in transformer insulation loss of life (insulation ageing). In IEEE C57.91-1995 standard [1], the following equations are suggested for calculating the insulation loss of life:

$$F_{AA} = \exp\left[\frac{15000}{383} - \frac{15000}{\theta_H + 273}\right] \; perunit \qquad (1)$$

$$LL = \int_0^T F_{AA}\, dt \qquad (2)$$

where

θ_H : Hot spot temperature

F_{AA} : Ageing acceleration factor (ageing rate).

LL : Insulation loss of life, hour.

T : Loading duration, hour.

In equation (1), "per unit" is based on the normal aging rate, i.e., the rate that would pertain if were continuously at the design temperature: 110 °C [6].

Based on these equations, transformer insulation ageing process under TOMS-based and traditional cooling control is shown in Fig.6. As seen, transformer daily ageing under traditional cooling control is about 30% more than TOMS-based cooling. So, transformer operational life may be extended using TOMS-based cooling control. It is obvious that additional cooling system wear due to earlier start in TOMS-based control is negligible in comparison with achievable transformer life conservation.

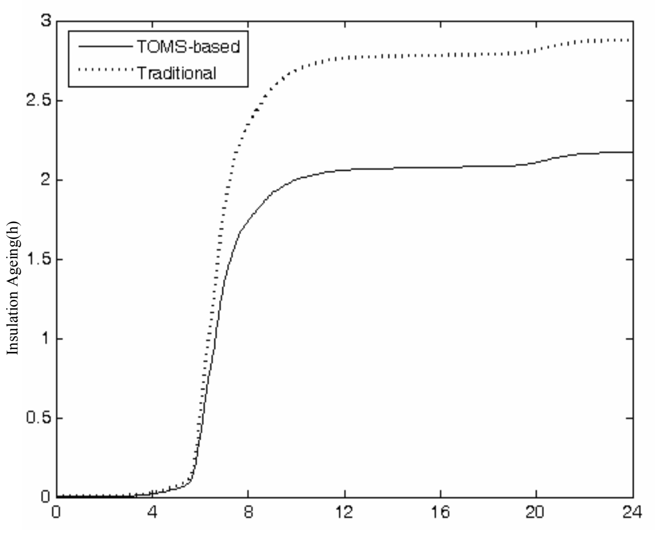

Fig. 5.Insulation Ageing

IV. CONCLUSION

The way of the transformer cooling system control has a direct effect on its thermal performance. So, transformer operating conditions can be optimized by effective cooling system control.

In this paper, the method of utilizing online monitoring system for transformer cooling control has been discussed. Simulation results show that using this method some operational advantages may be achieved. The main advantages are extended transformer operational life and avoiding critical hot spot temperature.

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