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An Investigation on Hot-Spot Temperature Calculation Methods of Power Transformers

Ahmet Y. Arabul, Ibrahim Senol, Fatma Keskin Arabul, Mustafa G. Aydeniz, Yasemin Oner, Gokhan Kalkan

Abstract**—**In the standards of IEC 60076-2 and IEC 60076-7, three different hot-spot temperature estimation methods are suggested. In this study, the algorithms which used in hot-spot temperature calculations are analyzed by comparing the algorithms with the results of an experimental set-up made by a Transformer Monitoring System (TMS) in use.

In tested system, TMS uses only top oil temperature and load ratio for hot-spot temperature calculation. And also, it uses some constants from standards which are on agreed statements tables. During the tests, it came out that hot-spot temperature calculation method is just making a simple calculation and not uses significant all other variables that could affect the hot-spot temperature.

Keywords**—**Hot-spot temperature, monitoring system, power transformer, smart grid.

I. INTRODUCTION

IT is, today, a very important study subject to analyze the ways of conducting electricity to end-users in an efficient and uninterrupted manner, since the dependence of electrical energy is very high. The most important matter of this subject called "smart grid" is to measure and manage every single stage of the process starting with the generation of the energy, until it is consumed [1]. Since they are built with massive budgets, the lives of power lines are very important issue. It should also be kept in mind that Transformer Monitoring Systems (TMS) have an important role as a substructure part for smart grids and have become mandatory in many countries. TMS is also a part of smart grids. TMS' role is to transfer the energy flow data, as well as its function of giving information about the sustainability of the energy flow, based on its calculations regarding the transformer's life. TMS calculates the lifetime data of the transformer, depending on the load conditions and the heat of the transformer. Hot-spot temperature is the main variable of lifetime calculation [1], [2].

Smart grid technology begins to take an important role in the continuity and quality of energy has increased the importance of the power transformer which is the one of the most important and expensive element in power transmission lines. Power transformers average life is 30 years; if there is an unexpected failure in the operating, there will be huge economic losses. The online monitoring of the specific parameters of the power transformers and processing these parameters by using specifically developed algorithms will help the power transformer to last for the expected service life. This will also help to foresee the possible failures and take the necessary measures, thus preventing these particular failures to occur.

Online monitoring of power transformers and can be made of its potential life calculation has become possible with TMS. GTM Research forecasts the annual market for transformer monitoring hardware in the U.S. to grow drastically from $113 million in 2012 to more than $755 million in 2020. In the U.S., a variety of factors, including an aging workforce, aging assets, and the increasing volume of data created by smarter devices on the grid such as smart meters and distribution automation hardware, is creating the need to invest in intelligent transformers and software. The outfitting of new and the retrofitting of old power, distribution and secondary transformers with additional sensors and monitoring equipment will take quite some time, as they are replaced gradually as they fail or are phased out due to perceived or verified insulation aging [1].

According to Turkish Electricity Transmission Company (TEIAS) specifications, it is mandatory to use monitoring systems for transformers which have 50 MVA capacities and over. However; with smart grid technology, not only power transformers but also secondary and consumer transformers are expected to become mandatory in the near future of the monitoring system.

Safe and reliable operation of the power transformer is a study subject for decades. Although there are periodic maintenances to ensure that disabling transformers to disrupt the continuity of power supply transformer major failures may occur. Because of scheduled or unscheduled maintenance cost and still cannot be avoided the fault, various studies have been conducted to monitor the transformer and equipment in recent years [2]–[5].

Monitoring systems, in general gives the transformers' using the measured top and bottom oil temperature readings, the current flowing from the low and high voltage windings, stage information and heated oil from the gas analysis results, the possible fault conditions and transformer aging (life) information [6]–[8]. In these systems, the main parameter affecting the life of the transformer is the temperature [9]. The effect of harmonic currents and overload increases copper

A. Y. Arabul is with the Electrical Engineering Department, Yildiz Technical University, Istanbul, 34220, Turkey (corresponding author to provide phone: +90(212) 383-5859; fax: +90(212) 383-5858; e-mail: arabul@yildiz.edu.tr).

I. Senol, F. Keskin Arabul, M. G. Aydeniz and Y. Oner are with the Electrical Engineering Department, Yildiz Technical University, Istanbul, 34220, Turkey (e-mail: senol@yildiz.edu.tr, fkeskin@yildiz.edu.tr, aydeniz@yildiz.edu.tr, yoner@yildiz.edu.tr).

G. Kalkan is with the Research & Development Department, Best Transformer, Balikesir, 10100, Turkey (e-mail: gokhan.kalkan@besttransformer.com).

losses and hence the temperature is increased [10]–[12].

Hot-spot temperature describes the highest temperature on the oil or winding is the most important parameters of the transformer's life calculation [12], [13].

Hot-spot temperature is one of the most important parameters of power transformer designs. Hot-spot temperature is a function of the oil temperature and the heat caused by the eddy current and joule losses on the winding and it is the highest temperature on the winding. The most commonly used hot-spot calculation methods are the methods that specified in the standards IEC 60076-2, IEC 60076-7 and IEEE C57.91.

Grid giants like ABB, Alstom, GE, Schneider and S&C Electric Company have already caught on to the opportunity that transformer technology offers and are well positioned to lead the market.

In this study, one of the most used TMS in Turkey is used for a test system which is also used for another project by a firm which is partner for a project sponsored by Ministry of Science, Industry and Technology. The effect of the changes of all parameters on hot-spot calculation were investigated.

II. METHODOLOGY

Thermal diagram, underlying three different methods set out in the IEC standards is shown in Fig. 1. By this diagram it is assumed that the oil temperature inside the tank increases linearly from bottom to top, whatever the cooling mode.

Gradient value between the average oil temperature and the average winding temperature value is multiplied with the hot-spot factor (H) and is added to the top oil temperature and the point P is located which is indicated the hot-spot temperature. Thus the difference between the hot-spot and the top oil temperature in the tank is shown as H x g_r. IEC standards committee, in the thermal diagram has an important role in the presence of the hot-spot temperature the value of the H factor, updated in 2011 so that H = Q.S. Here is Q factor is an original value of the coil depends on the characteristics, and S factor is a value that relevant to the efficiency of the cooling liquid in the windings [14], [15].

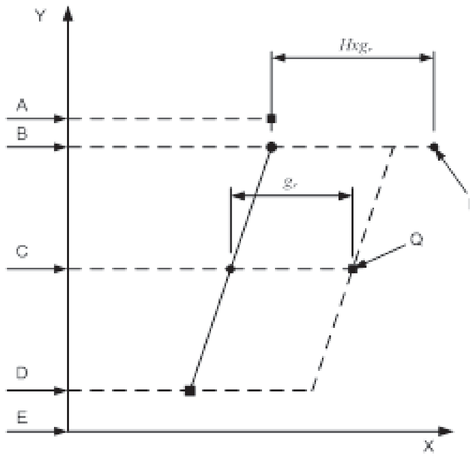

Fig. 1 Thermal Diagram [15]

A. Concept Designing Stage Hot-Spot Calculation Methods

In IEC 60076-2 and IEC 60076-7, three different hot-spot estimation methods are suggested. First method is the easiest one that enables to make an approximate hot-spot estimation in concept designing stage. The basic mathematical equation used in this method is shown in (1):

$$\theta_{HS} = \theta_O + H \times g \times K^y \tag{1}$$

θ_{HS} = Hot spot temperature; θ_O = Top oil temperature; g = Winding-oil gradient; K = The ratio of the applied load to the nominal load; y = Oil gradient exponential constant; H = Hot-spot factor. In this equation, “y” ranges fixed by the cooling type and obtained from experimental methods.

TABLE I
DEFINITIONS OF PARAMETERS IN THERMAL DIAGRAM

Symbol	Description
A	Top-oil temperature derived as the average of the tank outlet oil temperature and the tank oil pocket temperature
B	Mixed oil temperature in the tank at the top of the winding (often assumed to be the same temperature as A)
C	Temperature of the average oil in the tank
D	Oil temperature at the bottom of the winding
E	Bottom of the tank
g_r	Average winding to average oil (in tank) temperature gradient at rated current
H	Hot-spot factor
P	Hot-spot temperature
Q	Average winding temperature determined by resistance measurement
X-axis	Temperature
Y-axis	Relative positions

B. Exponential Equations Solution

Another method is developed to estimate the hot-spot temperature of the transformer load variation according to a step function and IEC 60076-7 method is called as "exponential solution". This method is suitable for step loads and develop for the remaining transformers are subjected prolonged loading.

The hot-spot temperature is equal to the sum of the ambient temperature, the top-oil temperature rise in the tank and the temperature difference between the hot-spot temperature and top-oil temperature in the tank.

The temperature increase to a level corresponding to a load factor of K is given by (2):

$$\begin{gathered}\theta_h(t) = \theta_a + \Delta\theta_{oi} + \left\{ \Delta\theta_{or} \times \left[\frac{1 + R \times K^2}{1 + R} \right]^x - \Delta\theta_{oi} \right\} \times f_1(t) + \\ \Delta\theta_{hi} + \left\{ H g_r K^y - \Delta\theta_{hi} \right\} \times f_2(t)\end{gathered} \tag{2}$$

Correspondingly, temperature decrease to a level corresponding to a load factor of K, is given by (3):

$$\theta_h(t) = \theta_a + \Delta\theta_{or} \times \left[\frac{1+R\times K^2}{1+R}\right]^x + \left\{\Delta\theta_{oi} - \Delta\theta_{or} \times \left[\frac{1+R\times K^2}{1+R}\right]^x\right\} \times f_3(t) + Hg_r K^y \tag{3}$$

f₁, f₂ ve f₃ could be calculated by (4)-(6). The constants which indicate in these equations can found by using Table II.

$$f_1(t) = \left(1 - e^{(-t)/(k_{11}\times\tau_0)}\right) \tag{4}$$

$$f_2(t) = k_{21} \times \left(1 - e^{(-t)/(k_{22}\times\tau_w)}\right) - \left(k_{21} - 1\right) \times \left(1 - e^{(-t)/(\tau_0/k_{22})}\right) \tag{5}$$

$$f_3(t) = e^{(-t)/(k_{11}\times\tau_0)} \tag{6}$$

C. Difference Equations Solution

The difference method is another method which uses the heat transfer equations to determine the upper oil and the hot-spot temperatures. Within three methods this method gives the closest result to the test results under the sudden loading conditions and the proposed method for monitoring systems in IEC 60076-7 standard [12], [14].

The differential equations are represented in block diagram form in Fig. 1. Observe in Fig. 1 that the inputs are the load factor K, and the ambient temperature θ_a on the left. The output is the desired hot-spot temperature θ_h on the right. The Laplace variable s is essentially the derivative operator d/dt.

In Fig. 2, the second block in the uppermost path represents the hot-spot rise dynamics. The first term (with numerator k_{21}) represents the fundamental hot-spot temperature rise, before the effect of changing oil flow past the hot-spot is taken into account. The second term (with numerator $k_{21}-1$) represents the varying rate of oil flow past the hot-spot, a phenomenon which changes much more slowly. The combined effect of these two terms is to account for the fact that a sudden rise in load current may cause an otherwise unexpectedly high peak in the hot-spot temperature rise, very soon after the sudden load change. Values for k_{11}, k_{21}, k_{22} and the other parameters shown are discussed and suggested values given in Table II [14].

According to the IEC standards “If, the load bearing capacity of an insulation material decreases to half of the load bearing capacity of the unused insulation material, it indicates that the material is completely aged and its service life is expired”. Equations (1)-(6) have been formulized and standardized due to the results of tests and extensive research. Therefore, by determining the hot-spot temperature correctly, the loss of life of a transformer can be estimated.

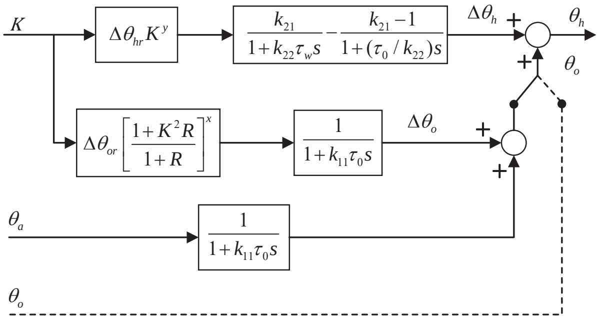

Fig. 2 Block diagram representation of the differential equations

TABLE II
RECOMMENDED THERMAL CHARACTERISTICS FOR EXPONENTIAL EQUATIONS

		Medium and large power transformers						
	ONAN*	ONAN**	ONAN	ONAF**	**ONAF**	OF**	OF	OD
Oil exponent *x*	0,8	0,8	0,8	0,8	**0,8**	1,0	1,0	1,0
Winding exponent *y*	1,6	1,3	1,3	1,3	**1,3**	1,3	1,3	2,0
Constant k_{11}	1,0	0,5	0,5	0,5	**0,5**	1,0	1,0	1,0
Constant k_{21}	1,0	3,0	2,0	3,0	**2,0**	1,45	1,3	1,0
Constant k_{22}	2,0	2,0	2,0	2,0	**2,0**	1,0	1,0	1,0
Time constant τ_0	180	210	210	150	**150**	90	90	90
Time constant τ_w	4	10	10	7	**7**	7	7	7

* Distribution transformers
**Restricted
NOTE: If a winding of an ON or OF-cooled transformer is zigzag-cooled, a radial spacer thickness of less than 3 mm might cause a restricted oil circulation, i.e. a higher maximum value of the function f2(t) than obtained by spacers ≥ 3 mm.

III. TEST SYSTEM

In the transformer monitoring test system, it is provided that transporting the necessary signals to TMS panel by simulating the signals and information used in transformer (Fig. 3).

Transformer bottom oil and top oil temperature information, tap-changer temperature information, in the sun and in the shade at ambient temperature information is provided by pt100s. Related pt100s installation are made to the appropriate place on the boiler. And also the ambient temperature in the sun and shade is provided by pt100s.

In the transformer monitoring units, transformer’s secondary and primary current information based on a current of 2 A, on the other hand transducers provides to read transformer current information on screen by converting 4-20 mA. This regulated power supply using simulations by providing the current status of 0-2 A is provided current information necessary to TMS board.

Fig. 3 Transformer Monitoring Test System

The knowledge level of the switch to read the information from TMS board level signal is provided on the resistance output module card (There are 10 Ω resistor at each level.). This situation simulates the resistance output module are mounted on the board. Step information on the movement of the shaft by inserting the shaft lever switch satisfies the card is intended to change the level.

HYDRACOL is used for transformer oil analysis which is the most widely used transformer oil analysis device. The communication of HYDRACOL with TMS panel is made from the RS485 port on the HYDRACOL.

Transformer protection devices transport the signals as contact information to TMS board. In case of the protection device gives signals can be read which protection signal gives what signal from TMS board. In this case, the latch button is used to simulate, button has 2 open contacts are used. The first open contact with the signal light is used to see if its visual signal, the second contact was sent as a signal to the TMS cabinet. In the same way the operation of the fan groups are used latch buttons. Operation of the fan which is assembled on the boiler is provided by first contact. The second contact was sent as a signal to the TEC cabinet.

IV. RESULTS AND DISCUSSION

After the test system is prepared, parameters; top oil temperature (TO), hot-spot temperature (HS), bottom oil temperature (BO), ambient temperature in the sun, ambient temperature in the shade, load ratio (LR), tap changer position (TC Pos) and the tap changer temperature (TC) that connected to system are changed by order for observing the changes of hot-spot temperature and compared with the results that calculated (Calc.) by concept designing stage formula and the correction (Corr.) is given at the end of all tables. First of all, transformer's loading ratio (LR) are analyzed and shown in Table III. As shown in this table, load factor is one of the most important factors that effects hot-spot temperature.

TABLE III
LOADING CHANGES OF TRANSFORMER

TO ˚C	**HS ˚C**	BO ˚C	Ambient		**LR (%)**	TC Pos	TC ˚C	Calc. ˚C	Corr. (%)
			☼	☀					
47	**71**	30	34	30	**120**	1	40	71,72	98,99
47	**49**	30	33	30	**18**	1	40	49,10	99,80
47	**57**	32	32	31	**59**	2	47	56,82	99,69
47	**50**	32	32	31	**25**	2	48	50,22	99,57

TABLE IV
TOP-OIL CHANGES OF TRANSFORMER

TO ˚C	**HS ˚C**	BO ˚C	Ambient		LR (%)	TC Pos	TC ˚C	Calc. ˚C	Corr. (%)
			☼	☀					
40	**50**	31	33	30	60	1	40	50,04	99,92
35	**45**	32	33	30	60	1	40	45,04	99,92
22	**32**	32	34	30	60	1	41	32,04	99,88
20	**29**	32	34	30	60	1	40	30,04	96,42

Secondly the top oil temperature which can be see that has a direct effect to the calculations of hot-spot temperature. As it is revealed from here how much top oil temperature changed, the hot-spot temperature has increased or decreased by the same value. So, in the hot-spot calculation method, top oil temperature is calculated without a factor (see Table IV). After this, bottom oil temperature changes are studied and shown in Table V. It is observed that, bottom oil temperatures' changes didn't affect any parameter for HS is observed. Also, if we look at the last values of Table IV it is seen that the HS temperature lower than the bottom oil. This is the one of the indicators for ignorance the bottom oil temperature has no effect on HS calculation.

To observe whether the temperature of the ambient temperature effect on the HS temperature, the sun and the shade ambient temperature changes were examined. As is seen in these parameters have no effect on the HS temperature (See Table VI).

TABLE V
BOTTOM-OIL CHANGES OF TRANSFORMER

TO ˚C	HS ˚C	**BO ˚C**	Ambient		LR (%)	TC Pos	TC ˚C	Calc. ˚C	Corr. (%)
			☼	☀					
47	57	**30**	34	30	61	1	40	57,26	99,55
47	57	**34**	34	30	62	1	41	57,47	99,17
47	57	**36**	34	30	62	1	40	57,47	99,17
47	57	**44**	34	30	61	1	40	57,26	99,55
47	57	**45**	33	30	61	1	41	57,26	99,55
47	57	**32**	33	30	61	1	40	57,26	99,55

TABLE VI
AMBIENT TEMPERATURES CHANGE OF TRANSFORMER

TO ˚C	HS ˚C	BO ˚C	**Ambient**		LR (%)	TC Pos	TC ˚C	Calc. ˚C	Corr. (%)
			☼	☀					
47	57	32	**34**	**30**	59	1	40	56,82	99,69
47	57	32	**54**	**30**	59	1	41	56,82	99,69
47	57	32	**28**	**30**	59	1	40	56,82	99,69
47	57	32	**27**	**30**	59	1	40	56,82	99,69
47	57	32	**26**	**44**	59	1	41	56,82	99,69
47	57	32	**26**	**51**	59	1	41	56,82	99,69

TABLE VII
TAP CHANGER VALUES CHANGE OF TRANSFORMER

TO ˚C	HS ˚C	BO ˚C	Ambient		LR (%)	**TC Pos**	**TC ˚C**	Calc. ˚C	Corr. (%)
			☼	☀					
47	57	31	31	30	59	**1**	**41**	56,82	99,69
47	57	32	32	31	59	**1**	**40**	56,82	99,69
47	57	32	32	31	59	**1**	**45**	56,82	99,69
47	57	32	32	30	59	**1**	**48**	56,82	99,69
47	57	32	31	30	59	**5**	**48**	56,82	99,69
47	57	32	32	30	59	**17**	**48**	56,82	99,69
47	57	32	32	30	58	**3**	**48**	56,60	99,31

Finally, changes in the tap-changer were examined. For this, priorly the tap changer’s temperature variations are analyzed, than the positions of the tap-changer are changed and shown on Table VII. As seen from the table, this parameter has no place in the calculation of the hot spot temperature.

When all results are analyzed, it is observed that TMS doesn’t use tap-changer position, tap-changer temperature, both ambient temperatures and bottom oil temperature values for calculating HS temperature. In calculation, only load ratio and top oil temperature values affect the HS temperature.

If it is calculated by concept designing stage formula results are correct by a ratio of 99,49%. The reason of the difference in these results may be of rounding the values of TMS. However, the results are negligible.

V. CONCLUSION

The use of TMS will provide transformers to spend a long life without a failure. This will bring huge plus in terms of energy policies to countries. At the same time, this is an important tool for smart grid technology by continuity and increase the quality of energy.

In tested system, TMS using only top oil temperature and load ratio for hot-spot temperature calculation. And also, some constants are using from standards which are on agreed statements tables.

During the tests, it came out that hot-spot temperature calculation method is just making a simple calculation and not receive significant all other variables that could affect the hot-spot temperature. Also it is observed in some results that hot-spot temperature which describes the hottest point temperature of the transformer is less than bottom oil temperature, are illogical.

For future study, calculation correctness of the hot-spot temperature can be made finer by increasing the number of variables used in the algorithm.

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Ahmet Yigit Arabul was born in Istanbul/Turkey in 1987. He received his BC degree in 2008 and MSc degree in 2010 in Electrical Engineering from Yildiz Technical University, Istanbul, Turkey. He is currently a PhD. Candidate at Yildiz Technical University. His research areas are power transformer, monitoring systems and electrical machine.

Gokhan Kalkan graduated his MSc degree with a first in 2007 from University of Manchester. And he received his PhD. in 2012 from Imperial College London. He has been working at BEST Transformer Company as a R&D Department Manager since 2002. His research areas are mechanical and physical properties of cellulose materials used in power transformers, structural integrity of the charged materials in term of electromagnetics, composite materials, and electrical analyses of electromechanical objects under high voltage and coupled magnetic field analyses.