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ENVIRONMENTAL EFFECT ON THE THERMAL PERFORMANCE OF POWER TRANSFORMER

1Vinit Mehta, 2Jayashri Vajpai

[1]Associate Professor, [2]Professor
[1]Department of Electrical Engineering,
[1]Jodhpur Institute of Engineering and Technology, Jodhpur, India

Abstract: With the continuous rise in the load demand at consumer end, the performance of the existing operating electrical machines gets affected. The increasing temperature of earth's surface due to solar radiation is another reason of the rise in the temperature of the electrical machines. Power transformers are one of the electrical machines whose performance is directly affected by its inner and outer temperature values as they are generally installed outdoors. The life of the power transformer reduces gradually with the time and sometimes the severe outdoors surface temperatures may lead to sudden explosions that also obstruct the operation of the other associated machines as well. Therefore, thermal modeling of outdoor power transformers should include the consideration of variation in environmental temperature. This is expected to create an opportunity for the research in this field. This includes developing computational thermal models simulation using appropriate software tools. These models can be employed to evaluate the actual operational age of power transformers by estimating equivalent life at the reference temperature on the basis of the time period of the estimated temperature cycle causing acceleration of aging. This paper presents a MATLAB/ Simulink based thermal model determining temperature in increasing the aging acceleration factor, which has been used for estimation of the loss of life of the transformer. Further, the effect of outdoors surface temperature due to the influence of solar radiation for increasing the loss of life of power transformer has also been studied and verified by using the thermal model. The proposed model has been validated using real time data gathered from the power transformer in operation at 220kV GSS, Jhalamand, Jodhpur.

Index Terms **- life of power transformers, solar radiation, thermal modeling, aging acceleration factor, loss of life.**

I. INTRODUCTION

Power transformers are one of the main electrical machines in any electrical substation whose functioning directly governs the operational efficiency and the economic capability of the power system. The reliability of any electrical substation is directly affected by the performance of the constituent power transformers. Any kind of failure in the power transformer normally occurs due to the failure of inner insulation materials caused by high stress, under abnormal or critical operating conditions. The most challenging problem in every power transformers is heat dissipation. Greater the heat accumulated without being dissipated, lesser is the life of the power transformer. Although, the design concept of the power transformers include a robust cooling arrangement system, still the changing environmental conditions outside the power transformers always affect its thermal performance. The inner temperature of the power transformer is directly affected by its inside as well as outside conditions.

The inside conditions include the increase in the power losses of the windings and the core which rises the temperature of the power transformer drastically. This generally happen due to the increase in the load of the power transformers. The insulating oil circulating inside the power transformer absorbs heat from the interior of transformer windings and core through conduction. This heat must be transferred to the transformer oil by convection and further, from the oil to the cooling medium via a heat exchanger.

The outside surrounding conditions that impact on the heat dissipation process may include natural conditions as well as built in conditions. The natural conditions include the effect of solar radiation, wind, rain, dust, natural landscape and humidity. Likewise, the built in condition includes transformer external layout, sheds, buildings, abstractions and design of enclosures, etc. The IEEE loading guides and IEC standard documents of the oil- immersed power transformers provide no such information regarding the above surrounding effects and their impact on the thermal performance of power transformer. By doing the thorough study of the above mentioned environmental conditions, it was found that all those factors have different level of harshness which affects the safe and reliable operation of the power transformers.

This paper presents a technique for estimating the loss of life of power transformer with the help of computational thermal model and employing it to calculate the accelerated aging. Further, the proposed thermal model is modified by incorporating the effect of solar radiation on the surface of power transformer. The most important factor while determining the accelerated aging is the hot spot temperature (HST), which is a major reason for the loss of life of transformer. The HST of a transformer primarily depends on the ambient temperature, the rise in the top oil temperature (TOT) over the ambient temperature and the rise in the winding HST over the top oil temperature. HST values for different load conditions can be estimated with the help of these thermal models on the basis of the thermal characteristics of the power transformer and the cooling system.

The proposed thermal model has been used to predict the loss of life of a 160MVA power transformer in operation at 220kV GSS, Jhalamand, Jodhpur (Rajasthan, India). After Introduction section, the paper includes four more sections that present the state of art, proposed methodology, MATLAB/ Simulink model, results and discussion.

II. State of Art

The research work in the field of thermal modeling of power transformers is having some commonly accepted procedures that primarily come under either IEEE or IEC guidelines. IEEE Guide for Loading Mineral Oil-Immersed Transformers [1] is applicable to oil- immersed distribution and power transformers, with different types of constructions, along with special considerations for the degree of conservatism involved in the loading. This has paved the way for understanding and developing models for the simulation of thermal characteristics of power transformers as attempted in this paper. The International Standard IEC 60076-2 [2] identifies power transformers according to their cooling methods, defines temperature rise limits and details the methods of test for temperature rise measurements.

G. Swift et. al. [3] have studied the theory behind the thermal model of power transformer and developed an equivalent circuit for analysis of its dynamic temperature behavior. For this, the authors have verified the physical experimental data of an in service 250MVA power transformer by considering ambient temperature as a variable input. D. Susa et. al. [4] have developed hot spot and top oil temperature rise thermal models for accurate temperature calculation based on the thermal-electrical analogy during transient states. The authors have also taken the transformer oil viscosity and loss variation into account to validate the thermal models using experimental results for varying load.

P. K. Saha and and P. Purkait [5] have investigated the effect of temperature on the insulation used in the power transformer and also showed the dependency of the moisture content in the temperature rise of the insulation oil. O. A. Amoda et. al. [6] have presented an study into the acceptability of the IEEE thermal model of oil immersed power transformers, when the model parameters are to be determined from measured field data. Z. Radakovic et. al. [7] have designed a dynamic thermal model of an indoor oil immersed power transformer and extended it with the thermal models of walls and ceiling of the kiosk and natural air ventilation through the ventilation holes. The model is validated by comparing calculation results with the results of measurements on the transformer.

A. Gamil et. al. [8] have presented an approach for matching the thermal performance of power transformers with measurements adapting some well-known and used assumptions for building a theoretical thermal model to meet the specified temperature rises while providing an optimized high economical cooling system. A. Santisteban et. al. [9] have developed a Thermal- Hydraulic Network Model (THNM) for determining the thermal characteristics of a power transformer tested with three different fluids, namely; mineral oil, natural ester and synthetic ester. The results are then compared with the Computational Fluid Dynamic (CFD) model for estimating the temperature inside a power transformer. The predicted results of the THNM model have a good agreement with the CFD results. H. Wang et. al. [10] have conducted an in-depth study on the overload capacity of the distribution transformer based on the HST model. Further, they have determined the allowable overload time of the distribution transformer during the short term and long term emergency load period. B. Jia et. al. [11] have evaluated the aging life of oil-paper insulation of a traction transformer under shock load by developing an optimization model considering the effect of shock temperature, shock duration and shock interval on cellulose degradation rate of insulating paper.

There is very limited literature available that studies about the influence of environmental conditions on the thermal performance of the power transformers. Y. Odarenko of Wilson Transformer Company, Australia, [12] has made an attempt to clarify the effect of environmental conditions on the power transformer surface. The author has categorized these conditions into natural and built in conditions. B. Gorgan et. al. [13] have modified the existing hot spot temperature model of power transformer by taking into account the influence of solar radiation. The authors have shown the effect of solar radiation on the winding paper insulation by determining its remaining life. In this study, the authors have used the IEC60076-7 thermal model for the temperature calculation and the solar radiation is modeled with Adnot model. M. Srinivasan [14] has proposed a physical model comprising of variable environmental conditions for the estimation of hot spot temperature in power transformer and along with a MATLAB/Simulink-based valid model.

In general, many simplifying assumptions have been made in the various proposed methods for calculating the HST of power transformers and considering environment factors, as reported in the standards documentation and published literature. The aim of this paper is to develop a dynamic thermal model of power transformer for estimating hot spot temperature, accelerated aging factor and loss of life, along with the consideration of solar radiation on the power transformer surface.

III. Proposed Methodology

In this section, the salient features of the proposed thermal model of a power transformer is presented. Further, the thermal model is modified by incorporating the effect of solar radiation on the surface of power transformer followed by the algorithm.

3.1. Thermal Modeling of Top Oil Temperature Rise

The rise of top oil temperature over ambient temperature is an indication of continuous loading of power transformer. An increase in the load increases the losses thus increasing the overall temperature inside the power transformer. The rate of change of temperature depends upon the overall thermal time constant of the power transformer, which in turn depends upon the heat capacity of the transformer, i.e. the mass of the core, coils, and oil, and the rate of heat exchange from the transformer. The change of top oil temperature is modeled as a first-order differential equation as follows[4].

$$T_{TO}\frac{d\Delta\theta_{TO}(t)}{dt} = \Delta\theta_{TO}(u) - \Delta\theta_{TO}(t) \qquad (1)$$

where, T_{TO} is the top oil time constant in minutes, $\Delta\theta_{TO}(t)$ is the top oil temperature rise over ambient temperature in ºC, $\Delta\theta_{TO}(u)$ is the final top oil temperature rise in ºC, and t is the time referenced to the time of the loading change.

Equation (1) is solved to obtain the following exponential response from the initial temperature state to the final temperature state.

$$\Delta\theta_{TO}(t) = [\Delta\theta_{TO}(u) - \Delta\theta_{TO}(i)]\left[1 - e^{-t/T_{TO}}\right] + \Delta\theta_{TO}(i) \qquad (2)$$

where, $\Delta\theta_{TO}(i)$ is the initial top oil temperature rise in ºC.

The final rise in the top oil temperature depends upon the load factor and can be approximated by the following equation:

$$\Delta\theta_{TO}(u) = \Delta\theta_{TO}(r)\left[\frac{K^2R+1}{R+1}\right]^n \quad (3)$$

where, $\Delta\theta_{TO}(r)$ is the full load top oil temperature rise over ambient temperature in °C, R is the ratio of load loss at rated load to no-load loss, K is the ratio of the specified load to rated load, n is an empirically derived exponent that depends upon the cooling method. The IEEE loading guide recommends the use of n=0.8 for natural convection and n=0.9 to1.0 for forced cooling. The top oil time constant at the considered load is given by the following:

$$T_{TO} = 60 * \frac{C_{th-oil} * \Delta\theta_{TO}(r)}{q_{tot}} \quad (4)$$

where, q_{tot} is the total supplied losses in W, and C_{th-oil} is the equivalent thermal capacitance of the transformer oil in W-h/°C.

The equivalent thermal capacitance of the transformer oil is given by the following equation:

$$C_{th-oil} = 0.48 * M_{Oil} \quad (5)$$

where, M_{Oil} is the weight of the oil in kg.

3.2. Thermal Modeling of Hot Spot Temperature Rise

The increase in the transformer current due to losses increases the oil and winding temperature. The change of hot spot temperature is modeled as a first-order differential equation shown in Equation(6)[4]:

$$T_{HS}\frac{d\Delta\theta_{HS}(t)}{dt} = \Delta\theta_{HS}(u) - \Delta\theta_{HS}(t) \quad (6)$$

where, T_{HS} is the hot spot time constant in minutes, $\Delta\theta_{HS}(t)$ is the hot spot temperature rise over top oil temperature rise in °C, $\Delta\theta_{HS}(u)$ is the final hot spot temperature rise in °C and t is the time referenced to the time of the loading change.

This can be solved to obtain

$$\Delta\theta_{HS}(t) = [\Delta\theta_{HS}(u) - \Delta\theta_{HS}(i)]\left[1 - e^{-t/T_{HS}}\right] + \Delta\theta_{HS}(i) \quad (7)$$

where, $\Delta\theta_{HS}(i)$ is the initial hot spot temperature rise in °C.

Based on the IEEE model, the final rise in the hot spot temperature considering the load factor can be obtained by the following equation:

$$\Delta\theta_{HS}(u) = \Delta\theta_{HS}(r)[K]^{2m} \quad (8)$$

where, $\Delta\theta_{HS}(r)$ is the rated hot spot temperature rise over top oil temperature and m is an empirically derived exponent that depends on the cooling method.

The winding hot spot time constant can be calculated as follows:

$$T_{HS} = 2.75 * \frac{\Delta\theta_{HS}(r)}{(1+P_e)*S^2} \quad (9)$$

where, T_{HS} is the winding hot spot time constant in minutes at the rated load, P_e is the relative eddy current losses (W), S is the current density in A/mm² at rated load.

Finally the hot spot temperature is calculated by adding the ambient temperature, the top oil temperature rise over ambient, and the hot spot temperature rise over top oil. This can be expressed by the following equation.

$$\theta_H = \theta_A + \Delta\theta_{HS}(t) + \Delta\theta_{TO}(t) \quad (10)$$

where, θ_A is the ambient temperature in °C and θ_H is the ultimate hot spot temperature in °C.

3.3. Estimation of Equivalent Aging Factor

In oil-immersed transformers, paper or cellulose material along with oil forms the major insulation. Therefore, the insulation must maintain adequate dielectric strength against voltage surges and adequate mechanical strength against short-circuit forces.

As cellulose ages thermally in an operating transformer; three mechanisms contribute to its degradation, namely; hydrolysis, oxidation, and pyrolysis. The agents responsible for the respective mechanisms are water, oxygen, and heat. Each of these agents will have an effect on degradation rate so they must be individually controlled. Water and oxygen content of the insulation can be controlled by the transformer oil preservation system but control of heat is left to transformer operating personnel.

Transformer insulation life is defined as the total time period between the initial state for which the transformer insulation is considered new and the final state for which dielectric stress or short circuit stress could occur in normal service and cause an electrical failure.

Experimental evidence indicates that the relation of insulation deterioration to time and temperature follows an adaptation of the Arrhenius reaction rate theory that has the following form[1]:

$$\text{Per unit life} = A * \exp\left[\frac{B}{\theta_H+273}\right] \quad (11)$$

where, A is a modified per unit constant and B is the aging rate. The temperature of 110°C is selected for one per unit life.

The Aging Acceleration Factor (F_{AA}) per unit transformer insulation life is given by the following equation.

$$F_{AA} = \exp\left[\frac{1500}{383} + \frac{1500}{\theta_H+273}\right] \quad (12)$$

The equivalent loss of life (in hours or days) at the reference temperature in a given time period for the given temperature cycle is given as follows.

$$F_{EQA} = \frac{\sum_{n=1}^{N} F_{AA_n} * \Delta t_n}{\sum_{n=1}^{N} \Delta t_n} \quad (13)$$

where, F_{EQA} is the equivalent aging factor for the total time period, n is the index of the time interval, N is the total number of time intervals and F_{AAn} is the aging acceleration factor for the temperature which exists during the time interval Δt_n.

3.4. Estimation of Percentage Loss of Life

The insulation per unit life curve is used to calculate percent loss of total life of a transformer. The normal insulation life at the reference temperature is defined in hours or years. The percentage loss of life is given as follows[1]:

$$\text{Percentage Loss of Life} = \frac{F_{EQA} * t * 100}{\text{Normal Insulation Life}} \qquad (14)$$

3.5. Effect of solar radiation on transformer surface

There are three major conditions involved during the heat transfer in the power transformers due to the solar radiation at the outside surface[12].

Condition I: From sunset on Day 1 to sunrise on Day 2: During this period of heat transfer, the inner transformer oil gets highest temperature values over the outside surface temperature. The heat dissipation is by, firstly, convective heat transfer on the inner surface of the transformer wall in oil, secondly, by thermal conduction through the transformer wall and, finally, by convection and radiation on the outside surface to the ambient air.

Condition II: From sunrise on Day 2 to sunset on Day 2: During this interval of time, solar radiation appears directly on the transformer outside surface. The temperature of the outside surface increases to the same level as that of inside transformer oil. Gradually, the heat dissipation through the inner surface reduces to zero. After that, the outside surface temperature will start to rise above corresponding inner oil temperature and start transfer heat into the inner oil. The inner temperature of the power transformer may also rises even if it is out of service.

Condition III: From sunset on Day2 to sunrise on Day3: During this stage, the temperature of the transformer surface get reduces until the temperature of the transformer surface reach steady state.

The effect of solar radiation on the inner temperature of the power transformer is modeled by adding an additional $P_{SUN(t)}/(P_{NL}+P_{LL})$ in the equation of top oil temperature rise. Here, $P_{SUN(t)}$ is the solar power at time t, $P_{NL}$and P_{LL} are the no load and load losses respectively. The solar power $P_{SUN(t)}$ is given by[13]:

$$P_{SUN}(t) = c \ . \ A_{tr} \ . \ IR(t) \qquad (15)$$

where, c is the emissivity factor, A_{tr} is the collecting surface area of the solar radiation and IR(t) is the solar irradiation at time t.

The emissivity factor c depends on the material of the surface and its colour. This factor affects the amount of radiation being absorbed and being emitted. The factor c of solar irradiation for different surface conditions are given in Table I.

TABLE I. FACTOR C OF SOLAR IRRADIATION FOR DIFFERENT SURFACE CONDITIONS

Type of Surface	Factor c
White paint	0.25
Light cream paint	0.35
Aluminum paint	0.55
Gray paint	0.75
Mat black paint	0.97

The solar irradiation IR(t) represents the global radiation in the outdoor condition and is the sum of direct and diffuse radiation. This parameter was modeled using the ADNOT model, which is the efficient method for estimating the global radiation in outdoor conditions.

$$IR(t) = 951.39(\sin\alpha)^{1.15} \qquad (16)$$

Where, α is the sun elevation angle which is given by

$$\alpha = \{\sin[\sin\delta . \sin(L) + \cos\delta . \cos(L) . \cos(HRA)]\}^{-1} \qquad (17)$$

Here, δ is the declination angle (in degrees), L is the Latitude of area (in degrees) and HRA is the hour angle (in degrees)

Here, the value of declination angle is given by:

$$\delta = 23.45^0 \sin\left[\frac{360}{365}(\text{day} - 81)\right] \qquad (18)$$

$$HRA = 15^0(LST - 12) \qquad (19)$$

$$LST\ (\text{in hours}) = \text{Local Time} + \text{Correction Factor} \qquad (20)$$

The block diagram of the thermal models of power transformer including the effect of solar radiation is now presented.

IV. MATLAB/SIMULINK MODEL

Fig. 1 shows a simplified block diagram of the MATLAB/ Simulink dynamic thermal model of a power transformer. Fig. 1(a) shows the thermal model to determine the hot spot temperature of a power transformer on hourly basis neglecting the effect of solar radiations. Fig. 1(b) shows the thermal model to determine the hot spot temperature of the same power transformer on hourly basis including the effect of solar radiation.

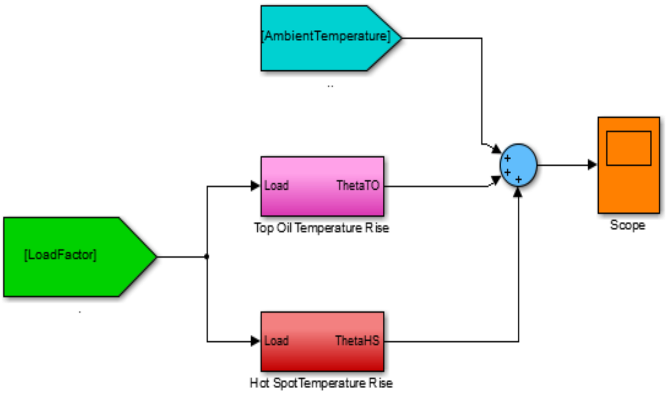


Fig. 1(a) MATLAB/ Simulink thermal model of a power transformer neglecting the effect of solar radiation

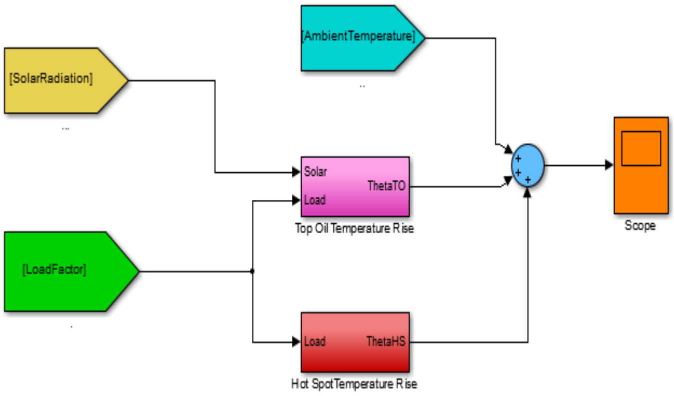


Fig. 1(b) MATLAB/ Simulink thermal model of a power transformer including the effect of solar radiation

Equation (2) and Equation (7) are solved using MATLAB program for determination of the top oil temperature rise $\Delta\theta_{TO}(t)$ and hot spot temperature rise $\Delta\theta_{HS}(t)$ respectively. At each discrete time interval of 60 minutes, the top oil temperature rise and the hot spot winding temperature rise are calculated.

The hot spot temperature θ_H is the sum of ambient temperature, top oil temperature rise and hot spot temperature rise. The measured hot spot temperature θ_H results for a 160MVA, 220/132 kV power transformer during the given load cycle are then used to determine the residual life of the transformer. The same process of modeling the above thermal model is done including the effect of solar radiation.

V. Results & Discussion

In order to validate the proposed thermal model, data gathered under various load conditions on hourly basis from an operating power transformer have been used. In this study, work has been carried out on a 160MVA power transformer situated at 220kV GSS, Jhalamand, Jodhpur substation and the data has been recorded from 18:00 (21st September 2020) to 06:00 (23rd September 2020), for the interval of 40 hours. The specification, cooling arrangements and temperature measuring equipment of the proposed power transformer are as shown in Table II, III and IV, respectively.

TABLE II: Specification of a 160MVA 220/132kV Power Transformer

MVA rating	160MVA
Rated voltage (HV)	220kV
Rated voltage (LV)	132kV
Rated current (HV)	419.9A
Rated current (LV)	699.8A
Current Density	0.28A/mm^2
No. of phase	3
Frequency	50Hz
Connection Symbol	Ynaod1
Weight of core and end frame	52000kg
Weight of winding and insulation	30500kg
Weight of Oil	42700kg/ 48000lt
Rated top oil rise over ambient temperature	40°C
Rated hot spot rise over top oil temperature	55°C
Ratio of load loss at rated load to no-load loss	5
Exponent ‘n’	0.8
Exponent ‘m’	0.9
No load and Full load losses	40kW and 200kW

TABLE III: COOLING EQUIPMENT USED

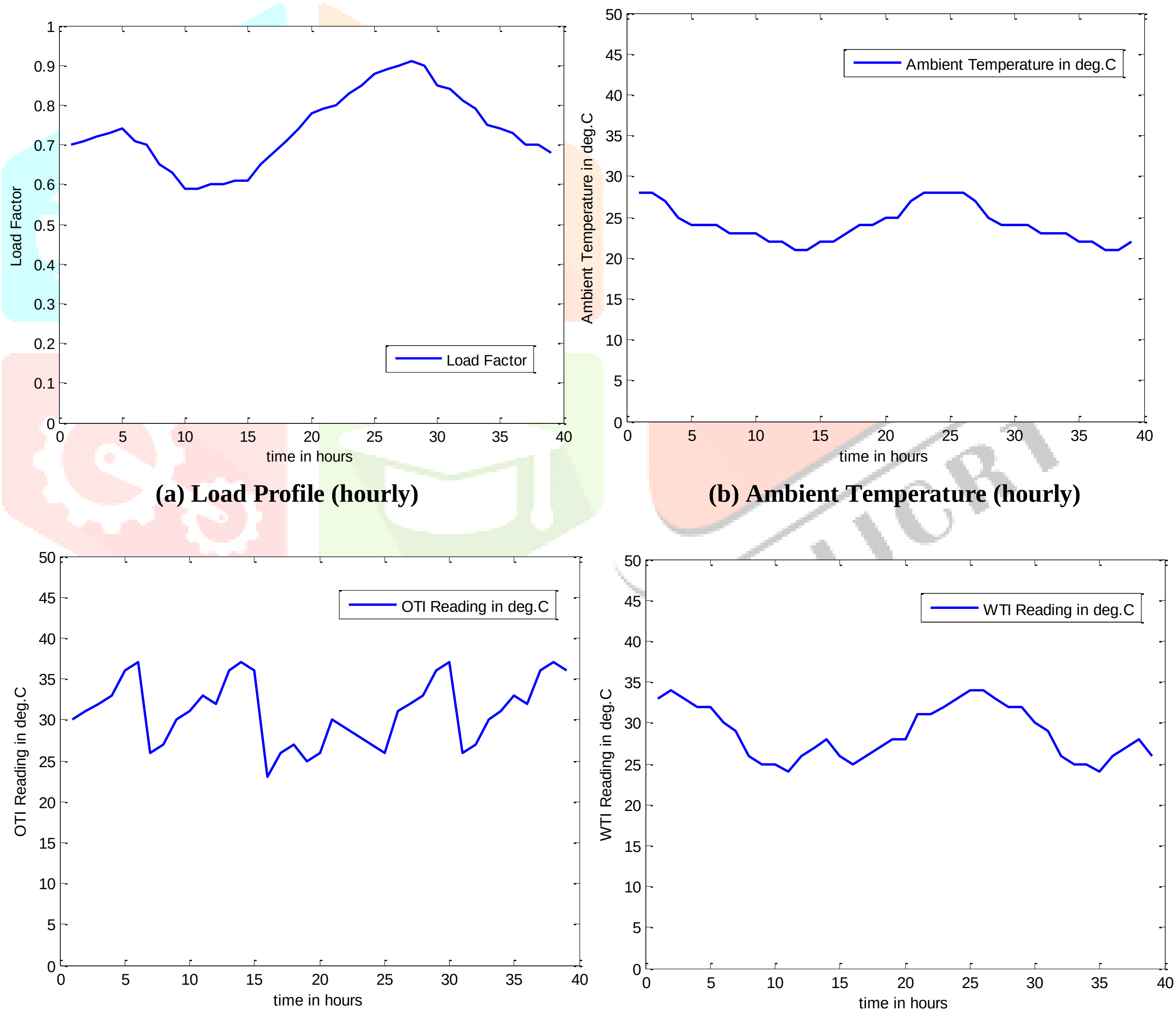
Oil pumps & Fans capacity	Pump (600 gpm)	Fan (467 cum per min)
No. of oil pumps & fans (Running + Standby)	4 (2+2)	10 (8+2)

TABLE IV: OTI AND WTI AUXILIARY CONTACTS SETTINGS

OTI	Alarm Trip	95ºC 100ºC
WTI	Fan Start Pump Start Alarm Trip	85ºC 95ºC 115ºC 125ºC

The thermal behavior of the power transformer has been evaluated and verified using the top oil and hot spot temperature thermal models. Results of these thermal models are discussed in the following section.

The normal load profile, ambient temperature, OTI and WTI readings for a 160MVA, 220/132kV power transformer for 40 hours are recorded from 18:00 (21st September 2020) to 06:00 (23rd September 2020) as shown in Fig. 2. It is clear from the Fig. 2, that the maximum value of the load factor is 0.91 occurring at 19:00 on 22nd September 2020. The hourly data of the ambient temperature are gathered from the weather information website [15]. The practical data of the WTI and OTI readings are gathered from the operating 220kV/132kV power transformer in GSS yard on hourly basis.



(a) Load Profile (hourly) (b) Ambient Temperature (hourly)

(c) Oil Temperature over Ambient (hourly) (d) Winding Temperature over oil (hourly)

Fig. 2. Load profile, Ambient Temperature, OTI and WTI Readings for a 160MVA, 220/132kV Power Transformer for interval of 40 hours

The HST for every hour is evaluated by using a MATLAB based thermal model. The effect of heat dissipated due to various losses, i.e., constant and variable losses in a transformer on the useful life of a cellulose insulation material has first been estimated on a per unit basis. Cumulative loss of life has been calculated for varying load conditions with the understanding that one real day of operation will produce less or more aging than one day. Fig. 3 shows the graphical representation of the hot spot temperature rise over oil, including the top oil temperature rise over ambient and the ambient temperature as shown in Fig. 3.

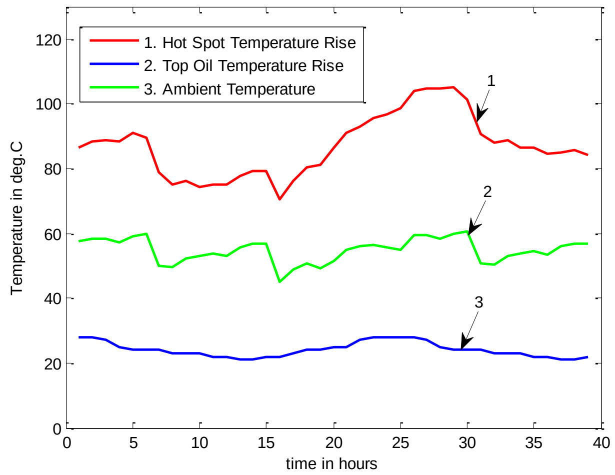


Fig. 3. Hot Spot Temperature Rise, Top Oil Temperature Rise and Ambient Temperature Values

Fig. 4. presents the variation of the solar radiation (in W/m^2) during the interval of 40 hours. It is clear that the maximum value of solar radiation occurs at 12:00 noon on 22nd September 2020. Also, the effect of solar radiation on the hot spot temperature of the power transformer is valid only for 14 hours during the proposed time interval of 40 hours. Therefore, the graph of hot spot temperature gets modified while considering the effect of solar radiation for that duration as shown in Fig. 5. The results have showed that the hot spot temperature values get raised upto 6^{0}C.

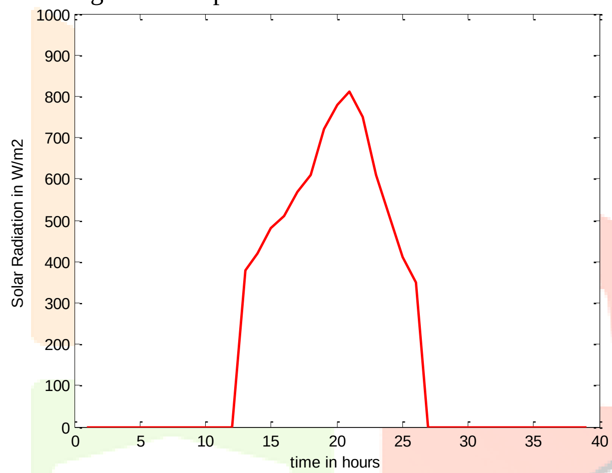


Fig. 4. Variation of Solar Radiation during the proposed interval of 40 hours

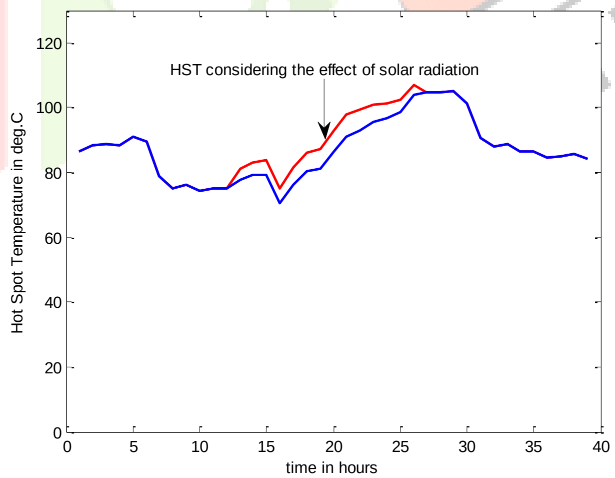


Fig. 5. Graphical representation of hot spot temperature considering the effect of solar radiation

The graphical representation of transformer insulation life throughout the time frame is shown in Fig. 6.

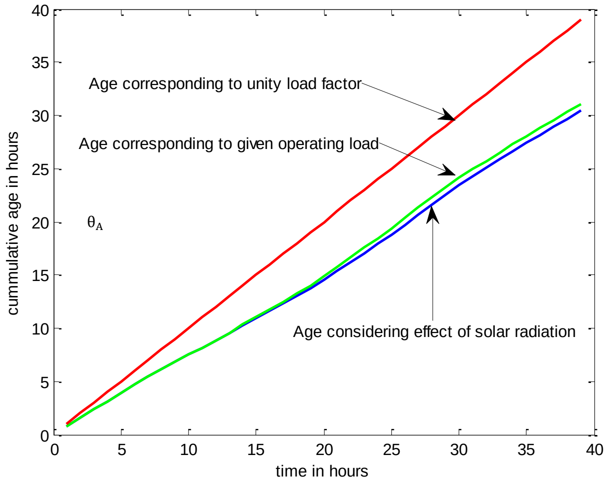


Fig. 6. Insulation Life of Power Transformer during the time interval

The percentage loss of life is evaluated corresponding to the given operating load as well as by considering the effect of solar radiation as shown in Fig. 6. It has been observed that the effect of solar radiation on the power transformer surface for the given time interval rises the life by 0.63 hour.

The proposed model gives the approximate HST values that are in close agreement with the measured field data. It can be concluded that with the inclusion of the effect of solar radiation, the life of the power transformer also reduces. Further, the study of insulation ageing is important, as it reduces both the mechanical and dielectric-withstand strength of the transformer. An ageing transformer is subjected to faults that result in high radial and compressive forces. Also, the conductor insulation gets deteriorated and becomes unable to sustain the mechanical stresses caused by a fault. Hence, it is the dominant factor in limiting the lifetime of the transformer. Providing proper cooling arrangements during the impact of solar radiation has great potential to save the percentage loss of life.

The thermal model proposed in this paper is only considering the effect of solar radiation assuming the negligible effect of the other environmental factors. Therefore, it will be important to develop such thermal models that consider the effect of other environmental conditions so that more accurate and precise results can be achieved. However, further research and development is needed to improve the existing monitoring systems and introduce designs and applications that include better thermal modeling. These thermal models will allow the power transformer manufacturers to provide better specifications and users to operate the power transformers on appropriate loading by considering the ambient temperature conditions.

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