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RESEARCH PAPER

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PREDICTION AND SIMULATION OF HOT SPOT TEMPERATURE WITH AN EFFECT OF ENVIRONMENTAL DRIVING VARIABLES

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Abstract: The Hot Spot Temperature (HST) value 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. In this paper a new semi-physical model comprising of the environmental variables for the estimation of HST in transformer is proposed and also MATLAB/Simulink-based valid model of hot spot temperature under variable environmental condition is proposed. The winding hot-spot temperature can be calculated as a function of the top-oil temperature that can be estimated using the transformer loading data, top oil temperature lagged regressor value, ambient temperature, wind velocity and solar heat radiation effect. The estimated HST is compared with measured data of a power transformer in operation.

Keywords: Hot Spot Temperature - Top Oil Temperature - Semiphysical model.

INTRODUCTION

A prospective the transformer designer employs detailed electrical models to develop reliable and cost effective transformer insulation. Transformer aging can be evaluated using the HST. The increase in TOT and there by increase in HST has the effect of reducing insulation life [1],[2],[3],[4]. Abnormal conditions, such as overloading, supplying non-sinusoidal loads or exposure to higher ambient temperature than normal, can accelerate transformer aging and accordingly accelerate the time to end of life. The increase in TOT and HST accelerates the end of the transformer lifetime. The average lifetime of oil-immersed transformers based on the lifetime of the solid insulation is well defined in [5], in which the average lifetimes based on different end of life criteria are summarized. The load on a transformer cannot be increased indefinitely without causing premature aging of transformer's insulation. Aging or deterioration of insulation is a time-function of temperature, moisture content, and oxygen content. The moisture and oxygen contributions to insulation deterioration can be minimized with modern oil preservation systems, leaving insulation temperature as the primary parameter.

The primary contributor to insulation temperature is the heat generated by load losses. Since the deterioration in the insulation is related to the insulation temperature and the temperature distribution due to load losses is not uniform in the windings in most cases, it is reasonable to believe that the greatest deterioration to the insulation will happen at the part of the winding operating under the highest temperature condition. Therefore, in aging studies it is usual to consider the aging effects caused by the HST.

Several models for prediction of HST have been presented in the literature [8]. Since the thermal phenomena are quite complex, it is not easy to consider all the details in the thermal model precisely. There are some simplified thermal models in the appropriate standards such as IEEE which have limited accuracy. The commonly used model is described in clause 7 in the IEEE loading guide [1]. The top oil rise equation of clause 7 of the IEEE guide is modified to allow for continuously varying ambient temperature [6]. An alternative method is suggested in Annexure G. The method requires the use of bottom oil rise over ambient at rated conditions. The duct oil temperature is introduced which may be higher than the top oil temperature under certain conditions [3]. Also this model requires more test parameters for calculating HST. In this paper, we report on the results of several attempts to improve the model used for predicting transformer HST. The result of this research lends additional support to the hypothesis that accurate prediction of transformer HST is due to noise in the input data and the absence of measurements for significant driving variables.

In this paper, introduce the additional environmental variation factors such as wind velocity and solar radiation and to develop the simulink model. It is useful to assess the loss of life of model.

TOP OIL TEMPERATURE EQUATION

The traditional ANSI top-oil-rise (Clause7) model [1], is governed by the differential equation:

$$T_0 \frac{d\theta_0}{dt} = -\theta_0 + \theta_u \tag{1}$$

Solution of above differential equation:

$$\theta_0 = (\theta_u - \theta_i)(1 - e^{-t/T_0}) + \theta_i \tag{2}$$

Where

$$\theta_u = \theta_{fl}\left(\frac{K^2 R + 1}{R + 1}\right)^n \tag{3}$$

$$T_0 = \frac{C\theta_{fl}}{P_{fl}} \tag{4}$$

θ_o - top-oil rise over ambient temperature (°C);
θ_u - ultimate top-oil rise for load L (°C);
θ_i - initial top-oil rise for t=0 (°C);
θ_{fl} - top-oil rise over ambient temperature at rated load (°C);
T_o - time constant (h);

C- thermal capacity (MWh/°C);
P_{fl} - total loss at rated load (MW);
n - oil exponent
I - ratio of load L to rated load;
R - ratio of load loss to no-load loss at rated load.

However, this fundamental model has the limitation that it does not accurately account for the effect of variations in ambient temperature, and therefore is not applicable for an on-line monitoring system. B.C. Lesieutre [10] has proposed a modified top-oil temperature model developed from the IEEE top-oil rise temperature model by considering the ambient temperature at the first-order characterization. Moreover, in place of mention in top-oil rise over ambient temperature, the final temperature state is considered in the model. To correct this for ambient temperature variation, recognize that the time-rate-of-change in top-oil temperature is driven by the difference between existing top-oil temperature and ultimate top-oil temperature (θ_u+θ_{amb}):

$$T_0 \frac{d\theta_{top}}{dt} = -\theta_{top} + \theta_u + \theta_{amb} \qquad (5)$$

Where
θ_{amb} - ambient air temperature (°C);

Discretizing this model using the backward Euler rule because of its stability properties, rearranging the above equation yields,

$$\theta_{top}(k) = \frac{T_0}{T_0 + \Delta t}\theta_0[k-1] + \frac{\Delta t \theta_{fl} R}{(T_0 + \Delta t)(R+1)}\left(\frac{I[k]}{I_{rated}}\right)^{2n} + \frac{\Delta t \theta_{fl}}{(T_0 + \Delta t)(R+1)} + \theta_{amb}(t) \qquad (6)$$

Where
n = 0.8 for Oil Natural Air Natural (ONAN)
= 0.9 for Oil Natural Air Forced (ONAF) or Oil Forced Air Forced (OFAF) Non Directed
= 1.0 for Oil Forced Air Forced Directed (OFAFD)

For forced cooling systems using the value n = 1, the above model is simplified to,

$$\theta_{top}[k] = \frac{T_0}{T_0 + \Delta t}\theta_{top}[k-1] + \frac{\Delta t}{(T_0 + \Delta t)}\theta_{amb}[k] + \frac{\Delta t \theta_{fl} R}{(T_0 + \Delta t)(R+1)}\left(\frac{I[k]}{I_{rated}}\right)^{2} + \frac{\Delta t \theta_{fl}}{(T_0 + \Delta t)(R+1)} \qquad (7)$$

Rewriting the above equation in a discretized form, substituting K's for the constant coefficients,

$$\theta_{top}[k] = k_1\theta_{top}[k-1] + (1-k_1)\theta_{amb}[k] + k_2 I[k]^2 + k_3 \qquad (8)$$

Where K_1 – K_3 are complex functions of the respective differential equation coefficients, and is the per-unit transformer current (based on the rated value of the transformer) at time-step index k.

The coefficient (1-k) is replaced by another coefficient k_4,

$$\theta_{top}[k] = k_1\theta_{top}[k-1] + k_4\theta_{amb}[k] + k_2 I[k]^2 + k_3 \qquad (9)$$

The linearized models in (8) and (9) are both physical models; they are based on physical principles.

HOT SPOT TEMPERATURE EQUATION

Our goal in this paper is to develop the simulink model using the physical equation. It is to be made several changes to the top-oil model in hopes of improving its performance. This is to be expected since, by adding another coefficient, we have added an extra degree of freedom that the linear optimization routine can use to find a better model. The resulting model is known as a semi-physically based model because it is not entirely based on physical principles.

We made to the model was to account for solar radiation and wind velocity ref. in [11] [12]. Solar radiation and wind velocity is a significant source of environmental variation factors when transformer placed in outdoor. The equations (10) and (11) are used to predict the HST via top oil temperature rise.

$$T_0 \frac{d\theta_{top}}{dt} = -\theta_{top} + \theta_u + \theta_{amb} + \theta_R + \theta_{wx} + \theta_{wy} \qquad (10)$$

Discretizing (10) using the backward Euler discretization rule gives the linear form,

$$\theta_{top}[k] = k_3\theta_{top}[k-1] + k_2\theta_{amb}[k] + k_1 I[k]^2 + k_4 + k_5 \mathrm{S_{rad}}[k] + k_6 V_x[k] + k_7 V_y[k] \qquad (11)$$

Where, coefficients K_1 – K_7 can be calculated from measured data using standard linear least squares technique, since all of them appear linearly in the model.

Using TOT predicted by the model (11), we can calculate the HST from the following equation :

$$\theta_h = \theta_{top} + \theta_{hm}\left(\frac{I(k)}{I_{rated}}\right)^{2m} \qquad (12)$$

Where □hm is the maximum HST over TOT in the rating load that provided by manufacturer. In this case study □hm is 36℃. Also, m is the cooling coefficient and can vary in the range of 0.8-1. In this study forced cooling system is considered in which *m* is 1.

TRANSFORMER DESCRIPTION

To validate the proposed model, data gathered under various load conditions from a real power transformer (100 MVA and 230/110 kV) which are recorded in mid day of May have been used. These data are shown in Table 1. In this study, work has been carried out in a power transformer situated at Perundurai, Tamilnadu, with the specifications as shown in Table 1. Top Oil Temperature, Load and ambient temperature were sampled every 30 minutes. Similarly, wind velocity and solar radiation measured every 30 minutes and missed data were received from metrological department. The models built in this work use only the highest cooling mode (Forced cooling).

Table: 1 Rating of Substation Transformer

Parameter		Value
Rating		100 MVA
Rated Voltage	HV	230 kV
	LV	110 kV
Rated Line Current	HV	251.3 A
	LV	525.5 A
Weight of core & Coil		74,000 kgs.
Weight of Tank and Fittings		35,000 kgs.
Oil mass		41,800 kgs.
Total Weight		1,50,800 kgs.
Volume of Oil		4,700 lit.
Top Oil Temperature Rise		55 °C
Hottest Spot Conductor rise over Top Oil temp. rise at rated load		36 °C
Ratio of Load loss at rated load to no-load loss (R)		5.0
Oil time constant (Watt-hour/ °C)		3.0

DESCRIPTION OF SIMULATION MODEL

The top oil temperature and hot spot temperature model has been calculated based on IEEE clause 7 and semiphysical model equations (1) and (11).

Load and ambient temperature data's are saved in workspace and it is fed to an input of TOT model and the output of top oil temperature rise as a input of hot spot temperature model. Fig. 1 shows the Simulink model of proposed systems which allows additional input of solar radiation and wind velocity to the existing model inputs of load and ambient temperature. The wind velocity component divided in to two orthogonal components and it is fed it separately. Fig.2 shows the subsystem of proposed system which is top oil temperature rise model. Fig. 3 shows the subsytem1 of proposed system which is hot spot temperature model comprising the function of equation (12) and its output is hot spot temperature.

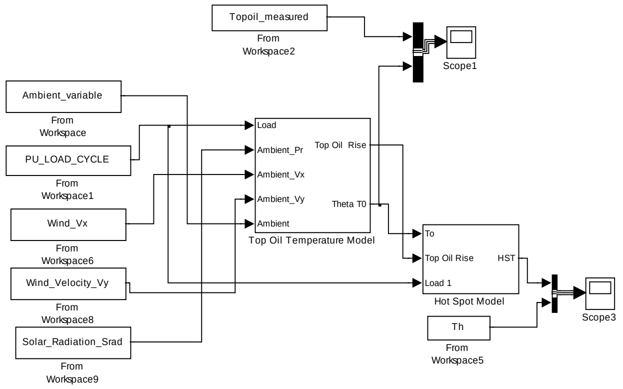

Figure 1. MATLAB/Simulink Model of proposed system

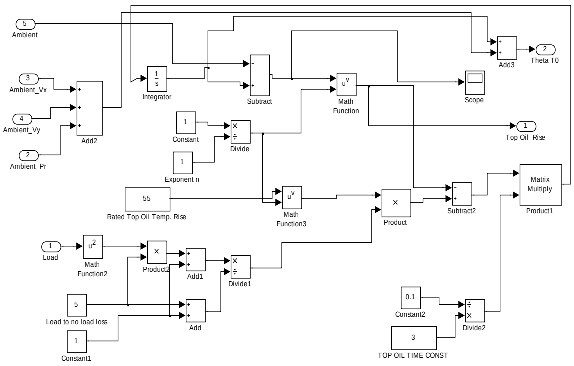

Figure 2. Top Oil Temperature rise model

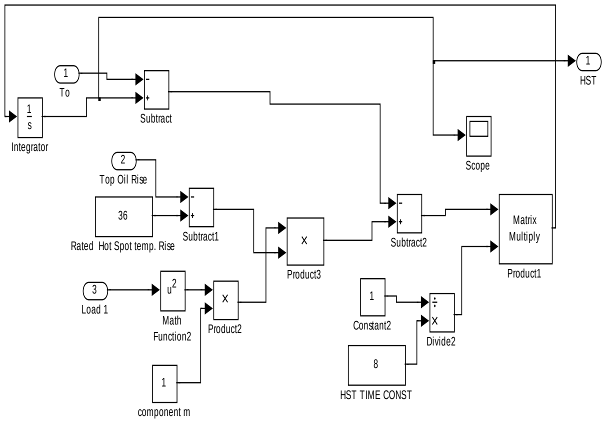

Figure 3. Hot Spot Temperature model

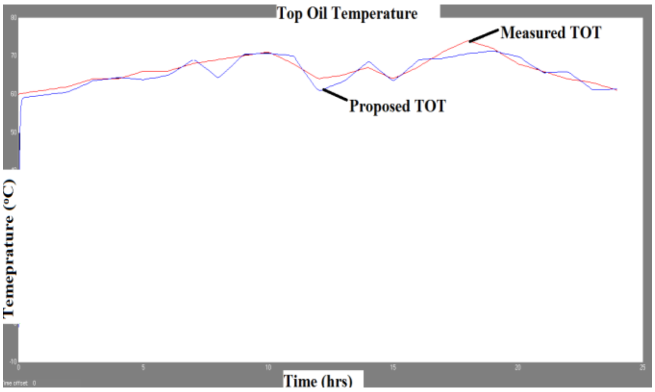

Figure 4. Top Oil Temperature waveform

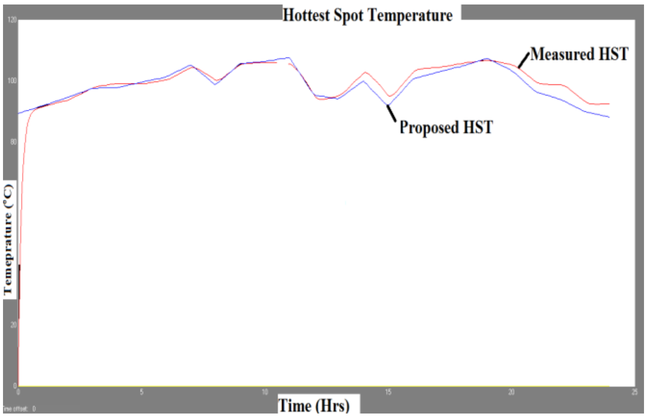

Figure 5. Hot Spot Temperature waveform

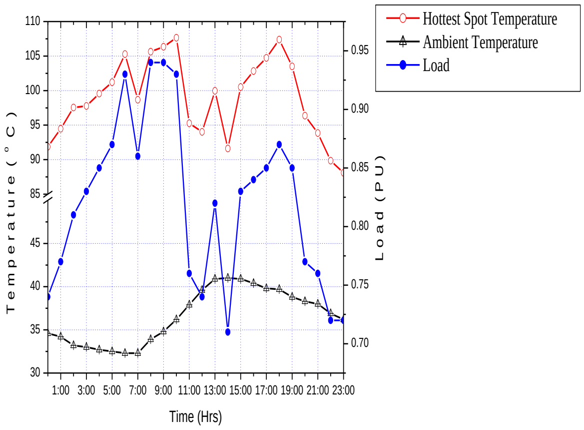

Figure 6. Load , Ambient Temperature and Hot Spot Temperature for normal load values

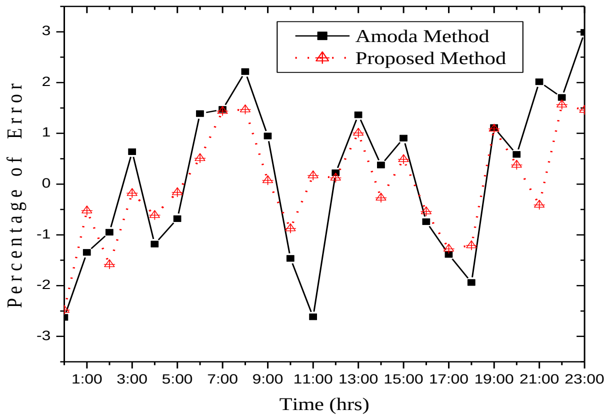

Figure 7. HST Error Comparision

RESULTS AND DISCUSSIONS

Fig. 4 and 5 shows that MATLAB/Simulink simulation output of TOT and HST of waveform for semi physical model with normal load profile. Simulation of TOT and HST are closer to measured value.

In order to show the performance of the model as well as its precision and accuracy in HST modeling, 24 hours data's are used to predict HST in all ranges for normal load profile. Fig. 6. Shows the load, ambient temperature and hot spot temperature variation with respect to time. Fig.6 shows that addition of wind velocity and solar radiation of proposed model. It is able to produce better result. Fig. 7. Shows the error comparison between existing and proposed method. Also, Fig.7 shows that the error between measured and predicted values of HST is minimum.

CONCLUSIONS

The authors have used proposed model to attempt to accurately predict transformer temperature and loss of life for normal load profile. The actual 24 hours data's are used in normal working load periods, ambient temperature, solar heat flux, and wind velocity in summer season are the base parameters. The semi-physically based proposed model leading to the conclusion that any of several models are satisfactory for predicting transformer Hot-Spot-Temperature. In this method, to expected that the addition of solar radiation and wind velocity to significantly reduce the gap between actual and predicted. Using the proposed MATLAB/ Simulink model, the effect of ambient temperature and environmental variables on hot spot temperature was investigated. Although in this study the proposed model was used to study the effect of environmental variables on insulation life, it is an exact model and used to predict the percentage loss of life of the transformer.

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