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Dynamic Thermal Model for Power Transformers

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ABSTRACT The prediction and determination of thermal response for the metallic parts is a very crucial step in the design of power transformers. This paper presents a comparative analysis of different thermal models for predicting the hotspot temperature and top oil temperature of power transformers. Also, a new thermal model is proposed for the monitoring of transformer operation which is capable of identifying the hotspot temperature and the top oil temperature by taking into account the ambient temperature and the load variation with respect to real time. The model is experimentally validated and compared with the actual field data. It is found that results obtained from the proposed model and the actual field data are in good agreement.

INDEX TERMS Transformer, hotspot temperature, transformer faults, thermal model.

I. INTRODUCTION

Estimation of a transformer's health requires thermal monitoring of winding insulation by tracking the incipient activities. These incipient faults in a transformer rise gradually with the passage of time and if necessary actions are not taken, can cause catastrophic failures. Partial discharges (PD) is one of the most encountered incipient activity in power transformers which indicates the growth of some precarious activity inside the transformer tank. PD is the root cause in the deterioration of electrical and mechanical strength of transformer winding insulation. Therefore, it must be mitigated in initial stages [1].

The PD activity is predominantly accompanied by thermal events such as the creation of local hot-spots. The voids where PD activity takes place are randomly distributed and it is difficult to indicate their actual location and therefore the top oil temperature is the best indicator for any PD activity within the transformer winding. It has been documented that the maximum top oil temperature can reach about $100°C$ to $110°C$ [2]. Similarly, the hot-spot temperature (HST) depends on the magnitude and re-occurrence of PD activity during continuous voltage application [3] and is a critical factor which results in the deterioration of winding insulation [4].

An accurate estimation of the winding HST is required to assess the health of power transformer. It is one of the critical limiting factors for transformer loading, thus it increases the significance of determining the HST at every moment of transformer operation with real load condition and ambient temperature [5]. There are two possible methods for determining the HST. One of them is using fiber optic temperature sensors placed in the intended hotspot of the windings [6], [7]. Thermal sensors, attached to the end of the optical fiber, are usually placed between the insulated conductor and the spacer and the optical fiber signals are transmitted out of the tank. However, the cost penalty due to the sensor installation sometimes becomes difficult to justify. Furthermore, it is not practical to adapt this technique into already assembled transformer units. Another difficulty with the direct measurement technique is to accurately locate the hotspot position and optimum sensor deployment [8], [9]. The second method which is a statistical approach determined by calculating the internal temperature of the transformer (HST) is a very complicated and a difficult task [10]–[12].

A significant amount of work has been done on predicting the winding HST [13]. The most commonly used hotspot thermal model is presented in the clause 7 of IEEE loading guide manual [14]. Moreover, Swift *et al.* [15] suggested a methodology to use the IEEE clause 7 model based on the fundamentals of heat transfer theory. Susa *et al.* [16], [17]

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TABLE 1. Classification of different techniques for estimation of hot spot temperature.

S.No	Name	Brief Description	Advantages	Disadvantages
1	Stochastic Technique [23]	Stochastic methods include artificial intelligence (AI) techniques such as Genetic Algorithms (GA).	Reliable. It is a powerful computational tool in seeking optimum results and also considers the most up-to-date data.	It always takes a long time-period. It might not find the most optimal solution to the defined problem in all cases. Not applicable to problems with too many variables.
2	Numerical Technique [24], [25]	These techniques are based on the finite element methods (FEM).	Modeling of complex geometries and irregular shapes is easier as varieties of finite elements are available for discretization of domain. Different types of material properties can be easily accommodated in modeling from element to element or even within an element.	It requires longer execution time. Output result will vary considerably. It requires a digital computer and fairly extensive.
3	Thermal equivalent circuit Technique [26]	This technique is based on equivalent circuit of the transformer. It can provide reliable results, especially in cases of standardized geometries.	The thermal circuit is easy to analyze because equivalent model is mathematically concise.	It needs to have accurate data on the values of each of the elements for the equivalent circuit to be valid. It also needs to assume that the circuit is totally linear or requires to account for non-linearity in the magnetic core.
4	Practical Experiment Techniques[27]	Experimental methods rely on the data provided by measurements with analytical or other methods.	The big advantage which the experimental methods obviously have is the better validity of the results.	Subject to human error

presented a more accurate thermal model of transformer by considering the dynamic load conditions. An analogous approach has been used by Elmoudi *et al.* [18]–[20] to develop a simplified thermal-electrical equivalent mathematical models to calculate the real time top oil and hotspot temperatures of a substation transformer.

The hot-spot temperature has a direct effect on the mechanical and electrical strengths of transformer winding insulation [21]. Utilizing the accuracy of the dynamic thermal models, the hot spot temperature can be used to monitor the winding insulation for the transformer. Various computational methods and engineering models proposed for transformers and accurate prediction of their features are classified into four main groups as shown in the table 1.

Partial discharges, as discussed earlier, occur in voids and defects inside the insulation and is accompanied by generation of frequency noise which results in deteriorating the insulation, so in order to better understand the phenomenon of PD inside the transformer winding insulation, the most cost effective approach is the computer based modelling and simulation. This approach is widely adopted by the industries for the condition assessment and estimation of life of the transformers [22]. Simulation models can portray an accurate estimation of the real-time behavior of any equipment.

The proposed research attempts to compare different existing thermal models of transformers and developing a generalized thermal model for power transformer which is capable of identifying the hotspot temperature and top oil temperature by taking into account the ambient temperature and the load variation. The thermal model is validated using the experimental results obtained by varying the load current on

TABLE 2. Comparison table of various thermal models for transformers.

Model	Models based on Thermo-electric analogy and heat transfer theory	Effect of variable oil viscosity with the top oil temperature	Made up of a top oil and hotspot model	Model as first order differential equation based on heat transfer principles.	Temperature increase is influenced by transformer loading as well as the type of cooling.	Models use the load current and ambient temperature as a variable	Dynamic increase or decrease hotspot temperature
IEC Model [9]	✓	×	✓	✓	✓	×	×
D. Susa Model [10]	✓	×	✓	×	✓	×	×
G. Swift Model [11, 12]	✓	×	✓	×	✓	×	✓
IEEE Model [13, 14]	✓	×	×	✓	✓	×	×
Proposed Model in this research	✓	✓	✓	✓	✓	✓	✓

different phases of the transformer. The real-time application provides an accurate picture of the operation condition of the transformer, which allows the operator to detect early signs of failure. A significant advantage of the proposed thermal model is that unlike other models, the ambient temperature is considered variable. Moreover, the model can effectively explain the temperature dependent factors. Furthermore, the model has been developed for in-service transformer. To the best of the knowledge of the authors, this has not been attempted in previous publications.

II. COMPARATIVE ANALYSIS OF VARIOUS THERMAL MODELS

A comparison of different thermal models with the proposed thermal model is carried out to extract the parameters that characterize the thermal model from on-line measurements to avoid shutdown of the transformers during operation as shown in table 2.

III. DEVELOPMENT OF PROPOSED THERMAL MODEL

A thermal insulation model for oil-immersed 10 KVA, 1100/400V, 50 Hz distribution transformer is developed in MATLAB Simulink that employs the hot spot temperature from the dynamic thermal model of the transformer and then compared with the IEEE thermal guideline model. The two important general properties of the transformer oil are its heat capacity and thermal conductivity. These properties are fixed for a particular volume of oil, and hence can be used as thermal capacitance and thermal resistance. According to the electrical laws for defining a resistance and capacitance, we have:

$$v = i.R \;\&\; i = C.\frac{dv}{dt} \tag{1}$$

The corresponding thermal laws are

$$\theta = R_{th}.q \;\&\; q = C_{th}.\frac{d\theta}{dt} \tag{2}$$

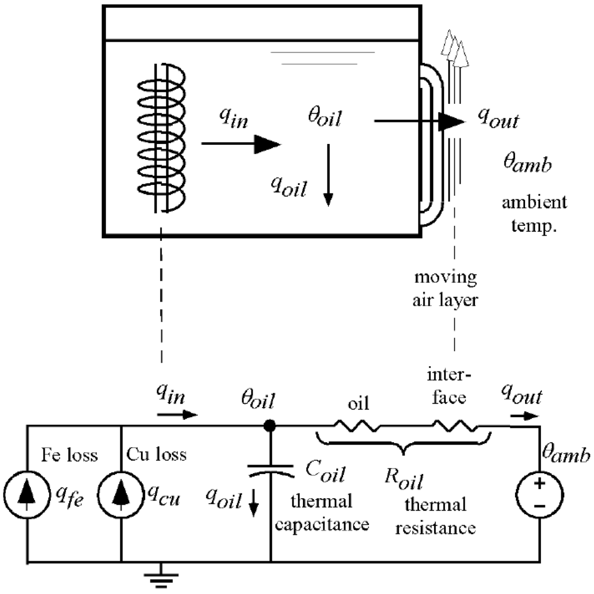

FIGURE 1. RC circuit for transformer [4].

A. TOP-OIL MODEL

Top-oil modelling is based on the fundamentals of oil-air model. Fig 1 shows the electrical equivalent thermal model of transformer top-oil, i.e. between the transformer top-oil and ambient temperature surrounding the transformer steel tank.

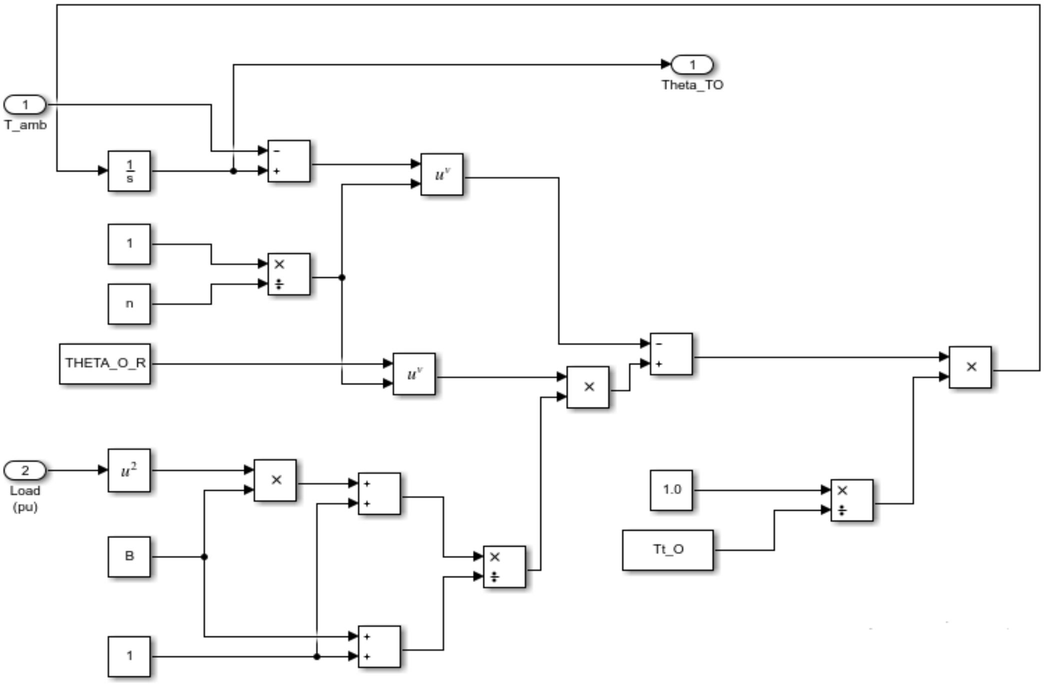

FIGURE 2. **Simulink model for top oil temperature.**

All the transformer losses are current sources injecting heat into the system. The thermal capacitance is shown as a lumped capacitance and the thermal resistance is shows as a non-linear term. The differential equation representing the top-oil model is:

$$q_{in} = C_{th-oil}\frac{d\theta_{oil}}{dt} + \frac{1}{R_{th-oil}}.\,[\theta_{oil} - \theta_{amb}]^{1/n} \tag{3}$$

where,

q_{in}	the heat generated by total losses, W
C_{th-oil}	the oil thermal capacitance, W.min/$^\circ C$
R_{th-oil}	the thermal resistance, $^\circ C$/W
θ_{oil}	the top-oil temperature, $^\circ C$
θ_{amb}	the ambient temperature, $^\circ C$
n	non-linearity exponent

$$q_{in}.R_{th-oil} = R_{th-oil}.C_{th-oil}\frac{d\theta_{oil}}{dt} + [\theta_{oil} - \theta_{amb}]^{\frac{1}{n}} \tag{4}$$

Or

$$q_{in}.R_{th-oil} = T_{oil}\frac{d\theta_{oil}}{dt} + [\theta_{oil} - \theta_{amb}]^{\frac{1}{n}} \tag{5}$$

Equation (5) can be reduced as:

$$\frac{I_{pu}^2\beta + 1}{\beta + 1}[\Delta\theta_{oil-R}]^{1/n} = \tau_{oil}\frac{d\theta_{oil}}{dt} + [\theta_{oil} - \theta_{amb}]^{1/n} \tag{6}$$

where,

I_{pu}	the load current as a function of time
β	the ratio of load to no-load losses
τ_{oil}	the top-oil time constant, min
$\Delta\theta_{oil-R}$	the rated top-oil rise over ambient temperature, K.

Equation (4) is a non-linear, first order, non-homogeneous differential equation with numerical solution possible. The complementary part of the solution, however, will have a general form that contains an exponential function. Based on equation (6), a Simulink model has been developed in MATLAB as shown in fig.2.

Where as in fig.2 "T_amb (Ambient temperature)", "Load Current (pu)", "Tt_O (top-oil constant)" and "theta_o_R (Rated top-oil rise over ambient temperature)" are the input variables and give us the required top-oil temperature "Theta_TO" as output by solving the formula through mathematical blocks in Simulink. The ratio of load to no-load losses was obtained by knowing the no-load and full-load current from the nameplate and the impedance of secondary and primary windings in addition to the magnetizing resistance and reactance.

The time constant and the value of exponent "n" were obtained by performing a heat-run test on the transformer at quality control laboratory of Heavy Electrical Complex (HEC) Taxila, Pakistan. For the heat-run test, the newly manufactured power transformer 10KVA, 11/0.4kV, which passed all the required quality control tests was loaded by connecting dummy load based on oil cooled variable resistors so as allow the temperature of the oil in transformer to increase to a value of $+65^\circ C$ (the allowed rated maximum operating temperature limit by PESCO). The load on the transformer was then removed and the transformer was allowed to remain energized under no-load condition to monitor the drop in oil temperature to the desired ambient temperature of $24^\circ C$. The total time taken for the temperature to decay to the value of desired room temperature was noted in steps of each minute time-frame. The time taken for the

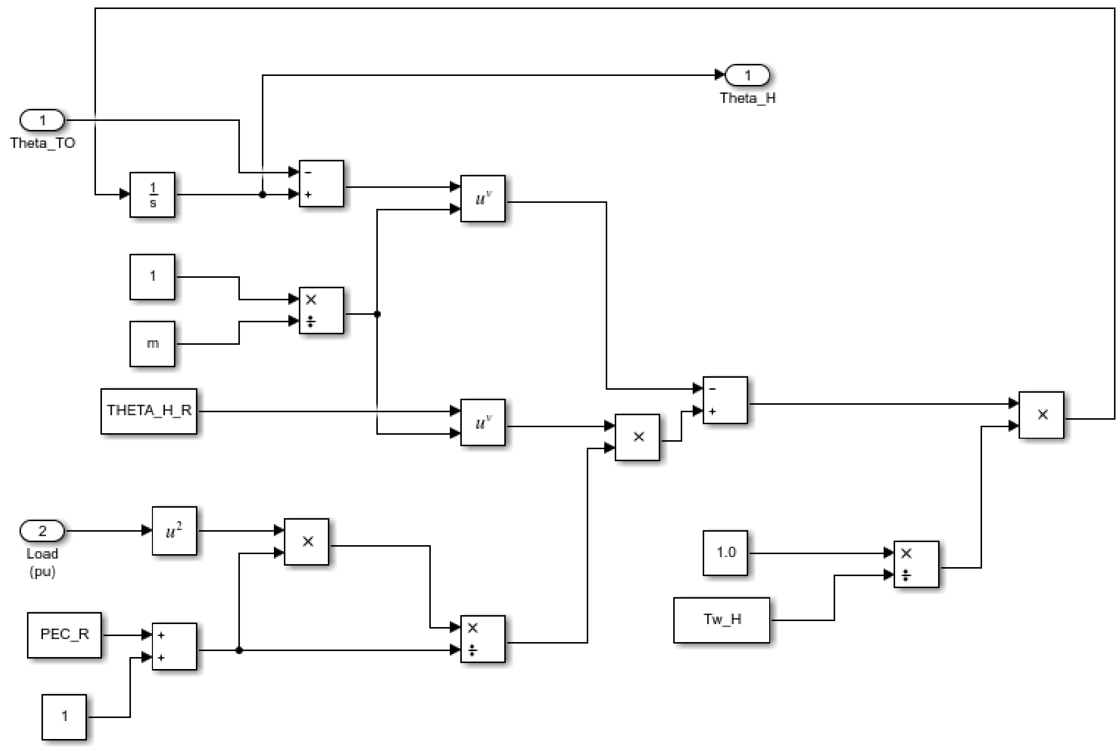

FIGURE 3. Simulink model for hotspot temperature.

temperature under oil natural cooling mode (ONC) to fall to room temperature was noted to be 22 minutes (1320 seconds).

B. WINDING HOTSPOT TEMPERATURE MODEL

Hot-spots are concentrated localized high temperature regions in transformer winding assembly which may be the result of cumulative PD activity. The modeling of hot-spots is based on the fundamentals principle of winding-to-oil model constituting an RC circuit with current source representing heat flow and a voltage source that represent temperature as shown in Figure.1. Like the top-oil model, the hot-spot model has also been implemented as a simple RC circuit to analyze the hot-spot temperature θ_{hs}. The transformer winding losses are shown as current source injecting heat into the system at the hot-spot location. The thermal capacitance of the oil is shown as a lumped capacitance and the thermal resistance of the insulation is shows as a non-linear term. Here the exponent defining the non-linearity will be m i.e. the coolant is oil. The differential equation representing the hot-spot model is,

$$q_{hs} = C_{th-hs}\frac{d\theta_{hs}}{dt} + \frac{1}{R_{th-hs}}.\,[\theta_{hs} - \theta_{oil}]^{1/m} \qquad (7)$$

where,

q_{hs}	the heat generated by winding losses at hot-spot location, W.
C_{th-hs}	the winding thermal capacitance at the hot-spot location, W.min/°C
R_{th-hs}	the thermal resistance at the hot-spot location, °C/W
θ_{hs}	the top-oil temperature, °C
m	the exponent for non-linearity

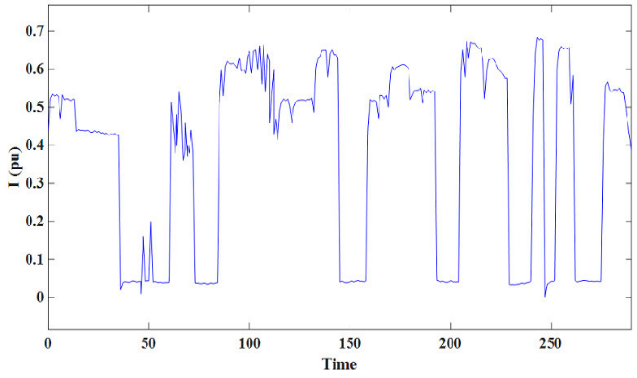

FIGURE 4. Input load current for the proposed Simulink model.

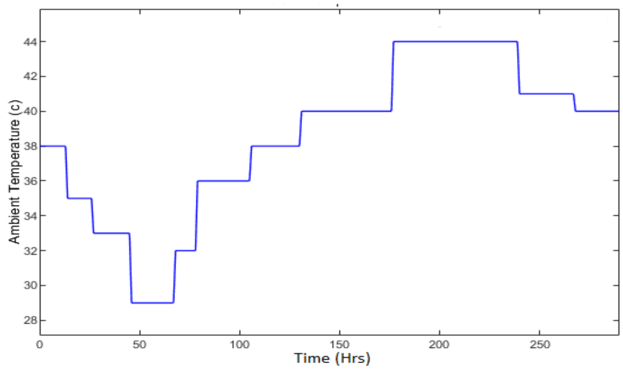

FIGURE 5. Input ambient temperature for the proposed Simulink model.

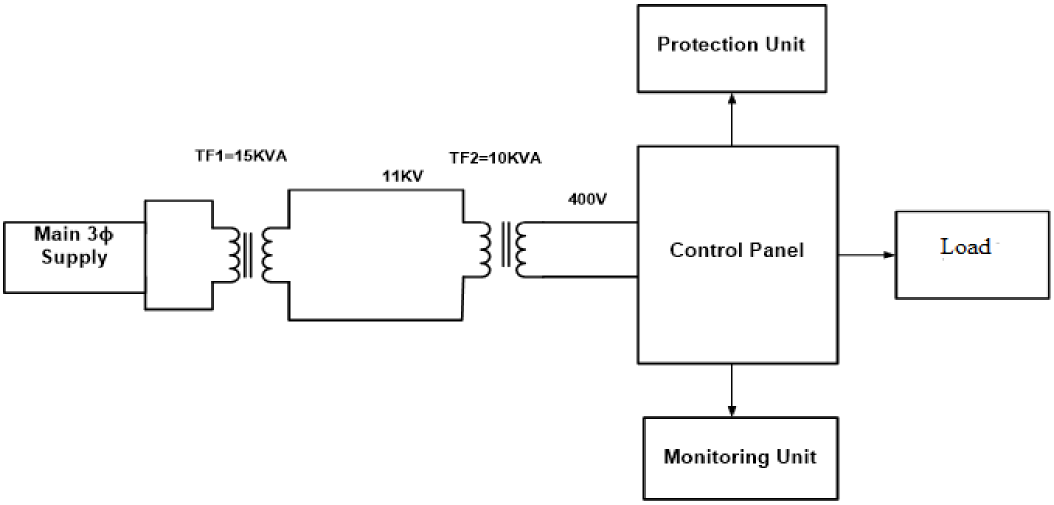

FIGURE 6. Schematic diagram of experimental setup for measurement of top oil temperature and hot spot temperature.

Equation (7) can be reduced as:

$$\frac{I_{pu}^2[1+P_{EC-R(pu)}]}{1+P_{EC-R(pu)}}[\Delta\theta_{hs-R}]^{1/m} = \tau_{hs}\frac{d\theta_{hs}}{dt} + [\theta_{hs}-\theta_{oil}]^{1/m} \tag{8}$$

where,

$P_{EC-R(pu)}$ is the rated eddy current losses at the hot-spot location.

τ_{hs} is the winding time constant at the hot-spot location, min.

$\Delta\theta_{hs-R}$ is the rated hot-spot rise over top-oil temperature, K.

The hot spot temperature model in Simulink is shown in fig. 3.

IV. MODEL SIMULATION

A. INPUT VARIABLES FOR THE PROPOSED MODEL

The daily load cycles per unit for each phase of the transformer and the ambient temperature as a function of time were measured using SEL-2414 monitoring device as shown in fig 4 and 5. Additionally, both the top-oil temperature and hot-spot temperature, which were recorded during a varying load current, are compared with the results obtained from the Simulink model.

It can be seen from the graph in fig 4 and fig 5, that the peaks; load and ambient temperature does not coincide with time. This would mean that the ambient temperature and load cycle are independent and are not function of each other. The parameters for the top oil and hot spot models are taken from the name plate of the transformer and shown in table 3.

TABLE 3. Transformer constants required for the proposed model.

FEATURE	VALUE
Rated top-oil rise over ambient	49 °C
Rated hot-spot rise over top-oil	18 °C
Ratio of load losses to no-load losses, β	4.90
Pu eddy current losses at hot-spot location, LV	0.42
Top-oil time constant	180 min
Hot-spot time constant	6 min
Exponent n	0.9
Exponent m	0.8

V. MODEL VALIDATION

A. EXPERIMENTAL DETAILS

In the proposed model, the input data required for the model is the daily load cycles (load current) and the ambient temperature. As the model is based on the prediction of real-time behaviour of the transformer, therefore, the real-time data has been taken from the distribution transformer. To measure the internal temperature of the transformer, we considered two distribution transformers:

1) 15KVA, used for the generation of 11KV line in the laboratory.
2) 10 KVA transformer used for the analysis in the experiment.

The entire setup installed in the High Voltage Laboratory located at the University of Engineering and Technology, Peshawar, Pakistan and data has been collected by installing (SEL)-2414 Transformer Monitor device by Schweitzer Engineering Laboratories. Fig 6 shows the schematic of experimental test setup and fig 7 shows complete laboratory testing and experimentation facility.

Since the proposed model is developed to predict the real-time behavior of the transformer performance in the actual

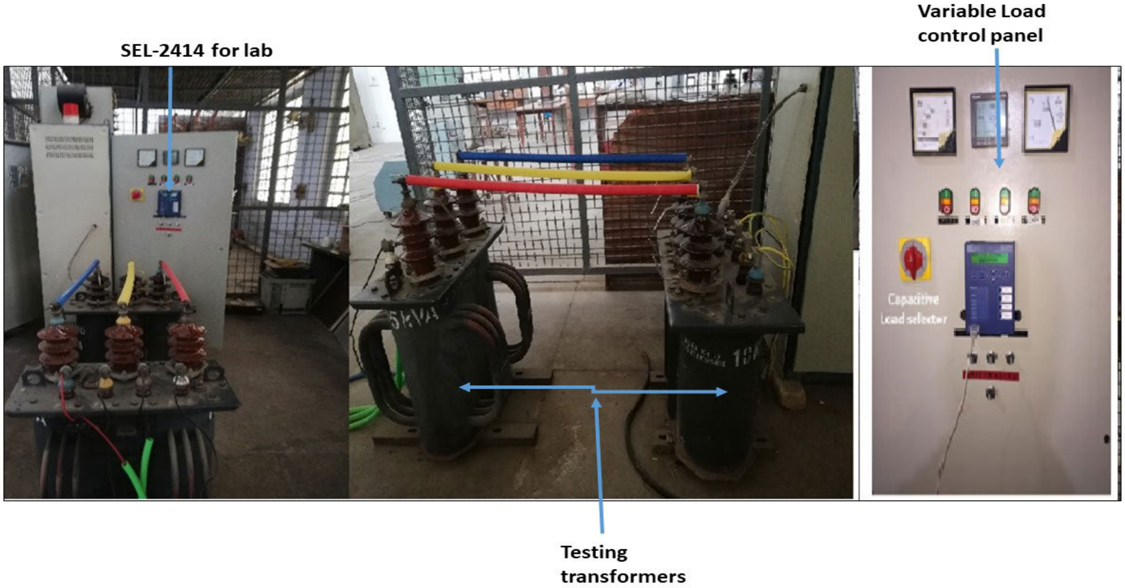

FIGURE 7. Laboratory testing and experimentation.

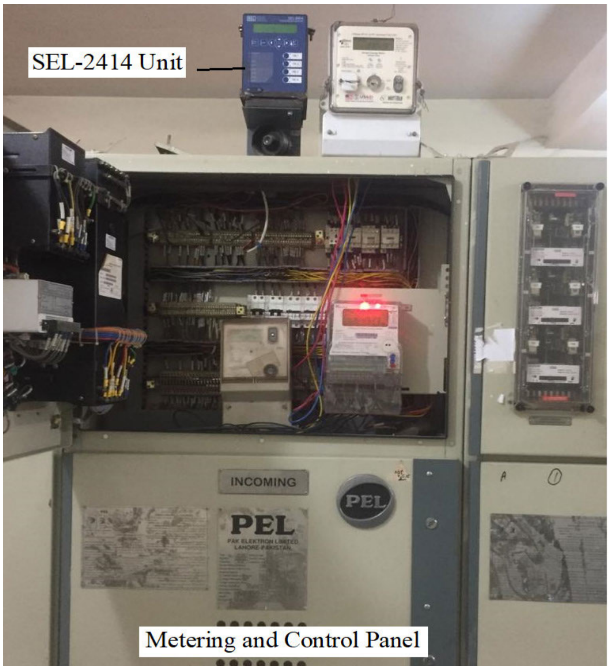

FIGURE 8. SEL-2414 Unit.

power system, therefore it was essential that the estimation of life of transformer has to be based on reliable field data. In order to acquire reliable field data, a three-phase, 50Hz, 10/13 MVA, 132/11 kV power transformer installed at 500kV Sheikh Muhammadi sub-station, Peshawar, Pakistan was considered and the same unit-2414 also installed as shown in fig 8.

B. METHOD FOR TEMPERATURE MEASUREMENT

For the temperature measurements, RTD pt100 sensors were installed at particular required locations in the 10 kVA transformer as shown in fig 9. The wires from the sensors were then connected to SEL-2414 transformer monitoring unit to measure the required temperatures.

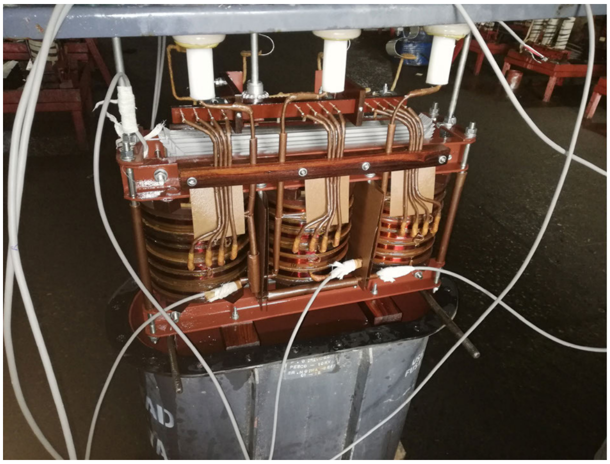

FIGURE 9. Installed Pt100 sensors for temperature measurement.

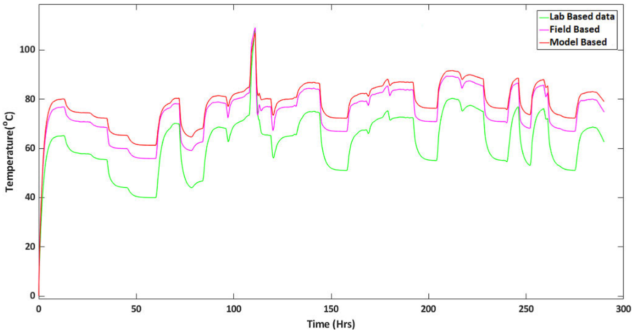

FIGURE 10. Top oil temperature as a function of time.

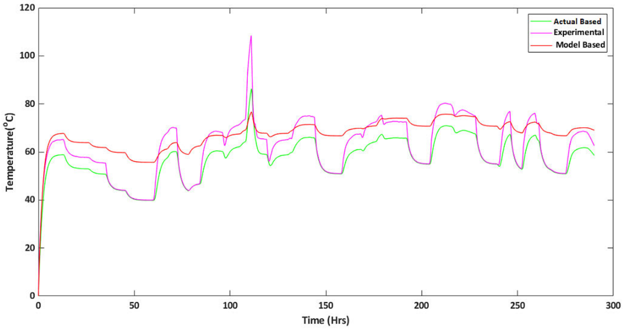

FIGURE 11. Hotspot temperature as a function of time.

VI. SIMULATION RESULTS

Fig 10 below compares the measured and the predicted top oil temperature of phase c winding in the distribution transformer in the lab and field along with the proposed model. Similarly, fig 11 shows the measured and the predicted hotspot temperatures of the transformer. For both the models, the input load is connected to the phase C of the transformer. The simulated results of the proposed thermal model are in good agreement with the measured values, showing good accuracy in case of top oil temperature and hotspot temperature.

VII. CONCLUSION

A Dynamic thermal model for Power transformers is presented in this paper. For the first time, a real-time experimental validation has been implemented for the dynamic thermal model. Thermal model is developed for the prediction of hot spot and top oil temperature of power transformers in Simulink MATLAB. Unlike the previously reported models, the proposed model takes into account the effect of varying load and ambient temperatures. For model validation an experimental setup was implemented at University of Engineering and Technology Peshawar Pakistan and Shiekh mohammadi Grid Station Peshawar respectively. Moreover, the state of the art IEEE model is used for model validation. As compared to the other thermal models, the analysis methodology presented in this study is based on the physical condition of the transformer and a real-time thermal monitoring results are visualized by utilizing the real-time data of a substation power transformer and a distribution transformer. The results predicted by the proposed model are in good agreement with the experimental and field based data. The model is demonstrably predicting the hotspot and top oil temperature successfully in the tests conducted. The model has been validated by comparison of the simulation and field data and exhibits significant enhancement over the existing models in prediction of the top oil and hotspot temperatures.

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