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Development of an Improved Model for Assessment of Hot Spot Temperature of Current Transformers

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ABSTRACT: Current transformers form important components that make up a large portion of capital investments. Failure of a current transformer results in an adverse effect in the operation of transmission networks which causes an increase in the power system operation cost and inability to deliver electricity with absolute reliability. The age of a transformer is the life of its insulation, majorly, paper insulation. Transformer aging can be evaluated using the hot spot temperature which has the effect of reducing the insulation life of transformers. Previous researchers have developed models for assessment of top-oil temperature of current transformers. Such models have the limitation that they do not accurately account for the variation effect in ambient temperature and hence not applicable for an on-line monitoring system. This research paper develops an improved model for assessment of hot spot temperature from the IEEE top-oil rise temperature model by considering the ambient temperature at the first-order characterization using appropriate mathematical notations. The ambient temperature, top oil rise over temperature and winding hot spot rise over temperature were used as input parameters for the development of the improved hot spot temperature model by considering the final temperature state since the time-rate-of change in top-oil temperature is driven by the difference between the exits top-oil temperature for ambient temperature variation. The improved model was then implemented in MATLAB to compute the hot spot temperature for 24-hour load cycle. The result of the improved model shows that the least and highest value of the hot spot temperature are 63^0C and 105.4^0C respectively indicating a retardation in the aging process of the transformers. The improved model helps to minimize the risk of failure and to extend the life span of transformers thereby controlling the hot spot temperature rise and top oil temperature.

Keyword: Current Transformers, Hot Spot Temperature, Top-Oil Temperature, Ambient Temperature, Insulation Failure, Aging Effect and Aging Process.

1. INTRODUCTION

Power transformers comprise of all transformers of larger size (250 kVA and above) and are used in generating stations and transmission substations for transforming the voltage at each end of a power transmission line. They are used in distribution systems whenever there is the need to interface between different voltage levels i.e. to step up and down voltages (Gouda, Amer and Salem, 2012; Anuradha and Satish, 2011; Jauregui and Tylavsky, 2008).

Distribution transformers are transformer that provides the final voltage transformation in the electric power distribution systems, stepping down the voltage used in the distribution lines to the level used by the consumer. The process of transformer operation causes gradual deterioration of the transformer. Most transformers are designed to accommodate load growth. Components which experience deterioration mostly include the insulation systems dielectric properties (Akbari *et al*., 2013; Swift, Molinak and Lehn, 2011; Diego, Robalino and Satish, 2008a).

When a power transformer fails, an adverse effect occurs in the operation of transmission and distribution networks resulting to an increase in the power system operation cost and decrease of reliability in electricity delivery (Dong-Jin *et al*., 2012; Diego, Robalino and Saish, 2008b; Srinvasan and Krishnan, 2005).

1.1 Function of a Power Transformer

The purpose of a power transformer is to transfer power efficiently and instantaneously from an external electrical source to an external load (Jalbert *et al*., 2012; Cheim *et al*., 2012).

Power transformers perform the following functions (Satish and Diego, 2010; Mohammed, Mohammed and Amir, 2010; Elmoudi, 2008; Karisson, 2007):

i. The primary to secondary turn's ratio can be established to efficiently accommodate widely, different input/output voltage levels.
ii. Multiple secondary terminals with different number of turns can be used to achieve multiple outputs at different voltage levels.
iii. Separate primary and secondary windings facilitate high voltage input/output isolation, especially in off-line applications.

2. MATERIALS AND METHOD

Insulation failure is responsible for most faults in current transformers. Insulation aging is a function of temperature. The aging effect is produced by Hot Spot Temperature (HST) whose value depends on the ambient temperature. The improved model is developed by considering the ambient temperature at the first-order characterization using appropriate mathematical notations. The addition of ambient temperature, top oil rise over temperature and winding hot spot rise over temperature rise is the Hot Spot temperature.
Hot sport temperature is:

$$T_S = T_A + T^1 + \Delta T_H \tag{1}$$

where;

T_S is the hot spot temperature

T_A is the ambient temperature

T^1 is the top-oil rise over ambient temperature in ^{0}C.

ΔT_H is the winding hot spot rise over top-oil temperature.

$$T_{ST} = T^1 + T_{hm} \left(\frac{I(t)}{I_{rated}}\right)^{2m} \tag{2}$$

where;

T_{hm} is the maximum HST over TOT in the rating load.

m is the cooling coefficient ($0.8 \leq m \leq 1$)

m = 1 in this case for forced cooling system.

The first order differential equation governing the top-oil temperature rise over temperature is expressed as:

$$T_0 \frac{\delta T^1}{\delta t} = -T^1 + T_S \tag{3}$$

Solving equation (3) gives:

$$T^1 = (T_S - T_i)\left(1 - e^{\frac{t}{T}}\right) + T_i \tag{4}$$

where;

$$T_S = T_{ft}\left(\frac{K^2R+1}{R+1}\right)^n \tag{5}$$

$$T_0 = {}^{C\theta_{ft}}/_{P_{ft}} \tag{6}$$

and

T^1 is the top rise over ambient temperature (°C).

T_S is the ultimate top-oil rise for load L (°C).

T_i is the initial top oil for t = 0 (°C).

T_{ft} is the top-oil rise temperature over ambient temperature at rated load (°C).

T_0 is the time constant (h).

C is the thermal capacity (MWh/°C).

P_{ft} is the total loss at rated load (MW)

N is the oil exponent

K is the ratio of load L to rated load or per unit load current.

R is the ratio of load loss to no-load loss at rated load.

3. MODIFICATION TO THE EXISTING TOP-OIL TEMPERATURE MODEL

In the top-oil rise over ambient temperature, the final temperature state is considered in the development of the improved version of the model. The time rate of change in top-oil temperature is driven by the difference between existing top-oil temperature and ultimate top-oil temperature with modification factor of ($T_S + T_{amb}$).

For ambient temperature variation, n = 1.0.
Therefore,

$$T_0 \frac{\delta T}{\delta t} = -T^1 + A \tag{7}$$

where;

$$A = T_S + T_{amb}$$

Therefore,

$$T_0 \frac{\delta T}{\delta t} = -T^1 + T_S + T_{amb} \tag{8}$$

where;

T_{amb} is the ambient temperature (°C).

Applying Euler's forward approximation to equation (3) gives:

$$T^1(t) = \frac{T^1}{T_0+\Delta t} T^1(t-1) + \frac{\Delta t}{T_0+\Delta t} T_{amb}(t) + \frac{\Delta t T_{ft} R}{(T_0+\Delta t)(R+1)}\left(\frac{I(t)}{I_{rated}}\right)^{2n} + \frac{\Delta t T_{ft}}{(T_0+\Delta t)(R+1)} \tag{9}$$

Substituting C'^{S} for the constant coefficients.

$$T^1(t) = C_1 T^1(t-1) + C_2 T_{amb}(t) + C_3 I(t)^2 + C_4 \tag{10}$$

where;

C_1 to C_4 represents the per-unit transformer current at time-step index't'.

Therefore;

$$\Delta T^1(t) = \frac{\Delta t}{T_0}\left[\left(\frac{C^2R+1}{R+1}\right)(T_{ft})^{\frac{1}{n}} - (T^1 - T_{amb})^{\frac{1}{n}}\right] \tag{11}$$

Equation (11) is the improved top oil temperature model.

Simulation in MATLAB application package was then used to investigate and estimate the effect of ambient temperature on transformer Hot Spot temperature.

4. DISCUSSION OF RESULTS

The load cycle for the 24 hours duration is illustrated in Figure 1.0. The load cycle fluctuated as the time progresses. Between 0.0 and 4.0 hours, the load decreases from 0.728 to 0.644 per unit. Within this range, a maximum load of 0.728 was recorded at 0.0 hour while a least load of 0.644 per unit was recorded within the first 4 hours. Between 4 hours and 8.0 hours, the load increases from 0.644 to 1.23 per unit. This load decreases between 1.23 per unit and 1.05 per unit as a result of the aging process of the current transformers. The load pattern fluctuates again between 1.07 per unit and 0.728 per unit within the first 10.0 hours and 24 hours. The largest load was recorded as 1.24 per unit at 20.0 hours while the least load was 0.638 per unit at 23.0 hours.

Figure 2.0 illustrates the ambient temperature for the 24 hours load cycle. The ambient temperature fluctuates as the time progresses. At 0.5 hours, 2.0 hours, 3.0 hours, 4.5 hours and 7 hours, the ambient temperature recorded were 26.5 °C, 26 °C, 17 °C, 22 °C and 28 °C respectively. The least ambient temperature of 17 °C was recorded in 3 hours while the highest ambient temperature of 36 °C was recorded at the end of the thirteeth hours.

The hot spot temperature for the 24 hours load cycle is depicted in Figure 3.0. The hot spot temperature fluctuates accordingly as the time increases. Within the first 4.0 hours, the hot spot temperature fluctuation between 71 °C and 67.5 °C at 0.0 hour and 4.0 hours respectively. The hot spot temperature at 6.0 hours, 8 hours, 15 hours and 20 hours are 68.5 °C, 96.5 °C, 105.5 °C and 80 °C respectively. The least hot spot temperature of 63 °C was recorded at 2.0 hours while the highest hot spot temperature of 105.4 °C was recorded at the end of the sixteenth hours because the aging process of the transformer is retarded at this time.

The variation of the ambient temperature with the hot spot temperature is illustrated in Figure 4.0. The ambient temperature and the hot spot temperature fluctuate accordingly over the time period. The ambient temperatures at 0.5 hour, 2 hours, 3 hours, 8 hours and 15 hours were 26.5 °C, 26 °C, 17 °C, 30 °C and 33 °C respectively which correspond to the hot spot temperatures of 70.5 °C, 63 °C, 67 °C, 96.5 °C and 103 °C respectively. Thus, within the 24-hours load cycle, the least ambient temperatures and hot spot temperatures are 17 °C at 3.0 hours and 63 °C at 2.0 hours respectively. In a similar manner, the highest ambient temperatures and hot spot temperature are 36 °C at 13.0 hours and 105.4 °C at 16.0 hours as a result of the retardation in the aging process of the transformer.

The variation of the ambient temperature and the hot spot temperature with time is shown in Figure 5.0. While the ambient temperature increases from 26.0 °C to 27.0 °C within the first 1.0 hour, the hot spot temperature decreases from 71 °C to 70 °C. Thus at 2.5 hours and 10.0 hours, the ambient temperatures are 23 °C, 22 °C, 26 °C, 29 °C and 32 °C respectively which correspond to hot spot temperature of 65.5 °C, 67 °C, 83.5 °C, 96.5 °C and 99 °C respectively as a result of the extension of the life of the transformers at this instance.

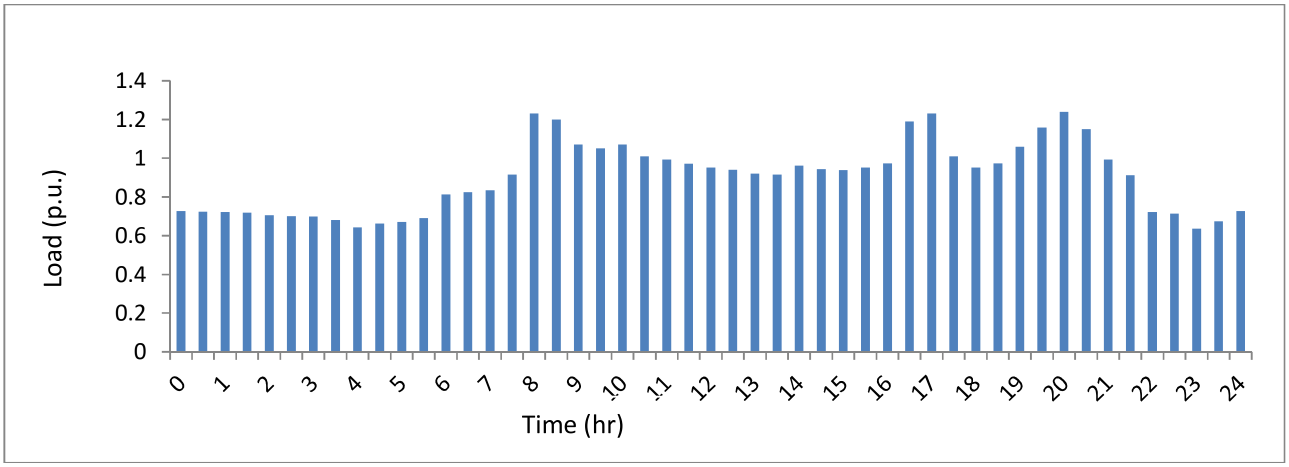

Figure 1.0: Load cycle for 24 hours load cycle.

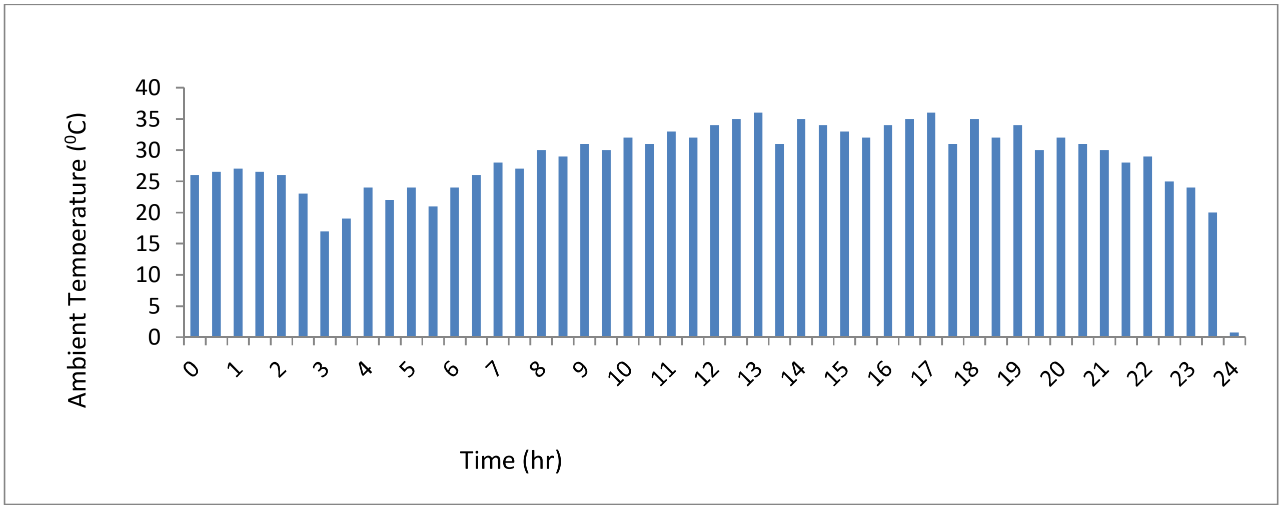

Figure 2.0: Ambient temperature for 24 hours load cycle.

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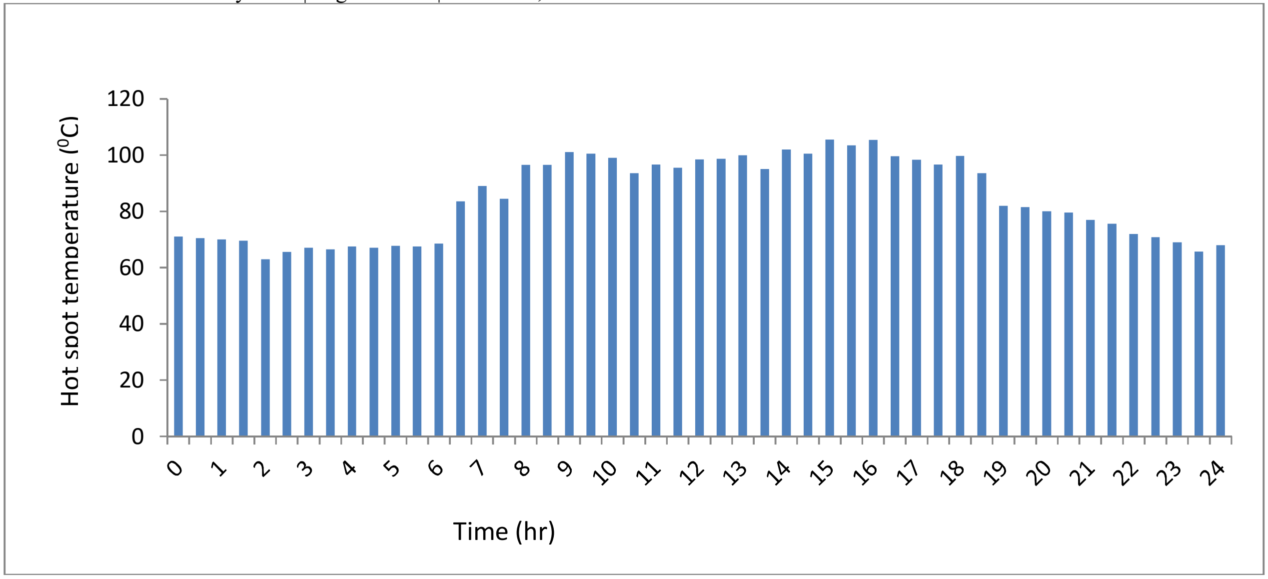

Figure 3.0: Hot spot temperature for 24 hours load cycle.

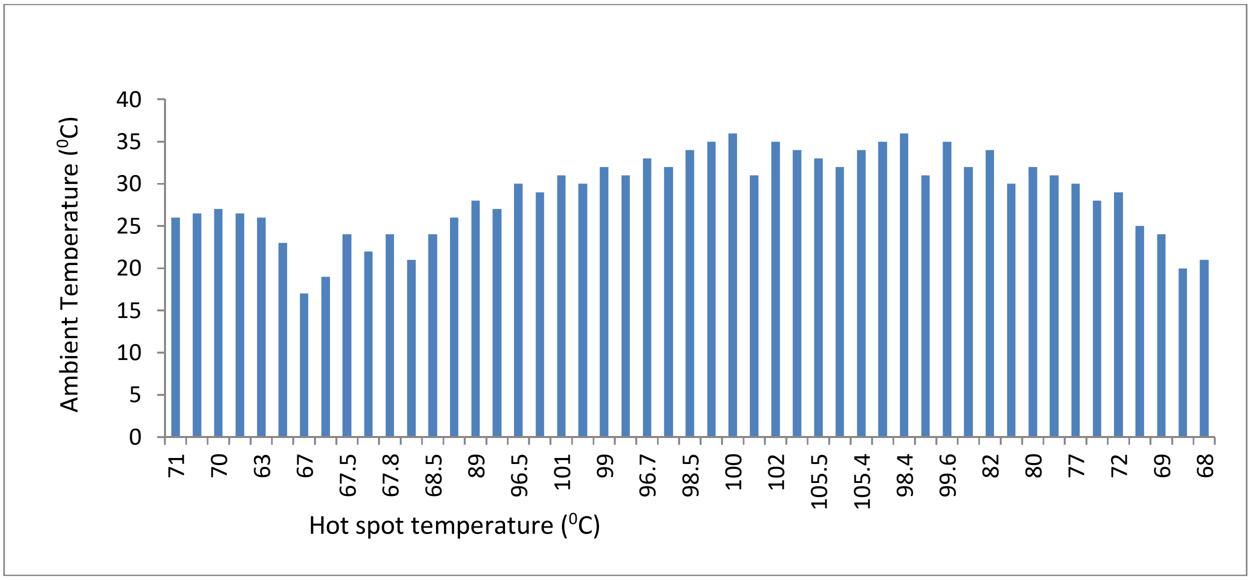

Figure 4.0: Ambient temperature versus the hot spot temperature for 24 hours load cycle.

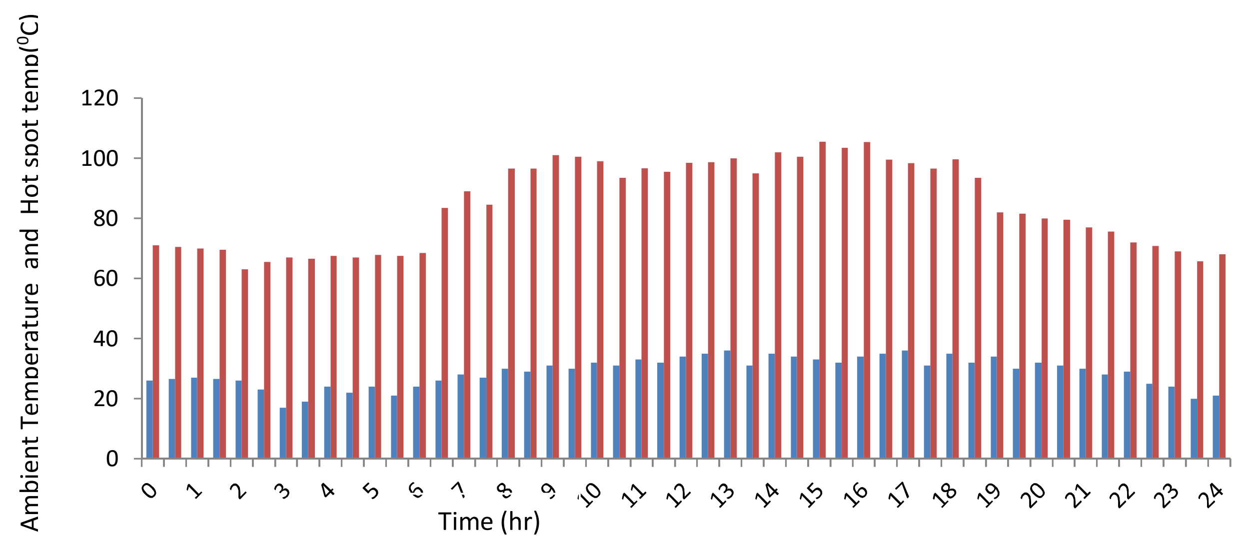

Figure 5.0: Ambient temperature and Hot spot temperature versus time for 24 hours load cycle.

5. CONCLUSION

This paper has developed an improved model for assessment of hot spot temperature of current transformer. The ambient temperature, top-oil rise over temperature and winding hot spot rise over temperature were used as input parameters for the development of the improved hot spot temperature model by considering the final temperature state. The improved model was then implemented in MATLAB to compute the hot spot temperature for a 24-hours load cycle. The results of the improved model show the least and highest values of hot spot temperatures of 63 ℃ and 105.4 ℃ respectively due to the retardation in the aging process of the current transformers.

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