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Estimation of Current Transformer Insulation Life with an Effect of Environmental Variables

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ABSTRACT: Current transformer is an important component of EHV substation & the power system. Most of the faults occurring in current transformers are due to insulation failure. Insulation aging is a function of temperature and other environmental factors such as solar radiation and wind velocity. The aging effect is produced by Hot Spot Temperature (HST). The 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. The winding hot-spot temperature can be calculated as a function of the Top Oil Temperature and that can be estimated using the transformer loading data, top-oil temperature, ambient temperature, wind velocity and solar radiation. This paper discusses the HST with considering environmental factor and without considering the environmental. The loss of life of insulation is related exponentially to the HST. This paper presents the mathematical model of Hot Spot Temperature under variable environmental condition in MATLAB.

KEYWORDS: Hot Spot Temperature, Top oil Temperature, Environmental variable

I. INTRODUCTION

Current transformers are the important components and constitute a large portion of capital investment. When a Current transformer fails, an adverse effect occurs in the operation of transmission networks resulting in increase of the power system operation cost and decrease of reliability in electricity delivery. The ability to evaluate the elapsed life of a transformer will greatly contribute to reduce maintenance charges, replacement costs, and strategic planned operation. Increasing cases of failure of current transformers has necessitated the study of insulation condition of instrument transformer. The age of a transformer is essentially the life of its insulation, primarily paper insulation. The three basic stresses that deteriorate the insulation are mechanical, thermal and electrical stress. Temperature is an important parameter for online monitoring of transformer. One of the most important parameters for a Transformer's life expectancy is the hot-spot temperature value which represents the hottest temperature in the transformer winding. Thermal sensing units, such as Thermocouples or fibre-optic sensors were embedded inside the CTs during the manufacturing stage, so that Top-Oil Temperature and Hot-Spot Temperature could be measured. Extreme care is required in installation of probes; nearly 25-33% of probes are damages during installation. The use of such measuring system could be costly, so an alternative method to calculate hot spot temperature through transformer thermal models Transformer aging can be evaluated using the HST. The increase in hot spot temperature has the effect of reducing insulation life of Transformer.

This paper discusses the loss of life of Current Transformer. The oil immersed Current Transformer of 245 kV, 800/1A is situated at Aurangabad, Maharashtra. The geographical location of Aurangabad with longitude and latitude is $75°23'$ and $19°53'$ respectively. Transformer loss of life evaluation based on the climatic parameters is included in the TOT and HST calculations [2]. Solar radiation is scattered, it does not have a unique direction. Heating of transformers is caused by copper and iron losses as the internal heat sources and by solar radiation as an external heat source. All heat must eventually be dissipated by the environment through the transformer tank. The hot-spot temperature during the summer may increase with almost 9 K and during the winter with almost 6 K in an area with strong solar radiation.

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IEEE Standard C57.91 recommends method to calculate hot spot temperature based on top-oil temperature and load [1]. The thermal phenomena are quite complex, it is not easy to consider all the details in the thermal model precisely. The top oil temperature rise equation of the IEEE guide is modified to allow for continuously varying ambient temperature. In HST proposed model, two additional factors is introduce such as solar radiation and wind velocity [2].

II. THERMAL MODEL OF TRANSFORMER

When a transformer is energized and loaded at ambient temperature(θ_A), dissipation caused by core losses, winding losses, stray losses in the tank and metal support structures are sources of heat which cause the transformer oil and winding temperature rise. During a continuous or steady state load, the I^2R losses cause the temperature of the winding increases. As the process continues, the heat is transferred to the surrounding oil. This heat transfer process continues until the heat generated by the windings equals the heat taken away by the oil under continuous load.

A. Hot Spot Temperature Equations:

Hot Spot Temperature is the sum of ambient temperature, top oil rise over temperature and winding hot spot rise over top oil temperature.

Hot Spot Temperature equation [6],

$$\theta_H = \theta_A + \theta_{top} + \Delta\theta_H \quad (1)$$

θ_A-Ambient temperature

θ_{top}-Top-oil rise over ambient temperature in ° C

$\Delta\theta_H$-Winding hot spot rise over top-oil temperature

$$\theta_{HST} = \theta_{top} + \theta_{hm}\left(\frac{I(t)}{I_{rated}}\right)^{2m} \quad (2)$$

Where θ_{hm} is the maximum HST over TOT in the rating load that provided by manufacturer. In this case study θ_{hm} is 55. Also, m is the cooling coefficient and can vary in the range of 0.8–1. In this study forced cooling system is considered m=1.

B. Top oil Temperature equation:

Top-oil temperature rise over ambient temperature is governed by the first order differential equation [1], [7], [10]:

$$T_0 \frac{d\theta_{top}}{dt} = -\theta_{top} + \theta_u \quad (3)$$

Solution of above differential equation:

$$\theta_{top} = (\theta_u - \theta_i)\left(1 - e^{-\frac{t}{T_0}}\right) + \theta_i \quad (4)$$

where,

$$\theta_u = \theta_{fl}\left(\frac{K^2R+1}{R+1}\right)^n \quad (5)$$

$$T_0 = \frac{C\theta_{fl}}{P_{fl}} \quad (6)$$

and

θ_{top} -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 temperature over ambient temperature at rated load (°C);

T_0 - time constant (h);

C - thermal capacity (MW h/°C);

P_{fl} - total loss at rated load (MW);

n - oil exponent ;

K - ratio of load L to rated load or per unit load current;

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

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. Modified top-oil temperature model is developed from the IEEE top-oil rise temperature model by considering the ambient temperature at the first-order characterization [2]. 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 $(\theta_u + \theta_{amb})$. For Oil Forced Air Forced Directed (OFAFD), $n = 1.0$

$$T_0 \frac{d\theta_{top}}{dt} = -\theta_{t0p} + \theta_u + \theta_{amb} \qquad (7)$$

where ,

θ_{amb} –ambient temperature (℃)

$\Delta t =$ Sampling period

By using Euler's forward approximation and discretizing equation (3) leads to

$$\theta_{top}(t) = \frac{T_0}{T_0+\Delta t}\theta_{top}(t-1) + \frac{\Delta t}{T_0+\Delta t}\theta_{amb}(t) + \frac{\Delta t\theta_{fl}R}{(T_0+\Delta t)(R+1)}\left(\frac{I(t)}{I_{rated}}\right)^{2n} + \frac{\Delta t\theta_{fl}}{(T_0+\Delta t)(R+1)} \qquad (8)$$

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

$$\theta_{top}(t) = K_1\theta_{top}(t-1) + K_2\theta_{amb}(t) + K_3 I(t)^2 + K_4 \qquad (9)$$

where, $K_1 - K_4$ complex are 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 t.

Modified Top oil temperature Model [3],[4],[8],[9] is

$$\Delta\theta_{top}(t) = \frac{\Delta t}{T_0}\left[\left(\frac{K^2R+1}{R+1}\right)(\theta_{fl})^{\frac{1}{n}} - (\theta_{top} - \theta_{amb})^{\frac{1}{n}}\right] \qquad (10)$$

By adding another coefficient i.e solar radiation and wind velocity which is important factor when transformer placed in outdoor. Solar radiation is a significant source of heat flux. Heat flux could contribute as much heat as that produced by 25% of the full load losses of the transformer. Wind changes the thermal performance of Current Transformer.

$$T_0 \frac{d\theta_{top}}{dt} = -\theta_{top} + \theta_u + \theta_{amb} + \theta_R + \theta_w \qquad (11)$$

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

$$\theta_{top}(t) = K_1\theta_{top}(t-1) + K_2\theta_{amb}(t) + K_3 I(t)^2 + K_4 + K_5 S_{rad}(t) + K_6 V(t) \qquad (12)$$

Top oil temperature and hot spot temperature has been calculated from equation (2), (3) & (12) for current transformer. Proposed model is form using Top oil temperature and Hot spot temperature equations.

III. TRANSFORMER INSULATION LIFE CHARACTERISTICS:

Insulation aging is a function of temperature and other environmental factors. Today with modern cooling systems, the effect of solar heat flux can be reduced, but the temperature is a limiting factor that should not be exceeded from a predetermined value. Since, in most apparatus, the temperature distribution is not uniform, that part which is operating at the highest temperature will ordinarily undergo the greatest deterioration. Therefore, in aging studies, it is usual to consider the aging effects produced by hottest spot temperature. The aging effects on Current Transformer are estimated from the aging acceleration factor.

A. Calculation for Aging Acceleration Factor

Aging Acceleration Factor (F_{AA}) for a given hottest-spot temperature is the rate at which transformer insulation aging is accelerated compared with the aging rate at a reference HST [1]. The Current Transformer winding was rated for a hot spot rise temperature of 65℃.The mathematical formulation for F_{AA} is given in following equation [5]:

$$F_{AA} = e^{\left[\frac{B}{\theta_{HSTref}+273} - \frac{B}{\theta_{HST}+273}\right]} \quad (13)$$

where, B-is the aging rate constant which a value of 15,000 is considered to be appropriate θ_{HSTref} - is the winding-hot-spot reference temperature

If $\theta_{HSTref} = 110℃$ then,

$$F_{AA} = exp^{\left[\frac{15000}{383} - \frac{15000}{\theta_{HST}+273}\right]} \quad (14)$$

After 130℃ HST,the (F_{AA}) is exponential increases as show in Fig.1.Aging Acceleration Factor at different HST values show that insulation life is an exponential function of HST. If θ_{HST} for insulation life to be 110°C, its life will be one per unit.

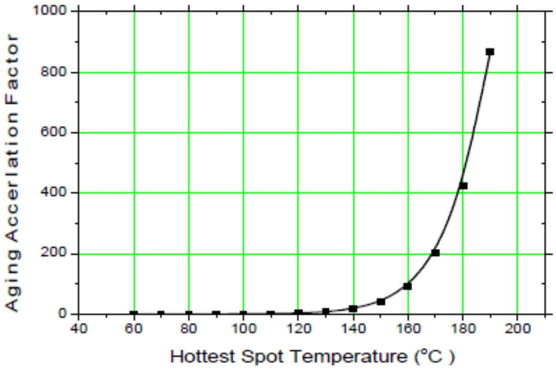

Fig.1. Increasing F_{AA} with respect to HST

B. Calculation for equivalent aging acceleration factor

The equivalent aging acceleration factor at the reference temperature in a given time period for the given temperature cycle is defined as [1]:

$$F_{EAA} = \frac{\sum_{n=1}^{N} F_{AA,n} \Delta t_n}{\sum_{n=1}^{N} \Delta t_n} \quad (15)$$

where, F_{EAA} is equivalent aging acceleration factor for the total time period *N* is total number of time intervals. Δt_n is nth time interval and $F_{EAA,n}$ is aging acceleration factor for the temperature which exists during the time interval Δt_n.Transformer insulation’s aging is directly connected with the hot spot winding temperature [1].

$$\%\text{ of Insulation life} = A.e^{\left(\frac{15000}{\theta_{HST}+273}\right)} \quad (16)$$

$$\text{Per unit life} = 9.8 \times 10^{-18} e^{\left(\frac{15000}{\theta_{HST}+273}\right)} \quad (17)$$

C. Percentage Loss of Life

The equivalent loss of life in the total time period is determined by multiplying the equivalent aging by the time period (t) in hours. In this case total time period used is 24 hours. Therefore, the equation of percent loss of life equation is as follows [7],

$$\%\, Loss\ of\ Life = \frac{F_{EAA} \times t \times 100}{Normal\ \ Insulation\ \ Life} \quad (18)$$

IV. CALCULATION OF LOSS OF LIFE FOR CURRENT TRANSFORMER:

For estimation of loss of life of Current Transformer, the HST is calculated. HST model is implemented in MATLAB. From this model the HST is estimated using TOT. This paper discusses about, 245 KV, 800/1A oil immersed Current Transformer situated at Aurangabad, Maharashtra.

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Table1.Rating of current transformer

Parameter	Value
Rating	245kV,800/1A
Top oil temperature rise	60℃
Hottest Spot conductor rise over Top oil temperature rise at rated load	55℃
Ratio of Load loss at rated load to no-load loss	5
Top Oil time constant (Watt-hour/ ℃)	4
Total weight	1400 kg
Oil weight	350 kg

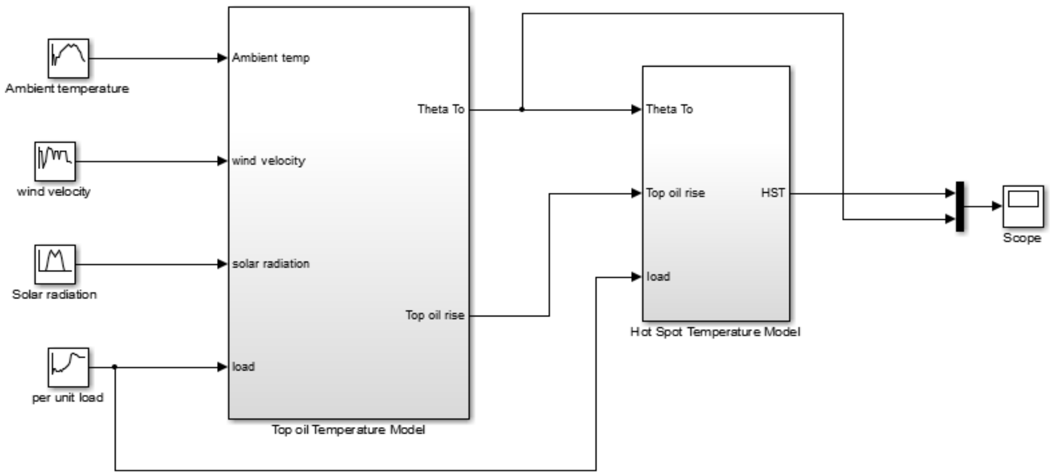

Fig.2 Simulation model of HST in MATLAB

The solar radiation, wind velocity, ambient temperature and per unit load are the parameters required for estimation of TOT. The output of TOT is fed to an input of HST model as shown in Fig.2.

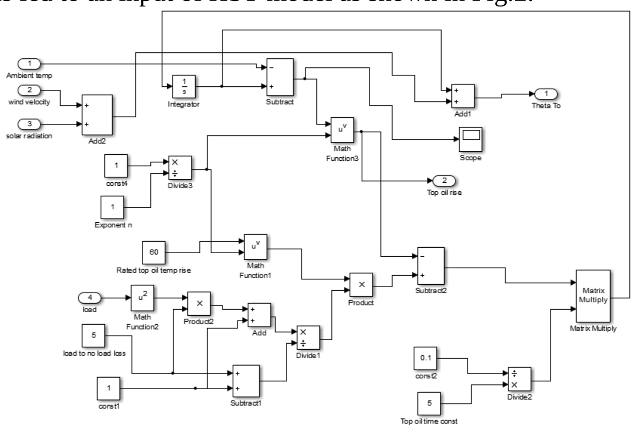

Fig.3.Subsystem of TOT model

The subsystem of top oil temperature model is as shown in fig.3.

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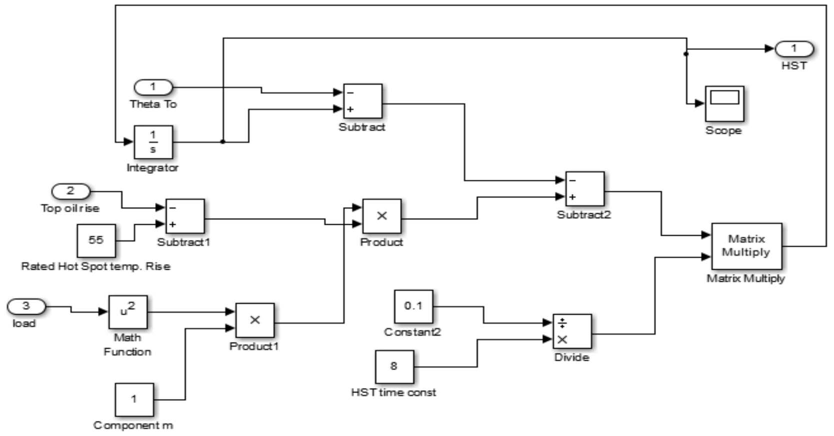

Fig.4. subsystem of Hot Spot Temperature model

Fig.4 shows the subsystem of Hot spot temperature model. From geographical location of Aurangabad Solar radiation is plotted with respect to time (24hrs).

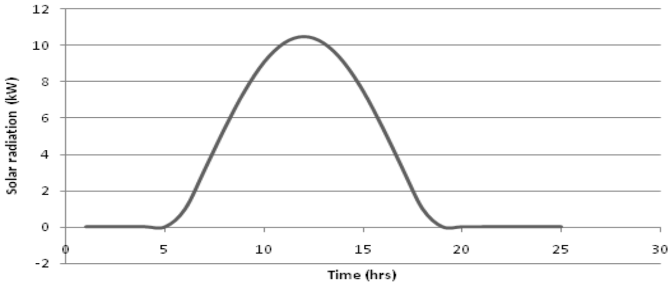

Fig.5.Variation of heat flux with respect to time

The wind velocity is recorded in the month of May (4^{th} May) for 24 hrs. The graph plotted between the variation of solar radiation (kW) and wind velocity (m/s^2) with respect to time is as shown in Fig.5 and Fig.6.

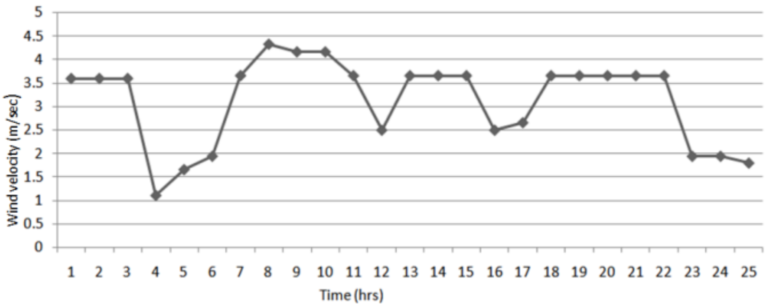

Fig.6. Variation wind velocity with respect to time

The output waveform of hot spot temperature model and top oil temperature model is as shown in Fig.7 and Fig.8.The maximum hot spot temperature with and without considering the environmental factor is found to be 110.5℃ and 87.5℃ respectively.

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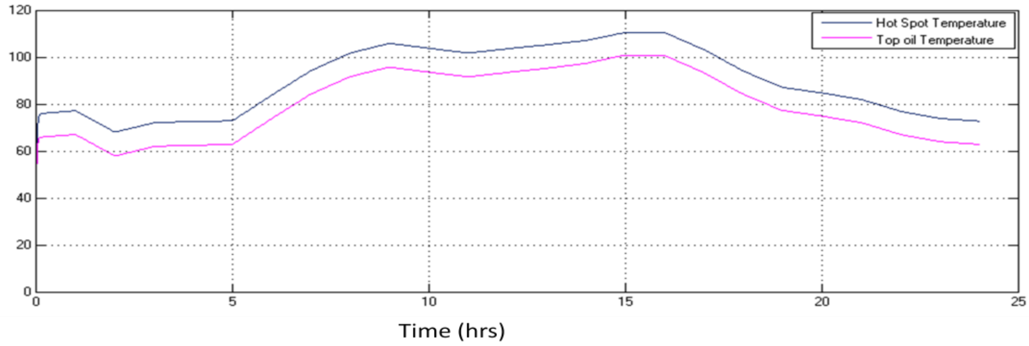

Fig.7. HST and TOT waveform (with considering Environmental factor)

Hot Spot Temperature and Top Oil Temperature is more when environment factors are consider as shown in Fig.7 and Fig.8.

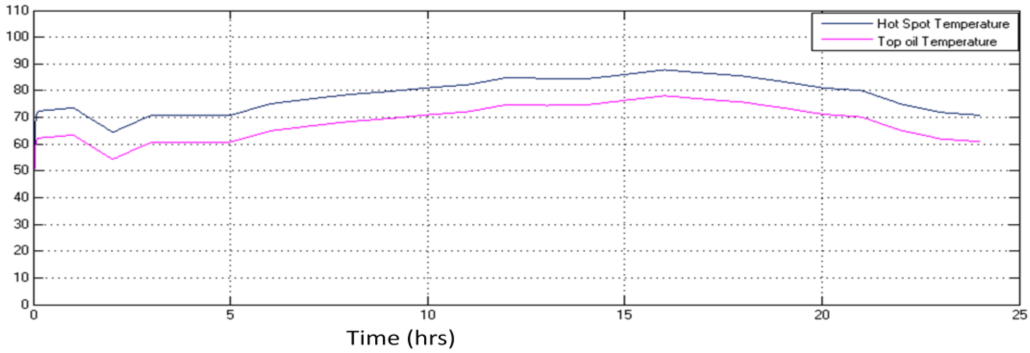

Fig.8. HST and TOT waveform (without considering Environmental factor)

The aging acceleration factor (F_{AA}) is calculated from the HST from equation (14) and % loss of life of insulation is calculated from equation (18). With the help of the proposed model, hot spot temperature and F_{AA} has been calculated for 24-hour load cycle as shown in Table.2.

Table2. Loss of Life data for 24-hour load cycle

Time (hr)	Load (per unit)	Ambient Temperature(℃)	HST(℃)	F_{AA}(per unit)
0.00	0.838	31	76	0.0220
1.00	0.833	32	75	0.0194
2.00	0.815	31	68	0.0080
3.00	0.801	22	72	0.01338
4.00	0.754	29	72.5	0.01425
5.00	0.782	29	72.8	0.01479
6.00	0.9	29	83.5	0.0544
7.00	0.968	33	94	0.1813
8.00	1.02	35	101.5	0.4111
9.00	0.996	36	106	0.6614
10.00	0.996	37	104	0.5361
11.00	0.978	38	101.7	0.4199
12.00	0.936	39	103.5	0.5194
13.00	0.894	41	105	0.5956
14.00	0.917	40	107	0.7340
15.00	0.912	38	110.5	1.0523

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16.00	0.982	39	110.4	1.0417
17.00	1.02	41	103.4	0.5032
18.00	0.819	40	94.2	0.1854
19.00	0.912	39	87	0.0819
20.00	0.961	37	85	0.06489
21.00	0.903	35	82	0.0455
22.00	0.884	34	77	0.0249
23.00	0.824	29	74	0.01719
24.00	0.829	26	73	0.01517

The equivalent aging acceleration factor (F_{EAA}) is calculated from Table 2.

$$F_{EAA} = \frac{\sum_{n=1}^{N} F_{AA,n}\Delta t_n}{\sum_{n=1}^{N} \Delta t_n} = \frac{7.7079}{24} = 0.3211 \text{ days or } 7.7079 \text{ hrs}$$

$$\%\ Loss\ of\ Life = \frac{F_{EAA} \times t \times 100}{Normal\ Insulation\ Life} = \frac{0.3211 \times 24 \times 100}{180000} = 0.004281\%$$

The equivalent aging acceleration factor (F_{EAA}) for normal 24 hrs load is 0.3211days or 7.7079 hours. Accumulated aging is 7.7079 hrs of 180000hrs (20.5year). The percent loss of life is *0.004281*(%), at normal insulation life of 180000 hours. The maximum HST,considering the environmental factor is *110.5*℃ and relatively F_{AA} is 1.0523.The remaining life of transformer is given by following equation [10]:

$$Remaining\ life = \frac{Normal\ Insulation\ life}{F_{AA}} = \frac{180000}{1.0523} = 171053.88hrs = 19.52years$$

V. RESULT AND DISCUSSION

The proposed model is used to estimate the improved model for the estimation the HST transformers. The 24 hours data of ambient temperature, per unit load, solar heat flux and wind velocity in summer season are the base parameters for this method as shown in Fig.5 and Fig.6. The additional parameter of solar radiation and wind velocity is considered to improve the accuracy for estimation of HST. Using the proposed MATLAB model, the effect of ambient temperature and environmental variables on hot spot temperature was investigated. The loss of life of transformer insulation is related exponentially to the HST. When aging acceleration factor and %loss of life is more, actual transformer life will be reduced. The actual life of transformer is 20.54 years but due to HST, the life of transformer is reduced about 4.96%. In this paper the Hot Spot Temperature, using Top Oil Temperature with proposed HST is calculated. The estimation of HST value with considering the environmental factor is greater as compared to the HST value without considering the environmental factor from Fig.7. The proposed model implemented in MATLAB helps to estimate the life of transformer. To minimize the risk of failure and to extend the serving life time of transformers, hot spot temperature rise and top oil temperature should be controlled. Hence it is necessary to monitor the temperature rise of transformer. The proposed model was used to study the effect of environmental variables on insulation life, percentage loss of life of the transformer. Aging process is accelerated when HST is greater than 110℃, hence when HST is maintained below this value, the life of the transformer is extended.

REFERENCES

[1] IEEE Standard, C57.91-1995, “IEEE Guide for Loading Mineral Oil Immersed Transformer”,1996.
[2] M. Srinivasan and A. Krishnan, “Prediction of transformer Insulation life with an effect of environmental Variables”, International Journal of Computer Applications, vol. 55, no.5,Oct. 2012.
[3] G. Swift, T. S. Molinski, and W. Lehn, “A fundamental approach to transformer thermal modeling—Part I: Theory and equivalent circuit”, IEEE Trans. Power Del., vol. 16, no.2, pp. 171–175, April 2001.

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Vol. 4, Issue 5, May 2015

[4] Satish M. Mahajan, Diego M. Robalino, "Thermal Modeling of an Inverted-Type oil-immersed current transformer", IEEE Transaction on power delivery vol.25,no.4, Oct. 2010.

[5] Diego M. Robalino Vanegas and Satish M. Mahajan, "Effects of Thermal Accelerated Ageing on a Medium Voltage Oil-Immersed Current Transformer", IEEE 2008.

[6] Diego M. Robalino Vanegas and Satish M. Mahajan, "Correlation between Hot-Spot Temperature and Aging Factor of Oil-Immersed Current Transformers", IEEE 2008.

[7] Anuradha Kumar and Satish M. Mahajan, "Time Domain Spectroscopy Measurement for the Insulation Diagnosis of a Current Transformer", IEEE Transactions on Dielectrics and Electrical Insulation vol. 18, no. 5, Oct. 2011.

[8] A Elmoudi, "Transformer Windings Hot Spot Temperature Modeling and Simulation", IEEE 2014

[9] Jauregui-Rivera.L and Tylavsky.D.J, "Acceptability of four transformer top-oil thermal models-Part 1: Defining metrics", IEEE Trans. Power Delivery, vol. 23, no.2, pp..860–865,2008.

[10] Mohammad Yazdani-Asrami, Mohammad Mirzaie and Amir Abbas Shayegani Akmal, "Investigation on Impact of Current Harmonic Contents on the Distribution Transformer Losses and Remaining Life", IEEE International Conference on Power Energy 2010.