Online Estimation of Transformer Hot Spot Temperature by Considering the Effects of Load Profile Modeling

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Abstract

One of the most valuable components in power systems is power transformer whose failure may result in a significant power loss. Therefore, one of the critical issues in power transformer operation is its health monitoring. Moreover, it was shown that the aging rate of transformers is very sensitive to the hot spot temperature, and when this temperature exceeds a threshold value, the aging rate increases. Given the fact that using temperature sensors in prefabricated and built-in transformers is not practical, thermal models are used to estimate transformer hot spot temperature. Since the transformer hot spot temperature is a key factor in the condition monitoring of a transformer, and in case it will exceed a threshold value, preventive actions should be taken in the proposed algorithm, the sensitivity of this important parameter with respect to the load profile sampling time is investigated. This paper proposes a fast online algorithm for the estimation of power transformer hot spot temperature by reducing the number of calculations without sacrificing accuracy. The proposed algorithm is applied to a 250 MVA transformer using MATLAB software. The results were compared with the actual factory test results and the efficiency of the proposed algorithm was shown.

Keywords: *Transformer, Aging, Hot Spot Temperature, Thermal Model, Load Profile*

1. Introduction

Asset management has become more important in power systems in recent years as a result of reliability and economic issues [1], [2]. Considering the importance of power transformers in the power networks, transformer life management is very important [3]–[7]. A power transformer is a key element in power transmission, and distribution systems. Therefore, for financial reasons, they ought to be serviced for as long as feasible under normal and overload situations. At the present time, failure time for power transformers is mainly determined by their operating years, regardless of their physical conditions [8]–[10]. In today's power systems, the rapid growth of consumption leads to overload conditions that cause the transformers to face more thermal stresses. However, major factor limiting their longevity is the deterioration of transformer's windings' paper insulators, which have the lowest capacity to withstand high temperatures. Typically, the transformer hot spot temperature is used to describe this temperature. Electrical and mechanical resistance of winding insulator of transformer are affected by Hot spot temperature directly [11]–[13]. When the hot spot temperature exceeds a threshold value, e.g. 98 °C for non-thermally upgraded paper and 110 °C for thermally upgraded paper, the aging of transformer is accelerated [14]. Therefore, electric companies should use condition monitoring methods to keep characteristic temperatures, especially hot spot temperatures, within a predefined permitted range [15]–[17].

As stated earlier, hot spot temperature is one of the critical limiting factors for transformer loading. There are two possible methods to determine transformer hot spot temperature. One is the use of fiber optic temperature sensors that are placed at desired connection points in the windings [14], [18]–[20]. Direct measurement using fiber optic sensors became available in the mid-1980s. Thermal sensors are connected to the end of optical fiber and are usually installed between the insulated conductor, and spacer and their signals are transmitted out of the chamber. It can, however, be difficult to justify the cost of installing a sensor due to its high price. Additionally, this method is not practical for transformers with built-in transformers. The optimal position of the sensor and the exact location of the hot spot are also problems with direct measurement [21]–[23]. Statistical approach is another method which determined by calculating the transformer internal temperature. The implementation of this method is complicated and difficult [24], [25].

Much work was done to estimate a transformer hot spot temperature based on transformer thermal models. The most common thermal models to calculate hot spot temperature were presented in IEEE C57.91-2011 and IEC 60076-07 standards [14], [26]. Besides, a method was proposed for using the IEEE model based on heat transfer theory principles by Swift et al. [27]. In [28], [29], considering the dynamic load conditions, a more precise thermal model of transformer was developed by Susa et al. A similar method used by Elmoudi et al. [30], [31] was used to develop simplified thermoelectric equivalent mathematical models with the aim of calculating top oil temperature and transformer hot spot in real time.

In general, computational methods and proposed models to estimate hot spot temperature of transformers can be classified into the following four main groups.

1- Statistical methods that use genetic algorithms and other artificial intelligence techniques. These methods are reliable and powerful to find the optimal solution, but it normally requires a long time to respond which is not practical for problems with numerous variables [32].

2- Numerical methods that are based on finite element techniques. In these methods, irregular geometric shapes, and different materials can be modeled. But, these methods need a long time to run and simulate which requires powerful digital computers [33], [34].

3- Thermal equivalent circuit methods, which originate from the equivalent circuit of transformer. Especially in standard geometric shapes, these methods yield reliable results. It is necessary to determine the exact amount of each equivalent circuit element when using these techniques. Moreover, it should consider whether the circuit is entirely linear or whether the magnetic core's nonlinearity should be considered. [35], [36].

4- Practical test methods which are based on measurement and data analysis by helping other methods. The results of this method are highly valid, but human error is one of the disadvantages of such methods [37].

In summary, to monitor the health condition of a transformer, it is important to know the hot spot temperature status of the transformer. As mentioned earlier, the installation of temperature sensors in prefabricated transformers is not practically possible. Thermal models are therefore necessary for estimating hot spot temperatures. It is proposed to develop an algorithm that can estimate the hot spot temperature of a transformer online in this paper. One of the important issues in a transformer hot spot temperature calculation is its load profile modelling, whose effect appears by the load sampling time and synchronicity of the load sampling with respect to load changes. These issues were not considered in previous works and are included in the proposed algorithm. The proposed algorithm has the ability to calculate an optimized calculation time period for online processing despite load changes with time and different time constants for every transformer. Online processing should note that calculations should be reduced. This reduces the amount of the information needed to be sent to the main processor and decreases the computing speed. If the number of transformers to be monitored increases, it becomes more important to reduce the size of information collected from the transformers. In this algorithm, it was attempted to obtain a suitable approximation of the transformer hot spot temperature at any time with a fewer number of calculations. It is possible to estimate the transformer hot spot temperature continuously and online in this way. The rate of aging is accelerated beyond normal for temperature above 110 °C (for thermally upgraded paper and 98 °C for non-thermally upgraded paper) and is reduced below normal for temperatures below 110 °C (or 98 °C). This temperature is referred to as the threshold temperature. Using an online estimation of the transformer hot spot temperature, it is possible to quickly warn of crossing the threshold temperature so that further actions can be taken with the aim of physical asset life management.

The contributions of this paper are briefly as follows:

- Presenting an online algorithm for transformer hot spot temperature estimation
- Considering the effects of load profile modeling in the proposed algorithm
- Reducing the number of calculations

The structure of this paper is as follows. Section 2 introduces the IEEE thermal model and its relationships. In Section 3, the effect of load profile modeling on the hot spot temperature calculation was studied. The proposed algorithm has been presented in Section 4, and the simulation results were presented in Section 5. Section 6 concludes the paper.

2. IEEE Thermal Model

The model presented in IEEE C57.91-2011 [26], is a non-iterative method to calculate oil, and winding temperature of a power transformer. Considering the fact that the temperature distribution inside a transformer is not uniform, and the part of the transformer with the highest operating temperature (hot spot) is most exposed to damage, the IEEE model calculates the hot spot temperature, θ_H, as follows:

$$\theta_H = \theta_A + \Delta\theta_{TO} + \Delta\theta_H \tag{1}$$

θ_A is the ambient temperature, $\Delta\theta_{TO}$ is the top-oil rise over ambient temperature and $\Delta\theta_H$ is the winding hottest-spot rise over top-oil temperature.

The parameters $\Delta\theta_{TO}$ and $\Delta\theta_{H}$ are obtained from the first-order differential equations as following, respectively:

$$\Delta\theta_{TO} = \Delta\theta_{TO,i} + (\Delta\theta_{TO,u} - \Delta\theta_{TO,i})(1 - e^{-(t/\tau_{TO})}) \quad (2)$$

$$\Delta\theta_{H} = \Delta\theta_{H,i} + (\Delta\theta_{H,u} - \Delta\theta_{H,i})(1 - e^{-(t/\tau_{W})}) \quad (3)$$

where

$\Delta\theta_{TO,u}$ and $\Delta\theta_{TO,I}$ are ultimate, and initial top-oil rise over ambient temperature, respectively. Also $\Delta\theta_{H,U}$ and $\Delta\theta_{H,I}$ are ultimate, and initial winding hottest-spot rise over top-oil temperature, respectively. τ_{TO} and τ_{W} are oil and winding time constants of transformer, respectively.

The parameter t in Equations (2) and (3) is the duration of load and can be considered the load sampling time and denoted by T_L.

In this model, a 250 MVA transformer, 230±8×1.5% / 118 kV, Z = 12%, YN0ynd11 connection and ONAF cooling system is used for simulation. The thermal model parameters have been given in Table 1 [38]. The load cycle used to test this transformer is depicted in Figure 1.a. Hot spot temperature values were recorded in the factory which are given in Figure 1.b [38], [39].

The results of the hot spot temperature calculated using IEEE thermal model (T_L=1 min) are shown in Figure 2.

3. The Effects of Load Profile Modeling on the Hot Spot Temperature Calculation

One of the important issues in the transformer hot spot temperature calculation is the load profile modelling, which is usually done in stepped form. Considering the load changes, the length of steps, which is the sampling time, and the start time of sampling and calculation can affect the results. Therefore, the effects of sampling time and the synchronicity of load sampling and load changes are investigated in the following. We compare the factory test results of transformers [35] and [36] with the results of the hot spot temperature calculated using IEEE thermal model.

3.1. Sampling Time

The hot spot temperature of test transformer with the load profile shown in Figure 1(a) was estimated for different load sampling times, and the results are given in Figure 3. Different graphs in this Figure correspond to a load sampling time of 1, 2, 3, 5, 10, 15, 20, and 30 minutes.

To analyze the effects of load sampling time, the average difference between recorded and calculated hot spot temperature is defined as E_1:

$$E_1 = \text{average}(\left|\theta_H^{Test} - \theta_H^{TL}\right|) \tag{4}$$

θ_H^{Test} is the hot spot temperature recorded in the factory, and

θ_H^{TL} is the hot spot temperature calculated using the sampling time T_L

Considering that the higher hot spot temperature has a greater effect on the transformer, the error at higher temperatures is more important. Therefore, the error index E_2 is defined as follows:

$$E_2 = \text{average}(F_{AA}^{\theta_H^{Test}} \left|\theta_H^{Test} - \theta_H^{TL}\right|) \tag{5}$$

$F_{AA}^{\theta_H^{Test}}$ is aging acceleration factor for hot spot temperature θ_H^{Test} and is calculated as mentioned in [14], [26].

If the hot spot temperature of the transformer rises above a threshold value, the transformer operator should receive an alert to take necessary measures. On the other hand, any false alarm which may result in an intentional disconnection of a power transformer is not desirable. To study this issue, another index, i.e. E_3, is defined as the number of false flags detected over the complete load cycle as shown in Figure 1(a). A false flag occurs when the hot spot temperature is falsely estimated above the alarm threshold value. The three indices E_1, E_2 and E_3 have been calculated and shown in Table 2 based on the graph traces in Figure 3.

As can be seen, when the load sampling time in increases, the errors in the hot spot estimation and the number of false alarms have increasing trend.

3.2. Start Time

For high values of load sampling time T_L, the start time of load sampling can result in an error in the estimation of transformer hot spot. For a given load sampling time of T_L, the start time can change from 0 to T_L -1. To further investigate the effect of the start time of load sampling, for the load cycle given in Figure 1(a), for a given T_L, the start time is changed from 0 to T_L -1, and the difference between the maximum, and minimum hot spot estimated temperature θ_H^{ST} with respect to the real measured temperature at the factory site, θ_H^{Test}, is defined as E_4. The results are summarized in Figure 4:

$$E_4 = \frac{\max(\theta_H^{ST}) - \min(\theta_H^{ST})}{\theta_H^{Test}} \quad \text{for a given } T_L \tag{6}$$

As can be seen in Figure 4 and as it was expected, as the load sampling time increases, the sensitivity of the hot spot estimation process with respect to the change in the start time of the load sampling time increases.

If the hot spot temperature difference is calculated at any instant according to the start time of the load sampling, false alarms may occur at every instant and at every moment. The average number of false alarms which can be issued in terms of falsely estimated hot spot temperature for different load sampling times is calculated, and defined by E_5. The results are summarized in Table 3. The difference in the two values of E_3 and E_5, especially for higher values of T_L, shows that the start time of the calculations can affect the number of correct warnings and the accuracy of the results.

4. Proposed Algorithm for Online Estimation of Transformer Hot Spot Temperature

Based on what was explained in previous section, in this section, an algorithm was proposed to calculate a transformer's hotspot temperature online. In this algorithm, the following items have been considered:

- decreasing the sensitivity of the hot spot temperature estimation with respect to the start time of load sampling, and
- reducing the number of calculations

Figure 5 demonstrates a flowchart of the proposed algorithm. The first part of the flowchart is initializing the calculation parameters the hot spot temperature such as full load current, rated top oil rise over ambient, rated hot spot rise over top oil, ratio of load loss to no load loss, top oil and winding time constants, exponents n and m, ambient temperature and load data.

The second part of the flowchart is the calculation of transformer hot spot temperature as the load changes. At each step, the sampled load value is compared with its previous step to determine whether the load has changed or not. Based on the elapsed time from the detection moment of the load change, which is denoted by t_S, the needful decision to perform calculations is made based on the rule explained following.

- If the load changes:

$\Delta\theta_H$ and $\Delta\theta_{TO}$ are calculated by calculation time period $[0.5\tau_W]$. Then transformer's hotspot temperature is calculated using s (1).

- If the load does not change:

- If t_S is less than $3\tau_W$, $\Delta\theta_H$ is calculated by calculation time period $[0.5\tau_W]$ and the $\Delta\theta_{TO}$ is considered equal to its value in the previous step.
- If t_S is equal to $3\tau_W$, $\Delta\theta_H$ is calculated by calculation time period $[0.5\tau_W]$ and $\Delta\theta_{TO}$ is calculated by calculation time period $3\tau_W$.
- If t_S is greater than $3\tau_W$ and less than $3\tau_{TO}$, $\Delta\theta_H$ and $\Delta\theta_{TO}$ are calculated by calculation time period $3\tau_W$.
- If t_S is greater than or equal to $3\tau_{TO}$, $\Delta\theta_H$ and $\Delta\theta_{TO}$ are considered equal to their value in the previous step.
- Then transformer's hotspot temperature is calculated using equation (1).
- After calculating the hot spot temperature, the load is considered equal to the load of the previous step so that the gradual changes of the load can also be sensed.

In the third and final part of the flowchart, necessary warnings are issued by comparing the calculated transformer hot spot temperature with the threshold value.

Principles of operations of the proposed techniques are as follows.

A. Sampling Time and Calculation Time Period

IEC 60076-07 states that the load sampling time should not be more than half of the smallest time constant [14]. Therefore, sampling time is considered as $0.5\tau_W$. The approximate range of the time constant of the oil and winding of a power transformer are shown in Table 4 [14]. As can be seen, the time constant of the oil is about 20 times greater than that of the winding. Therefore, the changes in the transformer hot spot temperature at the beginning of a load change are mostly in terms of the changes in the winding temperature, and the effect of the top oil temperature appears with a delay. To reduce the number of calculations, at the beginning of a load change, $\Delta\theta_H$ is calculated first and then $\Delta\theta_{TO}$ whose effect appears with a delay. To reduce the number of calculations, the top oil and winding temperatures are calculated up to three times their time constant.

Before the winding temperature reaches its steady state, it is necessary to calculate the top oil hot spot temperature to avoid long steps. The winding temperature reaches its steady state after about three times the winding time constant, but this must be done before this time. Therefore, the calculation time period for the winding and top oil temperature are [0.5 τ_W] and min{$3\tau_W$,[$0.5\tau_{TO}$]} respectively. It is worth noting that based on the range of the top oil and winding time constant ($\tau_{TO} > 20\tau_W$), the value of min {$3\tau_W$, [$0.5\tau_{TO}$]} will be equal to $3\tau_W$.

B. Load Change Detection

First, we assume that the transformer has been operating for a long time at 1 per unit load, and then the load is changed within a range from -25% to +25%, and the estimated hot spot temperature variation is compared with the hot spot temperature when operating at 1 pu. The results are shown in Figure 6. As can be seen, for load within the range of -10% to +10%, the change in the transformer hot spot temperature is less than 1 °C. Therefore, as long as the load changes are less than 10%, the load is assumed to be constant.

C. Calculating the Hot Spot Temperature

After calculating top oil and winding temperatures, the hot spot temperature of the transformer is calculated at every moment. If the hot spot temperature exceeds the threshold temperature, necessary warnings will be issued so that further actions can be taken with the aim of physical asset life management.

5. Simulation

As stated in the previous section, in the proposed method, calculation time period is variable and is determined according to the load profile. But in the common method, calculation time period is equal to sampling time and is a constant value during the load period.

Using the proposed algorithm, the transformer hotspot temperature has been calculated and shown in Figure 7. To investigate the effect of the start time of load sampling on the proposed algorithm, the hot spot temperature was estimated for different start times of 0, 1 and 2 minutes. The results are shown in Figure 8. In this study, E_1 to E_5 are calculated using the proposed method, and the results are compared with those obtained by constant calculation time period. The results are summarized in Table 5.

The calculation error is observed at the beginning of simulation. This error is reduced after several times of calculation, so that the critical values of transformer hot spot temperature are not missed.

Table 5 indicates that if the proposed algorithm is used, the hot spot temperature estimation accuracy increases while decreasing the required number of calculations. It is important to monitor the health of transformers in a power system since there are too many important ones. Based on the simulation results, it can be seen that the calculation errors for the proposed algorithm are almost equal to the case of T_L=3 min, while the number of calculations (110) is even less than that of T_L=10 min, which is equal to 150.

6. Conclusion

This paper proposes an optimized online algorithm for transformer hot spot temperature estimation based on the IEEE thermal model. One of the important issues in a transformer hot spot temperature calculation is the load profile modelling whose effect appears by the sampling time and its synchronicity with the load sampling and changes.

Therefore, a variable calculation time period was considered for the calculations, whose value, at the beginning of a load change time, is affected by the transformer winding time constant and later by the transformer oil time constant.

By eliminating a number of computational steps in this algorithm, and calculating an optimized calculation time period, the computational speed and volume of the information needed to be sent to a main processor was reduced. The proposed algorithm was simulated using MATLAB software for a 250 MVA test transformer, and the results are compared with those of the real test data. it is observed that the proposed algorithm offers acceptable accuracy and follows the transformer hot spot temperature change curve well. Using the proposed algorithm, the calculation errors are almost equal to those of T_L=3min, while the number of calculations has significantly decreased. Regarding the impracticality of using temperature sensors in prefabricated transformers and the importance of high computational speed and low volume of information sent in online processing, using this algorithm can be a significant help to monitor a group of transformers’ health conditions.

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Figures and Tables Captions:

Table 1: Thermal Model Parameters [38]

Figure 1: (a) Test Load Applied to the Transformer, (b) The Measured Hot Spot Temperature [38], [39]

Figure 2: Hot Spot Temperature Using IEEE Thermal Model

Figure 3: The Calculated Hot Spot Temperature for Different Load Sampling Times

Table 2: The Value of E_1, E_2 and E_3

Figure 4: Error Index E_4

Table 3: The Value of E_3 and E_5

Figure 5: The Flowchart of the Proposed Algorithm

Table 4: Recommended Values for Time Constant [14]

Figure 6: Transformer Hot Spot Temperature Variation During $0.5\tau_W$ for 25% Load Change

Figure 7: Estimated Hot Spot Temperature Using the Proposed Algorithm

Figure 8: Estimated Hot Spot Temperature with the Load Sampling Start Time (ST) of 0, 1 and 2 Minutes Using the Proposed Algorithm

Table 5: Comparison of Simulation Results

Table 1

Parameter	Value
Rated Top Oil Rise over Ambient	38.3 °C
Rated Hot Spot Rise over Top Oil	20.3 °C
Ratio of Load Loss to No Load Loss	6.20
Top Oil Time Constant	170 min
Winding Hot Spot Time Constant	7 min
Exponent n	0.9
Exponent m	0.8

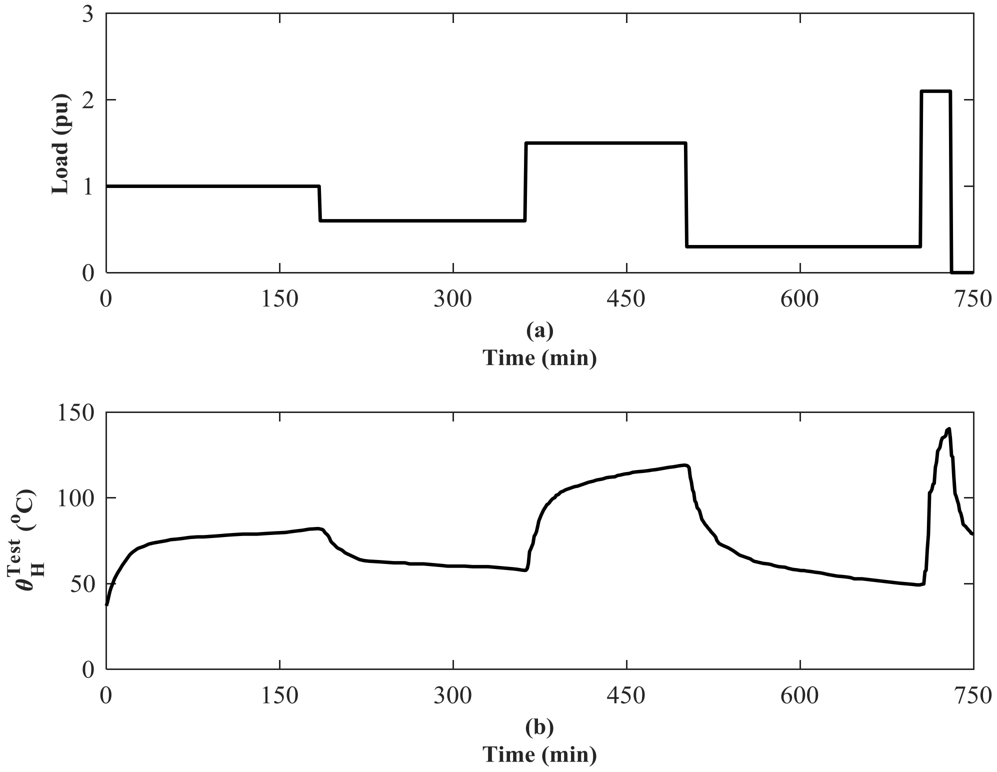


Figure 1

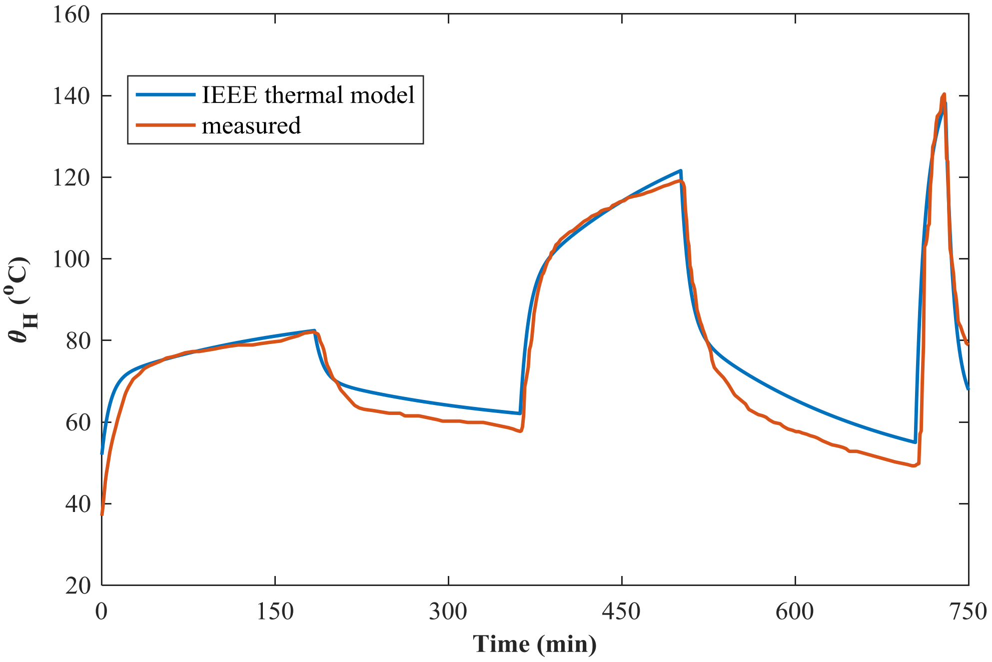


Figure 2

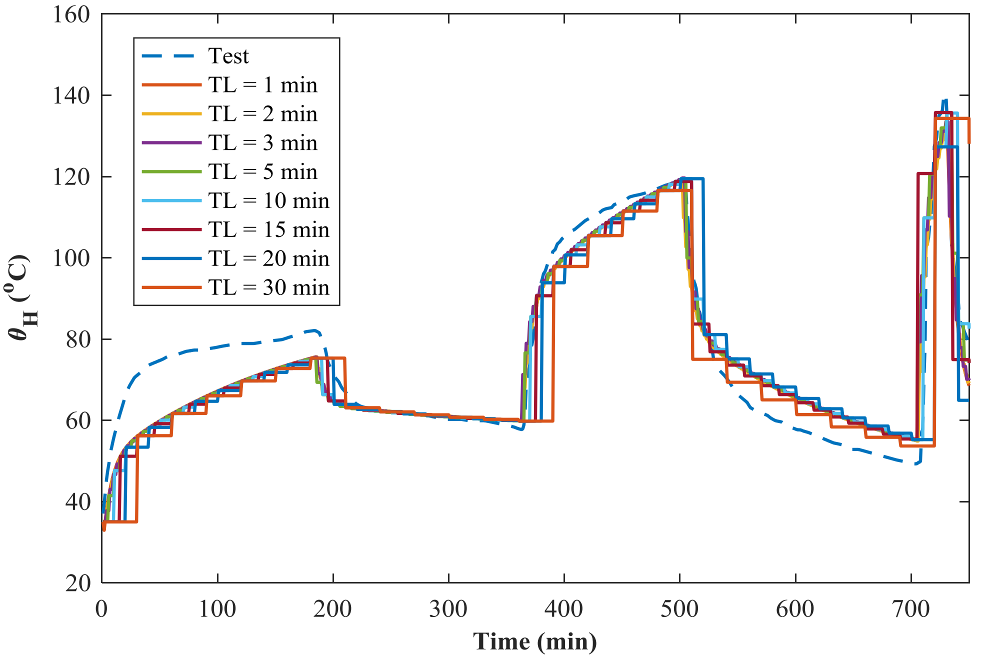


Figure 3

Table 2

T_L (min)	E_1 (ºC)	E_2 (ºC)	E_3
1	6.460	2.388	27
2	6.412	2.612	26
3	6.764	2.392	27
5	6.922	2.718	26
10	7.217	3.480	40
15	7.564	3.721	44
20	8.776	4.147	40
30	9.162	4.013	60

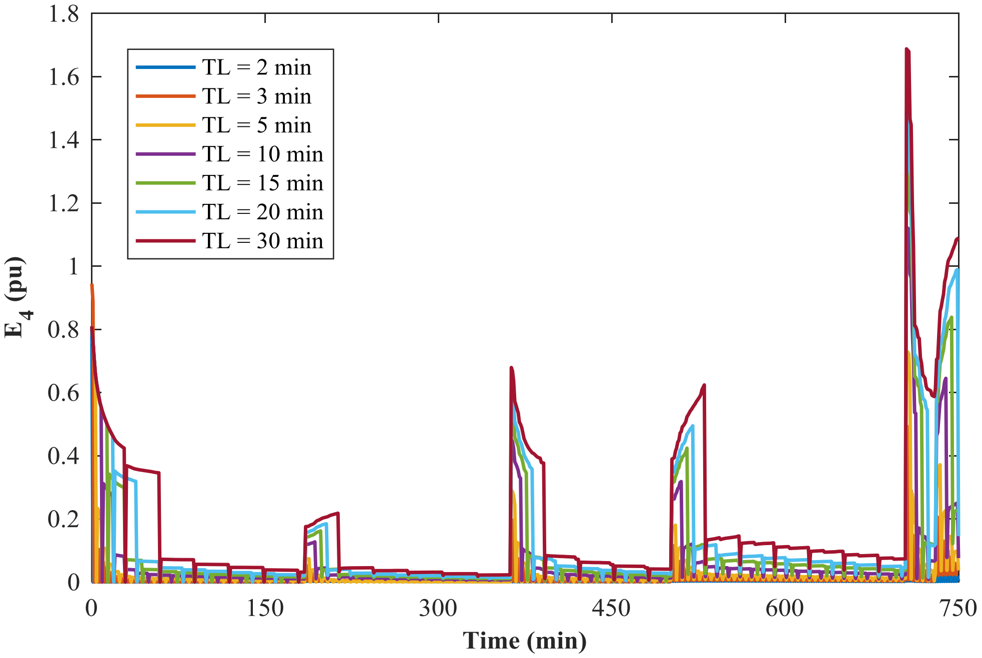
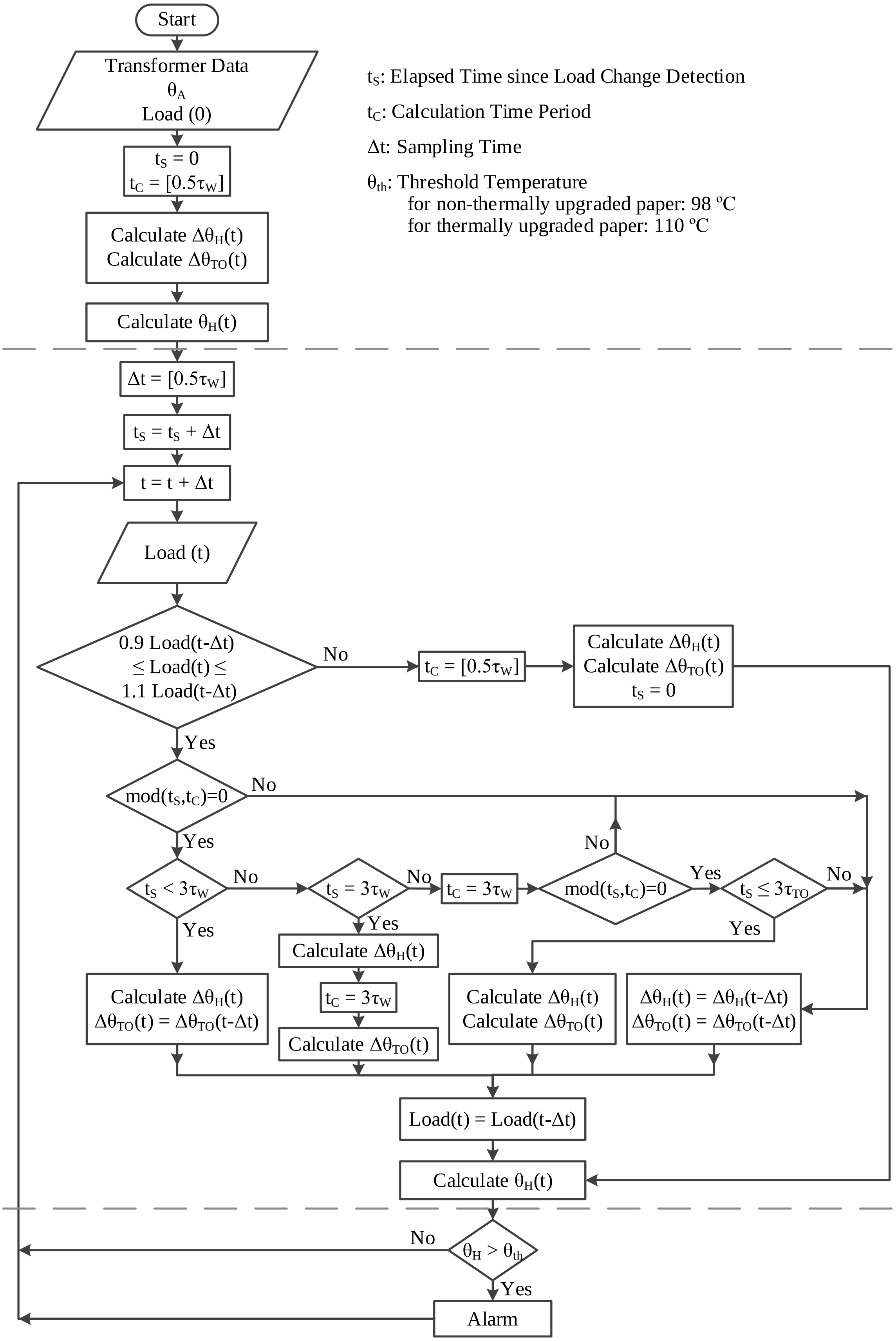


Figure 4

Table 3

T_L (min)	E_3	E_5
1	27	27
2	26	25
3	27	29
5	26	27
10	40	33
15	44	37
20	40	48
30	60	44



t_S: Elapsed Time since Load Change Detection

t_C: Calculation Time Period

Δt: Sampling Time

θ_{th}: Threshold Temperature
for non-thermally upgraded paper: 98 ºC
for thermally upgraded paper: 110 ºC

Figure 5

Table 4

Transformer Type	Distribution Transformers	Medium and Large Power Transformers	
Cooling Type	ONAN	ONAN	ONAF
τ_{TO} (min)	180	210	150
τ_W (min)	4	10	7

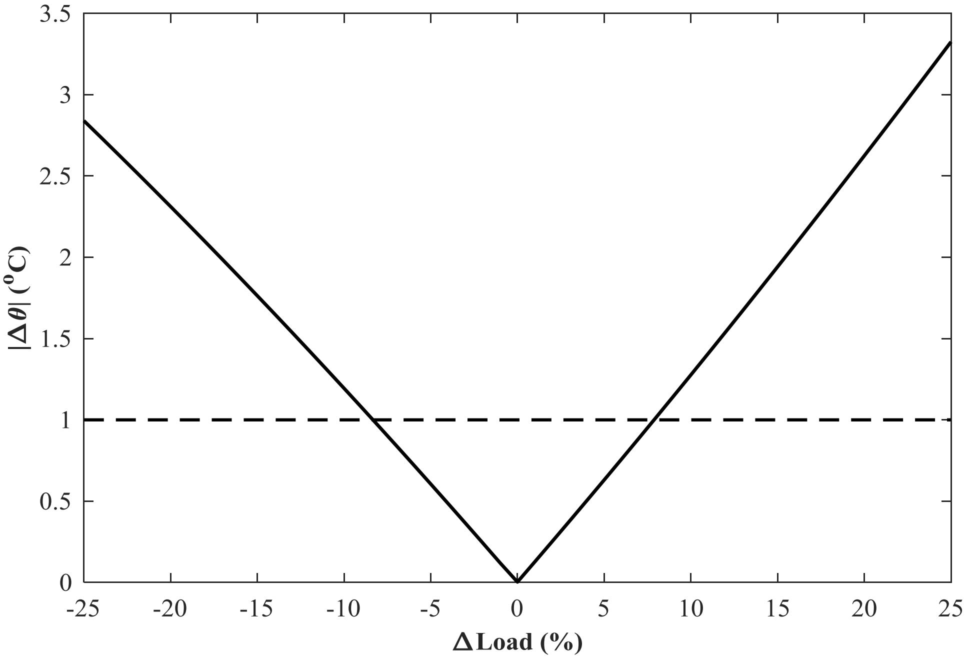


Figure 6

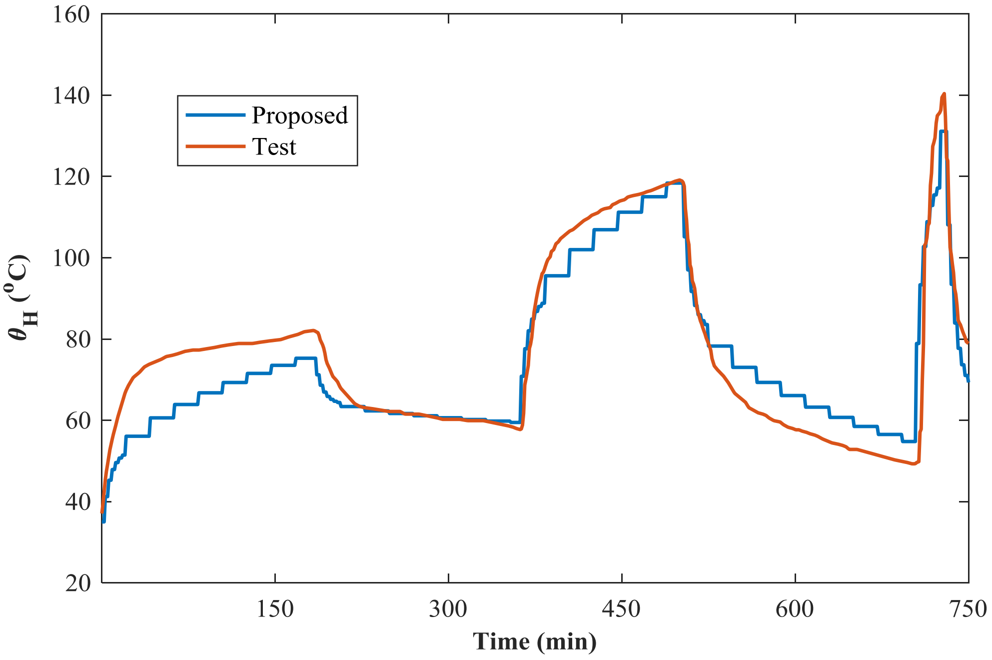


Figure 7

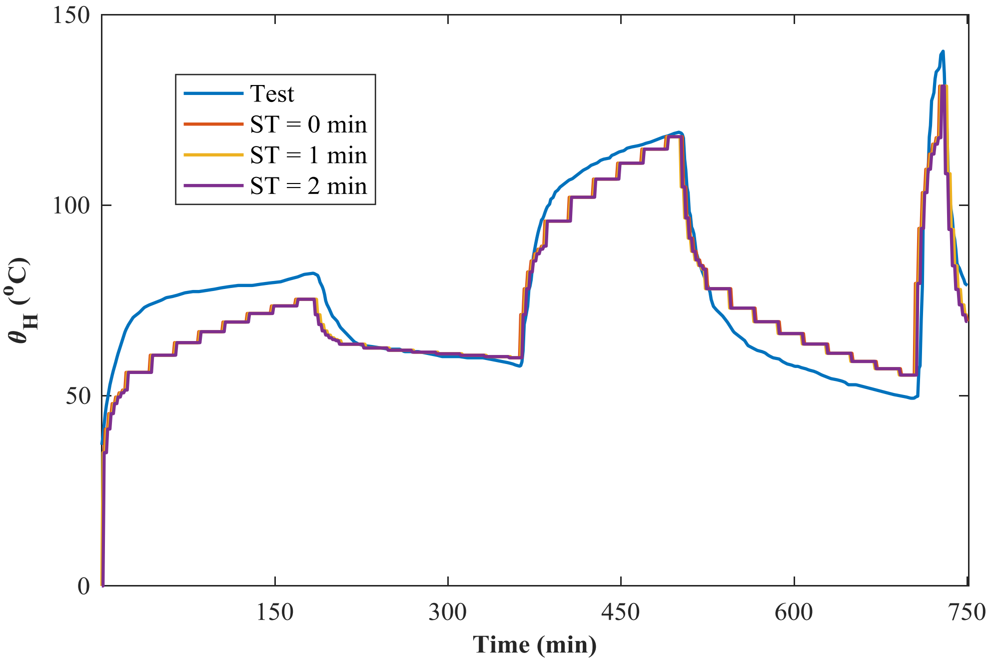


Figure 8

Table 5

T_L (min)	**No. of Calculations**	**E_1 (ºC)**	**E_2 (ºC)**	**E_3**	**Average of E_4**	**E_5**
1	1500	6.460	2.388	27	-	27
2	750	6.412	2.612	26	0.008	25
3	500	6.764	2.392	27	0.016	29
5	300	6.922	2.718	26	0.029	27
10	150	7.217	3.480	40	0.065	33
15	100	7.564	3.721	44	0.098	37
20	74	8.776	4.147	60	0.129	48
30	50	9.162	4.013	50	0.183	44
Proposed Algorithm	110	6.271	3.222	28	0.013	31

Biographies

Khadijeh Moosavi was born in Iran. He received B.S. & M.S degrees in electrical engineering from Amirkabir University of Technology, Tehran, Iran in 2015 & 2017. Presently, he is a PhD. student at the department of electrical engineering of Sharif University of Technology, Tehran, Iran. His main fields of research are power quality, power market, restructuring, and deregulation in power systems.

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