A Method for Estimating Transformer Temperatures and Elapsed Lives Considering Operation Loads

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Abstract: - A simplified temperature model is presented to substitute for the traditional temperature measurement. First, the temperature model of a transformer, based on IEEE std. C57.91, is briefly reviewed and then a load assumption is proposed to simplify the temperature formula. Second, a test case from the appendix of IEEE C57.91 is used to indicate that the measured and calculated temperatures are nearly the same using the proposed method. Finally, error analysis illustrates that the simplified models can be an alternative way to calculate the transformer temperatures and the transformer elapsed life.

Key-Words: - Temperature model, measurement and calculation temperatures, elapsed life

1 Introduction

Temperatures are critical to the performance of a transformer. Recently, many sophisticated studies have investigated the factors which would affect the temperatures of a transformer, and many methods have been published to illustrate and extend the application of temperature characteristics. In 1992, the forerunner of IEEE std. C57.91 was published to provide the guide for insulation thermal life considerations for transformer loading [1]. In 1995, the IEEE std. C57.91, the guide for loading mineral-oil-immersed transformers [8], became a milestone for modeling the formula of transformer temperatures. Thereafter, a calculation methodology of transformers' hottest spot and top oil temperatures was evaluated by means of factory testing [2] which provided an accurate method to calculate temperatures. Transformer temperatures within intelligent systems were considered in the transformer design to provide a novel power transformer design methodology [3]. Furthermore, selection of parameters was a discussion topic to accurately estimate the transformer temperatures considering the hottest-spot and equivalent aging of a transformer [2]. Currently, the temperature topic has become more important. Even a power transformer temperature monitoring system is used in the supervision system [4]-[6] and the technology of dynamic loading visualization from real time power flow data can be used to realize the reality of power transformer temperatures [7]. However, it is frustrating to an engineer who always deals with the complicate factors and calculation of the temperatures from the loads of transformer. Some negligible factors of calculating the temperature of transformers, mentioned in IEEE std. C57.91, should be ignored for accelerating the computing speed, and the brief calculation manner could be instead of the formal sophisticated calculation procedure.

A simple method to estimate the operation temperatures and the elapsed life might be of more concern to power system operators, even though comprehensive calculations can accurately estimate transformer temperatures. According to the proposed method, the results of the case studies shows that the measured temperatures are nearly the same as the calculated temperatures. Therefore, the proposed method provides an alternative means of observing the transformer temperatures and the elapsed life upon transformer current loads. The method could also provide a niche for further research in calculating transformer temperatures with transformer loads.

2 Problem Formulation

Transformer temperatures are the chief factors, which could affect the transformer characteristics. This paper presents a simplified model with a load assumption, based on IEEE std. C57.91 [8]. Transformer temperatures and elapsed life can be obtained by the current load of a transformer. In this section, the fundamental temperatures and elapsed life models are discussed, and then a simplified temperature model is developed.

2.1 Fundamental temperature model

Beginning with the most recent IEEE standard C57.91-1995 [8]-[9], a fundamental temperature model has been presented to predict transformer temperatures and those relative factors. The fundamental model can be used with controlled variables, providing the necessary transformer variables, and can offer operators means of calculating the transformer temperatures. The hottest-spot temperature is assumed to consist of three components given by the following equation: [8]-[9]

$$\Theta_H = \Theta_A + \Delta\Theta_{TO} + \Delta\Theta_H \,. \qquad (1)$$

Here *the top-oil temperature rise* $\Delta\Theta_{TO}$ and *the transient winding hottest-spot temperature rise over top-oil temperature* $\Delta\Theta_H$ are given by the following exponential expressions, as shown in (2) and (3), respectively.

$$\Delta\Theta_{TO} = \left(\Delta\Theta_{TO,U} - \Delta\Theta_{TO,i}\right)\times\left(1-\exp^{\frac{-t}{\tau_{TO}}}\right) + \Delta\Theta_{TO,i} \qquad (2)$$

$$\Delta\Theta_{H} = \left(\Delta\Theta_{H,U} - \Delta\Theta_{H,i}\right)\times\left(1-\exp^{\frac{-t}{\tau_{W}}}\right) + \Delta\Theta_{H,i} \qquad (3)$$

where

Θ_A ambient temperature, °C.

τ_{TO} oil time constant of transformer.

τ_W winding time constant at hot spot location, hours.

t duration of load, hours.

$\Delta\Theta_{TO,U}$ ultimate top-oil rise over ambient temperature, °C.

$\Delta\Theta_{TO,i}$ initial top-oil rise over ambient temperature, °C.

$\Delta\Theta_{H,U}$ ultimate winding hottest-spot rise over top-oil temperature, °C, respectively.

$\Delta\Theta_{H,i}$ initial winding hottest-spot rise over top-oil temperature, °C, respectively.

The temperature Θ_H in (1) has been determined by several variables in (4)-(7), in which the initial load k_i and the ultimate load k_u are the critical variables. Other variables could generally be regarded as constants to better visualize and to quickly evaluate the transformer temperatures [8]-[9].

$$\Delta\Theta_{TO,U} = \Delta\Theta_{TO,R}\times\left(\frac{k_u^2 R+1}{R+1}\right)^n \qquad (4)$$

$$\Delta\Theta_{TO,i} = \Delta\Theta_{TO,R}\times\left(\frac{k_i^2 R+1}{R+1}\right)^n \qquad (5)$$

$$\Delta\Theta_{H,U} = \Delta\Theta_{H,R}\times k_u^{2m} \qquad (6)$$

$$\Delta\Theta_{H,i} = \Delta\Theta_{H,R}\times k_i^{2m} \qquad (7)$$

where

$\Delta\Theta_{TO,R}$ top-oil rise over ambient temperature at rated load.

$\Delta\Theta_{H,R}$ winding hottest-spot rise over top-oil temperature at rated load, °C.

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

k_u ratio of ultimate load to be carried to 100% rating.

k_i ratio of initial load to be carried to 100% rating.

n empirically derived exponent used to calculate the variation of $\Delta\Theta_{TO}$ with changes in load.

m empirically derived exponent used to calculate the variation of $\Delta\Theta_H$ with changes in load.

2.2 Load assumption

Several precise temperatures used in (4)-(7) can be obtained from the initial load k_i and the ultimate load k_u. In practice, the k_i is close to k_u when the duration of operation is short enough. Thus, the minor load difference between the initial and ultimate state in this paper is neglected to facilitate a quick calculation, especially in the event of an emergency overloading.

From (4)-(7), the assumption, $k = k_i = k_u$, yields the following equations (8) and (9),

$$\Delta\Theta_{TO,U} = \Delta\Theta_{TO,i} = \Delta\Theta_{TO,R} \times \left(\frac{k^2 R + 1}{R+1}\right)^n \quad (8)$$

$$\Delta\Theta_{H,U} = \Delta\Theta_{H,i} = \Delta\Theta_{H,R} \times k^{2m}. \quad (9)$$

From (2) and (3), the assumption, $k = k_i = k_u$, yields the following equations (10) and (11),

$$\Delta\Theta_{TO} = \Delta\Theta_{TO,i} = \Delta\Theta_{TO,R} \times \left(\frac{k^2 R + 1}{R+1}\right)^n \quad (10)$$

$$\Delta\Theta_{H} = \Delta\Theta_{H,i} = \Delta\Theta_{H,R} \times k^{2m} \quad (11)$$

2.3 Simplified temperature model

Based on the aforementioned load assumption in (8) - (11) and the fundamental temperatures model in (1), the simplified hottest-spot temperature Θ_H model is shown as below,

$$\begin{aligned}\Theta_H &= \Theta_A + \Delta\Theta_{TO} + \Delta\Theta_H \\ &= \Theta_A + \Delta\Theta_{TO,R} \times \left(\frac{k^2 R + 1}{R+1}\right)^n + \Delta\Theta_{H,R} \times k^{2m}.\end{aligned} \quad (12)$$

The operating load k could be instead of initial load k_i or ultimate load k_u, because the simplified model (12) ignores the minor effect of the ultimate and initial load of a transformer. The following sections will use the simplified models to calculate the elapsed life of a transformer.

In observing characteristics of a transformer in temperature using (12), some variables of (8)-(11) are assumed to be constant. Fig. 1 shows the plots of temperatures of a transformer with respect to changes in loading level of the transformer. The temperature rises in oil $\Delta\Theta_{TO}$ by (10) and in winding $\Delta\Theta_H$ by (11) are also given. This means the final hottest-spot temperature Θ_H in (12) can be determined by managing the load k when the ambient temperature Θ_A is assumed to be constant [10].

For the purpose of simulation in this paper, some values in (8)-(12) are assumed to be constants, as follows : $n = 0.42$, $\Theta_A = 25$ °C , $m = 0.8$, $R = 1.0$, *normal insulation life* = 180,000 hours, $\Delta\Theta_{H,R} = 40$ °C, $\Delta\Theta_{TO,R} = 45$ °C .

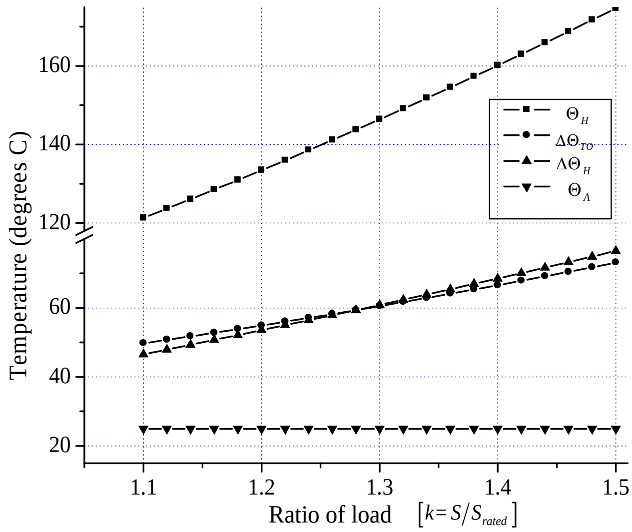


Fig. 1. Transformer temperatures.

2.4 Equivalent aging factor model

For estimating the accumulation of the effect in temperatures, the equivalent life (in hours) at the reference temperature that will be consumed in a given time period for the given temperature cycle is the following [8]:

$$F_{EQA} = \left(\sum_{n=1}^{N} F_{AA,n} \Delta t_n \right) \Big/ \left(\sum_{n=1}^{N} \Delta t_n \right) \qquad (13)$$

where n is an index of the time interval, N is the total number of time intervals, Δt_n is time interval, hours. A qualitative assessment of the life essentially incorporates the hottest-spot temperature Θ_H in (14) what is called an accelerated aging factor [8]-[9]. The Θ_H was mentioned in (12).

$$F_{AA} = Exp\left(\frac{15,000}{383} - \frac{15,000}{\Theta_H + 273} \right). \qquad (14)$$

2.5 Elapsed life model

From the IEEE standard C57.91-1995 and its corrigendum, an elapsed model has been presented to predict the transformer elapsed life of a transformer. The model can be used with controlled variables providing the necessary transformer variables and can provide operators with the elapsed life of a transformer. *Elapsed life* in the time period is equivalent hours life consumed divided by the definition of total normal insulation life (hours) and multiplied by 100, given as below [8]-[9]

$$Elapsed\ life\ (\%) = \frac{F_{EQA} \times t \times 100}{Normal\ insulation\ life}. \qquad (15)$$

For a given temperature of the transformer insulation, the total time between the initial state, when the insulation is considered brand new, and the final state, when dielectric stress, short circuit stress, or mechanical movement could occur in normal rated service and cause an electrical failure, is called *normal insulation life* in (15).

3 Case Study

3.1 System description and associated data

According to the measured data gotten from [8], a working tansformer is used to observe loads and temperatures of the transformer. There are two cases to demonstrate the proposed model, which are the *mild overload case* and *short-time emergency load case,* as shown in Table 1. The variation of the loads and hottest-spot temperatures within a time period of 24 hours are also illustrated in Table 1.

(1) Case 1 (*Mild overload*) : The transformer is working regularly at mild overload from the 1st hour to the 24th hour of a duty day, and there are no extremely high measured temperatures in the transformer.

(2) Case 2 (*Short-time emergency load*) : Only the load at the 17th hour is extremely high, and the measured temperatures in the short-time emergency load case are higher than those in the mild overload case.

The variations of load operating at mild overload and short-time emergency load are shown in Fig. 2 (a) and (b), respectively. The maximum load at the mild overload case and short-time emergency load case are 1.2 (pu.) and 1.69 (pu.), respectively, in the 17th hour. However, the temperature cannot be

Table 1 Transformer temperatures and loads

Time (hour-th)	Case 1		Case 2		Time (hour-th)	Case 1		Case 2	
	Load (pu.)	Temp. (℃)	Load (pu.)	Temp. (℃)		Load (pu.)	Temp.(℃)	Load (pu.)	Temp. ℃)
1	0.60	80	0.60	80	13	1.09	109.2	1.09	109.2
2	0.58	72.8	0.58	72.8	14	1.10	112.8	1.10	112.8
3	0.56	72.9	0.56	72.9	15	1.10	116	1.10	116
4	0.54	72.8	0.54	72.8	16	1.11	117.8	1.11	117.8
5	0.54	71.8	0.54	71.8	17	***1.2***	***125***	***1.69***	***180***
6	0.57	71.8	0.57	71.8	18	1.08	130	1.08	130
7	0.66	73	0.66	73	19	0.98	125	0.98	125
8	0.84	74.2	0.84	74.2	20	0.91	114	0.91	114
9	0.96	85.1	0.96	85.1	21	0.88	104.8	0.88	104.8
10	1.02	92.2	1.02	92.2	22	0.87	97.9	0.87	97.9
11	1.05	99.1	1.05	99.1	23	0.83	93.2	0.83	93.2
12	1.08	104.6	1.08	104.6	24	0.79	87.6	0.79	87.6

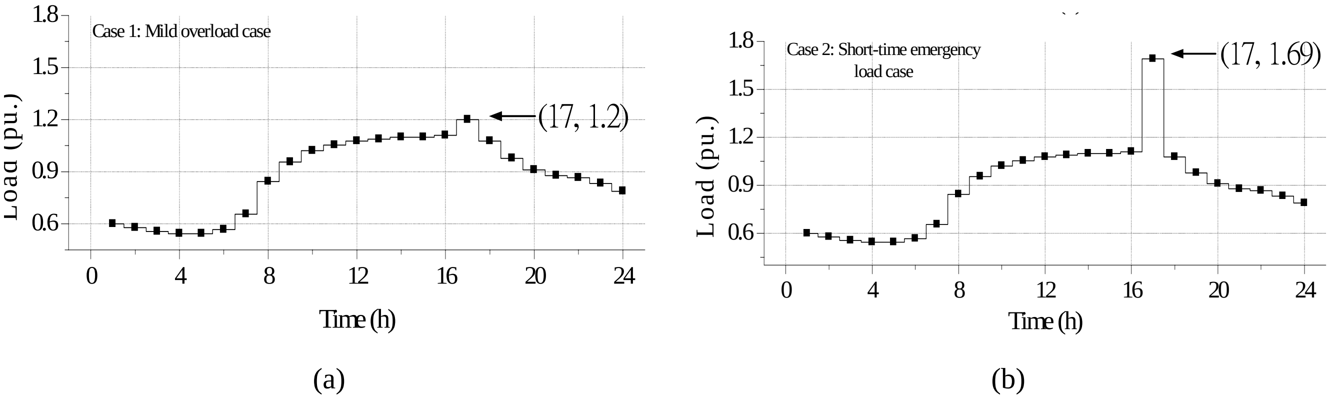


Fig. 2. Load variations.
(a) Mild overload case. (b) Short-time emergency load case

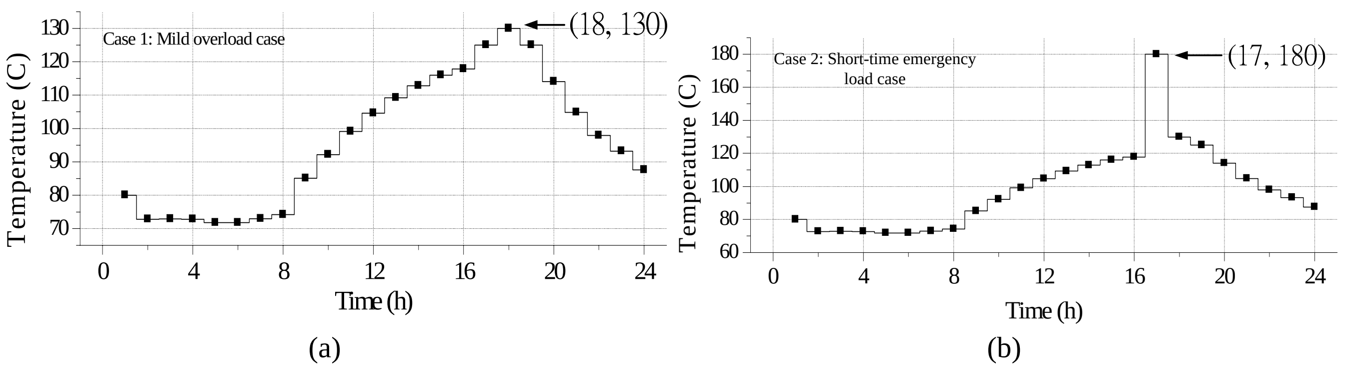


Fig. 3. Variations of hottest-spot temperatures.
(a) Mild overload case. (b) Short-time emergency load case.

reflected immediately from the load increasing because of the physical property of transformers, which means the temperature of transformer need the time to accumulate heat when the load increases. Thus, the variations of the hottest-spot temperatures are shown in Fig. 3 (a) and (b), respectively, measured by IEEE C57.91 [8]. The maximum hottest-spot temperature at the mild overload and short-time emergency load are 130 (°C) and 180 (°C), respectively, in the 18th and 17th hour, respectively.

To easily observe the physical property of the transformer, we combine Figs. 2 and 3 to draw the simplified curve to illustrate the characteristic variation of transformer temperatures when the loads vary, as shown in Fig. 4. In Fig. 4(a), the temperature of the mild overload case only reaches 125(°C), not the point of highest temperature, 130(°C), when the load increases from 0.6 (pu.) to 1.2(pu.). The highest temperature point shows up when the operating load is 1.08(pu.). The phenomenon is called *temperature lag* in this paper. In addition, when the operating load decreases and back to the end point of Fig. 4(a), 0.79(pu.), the temperature is larger than the temperature when the operating load is around 0.79(pu.) in the section 1 of Fig. (4). At this moment, the transformer keeps part of the heat, and the characteristic will not the same as the situation from the beginning.

In Fig. 4(b), the highest temperature of the short-time emergency load case is 180 (°C) when the operating load is 1.69 (pu.) at the 17th hour. At the 18th hour, the load decreases largely and suddenly and the temperature also decreases largely. The *temperature lag* is not much conspicuous as the mild overload case of Fig. 4(a).

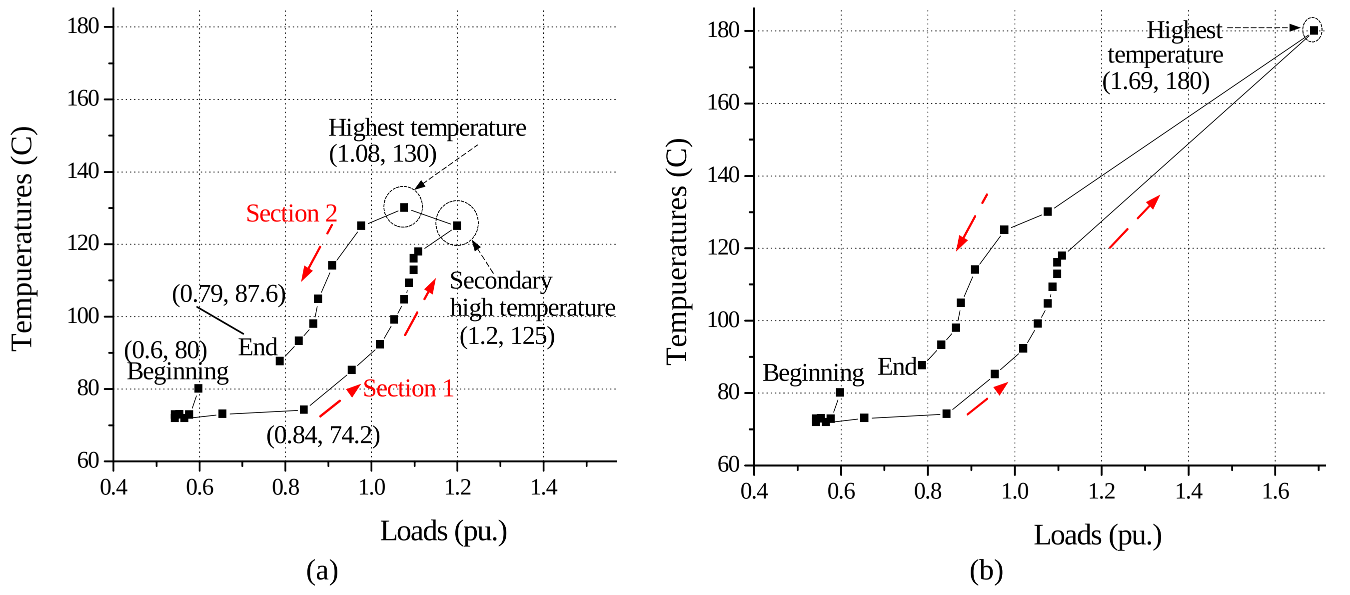


Fig. 4. Load variations.
(a) Mild overload case. (b) Short-time emergency load case

3.2 Elapsed Life Calculation

Fig. 5 illustrates the construction of the following case studies. There are two methods to estimate the elapsed life a transformer: the *measurement method* and *calculation method*.

3.2.1 Measurement method

The temperature data from IEEE std. C57.91 is measured, which is treated as real in this paper. Although we do not the submit any measurement manner in this paper, and just use the measured temperature, called temperature data in Fig. 5, from IEEE std. C57.91 to be the base of the comparison, the procedure from the temperature data in Fig. 5 to the elapsed life in Fig. 5 is called the measurement method for easily discussed.

3.2.2 Calculation Method

The case study of IEEE std. C57.91 provides the data of measured loads and temperatures with apparatus. In this method, we do not use the measurement temperature data part and calculate the temperatures from load data in Fig. 5 with the proposed method in this paper. The procedure from the load data, proposed method, calculated temperature to the elapsed life in Fig. 5 is called the calculation method.

3.2.3 Comparison

From another perspective, the stage 1 of Fig. 5 depicts the calculation way from the load to the temperature by (8)-(12), and the stage 2 of Fig. 5 shows the calculation way from the temperature to elapsed life by (15). Finally, we compare the temperature error between utilizing the calculation and measurement methods, and compare the elapsed life error between the two methods.

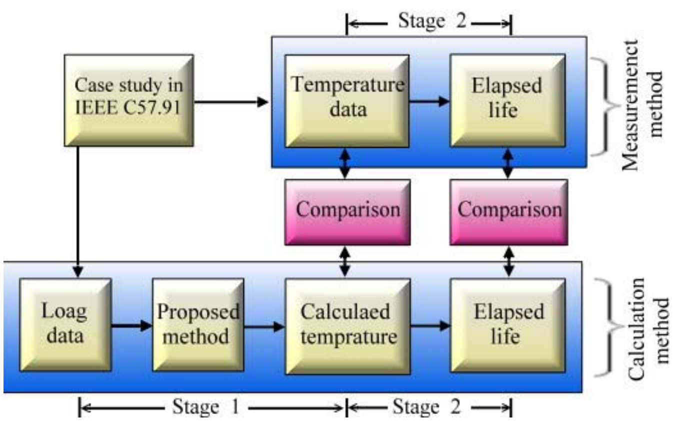
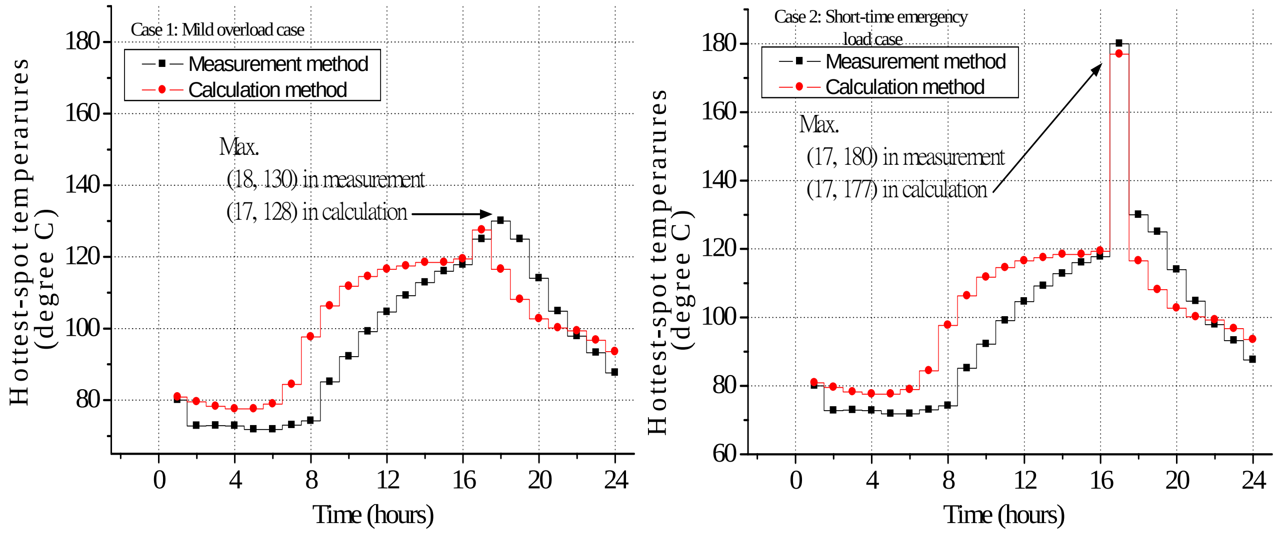


Fig. 5. Introduction of the case study.



(a) (b)

Fig. 6. Hottest-spot temperatures.
(a) Mild overload case. (b) Short-time emergency load case.

3.3 Numerical results and comparisons

According to (12), the hottest-spot temperatures of the mild overload case and of the short-time emergency load case can be obtained utilizing the current loads. The temperatures obtained utilizing the measurement method and the calculation method are illustrated in Fig. 6(a), in which the temperatures obtained utilizing the measurement method is nearly the same as that obtained utilizing the calculation method. Even in the case of short-time emergency, the temperature errors between the two methods are small, as shown in Fig. 6(b).

The calculation method ignores the physical property of transformer and immediately response the temperature from the load data variations. In Figs. 6(a) and 6(b), the temperatures of the measurement method always chase the temperature of the calculation method when the operating loads vary at every single hour.

The error between the hottest-spot temperature obtained by the measurement method and the calculation method is shown in Fig. 7, in which the maximum value is 31.6 % in the 8th hour. This means that the higher slope of temperature rise causes the larger temperature error because real temperature cannot be responded immediately by the sudden load variations. Table 2 shows the transformer temperatures with the two cases by the two methods. The measurement temperatures of Table 2 is the same as the temperatures of Table 1. The calculation temperatures is obtained from the load data in Table 1 and the proposed model in (8)-(12). The temperatures are the same no matter the temperatures obtained in the mild overload case or in the short-time emergency case, beside the temperature of the 17th hour.

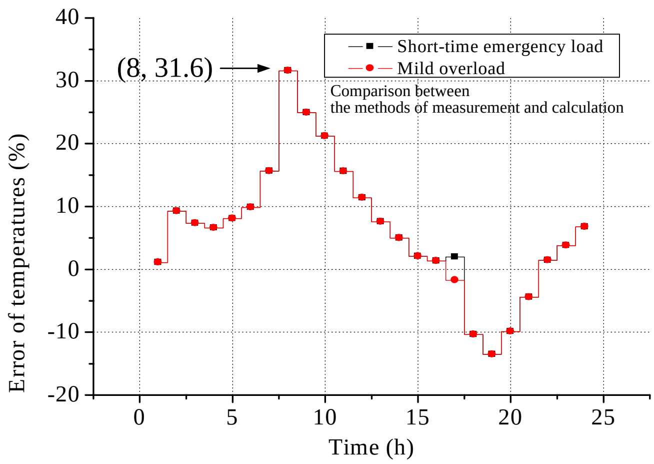


Fig. 7. Error of hottest-spot temperatures.

The equivalent aging factor, F_{EQA}, is the chief factor to determine the elapsed life of a working transformer. According to (13), the F_{EQA} of the mild

Table 2 Transformer temperatures by the methods

Time (h)	Temperatures Case 1 & 2 Measurement (°C)	Calculation (°C)	Error (%)	Time (h)	Temperatures Case 1 Measurement (°C)	Calculation (°C)	Error (%)	Case 2 Measurement (°C)	Calculation (°C)	Error (%)
1	80	80.9	1.1	13	109.2	117.5	7.6	109.2	117.5	7.6
2	72.8	79.5	9.3	14	112.8	118.4	5.0	112.8	118.4	5.0
3	72.9	78.2	7.3	15	116	118.4	2.1	116	118.4	2.1
4	72.8	77.6	6.6	16	117.8	119.4	1.4	117.8	119.4	1.4
5	71.8	77.6	8.1	***17***	***125***	***127.5***	***2.0***	***180***	***176.9***	***-1.7***
6	71.8	78.9	9.9	18	130	116.5	-10.4	130	116.5	-10.4
7	73	84.4	15.6	19	125	108.1	-13.5	125	108.1	-13.5
8	74.2	97.7	***31.6***	20	114	102.7	-9.9	114	102.7	-9.9
9	85.1	106.3	24.9	21	104.8	100.2	-4.4	104.8	100.2	-4.4
10	92.2	111.8	21.2	22	97.9	99.3	1.5	97.9	99.3	1.5
11	99.1	114.5	15.6	23	93.2	96.8	3.8	93.2	96.8	3.8
12	104.6	116.5	11.4	24	87.6	93.5	6.8	87.6	93.5	6.8

overload case and the short-time emergency load case can be obtained. The F_{EQA} obtained utilizing the measurement method and the calculation method are illustrated in Fig. 8(a), in which the F_{EQA} obtained utilizing the measurement method is nearly the same as that obtained utilizing the calculation method, even in the case of short-time emergency.

The error of the F_{EQA} between utilizing the two methods are shown in Fig. 9. In Figs. 9(a), the error of equivalent aging factors obtained by measured and calculated method are almost the same in case of short-time emergency or of mild overload. The enlarged figure of Fig. 9(a) is illustrated in Fig. 9(b), in which the error at the 24th hour is smaller than 6% in case of mild overload or of short-time emergency load. Although the huge temperature errors are from the 8th hour to 16th hour in cases of heavy loads, the final F_{EQA} is the determiner in calculating the elapsed life, and the temperature error in the final hour is small. The results mean that the equivalent aging factor F_{EQA} and the elapsed life obtained utilizing the measured method is nearly the same as that obtained utilizing the calculated method.

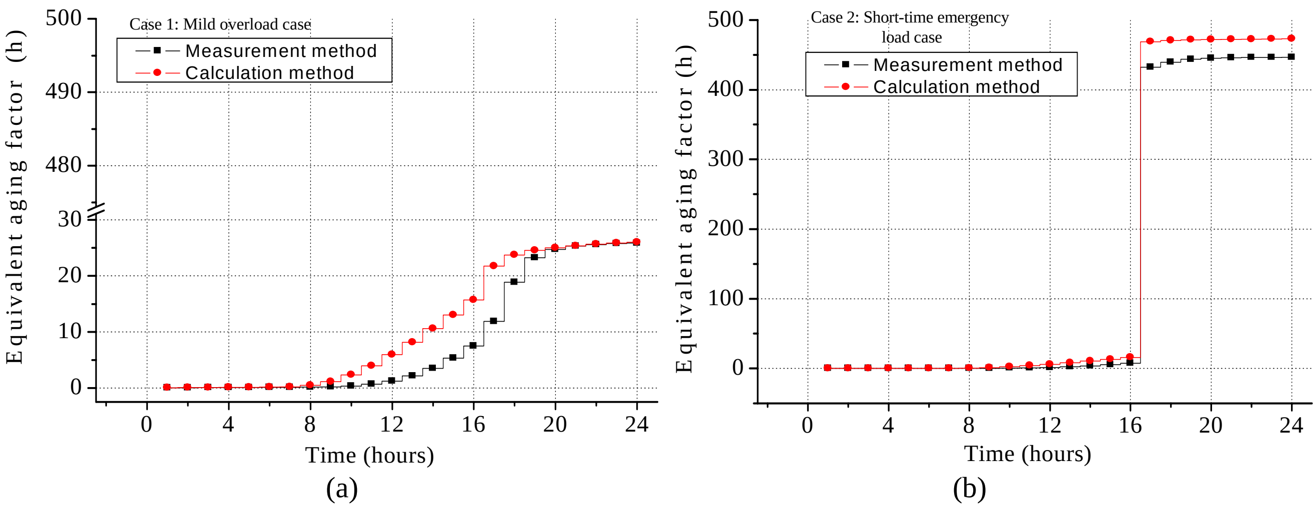
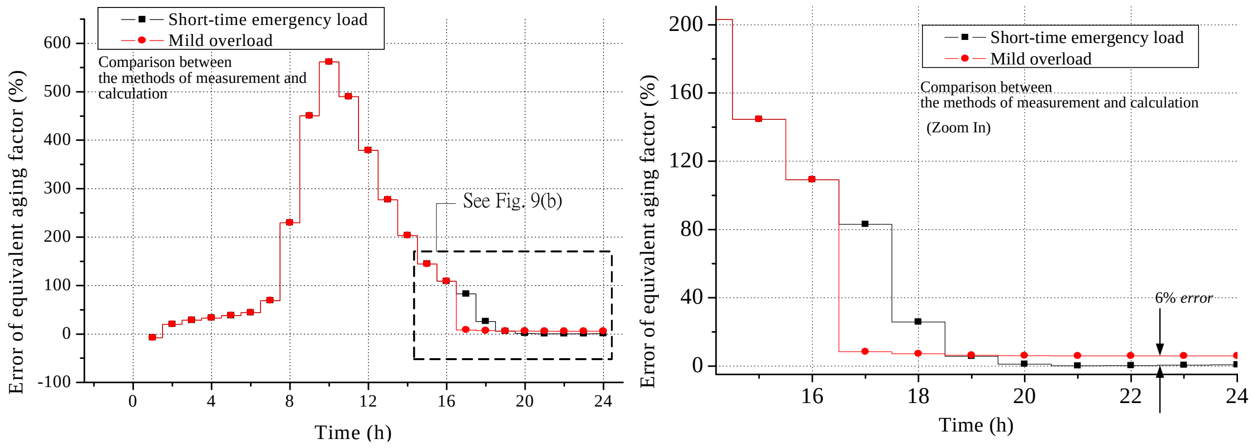


Fig. 8. Variations of equivalent aging factors.
(a) Mild overload case. (b) Short-time emergency load case.



(a) (b)

Fig. 9. Error of equivalent aging factors obtained by measured and calculated method. (a) Overall view. (b) Zoom in view.

3.3 Case discussion

In this paper, the temperatures data in the *Measurement method* is for IEEE C57.91 and the data of temperatures of the *Calculation method* is obtained by the proposed method. We use the temperatures to calculate the F_{EQA} and elapsed life, as shown in Table 3, in which Table 3 depicts the elapsed life of a transformer caused by the temperature effect from the 1st hour to the 24th hour. The measured temperatures in the appendix of IEEE C57.91 [8] are used to calculate the F_{EQA} , as shown in the first column of the two cases in Table 3. Meanwhile, the calculated temperatures can be obtained by means of the measured loads and the proposed method, as shown in the second column of the two cases in Table 3. Thus, the elapsed life can be calculated from F_{EQA} in these cases. Finally, the difference in error between the two methods shows that the elapsed life calculated by IEEE C57.91 is nearly the same as that calculated by the proposed method.

As previously noted, each transformer may have its own characteristic parameters. Appropriately manipulating the parameters is necessary to various cases. Although the error of elapsed life between the two methods would be changed by the varied parameters of the various tested transformer, the paper provides an alternative method to estimate the transformer temperatures and the results can be a niche to further research in relative applications.

Table 3 Error of the elapsed life difference

Case \ Error		F_{EQA} (hours)	Elapsed life (%)	Error (%)
Case 1	Measurement	25.9	0.014	2.63
	Calculation	26.6	0.015	
Case 2	Measurement	446	0.248	5.71
	Calculation	473	0.263	

4 Acknowledgement

Support for this research by the National Science Council of the Republic o China under Grant NSC 97-2218-E-033-004 is gratefully acknowledged.

5 Conclusion

This study presents a simplified temperature model, based on IEEE std. C57.91, which provides a way of calculating the relationship between the loads and temperatures of a transformer. According to the calculated temperatures, the elapsed life of a transformer can be obtained by the IEEE life fundamental model. Finally, the measured temperatures from the case study of IEEE C57.91 are used to be contrast with the calculated temperatures. The error between the elapsed lives of the measured temperatures and the calculated temperatures is slight. This means that the proposed method can be an alternative means of calculating the temperature and elapsed life of a transformer.

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