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Transformer real-time reliability model based on operating conditions*

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Abstract: Operational reliability evaluation theory reflects real-time reliability level of power system. The component failure rate varies with operating conditions. The impact of real-time operating conditions such as ambient temperature and transformer MVA (megavolt-ampere) loading on transformer insulation life is studied in this paper. The formula of transformer failure rate based on the winding hottest-spot temperature (HST) is given. Thus the real-time reliability model of transformer based on operating conditions is presented. The work is illustrated using the 1979 IEEE Reliability Test System. The changes of operating conditions are simulated by using hourly load curve and temperature curve, so the curves of real-time reliability indices are obtained by using operational reliability evaluation.

Key words: Operational reliability, Real-time reliability model, Transformer, Winding hottest-pot temperature (HST)
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INTRODUCTION

Traditional reliability evaluation (Zhou, 2000; Billinton, 1969; Billinton and Allan, 1996; Billinton and Li, 1994; Guo, 2003; Cheng *et al.*, 2004; Zhao *et al.*, 2003) provides long-term average reliability level of power system, is mainly applied to power system planning. Failure rates of components used in conventional techniques are their mean values. Sun *et al.* (2005) present the concept and algorithm of operational reliability, which also indicates that the component's failure probability varies with operating conditions. Reliability models of transmission lines, generators and loads based on real-time operating conditions are established accordingly. Cheng *et al.* (2006) analyze the impact of transmission line's real-time reliability model parameter upon power system operational reliability evaluation. He *et al.* (2006) put forward modelling principles of components' reliability models based on real-time operating conditions. The works above are all based on component's real-time failure probability and constant repair rate. Therefore, it is confirmed that component's failure rate varies with operating conditions.

Based on the detected degree of polymerization (DP) value of insulation paper on power transformer, Guo (2001) deduces a formula to describe the relationship between DP and the lifetime of power transformer. The formula shows that the power transformer lifetime is a function of its oil temperature. So it is clear that the failure rate of transformer is related to oil temperature.

The factors affecting the life of a mineral-oil-immersed transformer are analyzed in (IEEE/ANSI C57.115, 1991; IEEE/ANSI C57.92, 1981; IEEE/ANSI C57.91, 1981; 1995). Aging or deterioration of transformer insulation is a time function of temperature, moisture content, and oxygen content (IEEE/ANSI C57.91, 1995). However, the insulation temperature is the controlling parameter. Transformer insulation life is a function of operating conditions such as ambient temperature and MVA loading which influence the winding hottest-spot temperature (HST). This proves that the failure rate of transformer is not constant, but varies with operating conditions.

Fu *et al.*(2001) present a risk-based probabilistic method to assess transformer loading capacity, taking

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into account the probabilistic nature of time-varying loads and ambient temperature. The approach considers two impacts due to the transformer overloading: loss of life and dielectric failure. Therefore, the impact of ambient temperature and transformer MVA loading on transformer failure rate should be considered when assessing risk or reliability of transformer or power system.

FACTORS AFFECTING TRANSFORMER LIFE

For a given temperature of transformer insulation, its life is the total time between the initial state for which the insulation is considered new and the final state for which dielectric stress, short circuit stress, or mechanical movement could occur in normal service and would cause electrical failure (IEEE/ANSI C57.91, 1995). From the viewpoint of reliability, since the weakest parts of transformer are insulation paper and insulation oil (Guo, 2001), it is approximately considered that transformer life is transformer insulation life in this paper, though the relationship between insulation life and transformer life is a question that remains to be resolved (IEEE/ANSI C57.91, 1995).

The main factors affecting transformer insulation life are transformer MVA loading, ambient temperature, moisture content and oxygen content of transformer oil (Guo, 2001; IEEE/ANSI C57.91, 1995; Muthanna *et al.*, 2006). With modern oil preservation systems, the moisture and oxygen contributions to insulation deterioration can be minimized. What we care more are transformer loading and ambient temperature, which determine the transformer's winding HST. In aging studies it is usual to consider the aging effects produced by the highest (hottest-spot) temperature (IEEE/ANSI C57.91, 1995).

Experimental evidence indicates that the relation of insulation deterioration to time and temperature follows an adaptation of the Arrhenius reaction rate theory. IEEE/ANSI C57.91 (1995) introduces the concept of aging acceleration factor (F_{AA}) to describe this relationship. The equation for F_{AA} is as follows:

$$F_{\mathrm{AA}} = \exp\left(\frac{B}{\Theta_{\mathrm{Href}} + 273} - \frac{B}{\Theta_{\mathrm{H}} + 273}\right), \qquad (1)$$

where Θ_{H} is the winding HST, B is nearly constant and approximates 15000 according to experiments, and Θ_{Href} is the reference of HST. For instance, transformers with average winding rise of not more than 65 °C (55 °C) and hottest-spot winding rise of not more than 80 °C (65 °C) are referred to as 65 °C (55 °C) rise transformers (IEEE/ANSI C57.91, 1995; IEEE/ANSI C57.91-1995/Corl, 2002), and their Θ_{Href} equals 110 °C (95 °C).

When HST exceeds Θ_{Href}, transformer insulation aging rate is greater than that in normal state, and F_{AA} has a value greater than 1. Thus, transformer life expectancy is reduced. Percent loss of insulation life (*Loss*) in the period T is given in Eq.(2):

$$Loss = \int_0^T F_{\mathrm{AA}} \mathrm{d}t \,/\, NIL, \qquad (2)$$

where *NIL* is normal insulation life or normal life expectancy at reference temperature. IEEE/ANSI C57.91 (1995) recommends that users select their own assumed insulation lifetime estimate. In (IEEE/ANSI C57.91, 1995), 180000 h is used in examples, as an apparently prudent assumption for normal life expectancy (Swift *et al.*, 2001). However, we recommend an economical and effective method in (Guo, 2001) to calculate *NIL*, which is based on DP value of insulation paper on power transformer.

Eq.(1) and Eq.(2) are adaptive to loading mineral-oil-immersed transformers universally as the basic theory of transformer loading remains the same, whether it is for distribution transformer or power transformer.

It can be seen in Eq.(1) that the main factor affecting transformer life is Θ_{H}. In power system operation, Θ_{H} is a function of transformer MVA loading and ambient temperature. Therefore, the impact of loading and ambient temperature on transformer life will be studied below.

CALCULATION OF THE WINDING HST

It is usually considered that the winding HST is the worst (highest) temperature to which the transformer insulation system is subjected to that and the hottest-spot is usually assumed to be near the top of the high or low voltage winding (Fu *et al.*, 2001; Swift *et al.*, 2001; Wong, 1994). The winding HST is a time function of transformer MVA loading, ambient temperature and transformer characteristics.

The equations to calculate the winding HST in (IEEE/ANSI C57.91, 1995) have exponential form. The Guide uses a simple method to deal with ambient temperature, which is a conservative estimate. The block diagram of hottest-spot algorithm in (Weekes *et al.*, 2004) presents the entire heat transferring process which can be expressed as differential equations as follows:

(1) Calculate the top-oil temperature rise $\Delta\Theta_{\mathrm{TO}}$

$$\tau_{\mathrm{TO}}\frac{\mathrm{d}\Delta\Theta_{\mathrm{TO}}}{\mathrm{d}t}=\Delta\Theta_{\mathrm{TO,U}}-\Delta\Theta_{\mathrm{TO}}, \tag{3}$$

$$\Delta\Theta_{\mathrm{TO,U}}=\Delta\Theta_{\mathrm{TO,R}}[(K^2R+1)/(R+1)]^n. \tag{4}$$

(2) Calculate the winding HST rise $\Delta\Theta_{\mathrm{H}}$

$$\tau_{\mathrm{w}}\frac{\mathrm{d}\Delta\Theta_{\mathrm{H}}}{\mathrm{d}t}=\Delta\Theta_{\mathrm{H,U}}-\Delta\Theta_{\mathrm{H}}, \tag{5}$$

$$\Delta\Theta_{\mathrm{H,U}}=\Delta\Theta_{\mathrm{H,R}}K^{2m}. \tag{6}$$

(3) Calculate the lag ambient temperature Θ_{Ae}

$$\tau_{\mathrm{TO}}\frac{\mathrm{d}\Theta_{\mathrm{Ae}}}{\mathrm{d}t}=\Theta_{\mathrm{A}}-\Theta_{\mathrm{Ae}}. \tag{7}$$

(4) Calculate the winding HST

$$\Theta_{\mathrm{H}}=\Theta_{\mathrm{Ae}}+\Delta\Theta_{\mathrm{TO}}+\Delta\Theta_{\mathrm{H}}. \tag{8}$$

The meanings of symbols in Eqs.(3)~(8) are listed in Table 1.

Table 1 Meanings of symbols

Symbols	Descriptions
Θ_{A}	Instantaneous ambient temperature, °C
Θ_{Ae}	Lag ambient temperature, °C
Θ_{TO}	Top-oil temperature, °C
Θ_{H}	Winding hottest-spot temperature, °C
$\Delta\Theta_{\mathrm{TO}}$	Top-oil rise over ambient temperature, °C
$\Delta\Theta_{\mathrm{TO,R}}$	Top-oil rise over ambient temperature at rated load on the tap position to be studied, °C
$\Delta\Theta_{\mathrm{TO,U}}$	Ultimate top-oil rise over ambient temperature for load L, °C
$\Delta\Theta_{\mathrm{H}}$	Winding hottest-spot rise over top-oil temperature, °C
$\Delta\Theta_{\mathrm{H,R}}$	Winding hottest-spot rise over top-oil temperature at rated load on the tap position to be studied, °C
$\Delta\Theta_{\mathrm{H,U}}$	Ultimate winding hottest-spot rise over top-oil temperature for load L, °C
K	Ratio of load L to rated load, per unit
R	Ratio of load loss at rated load to no-load loss on the tap to be studied, per unit
τ_{TO}	Oil time constant of transformer, h
τ_{w}	Winding time constant at hot spot location, h
m, n	Empirical constants depending on transformer cooling mode

From the above algorithm, we can draw the conclusion that if transformer load and ambient temperature have been measured, the winding HST can be obtained by solving the differential equations.

TRANSFORMER REAL TIME RELIABILITY MODEL

If we assume that the winding HST has been keeping constant since the initial operating state of a transformer, F_{AA} will be constant all the time. When the transformer reaches its final state for which *Loss* equals 1 in Eq.(2), T is its life expectancy at the specified HST which is given as

$$T=NIL/F_{\mathrm{AA}}. \tag{9}$$

Another expression of T can be obtained by substituting Eq.(1)~(9) as follows:

$$T(\Theta_{\mathrm{H}})=NIL\cdot\exp\left(\frac{B}{\Theta_{\mathrm{H}}+273}-\frac{B}{\Theta_{\mathrm{Href}}+273}\right). \tag{10}$$

Power system is considered as repairable system in traditional power system reliability evaluation theory, and state transition rates are assumed to be constant. Therefore, in reliability evaluation, the transformer's mean time to failure, *MTTF*, equals T in Eq.(10). Thus, the transformer real-time reliability model based on loading and ambient temperature is obtained, with its failure rate is represented as

$$\lambda(\Theta_{\mathrm{A}},K)=1/MTTF=$$

$$1/NIL\cdot\exp\left(\frac{B}{\Theta_{\mathrm{Href}}+273}-\frac{B}{\Theta_{\mathrm{H}}(\Theta_{\mathrm{A}},K)+273}\right). \quad (11)$$

There are several approaches to get Θ_{H} in Eq.(11). According to different practical situations, different approaches should be chosen. Eqs.(3)~(8) can be used for off-line reliability evaluation to calculate the winding HST. However, the winding HST can also be measured for transformers equipped with HST indicators or fiber optic detectors (Working Group 09 of Study Committee 12, 1990). The winding HST obtained by those equipments is usually more accurate than that by calculating, but the cost of the equipment may be too high.

We can use the algorithm presented in (Sun *et al.*, 2005) to get the operational reliability evaluation by using the transformer real-time reliability model.

CASE STUDY

In this section, we apply transformer real-time reliability model to the IEEE RTS-79 system (Reliability Test System Task Force, 1979), and evaluate the system's operational reliability. Transformers' reliability models adopt the real-time ones established above, and the variables of operating condition are considered as ambient temperature and transformer loading. The reliability models of other components such as lines and generators adopt the traditional ones which have constant failure rates and repair rates. All the rating data on transformers and lines use the normal rating given in (Reliability Test System Task Force, 1979).

There are five transformers in the system. When the system is at normal load level, all the transformers are loaded far below their rated value. In order to accentuate the problem being studied, we arrange the system in special operating mode as follows:

(1) Increase the total system load to 3292.8 MW and all the generators to full load state that is 3405 MW, and choose this state to be the peak load mode;

(2) Three transformers are outage, which are *T*14 (bus 9~bus 11), *T*15 (bus 9~bus 12) and *T*16 (bus 10~bus 11). More attention is paid to transformer *T*7 (bus 3~bus 24) and *T*17 (bus 10~bus 12) which influence the operational reliability of the system.

We assume all the transformers have the same characteristics shown in Table 2. Each transformer is rated 400 MVA, with 65 °C average winding rise.

Table 2 Transformer characteristics

Parameter	Value
$\Delta\Theta_{\mathrm{TO,R}}$	36.0 °C
$\Delta\Theta_{\mathrm{H,R}}$	28.6 °C
R	4.87
τ_{TO}	3.5 h
m	1.0
n	1.0
NIL	180000 h

The load cycle which repeats every 24 h is simulated by summer weekday hourly load model, and the ambient temperature cycle is simulated by a 24 h temperature curve generated at random. The system is evaluated every hour, so there are 24 sets of data. The curves of operating conditions varying with time are shown in Fig.1.

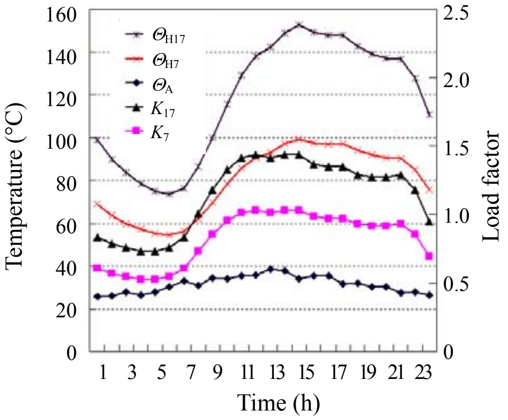

Fig.1 The HST and loading curves of *T*7 and *T*17

In Fig.1, Θ_{A} is the curve of ambient temperature, K_7 and K_{17} are loading curves of *T*7 and *T*17 respectively, and Θ_{H7} and Θ_{H17} are the winding HST curves of *T*7 and *T*17 respectively.

Transformers' failure rates in each hour are calculated by Eq.(11) based on the HST in Fig.1. Transformer failure rate curves are shown in Fig.2. λ_7 and λ_{17} represent failure rate curves of *T*7 and *T*17, which is varying with time. $\overline{\lambda}$ represents the failure rate adopted by traditional reliability model. The vertical coordinate axis of Fig.2 is logarithmic. It can be seen from Fig.2 that failure rate of transformer used in conventional techniques is constant. However, the real-time model presented in this paper can provide real-time reliability of components and system influenced by operating conditions.

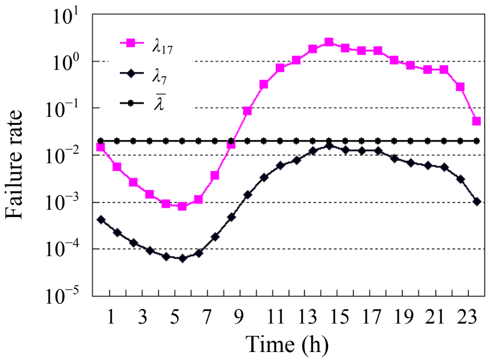

Fig.2 Transformer failure rate curves

Evaluating the system every hour by using the failure rate data shown in Fig.2, we can get the system operational reliability indices such as Probability of Load Curtailments (PLC), Bulk Power Interruption Index (BPII, MW/MW-yr), and Bulk Power Energy Curtailment Index (BPECI, MWh/MW-yr) as shown in Fig.3.

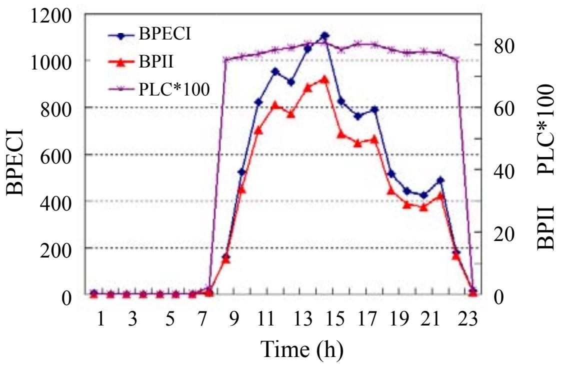

Fig.3 The system operational reliability indices

The results in Fig.3 show that system operational reliability indices vary with operation conditions. Since it is summer, the ambient temperature and load demand reach the peak during 14:00 to 15:00. The system indices during this period are the highest. In another words, the system reliability is lowest at noon.

The reliability of power system depends on not only the network topology but also the system components parameters such as failure rate, repair rate, generation or transmission capacity, load level, etc. (Zhao *et al.*, 2005). The results obtained by on-line traditional reliability evaluation can only reflect the variation of load level. However, the results obtained by operational reliability evaluation can reflect not only the variation of load but also other operating conditions. In order to distinguish them clearly, Fig.4 plots the BPECI curves named as BPECIop and BPECItr which are calculated by operational and traditional reliability evaluation respectively.

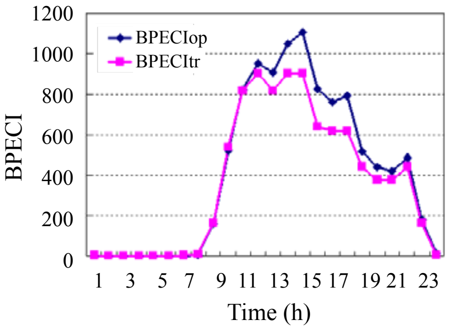

Fig.4 The operational and traditional reliability indices

When the hourly load is at the same level, e.g. at 12:00, 14:00 and 15:00 as shown in Fig.4, the traditional indices are identical but the operational indices are different. Therefore, the differences between BPECIop and BPECItr show the impact of the transformers' time-varying failure rates on evaluation results. In normal states, the results obtained by traditional evaluation are almost the same as those by operational evaluation. However, when the system is operating in some special states, for example, some key components are on outage at peak load time, only the operational evaluation can fully reflect the system's reliability.

Through the case study, it is clear that if the impact of time varying component failure rates is neglected in reliability evaluation, the more frequent failures in some operating conditions cannot be explained. Therefore, it is necessary to use operational reliability evaluation technique to evaluate power system's reliability in the current operating states.

CONCLUSION

Operational reliability evaluation, the basis of which is component's real-time reliability model based on operating conditions, can reflect the real-time reliability level of power system. This paper presents the transformer's real-time reliability model.

The results obtained by operational reliability evaluation on IEEE RTS-79 system show that the transformer's real-time reliability model is reasonable and effective. The real-time evaluation results can help dispatchers analyze current operation states of power system and make decision.

It is necessary to emphasize that the main factors considered in this model are ambient temperature and transformer loading, and that several factors affecting transformer failure rate have not been included, such as weather effects, common mode failures, etc. These will be researched in our future work.

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