An Approach to Comprehensive Health Status Evaluation of Oil-Immersed Transformers

Feng-bo Tao[1],Chao Wei[1],Cheng-bo Hu[1], Bi-junChen[2],You-yuanWang[2]*

[1]*JiangSu Electric Power Company Research Institutes, Jiangsu, Nanjing, 211103, China*

[2]*State Key Laboratory of Power Transmission Equipment&System Security and New Technology, School of Electrical Engineering, Chongqing University, Chongqing, 400044, China*

Received 1 March 2014, www.cmnt.lv

Abstract

The oil-immersed transformers take upon important position in transmission and distribution engineering. The operation life cycle of oil-Immersed transformers is far and away lower than its designed life for the most part in Jiangsu province of China. One of its major reasons is the insufficientof running status evaluation. As everyone knows, the health condition ofpower transformer has a high degree of availability, and provides the foundation forcondition based maintenance (CBM) and decommission. The article puts forward a comprehensive health condition assessment model based on non-repairable model (aging failure model) and repairable model (status evaluation model).Therein, the first mentioned of two contains parameters which have irreversibledamage to insulation, such as long-term loading and operating environment, and the other one includes parameters which would be able to recover from the damage trough maintenance, such as oil quality test and partial discharge test.The health status value is quantized into scores between 0-100 by means of mathematical toolslike conditionclassification and fuzzy inference and so on. The model represents health condition intuitively, and modified by defectivework condition information, which has anirreversibledamage on insulating materials, and enhances theaccuracy rating. The article provides a visualized and reliable basis of CBM.

Keywords: transformer, health condition, non-repairable model, repairable model, defectiveworkcondition

1 Introduction

In our country, with the enlargement of the power system scale and the gradually rising of the management level, therefore, as the important part of the transmission and distribution, transformer has gain much attention[1].

On the one hand, in order to ensure the safe and reliable operation of power system, the requirement of the operation reliability has been raised to the nearly perfect level. On the other hand, because of the high operational costs of transformer and optimizing the equipment asset management is related to the sustainable development of power system, so, it needs much more attention than it gains now.

Comparatively speaking, in our country, there are few studies on the retirement management and the healthy state and life characteristics of the power equipment, also, there are no scientific equipment retirement decisions and the retirement age of the electric power equipment is far lower than the international level.

The average retirement age of the electric power equipment has been more than 40a in America and Japan[2], however, it only about 16a in Jiangsu province, it far did not play its due role. So, we need real-time monitoring and evaluation for the transformer, it can give us the scientific equipment retirement decisions and has an advantage over extending retirement age of the transformer and saving money and improving the reliable operation of power system.

Oil-immersed transformer accounts for almost all main transformers in the 110 kV or above grid substation and about three-quarters distribution transformer in the distribution network, because it has many advantages, such as large capacity, low loss and high reliability and so on. So, studying on the health status of oil-immersed transformer has significant meaning[1,2, 3].

This paper proposes a comprehensive health assessment model for oil-immersed transformer, which is based on the irreversible and repairable fault information.

Through the collaborative use of multi-source information, it can weaken the extent of evaluation results caused by missing or single parameter error. The irreparable fault information reflects the insulation aging condition in the long running situation, including the damage to insulation made by long running environment and long term load cannot be repaired.

In addition, the repairable fault information mainly includes online monitoring, inspection records, periodically testing and defect management, the fault caused by these parameters can be repaired or eliminate by itself and the damage of the insulation is repairable.

What's more, we also make correction on the comprehensive health status value considered by the short circuit impulse and emergency load. The model covers almost all health information of the transformer and through example proves the availability.

2 The health status evaluation parameters

The first step to assess the health status is confirming the state parameters. Under normal conditions, we must analyze

*** *Corresponding author's* e-mail: bijunch@cqu.edu.cn

some phenomenon of operation process or measure the parameters which reflecting the state of the equipment to get the current state of the equipment indirectly due to can't determine the health status of equipment directly. This requires determining the state of health assessment for state parameters before determining evaluation algorithm[4].

The determination of state parameter system generally can be divided into five steps:

1. Collect information about the equipment, on-line monitoring and test as much as possible, including equipment parameter, factory test, operation parameters, and historical records and so on;
2. The correlation analysis of the information and the health status of the equipment, used for the chaotic information classification.According to the nature of the parameters, this text divided information layer into three categories, not repair, can repair, bad working conditions;
3. The quantitative analysis of the corresponding relationship between single parameter and the health status,called functional layers.According to the nature of parameters, fault mechanism, influence factors to determine a differentiation, personalized health analysis model of the single parameters;
4. The constructing of the parameters system. After determining the index level, it must have the constraint of architectural layer to normalize the multidimensional and multifaceted parameters to the same level, and conduct follow-up evaluation. It is based on the Correlation between parameters and the importance of health status to construct architectural layer.
5. Decision fusion of mass parameters. Determine fusion method between the parameter through the construction of the architectural layer, this paper use weight distribution method to fuse the decision-making level[5].

The flow path of state parameter systematic confirmation is shown in Fig. (1).

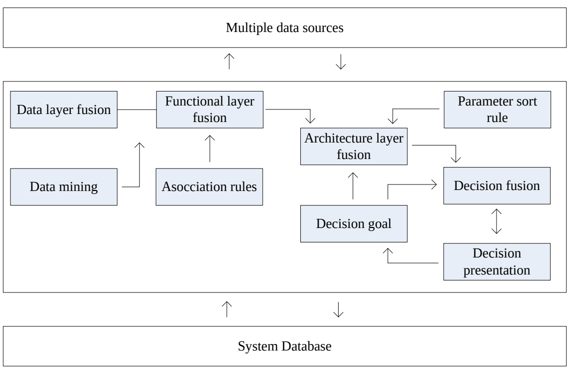

FIGURE 1 The flow path of state parameter systematic confirmation

3 Non-repairable fault model

Non-repairable model, also called aging failure model, is a kind of failure rate model due to cumulative heat effect of the load and the filth of the operating environment for a long time which cause irreversible loss and non-repair of the solid insulating material[6,7].

The model describes the regulation where the failure rate gradually increasing in aging period of the tub curve through Weibull distribution. However, the limitation of the model is unable to respond to the failure caused by discharge, being damp, shock, and deformation except thermal ageing.

What's more, it can't achieve the effects of reducing failure rate andextending the lifespan by maintenance, repair, and defect elimination in repairable failure.The non-repairable fault has an influence on health status, as shown in Fig.(2).

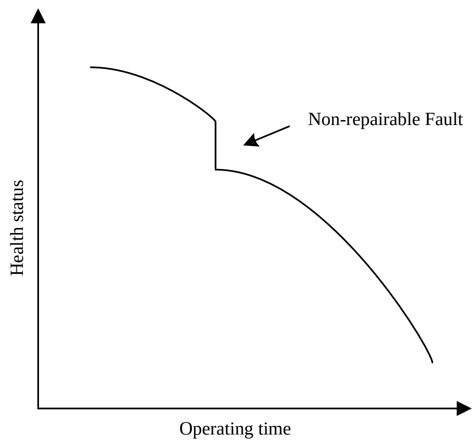

FIGURE 2 The influence of non-repairable fault

Active power, reactive power, current and voltage of transformer are the basic information which recorded timely in the operation of the power grid. The statistical information of equipment's load rate for every moment is rich because they are obtained by combining the nameplate and the rated value. The critical temperature, also called hot temperature, used to measure life aging rate in transformers, can be calculated based on load data through the simulation in the process of radiation, convection and conduction in heat production and heat loss of transformers, and the health state evaluation model is set up using the hot temperature. This model selects the hierarchy value in article [10] after the contrast analysis, as shown in Table 1.

TABLE 1 Oil-Immersed transformer rating based on health index mark

Grade	1	2	3	4	5
Health Index Mark	**0-0.35**	**0.35-0.6**	**0.6-0.75**	**0.75-0.9**	**0.9-1**
Health Status	Very poor	poor	Need Caution	Accept able	Good

Operating environment includes altitude, temperature, and wind speed, humidity and pollution level. These parameters have direct or indirect relationship to defect the heat dissipation, mechanical strength, creeping discharge and metal corrosion of the transformer and its accessories, which act on the transformer for a long time and have non-reparable influence. The operating environmentdegrees are graded as reference [10], as shown in Table. (2).

TABLE 2 The operating environment rating according to reference

Degree of environment	**1**	**2**	**3**	**4**	**5**
environment	mean annual temperature far below 20℃, ultimate temperature never ≥40℃ or ≤-25℃	mean annual temperature below 20℃, ultimate temperature occasionally ≥40℃ or ≤-25℃	mean annual temperature close to 20℃, ultimate temperature ≥40℃ or ≤-25℃ at times	mean annual temperature above 20℃, ultimate temperature ≥40℃ or ≤-25℃ at times	mean annual temperature≥20℃, ultimate temperature constantly ≥40℃ or ≤-25℃
humidity	＜40%	40%~60%	60%~80%	80%~90%	＞90%
degree of contamination	adequate air quality, class of pollution I	preferable air quality,class of pollution II	general air quality, class of pollution III	class of pollution IIIand above, with air humidity ＞60%	class of pollution III and above, with air humidity ＞80%

4 Repairable fault model

Repairable model adequately quantizes information such as on-line monitoring, maintenance record, routine test. It puts particular emphasis onaffect repairable fault on equipment failure rate. But this model can acquire the mean value of failure rate under all kinds of health status on the statistical areas only through method of inversion. Therefore, failure rateassessment of individual equipment has a relative high error rates. Meanwhile, it is incapable to response the potentialdevelopmentlaw of gradually increasing weight for nonreciprocal aging fault during the degradation period[8,11,12].

The repairable fault also has an influence on health status, as shown in Fig. (3).

The original data of repairableparameters are from on-line monitoring, maintenance record, routine test and defect management situation by means of data mining analyze, and the details are put as bellow:

On-line monitoring information: the concentrations of the dissolved gases in transformer oil, partial discharge, dielectric loss, capacitance, etc.[13]

Maintenance and test information: oil quality test, routine experiment, diagnosticexperiment and routing inspection.

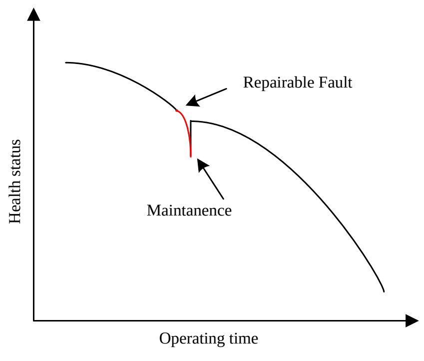

FIGURE 2 The influence of repairable fault

Defect managementsituation: defect property, defect type, defect details.

The health status computing methods of the three kinds of information are shown in reference [14], here it is needless to take up particularly. The variation tendency scores are acquired by several recent monitoring data. They are imports of grey prediction method, and forecast the parameter value of next sampling instant. The predicted value is imported into the evaluation model to acquire the health status score. The relationship

The comprehensivegradedresults of transformer health status include four types:

S_o: evaluation total points of on-line monitoring information (maximum score is 1)

S_m: evaluation total points of maintenance and test information (maximum score is 1)

S_t: evaluation total points of variation tendency on monitoring and test information (maximum score is 1)

S_d: evaluation total points of defect management situation (maximum score is 1)

5. The comprehensive health status evaluation of oil-immersed transformer and defective work condition correction

5.1. THE QUANTITATIVE EVALUATION OF THE COMPREHENSIVE HEALTH STATUS

The flow diagram of oil-immersed transformers health status evaluation is shown in Figure (4).

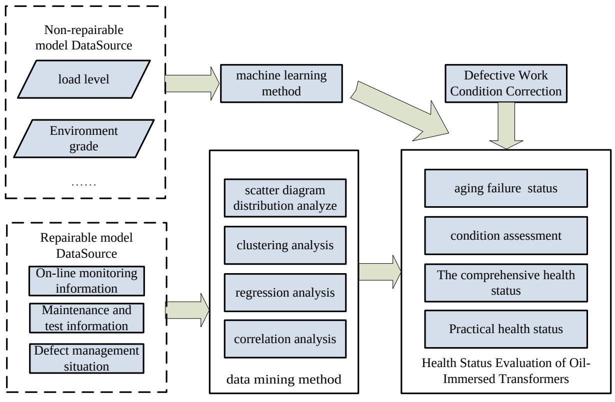

FIGURE 3 The flowdiagramof oil-immersed transformers health status evaluation

The load level and circumstance grade in non-repairable modelare divided into five levels, which sketchy regard the five levels as 100, 80, 50, 30, 10 scores corresponding tohundred-mark system.The aging failure total weighted average points the sum of the values, but each weighted by a certain coefficient.The temperature rise caused by load rate is primary cause of aging, therefore, it is recommended that the weight allocate to 0.8, and the weightof circumstanceallocate to 0.2, as shown in Eq. (1).

$$S_A = 0.8S_l + 0.2S_e \quad (1)$$

The synthesis scoreof repairable model is gained as

$$S_M = \omega_o S_o + \omega_m S_m + \omega_t S_t + \omega_d S_d , \quad (2)$$

ω for respective weight, S for relevant score.

The comprehensive healthstatus score is shown as

$$S_H = \omega_A S_A + \omega_M S_M . \quad (3)$$

5.2. DEFECTIVE WORK CONDITION CORRECTION

The life of transformer insulation is a time function with three factors such as temperature, water content and oxygen content. The impact of insulation life greatly reduced when the water content and oxygen content in transformer are effectively controlled, so the temperature becomes the leading factor influencing life of transformer insulation. What's more, the internal temperature distribution of transformer is uneven, the higher the temperature, the faster the speed of aging, so the hot-spot temperature of transformer windings is the most significant impact on loss of insulation life[15].

A large number of experimental results indicate that the life of transformer insulation and the hot-spot temperature of windings θ_h following the Arrhenius law[16,17], which can be calculated by Eq. (2).

$$L_{pu} = A\exp(\frac{B}{\theta_h + 273}) . \quad (4)$$

Where L_{pu} is the per unit value about the life of transformer insulation, which is the ratio between the actual life of insulation and the normal life of insulation. A, B are constant.

The reference value of the hot-spot temperature is 110°C, and the values of A and B are given respectively for A=9.8×10-18, B=15000, according to IEEE C57.91-1995. The accelerated aging factor F_{AA} is also defined when the load factor and the environment temperature are given as Eq. (5).

$$F_{AA} = \exp(\frac{1500}{383} - \frac{1500}{\theta_h + 273}) \quad (5)$$

$F_{AA} > 1$, When the hot-spot temperature is greater than 110°C. The formula is used to calculate the accelerated aging factor F_{EQA} when the time and the temperature cycle are given, with the transformer running under the reference temperature, which is got according to Eq. (6).

$$F_{EQA} = \frac{\sum_{n=1}^{N} F_{AA_n} \Delta t_n}{\sum_{n=1}^{N} \Delta t_n} , \quad (6)$$

Δt_n in the formula is the length of time in the n st monitoring period, which calculated in hours. F_{AA_n} is the accelerated aging factor in Δt_n. So the value of the accelerated aging factor is gain.

L_n, the statistics value about the life of transformer, will be 180000h if the transformer runs normally under the reference temperature and in dry, oxygen-free environment. The rate of life loss $L\%$ in monitor cycle t can be calculated by Eq. (7).

$$L\% = \frac{F_{EQA} \times t \times 100}{L_n} . \quad (7)$$

The equipment life distributes the health status to exponential rates-of-change, as shown in Fig 1. Therefore, the loss ratio of life caused by overload can be modified by decline degree of the health status, as shown in Eq. (8).

$$HI_2 = HI_1 \times e^{B \times (T_2 - T_1)} , \quad (8)$$

$$HI\% = 1 - e^{C \times (L\% - 1)} , \quad (9)$$

B,C are coefficients, $HI\%$ is the loss of HI.

Thus, the revised health status score is shown in Eq. (10).

$$S_H^{'} = S_H \times HI_h\% \times HI_s\% , \quad (10)$$

$HI_h\%$ is the loss ratio of life caused by overload, $HI_s\%$ is the loss ratio of life caused byshort circuit impact.

6 Results and discussion

Jiang Su Electric Power Company verified this model, and the result shows that: when health index is between 0.6 and 0.75, about 70% of the condition assessment results addict exceptional situation, but still merely breakdown; when health index is below 0.6, about 75% appears to have kinds of operational defects, a part of them need to shift loading to eliminate defects. The existing evaluation system wide spread used estimatedefect and fault by nothing but breaker tripping or manual observation. The condition assessment methods mentioned in the references are mostly used one-sided ones such as dissolved gas analysis. The buildup of most models is on the basis of idealdata sources, and the data missing is one of important issues in reality. These consequences indicate that the model of this article have reliable data sources as well as comparatively com pre hen sive evaluation results, and moreover, the accuracymeets requirements.

7 Conclusion

This paper proposes a comprehensive health assessment new model for oil-immersed transformer, which is based on the irreversible (aging) and repairable fault information. This new model puts the equipment operation management information associated with health status, health status is introduced into the aging failure model, thus, this new method reflecting health status are realized from the angles of development of aging and condition assessment. This paper also makes consideration on the comprehensive health status value affected by the short circuit impulse and emergency load, presents a calculating method for the damage degree, which improves the accuracy of the model.

Acknowledgements

We thank Jiang Su Electric Power Company for offering the test data of the model, and Professor Lu Yun-cai and Professor Du lin for critical reading of the manuscript. The project was supported by JiangSu Electric Power Company Research Institutes, respectively.

References

[1] ChinaElectricityCouncil.China electric powerindustrystatistical-report (2006-2011)[EB/OL].http://tj.cec.org.cn/tongji/niandushuju/2012-01-13/78769.html.
[2] State Electricity Regulatory Commission Power Reliability Management Center. In 2005-2011China electric power reliability index[EB/OL].http://www.chinaer.org/list.aspx?m=20100424125434250110.
[3] Jahromi A, Piercy R,Cress S, et al. An Approach to Power Transformer Asset Management Using Health Index[J]. IEEE Electrical Insulation Magazine, 2009, 25(2): 20-34.
[4] Zhang Jing Ping. Evaluation of Health Condition for Electric Power Equipment Based on the Preventive Test Result [D]. Beijing: master degree theses of master of north China electric power university, 2004.
[5] ChenFa-guang, Zhou Bu-xiang, ZengLan-yu, State Evaluation Model of Transformer Operation Based on Multi-information Fusion [J], Proceeding of the CSU-EPSA, 2013,25(4):140-144
[6] Hughes D. Condition based risk management (CBRM) -enabling asset conditioninformation to be central to corporate decision making[C]// Proceedings of the 18thInternational Conference and Exhibition on Electricity Distribution. Turin,Italy: IEEE, 2005: 1-5.
[7] He Jian, Cheng Lin, Sun Yuan-zhang. Transformer real-time reliability model based on operating conditions[J]. Journal of Zhejiang University: Science A, 2007,8(3): 378-383.
[8] Zhang Xiang. Failure rate model and overload capability of oil-immersed transformers[D]. Hangzhou: Zhejiang University, a master's degree thesis, 2013.
[9] He Jian, Cheng Lin, Sun Yuan-zhang, Wang Peng. Condition Dependent Short-term Reliability Models of Transmission Equipment[J]. Proceedings of the CSEE,2009, 29(7): 39-46.
[10] Wang You-yuan. Study on condition maintenance decision making method of power transformer based on reliability and risk evaluation[D]. Chongqing: Chongqing University, 2008.
[11] Wang Hui-fang, Yang He Juan, He Ben Ten. Improvement of State Failure Rate Model for Transmission and Transforming Equipment[J].Automation of Electric Power Systems, 2011, 35(16): 27-31.
[12] Anders G,OtalS,Hjartarson T. Deriving asset probabilities of failure: effect of conditionand maintenance levels[C],Power Engineering Society General Meeting. Montreal,Quebec. Canada: IEEE, 2006: 1 -7.
[13] The state grid corporation of China.Q/GDW 169-2008 Oil-immersed transformer (reactor) state evaluation guideline[S]. Beijing: China Electric Power Press,2008.
[14] Hu Cheng-Bo, Tao Feng-Bo, Lu Yun-Cai, et al. Life Estimation of Power Transformers Based on Information Management System[J]. Information Technology Journal: 2013,12(17): 3986-3990.
[15] Yang Li-jun. Study on aging characteristic of oil-paper in transformer and its lifetime estimation method[D]. Chongqing: Chongqing University, 2009.
[16] IEC 60076-7–2005 Power transformers - Part 7: loading guide for oil-immersed power transformers[S].
[17] IEEE Std C57.91–1995 IEEE guide for loading mineral-oil-immersed transformers[S].

Authors

Wei Chao, 1984.12, Laiwu,Shandong Province of China

Current position, grades: Engineer.
University studies: High voltage technology
Scientific interest: Transformer condition assessment and diagnostic techniques.
Publications: 5
Experience: Since 2010 July, working in Jiangsu Electric Power Company Research Institute

Hu Chengbo, 1984.6, Xinyu, Jiangxi Province of China

Current position, grades: Engineer.
University studies: Electrical machinery and appliance.
Scientificinterest: Condition assessment of electrical equipment
Publications number or main: 6
Experience: Gain master's degree of Xi'an Jiaotong University in 2011. Work in Jiangsu Electric Power Company Research Institute since 2011.7.

Tao Fengbo, 1982.6, Changzhou, Jiangsu Province of China

Current position, grades: Senior engineer.
University studies: High voltage technology.
Scientificinterest: Condition assessment of electrical equipment
Publications number or main: 13
Experience: Gain doctor's degree of Xi'an Jiaotong University in 2009.Work in Jiangsu Electric Power Company Research Institutesince 2009.7.

ChenBijun, 1990.1, Xingyang, Henan Province of China

University studies: High voltage technology.
Scientific interest: Transformer condition assessment and diagnostic techniques.
Publications: 3
Experience: Since 2012 September, studying in State Key Laboratory of Power Transmission Equipment & System Security and New Technology, School of Electrical Engineering, Chongqing University.