Condition Assessment for Power Transformer Using Health Index

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Abstract. To improve the forecasting accuracy and ensure reliable and stable operation of transformer, based on health index estimation model is proposed. The transformer data is divided into different levels and parts, so multi-parameter statistical analysis is carried on. The indicator system is scored and weighted by computing history data (inspection and maintenance, family defects, basic information and loading history) and condition data (such as routine test data). The condition parameters, which are classified on the component level, are scored and weighted, using statistical tools calculation. By using the statistical tools SPSS (statistical product and service solutions), multivariate statistical analysis was carried out. On the basis of studying the relationship between various parameters, a health evaluation model, which is based on contribution analysis, is presented. A condition-based evaluation tool, that quantifies power transformer degradation and clarifies the relationship between each health index, is put forward. Results are presented to verify the validity and feasibility of evaluating model and assessment algorithm. This paper provides a scientific method for the transmitting and transforming field.

1. Introduction

As the vital power grid equipment, power transformer, which is the most expensive and important equipment, is crucial for safe and stable operation of power system. Each year, huge direct and indirect losses are causes by the scheduled outages maintenance, and its social impact is difficult to measure. In order to find the defects of power transmission and transformation equipment accurately and efficiently, to reduce the failure rate and the operation risk, at present, the state overhaul of ways at home and abroad. This way of maintenance depends on scientific and comprehensive evaluation index system and calculation method. Therefore, the health status evaluation for power transformer, power transmission and transformation equipment is an important link in the whole process of full life cycle assessment [1-4].

Some of studies regard the characteristic parameters of transformer oil as the main characteristics, to evaluate transformer insulation aging life, however, the health index system involving many multivariate, five key components reflects the characteristics of the transformer health parameter. In particular, transformer evaluating data is divided into three categories, according to the basic information, routine tests and operating data.

Weight is assigned to each variable factor, on the basis of statistical tool and industrial standards, and then amended by experienced maintenance professionals and experts. The global health index is calculated by scoring and weighting each factor, by quantitative and objective method.

In this paper, based on the statistical tools, the relationship between the various parameters of transformer and the contribution values for global health index are deduced and health index calculation process is given. The conventional assessment methods usually focus on single or limited aspects of transformer. Compared with those methods, condition assessment using method is quantitative and comprehensive.

2. Brief review of transformer characteristics and scoring

In order to assess the power transformer health condition, first of all, index system should be constructed. The characteristics of transformer health include electrical properties, chemical properties, mechanical properties and appearance. From the component level, five parts are divided, which are active part, bushing, tap-changer and non-electricity protection, cooling system. In the evaluation, each part proportion is reflected by final health index calculation.

2.1. Test of oil-paper insulation system

Due to the effect of electricity and heat, and along with too much oxygen, moisture, oil-paper degrades. Because the oil-paper degradation results in aging substances (such as CO, CO_2, furfural, etc.), health condition can be assessed by substances and degree of polymerization of insulation paper [5-7].

2.1.1. Degree of polymerization of insulation paper. Polymerization degree reflects the tensile strength of the mechanical properties of paper. As the application of new materials, polymerization degree criterion will also be updated. At present, it is generally believed that the degree of polymerization of oil-paper of the new transformer is mostly at around 1000. Paper insulation polymerization degree criterion is shown as in table 1.

Table 1. Limit of the degree of polymerization of insulation paper

DPV	$>$500	500~250	250~150	$<$150
Advice	good	operation	attention	bad

2.1.2. Furfural . In the process of degradation of paper-board, macromolecular of cellulose degrades and the main oxygen heterocyclic compounds. While transformer is operating, the influencing factors of furfural content are several aspects, including the proportion of oil-paper, and the manufacturing technique, the running time of transformers, operating conditions, load rate, transformer oil processing mode. Transformer insulation aging local overheating, overload and other failure can also cause furfural content increasing. Furfural content could be measured by transformer oil samplings. Low content indicates that oil-paper of transformer with high intensity, good performance, and the transformer is in good condition [7, 8].

2.1.3. Dissolved gas analysis. Dissolved gas analysis is a widely used kind of fault monitoring and prevention methods. Transformer oil and oil-paper insulation system are under the effect of electric heat stress for a long time, so the molecular structure changes. A series of chemical reactions cause all kinds of gas, such as hydrogen, hydrocarbon, hydrocarbon.

Development at home and abroad a number of ways and can be used for judging the proportion of dissolved gas in transformer oil to judge the transformer internal fault, such as: overheating, poor electrical contact, partial discharge, etc. The rapid degradation of $CO/CO_2 < 5$, which indicates that the paper. The $CO_2 / CO > 7$, shows that insulation aging or large overheating fault in low temperature. Transformer failure occurs, of course, transformer oil will decompose the CO and CO_2 gas. Transformer oil degradation or failure can be summed up in transformer health, therefore, consideration of CO and CO_2.

2.2. Operating data and routine test

Equipment basic information includes the rated quantities, voltage grade, rated power and short-circuit impedance of a pair of windings, etc. Routine test including dc resistance of winding, dielectric loss factor and capacitance, frequency response test, insulation resistance, absorption ratio or polarization-ability factor, leakage current and so on, whether meet the requirements of technical regulations [9-13]. Some of operating data and routine as follows:

Defect data includes both the device itself and family defects. The defect record should contain operational patrol, inspection patrol, online detect and the defect that was found in the process of inspection, and its classification and measures. In the past 12 months, monthly history records of maximum load, overload or emergency load for a long time, would make the transformer performance degrade. Infrared thermal image could detect transformer ontology, wire connectors and cable terminal. Infrared thermal image shows should have no abnormal temperature, temperature difference and/or the relative temperature differences, can reveal the transformer internal hidden defect. The appearance inspection mainly referring to patrol records: equipment intact appearance, lead and bus-bar, joint is normal; Grounding is reliable; Noise and vibration; Whether air duct system is smooth or not, etc.

2.3. The transformer components

Transformer evaluation important part of health, including core insulation, winding, leakage current, dielectric loss, short-circuit impedance and oil test, infrared temperature test and daily inspection data: appearance, short-circuit current, the leakage of oil, and so on. The transformer bushing evaluation, which includes gases dissolved in transformer oil, infrared temperature measurement, dielectric loss, insulation resistance, external insulation distance, meets the requirements. The operational record of tap-changer, includes oil leakage, sliding gear of tap body, switching frequency, whether online oil filter devices pressure abnormal or not, and the gases dissolved in oil. Transformer cooling system mainly refers to the daily inspection, motor fan operation, whether cooling devices surface is clean or not, air duct is without any foreign body or not, whether there is leakage of oil, water, whether the controller is normal or not. Non-electricity protection includes gas motion, pressure release valve, oil temperature and oil level and etc.

Single test data could reflect certain aspects of the transformer performance, while comprehensive test results and related defect information is necessary for accurate assessment of transformer health condition. Based on health index, this article collects and processes the record of equipment basic information, field operating record, and routine test results. Weight allocation reflects the impacting extent of each parameter on the transformer health condition. Weight is assigned by statistical tool and industrial standards, and corrected by experienced maintenance professionals and experts[14-18].

3. Multivariate analysis based on statistical tools

3.1. Data normalization

The important assumption is that the data conforms to normal distribution in the multivariate analysis, while testing results usually don't fit standard normal distribution. First of all, using SPSS tools, non-normal data would be transformed to normal data. SPSS is a statistical analysis tool, which could facilitate data docking, with built-in VBA language and powerful statistical processing. If the original data   is beyond the abnormal high value, it will be ignored in the multivariate analysis. The outlier would be preprocessed, and the abnormal value, which was caused by transformer fault, should be retained.

3.2. Public factor analysis

The correlation between different testing results may be unknown. By public factor analysis method, the relevance of each variable could be determined. Using SPSS tools, this paper carried out a statistical analysis on test results, it is concluded that the connection between the various testing items and public factors impact on individual items.

Figure 1 shows the test results, and x1~x12 represent the influence on the result of the test, while some factors is not quantitative, such as environmental temperature and humidity, electromagnetic environment interference, measure error, etc. F1~F5 mean public factors, they are associated with each variable, the higher the relevancy degree is, the larger the coefficient value. F1~F5 stand for the association degree between each other, which is expressed by a double sided arrow.

3.3. Public factor correlation analysis

In the evaluation of power transformer health condition, the performance of oil-paper insulation system is one of the most important indicators. Usually, the life of oil-paper insulation system directly determines the life of oil-immersed transformer. Therefore, this article mainly collected 87 groups of transformer oil sample test data, and conducted statistical analysis. Firstly, the relationship between the various parameters is studied, and secondly, it is concluded that the evaluation index by evaluating the contribution values of transformer.

As shown in figure 1, those items, which are similar to chemical properties and reactivity, are divided into one group. Under the condition of electricity and heat, oil-paper aging degradation or transformer failure occurs, meanwhile the oil decomposes raw chemical products, such as CO, CO_2. The higher impurities and moisture content of transformer oil is, the more likely it is to puncture. The parameters which have close connections, are divided into the same group. H_2, CH_4 and C_2H_6 are a group of highly correlated parameters, and those are related to public factor C3.

C2 and C3 have the strongest correlation and its correlation coefficient is 0.53; Times of correlation between C1 and C3, correlation coefficient is 0.47; C4 and C5 is negative correlation. In order to further determine the weight and health index, this paper analysis the relationship between characteristic parameters and public factors.
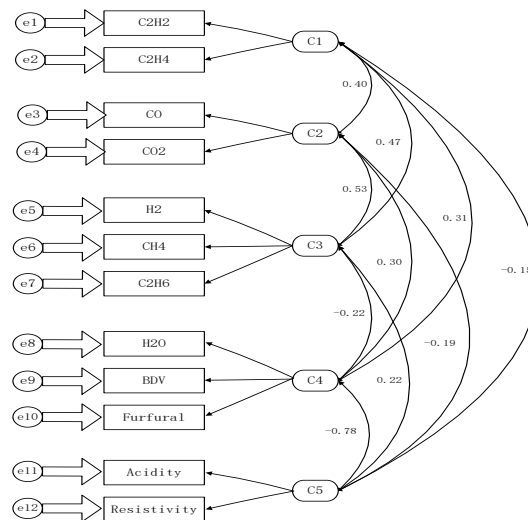

Figure 1. The degree of the correlation between the factors.

4. Transformer health index evaluation model

Transformer health index calculation steps mainly as follows:

- Based on the analysis of the factors in public relations, public factor analysis of health index HI contribution value;
- Determine the weight of health index;
- According to expert experience and standard, make correction factor;
- Amend the weight after modifying factor;
- Obtain the health index and evaluate the transformer overall health.

Among them, the first step is the key step, based on the analysis of contribution to the health index evaluation model as shown in figure 2.

Based on the analysis of the contribution to health index, the evaluation model is shown as figure 2.

As shown in figure 2, C4 has the largest influence on transformer's health, including the three parameters: the breakdown voltage, furfural, moisture content, therefore, the highest weight is given to C4 in the evaluation system. Moisture in the transformer oil, plays an important role in the transformer insulation performance degradation process. To a certain extent, furfural content reflects the performance of transformer oil paper insulation system. The higher furfural content is, the worse performance of insulation is. Based on the statistical analysis, the grouping and weight is consistent with the existing conclusions. In the transformer condition evaluation, the weight allocation need correction. In the end, the weight of each major projects and health index of HIF are obtained[19-21].

According to the different components, computation formula, which is used to assess the health condition of power transformer, is as the formula (1).
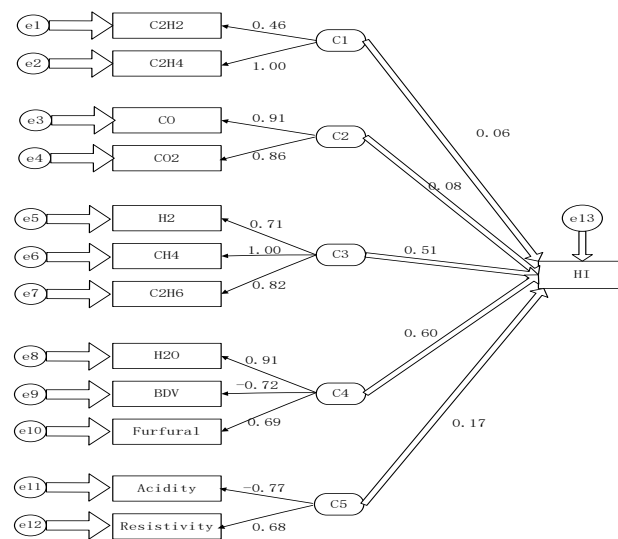

Figure 2. The HI estimate model on contribution degree analysis.

$$(\%)HI = \left(\begin{array}{c} 0.5\dfrac{\sum\limits_{i=1}^{i=12}(K_i * HIF_i)}{\sum\limits_{i=1}^{i=12}(HIF_{max} * K_i)} + 0.2\dfrac{\sum\limits_{i=13}^{i=16}(K_i * HIF_i)}{\sum\limits_{i=13}^{i=16}(HIF_{max} * K_i)} + 0.1\dfrac{\sum\limits_{i=17}^{i=17}(K_i * HIF_i)}{\sum\limits_{i=17}^{i=17}(HIF_{max} * K_i)} \\ +0.1\dfrac{\sum\limits_{i=18}^{i=21}(K_i * HIF_i)}{\sum\limits_{i=18}^{i=21}(HIF_{max} * K_i)} + 0.1\dfrac{\sum\limits_{i=22}^{i=22}(K_i * HIF_i)}{\sum\limits_{i=22}^{i=22}(HIF_{max} * K_i)} \end{array} \right) *100\% \qquad (1)$$

K_i is weight, HIF_i means the health index, HIF_{max} means the health index in best condition[9, 22]. The health index scale is shown as table 2. Based on the health condition of transformer, the health index is divided into five classes.

Table 2. The Health Index Scale

HI（%）	Health condition of transformer	Measures
85~100	perfect	Normal operation
70~85	Very good	Normal operation
50~70	Good	Keep watch
30~50	bad	Close to the weight allocation，enhanced surveillance，and arrange outage maintenance in due time
0~30	Very bad	Over the standard limit, to arrange outage maintenance as soon as

	possible

5. Multivariate analysis based on statistical tools

110kV Zhengyang station #2 main transformer, which specifications is SZ10-50000/110, 110 kV voltage class, 50 MVA capacity, self-cooling, Shandong Luneng Taishan power equipment co., LTD., was brought into operation in April 1994, running for 22 years.

220 kV Baodu#2 main transformer, which specifications is SFPSZ9-150000/220, 220 kV voltage class, 150 MVA capacity, Shandong electric power equipment co., LTD., was brought into operation in April 2002, running for 14 years.Two transformer operation and test data are shown in table 3.

Table 3. Operation and Measurement Data of Power Transformer

	Type	Load history	Defect	DC.Resistance ,variance ratio	Winding insulation resistance R15S/R60S(MΩ)	Absotption ratio of insulation resistance	Bushing diselectric loss	Main insulation resistance (MΩ)
1	SZ10-500 00/110	normal	serious/2	1.40%	49.8/53.3	1.24	2.575%	10000
2	SFPSZ9-1 50000/220	normal	serious /1	1.22%	1500/2500	1.53	0.35%	10000

As in the table 3, (1) stands for Zhengyang station #2 main transformer data, by using the formula (1), calculated HIF % of 110 kV Zhengyang station #2 transformer is 49.182, in the range of 30% ~ 50%. It can be seen that the overall performance is poor, close to or slightly over the standard limit, which should be monitored and arranged outage overhaul in the due time. The overall state of equipment: hydrogen exceeds limits greatly, and hydrogen accounting for over 90% of the total hydrocarbon, and total hydrocarbon exceeds limits, CH_4 accounting for over 75% of the total hydrocarbon, judging criterion for partial discharge characteristics of gases. Three ratio method code is 010, judged to be partial discharge [23, 24]. High voltage neutral bushing dielectric loss exceeds limits, and electric capacity is close to the alarm value, in the main transformer normal routine test. In conclusion, the equipment's overall performance is poorer, and close to equipment scrapping. Thus, it is concluded that the calculated value can fit the actual situation well based on health index method.

In order to verify the validity of the model, we conducted a comprehensive main transformer selection of different voltage grade, different working conditions and with different defects, at 220 kV Baodu station, which serial number (2) standing for its basic information and test data. Compared with the case one, although it also has a defect, but with different nature, and the test data also greatly different from each other. By the model, calculated HIF is 78.052, which shows that the equipment runs in good condition. The practical operation condition: the transformer has been run for 14 years, the indicators were basicly normal, bad working condition didn't occur. Although the cooling system had serious defects, it has been eliminated already. The evaluation results can be seen with the actual results match well.

6. Conclusion

Based on analysis of index system for power transformer, and using SPSS statistical tools, hierarchical health index model is proposed. Meanwhile, 87 groups sample test data of transformers were analyzed, and the relationship between various factors and parameters and the contribution of total health index value were studied. Using SPSS statistical tools for weighted index system, health index calculation model is established. In the future the research can be applied to the field of power transmission and transformation equipment evaluation field. Finally, taking an operating transformer of Shandong power grid as an example, both the effectiveness of the proposed evaluation model and calculation method is proved.

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