The Power Transformer Operating Condition Evaluation Based on the Genetic Projection Pursuit Model

Yue Hua¹, Yuanyuan Sun¹,a, Na Li¹, Shuo Ma¹ and Erdong Wang¹

¹School of electrical engineering, Shandong University, Jinan 250061, China.
aCorresponding author e-mail address: sunyy@sdu.edu.cn (Yuanyuan Sun).

Abstract: Transformer is a key equipment in the power system, and it is very important to accurately evaluate its operating state. In this paper, a new method is proposed to evaluate the operating state of the power transformer based on the genetic projection pursuit model. The proposed method can provide a more objective evaluation result for the health condition of the transformers compared with the traditional methods. Firstly, a three-layer evaluation index system is established with the precautionary test, oil chromatographic analysis and insulating oil properties as the core content. And then, the grading standard of the lowest level index in the indicator system is established. Secondly, the genetic projection pursuit model is used in combination with the grading standard to obtain the intermediate layer evaluation results, which overcomes the disadvantages of the traditional transformer evaluation method which is greatly influenced by subjective factors. Finally, the eigenvalue weighting method is used to integrate the intermediate layer evaluation results to obtain the final result. Case study results show that the evaluation method of transformer operating state based on genetic projection pursuit model is reasonable and effective.

1. Introduction

Power transformers are the key power transmission and transformation equipment in the power grid. It is of great significance to accurately assess the operating states of the power transformer and adopt a reasonable and effective operation and maintenance strategy in a timely manner in order to ensure the reliable operation of the power grid and national energy security [1].

For a long time, one of the main goals of the transformer researches is to evaluate the transformer operating conditions objectively and reasonably. References [2]-[4] uses fuzzy mathematics, Bayesian networks, cloud theory, etc. to comprehensively evaluate the power transformers, which makes a useful exploration for the quantitative evaluation of transformer states. However, when using the above methods for comprehensive evaluation, they are largely influenced by subjective factors. Due to the large uncertainty of human factors, the correctness and credibility of the evaluation results will be greatly affected [5,6].

In view of the above problems, this paper proposes to use the genetic projection pursuit model to assess the transformer operating conditions. Firstly, the method establishes a three-layer evaluation index system according to the actual project, and uses the genetic projection pursuit model to evaluate the lowest level indicators to obtain the intermediate layer evaluation results. Then, the eigenvalue weighting method is used to further synthesize the intermediate layer evaluation results, so as to obtain the evaluation result of the current state of the power transformer. The evaluation process is not
affected by human factors, and the obtained evaluation results fully reflect the operation states of the power transformer.

2. Power transformer comprehensive evaluation index system
Selecting the indicator information that can comprehensively and effectively reflect the real operating state of the transformer and establishing a scientific and objective state evaluation index system is the premise of establishing a correct and reasonable state assessment model, and is also a prerequisite for the state assessment of power transformers.

In order to make the evaluation index comprehensively and truly reflect the operating state of the transformer, the selection of indicators follows the principles of scientific principle, feasibility principle, comprehensiveness, system and hierarchy, and the combination of qualitative and quantitative [5]. Finally, the power transformer state evaluation index system shown in Figure 1 is established. The system is divided into three layers, which are the target layer, the middle layer and the indicator layer.

3. Evaluation of indicator layer states based on genetic projection pursuit model
The research focus of the comprehensive evaluation of power transformers is how to integrate the multi-indicator problems into a single indicator problem scientifically and objectively, that is, how to convert the high-dimensional space points composed of individual indicators of power transformers into the mapping problem of low-dimensional space.

The basic principle of projection pursuit is to project high-dimensional data in a certain direction through some combination. The flow chart of comprehensive evaluation of power transformer index layer based on genetic projection pursuit method is shown in Fig. 2.

3.1. Classification of power transformer evaluation indicators
In this paper, each individual indicator of power transformer is divided into three levels. Level 1 means that the power transformer is in good operating condition; level 2 means that the transformer needs attention, and in this level the power transformer has an abnormal state. Relevant personnel should come to check the operating condition of the power transformer. Level 3 means that the transformer is in a bad or serious operating condition. In this level, the operating state of the power
transformer is seriously deteriorated, and its situation is serious, requiring maintenance. The grading standards for each indicator are shown in Table 1. The establishment of other indicators is similar to those shown in Table 1, and will not be repeated.

Table 1. Insulating oil characteristic index and its grading standard

| Level   | Good      | Attention | Serious |
|---------|-----------|-----------|---------|
| H_2     | ≤ 50      | 50-160    | ≥ 160   |
| C_2H_2  | ≤ 6       | 6-10      | ≥ 10    |
| Total   | ≤ 0.08    | 0.08-0.2  | ≥ 0.2   |
| Hydrocarbon (10^-6) | ≤ 80 | 80-180 | ≥ 180 |
| Production rate | 8-12 | 12-80 | ≥ 12   |

3.2. Genetic projection pursuit state evaluation model

Using the projection pursuit method to comprehensively evaluate the power transformer, an objective function should be first established to describe the characteristics of the projection index. The main steps of objective function establishment are summarized as follows: ① According to the classification standard obtained in Section 3.1, the projection index is established by random value in each level range, thereby forming a sample set, where in each individual indicator normalized by the Equation (1) is a corresponding evaluation level; ② using the Equation (2) to integrate the projection index into a one-dimensional projection value as a projection direction; ③ Equation (3) establishes a projection objective function.

\[
x(i,j) = x^*(i,j) / x_{max}(j), i=1,2,...,n, j=1,2,...,m
\]

\[
z(i) = \sum_{j=1}^{m} a(j)x(i,j), i=1,2,...,n, j=1,2,...,m
\]

\[
f(a) = S_z \left| R_y \right|
\]

\[
S_z = \left[ \sum_{i=1}^{n} (z(i) - E_z)^2 / (n-1) \right]^{1/2}
\]

\[
R_y = \frac{\sum_{i=1}^{n} [z(i) - E_z][y(i) - E_y]}{\left\{ \sum_{i=1}^{n} [z(i) - E_z]^2 \sum_{i=1}^{n} [y(i) - E_y]^2 \right\}^{1/2}}
\]

In order to unify the range of indicators, the individual indicators \(x^*(i,j)\) of the power transformer are normalized \(x(i,j)\) using equation (1). Where \(n\) and \(m\) are the number of samples and the number of indicators, respectively, and \(x_{max}(j)\) is the maximum value of the \(j\)th indicator.

Based on (2), the dimensional data \(x(i,j)\) is integrated into a one-dimensional projection value \(z(i)\) as the projection direction \(a = (a(1), a(2),..., a(m))\), thereby establishing a mathematical relationship between the power quality assessment index \(x(i,j)\) and the evaluation level \(y(i)\).
In equation (3), \( S_Z \) is the standard deviation of \( z(i), \) and \( R_{zy} \) is the correlation coefficient between \( z(i) \) and \( y(i). \) The expression is as shown in equations (4) and (5), where \( E_z \) and \( E_y \) are the mean values of the sequences \( \{z(i)\} \) and \( \{y(i)\}, \) respectively. To show that this projection contains structures that are not reflected in the existing model, the projection value \( z(i) \) should extract the variation information in \( x(i,j) \) as much as possible, \( S_Z \) and \( |R_{zy}| \) should be as large as possible.

The projection objective function \( f(a) \) changes as the projection direction \( a \) changes, and the optimal projection direction can be estimated by solving the maximum value of the projection objective function, that is,

\[
\max f(a) = S_Z |R_{zy}|
\]

\[
s.t \sum_{j=1}^{n} a(j)^2 = 1, 0 \leq a(j) \leq 1
\]

This is a nonlinear optimization problem with \( a = (a(1), a(2), \ldots, a(m)) \) as the optimization variable. It is difficult to be solved by the conventional methods. Genetic algorithm is a general global optimization method, which can solve the above problems simply and effectively.

Substituting the best projection direction \( a^* \) obtained in Section 3.2.1 into equation (2) gives the projection value \( z^*(i) \) of the \( i^{th} \) sample. According to the scatter plot composed of \( z^*(i) \) and \( y(i) \), a mathematical model of the comprehensive evaluation of the power transformer can be established so that the evaluation result can be obtained.

**4. Middle layer state evaluation based on eigenvalue weighting method**

The key to the eigenvalue weighting method is to construct a reasonable comparison judgment matrix according to the actual situation, so as to achieve the purpose of reasonably reflecting the actual situation. The basic idea is described in [5]. The comparison judgment matrix is defined as: if the elements in the matrix \( N \) satisfy

\[
n_y > 0, i=1,2,\ldots,m
\]

\[
n_y = 1, i=1,2,\ldots,m
\]

\[
n_y = 1/n_y, i=1,2,\ldots,m
\]

Then, \( N \) is the comparison judgment matrix, where \( m \) is the number of evaluation indicators. Mathematically, the matrix \( N \) satisfying the equations (8) to (10) is a consistency matrix, and the normalized non-negative eigenvector corresponding to the eigenvalue \( \lambda_{max}(N) = m \) is called the ranking weight vector. According to the basic idea of the eigenvalue method, the weighting coefficient of the evaluation index is the normalized eigenvector \( w = (w_1, w_2, \ldots, w_m)^T \) corresponding to the eigenvalue \( m \) of \( N \).

**5. Case Study Results**

A precautionary test of a power company's transformer SFSZL7-31500/110 was conducted on April 20, 2015 and September 25, 2017 to evaluate the states of the main transformer. The \( H_2 \) content(volume fraction) is 9.65×10^{-6}, 40×10^{-6} . \( C_2H_2 \) content(volume fraction) is 0.3×10^{-6} .Total hydrocarbon content(volume fraction) is 5.58×10^{-6}, 80×10^{-6} .DC resistance phase difference is 0.53%,0.52%.Insulation resistance is 10000MΩ , 16500MΩ . Absorption ratio is 1.2,1.4. Leakage current is 19μA , 13μA .Dielectric loss is 0.18%, 0.20%.Core grounding resistance is 10000MΩ , 21000MΩ . Oil in water is 5×10^{-6}, 5×10^{-6} .Oil loss is 1.48%,1.8%.

- (1) Establishment of the projection indicators
First, according to the rating principles similar to Table 1, the projection indexes are randomly generated in each level and normalized to form a sample set. For each intermediate layer evaluation, 300 samples are generated. The sample includes the index $x(i,j)$, that is, the normalized individual indicators, and the corresponding evaluation level $y(i)$.

- (2) Establishment and optimization of the projection objective function
  After several experiments, the parameters of the last selected genetic algorithm were: population size $N=400$, hybridization probability $P_c=0.8$, mutation rate $P_m=0.2$, and acceleration number $C_i=15$.
  After optimization by genetic algorithm, the best projection direction of the indicators under each intermediate layer can be obtained. Taking oil chromatography analysis as an example, the optimal projection direction is $a_i^*=[0.4620, 0.3617, 0.4612, 0.3774, 0.4185, 0.3542]$.

- (3) Genetic projection pursuit model for comprehensive evaluation of power transformers
  Bring the best projection direction into (2), and obtain the scatter plot of the sample set. Take oil chromatographic analysis as an example. The result is shown in Fig. 3.

![Figure 3](image_url)

**Figure 3** the scatter plot between the projection value and the actual output value of insulating oil characteristic

Fig. 3 shows that the graph of $Z^*(i)$ and $y(i)$ is a stepped rising curve. A piecewise continuous function can be obtained by piecewise linear interpolation approximation of the curve. It can be seen from Fig. 3 that the piecewise continuous function corresponding to the scatter gram is as shown in (11).

$$y(i) = \begin{cases} 
1, & z^*(i) \leq 0.8034 \\
1+ (z^*(i) - 0.8034)/(0.8161 - 0.8034), & 0.8034 \leq z^*(i) \leq 0.8161 \\
2, & 0.8161 \leq z^*(i) \leq 1.9092 \\
2+(z^*(i) - 1.9092)/(1.9226 - 1.9092), & 1.9092 \leq z^*(i) \leq 1.9226 \\
3, & 1.9226 \leq z^*(i) 
\end{cases} \tag{11}$$

- (4) Comprehensive evaluation of power transformers using genetic projection pursuit model
  The test data is normalized according to equation (1) and multiplied by the optimal projection direction to obtain the results of Table 2.
Table 2. Intermediate layer evaluation result

|                    | 2015/4/20 | 2017/9/25 |
|--------------------|-----------|-----------|
| Oil chromatographic analysis | 0.51      | 1.3       |
| Precautionary test     | 0.22      | 0.21      |
| Insulating oil properties | 0.21      | 0.23      |

It can be seen from Table 2 that the test results on April 20, 2015, oil chromatographic analysis, high-voltage electrical test and insulating oil characteristics are all Level 1. For the test results on September 25, 2017, the oil chromatographic analysis is level 2, and the others are level 1. This is due to the fact that in the test results on September 25, 2017, the gas content showed a significant increase compared to the test results on April 20, 2015.

- (5) Middle layer state evaluation based on eigenvalue weighting method

Taking the test results on September 25, 2017 as an example, it can be seen from Table 2 that the evaluation results of the intermediate layer are 1.3, 0.21, and 0.23, respectively, and the comparison judgment matrix is established by using the evaluation level as shown in the formula (12).

\[
N = \begin{bmatrix}
1.3/1.3 & 1.3/0.21 & 1.3/0.23 \\
0.21/1.3 & 0.21/0.21 & 0.21/0.23 \\
0.23/1.3 & 0.23/0.21 & 0.23/0.23 \\
\end{bmatrix}
\]  \hspace{1cm} (12)

Using the "geometric mean" method, the eigenvector corresponding to the maximum eigenvalue of the comparison judgment matrix of equation (12) can be obtained, that is, the weight of each evaluation index is \( w = [0.74, 0.12, 0.14] \). It can be seen from the weights that when the level obtained by the genetic projection pursuit model is higher, the corresponding weight is also larger. That is to say, when the indicators of subordinates in a certain middle layer change significantly, people's attention will also be strengthened. This is in line with the objective actual situation and is more reasonable. Similarly, the intermediate layer weights of the test on April 20, 2015 can also be calculated, and the final transformer state evaluation results are obtained. The assessment result on April 20, 2015 is 0.39, the evaluation result on September 25, 2017 is 1.02. This is due to the obvious change of gas in the power transformer oil. The monitoring should be strengthened to maintain the safe operation of the transformer.

6. Conclusion

In this paper, the state of power transformer is evaluated by genetic projection pursuit model. Applying the algorithm to the actual state evaluation of power transformers, the case analysis shows that this method overcomes the deficiency of the traditional power transformer state assessment by subjective factors, and accurately reflects the influence of various indicators of power transformer on the state of power transformer.

Acknowledgments

This work was supported by The National Key Research and Development Program of China 2018YFB0904800.

References

[1] Liao Ruijin, Wang Youyuan and Liu Hang 2018 Research Status of State Evaluation Methods for Transmission and Distribution Equipment *High Voltage Technology* 44 3454-64.
[2] Liao Ruijin, Wang Qian and Luo Sijia 2008 Evaluation Model of Power Transformer Operation State Based on Fuzzy Comprehensive Evaluation Automation of Electric Power Systems 32 70-75.

[3] Zhao Wenqing, Zhu Yongli and Jiang Bo 2008 State evaluation of power transformer based on Bayesian network High Voltage Technology 34 1032-39.

[4] Zhang Yilie, Liao Ruijin and Yang Lijun 2012 Method for evaluating insulation state of power transformer based on cloud theory Transactions of China Electrotechnical Society 27 13-20.

[5] Liu Yingying, Xu Yonghai and Xiao Xiangning 2008 A New Method for Comprehensive Evaluation of Power Quality in Regional Power Grids Proceeding of the CSEE 28 130-136.

[6] Islam M M, Lee G and Hettiwatte S N 2018 Calculating a health index for power transformers using a subsystem-based GRNN approach IEEE Transactions on Power Delivery 33 1903-12.