An algorithm for prioritizing the maintenance of power transformers

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Abstract

This report presents an algorithm that takes into account power transformer (PT) technical conditions and their potential for failure risk assessment to help determine maintenance precedence. The technical condition integrated index is assessed through the weighted average of condition indexes determined by the results of PT traditional and special control methods. Each control type index is the three-dimensional space vector where the coordinates are next: X – damage seriousness, Y – damage development speed, Z – damage development duration. The traditional control method defect identification and coordinate determination are carried out by an expert system without any specialist participation. Risk failure assessment includes: damages of suppliers and to consumers of electricity; transformer design features; lifetime; ES transformer unit (system) failure potential. The PT unit failure potentials were calculated using the flows of failures and damage statistics of 350 reliable facts of PT damage accumulated by the ES for 20 years of operation. Firstly, priority ranking for serviceable transformer operational activities are excluded from the sample. Then there are calculated coordinates on each of the remaining transformers. It coordinates the points, which are marked by the PT plane. The plane includes three zones: additional scheduled inspections and emergency repairs. The ES ranks PT by the distance from the origin within each zone.
Keywords: power transformers, prioritized maintenance activities, assessment of technical condition, probability damage, risk of failure, weight indexes.

1 Introduction

Every enterprise has financial, personnel and time resource limitations. The necessary volume of technical service and maintenance (TSM) frequently

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exceeds the available company resources. Therefore the question of TSM actions order including equipment change is rather important for every company. The urgency of correct decisions increase because it becomes more difficult to provide the necessary reliability of equipment work in the conditions of prevailing equipment ageing over renovation. Furthermore, with the implementation of new technologies into the production, consumers lay financial claims to the low quality and unreliable energy supply against companies.

This report presents the solution of choosing order of necessary actions that takes into account the ranking of power transformer (PT) on technical conditions and possible consequences of their failures.

The given algorithm can be applied to different types of equipment but in this report we pay attention to PT. The algorithm is the twenty-year result of development and implementation of expert-diagnoses and informational system (EDIS) “Albatros” and the statistic collection of damaged equipment. At present the system EDIS is used at 367 workplaces in Russia and States of the former Soviet Union. There are collected more than 350 cases of PT damage development proved by the equipment unsealing in databases.

2 Russian experience of power transformers ranking on technical condition

In the article [1] it was offered to conduct PT ranking with the help of high qualified experts. They determine the necessary set of controllable parameters for PT expert-diagnostics. Next, the experts with high experience of analog work conduct ranking of PT range on the basis of expert-diagnostics results accounting characteristics of transformer construction and assessment of quality level and conditions of operation. The advantages of this approach are record of characteristic construction, level and condition of PT operation. Unfortunately, there are not enough high qualified specialists and that is why this approach is not rather efficient and does not allow encompassing the entire equipment range of Russia. Besides, an expert approach is more expensive than PT computer ranking.

In 2006–2007 the report [2] included the new methodology which counted the index of PT technical condition as rated sum criteria values of equipment unit multiplied by their weight indexes.

$$i = \frac{\sum_j K_j \cdot V_j}{\sum_j V_j \cdot M_j} \cdot 100 , \tag{1}$$

where K_j – j criterion value; V_j – j weight index; M_j – maximum criterion value.

Methodology covered the range of basic parameters for the PT assessment. The criterion with undefined value was not taken into account neither in the numerator nor in the denominator of the formula 1. The assessment of PT technical condition index had to include test results, the load modes, unit conditions lifetime and the possible consequences in the case of an accident. During data assessment by experts, 5 level criterion values were used: very good, good, satisfactory, below satisfactory; poor. The determinant factors of technical condition index were the test results, which were system assessed at 3-step scale. Disadvantages of this approach:

- Simplicity of the model and therefore its inadequacy to such a complex object as PT;
- The energy company expert must participate in the parameters assessment that reduces efficiency and neutrality of the PT ranking because of possible mistakes and low expert qualification;
- A formal approach to the parameters assessment of exceeding their maximum acceptable values that leads to the 1st and 2nd type errors;
- Ignoring lack of information (the less parameters are assessed, the better technical condition index).

In 2012 in the report [3] it was proposed to calculate the technical condition index of the multi-component object, as the weighted average number of indices of the condition of hardware components.

Weight indices that are taken with other components in the calculation of the condition index of multicomponent object are defined by the expert analysis on the component importance for the multicomponent object functioning. Thus, to calculate the condition index of multicomponent objects we use the next formula:

$$I_{imo} = \frac{\sum_i W_i \cdot I_i}{\sum_i W_i}, \qquad (2)$$

where I_{imo} – condition index of multicomponent object; W_i – i component weight; I_i – i component condition index.

Thus, each major unit was given its weight index and the condition index was calculated for each of these units. At present the methodology is not implemented in corpore. Technical condition index is calculated on the basis of PT measurements itself, excluding condition indices of its high-voltage bushings and tap-changer and other units. Firstly technical condition indices are calculated for each type of measurement, and then there is calculated (2) the resulting index. The calculation includes all measurements types regulated by management directive (MD) [4] for power transformers, without remoteness limitation of their execution. Disadvantages of this approach:

- A formal approach to the controlled parameters of exceeding their maximum acceptable values under the RD [4], ignoring most parameters trends and the PT construction characteristics that leads to the 1st and 2nd type errors;

- ignoring the fact that the measurement results that were carried out several years ago, may not reflect the current technical condition of PT;
- Ignoring the results of special diagnosis methods (e.g. vibration inspection, partial discharges measurement).

3 The assessment of the technical condition of the power transformer

The peculiarity of proposed assessment of PT technical condition is that during the calculating of technical condition index of Im object is used the assessment output of expert system (EDIS "Albatros"), but not the evaluation of controlled parameters themselves [5]. The analysis of the EDIS measurements results consists of two stages:

- the assessments of controlled parameters values and their trends;
- type defect identification and evaluation of its development.

For performing the 1st diagnosis stage EDIS uses 2 levels of values (permissible and maximum permissible) for all controlled parameters and their trends. These assessment criteria were derived by system developers during ten-year research work. As the derived criteria parameters assessments and their trends (in contrast to [4]) are differentiated on design features and PT lifetime, it reduces the 1st and 2nd type errors.

Next we will show the importance of technical condition index for Im 2nd stage diagnosis determining. Imagine that there is exceeding of regulated values for two PTs for the following gases concentrations: C_2H_6, C_2H_4, C_2H_2. But one transformer has gas pairs ratio C_2H_6/C_2H_4 and C_2H_2/C_2H_4 diagnosed as "low heat" and in the other as "arc". It is obvious that PT are in different technical conditions, but from the methodological point of view [2,3] the technical condition index of these transformers on DGA results will be the same . In addition, we propose to take into account the speed and defect development duration in the assessment of the technical condition index.

Summarizing the foregoing facts, we propose to calculate the technical condition index as a vector of n-dimensional space, where m is the number of measurement types.

$$\mathrm{Im} = \frac{\sqrt{\left(\sum_{n=1}^{n} x_n\right)^2 + \left(\sum_{n=1}^{n} y_n\right)^2 + \left(\sum_{n=1}^{n} z_n\right)^2}}{\sum_{n=1}^{n} M_{n\max}} \cdot 100\%, \tag{3}$$

where $M_{n\ max}$ – the maximum vector length of i dimension; n – the measurements number.

In turn, each measurement index is represented by a vector, which is the evaluation result of a 3-coordinate (x, y, z):
x –the index of heaviness assessment, the defect danger. The index value depends on the defect type that is identified by EDIS;
y – the index of speed assessment of defect development. The index depends on the trends assessment of controlled parameters and determination of defect type conducted by EDIS;
z – the index of working period assessment and duration of defect development observation. The index depends on the conducted and recommended by EDIS TSM operations, as well as length of defect development observation.

For different measurements values M_{max}, x, y, z are different, because measurements have different sensitivity degree and accuracy of defect identification.

Condition assessment made by other programs with special methods (vibration inspection, low-voltage pulses, PD control and thermal control), are fed into the system by experts.

EDIS “Albatros” analyzes each PT according to the following information:

- analysis of gases dissolved in oil (DGA);
- physico-chemical oil analysis, including surface tension and oil insulativity, its clarity, color and Vrmana index;
- the moister content of solid insulation and degree of its polymerization;
- insulating characteristics of solid isolation;
- windings ohm resistance;
- short-circuit resistance;
- conducted and planned TSM operations;
- description of the external influences on the equipment, conditions and work modes;
- lifetime and construction features of the equipment.

Thus, EDIS diagnoses each type of measurement according to the supposed defect nature, the degree of its development and, if possible, its localization. Moreover, the system makes recommendations to the personnel for further work, taking into account the diagnosis result and history of transformer operation as a set of TSM operations including additional tests. The index values (x, y, z) for each type of measurement (including for special kinds of measurements), diagnosis, maintenance and TSM operations and others are stored in the database of EDIS. They were determined by expert evaluation during the algorithm creating.

4 Risk assessment of power transformer failure

The specific feature of the proposed risk assessment failure of PT is that it is examined the consequences of failure both for the provider and consumer of electricity. Also, there are taken into account equipment construction features, its lifetime, probability of failure and the supposed place (unit, system) of PT damage. Failure probability of PT units was calculated by values of failure flows of transformers and the statistics of their defectiveness. The calculation was based on more than 350 reliable damage facts of 35–500kV PT accumulated by EDIS "Albatros" for 20 years of its operation in the power companies of the Russian Federation.

Assessing the risk of PT failure it is desirable to take into account the potential economic, environmental, social consequences and possible human losses, company's image deterioration, lost profit of provider and consumer of electricity, the duration and cost of repairs, operating conditions, the consumer category. In practice to take all these factors into account is not possible due to lack of (privacy) financial information. Aiming at the retention of comprehensive approach to the assessing of transformer risk failure we propose to calculate the risk by the following formula:

$$H = P_k \cdot \sum U \cdot \frac{1}{P_{\max}} = \left(P_k \cdot \Delta U_{repair} + \frac{P_k}{V} \cdot N \cdot K_{heat} \cdot t_{off} \cdot C_{rate} + \frac{P_k}{V} \cdot U_{cons} \right) \cdot \frac{1}{P_{\max}}, \tag{4}$$

where H – risk; P_k – probability of k unit damage; ΣU – total loss; N_{power} – transformer power; $\Delta U_{repair} = U_{urgent} - U_{planned}$ – the price difference between repairs of different urgency; K_{heat} – load index; t_{off} – interrupting time of energy supply; C_{rate} – the rate for consumer; V – the number of backup lines; U_{cons} – financial consumer claims at power failure (e.g. due to the production loss, break of the technological cycle, etc).

Determining probability of PT failure authors pay attention to several important factors. First, you need to take into account that the flow size of PT damage changes with the operation time of transformer. Based on the analysis of damage flows dependence on the transformer lifetime, we singled out five periods: the running-in period, the one of high reliability, mid-life and overhauls ones, the after recovery one and the period of rapid loss of residual efficiency.

Second, it is essential to remember of PT construction features, for example class voltage. It is known that PTs with high voltage classes have higher failure probability. Furthermore, the PTs of different voltage classes have different construction weaknesses. For example, for PT 35 kV are highly typical damages associated with dynamic winding instability and for PT 110 kV – damages of tap changer and bushings [5]. Tap changer of PT 220−500 kV are rarely damaged.

Third, calculating the risks it must be taken into account that PT systems and units are damaged with different frequency. The next formula is used for calculating the probability of transformer units' failure:

$$P_k = N_k \cdot F, \tag{5}$$

where P_k – failure probability of transformer k unit %; N_k – k unit damage frequency (%); F – the value of failure flow depending on the transformer age.

Based on the failure flow values of PT failures and statistics of their defectiveness [5] were calculated probabilities of individual units. Table 1 shows the calculation results of damage probability of PT individual units for different ages and voltage classes obtained by the authors.

Table 1: The probability of various units damage of 35–110kV transformers with different lifetimes.

	35 kV		110 kV	
	0-5 years	16-25 years	0-5 years	16-25 years
Winding and isolation	1.03%	0.78%	1.41%	0.93%
Tap changer	0.51%	0.39%	0.40%	0.56%
Bushings	0.26%	0.00%	0.40%	0.26%
Core	0.00%	0.00%	0.10%	0.11%
Oil protection system	0.00%	0.00%	0.00%	0.13%
Tank and fittings	0.00%	0.00%	0.00%	0.08%
Cooling systems	0.51%	0.91%	0.00%	0.03%

The data in Table 1 illustrates the need in differentiation during PT risk assessment the damage probability depending on the operation period, the class voltage and unit. The calculation was based on the 339 damage facts of PT 15–500kV accumulated by the database EDIS “Albatros” during its operation. The sample reliability is quite high, because every damage fact was examined by experts on the result compliance of technical condition assessment according to description measurements of detected damage during PT unsealing.

Thus, the assessment of PT risk failure is performed by EDIS “Albatros” by the formula 3. Firstly expert system on the base of PT measurements evaluates technical condition and identifies the proposed damage location (unit). Then the system chooses the appropriate probability Pk value from the database depending on the PT age, class voltage and the supposed damage place.

5 Algorithm of transformers ranking on the order of TSM operations

For PT ranking on the sequence of TSM operations from the sample of considered transformers are excluded objects that are in good condition. Then, the integral indicator of Im technical condition and its risk failure Hm are calculated for each remaining in the sample object.

These coordinates (Hm; Im) indicate the object on the graph shown in Figure 1, where the ordinate axis shows technical conditions indicator, and the abscissa – the risk amount. Next system EDIS conducts transformers ranking on the distance from the point with coordinates (Hm; Im) to the point (0, 0). The greater the distance, the more need of TSM operations.

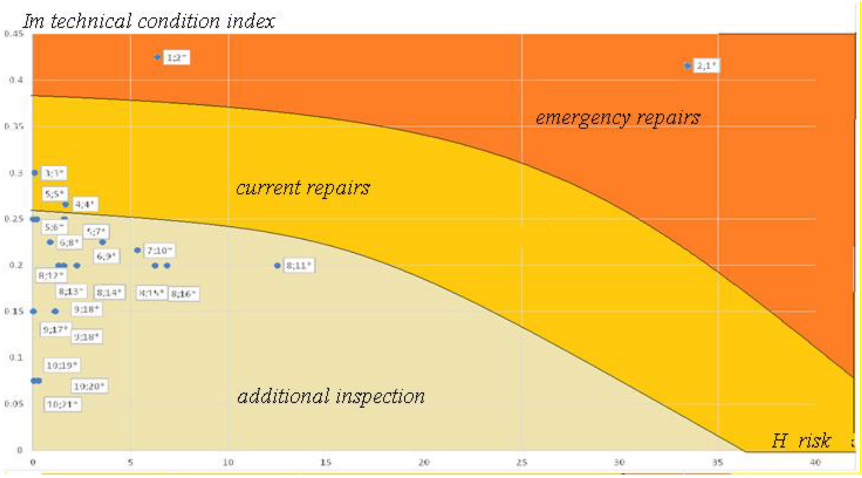

Figure 1: Example of displaying the ranking results of EDIS “Albatros”.

The graph is divided into three zones:

- additional inspection (there is developing defect in the transformer, it is taken under frequent control and additional test can be assigned to clarify the defect nature and its localization);
- current repairs (there is a defect in the transformer but not hindering its efficiency and requiring routine repairs);
- emergency repairs (there is a defect in the transformer, which will soon lead to the loss of its functionality and requiring mid-life or overhaul repairs or equipment replacement).

Figure 1 shows us that the areas vary greatly in the number of PT, that are marked. This distribution, obtained by system EDIS, corresponds to the data given in the reports of engineering centers in Russia, in the percentage of PT requiring immediate withdrawal of work, current maintenance and additional investigation. If transformers have the same coordinates (Hm; Im), the indicator of costly maintenance is used to determine the order. The indicator of costly maintenance – is the specific cost of PT service of homogeneous group for the given power company. Homogeneous group includes identical transformers in construction features, close terms of lifetime and quality of materials and manufacturing technologies. Primarily TSM operations are carried out for such PTs which service costs more for an energy company.

6 Conclusions

In the paper the algorithm for ranking PT on the order of TSM operations based on their technical condition and assessment risk of failures was proposed. This algorithm was verified in practice.

Benefits of the proposed algorithm in terms of assessing the technical condition of PT are the following:

- technical condition is calculated by the system without human participation;
- in index calculating are used not the marks of controlled parameters but system diagnoses;
- index calculating uses system recommendations accounting the history of the damage development and conducted TSM operations.

Benefits in terms of risk assessment of PT failures are the following:

- There are examined failure consequences both for the provider and consumer of electricity;
- probability of failure is selected on the basis of technical condition assessment with supposed defect(s) nature and place of its development;
- failure probability depends on the lifetime and class voltage.

One of the bottlenecks in the evaluation of risk failure is the lack of information about the financial claims of consumers, as well as the accuracy of the information about the losses of energy companies.

Using the proposed algorithm, including the structure of the informational and analytical systems in enterprises operating with PTs in engineering centers and maintenance organizations will increase efficiency and neutrality, reduce error of management operation, which in turn will reduce the risks of enterprises, enhance the lifetime and reliability of transformers.

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