Reliability forecasting model for power transformers that have fulfilled their standard service life

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Abstract. Today, the urgent tasks of the heat and power industry of the Russian Federation, as many other countries, are the problem of exceeding the service life of high-voltage electrical equipment of transformer and traction substations. This state of affairs leads to adverse consequences in the electric power system, which directly reduces the reliability of power supply to consumers, as well as to increase operating costs and technical losses of electric energy. Under the maximum load of transformers that have fulfilled the standard service life, constant monitoring is required to develop recommendations on the operation and operation modes of power transformers. The article considers the issue of calculating the reliability of power oil transformers. According to the collected statistical information, the most damaged parts of power transformers are identified. The main indicators that characterize the level and condition of the power transformer windings are shown. Using quantifiers of the distribution of the Chi-square, the upper and lower limits of the time between failure of the windings of power transformers for different periods of operation are determined, confidence limits with probability \( \alpha = 0.9, 0.95, 0.99 \) are determined. According to the obtained data, the distribution of the Chi-square received a failure flow of the main element - the windings of power transformers with different periods of operation. There is a linear dependence of the decrease in reliability of the power transformers depending on the period of operation.

1. Introduction

The share of electrical equipment that has developed a standard service life and switching resource leads to an increase in the number of electrical equipment failures, which increases the risk of emergencies and the cascade of accidents in the electric power system (EPS). In this regard, it is important to determine the elements of energy systems that have the greatest probability of failure [1-3].

Power transformers (PT) of modern EPS are one of the most critical elements of the main electrical equipment of EPS, the reliability of which largely depends on the reliability of a complex EPS as a whole [4-5]. The PT element, which is most affected by the external electric network - the winding. This primarily concerns short circuits (short circuits), the action of which, depending on the number and magnitude of short-circuit currents in the PT windings, can lead to their failure [6-7].
The aim of the work is to create and apply a model of the technical condition reliability of electrical power substations equipment to assess the risk of failures and prevent the occurrence of technological violations.

2. Reliability analysis of power transformers

The main indicators characterizing the state of PT windings are: wear of coil insulation and dangerous deformations caused by high currents of through faults.

Regarding the first indicator, it can be noted that in the absence of developed projects, the resource is usually largely determined by the paper insulation resource. A common method for assessing its condition is to measure the degree of polymerization of paper. The resource of paper coil insulation of windings is considered exhausted if the degree of polymerization of paper is reduced from 1000-1300 to 200-250 units [8].

The second indicator, which shows the possibility of PT failure, is the magnitude of the windings dangerous deformations caused by the action of short-circuit currents and is determined based on the measurement of short circuit resistance.

Based on the data [9, 10], systematized in table 1, the most damaged parts of power transformers are: winding - 52%; inputs - 27%.

| Damage location | Operating time, years |
|-----------------|-----------------------|
|                 | 0-5  | 6-15 | 16-20 | 26-39 | 40 and more |
| Winding         | 16   | 13   | 39    | 30    | 3           |
| Sealant         | 8    | 10   | 18    | 23    | 5           |
| Input           | 7    | 4    | 5     | 8     | 1           |
| Magnetic core   | 2    | 4    | 6     | 2     | 2           |

The percentage of damage to the transformer windings is distributed according to its elements as follows: main insulation - 12%, coil and inter-coil faults - 28%, thermal and dynamic effects - 12%.

Let us analyze the reliability of 35-110 kV power transformers and evaluate the average failure flow parameter for them, determining its confidence limits with probability $\alpha = 0.9, 0.95, 0.99$, according to the method specified in [11].

We accept the hypothesis of the exponentially of the mean time before failure (MTBF) distribution, since due to the planned and unscheduled preventive maintenance of transformers, wear failures are not taken into account.

The number of observed operating times $n$ is related to the number of observed failures $m$. If $m \neq 0$, then two cases are possible:

- Registered all the time between failures. In this case, $m = n$.
- Only the number of failures and the total time of tests or observations are recorded. Then the maximum number of registered operating time is more than the number of failures per unit; the minimum number of operating hours is equal to the number of failures.

From the definition of quantiles we get the following.

For $m = 0$, $n = 1$:
\[ \lambda^{up} = \frac{\chi^2(\alpha, 2)}{(2 \cdot S)} ; \]
\[ \lambda^{l} = 0. \]

For \( m \neq 0, n = m: \)
\[ \lambda^{up} = \frac{\chi^2(\alpha, 2 \cdot m)}{(2 \cdot S)} ; \]

where \( m \) is the number of failures of all test objects.
\[ \lambda^{l} = \frac{\chi^2(1-\alpha, 2 \cdot m)}{2 \cdot S}. \]

Since the number of MTBFs obeys inequality \( n \leq m + 1 \), we define:
\[ \chi^2(\alpha, 2 \cdot n) \leq \chi^2(\alpha, 2 \cdot m + 2); \]
\[ \lambda^{up} = \frac{\chi^2(\alpha, 2 \cdot m + 2)}{(2 \cdot S)} ; \]

Since the number of failures is no more than the number of operating hours \( (n \geq m) \), we determine:
\[ \chi^2(1-\alpha, 2 \cdot n) > \chi^2(1-\alpha, 2 \cdot m); \]
\[ \lambda^{l} = \frac{\chi^2(1-\alpha, 2 \cdot m)}{(2 \cdot S)} \]
\[ k = 2 \cdot m \]

where \( k \) is the number of freedom degrees.

For the exponential law of point estimation, the parameters are determined by formulas 8 and 9:

- For unbiased estimate:
  \[ \bar{\lambda} = \frac{(m-1)}{S}, \text{ at } m > 1; \]

- For biased estimate:
  \[ \bar{\lambda} = \frac{1}{S}, \text{ at } m = 1. \]

3. Reliability prediction model for power transformers using quantiles of Chi-square distribution

Using the quantiles of the Chi-square distribution \( \chi^2(\alpha, k) \) and \( \chi^2(1-\alpha, k) \), for the number of failures shown in table 1, we determine the upper \( \lambda^{up} \) and lower \( \lambda^{l} \) of the time between failures for the main element PT – windings (table 2).

According to the data obtained, the dependence of the failure rate curve is traced over the operating time, typical of many elements of electrical and power equipment, including electrical equipment of transformer and traction substations.

The failure flow of the main element (PT winding) with a different period of operation is shown in figure 1.
Table 2. Power transformer winding MTBF.

| Winding damage site | Operating time, years | 0-5 | 6-15 | 16-20 | 26-39 | 40 and more |
|---------------------|-----------------------|-----|------|-------|-------|-------------|
| $\alpha = 0.9$     | $\lambda_{up}$        | 0.011403 | 0.009518 | 0.02526 | 0.019914 | 0.002850642 |
|                     | $\lambda_{l}$         | 0.005961 | 0.004628 | 0.016724 | 0.012436 | 0.000588865 |
| $\alpha = 0.95$    | $\lambda_{up}$        | 0.012363 | 0.010401 | 0.026627 | 0.021167 | 0.003369914 |
|                     | $\lambda_{l}$         | 0.005372 | 0.004117 | 0.015699 | 0.01156  | 0.000438972 |
| $\alpha = 0.99$    | $\lambda_{up}$        | 0.014317 | 0.012216 | 0.029441 | 0.023656 | 0.004499465 |
|                     | $\lambda_{l}$         | 0.004379 | 0.003266 | 0.013895 | 0.010035 | 0.000232869 |
| $\bar{\lambda}$   |                       | 0.00803  | 0.006424 | 0.0020343| 0.00203  | 0.005080664 |

Figure 1. Calculation of the PT winding failure flow.

Based on the results of the power transformers failure flow (figure 1), it can be concluded that the most frequent damage to the windings of power transformers occurs from 26 to 39 years on. Consequently, timely monitoring of the substation equipment state that has developed a standard service life leads to a decrease in accident rate and an increase in the reliability of the entire electric power system as a whole.

4. Conclusion

It was revealed that the most damaged element of the power transformer is winding - 52% of the total number of damages, and the highest failure period falls on the interval from 26 to 39 years of operation.

At maximum transformer loads, it is necessary to determine the prospective state of transformer elements and recommended operating modes for their normal operation, as a calculation model, a model for predicting the reliability of power transformers using Chi-square distribution quantiles can be applied.
Using the proposed model, timely monitoring of the power substations equipment state that have developed a standard service life in real time is possible, which significantly increases technical reliability and prevents the cascade of accidents in the power system.

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