Influence of indicators of quality of electric power on reliability of work of power transformer equipment of power plants and distribution networks

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Abstract. The lifespan of power transformers is largely determined by the state of their internal insulation, which is prone to aging during operation, now this problem is especially relevant for the operation of power transformers that have worked out a nominal life. Direct control of internal insulation during the work is difficult due to the inaccessibility of windings for direct survey, and it is advisable to predict the residual resource for planning timely repairs. A refined model of the dependence of the speed of relative wear of the coil insulation not only on the load of the transformer, but also on the presence of asymmetry and higher harmonic components of the current is proposed.

Introduction
Power transformers are the main electrical equipment of power plants and distribution networks. A feature of most of them is the use of paper-oil insulation with oil cooling circulating in the transformer tank, protected from ambient air. The high power of transformers and their voltage classes determine the high degree of use of active materials that can withstand hazardous thermal effects and high electric and magnetic fields [1].

Damage to transformers directly affects the reliability of the power system as a whole, so care must be taken to maintain their operability.

The reliability of the transformer equipment is directly related to its service life. The duration of operation of the transformer depends on the permissible values of the operating mode factors and their number.

If the operating life of the transformer equipment is exceeded, especially under the influence of adverse conditions, its severe damage is possible with a violation of the power supply to consumers. The growing nature of the damage curve of transformers with time (or the "life curve" of a particular transformer) after working out its normalized service life is similar to similar dependences of aging of all types of electrical equipment [1].

1. Relevance
Currently relevant the problem of operating power transformers beyond the nominal service life. The growth of damage to transformers when operating outside the normalized service life increases the cost of their current repair and increases the likelihood of an emergency failure. Extension of the service life of transformer equipment is possible due to effective monitoring of the condition and optimization of preventive measures.
A feature of transformer equipment is that its service life is largely determined by the state of paper-oil insulation during its natural temporary aging and under the influence of external factors.

Most often, a transformer failure occurs due to insulation damage, which, in turn, occurs due to improper or poor installation, insulation deterioration, short circuit, significant or prolonged overload in emergency and post-emergency conditions, lightning or switching overvoltage, oil pollution, structural (production) errors [2].

The design features of large high-voltage power transformers, primarily the inaccessibility of windings for direct examination, make the task of monitoring their condition very difficult.

One of the main ways to maintain operational reliability in such conditions is the organization of effective control in order to predict the residual life of the operating equipment.

Monitoring the status of the power transformer during operation and during periodic inspections is part of preventive measures to maintain its performance. During operation, it becomes necessary to take into account the inevitable aging of paper insulation when the active part of the transformer is inaccessible.

2. Wear of winding insulation of power transformers

Requirements for the permissible loads of general-purpose power oil transformers with a capacity of up to 100,000 kVA inclusive with cooling types M, D, DC and C, as well as the method of calculating the relative wear of coil insulation, are established [3]. The standard establishes a method for calculating permissible systematic loads and emergency overloads according to specified initial data, as well as the norms of such loads and overloads for the daily load schedule of transformers taking into account the temperature of the cooling medium. However, the above methodology for calculating the relative wear of the coil insulation of transformer equipment does not take into account the influence of indicators of the quality of electric energy on reducing the life of the transformer insulation. The degree of compliance of electric energy with standardized indicators is established [4]. This standard contains requirements for distortion coefficients of a sinusoidal voltage curve and for voltage asymmetry coefficients. Higher harmonic components of voltages and currents, as well as distortion of the symmetry of currents and voltages, cause additional power losses in the transformer. Sources of the higher harmonic components of voltage and current are electric receivers with non-linear current-voltage characteristics, the cause of distortion of the symmetry of voltages and currents is the uneven distribution of single-phase electric receivers in phases.

The increase in additional power loss in the transformer $\delta P$, due to the appearance of the voltage of the negative sequence and higher harmonic voltage components [5]:

$$\delta P = (k_2 \cdot U_2 + k_{\nu} \cdot \sum_{\nu=2}^{\infty} U_{\nu}^2 \cdot \frac{0.05 \cdot \nu^2}{\nu^2} \cdot S_{nom} \cdot 10^4, \quad (1)$$

where $U_2$, $U_{\nu}$ are the voltages of the negative sequence and the $\nu$-th harmonic, $\%$;

$S_{nom}$ - rated power of the transformer;

$k_2$ - coefficient voltage asymmetries in the reverse order;

$k_{\nu}$ - coefficient $\nu$-th harmonic component of voltage;

$\nu$ - harmonic number.

Additional power losses lead to increased heating of the transformer windings and an increase in the temperature value of the most heated point $\theta_{hi}$, which accelerates the wear of the coil insulation.

Relative wear rate of coil insulation [3]:

$$V_i = 2^{(\theta_{hi} - 90)/6}, \quad (2)$$

where $\theta_{hi}$ is the temperature of the most heated point of the power transformer [3]:

$$\theta_{hi} = \theta_a + \Delta \theta_{bt} + \Delta \theta_h \quad (3)$$

$\theta_a$ - temperature of the cooling medium, °C;

$\Delta \theta_{bt}$ - excess oil temperature in the lower part of the tank at time $t$, °C;
\( \Delta \theta_h \) - excess of the temperature of the most heated point over the oil temperature, ° C.

The excess temperature of the oil in the lower part of the tank at time \( t \) [3]:

\[
\Delta \theta_{bt} = \Delta \theta_{bi} + (\Delta \theta_{bu} - \Delta \theta_{bi}) \cdot \left(1 - e^{-\frac{t}{\tau}}\right),
\]

where \( \Delta \theta_{bi} \) - the initial temperature rise of the upper layers of the oil over the temperature of the cooling medium, ° C;
\( \Delta \theta_{bu} \) - steady excess of oil temperature in the lower part of the tank, ° C;
\( t \) - current time value;
\( \tau \) - the time constant of the transformer.

The initial temperature rise of the upper layers of oil over the temperature of the cooling medium [3]:

\[
\Delta \theta_{bi} = \Delta \theta_{or} \cdot \left(\frac{1+dK^2}{1+d}\right)^x,
\]

where \( K \) - values of loads;
\( d = \frac{dP}{dx} \) - ratio of short circuit losses to idle losses;
\( x \) - oil exponent;
\( x = 0.9 \) for cooling systems M (ONAN) and \( \Delta \) (OFAN);
\( x = 1.0 \) for cooling systems \( \Delta \zeta \) (OFAF) and \( \zeta \) (OFWF).

\( K_1 \) initial load factors and \( K_2 \) overload factors:

\[
K_1 = \frac{1}{nS_{norm}} \cdot \left(\frac{S_1^2 \Delta t_1 + S_2^2 \Delta t_2 + \cdots + S_n^2 \Delta t_m}{\Delta t_1 + \Delta t_2 + \cdots + \Delta t_m}\right)^{1/2},
\]

\[
K_2 = \frac{1}{nS_{norm}} \cdot \left(\frac{S_1^2 \Delta h_1 + S_2^2 \Delta h_2 + \cdots + S_n^2 \Delta h_p}{\Delta h_1 + \Delta h_2 + \cdots + \Delta h_p}\right)^{1/2},
\]

where \( n \) is the number of transformers;
\( t = \Delta t_1 + \Delta t_2 + \cdots + \Delta t_m \) - the duration of the initial load;
\( h^* = \Delta h_1 + \Delta h_2 + \cdots + \Delta h_p \) - the duration of the preload section.

The temperature rise of the most heated point over the oil temperature [3]:

\[
\Delta \theta_h = H_{gr} \cdot K^y
\]

\( H_{gr} \) - temperature gradient of the most heated point, ° C;
\( K \) - values of loads;
\( y \) - indicator of the degree of winding [3]:
\( y = 1.6 \) for transformers with cooling types M (ONAN) and \( \Delta \) (OFAN);
\( y = 1.8 \) for transformers with types of cooling \( \Delta \zeta \) (OFAF) and \( \zeta \) (OFWF).

The relative wear of the coil insulation of the transformer is:

\[
L = \frac{1}{24} \cdot \sum_{i=1}^{N} \Delta t_i V_i,
\]

where \( N \) - total number of time intervals;
\( i \) - serial number of the time interval;
\( V_i \) - the relative rate of wear of the insulation on the \( i \)-th interval;
\( L \) - the relative wear of the coil insulation, “day normal wear”.

3. Consideration of influence of higher harmonic components of current on reduction of transformer service life.
For the accounting the influence of the higher harmonic components of the current on the daily reduction in the service life of the coil insulation of the transformer, the coefficient of influence of indicators of the quality of electricity on the increase in the relative wear rate of the coil insulation can be used:

\[ k_v = \frac{V'}{V} = 4.22 \cdot 10^{-3} e^{5.468 \cdot k_i} \]  

(10)

\( V' \) - the relative wear rate of the coil insulation, taking into account the higher harmonic components of the current;

\( k_i \) is the distortion coefficient of the shape of the current curve.

\[ k_i = \frac{\sum I_v^2}{I_1} \]  

(11)

where \( I_v \) is the current of the \( v \)-th harmonic component;

\( I_1 \) is the fundamental current.

Accounting reverse sequence currents are produced similarly.

Figure 1 shows the dependence of the ratio \( k_v \) on the distortion coefficient of the current curve shape \( k_i \).

![Figure 1](image)

**Figure 1.** Dependence of \( k_v \) on the distortion coefficient of the current curve shape.

Graph 1 in figure 1 is constructed for the transformer TDN 16000/110, graph 2 - for the transformer TM 6300/35, graph 3 - according to the proposed formula, which with a 10% confidence interval allows you to determine the rate of relative wear of the insulation, taking into account the higher harmonic components of the current.

**Conclusion**

Taking into account the higher current harmonics in calculating the rate of relative wear of the coil insulation and the daily reduction of its service life will allow you to predict the remaining life of transformers and plan for timely equipment commissioning for repair according to the current state.

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References

[1] Alekseev B A 2002 *Condition Monitoring (Diagnostics) of Large Power Transformers* (Moscow: ENAS) p 211

[2] Ilyushin P V, Dogadkin D I 2012 Ways to improve reliability and reduce the cost of operating power transformers 6-220 kV in distribution networks *EnergoExpert* 5 74-79

[3] GOST 14209-85 Power oil transformers for general use. Permissible loads.

[4] GOST 32144-2013 Electric energy. Electromagnetic compatibility of technical equipment. Quality standards for electric energy in general-purpose power supply systems.

[5] Zhelezko Yu S 2009 *Loss of electricity. Reactive power. Electricity quality: A guide for practical calculations* (Moscow: ENAS) p 456