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# STUDY OF PHASE REACTANCES OF SPECIAL-PURPOSE TRANSFORMERS DURING DIAGNOSTICS OF THE EXCITATION SYSTEM OF THE ELECTROMAGNETIC SCATTERING FIELD

The study of phase reactances of special-purpose transformers was conducted for the diagnostics of electromagnetic scattering excitation systems. Special attention is paid to assessing the technical condition of power transformers that supply energy-intensive technological complexes, as the current and voltage in them change according to complex periodic laws, leading to asymmetrical modes and accidents. To improve the reliability of transformer equipment, there is a need to develop specialized microprocessor and software tools for automated analysis and prevention of failures. Accident analysis has shown that electromagnetic scattering excitation systems are the most frequently damaged elements. A methodology for investigating the phase short-circuit resistances of power transformers with complex galvanic winding connections without disassembling the tank is proposed. The research aims to obtain reliable information about the current technical condition of transformer windings based on measured external parameters. The scientific novelty lies in establishing analytical dependencies between interphase short-circuit resistances and phase resistances. The developed program algorithm for automated analysis of winding conditions was implemented in "Turbo Pascal". Experimental studies on a TRDN-63000/150/35 transformer confirmed the accuracy of the methodology and revealed deformation of the low voltage winding. The predominant causes of winding damage include charring and polymerization of inter-turn insulation due to excessive electrical load. The proposed method allows for the detection of deformations without disassembling transformers, which is useful in multi-parameter diagnostic systems to prevent emergencies. Further research is needed to integrate this approach with other diagnostic and automation methods. The methodology can be applied to multi-winding transformers with a "star-delta-delta" winding connection scheme.

**Keywords:** power transformer; phase reactance; diagnostics; electromagnetic scattering; automated analysis; winding damage.

**Introduction.** In the process of operation and maintenance of electrical equipment and, to a large extent, power transformers, very responsible attention is given to the assessment of the current technical condition [1–10] and methods of processing the results of the experiment [11–13]. A special attention is paid to these issues when power supply of power-consuming technological complexes, such as arc and induction steelmaking furnaces, rolling mill drives, DC lines and inserts, etc. is carried out from general-purpose power transformers [14–23]. Their development result was carried out according to the requirements of state standards and normative-technical documentation in which current and voltage change in time according to the periodic law

$$I = I_m \sin(\omega t + \phi).$$

Non-significant overloads are strictly limited in multiples and duration due to the limitation of electromagnetic and high-voltage processes, the excess of which leads to reliability degradation [23–26, 28].

When powering energy-intensive electrical process plants in transformers, current and voltage vary in time according to complex periodic laws

$$I_\Sigma = I_0 + \sum_{\nu=1}^{\nu=N} I_\nu \sin(\omega_\nu t + \phi_\nu).$$

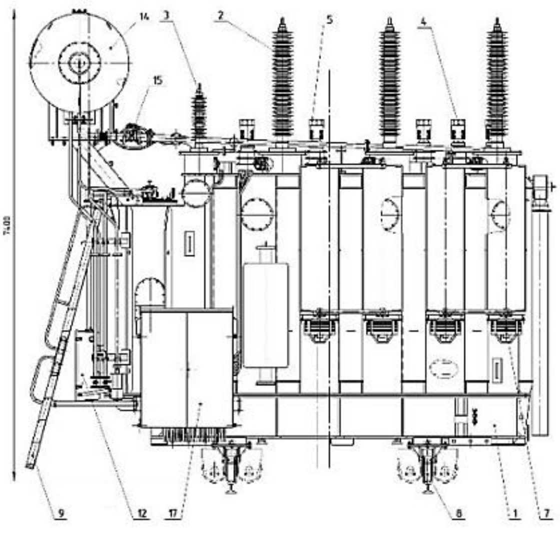
In the literature, such regimes are called sharply variable [13–16].

For more efficient utilisation of electrical energy and technologies, power transformers with split low-voltage windings are used. This allows, on the one hand, to forcibly redistribute the power between electrical and technological installations, and on the other hand leads to the emergence of asymmetrical modes and the formation of a number of undesirable causal factors that lead to cumulative effects and subsequent accidents. Therefore, to improve the reliability of transformer equipment, the requirements of practice formed the need to develop specialised microprocessor and software devices for automated analysis of the current technical condition and prevention of emergency failures.

For a clearer representation of the investigated problem, Fig. 1 shows a general view of one of the power transformers that supply energy-intensive technological installations, and Fig. 2 and 3 show oscillograms of one of the sharply variable modes [23–26] and a fragment of the deformation of the excitation system of the electromagnetic dissipation field of the transformer.

Analysis of the accident rate of electrical equipment has shown that the most damaged elements of such transformers are the excitation systems of the electromagnetic dissipation field, one of the fragments of which is shown in Fig. 2, and Fig. 3 shows oscillograms of currents that took place in the transformer when feeding an arc steelmaking furnace [23–27].

It should be noted that in electrical equipment and power transformers there are excessive additive and total losses in relation to those allowed by normative and technical documentation, increased electrodynamic forces and loss of electrodynamic stability of the excitation systems of the electromagnetic dissipation field.



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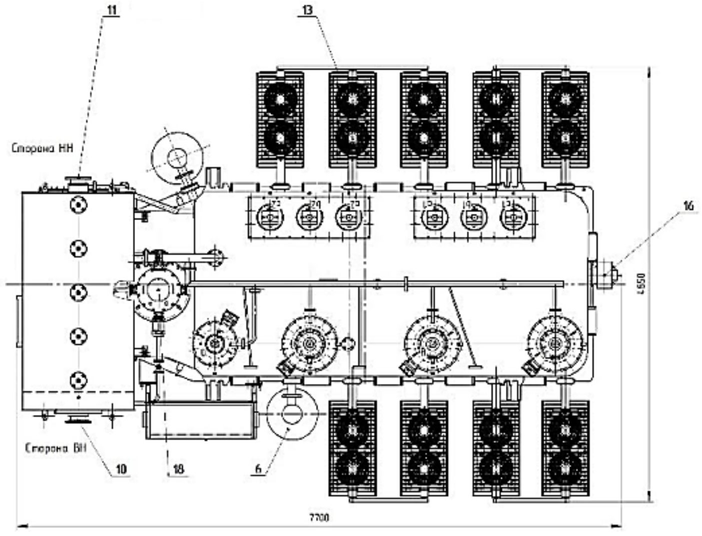


*b*

Figure 1 – General view of a power oil transformer type TRDN-63000/150/35 with split low-voltage windings (*a*) and arrangement of cooling and on-load tap-changer systems (*b*)
1 is a transformer tank; 2 is a bushing of high-voltage windings (HV); 3 is a bushing of neutral of HV winding; 4 and 5 are bushings of low-voltage (LV) windings HH1 and HH2, respectively; 6 is a thermosiphon filter; 7 is a fan; 8 is a carriage; 9 is a ladder; 10 is an oil indicator in on-load tap-changer (OLTC) oil conservator; 11 is an oil indicator in transformer tank conservator; 12 is an OLTC electric drive; 13 is an oil cooler; 14 is an oil conservator; 15 is a Buchholz relay; 16 is an emergency valve; 17 is a control cabinet; 18 is an OLTC

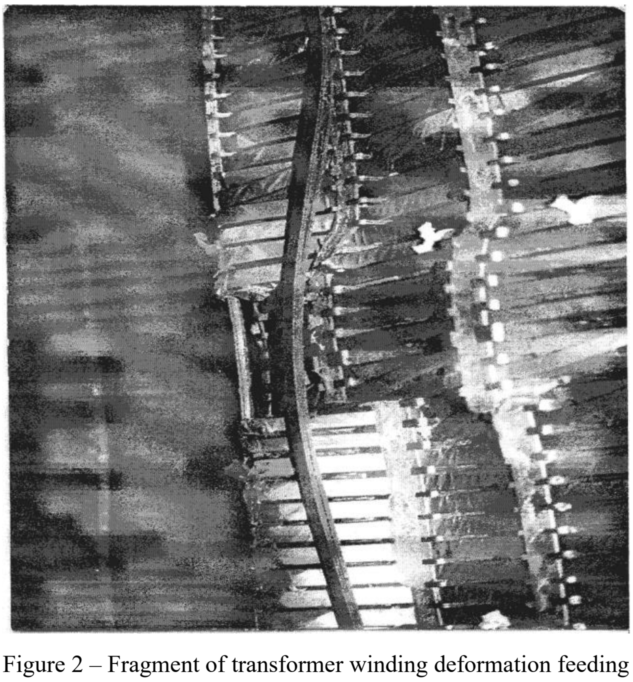
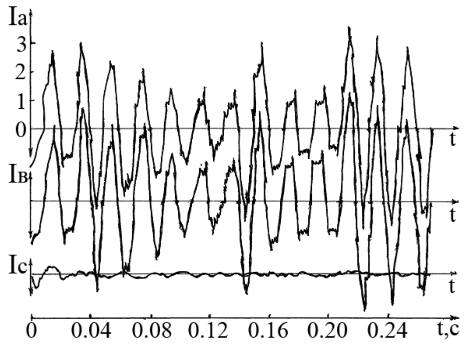


Figure 2 – Fragment of transformer winding deformation feeding arc steelmaking furnaces

Numerous exceedances of current and voltage multiples, excessive local overheating of inactive and active parts of the structure and loss of electrodynamic stability lead to emergency transformer failures and significant technical and economic damages [27].

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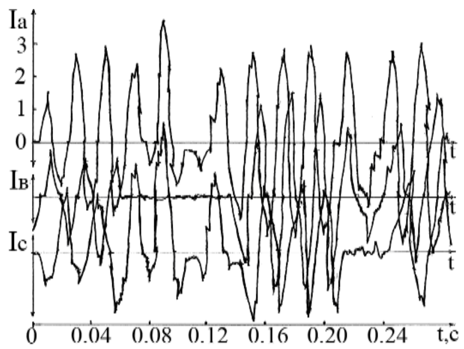


*b*

Figure 3 – Oscillograms of sharply alternating currents in the LV windings of a network transformer of typical capacity 63 MVA in the mode of two-phase (*a*) and alternating technological short circuit (*b*)

For this reason, the accident rate of transformers operating under such conditions was significantly higher than in general-purpose systems. For more optimal energy supply of individual technical objects, the transformers have split low-voltage windings. The high-voltage phase windings are galvanically connected in a delta in the tank, and the leads are located on the tank surface. Each of the low voltage windings are delta connected inside the tank and the leads are located on the tank. This does not allow direct measurement and control of phase resistances and reactances during revisions, various repair works and control of current technical condition of winding transformers.

The existing methods of determining the current technical condition of transformer equipment are based on the methods of analysing insulation, partial discharges in the tank volume, chromatographic analysis of transformer oil, short-circuit resistance measurement, general background noise (spectral composition is not controlled), tank vibration, local overheating measurements, etc. The most acceptable scientific and technical approach to analysing the current technical condition of transformers is the simultaneous analysis of the most informative electromagnetic parameters, which change with the formation of initial deviations in the design, as well as the influence of external factors. These include three-level and multilevel methods of analysing the current technical condition of transformer equipment and forced shutdown in the presence of preconditions of emergency failure [23–29].

The present work deals with the methodology of investigating the phase short-circuit resistances of power transformers with complex galvanic connections of the windings without disassembling the tank. The technical difficulty in solving the issue is that it is not possible to measure the phase reactances directly. Therefore, the first step is to consider a mathematical model to convert the phase-to-phase resistances in the short-circuit experience to phase resistances. Then it is necessary to identify the reactive component by the dynamics of its change to determine the initial deviations in them (winding pairs). Then, on the basis of a series of measurements of various combinations of winding pairs, it is possible to predetermine the formation of deviations in a particular winding.

**The relevance of the work** is demanded by the urgent need of practice – obtaining reliable information on the formation of initial deviations in the excitation system of the electromagnetic scattering field to prevent emergency failures of transformers.

**The goal of research** is to develop a methodology for obtaining reliable information on the current technical condition of power transformer windings based on measured external load parameters.

**The object of research** is the system of excitation of electromagnetic field of scattering at scheme of galvanic connections of windings “star-delta-delta”.

**Scientific novelty** consists in the establishment of analytical dependences between interphase short-circuit resistances to phase resistances of power transformers with the subsequent development of an algorithm for bringing interphase to internal phase reactive components of resistances.

**Research Results.** To determine the current technical condition of power transformers, a number of methods are used, which are based on the measurement of partial discharges, overvoltages, vibration processes, multilevel diagnostic systems, the influence of the quality of electrical energy, control of dielectric properties of transformer oil and others. [20–24]. As analyses of the results of transformer equipment failure have shown, the most common cause of failure is windings. During operation they are subjected to thermal, electrodynamic, electromagnetic and high-voltage influences. As a result, there is accelerated ageing of insulation, partial compression, formation of initial winding deformations and, finally, loss of electrodynamic resistance with subsequent accident development. Therefore, the most effective method of accident prevention is to analyse the current technical condition of windings, but there is no denying the use of other approaches depending on the needs of practice.

Let’s consider the physical process of transferring electrical energy from the high voltage windings to the split low voltage windings. The high-voltage windings are galvanically connected in a star inside the tank and the terminals are located on the tank. The low-voltage windings are connected in delta and the terminals are also located on the tank. We consider the scheme of connection of windings of the excitation system of electromagnetic field dissipation “star (HV)-delta(HH1)-delta(HH2)”. In this case, the short-circuit resistance can be represented in the following form:

$$Z_{AB}(l,\omega) = Z_A(l,\omega) + Z_B(l,\omega);$$
$$Z_{AC}(l,\omega) = Z_A(l,\omega) + Z_C(l,\omega);$$
$$Z_{BC}(l,\omega) = Z_B(l,\omega) + Z_C(l,\omega).$$

Representing inter-phase short-circuit resistances through phase resistances and solving the resulting system with respect to phase resistances we arrive at the following system:

$$Z_A = [Z_{AB}(l,\omega) + Z_{AC}(l,\omega) - Z_{BC}(l,\omega)] \cdot 0.5;$$
$$Z_B = [Z_{AB}(l,\omega) + Z_{BC}(l,\omega) - Z_{AC}(l,\omega)] \cdot 0.5;$$
$$Z_C = [Z_{BC}(l,\omega) + Z_{AC}(l,\omega) - Z_{AB}(l,\omega)] \cdot 0.5.$$

It is known that the short-circuit resistance consists of active $R\ (l)$ and reactive$X(l,\omega)$ components. Due to the nature of electromagnetic processes, the formation of initial winding deformations will be reflected on the reactive component. Considering that the reactive component also depends on the frequency of the applied voltage, in order to achieve greater accuracy in measurements it is necessary to take into account even the smallest deviations from the specified frequency and temperature according to the following formula:

$$X_{AB}(l,\omega) = [Z_{AB}^2(l,\omega) - R^2(l)]^{0.5} \cdot k_{fT},$$

where $k_{fT} = 1 + f_{50} \cdot f_{on}^{-1}$ is the coefficient of reduction to industrial frequency.

In our case, it is not reasonable to take into account the coefficient of converting the results by temperature, because the temperature affects the active component. In order to obtain reliable results, it is advisable to perform at least three measurements of interfacial resistances and bring them to the same conditions according to the following expressions:

$$X_{AB}(l)_{cp} = \left[\sum_{n=1}^{n=4} X_{AB}(l,\omega)_i\right] :n;$$

$$X_{AC}(l)_{cp} = \left[\sum_{n=1}^{n=4} X_{AC}(l,\omega)_i\right] :n;$$

$$X_{BC}(l)_{cp} = \left[\sum_{n=1}^{n=4} X_{BC}(l,\omega)_i\right] :n,$$

where n is the number of measurements in the short-circuit experiment.

The rod reactances are determined similarly to the above approach using the following relations:

$$X_A(l) = \left[X_{AB_{cp}}(l) + X_{AC_{cp}}(l) - X_{BC_{cp}}(l)\right] \cdot 0.5;$$

$$X_B(l) = \left[X_{AB_{cp}}(l) + X_{BC_{cp}}(l) - X_{AC_{cp}}(l)\right] \cdot 0.5;$$

$$X_C(l) = \left[X_{BC_{cp}}(l) + X_{AC_{cp}}(l) - X_{AB_{cp}}(l)\right] \cdot 0.5.$$

To obtain a reference resistance result, we will use the normalisation technique a:

$$X_T(l) = [X_A(l) + X_B(l) + X_C(l)]/3.$$

By the absolute deviation of the reactance $\Delta X(l)$, we determine the pair of windings used in the experiment, one of which has a deformation:

$$\Delta X_A(l) = [X_A(l) - X_T(l)] : X_T(l);$$

$$\Delta X_B(l) = [X_B(l) - X_T(l)] : X_T(l);$$

$$\Delta X_C(l) = [X_C(l) - X_T(l)] : X_T(l).$$

The above approach was used to assess the technical condition of a power transformer with a typical capacity of 63 MVA.

The algorithm of the programme for automated analysis of the technical condition of the windings of three-phase power transformers by current load parameters is shown in Fig. 4.

Let us consider the sequence of transformation of interphase load parameters (I, U, P f) in the short circuit experience to phase reactances (X, R) of the electromagnetic field excitation system in accordance with the analytical relations and connection scheme.

**The programme for converting phase-to-phase reactances to phase reactances** was developed in the "Turbo Pascal" language. It was used in the system of automated assessment of technical condition of power multiwinding transformers. It converts the phase-to-phase resistances obtained in the experiment to the industrial frequency and 200 °C temperature. On their basis, the current phase reactances are determined, changes in which inform about the presence of deformations. It consists of five main parts, which are interconnected by a logical sequence. The direct text of the programme is given below.

In the first step the constant coefficients of the measuring instruments and the current values of the measured currents, voltages, power and frequency are set:

f50 :=50   Ipr :=20   Npri :=100   Upr :=50

Npru :=100   Ppr :=100   Nprp :=100

$$\alpha i := \frac{Ipr}{Npri} \quad \alpha u := \frac{Ppr}{Npru} \quad \alpha p := \frac{Ppr}{Nprp} \cdot 0.1$$

Ppr :=IwUw

M :=D\Sse\mcd\dat.txt   M :=M^T

NIab := M<1>   NIbc := M<2>   NIac := M<3>

Iab :=αi·NIab   Ibc :=αi·NIbc   Iac :=αi·NIac

$$Iab = \begin{pmatrix} 1 \\ 1.1 \\ 1.2 \end{pmatrix} \quad Ibc = \begin{pmatrix} 0.8 \\ 1 \\ 1.2 \end{pmatrix} \quad Iac = \begin{pmatrix} 1.2 \\ 1 \\ 0.9 \end{pmatrix}$$

NUab := M<4>   NUbc := M<5>   NUac := M<6>

Uab :=αu·NUab   Ubc :=αu·NUbc   Uac :=αu·NUac

$$Uab = \begin{pmatrix} 4.5 \\ 4.75 \\ 5 \end{pmatrix} \quad Ubc = \begin{pmatrix} 5 \\ 4 \\ 4.5 \end{pmatrix} \quad Uac = \begin{pmatrix} 5 \\ 5.5 \\ 6 \end{pmatrix}$$

NPab := M<7>   NPbc := M<8>   NPac := M<9>

Pab :=αp·NPab   Pbc :=αp·NPbc   Pac :=αp·NPac

$$Pab = \begin{pmatrix} 1.3 \\ 1.2 \\ 1 \end{pmatrix} \quad Pbc = \begin{pmatrix} 0.8 \\ 0.9 \\ 1 \end{pmatrix} \quad Pac = \begin{pmatrix} 1.1 \\ 1.2 \\ 1.3 \end{pmatrix}$$

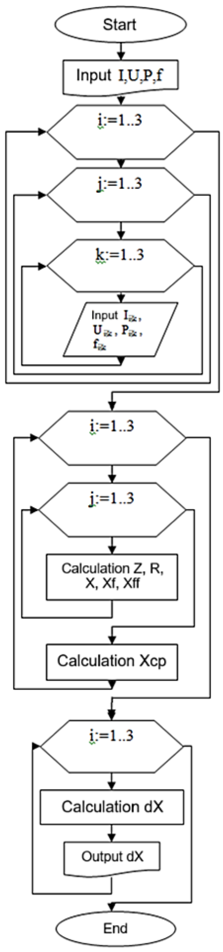


Figure 4 – Algorithm of the programme of reduction of external electromagnetic parameters to phase reactances for estimation of technical condition of the excitation system of the electromagnetic dissipation field of a three-phase transformer with split low-voltage windings

This part of the programme can be partially modernised in relation to the devices to be used, as well as other winding connection schemes.

At the second stage the calculation of interphase rod resistance, its active and reactive components is carried out according to the following expressions:

a. $Zab := \overrightarrow{\left(\frac{Uab}{Iab}\right)}$ $\qquad Rab := \overrightarrow{\left(\frac{Pab}{Iab^2}\right)}$

$$Zab := \begin{pmatrix} 4.5 \\ 4.318 \\ 4.167 \end{pmatrix} \qquad Rab := \begin{pmatrix} 1.3 \\ 0.992 \\ 0.694 \end{pmatrix}$$

$$Xab = \sqrt{Zab^2 - Rab^2} \qquad Xabf = \frac{Xab1_1 + Xab1_2 + Xab1_3}{3}$$

$$kf = \frac{50}{fop} \qquad Xabf = 1.052$$

b. $Zab := \overrightarrow{\left(\frac{Uac}{Iac}\right)}$ $\qquad Rab := \overrightarrow{\left(\frac{Pac}{Iac^2}\right)}$

$$Xac = \sqrt{Zac^2 - Rac^2} \qquad Xac1 = Xac * kf$$

$$Xacf = \frac{Xac1_1 + Xac1_2 + Xac1_3}{3}$$

$$Xacf = 1.328$$

c. $Zbc := \overrightarrow{\left(\frac{Ubc}{Ibc}\right)}$ $\qquad Rbc := \overrightarrow{\left(\frac{Pbc}{Ibc^2}\right)}$

$$Zbc := \begin{pmatrix} 6.25 \\ 4 \\ 3.75 \end{pmatrix} \qquad Rab := \begin{pmatrix} 1.25 \\ 0.9 \\ 0.694 \end{pmatrix}$$

$$Xbc = \sqrt{Zbc^2 - Rbc^2} \qquad Xbcf = \frac{Xbc1_1 + Xbc1_2 + Xbc1_3}{3}$$

$$Xabf = 1.142$$

The third stage of the automated analysis programme allows the technical condition of the power transformer winding pair to be assessed from the current measured parameters. Here the core reactive components of the coresistance are determined on the basis of the interfacial ones according to the following relations:

$$Xaf = \frac{1}{2} \cdot (Xabf + Xacf - Xbcf)$$

$$Xaf = 0.619$$

$$Xbf = \frac{1}{2} \cdot (Xabf + Xbcf - Xacf)$$

$$Xaf = 0.433$$

$$Xcf = \frac{1}{2} \cdot (Xbcf + Xacf - Xabf) Xaf = 0.709$$

$$Xcf = \frac{(Xaf + Xbf - Xcf)}{3}$$

$$Xaf = 0.587$$

At the fourth stage of the programme for automated analysis of the technical condition of the windings of power transformers, the phase reactive components of the short-circuit resistance are adjusted and analysed with respect to the initial ones (or those given in the technical documentation). If such data are not available, it is necessary to use the method of averaging the data obtained in the experiment according to the following formulae:

$$\Delta Xa := \frac{Xaf - Xf}{Xf} \cdot 100 \qquad \Delta Xa = 5.399$$

$$\Delta Xb := \frac{Xbf - Xf}{Xf} \cdot 100 \qquad \Delta Xb = -26.232$$

$$\Delta Xc := \frac{Xcf - Xf}{Xf} \cdot 100 \qquad \Delta Xc = 20.833$$

range (l0, up, xa, xb, xc):= | s←""
s←concat(s, "deltaXa") if (│xa│≥lo) ∧ (│xa│<up)
s←concat(s, "deltaXb") if (│xb│≥lo) ∧ (│xb│<up)
s←concat(s, "deltaXc") if (│xc│≥lo) ∧ (│xc│<up)
s←concat(num2str(lo), "%<=", s, "<", num2str(up), "%") if s ≠ ""

At the fifth stage of the programme the classification of overhangs (changes) of reactive components of resistance is carried out in the following gradation: from 0,0÷1,0; 1,0÷1,5; 1,5÷2,0; 2,0 and more. These boundary limits indicate the presence of corresponding deviations in the geometrical dimensions of the winding pairs and characterise their technical condition. It is practically unsafe to operate the transformer within the limits of 1.5÷2.0. At such values there are deformations in the windings, at which further operation will lead to loss of electrodynamic stability and emergency condition of the transformer.

The programme grading of exceeding limits of reactive components of resistances takes the following form:

range(0, 1.0, ΔXa, ΔXb, ΔXc) = ""
range(1.0,1.5 , ΔXa, ΔXb, ΔXc) = ""
range(1.5, 2.0, ΔXa, ΔXb, ΔXc) = ""
range(2.0, 100, ΔXa, ΔXb, ΔXc) = ""

**The listing of the programme** for determining the technical condition of the windings of a power transformer with split low-voltage windings is shown below:

```
USES crt;
var
i,j,k:integer;
xa,xb,xc,dxa,dxb,dxc,a,Xcp:real;
name: array [1..3] of string;
Xf,Xff,dX:array[1..3] of real;
matr: array[1..3,1..3,1..4] of real;
z,R,X: array[1..3,1..3] of real;
begin
textcolor(white);
name[1]:='ab';name[2]:='ac';name[3]:='bc';
clrscr;
for i:=1 to 3 do
begin
writeln('enter the data for',name[i]);
```

```
for j:=1 to 3 do
begin
writeln('enter sequentially I,U,W,f for 'j,'option');
for k:=1 to 4 do
read(matr[i,j,k]);
end;
clrscr;
end;
for i:=1 to 3 do
begin
for j:=1 to 3 do
begin
	Z[i,j]:=matr[i,j,2]/matr[i,j,1];
	R[i,j]:=matr[i,j,3]/((matr[i,j,1])*(matr[i,j,1]));
X[i,j]:=(sqrt(z[i,j]*z[i,j]-R[i,j]*R[i,j]))*(50/matr[i,j,4]);
Xf[i]:=Xf[i]+X[i,j]/3;
If i=(4-j0 then a:=Xf[j]*(-1) else a:=Xf[j];
Xff[i]:=Xff[i]+a;
```

Experimental research was carried out on a power transformer of typical capacity 63 MVA using the methodology given in GOST 3484.3 [30]. On the basis of the obtained research results, which are given in Table 1, it was decided to dismantle the transformer with the conventional designation T3 for revision. Taking advantage of this, it was experimentally measured phase reactances in order to verify the accuracy of the results obtained using the proposed method. In the experiment, this transformer was powered at reduced voltage from the side of a pair of the corresponding high-voltage windings according to the method of GOST 3484.3 [30], with short-circuited corresponding low-voltage windings and schemes of their connection, as shown in Table 1. The results of the study are given in the same table. The results of T1 and T2 transformers corresponded to the passport results. In the experiment, this transformer was powered at reduced voltage from the side of a pair of the corresponding high-voltage windings according to the method of GOST 3484.3 [30], with short-circuited corresponding low-voltage windings and schemes of their connection, as shown in Table 1. The results of the study are given in the same table. The results of T1 and T2 transformers corresponded to the passport results.

A comparative analysis of the results of the studies showed that the discrepancy between the phase reactances in transformers T1 and T2 are within acceptable limits. Recall that in these measurements three windings on each core are used. At transformer T3, when the windings are connected similarly to T1 and T2 (HV-HH1+HH2), some discrepancies between the phase reactances are observed and are +1.19 and –1.27. From these results, it is not possible to determine in which winding the fault occurs. However, these results inform about the presence of a deformation in one of the pair of windings of phases "B" or "C" (The presence of a winding is excluded). The presence of winding short circuits or shorting out of individual windings or disturbance of galvanic connections between the windings would lead to emergency consequences. Therefore, it was decided to perform measurements of paired reactances, the results of which will make it possible to specify the winding damage. In the HV-HH1 circuit mode the deviations in phase reactances reach 2.51 %, and in the HV-HH2 circuit mode the deviations in reactances are +0.86 and –0.33. This indicates that there is damage to winding HH1 of phase "B" and further operation of the transformer is not acceptable.

Dismantling of this transformer confirmed the deformation of winding HH2, which is shown in Fig. 2.

The predominant causes of winding damage are: Charring and polymerisation of the inter-turn insulation due to excessive electrical load in relation to the standard values and, as a consequence, an increase in added losses, local overheating in active and inactive parts of the structure, as well as the development of relaxation and cumulative processes.

Table 1 – Reactive phase resistances of network transformers with typical capacity of 63 MVA, which supplied electrical technological complexes with sharply variable loads

| Expert | Transformer No. | Winding connection diagram | Phase | Phase resistances, Ohm. | Averaged resistances Ohm. | Relative deviation, % | Connection diagrams of LV windings in the experiment |
|---|---|---|---|---|---|---|---|
| 1 | T1 | HV— LV1+LV2 | A<br>B<br>C | 38,36 pro.<br>38,36 pro.<br>38,37 pro. | 38,43. pro | 0,07. pro.<br>0,07. pro.<br>0,08. pro. | LV windings short-circuited |
| 2 | T2 | HV— LV1+LV2 | A<br>B<br>C | 38,46 pro.<br>38,46 pro.<br>38,46 pro. | 38,46. pro | 0,00. pro.<br>0,00. pro.<br>0,00. pro. | LV windings short-circuited |
| 3 | T3 | HV— LV1+LV2 | A<br>B<br>C | 39,03 pro. 39,01. ex.<br>39,46 pro. 39,39. ex.<br>39,50 pro. 39,45. ex. | 38,99. pro | 0,08. pro.<br>**1,19**. pro.<br>**–1,27**. pro. | LV windings short-circuited |
| 4 | T3 | HV — LV1 | A<br>B<br>C | 71,96 pro. 71,94. ex.<br>73,85 pro. 73,83. ex.<br>70,30. pro. 70,27. ex. | 72,04. pro | 0,11. pro.<br>**2,51**. pro.<br>**–2,41**. pro. | LV windings short-circuited |
| 5 | T3 | HV — LV2 | A<br>B<br>C | 71,71 pro. 71,69. ex.<br>72,72 pro. 72,70. ex.<br>71,86 pro. 71,81. ex. | 72,1. pro. | 0,54. pro.<br>0,86. pro.<br>**–0,33**. pro. | LV2 short-circuited, LV1 is not |
| The indices 'pro' and 'ex' denote the results obtained using the developed programme and experimental measurements on the dismantled transformer, respectively | | | | | | | |

**Conclusions.** The obtained research results allow us to formulate the following conclusions.

1. The proposed method of determining phase reactive resistances by current (measured) interphase supply parameters allows to determine the presence of deformations in the corresponding pairs of windings of the excitation system windings of the electromagnetic dissipation field without resorting to disassembly of powerful transformers.

2. It is expedient to use the methodology in multi-parameter systems of automated analysis and diagnostics of the current state of energy-intensive transformers operating in systems with sharply variable loads to prevent emergency failures and technical and economic damages.

3. It is expedient to continue researches with the purpose of integration of this approach with other methods of diagnostics, modern microprocessor and software methods of automation and optimisation of current load in the process of power supply of energy-intensive technological complexes.

4. It is seen that in further researches it is most effective to use physical processes of electromagnetic character such as magnetostrictive, ferroresonance, electrodynamic, formation of streamers of electric field in insulation, etc., which in aggregate reflects the formation of occlusions in the structure and allows to determine the formation and predetermine the further development of pre-accident situations of transformers.

5. The above methodology can be used for multiwinding transformers with star-delta+delta winding connection. For other winding connection schemes, it is necessary to consider the mutual electromagnetic couplings, taking into account the relevant galvanic connections and the subsequent development of the programme and algorithm.

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## ДОСЛІДЖЕННЯ ФАЗОВИХ РЕАКТИВНИХ ОПОРІВ ТРАНСФОРМАТОРІВ СПЕЦІАЛЬНОГО ПРИЗНАЧЕННЯ В ПРОЦЕСІ ДІАГНОСТИКИ СИСТЕМИ ЗБУДЖЕННЯ ЕЛЕКТРОМАГНІТНОГО ПОЛЯ РОЗСІЮВАННЯ

Дослідження фазових реактивностей спеціалізованих трансформаторів було проведено для діагностики систем збудження електромагнітного розсіювання. Особлива увага приділяється оцінці технічного стану енергетичних трансформаторів, що живлять енергоємні технологічні комплекси, оскільки струм і напруга в них змінюються за складними періодичними законами, що призводить до асиметричних режимів та аварій. Для підвищення надійності трансформаторного обладнання виникла потреба у розробці спеціалізованих мікропроцесорних та програмних засобів для автоматизованого аналізу та запобігання відмовам. Аналіз аварійності показав, що найчастіше пошкоджуються системи збудження електромагнітного розсіювання. Запропоновано методику дослідження фазових опорів короткого замикання силових трансформаторів зі складними гальванічними з'єднаннями обмоток без розбирання бака. Мета дослідження – отримати достовірну інформацію про поточний технічний стан обмоток трансформатора на основі виміряних зовнішніх параметрів. Наукова новизна полягає у встановленні аналітичних залежностей між міжфазними опорами короткого замикання та фазовими опорами. Розроблений алгоритм програми для автоматизованого аналізу стану обмоток був реалізований на "Turbo Pascal". Експериментальні дослідження на трансформаторі ТРДН-63000/150/35 підтвердили точність методики та виявили деформацію обмотки низької напруги. Основними причинами пошкоджень обмоток є обвуглювання та полімеризація міжвиткової ізоляції через надмірне електричне навантаження. Запропонований метод дозволяє визначати деформації без розбирання трансформаторів, що доцільно використовувати в багатопараметричних системах діагностики для запобігання аваріям. Необхідно продовжити дослідження для інтеграції цього підходу з іншими методами діагностики та автоматизації. Методика може бути використана для багатообмоткових трансформаторів зі схемою з'єднання обмоток «зірка-трикутник-трикутник».

**Ключові слова:** силовий трансформатор; фазова реактивність; діагностика; електромагнітне розсіювання; автоматизований аналіз; пошкодження обмоток.