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Planning of the experiment for the defining of the technical state of the transformer by using amplitude-frequency characteristic

***Abstract**. The article analyzes existing methods of diagnosing power transformers (PTs). The technique of experiment planning using D-optimal plans is investigated. According to the results of the study, a D-optimal plan of the frequency response measurements was created, which defines the algorithm of the studies. On the example of PT type TMG 1000/10 it is determined that 13 measurements are required to evaluate the condition of the PT during the interpretation of the results of the frequency response measurements. The method of determining the average frequency characteristic of PT is given. This amplitude-frequency characteristic can be used to check the PT status and to detect damage at an early stage of their development.*

Streszczenie.** Artykuł analizuje istniejące metody diagnozowania transformatorów mocy (TM). Badana jest technika planowania eksperymentu z wykorzystaniem planów optymalnych. Zgodnie z wynikami badań opracowano optymalny D-plan pomiarów odpowiedzi częstotliwościowej, który określa algorytm badań. Na przykładzie TM typu TMG 1000/10 ustalono, że do oceny stanu TM podczas interpretacji wyników pomiarów odpowiedzi częstotliwościowej potrzeba 13 pomiarów. Podano metodę wyznaczania charakterystyki średniej częstotliwości TM. Ta charakterystyka amplitudowo-częstotliwościowa może być używana do sprawdzania stanu TM i wykrywania uszkodzeń na wczesnym etapie ich rozwoju.* ***Planowanie eksperymentu przy określaniu stanu technicznego transformatora mocy

Keywords: diagnosis, faults, power transformer, frequency analysis, windings.
Słowa kluczowe: diagnostyka, awarie, transformator mocy, analiza częstotliwości, uzwojenia.

Introduction

Nowadays, there are many means and methods available for the diagnosis of power transformers. Statistics data show that PTs continue to be damaged. This, for example, it may have been possible to make electricity companies change a mode of operation and change the parameters of power transportation. These changes led to increasing technical power losses. One of the modern methods of PT diagnosis is to compare value the frequency response with the previous measured [1]. Although this method is relative simple, the interpretation of the frequency response requires high qualification staff to find the kind and possible fault location [1].

In the conditions of influence on the diagnostic equipment of the powerful electromagnetic field of the substation, interference generated by the corona discharge and for other reasons, it is desirable to duplicate the measurement, which creates the prerequisites for reducing the influence of accidental and systematic errors on the result of diagnosis. However, a significant increase in the number of experiments leads to an increase in time spent on diagnosis and an increase in the cost of work related to the determination of the technical state of the PT. Therefore, it is necessary to justify the number of experiments in order to reduce the possible error and improve the reliability of the conclusions regarding the technical state of the PT.

Materials and methods

The goal and tasks. The goal of the research is to optimize the measurement plan to determine the technical condition of the transformer using the amplitude-frequency characteristics. According to the goal, the following tasks are solved in the article:
- research of existing methods and means of diagnosing the technical state of the CT;
- to investigate the peculiarities of the method of creating D-optimal plans of transformer frequency response;
- determination of the required number of measurements, for an adequate assessment of the PT state, when interpreting the results of the frequency response measurements.

Literature review and problem statement

Currently, methods and tools for diagnosing PT are rapidly evolving. For example, by controlling the tangent of the dielectric loss angle $tg\ (\delta)$, determining the resistance of the DC windings, conducting short-circuit and no-load experiments, chromatographic analysis of the gases dissolved in the transformer oil, it is possible to detect PT defects [1, 2]. But at the same time, it is known from [3] that a lot of damage to the windings and the magnetic core of the PT occurs during operation. This indicates that the existing methods and means of controlling and determining (by their results) the technical state of the PT, the causes and the location of the damage need further development.

Among these methods is the frequency response analysis method, which involves the analysis of the amplitude values of the response signal to the test signal and, in our time, is used to diagnose PT [4, 5].

This method consists of the first measurement of the amplitude values of the test signal response voltage ($U_{amp.res.}$) and the test signal voltage ($U_{amp.test.}$). Next, the transmission coefficient of the test signal at different frequency (value of the transfer function) is determined as the result of dividing the amplitude value of the voltage $U_{amp.}$ (the response signal to the test signal for the current frequency of this signal) by the amplitude value of the voltage (test signal for the same frequency) $U_{amp.test}$. This result is often written in decibels. It is then determined by the following formula, which is the transfer function of [4] test signal (1) (F):

$$F = 20 \cdot log_{10}\ U_{amp.res.} / U_{amp.test.} \tag{1}$$

The paper [6] notes that the idea of FRA analysis on the state of the winding PT is based on the fact that the deviations or geometric deformations of the winding relate to changes in the internal distances between the turns and the windings, which determine its capacitance and inductance. Also, [4, 7] draws attention to the influence of the PT parameters on the response signal voltage and the test signal in general. The authors of [1] confirm the feasibility of using frequency response in the diagnosis of PT. The detection of PT defects at an early stage of their development is possible through the use of the FRAnalizer, which is described in [7, 8]. As stated in [8, 9] the deformation of the windings in the form of their axial displacement or radial bending causes a change in capacitance and inductance on the alternating circuit PT and therefore influences the change of the controlled voltage of the test signal. The peculiarities of the frequency response analysis are described in [7; 4; 10], which indicates the feasibility of using frequency response analysis for the diagnosis of PT. The peculiarity of the method of diagnosing with the use of AFC PT is the need to compare at least two AFC PT of the same PT received at different times (the interval of AFC PT – removal is one year, or five-ten years, etc.).

The justification of the conclusions on the results of the use of such diagnostic equipment in Ukraine is limited by the lack of regulatory technical documentation. Defects in windings and PT conductors appear in different frequency bands [1, 7, 8, 11, 12] and not always these ranges for Transformers manufactured and operated in Ukraine are the same as others, because it is known that the frequency response of a particular power transformer is unique and often different from the characteristics of other PTs. For the same type of equipment, the deviation of frequency characteristics will be in some limits probability.

If the diagnostic service accumulated the normative base of the frequency characteristics put into operation of the PTs, then it is possible to quickly determine the technical state of the PT by analysing its current AFCs. Such tasks occur during a scheduled or unplanned shutdown, for example, in the event of a minor accident. But at the same time, how to solve of the situation, if, for example, the PT was put into operation recently, and during the operation, a short circuit near such a node of the power company, occurred, because there are no accumulated AFCs, it is impossible to compare AFC. Typically, a short circuit near such a PT will be turned off by the relay protection of the PT or the transmission line. However, it is known [13] that the current and electrodynamic forces present during such a short circuit may, for example, weaken the mounting of the brace or cause the windings to shift. Often, given the speed of relay protection, such damage can be minor, but over time, it can develop and cause more serious consequences, such as failure of the PT.

Therefore, the article answers the question whether it is possible to detect damage and to adequately assess the technical condition of the recently commissioned PT in the absence of the previously received AFC of this PT.

The initial tests of the transformer presented by the authors were carried out in several iterations. A number of experimental researches were conducted at different PT temperatures (daily fluctuations in air temperature ranged from 15°C to 27°C). As a result of the tests the characteristic of the transfer function for different frequencies of the test signal is obtained. The following are the frequency response formed in the form of a table. Then, by approximation of the tabular data and regression analysis, the polynomial equation of the transmission coefficient (transfer function of the test signal) $k_u\ (f,\ t)$ on the frequency f and temperature t is obtained. In order to simplify the understanding of the planning procedure and to prevent the denotation of different values by identical letters, the frequency f will be denoted by X_1, the temperature t will be denoted by X_2, and the test signal transmission coefficient $k_u\ (f,\ t)$ shall be denoted by Y.

Consider checking the status of the PT, for example, after a short circuit (SC). Eight months before the short circuit the parameters of its frequency response were measured.

On external grounds, it can be assumed that the state of the PT after switching off the external SC – serviceable. However, to confirm this condition, you need to perform unscheduled monitoring of diagnostic parameters. Consider the case when you want to reduce the error during measurements, at a frequency response that corresponds to the characteristic signs of shifting windings or weakening the bandage.

Consider one example when you need to make sure that there is an over-normalized shift of the windings in the PT, or whether there is a deterioration in the properties of the magnetic circuit.

Experiments should be performed several times. After comparing the results of duplicate experiments, it is suggested to remove the frequency response (reduce the effect of random error), in which the deviations of the parameters exceed the set accuracy of the device.

Next need to compare the average frequency response with the measured frequency response at the interval frequency response, which corresponds to the characteristic features of the types of defects researched. Measurement results during which the deviation of the frequency response exceeds the error of the instrument are a sign of a defect. At the same time, this is the basis for the conclusion about the faulty condition of the PT.

However, the number of retry experiments must be justified. To do this, suggest using D-optimal plans. The D-optimal plan minimizes the amount of confidence ellipsoid on many of all plans in area G. The confidence ellipsoid is such an ellipsoid that covers the true values of the coefficients with a given probability level. Since the volume of this ellipsoid V is proportional $det(F^T F)^{-1}$, minimizing this determinant across the set of plans in area G will provide a minimal amount of experimentation.

For the example discussed in the article, the equation is studied can present:

$$y(\vec{x}) = \sum_{k=0}^{d} \beta_k \vec{f}_k(\vec{X}) \qquad (2)$$

where $d = 6$ – the number of terms in the polynomial equation. $\vec{f}_k$ – known functions of the input variables X_1, X_2, for example, k=6 – applications in the test expression. Vector $\vec{X} = (X_1, X_2)$ is a vector of input variables. The results of observations y_1, y_2, ..., y_9. $\vec{f}_g^T = (f_{g1}\ f_{g2} \ldots f_{g6})$ – vector which defines a set of functions f_{gk} g-th observation, T – sign of transposition; $\vec{B}^T = (b_0\ b_1 \ldots b_6)$ – *d*-dimensional vector of coefficient estimates β – coefficient in front of summands.

So, the plan of the experiment consists of 9 variants of the experiments for various possible combinations of values of functions f_{gk} which are components of the investigated functions (2). Experiments can be repeated different number of times. Are set to -1, 0 and 1. (-1) corresponds to the minimum value f_{gk}, which corresponds to the minimum value of X_1 or X_2. (0) corresponds to the average value f_{gk}, which corresponds to the average value of X_1 or X_2. (1) corresponds to the maximum value f_{gk}, which corresponds to the maximum value of X_1 or X_2. Therefore matrix F has the form (3):

$$F = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 1 & 0 & 0 \\ 1 & -1 & 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & 1 & -1 & 1 \\ 1 & 0 & -1 & 0 & 0 & 1 \\ 1 & 1 & -1 & 1 & -1 & 1 \\ 1 & -1 & -1 & 1 & 1 & 1 \end{pmatrix} \qquad (3)$$

Results

Development of D-optimal plan

When designing D-optimal plans, two formulations of the problem are possible. The first of these sets the finite number of N observations and is the location of the experimental points for which measurements will be made within the confidence interval. The D-optimal plans thus obtained are called exact. When implementing accurate D-optimal plans, a consistent experimentation strategy is used in practice, at which the point of setting a new experiment is determined based on the results of previous experiments.

A different formulation of the problem is also possible. It is related to the concept of a generalized plan. A generalized (or continuous) plan is a set of $2h$ numbers:

$$\vec{X}_1, \vec{X}_2, \ldots \vec{X}_h, \quad W_1, W_2, \ldots, W_h \tag{4}$$

where $\vec{X}_l$, $(l = 1,2,3,\ldots,h)$ – the points at which observations are made, and W_l – the proportion of observations at this point with the total number of observations taken per unit.

In this case

$$\sum_{l=1}^{h} W_l = 1,$$

where W_l, $(l = 1,2,3,\ldots,h)$ – these are any real numbers, including irrational ones. Therefore, such plans are not related to any specific number of observations.

A continuous D-optimal plan is both minimizing $max\ d(\vec{X})$, and

$$max\ d(\vec{X}) = \max_{\vec{X}\hat{I}G} \vec{f}^{\,T}(\vec{X})(F^T F)^{-1}\vec{f}(\vec{X}) = \frac{k}{N} \tag{5}$$

where k – is the number of regression coefficients;
N – is the number of points of the experimental plan.

The relative deviation of this plan from the D-optimal can be estimated by the formula

$$\delta = \frac{N \times \max_{\vec{X}\hat{I}G} \vec{f}^{\,T}(\vec{X})(F^T F)^{-1} f(\vec{X}) - k}{k} \tag{6}$$

In the following, we will consider only continuous D-optimal plans. In the implementation of continuous D-optimal plans in practice, a consistent experimentation strategy is applied, at which point the setting of a new experiment is determined based on the results of previous experiments.

Consequently, observations are terminated as soon as the results of the observations meet the specified criteria. The maximum point $max\ d(\vec{X})$ is the starting point for a new experiment. The algorithm for choosing the next experimental point, based on the procedure of sequential planning of Sokolov experiments [14]. The choice of the point of the next experiment is not related to the results of previous experiments (because $d(\vec{X})$ is independent of y_g), so the order of the points and the minimum eigenvalues of the matrix $F_N^T F_N$ can be determined before the experiment begins. First, the order of passage of the points of the D-optimal plan is determined, and then the minimum eigenvalue of the matrix $F_N^T F_N$ – $\lambda_{N\ min}$ is calculated after each new observation [14].

Planning is performed before the experiment is performed, the results of the experiment are not required to create the plan [14].

Fill in the matrix of experiments F, in which each row is a new experiment. It is filled in by rows: $f_0 = 1;\ f_1 = X_1;\ f_2 = X_2;\ f_3 = X_1^2;\ f4 = X_1 X_2;\ f_5 = X_2^2$.

Defined result of the $F^T F$ multiply (for nine experiments):

$$F^T F = \begin{bmatrix} 9 & 0 & 0 & 6 & 0 & 6 \\ 0 & 6 & 0 & 0 & 0 & 0 \\ 0 & 0 & 6 & 0 & 0 & 0 \\ 6 & 0 & 0 & 6 & 0 & 4 \\ 0 & 0 & 0 & 0 & 4 & 0 \\ 6 & 0 & 0 & 4 & 0 & 6 \end{bmatrix} \tag{8}$$

We define an array of eigenvalues of the $F^T F$ matrix:

$$eigenvals\left(F^T F\right) = \begin{bmatrix} \ldots \\ \ldots \\ 4 \\ \ldots \\ 1 \\ 18 \end{bmatrix} \tag{9}$$

Find the minimum eigenvalue of the matrix $F^T F \lambda_{min} = 1$.

The matrix F with each experiment changes its dimension F (6: N), where N is the number of the experiment in which we find λ_{min}.

The following value λ_{min} is found as the minimum eigenvalue of the $F^T F$ matrix, but with the dimension 6:10. Now the product of matrices will be as follows (for ten experiments)

$$F^T \times F = \begin{bmatrix} 10 & 1 & -1 & 7 & -1 & 7 \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ 7 & 1 & -1 & 5 & -1 & 7 \end{bmatrix} \tag{10}$$

Array of eigenvalues of the matrix

$$F^T \times F = \begin{bmatrix} 6 \\ \ldots \\ 21.621 \end{bmatrix} \tag{11}$$

Among these, the minimum will be 1.031. Hence, λ_{min} = 1.031.

Determine the table of values λ_{Nmin} is the minimum eigenvalue, and δ is the valid value of the confidence ellipsoid, for a given point, for two variables X_1, X_2, and for a second-order polynomial equation. The table changes as conditions change.

Note that after determining the number of observations, the order of their conduct is irrelevant. Table 1 shows the D-optimal plan for the type equation:

$$\eta = b_0 + b_1 X_1 + b_2 X_2 + b_{11} X_1^2 + b_{12} X_1 X_2 + b_{22} X_2^2 \tag{12}$$

Table 1. The values of λ_{Nmin} and δ after each observation

№	X_1(F)	X_2(t)	λ_{min}	δ
1	0	0	-	–
2	1	0	–	–
…	…	…	…	…
12	–1	1	1.138	0.115
13	0	0	1.717	0.168
…	…	…	…	…

To move on to the next experiment, we find the value of the set point of the new experiment $d(\vec{F})$ [14] for each experiment, and choose the maximum from them. In which experiment $d(\vec{F})$, the value of the setting point of the new experiment will be the largest, we choose as the next experiment. We substitute the same value in the formula above.

The sequence of experiments after the first 9 experiments was determined by calculating the maximum value at each step and adding the point at which this maximum is reached. The compiled table 1 allowed us to determine the required number of experiments during the experiments for the construction of frequency response to further diagnose PT.

Determination of generalized AFC for a typical PT

For defining to the tasks, it is proposed to create a generalized frequency response for a TMG 1000/10 power transformer. On the basis of the obtained characteristics (some of them are presented in Fig. 1), measured on the operating PT, which as a result of diagnostic tests have a good technical condition, we perform a generalization of the obtained measurement results, for typical FRAnalizer connection circuits to the PT.

Next, remove the characteristics that have significant deviations, because during the experiment there are random measurement errors, such as not properly attached probes of the device, power failure, the influence of short-term electromagnetic interference near the powerful electromagnetic equipment, etc.

Further, according to Table 2, we determine the frequency range at which further studies will be conducted.

Known [8, 12] that the frequency response characterize the state of the PT, taking into account the state of its various nodes.

For the considered in this article, the quality of the example, the production situation, when it is necessary to investigate the technical state of the windings of the PT after a close short circuit, for axial displacement of turns, some of the frequency intervals of the frequency response is impractical, since these intervals at the frequency response need not be informative in the case of the expected type of defect [8, 9, 11, 12].

According to [8, 9, 12], the calculations will be performed in the frequency range from 400×10^{3} Hz to 3×10^{6} Hz. Since the studies will be conducted to determine the technical state of the windings of the CT, for axial displacement of the coils, the results of some of the original measurement data are shown in Table 2..

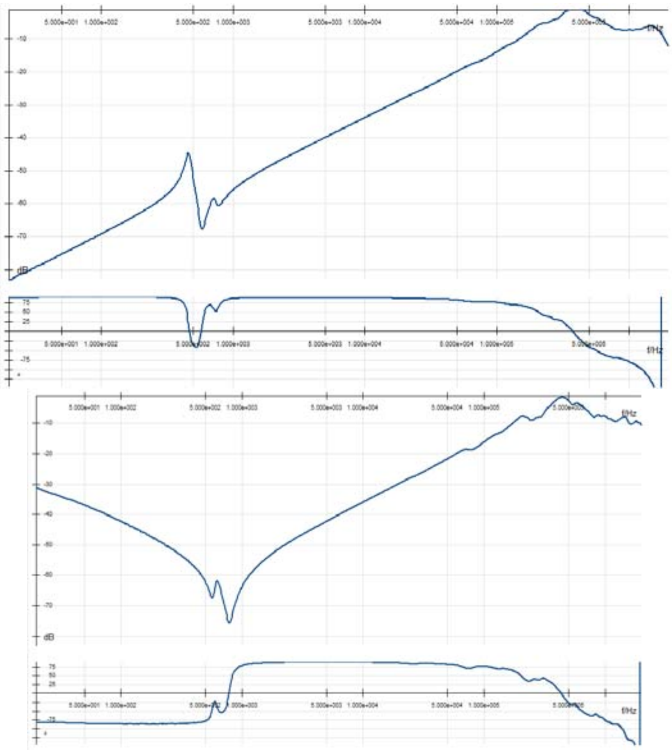

Fig. 1 - Fragments of measurements results of the same type of power transformers

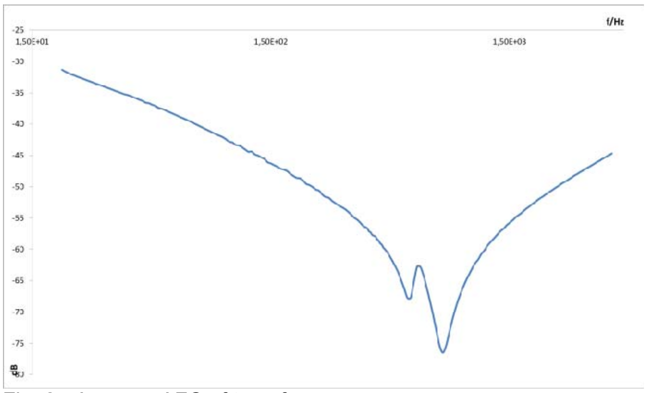

Fig. 2 - Average AFC of transformer

Table 2. Determination of generalized frequency response for a typical PT

№. meas.	1	…	143	…	182	…	199		Averages
f/Hz	$k_u(f)$ dB								
20	–30.736	…	–26.238	…	–14.382	…	–26.767		–29.40582688
…	…	…	…	…	…	…	…		…
4020	–43.869	…	–37.449	…	–20.526	…	–38.203		–41.97030754

On the basis of the obtained, during the experiments, the parameters of the frequency response of the PT type TMG 1000/10 and according to the results of the calculations, an average characteristic was constructed, with a frequency range from 400×10^{3} Hz to 3×10^{6} Hz. The result of the calculations is shown in Fig. 2.

Having received a generalized calculation characteristic, propose to compare it with the frequency response obtained from the results of the first measurements of the frequency response of the investigated PT, which is in operation. When solving this task, there is a problem in choosing the number of retry experiments, in order to determine the frequency response, because the quality of diagnosis of PT depends on the results of the obtained measurements, namely the adequacy of the proposed conclusions to the actual technical state.

Mathematical model of PT

According to the results of the frequency response analysis of the same type of PT, obtained averaged values of the test signal transmission coefficient for different frequencies. Next, build the AFC of PT by the average values of the transmission coefficient. Let's call this AFC "Average typical AFC of PT type TMG 1000/10". Or abbreviated (in the article) "Average typical AFC". This AFC is a typical (within the FRAnalizer error) AFC of TMG 1000/10 power transformers. Using the least-squares method and MathCAD software, based on the experimental data, obtained a mathematical model of PT as a function of the dependence of the test signal transmission on two parameters (variables), namely: the frequency and the air temperature at the place of the experiments (it is simplified to assume that the air temperature corresponds to the temperature of the de-energized PT). This model is described by the second-order polynomial equation (2). After completing the calculations got:

$$I=\begin{bmatrix}1 & 1\\ \ldots & \ldots\\ 2 & 0\end{bmatrix} \qquad coef=\begin{bmatrix}-8.864\times10^{-7}\\ \ldots\\ -1.04\times10^{-4}\end{bmatrix}$$

where I is a matrix showing the degree of variables. In this matrix, the first column is responsible for changing the часто "test signal frequency" (F) and the second column is responsible for changing the "air temperature" (t). In each row, the degrees of variables F and t, which after multiplying by $coef^{(j)} \cdot F^{I(1,j)} \cdot t^{I(2,j)}$, allow us to obtain the value of the additive of the equation of the transfer function, which is the mathematical model of CT; $coef$ - vector of coefficients b_n before additives of additiving equation of transfer function; j is the number of the complement and simultaneously the row number in the matrix I and in the *coef* vector. The polynomial equation thus obtained:

(13) $$\eta = -t^1 \times F^1 \times 8.864 \times 10^{-7} + t^0 \times F^2 \times 6.855 \times 10^{-6} - -t^0 \times F^1 \times 0.024 - t^0 \times F^0 \times 41.924 + +t^1 \times F^0 \times 4.875 \times 10^{-3} - t^2 \times F^0 \times 1.04 \times 10^{-4}.$$

The error of approximation of tabular data makes 7.7%.

Definding the optimal number of measurements made during the experiment

In our formulation of the problem, finding the optimal number of experiments of equation 2 looks like the following equation:

(14) $k_U(f) = -41.924+0.00485 \cdot F-0.000104 \cdot F^2-0.0000008864 \cdot F \cdot t+0.000006855 \cdot t^2-0.024 \cdot t,$

hence: $b_{0,} = -41.924$, $b_1=0.00485$. $b_2= -0.000104$, $b_{11} = -0.0000008864$, $b_{12} =0.000006855$, $b_{22} = -0.024$

Then defined the confidence probability $P = 0.5$ %. According to fig. 2 the average frequency value for generalized AFC $F_{aver} = 2020$ Hz, deviation of the frequency from the average value $\Delta F = 2000$ Hz ($F_{aver} + \Delta F$ – maximum frequency of generalized AFC; $F_{aver}-\Delta F$ – minimum frequency of generalized AFC); average temperature for generalized AFC $t_{aver} = 35$ °C, deviation of temperature from the average value, $\Delta t = 25$ °C ($t_{aver} + \Delta t$ - maximum value of frequency of generalized AFC; $t_{aver} -\Delta t$ - minimum value of frequency of AFC response). Defined the standard deviation σ. For decision this task, values of the function were determined and the experimental values measured are as follows: $y_{meas\ 1} = 0.87$; $y_{cal\ 1} = 1$; $y_{meas\ 2} = 144718$; $y_{cal\ 2} = 144721$; ……; $y_{meas\ 9} = -574$; $y_{cal\ 9}= -519$. The obtained experimental and theoretical values of the function are substituted into the Bessel formula and defined the variance σ [14]:

$$\sigma = \left\{\left[\left(\frac{0.87-1}{1}\right)^2+\left(\frac{144718-144721}{144721}\right)^2+...+\left(\frac{-574-(-519)}{-519}\right)^2\right]/8\right\}^{\frac{1}{2}} = 0.06$$

For a given confidence probability $P = 0.952$, the percentage point of degrees of freedom σ for 6 coefficients of the equation of type (2) becomes significant $\chi^2=7.8$ [14].

On the basis of the values found, we find the relative deviation of the D-optimal plan from the experiment δ conducted earlier: $\delta = \sqrt{0.06^2 \times 7.8} = 0.168$.

Defined this or the approximate value of δ in Table 1. Keep in mind that there may be several such values. The number was looked for is between 12-th and 13-th, 23-rd and 24-th, 26-th and 27-th, experiments. Was need to choose the 13-h, 24-th, 27-th, experiments respectively.

Since had several variants of experiments, checked the condition of λ_{Nmin} for the *i-th* experiment $\lambda_{min} \times \rho^3\delta^2$ for this task to define the value of the radius of the sphere, which limits the admissible area:

$$\rho = \left(0.1\times\left((-42.324)^2+(-0.024)^2+...+(-0.0001324)^2\right)\right)^{\frac{1}{2}} = 13.384$$

For the first case, when $\lambda_{Nmin} = 1.717 \rightarrow 1.717 \cdot 13.3842 \geq 0.028$. For the second case, when $\lambda_{Nmin} = 2.225 \rightarrow 2.225 \cdot 13.3842 \geq 0.028$, For the second case, when $\lambda_{Nmin} = 2.86 \rightarrow 2.86 \cdot 13.3842 \geq 0.028, = 2.86.$

The condition is fulfilled in all cases, so could stop at the 13-th experiment.

To determine the influence of the coefficients, the polynomial equation, b, we determine the estimates of the influence of β in 13 experiments. To do this, defined a system of equations of type $\overline{C} \times \vec{\beta} = \vec{\alpha}$, where $\overline{C}$ is the matrix of values of the coefficients for unknown β; $\vec{\beta}$ is the vector of unknown impact estimates; $\vec{\alpha}$ is the vector of the obtained values, when substituting the measured values into the received function of type (2). Defined the elements of the matrix C. For decision this task, calculated values for 13 experiments in substituting the values of F and t, which take the values of ΔF, Δt, F_{aver}, t_{aver}.

$$y_1 = -41.924 + 0.00485 \cdot 2020 - 0.000104 \cdot 2020^2 - 0.0000008804 \cdot 2020 \cdot 35 + +0.000006855 \cdot 35^2 - 0.024 \cdot 35 = -39870$$

.....

$$y_{13} = -41.924 + 0.00485 \cdot 20 - 0.000104 \cdot 20^2 - -0.0000008804 \cdot 20 \cdot 60 + 0.000006855 \cdot 60^2 - 0.024 \cdot 60 = -47.172$$

By the same formula calculated k - values of correlation coefficients for each of the experiments. To do this, instead of the values of the arguments F and t, substituted the value -1. 0. 1, which correspond to ΔF, Δt, F_{aver}, t_{aver} [14-18]:

$$k_1 = -41.924 + 0.00485 \cdot 0 - 0.000104 \cdot 0^2 - 0.0000008804 \cdot 0 \cdot 0 + +0.000006855 \cdot 0^2 - 0.024 \cdot 0 = -42.324$$

.....

$$k_{13} = -41.924 + 0.00485 \cdot 1 - 0.000104 \cdot 1^2 - 0.0000008804 \cdot 1 \cdot 1 + +0.000006855 \cdot 1^2 - 0.024 \cdot 1 = -42.31$$

Then formulated the experimental values of y by means of proportion. The empirical $y_1 = 1$ corresponds to the true $y_1 = -39866.222$. Created the proportion [14, 15].

$$1 \rightarrow -39866.222$$
$$y_1 \rightarrow 19700.14.$$

Defined y_n in 13 measurements:

$y_{meas\ 1} = -39866.222$ $y_{cal\ 1} = 19700.14$

$y_{meas\ 2} = -157669.583$ $y_{cal\ 2} = 78240.627$

……

$y_{meas\ 13} = -47{,}172$ $y_{cal\ 13} = -39{,}787.$

The next step is to determine the real experimental values of y for the equation of type (2), taking into account the calculated values of y and the correlation coefficients k:

$$y_1 = \frac{-42.32 \times -39866.222}{19700.14} = 85.649$$

......

$$y_{13} = \frac{-42.31 \times -47.172}{-39.787} = -50.162$$

Used these values to find the coefficients of α [14]:

$$\alpha_{11} = 85.649 \cdot 1 + 85.359 \cdot 1 - 49.159 \cdot 1 +,...,+ 85.361 \cdot 1+ 85.357 \cdot 1 - 48.857 \cdot 1-50.162 \cdot 1=690.194;$$
$$\alpha_{16} = 85.649 \cdot 0 + 85.359 \cdot 0 - 49.159 \cdot 0 +,...,+ 85.361 \cdot -1+ 85.357 \cdot -1 - 48.857 \cdot -1-50.162 \cdot -1=424{,}947.$$

Next, defined values of elements of the matrix C [14]

$$C_{11} = 1^2 + 1^2 + 1^2 + 1^2 + 1^2 + 1^2 + 1^2 + 1^2 + 1^2 + 1^2 = 12;$$
$$C_{12} = C_{21} = 0 \cdot 1 + 0 \cdot 1 - 0 \cdot 1 + 0 \cdot 1 + 0 \cdot 1 - 0 \cdot 1 + 0 \cdot 1 + 1 \cdot 0 - 1 \cdot 0 + 1 \cdot 0 = 0;$$
$$C_{22} = 0^2 + 1^2 + (-1)^2 + 0^2 + 1^2 + (-1)^2 + 0^2 + 1^2 + (-1)^2 + + 1^2 = 8; ...$$

Matrix C and Matrix α will have the following view:

$$C = \begin{bmatrix} 12 & 0 & 0 & 0 & -2 & -2 \\ ... & ... & ... & ... & ... & ... \\ 2 & -2 & 0 & 0 & -1 & 10 \end{bmatrix} \qquad \alpha = \begin{bmatrix} 690.194 \\ ... \\ 424.947 \end{bmatrix}$$

From these matrices, created a system of equations to determine impact estimates [14].

$$\begin{cases} 12\times\beta_0 + 0\times\beta_1 + 0\times\beta_2 + 0\times\beta_3 - 2\times\beta_4 - 2\times\beta_5 = 690.194 \\ .... \\ 2\times\beta_0 - 2\times\beta_1 + 0\times\beta_2 + 0\times\beta_3 - 1\times\beta_4 + 10\times\beta_5 = 424.947 \end{cases}$$

Solving the obtained system of equations got:
$\beta_0 = -41.8760; \beta_1 = 0.00474258; \beta_2 = - -0.000099108; \beta_{11} = -0.00000087074879; \beta_{12} = -0.0000069107; \beta_{22} = -0.0242724525$. In the coefficients β_n and b_n they are slightly different. Need to calculate an error in the calculations of the coefficients β_n. Defined $\Delta\beta_n$ with the coefficients previously obtained: $b_0 = -41.924; b_1 = 0.00485, b_2 = -0.000104, b_{11} = -0.0000008804, b_{12} = 0.000006855, b_{22} = -0.024$.

$$\Delta\beta_0 = \left(\frac{-41.924 - (-41.8760)}{-41.924}\right)\times 100\% = 0.114$$

According to this principle, we calculate for other coefficients: $\Delta\beta_1=2.215\ \%$, $\Delta\beta_2=4.703\%$, $\Delta\beta_{11}=1.096\%$, $\Delta\beta_{12}=0.813\%$, $\Delta\beta_{22}=-1.135\%$. The largest error was obtained when calculating β_2. Thus, the results of the calculation showed that at this interval of AFC for the investigated type of PT, in order to adequately assess the technical state of the PT, 13 measurements should be made.

In order to determine the technical state of the PT, the optimal number of measurements was calculated to confirm or refute such damage as the "Axial displacement of turns".Thus, according to [1] the result of comparison of the AFC showed that the deviation of the average AFC of the investigated PT from the parameters of the generalized typical AFC does not exceed 2%.

Conclusions

The analysis of the existing methods of technical diagnostics of the PT indicates the high informativeness of the method of investigation of the frequency response of the PT, reveals damage to the windings of the PT, the magnetic circuit (core), the deterioration of the insulation and the contact connections of the windings, even at an early stage of their development.

The peculiarities of the method of creating D optimal plans of the transformer frequency response measurements are that, based on the equivalence theorem, a computational procedure was created, which allows us to construct continuous D-optimal plans for an arbitrary shape of the planning area G.

In the implementation of continuous D-optimal plans, a consistent experimentation strategy is applied in practice, at which the point of setting a new experiment is determined based on the results of previous experiments.

On the example of PT type TMG 1000/10 it is determined that 13 measurements are required to evaluate the condition of the PT during the interpretation of the results of the frequency response measurements.

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