Determination of Technical Condition of the Power Transformer by Frequency Response Analysis Method

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***Abstract*—In 10 kV electrical distribution networks, many power transformers have been in operation for more than 25 years, which exceeds their passport life and in conditions of rapid growth of power generated by photovoltaic stations can cause a decrease in the reliability of these networks. Therefore, it is necessary to improve the quality of modern means of determining the technical condition of such transformers. It is proposed to determine the defective node of the transformer by comparing the current frequency response of the studied transformer with the sample, which is obtained by averaging the values of the frequency characteristics of other transformers, the same type with the test.**

Keywords—power transformer, technical condition, frequency response analysis method, diagnostics.

I. Introduction

The power transformer is an important electrical device for all power grids of all countries [1-3]. It should be noted that the quality operation of the power system depends on reliable operation power transformers as a whole [4-6]. It directly depends on the residual life of the power transformer [7, 8]. Therefore, maintaining the power transformer in good condition is an important task for enterprises operating power transformers. However, more than 40% of power transformers (PT) of distribution electric networks have worked for more than 30 years, which exceeds their passport life (25 years). However, the authors [9-13] argue that the technical condition of PT depends on how to operate PT. Often PT defects occur throughout the operation of the PT, taking into account the complexity and specificity of the PT.

Nowadays, the number of photovoltaic stations (PVSs), their number, and the electric power generated by them are growing rapidly in Ukraine [14-18]. These PVSs are often controlled by the voltage transmitted through the distribution networks of the regional power supply companies. PVSs inverters are nonlinear elements of distribution networks. PVSs have a variable generation schedule depending on weather conditions, causing transients, the appearance of harmonics of high to low (compared to industrial frequencies) changes in currents and voltages in the equipment of 10 kV enterprises of district power grids during on and off PVSs. The uncoordinated growth of the generated electric power of the PVSs causes overloading of the PT of the enterprises of the district electric networks, which is especially dangerous in the conditions of operation of transformers with the low residual resources. However, according to the authors of [2, 19, 20], frequent damage to the PT in Ukraine is damage to the windings and magnetic circuit of the PT. Given the large number of 10 kV PTs operated in power grids and PVSs, there are currently no monitoring systems for their technical condition. Therefore, it is necessary to introduce means of periodic monitoring of the state of the PT in order to qualitatively detect damage to the windings and the magnetic circuit of the PT, even at an early stage of their development.

One of the ways out of this situation is their timely maintenance, timely decommissioning of PTs for repair or replacement of PTs with new ones [19], which allows the operating company to improve the reliability of PTs and maximize their service life. Nowadays, many methods and means of determining the technical condition of PT are known. Currently, in Ukraine, there are methods for determining the technical condition of PT, which, for example, by controlling the tangent of the dielectric loss angle tgδ, chromatographic analysis of gases dissolved in transformer oil, measuring the idle power P_{idp}, allow to detect defects of PT windings and magnetic conductors at an early stage [2]. However, the amount of damaged power transformers continues to increse [21-23]. This indicates that it is necessary to improve not only the existing methods and means of monitoring the technical condition of PT, but also to ensure a qualitative analysis of the results of control, testing, and measurement of diagnostic parameters. Decisions about the current technical condition are substantiated by analyzing the detected PT defects at an early stage of their development [21-23]. So the topic of the article is relevant.

To implement such a task requires a reliable diagnostic tool. One of the modern methods of diagnosis is the method of analysis of frequency characteristics (FC) of power transformers.

The method of Frequency Response Analysis (FRA) PTs diagnosis using the FRAnalizer device is accurate and, most importantly, a non-destructive method for studying the mechanical integrity of transformer assemblies, especially in terms of determining the technical condition of windings and magnetic circuit [23-26].

The authors in [19] claim that if the normative base of frequency characteristics is accumulated, then during the determination of the technical condition, it is possible to perform the study of PT, and determine its technical condition. However, from [19], it is known that the statement about the current state of PT in Ukraine is limited by the lack of regulatory technical documentation. This limits the ability to take full advantage of costly equipment such as FRA Analysis. At the same time, the authors [23-25] investigate the possibility of accurate interpretation of the obtained results, which under certain conditions will allow to confidently judge the current technical condition of PT, and even predict further actions that will increase the reliability of PT.

In papers [23-25] presented the results of research, during the analysis of which, from the accumulated frequency response database, data corresponding to a random error was removed. However, the authors of this work, after a more extensive analysis, propose to consider this phenomenon, not as a random error during measurements and analysis of the results, but as an indicator that characterizes the deviation of the frequency response from normal and indicates a probable defect at an early stage development.

In this article, it is proposed to investigate the significance of the effect of abrupt deviation of the measured frequency response parameters from the previously obtained values, to confirm the possibility of the existence of PT damage at an early stage of their development.

II. The Goal and Tasks

The main goal of the research, the results of which are presented in the paper, is to analyze the obtained frequency characteristics of the power transformer and determine its technical condition based on the results of their analysis.

In accordance with this goal, the following tasks are solved in the work:

1. Investigate the decommissioned 10 kV substations, which are stored at the repair sites of the power supply company (Vinnytsiaoblenergo), analyze their damage and defects that are detected by analyzing the frequency characteristics of the power transformer.

2. To determine the main dependences of the parameters of the power transformer and find approximation equations for them.

3. To offer a technique for determining the optimal value of frequency of the test signal, which must be used to detect a defect in the transformer.

4. Determining the conformity of the informative frequency corresponding to the defect is carried out by own observations and analysis of literature sources.

5. On the example of a power transformer in operation to confirm or deny its good technical condition.

III. Damaged and Repaired Power Transformers of 10 kV

When deciding on the possibility of further operation or the feasibility of changing the mode of operation of PT, operating companies must take into account the risk of failure of PT [19]. However, the problem with determining the probability of damage is that this figure is usually low. This is often due to the small amount of qualitative statistical information that can be analyzed.

In order to increase the quality of statistical information on the frequency response parameters, a number of experimental studies were conducted at the power supply enterprises operating voltage level 6-35 kV in Vinnytsia, Khmelnytsky, and Kherson regions in Ukraine (Fig.1: (a) 10 kV PTs that have failed, are in storage for repair and a device for analysis of their technical condition FRAnalizer; (b) 35 kV PTs before and after repair; (c) windings of the damaged PT of 35 kV).

The studies were performed on PTs that are in operation and on PTs that have been taken out of operation, in order to determine their damage, at the place of their operation using the method of analysis of parameters of amplitude-frequency characteristics of PTs [19, 23-25]. Damaged PTs stored at the repair sites of power supply company (Vinnytsiaoblenerho) were also tested (Fig. 2: (a) 10 kV power transformers damaged during repair; (b) repaired and damaged 10 kV power transformers and diagnostic equipment during diagnostics). Most of the 10 kV PTs have been in operation for over 25 years. Studies of PTs stored at the repair sites of the power supply company (Vinnytsiaoblenerho) showed that

(a) (b) (c)

Fig. 1. Investigated PTs.

Fig. 2. Damaged and repaired power transformers of 10 kV section of repair of PTs power supply company (Vinnytsiaoblenergo).

their frequent damage is damage to the windings and magnetic circuit, which were detected by analyzing the frequency characteristics of the transformer, and confirmed later, during the opening of the tank by operating personnel.

A modern and promising method of diagnosing PTs is the method of FRA. It is known that the power transformer is a complex diagnostic system that can be represented as a quadrupole (four-terminal network). If the input of such a quadrupole is supplied with a "test" voltage of sinusoidal shape of different frequencies, then the output will receive the voltage of the signal "response" to the test voltage of different frequencies.

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The modulus of the complex transmission factor of the quadrupole is by expression (1):

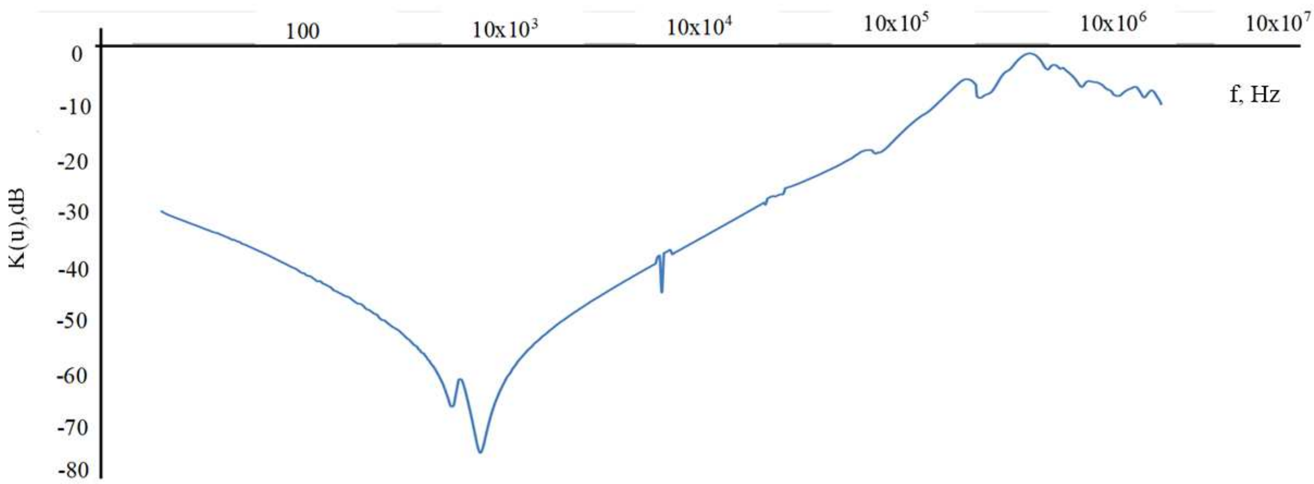

Fig. 2. The graph of the dependence of k on the frequency f PT (phase B) was obtained during research at one of the PVS in the Khmelnytsky region.

$$K(f)=\left.\frac{U_{t\_in}}{U_{t\_out}}\right|_{f=\mathrm{var}}, \qquad (1)$$

where U_{t_in} is the amplitude value of the voltage of the "test" signal at the input of the device (at the output of the quadrupole), U_{t_out} is the amplitude value of the voltage of the "test" signal at the output of the device (at the input of the four-terminal), f is the variable frequency of the "test" signal:

$$u_{out.(t)} = U_{t\_out}\cdot \sin(\omega t+\psi_{out}) \text{ and } u_{in.(t)} = U_{t\_in}\cdot \sin(\omega t+\psi_{in}), \qquad (2)$$

ω is angular frequency of the "test signal", $u_{in.(t)}$ and $u_{out.(t)}$ are instantaneous voltage values for time t, ψ_{in} and ψ_{out} are initial phases of voltages at the input and output of the device. The well-known method of PT diagnosis used involves the use of the FRAnalizer device. During the research, the voltage, which had the shape of a sinusoid of automatically variable frequency and constant amplitude (from the output of the device) was applied to one of the phases of the high voltage winding of the studied PT. The "test" voltage of one of the phases of the low (or medium) voltage winding was applied to the input of the device FRAnalizer.

Hardware and software for each of the fixed frequencies, the voltage at the output of the device FRAnalizer (hereinafter the device) were determined by the transformation coefficient of PTs $k(f)$, as the ratio of the measured voltage amplitude values at the input $U_{amp.\_in(f)}$ of the device (for each value of frequency f in the range from 10 Hz to 20 MHz) to amplitude values of voltage at the output $U_{amp.\_out(f)}$ of the device (does not depend on frequency).

Next, in order to facilitate the analysis of the results, modulus of the complex transfer coefficient k of the quadrupole is presented the in logarithmic units by the following expression for each of the frequencies used during the research f [19]:

$$k = 20\cdot \log_{10} U_{amo.in,f}/U_{amp.out}, \text{ [dB]}. \qquad (3)$$

This allowed us to construct graphs of the dependence (hereinafter - the graph) of the coefficient k depend on f, one of which is shown in Fig. 3. This curve built for oil-immersed transformer 1000 kVA 10 kV, which is installed at one of the PVS, located in the Khmelnytsky region, Ukraine.

During the processing of the obtained graphs, in the frequency range of the test signal 6060 ÷ 7010 Hz, the deviation of the current values of the coefficient k from the values of the frequency f (on which k is measured) of the sample graph (Table 1 and Fig. 4).

For the values of the parameters of the sample schedule, we propose to take the average values of the coefficient k according to the results of studies of serviceable (identical to the studied) power transformers that were obtained, or research results when the transformer was found to be serviceable (according to tests at the enterprise during the commissioning of the studied PT).

During the study of the state of PT, only those measurement results were taken into account, in which the deviation of the current values does not exceed the error of FRAnalizer (2%), in accordance with the recommendations [19].

Thus, the method of determining the frequency of the test signal, which must be taken into account to detect a defect in the transformer corresponds to the above expressions, to construct the amplitude-frequency characteristic (AFC).

TABLE I. DEVIATIONS OF FR CHARACTERISTICS

F	k	$k_{average}$
Hz	*dB*	
6060	-39.38	-40.38
6210	-39.16	-40.16
6360	-68.95	-39.95
6520	-38.72	-39.72
6680	-38.51	-39.51
6840	-38.29	-39.29
7010	-38.08	-39.08

The next step, during the study, was determined by the standard deviation of the obtained values (4):

$$\sigma=\sqrt{\sigma^2}=\sqrt{\frac{1}{N}\cdot\sum_{i=1}^{n}\left[k_i-\overline{k}_{average}\right]^2}, \qquad (4)$$

where N is the number of measured points for different frequencies, k is the value of the coefficient, $k_{average}$ is the average value of the coefficient of averaged values.

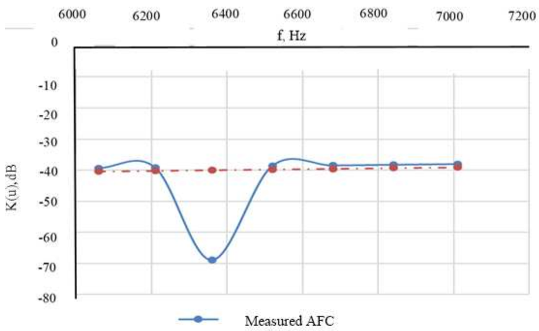

Fig. 3. Comparison of the obtained graph AFC (phase B study).

Then by (5), the average value of the coefficient of the transfer function of the averaged values [27]:

$$\overline{k}_{average}=\frac{\sum_{i=1}^{N}k_{i\_average}}{N}, \qquad (5)$$

$$\overline{k(u)}_{average}=\frac{-40.38-40.16-39.95-39.72-39.51-39.9-38.08}{7}=$$
$$=-39,7271(dB).$$

The next step in (4) is the standard deviation of the obtained values:

$$\sigma=\left\{\frac{1}{7}\cdot\left[\begin{array}{c}(-39.38-(-39.7271))^2+(-39.16-(-39.7271))^2+\\+(-68.95-(-39.7271))^2+(-38.72-(-39.7271))^2+\\+(-38.51-(-39.7271))^2+(-38.29-(-39.7271))^2+\\+(-38.08-(-39.7271))^2\end{array}\right]\right\}^{\frac{1}{2}}=11.095\,dB$$

Using the rule $|k - k'| > 2\sigma$, [27] at a confidence level of $P=0.95k$, the measurement results at such points were removed and were not taken into account in further calculations and the conclusions were not affected. But a decision was made on the good condition of the PT.

However, during additional measurements of the AFC PT, which took into account the required number of repeated (according to [19]) measurements of the AFC, the results are presented in Table 2 and in Fig. 5.

TABLE II. THE VALUE OF THE TRANSFER FUNCTION AT THE POINTS

F	k_1	k_2	k_3	k_4	k_5	k_6	k_{av}
Hz	*dB*						
6060	-38.38	-40.04	-38.25	-39.39	-39.32	-42.08	-40.38
6210	-38.16	-37.52	-35.93	-39.17	-35.63	-41.09	-40.16
6360	-67.95	-68.95	-76.80	-69.95	-81.03	-72.25	-39.95
6520	-37.72	-35.16	-36.62	-38.63	-38.02	-34.58	-39.72
6680	-37.51	-38.34	-34.14	-38.42	-35.49	-36.84	-39.51
6840	-37.29	-38.55	-40.03	-38.32	-38.75	-40.73	-39.29
7010	-37.08	-39.45	-37.10	-38.11	-39.91	-41.07	-39.08

These results should already be taken into account to substantiate the conclusions about the current technical condition of the PT and when deciding on the features of further operation of the transformer under study.

As you can see after repeated measurements, and a more thorough study of the obtained frequency response, a sudden deviation of the frequency response is observed in all obtained frequency response, during repeated experiments.

Therefore, taking into account the specifics of the study and [16] the frequency response can describe the change in the parameters of the replacement circuit of the windings of the PT, and describe the state of the PT.

IV. DISCUSSION OF THE OBTAINED RESULTS

As we can see from the research, it is necessary to take into account the recommendations of the authors [5, 23-25], and when planning the frequency response measurements, to determine the optimal number of measurements. Such solutions will reduce the measurement error and evaluate the obtained frequency response values at a sufficient level.

During the study, in the example presented in this article, the fluctuations of the measured values of the transfer function were taken as a mistake and removed from the results of the study. However, according to the recommendations of [23-25], the measurement according to one circuit of the measuring device was performed repeatedly, taking into account the optimal number of required measurements. During the analysis, the deviations that were previously removed were observed during each of the subsequent measurements at a frequency of 6060 ÷ 7010 Hz, which according to the results of our own observations and analysis of literature sources [5], [23-25], is defined as the correspondence of informative frequency, which corresponds to the probable defect "radial displacement of the turns" at an early stage of development.

Therefore, in the future a number of additional measures were taken to determine the technical condition of the PT, during which such damage was detected in Fig.1. Thus, the conducted researches, and additional diagnostic measures, allowed to confirm its actual technical condition on the example of PT, which is in operation of PVS.

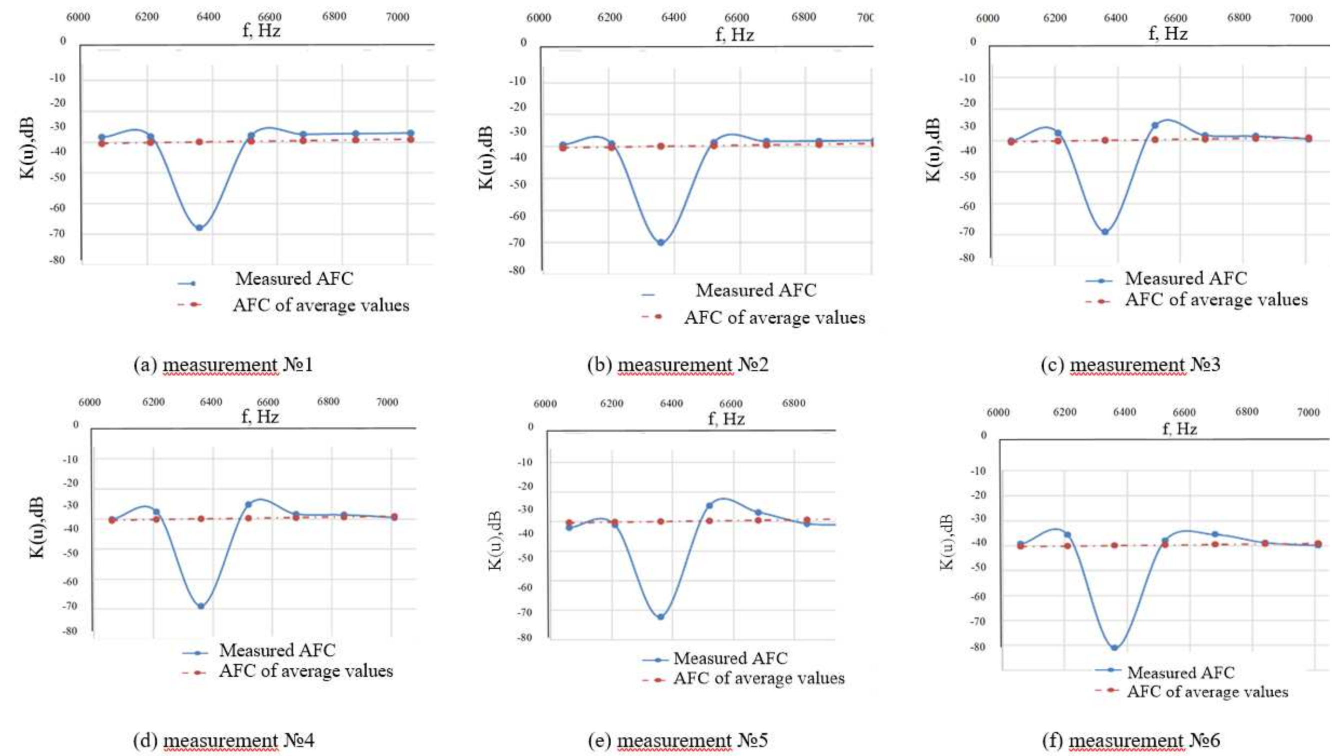

Fig. 4. Deviations observed in repeated studies.

V. Conclusions

1. Investigations of decommissioned 10 kV substations stored at the repair sites of the power supply company show that many of their damages are damages of windings and magnetic conductors, which can be detected by analyzing the frequency characteristics of the transformer.

2. An exemplary graph AFC a power transformer is a graph showing the average values of the transmission factor of the test signal of the device FRAnalizer (transformation factor) for the power transformer. AFC for different types of serviceable transformers depend on the frequency of the test signal. Only the results of the transmission factor measurements are taken into account and only the number of measurements in which the deviation of the current values does not exceed the FRAnalizer error (2%).

3. The frequency of the test signal that must be taken into account to detect a defect corresponds to the frequency at which the deviation of the value of the transmission coefficient of the frequency characteristic of the transformer under study differs from the value of the transmission coefficient AFC.

4. On the example of the investigated power transformer type 1000 kW 10 kV, its serviceable technical condition is confirmed. However, in the frequency range 6060 ÷ 7010 Hz, abrupt deviations were observed, which were previously removed from the calculations, considering them a miss.

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