Automation of diagnostic tools for agricultural power transformers

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Abstract. Power transformers are the main elements of power supply systems and are used in agriculture and industry. When testing an agricultural power transformer, no-load and short-circuit modes play an important role. The system for checking the power transformer is proposed to implement using a modern digital analyzer. Part of the measurements should be performed without disconnecting the power transformer from the network. At the same time, the test time is reduced, the accuracy and the ability to automate the processing of measurement results are increased.

1. Introduction
The reliable operation of rural electrical networks of the Russian Federation depends on the reliability of power transformers, a significant number of which have worked for a specified service life of 25 years.

One of the ways to extend the operation of agricultural power transformers is to diagnose their technical condition. Diagnostics allows preventing emergencies, reducing repair costs, assessing the condition of the transformer, and determining the margin of its operability. The cost of the power transformer TRDCN 63000/110/10/10 is within 30 million rubles (in 2010 prices), an overhaul is about 1 million rubles. In turn, the diagnosis of its technical condition is ten times less [1].

2. Materials and methods
Employees of the Department of the Application of Electrical Energy in Agriculture of the Stavropol State Agrarian University performed work on the automation of diagnostic tools for power transformers for agricultural purposes (Fig. 1).

The work uses a modern power quality analyzer PQA-824 (from now on "analyzer") and a personal computer [2].

Measurements during diagnostic work can be carried out on a transformer disconnected from the network and under load.

On the separate transformer, the ohmic resistance of the windings is measured. In this case, it is possible to detect a break in one or more of the parallel wires in the taps, a violation of soldering, poor contact of the connection of the winding taps to the bushings, and other defects.

When checking the group of connections of the windings of power transformers, the incorrect marking of the transformer bushings is detected, the wrong connection of the winding taps to the bushings.
The central importance in testing a power transformer is played by the no-load and short-circuit modes [3].

In no-load mode, it is possible to determine the transformation ratio of the transformer, no-load current, no-load losses.

During the operation of the transformer, no-load losses increase due to mechanical effects on the magnetic circuit due to heating of the magnetic circuit. Prolonged heating leads to structural changes in the magnetic circuit, due to which the magnetic properties of the magnetic circuit deteriorate. The manufacturer coordinates the process with the consumer with the harmonic composition of the no-load current.

The windings determine the limiting state of the power transformer. The technical condition of the windings is assessed by the absence of dangerous deformations of the windings. The deformation of the transformer windings is determined through the relative change in the short-circuit impedance ($\Delta Z_k = 3\%$) [3]. Determination of the short-circuit impedance $Z_k$ of the transformer is carried out during its operation (after the action on the transformer exceeding 70 % of the calculated value of the short-circuit current), during overhaul (on transformers with a capacity of 125 MVA and more, with a voltage of 110 kV and above) and is compared with the original ones. There are other methods for detecting deformation of the windings, for the implementation of which it is also necessary to disconnect the power transformer from the network [4-6]. In this case, high-precision instruments are used. Measurements must be carried out by specially trained personnel.

Mechanical deformations of the windings have a detrimental effect on the life cycle of power transformers of lower power and lower voltage class. Thus, the Ryazan City Distribution Networks MUP includes about 800 transformer substations with transformers ranging from 20 to 1000 kVA. About 20 % of failures occur due to electrodynamic stability changes of the windings and insufficient dielectric strength of the coil insulation. Statistical data on failures of 10 / 0.4 kV transformers with a capacity of 100-400 kVA show that the annual failure of power transformers in rural distribution networks is more than 55 % due to turn faults in the windings [7]. Turning fault is most often the result of dynamic loads acting on the winding during short circuits.

The most effective and less costly method is to identify the deformation of the windings by the parameters of the zero-sequence of the normal mode. When we use this method, it is possible to detect early deformation of the windings without disconnecting the power transformer from the network [8]. To determine the relative deviation of the short-circuit resistance of the transformer $\Delta X_{km}/X_k$, it is sufficient with the known before deformation $Z_N$ – the neutral resistance, $X_k$ – the short-circuit resistance, $X_0$ – the zero-sequence resistance, in the normal mode of the transformer after an external short circuit, the first harmonics of the zero-sequence voltage, the
current in the neutral and current in the HV winding of one or two deformed phases. According to the change in the short circuit resistance of the transformer $\Delta X_{\nu} / X_{\kappa}$ after an external short circuit, the relative change in the short circuit resistance $\Delta Z_{\kappa}$ is determined.

Diagnostics of the deformation of the windings of a power transformer are based on the use of a zero-sequence equivalent circuit of an asymmetrical three-phase transformer (Fig. 2).

![Figure 2. Equivalent circuit of the zero-sequence of an asymmetric three-phase transformer: $R_1, R_2$ – electrical resistances of the primary and secondary windings; $Z_N$ – grounding resistance; $X_{\mu0}$, $X_{\nu}$, $X_{\text{cmv}}$ – reactive resistances of zero sequence magnetization, short circuit and no-load stroke of the rod $\nu$ – that phase; $\dot{U}_0, \dot{I}_0$ – voltage and current of the zero-sequence of the HV winding; $\dot{I}_{\mu0}, \dot{I}_{\mu c0}$ – the current that magnetizes the space outside the magnetic circuit, the current of the zero-sequence magnetization of the rods.](image)

Deviations of the reactance of the two phases from the corresponding short-circuit resistance of a particular phase, for example, A:

$$\Delta X_{\nu} = X_{\nu} - X_{\kappa}; \quad \Delta S = X_{\kappa} - X_{\nu};$$

$$\Delta X_{\text{stv}} = X_{\text{stv}} - X_{\text{st}}; \quad \Delta X_{\text{sts}} = X_{\text{sts}} - X_{\text{cst}}.$$  

EMF of zero sequence due to inequalities of short-circuit resistances and inequalities of no-load resistances of phases

$$\Delta \dot{E}_{k0} = (j\Delta X_{\nu} / 3)(\dot{I}_{1\nu} - \dot{I}_{\mu0}) + (j\Delta X_{\text{st}} / 3)(\dot{I}_{1c} - \dot{I}_{\mu0});$$

$$\Delta \dot{E}_{\text{st0}} = (j\Delta X_{\text{st}} / 3)\dot{I}_{\mu\text{stv}} + (j\Delta X_{\text{st}} / 3)\dot{I}_{\mu\text{sts}}.$$  

The sum of three components can replace the neutral current $\dot{I}_N = 3\dot{I}_0$ of an asymmetric transformer: due to the zero-sequence voltage $\dot{U}_0$ on the HV buses – $\dot{I}_N'$; determined by the asymmetry of the windings $\Delta \dot{E}_{k0} - \dot{I}_N''$; caused by the asymmetry of the magnetic circuit $\Delta \dot{E}_{\text{cst}} - \dot{I}_N'''$. The parameters of the zero-sequences equivalent circuit are determined experimentally. Expression for the neutral current at

$$\dot{I}_N = \dot{I}_N' + \dot{I}_N'' = \frac{3\dot{U}_0}{jX_0 + 3Z_N} - \sum_{v=B,C} \frac{j\Delta X_{\kappa}}{jX_k + 3Z_N} \dot{I}_v.$$  

From (1), it is possible to determine the relative deviations of the short-circuit resistance of the transformer $\Delta X_{\nu} / X_{\kappa}$. Based on these changes after an external short circuit, the relative change in the short circuit resistance $\Delta Z_{\kappa}$ is calculated.
Detection of deformed windings makes it possible to take the transformer for repair, with the subsequent replacement of damaged units.

3. Results

Determination of the idling parameters of the power transformer was implemented on the model of the power transformer. A three-phase transformer with a power of 1.6 kVA, rated voltage 380/220/127 V, U-D / U-D circuit, no-load current 20 %, and efficiency 94.5 % was used as a power transformer model.

The no-load test was implemented by the method of phase-by-phase excitation of the windings. For greater measurement accuracy during the open-circuit test, the primary winding was the low voltage winding, and the second one was the high voltage winding. With phase-by-phase excitation of three-phase transformers, three experiments were carried out.

First experiment: short-circuiting the winding of phase \(a\), excited the windings of phases \(b\) and \(c\), measured the current and no-load losses \(I_{bc}, P_{bc}\) (Fig. 3).

The second experiment: short-circuited the winding of phase \(b\), excited the windings of phases \(a\) and \(c\), measured the current and idle losses \(I_{ac}, P_{ac}\). Third experiment: short-circuited the winding of phase \(c\), energized the windings of phases \(a\) and \(b\), measured the current and idle losses \(I_{ab}, P_{ab}\). Each experiment was carried out 5-7 times, then statistical processing of the measurement results was carried out. In the course of the experiment, we used the analyzer. Table 1 presented the results were obtained.

**Table 1. Results of the experiment of the no-load operation of a three-phase transformer**

| Voltage applied to phases | Phase closed | Voltage, V | Current, A | Losses, W |
|---------------------------|--------------|------------|------------|-----------|
| a–b                       | c            | 73.3       | 0.183      | 4.91      |
| b–c                       | a            | 73.3       | 0.173      | 4.84      |
| a–c                       | b            | 73.3       | 0.254      | 6.81      |

From Table 1, it follows that the losses \(P_{bc}\) and \(P_{ab}\) differ by 1.5 %. Losses \(P_{ac}\) are greater than losses \(P_{bc}\) and \(P_{ab}\) by no more than 40 %. These results show that the transformer is in good working order.

Figure 4 shows the current waveform for an open-circuit test with short-circuited phase \(b\).
Figure 4. Oscillogram of the current for an open-circuit test with a short-circuited phase $b$

Figure 5 presents the harmonic composition of the no-load current for an open-circuit test with short-circuited phase $b$.

Figure 5 shows that the no-load current distortion occurs due to the current's third and fifth harmonic components.

In [8], the determination of the deformation of the windings of a power transformer in laboratory conditions was checked. A check was carried out to identify the deformation of the windings of the power transformer by modeling the longitudinal unbalance of the transformer using a choke. The test results show that in the range of the inductor resistance from 0.8 to 8% of the phase short-circuit resistance, the relative error of the indirect measurement of the inductor resistance does not exceed 10% on average. These results show that the method for detecting deformation of the windings of power transformers by the parameters of the zero-sequence of the normal mode has been successfully tested in laboratory conditions.
The application of the method for detecting deformation of windings is possible for sensitive relay protection of a power transformer against a turn short circuit and for improving devices for monitoring the insulation of the bushings of a power transformer.

4. Conclusion
Using the PQA-824 power quality analyzer for automation of diagnostic tools for a power transformer for agricultural purposes simplifies and speeds up measurements and raises the test and diagnostics of a power transformer to a new level of quality. These results are important for using the analyzer in rural distribution networks. The use of a personal computer is necessary to obtain updated diagnostic results and facilitates the work on the formation of databases for the serviced equipment.

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