Development of a system for ensuring sustainable power supply to agricultural consumers based on an electronic model

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Abstract. In agriculture, single-transformer consumer substations are widely used. Failure of a transformer in such a substation adversely affects the reliability of power supply to agricultural consumers. The most common reason for the failure of consumer transformers (over 50%) is turn-to-turn short circuits in their windings. Therefore, timely diagnostics of turn-to-turn faults in the windings of such transformers is an urgent task. In this case, it is necessary to take into account the specific conditions of rural electrical networks. It is recognized as permissible to carry out diagnostics at idle running of the transformer. Designed with assumptions in mind, the diagnostic device is simple and easy to use. The operation of the device was investigated on an electronic model using the Matlab software package integrated with the design and programming environment based on Simulink models. As a result of research, it was found that the device is efficient and efficient.

1. Introduction
In agriculture, single-transformer consumer substations are widely used. Failure of a transformer in such a substation seriously affects the reliability of power supply to agricultural consumers. Meanwhile, up to 9% of transformers fail on average per year. Closing of turns in windings is the main reason (over 50%) [1-3]. The damage develops gradually and is difficult to detect at the initial stage. However, later on, when the damage develops into an internal short circuit, its consequences are so great that the restoration of the transformer will cost up to 60-65% of the cost of a new transformer.

Researchers have been working on diagnostics of damage in power transformers since the 70s of the last century. It was proposed to install the measuring devices directly into the transformer tank [4-7], but this way turned out to be unviable.
Currently, there are several competing and complementary directions, a review of which is presented in sufficient detail in various sources, for example [8-9]. The most popular are: the method of frequency analysis [10-12], the method of amplitude-phase characteristics of negative sequence currents [13-14]. Many researchers follow the path of increasing the sensitivity of the differential protection of transformers [15-17], etc. To construct diagnostic algorithms, various methods have been proposed for modeling transformers with turn-to-turn closures [18-19]. To analyze the results of diagnostics, special mathematical methods are used, for example, using artificial neural networks [20] and wavelet transforms [21]. The use of such methods is associated, as a rule, with the use of complex and expensive equipment, and also requires highly qualified specialists. Currently, such methods are used in large energy companies. In rural networks, their applications are limited.
2. Materials and methods

The specific features of the rural energy sector are the low power of consumer transformers (usually up to 1000 kV·A), a significant distance from large power units, a lack of maintenance personnel and, as a rule, a low level of personnel qualifications.

Under these conditions, an urgent issue is the creation of a device for detecting turn-to-turn faults in transformer windings that meets the requirements of efficiency, as well as ease of use.

It was assumed that diagnostics can be performed in the idle mode of the transformer [22].

It should be clarified here: a short-circuited turn (turns), regardless of its location (in the primary or secondary winding), itself forms a secondary winding loaded with a short-circuit current (figure 1).

Thus, the mode of operation of an unloaded transformer having a short-circuited turn in one of the windings, strictly speaking, cannot be considered an idle mode. However, in this article, we will conditionally call the no-load mode of the no-load transformer, neglecting the load caused by the short-circuited loop.

The signs of a short-circuited turn in the transformer winding were identified.

For this, a transformer was taken with the following parameters: \( S_{pot} = 120 \) B·A; \( U_{HN} = 220 \) B; \( U_{LN} = 20 \) B; \( w_1 = 858 \); \( w_2 = 78 \). Winding connection diagram - Y / Yn

3. Results and discussion

In the idle mode, the currents in the phases were measured. Then one of the turns in one of the phases of the HN winding was short-circuited, and the measurements were repeated.

Figure 2 shows a vector diagram of voltages and currents before closing the loop, i.e. undamaged transformer. The decrease in current in phase B (current \( I_2 \)) compared to currents in phases A and C is due to the flat design of the transformer.

![Figure 1. Diagram of a two-winding transformer: a) - until a loop closure appears; b) - after short-circuiting one of the turns of the high voltage winding.

![Figure 2. Vector diagram of voltages and currents of an intact transformer.](image-url)
Then they arranged a loop closure in the HN winding of phase A. Note that the current in phase A increases in this case.

The vector diagram of currents when a turn is closed in the winding of phase A is shown in (figure 3).

![Figure 3. Vector diagram of no-load currents of a transformer with an interturn short circuit in the winding of phase A.](image)

If the short-circuited turn is in the winding of phase B, then the vector diagram takes the form shown in (figure 4).

![Figure 4. Vector diagram of no-load currents of a transformer with turn-to-turn closure in phase B winding.](image)

If the short-circuited turn is in the winding of phase C, then the vector one will take the form shown in (figure 5).

Analysis of the vector diagrams obtained during the experiment made it possible to determine the following signs of the presence of short-circuited turns in the windings of a three-phase transformer:

- In the presence of a short-circuited turn in the transformer winding, the current in the damaged phase increases;
- The currents in the other two phases also become larger (when the HN winding is connected in a star circuit with an isolated neutral);
- Phase angles between currents change their value;
- No-load losses increase.
Taking into account the listed features allows us to develop a device for diagnosing the presence of closed turns in the transformer windings.

We used the sign of an increase in the current in the phases. The proposed device is shown in Figure 6.

The device for diagnosing the presence of short-circuited turns in the transformer windings contains current transformers TA1, TA2 and TA3, which are included in the phase conductors of the transformer. One terminal of the secondary winding of each of the current transformers is grounded, and the second is connected to a diode (in this case, respectively, to diodes D1, D2, D3) and then to a common wire, which is connected to ground through a regulating resistor R and an ammeter A. For ease of understanding the principle of operation, the circuit does not conventionally show switching devices and resistors, shunt diodes and serve to prevent the appearance of overvoltage on the windings of current transformers.

First, an experiment is performed on an undamaged transformer in no-load mode. In this case, the currents passing in the phases of the primary winding of the transformer are rectified by diodes and their rectified values are added in a common conductor. A current flows through the resistor R and the ammeter A, which is directly proportional to the sum of the absolute values of the phase currents. The resulting value is the original and is remembered (fixed).

During the operation of the transformer, it is periodically checked, during which the load is disconnected. The high voltage winding remains on. Thus, a check is performed in the idle mode of the transformer. If, during operation, a short-circuited turn appears in one of the windings, then the current in this winding will increase. In addition, as it follows from the vector diagrams presented above, currents will also increase in undamaged phases. This will cause the sum of the absolute values of the phase currents to increase from the original value. By increasing the current in the ammeter, one can judge the appearance of a short-circuited loop in one of the windings.
To study the operation of the device for diagnostics of turn-to-turn closures, an electronic model was developed using the Matlab software package integrated with the design and programming environment based on Simulink models.

The electronic model is shown in (figure 7) as a block diagram.

![Block Diagram](image)

**Figure 7.** Model of the proposed device for diagnostics of turn-to-turn circuits.

In the developed model, current transformers are replaced by AC Current Source. The currents generated by these sources correspond to the currents obtained experimentally and reflected in the vector diagrams in (figures 2-5). The Diode blocks rectify the alternating currents. After half-wave rectification, currents flow to the Series RLC Branch units, which act as a load with a resistance of 1 ohm. A Multimeter element - an ammeter is used as a current meter. The Scope block is used to obtain accurate AC current graphs. The Display shows the averaged values of the phase currents taken in absolute value.

Let’s consider the operation of the device by examples.

The first experiment: an intact transformer.

In the normal operation of the transformer at idle, the currents in the phases in accordance with the diagram (figure 2) were, according to the results of the experiment:

\[ I_a = 15,8 - j1,4 = 15,86 \cdot e^{j354,94^\circ} \text{ mA} \]  
\[ I_b = -6,59 - j11,5 = 13,25 \cdot e^{j240,19^\circ} \text{ mA} \]  
\[ I_c = -9,2 + j12,9 = 15,85 \cdot e^{j125,49^\circ} \text{ mA} \]

These currents pass through the current transformers TA1, TA2 and TA3. On an oscilloscope, these currents look like this (figure 8).
Figure 8. Graphs of currents passing through current transformers in an undamaged transformer.

Each of the phase currents is subjected to half-wave rectification and at the output of diodes D1, D2, D3, the currents take the form shown in (figure 9).

Figure 9. Graphs of currents of three phases after half-wave rectification.

The currents of the three phases are added in the common wire and through the resistor R and the ammeter A a total current passes, proportional to the sum of the absolute values of the phase currents (figure 10).

Figure 10. The graph of the sum of the rectified currents of the three phases of an undamaged transformer.

As a result of the summation, the average value of the sum of the rectified phase currents turned out to be equal to 14.25 mA. We will take this value as the initial value.

Experiment two: closing a loop in phase A.

Closing a loop in phase A of the transformer changes the ratio of the currents in the phases in accordance with the diagram (figure 3). The currents were distributed as follows:
\[\dot{I}_a = 28,0 - j12,18 = 30,53 \cdot e^{j336,49^\circ} \text{ mA} \quad (4)\]
\[\dot{I}_b = -11,9 - j1,2 = 11,96 \cdot e^{j185,79^\circ} \text{ mA} \quad (5)\]
\[\dot{I}_c = -16,1 + j13,3 = 20,88 \cdot e^{j140,44^\circ} \text{ mA} \quad (6)\]

The sum of the rectified phase currents is shown in (figure 11).

Experience has shown that the average value of the currents in the phases of the higher voltage winding of the transformer in the presence of a closed loop in phase A is 21.57 mA.

The difference between the obtained value of the sum of currents of 21.57 mA and the initial value of 14.25 mA is 7.32 mA, which can be considered an essential indicator for diagnosing the presence of short-circuited turns in the transformer windings.

Third experiment: closing a loop in phase B.

Closing a turn in phase B of the transformer also changes the ratio of the currents in the phases in accordance with the diagram (figure 4). The currents were distributed as follows:

\[\dot{I}_a = 19,93 + j4,19 = 20,36 \cdot e^{j11,87^\circ} \text{ mA} \quad (7)\]
\[\dot{I}_b = -13,31 - j23,45 = 26,96 \cdot e^{j240,42^\circ} \text{ mA} \quad (8)\]
\[\dot{I}_c = -6,61 + j19,25 = 20,35 \cdot e^{j108,95^\circ} \text{ mA} \quad (9)\]

The sum of the rectified phase currents is shown in (figure 12).

Figure 11. The graph of the sum of currents in the phases of the higher voltage winding of the transformer in the presence of a closed loop in phase A.

Figure 12. The graph of the sum of currents in the phases of the higher voltage winding of the transformer in the presence of a closed loop in phase B.
Experience has shown that the average value of the currents in the phases of the higher voltage winding of the transformer in the presence of a closed loop in phase B is 21.62 mA. The difference between the obtained value of the sum of currents of 21.62 mA and the initial value of 14.25 mA is 7.37 mA, which can be considered an essential indicator for diagnosing the presence of short-circuited turns in the transformer windings.

Experiment four: closing a loop in phase C.

Closing a loop in phase C of the transformer also changes the ratio of currents in the phases in accordance with the diagram (figure 5). The currents were distributed as follows:

\[
\begin{align*}
\hat{I}_a &= 23.09 - j10.2 = 25.24 \cdot e^{j336.17} \text{mA} \\
\hat{I}_b &= -2.3 - j18.25 = 18.39 \cdot e^{j262.82} \text{mA} \\
\hat{I}_c &= -20.7 + j28.45 = 35.18 \cdot e^{j126.04} \text{mA}
\end{align*}
\]

(10) \hspace{5cm} (11) \hspace{5cm} (12)

The sum of the rectified phase currents is shown in (figure 13).

Figure 13. The graph of the sum of currents in the phases of the high voltage winding of the transformer in the presence of a closed loop in phase C.

Experience has shown that the average value of the currents in the phases of the higher voltage winding of the transformer in the presence of a closed loop in phase C is 25.94 mA. The difference between the obtained value of the sum of currents of 25.94 mA and the initial value of 14.25 mA is 11.69 mA, which can be considered an essential indicator for diagnosing the presence of short-circuited turns in the transformer windings.

4. Conclusion
From the above, we can say that:

- The signs of the presence of a short-circuited turn in the windings of a power transformer are determined;
- A device for detecting short-circuited turns in the windings of power consumer transformers has been developed;
- An electronic model of the device has been developed using the Matlab software package integrated with the design and programming environment based on Simulink models;
- As a result of research, it was found that the device is efficient and efficient.

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