The Detection of Winding Short Circuits in Single-Phase Double-Winding Transformers

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Abstract – ***The object of this research is to offer a new method of identification of winding short circuits in power transformers of all classes. This method presents fast acting and absolute selectivity during different emergency modes. It's based on the analysis of digital values of current and voltage in transformer's windings with further calculations of active resistance.***

Key words – winding short circuit, double-winding transformer, primary winding, secondary winding, simulation model, core, external short circuit, no-load mode, load.

I. Formulation of the Problem

Currently the power electric industry provides for the introduction a large amount of modern equipment. Currently, the power system of Ukraine is standing about transient condition: obsolete equipment is taking out, but sufficiently slow, the diagnostics of different modes of the new grids with further optimization and investigation of possible problems and faults is performing. The solution of these questions must provide qualitative and non-stopping supply of electric power for consumers. By now, a lot of obsolete oil-immersed transformers are replaced with better dry-type analogs, mainly in distribution grids up to 35 kV. The absence of the effective defense against the winding short circuits is a big problem for both of them. The present defense on oil and dry transformers works relatively slow and unreliable. As a result, appears a problem of creating a new fast-acting and effective relay protection.

II. The Analysis of Latest Studies

The experience of the transformers' operation in power grids showed that the winding short circuits (the flashover of winds insulation in one winding) are the most dangerous faults. It can cause the extensive fire of power transformer. As a result, the main elements of the construction may be hardly damaged. While the injured winding of transformer can be remote and fixed, the damaged core is beyond repair. Such equipment can't be used again.

In oil-immersed transformers there is a gas protection which detects the oil breakdown products in the tank during the winding short circuits. However, this defense doesn't provide fast-acting performance, because it reacts on the latter results of an accident. Often, the breakage can progress so rapid and extensive that a transformer will be destroyed because of oil's high combustibility.

By the deficiencies of using oil transformers, there was created the analog with dry insulation and air-cooling. Here we can avoid all problems connected with the utilization of oil. On the other hand, the absence of the possibility to use gas protection is perceptible. As a result, there is no specialized defense against winding short circuits.

The analysis of transformer's structure shows that it can handle large overloads and power surges, but only during a short period of time. Thus, the insulation of winding is not designed to hold up a transmission of a big amount of power.

The investigation of distribution network's features in Ukraine showed that such modes happen sufficiently often. Therefore, appears a danger of winding short circuits in transformers. Existing relay defenses doesn't provide full protection and reliability.

III. The Main Data and Results

Essentially, the construction of the core in different types of transformer is the same. The difference is only in types of cooling system, insulation, and other definite construction features of elements. However, the working principle is the same. Thus, the identification method of winding short circuits is suitable both for oil and dry-type transformers.

To create a simulation model we used a software package «RE» [1]. It can be used transformer's technical passport data, magnetization chart of the core and the quantity of winds to construct this model.

The identification method is based on the main physical laws of magnetic fields and Theoretical Foundations of Electrical Engineering, which describe the processes in transformer. The system of equations of the transformer is shown in Eqs. (1):

$$\begin{cases} u_1 = R_1 \cdot i_1 + L_1 \cdot \dfrac{di_1}{dt} + w_1 \cdot \dfrac{d\Phi}{dt}; \\ u_2 = R_2 \cdot i_2 + L_2 \cdot \dfrac{di_2}{dt} + w_2 \cdot \dfrac{d\Phi}{dt}; \\ w_1 \cdot i_1 + w_2 \cdot i_2 - U_M(\Phi) = 0, \end{cases} \tag{1}$$

where: u_1, u_2, – voltages of the primary and secondary windings; i_1, i_2 – currents of the primary and secondary windings; R_1, R_2, L_1, L_2 – active and inductive resistances of the of the primary and secondary windings; w_1, w_2 – quantity of the winds in primary and secondary windings; Φ – main magnetic flux; $U_M(\Phi)$ – voltage drop in the core of the transfomer.

Eqs. (1) describes the processes in the electrical and magnetic circuits of the transformer; the first equation relates to the primary winding, the second – to the secondary and the third – to the core of the transformer.

To analyze the transient processes in windings correctly Eqs. (1) should be converted into the one, suitable for software package "RE". Considering this fact we differentiated and divided the third equation in Eqs. (1) by w_1. To maintain the correspondence between other two equations, we bring them to a common parameter. As a result, we obtained Eqs. (2), which is suitable for conducting experiments

$$\begin{cases} u_1 = R_1 \cdot i_1 + L_1 \cdot \dfrac{di_1}{dt} + M_{13} \cdot \dfrac{di_3}{dt}; \\ u_2 = R_2 \cdot i_2 + L_2 \cdot \dfrac{di_2}{dt} + M_{23} \cdot \dfrac{di_3}{dt}; \\ M_{31} \cdot i_1 + M_{32} \cdot i_2 - L_3(i_3) \cdot \dfrac{di_3}{dt} = 0, \end{cases} \qquad (2)$$

where: i_3 – magnetizing current in the core; $M_{31} = M_{13} = 1$; $M_{32} = M_{23} = w_2/w_1 = k_t$ – fictitious and real coefficient of transformation intended to create a simulation model; $L_3(i_3) = -R_M(\Psi_1)$ where $R_M(\Psi_1)$ – relative magnetic resistance consolidated to the square of w_1, achieved from the no-load mode experiment of the transformer.

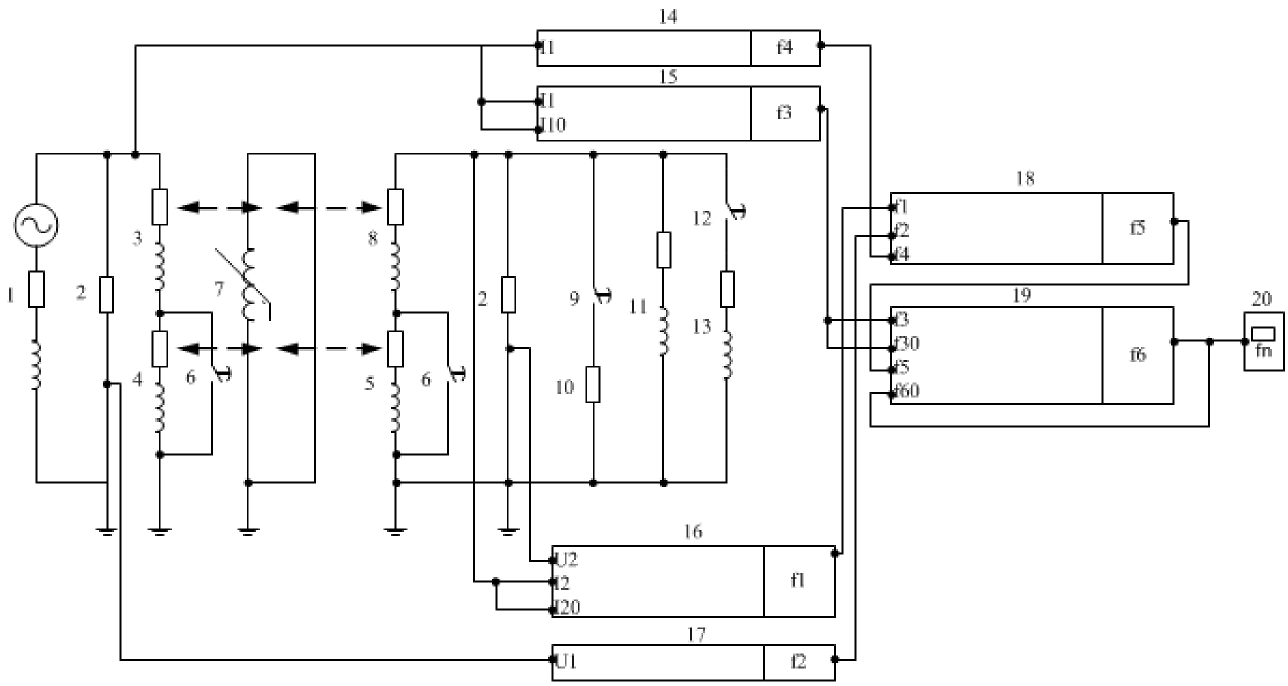
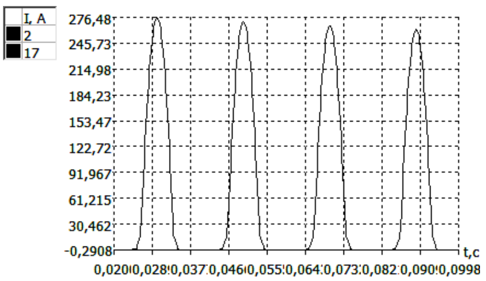
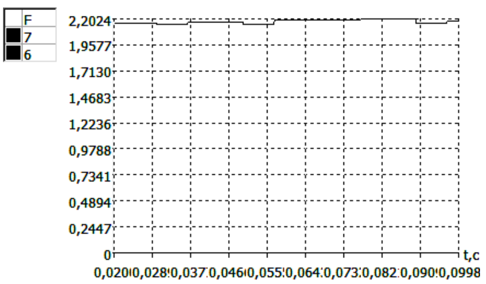


Fig. 1. Simulation model of the transformer: 1 – power grid's parameters; 2 – infinite resistances needed for obtaining primary and secondary voltages; 3, 8 – complex resistance of primary and secondary windings, respectively; 4, 5 – complex resistance of winds to be locked in primary and secondary windings; 6 – switch for imitating winding short circuit; 7 – magnetic resistance of the transformer's core; 9, 10 – branch for imitating external short circuit mode; 11 – transformer's load; 12, 13 – branch for imitating load increase; 14, 15, 16, 17, 18, 19, 20 – functional blocks, used in software package, to provide necessary calculations

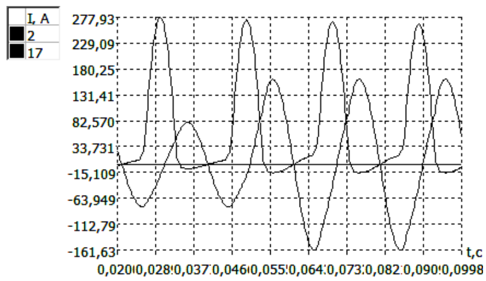


a

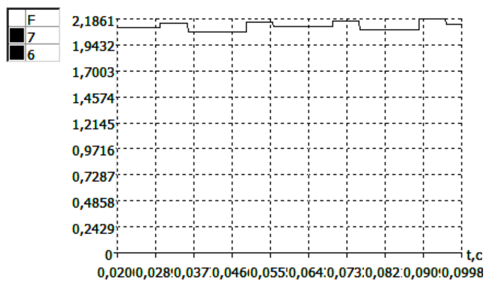


b

Fig. 2. Switching on the no-load mode:
a – primary current; b – identification parameter



a



b

Fig. 3. Switching on the load mode with rising it twice:
a – primary and secondary current; b – identification parameter

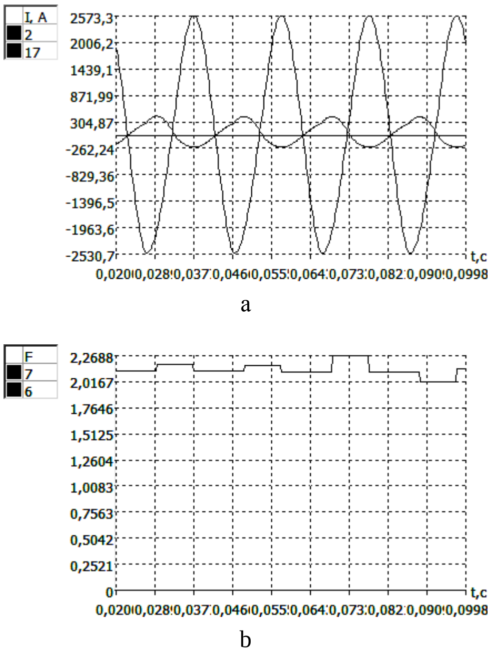


Fig. 4. Switching on the external short circuit:
a – primary and secondary current; b – identification parameter

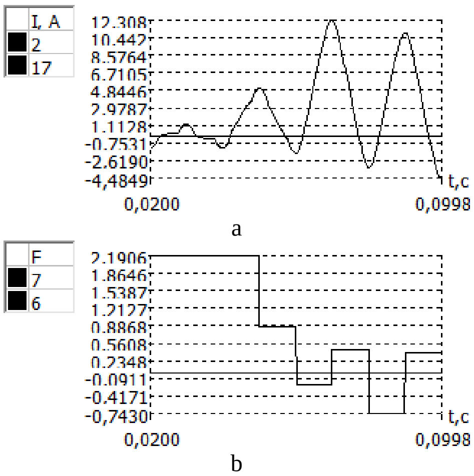


Fig. 5. Winding short circuit in the primary winding during the no-load mode: a – primary current; b – identification parameter

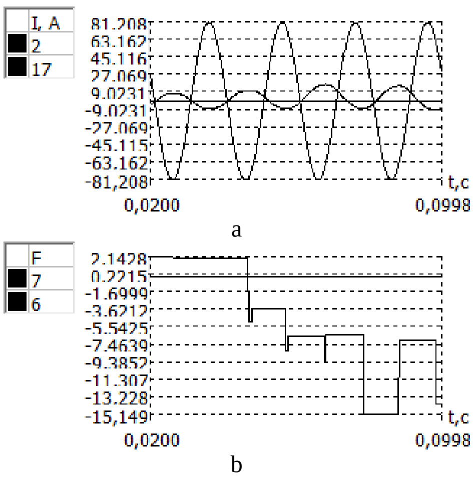


Fig. 6. Winding short circuit in the primary winding during the load mode: a – primary and secondary current;
b – identification parameter

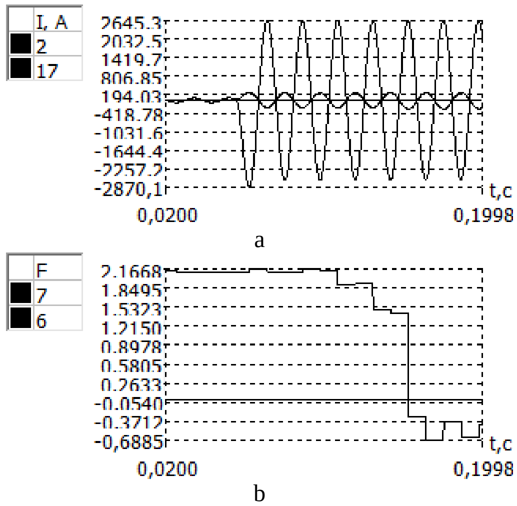


Fig. 7. Winding short circuit in the primar winding during the external short circuit: a – primary and secondary current;
b – identification parameter

Since, the winding short circuit is an emergency mode the options of the equations in Eqs. (2) differ from the nominal values; the biggest change we observe in active resistance. The method is based on the analysis of the instantaneous voltage and current of windings.

During the emergency mode we analyze the equation of the unharmed winding, express the magnetizing current's value and then substitute it into the equation of an emergency winding. After performing these actions, we are able to express the value of active resistance.

However, the result of this method does not show us the value of the result of active resistance's subtraction, but the identification parameter. It shows the discrete chance of active resistance. This diagram is very similar to relay graph, which can be used in digital relay defense as a triggering parameter. The oscillations on graph are caused with the calculation's precision. But still, on real power transformers the value of active resistance is not constant. It may have a wide range of alternating. Furthermore, there are a lot of regulative equipment, like regulating under load, etc.

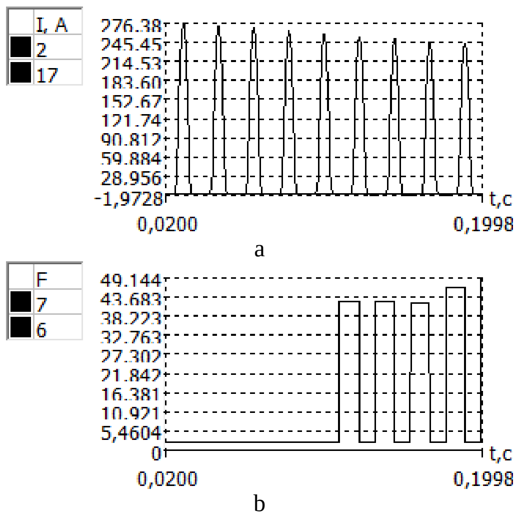


Fig. 8. Winding short circuit in the secondary winding during the no-load mode: a – primary current;
b – identification parameter

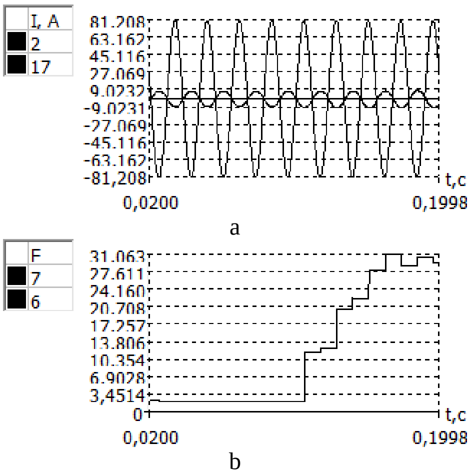


Fig. 9. Winding short circuit in the secondary winding during the load mode: a – primary and secondary current; b – identification parameter

This method automatically decides whether the emergency mode took place or not. It checks the transition terms of the derivative of primary current. If the triggering conditions are matching, we will have an emergency signal, else nothing happens and the transformer continues its work.

We analyze value of active resistance during the transition of the primary current's derivative through 0. It allows us to simplify the calculations, since it acts as a multiplier in Eqs (2). If the resistance differs from the value calculated on previous step the output signal will be "1".

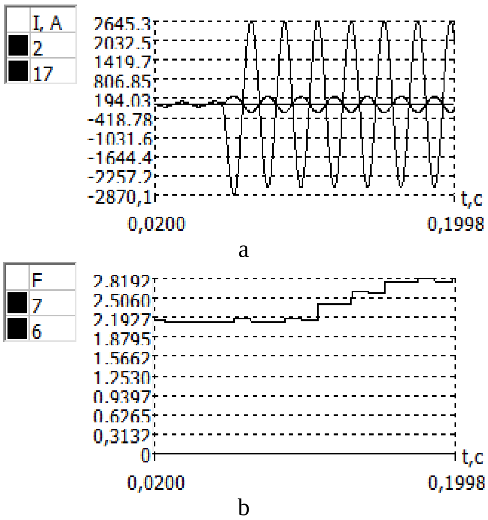


Fig. 10. Winding short circuit in the secondary winding during the external short circuit: a – primary and secondary current; b – identification parameter

The determination was conducted during the each half of the period.

The implementation of this method was carried out on the simulation model of single-phase double-winding power transformer (Fig. 1). Using switches 6 (Fig. 1) we were able to create electrical lintel on brunches 4 and 5 (Fig. 1) which correspond to the winding short circuit mode. By changing the value of complex resistance in 4 and 5 (Fig. 1) we implicated the respective quantity of winds which participated in short circuit. It allows investigating really wide variety of occasions.

The experiments were carried out during the most difficult emergency modes – short circuits of 1 up to 10 winds in primary winding and of 1 up to 3 winds in secondary winding.

It was also very important to check all of the operational cases comprehensively, since the power grid's state is changeable.

To prevent false triggering during the abnormal modes which, on the other hand, are suitable for the transformer, we investigated other processes: no-load mode (Fig. 2, 5, 8), nominal load mode (Fig. 3, 6, 9) and external short circuit mode (Fig. 4, 7, 10). According to the results the method shows absolute selectivity.

Furthermore, we are able to set the discretization of the analysis. Thereby, we can set the precision of experiments' results. It's very important to gain accuracy, since in the opposite case the behavior of calculations can be unpredictable.

Conclusions

Due to the obtained results, we can make such withdrawals:

1. The identification parameter obtained in several experiments shows the high reliability of detecting an emergency mode, namely the winding short circuit in single-phase double-winding transformers.
2. Proposed method shows absolute selectivity in other emergency modes.
3. This method is quite versatile, which means that it can be used in both dry and oil-immersed transformers.
4. The method is extremely fast-acting, since it was based on digital technologies.
5. This method is highly promising. If the results of experiments on real models of the power transformers will show the same success as in theory, we continue the investigation. It's means testing this method on three-phase double-winding transformers, three-phase triple-winding transformers and on autotransformers.
6. On further investigation there will be conducted more verification of this method. For example: if there is any possibility to react on the other emergency modes of the power transformer, like differential protection.

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