Investigation of Causes of Dry-Type Transformer On-Load Tap-Changer Insulation

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***Abstract*— The article represents the analysis of the causes of damage on the on-load tap-changer of a dry-type transformer installed at a 35 kV substation under ground fault in a network with isolated neutral. In order to analyze these processes, the well-known technique of modeling transients in a transformer [1, 2] is supplemented with account of the interturn and interwinding capacitances of the transformer determined from the picture of the electrostatic field.**

***Keywords*— dry-type transformer; on-load tap-changer; insulation breakdown; phase-to-earth fault**

I. Introduction

Two dry-type 35/10 kV transformers with capacity of 12,000 kVA are installed at the substation. The 35 kV bus section switch is switched on, while the 10 kV bus section switch is switched off in the normal circuit (Figure 1). In the normal circuit the substation S1 is fed from the substation S2 (Figure 1), the operation mode of the 35 kV network neutral is isolated.

In the evening on the day of the accident, when the load of the substation S1 began to increase, the flashover of the insulating gap between the taps of phase A of the transformer T2 occured during the movement of the contacts of the transformer's on-load tap-changer, which led to an interturn fault in the transformer and then to its switching-off by differential protection. As a result, the switches B35_T2 and B10_T2 were opened (Figure 1), which was followed by automatic load transfer at 10 kV ($\Delta t = 0.3$ sec). About 4 seconds after the triggering of automatic load transfer, the breakdown of phase C in the on-load tap-changer of transformer T1 occurred. As a result, the transformer was also disconnected by the action of differential protection, which led to the complete outage of the substation S1.

The inspection of the equipment after the accident showed that the movable contact stopped in an intermediate position, and there were multiple traces of arc burning in the on-load tap-changer.

II. Modeling

In order to reproduce adequately the electromagnetic transients in the transformer and to find the most probable causes of the accident, it is necessary to create a mathematical model of the transformer taking into account its internal capacitances between the windings, the capacitances between turns of the windings, and capacitances between the windings and the magnetic core of the transformer.

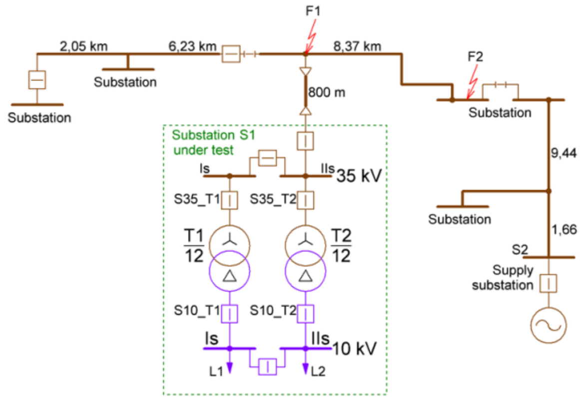

Fig. 1. Network layout

ATP draw is a program for transient simulation [3]. Modeling of the transformer has been carried out by adding a new element – a transformer model including the nonlinear properties of its magnetic core material and the capacitances described above, – in the program. Based on the data provided by the manufacturer, the computer model of the transformer has been developed. The model is based on the method of the joint solution of the equations obtained on the basis of the equivalent circuits of the magnetic and electrical circuits of the transformer [1, 2]. The capacitances considered in the model are shown in Fig. 2, where:

- C_{0hv} – the capacitance between the HV winding and the ground,
- C_{0lv} – the capacitance between the LV winding and the ground,

- C_{bw} – the capacitance between the HV and LV windings,
- C_{hv} – the longitudinal capacitance of the HV winding (equivalent capacitances between turns of the windings),
- C_{lv} – the longitudinal capacitances of the LV winding,
- C_{ph} – the capacitances between HV phases (A-B, B-C).

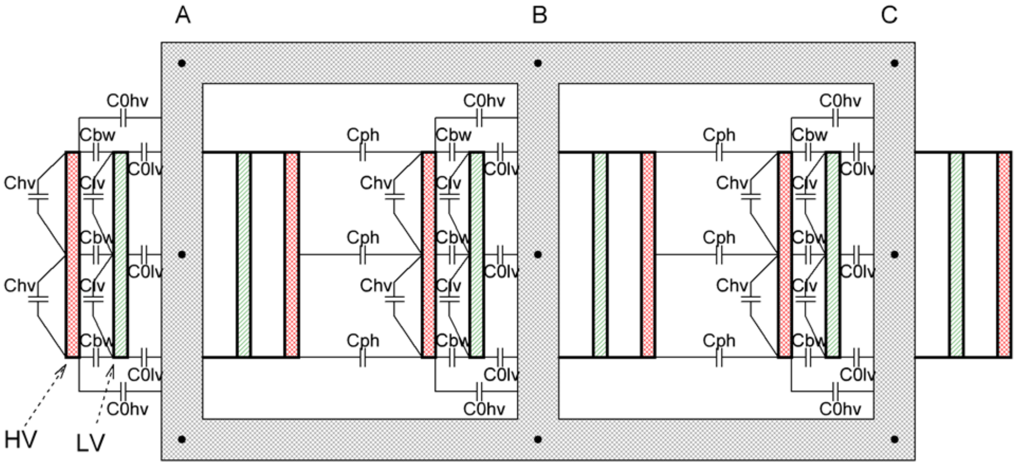

Fig. 2. Schematic presentation of the transformer and its internal capacitances (the concentrated capacitances for windings divided into two parts are shown)

The transformer windings have been divided into two parts to calculate the voltages at the intermediate points of the transformer windings. It is also reflected in the equivalent magnetic circuit of the transformer (Fig.3).

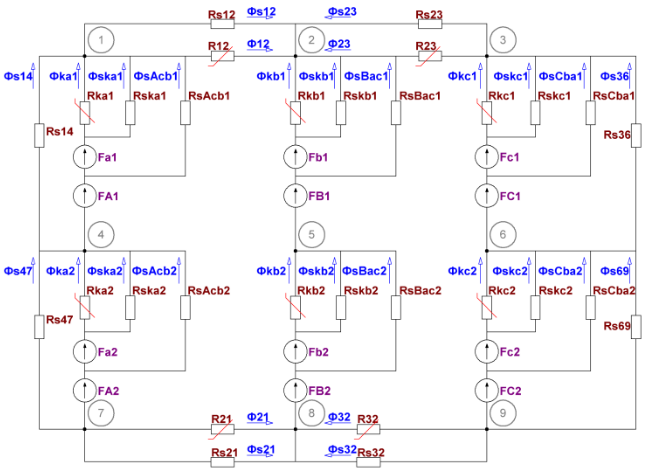

Fig. 3. The equivalent magnetic circuit of the transformer

Figure 3 shows an equivalent circuit which reflects the paths of the magnetic fluxes in the transformer (“the equivalent magnetic circuit”). The linear magnetic resistances of the equivalent magnetic circuit represent the paths of the magnetic flux in the air outside the transformer and in the spaces between the windings and the core. The nonlinear magnetic resistances represent the paths of the magnetic flux through the magnetic core of the transformer (core limbs and yokes), which has a nonlinear magnetization characteristic. Losses in steel are not taken into account. The sources in Figure 3 are the magnetomotive forces of the windings caused by currents flowing along them.

Equations for the first and second Kirchhoff laws are made up for the equivalent magnetic circuit.

The three-phase electrical equivalent circuit of a two-winding transformer ("the equivalent electrical circuit") is shown in Fig. 4. It represents: the winding connections, their active resistance and inductance, and also the interturn capacitance, interwinding capacitance, and capacitances to the ground. The inductances are calculated from the values of fluxes in the magnetic equivalent circuit. Depending on the chosen integration method [4], current derivatives in inductive elements and voltage derivatives on capacitances have been linearized by replacing each of them with an active two-pole containing current sources and linear conductivities (the implicit Euler integration method has been used for the model). The complete system of equations of the electrical equivalent circuit has been formed according the nodal-voltage method.

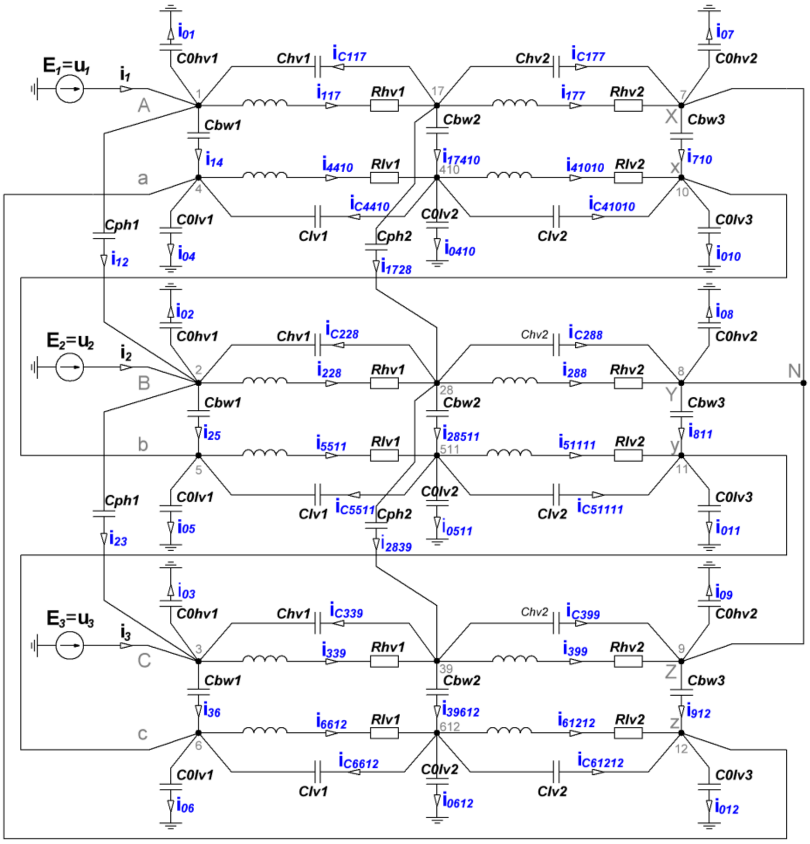

Fig. 4. The electrical equivalent circuit

TABLE I. THE MATRIX OF MUTUAL CAPACITANCES (PF) BETWEEN THE WINDINGS AND THE MAGNETIC CORE

	first part of the HV winding	**second part of the HV winding**	**first part of the LV winding**	**second part of the LV winding**
first part of the HV winding	18.091	327.90	194.03	8.1243
second part of the HV winding	327.90	18.091	8.1245	194.03
first part of the LV winding	194.03	8.1245	270.35	50.052
second part of the LV winding	8.1243	194.03	50.052	270.35

III. THE DETERMINATION OF THE TRANSFORMER WINDING CAPACITANCES

The calculation of the interwinding capacitances has been performed by using the COMSOL computer program complex [5]. This software allows analyzing different physical processes in complex devices using the finite element method taking into account the features of the materials which these devices are made of. Within the framework of the present investigation, the calculation of the transformer electrostatic field has been performed in order to estimate the values of interturn and interwinding capacitances for their further consideration in the mathematical model. For electrostatic field investigation it is necessary to choose process physics in the Electrostatics dc/ac module. This module allows getting the picture of electrostatic field and calculating different parameters of the system including mutual capacitances between charged elements of the construction.

In the system of several charged bodies the potential of each body is determined not only by the charge of the given body, but also by the charges of all other bodies. Therefore, to determine the capacitances in the complex system of the transformer conductors the physical model of the transformer has been constructed in the COMSOL computer program complex. It has been created with account taken of the geometric dimensions and constructive features of the windings and insulation construction of the transformer.

The transformer has been divided into 2 parts in order to determine the capacitance of each of the parts of the HV and LV windings. The experiment has been carried out in the following way: a certain potential (1 V) has been assigned to one part of the winding, and zero potential (the windings are grounded) has been assigned to the remaining parts; then, a similar experiment has been repeated for each of the windings. This experiment has made it possible to determine the coefficients of electrostatic induction [6], which have been converted into capacitances. In the end, the matrix of the windings capacitances of the transformer has been formed.

In the matrix the elements on the main diagonal are the capacitance of the windings to the earth (to the magnetic core), the remaining elements represents the capacitances between the windings. For example, the element C1,2 = 327.9 pF reflects the capacitance between the first and second half of the HV winding; this capacitance is considered as interturn.

The capacitance between the windings of different phases has been calculated analytically by the formula for two non-aligned cylinders [7].

IV. Steady-State Operation Condition of the Transformer

The transformer's on-load taps can be connected to different parts of the winding in order to change the transformation ratio by changing the number of turns of one of the windings (in two-winding transformers an on-load tap-changer is usually installed on the high-voltage winding). Two types of on-load tap-changer installation are considered in the article: in the first case, the on-load tap-changer is installed at the line inlet of the winding (such a design is used in the existing transformer), in the second case, the on-load tap-changer is installed at the neutral of the transformer.

If the on-load tap-changer is connected to the line inlet (Fig.5, a) of the transformer, some negative phenomena may occur during operation. First, it is greater voltage applied to the taps, secondly, it is the susceptibility of the on-load tap-changer to overvoltages in the supply network. If the on-load tap-changer is connected to the neutral (Fig. 5, b), the voltage applied to its insulation is lower, so this way of connection is more reliable.

Under steady-state operation conditions the rated phase voltages $U=\sqrt{2}/\sqrt{3}\times 35\ 000[V]=28\ 577$ V (the amplitude value of the rated phase voltage) are applied to high-voltage transformer lead-ins.

The HV winding of the transformer has 248 turns (w) under the nominal location of the tap changer (tap No. 5). Each tap of the on-load tap-changer contains 6 windings (w1) of the HV winding. If there is uniform voltage distribution along the windings and zero voltage on the neutral of the transformer, then the voltages on the tap-changers No. 6 and No. 4 of the transformer's on-load tap-changer for cases "a" and "b" will be, respectively (Fig. 5):

$$\Delta U=w_1/w\times U=6/248\times 28\ 577[V]=691.4\ V$$

a) $U_6=U-\Delta U=28{,}577[V]-691.4[V]=27\ 885.6$ V

b) $U_4=U_N+\Delta U=0+691.4[V]=691.4$ V

It can be seen from the obtained results that the voltage applied to the tap of the on-load tap-changer next to the tap where the movable contact is mounted (tap No. 5) is significantly larger if the on-load tap-changer is located near the line inlet of the transformer. The voltage value is practically equal to phase voltage of the network in this case.

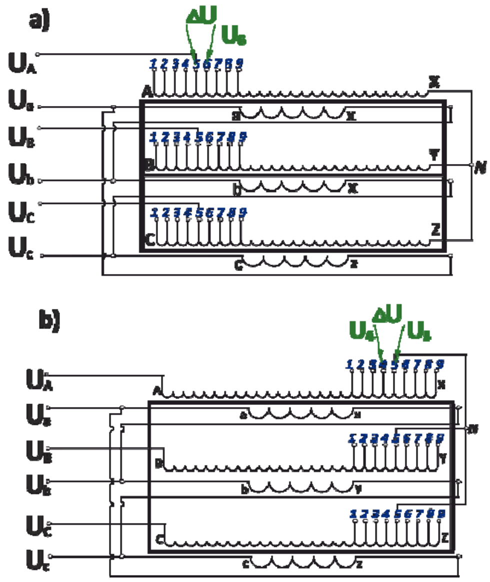

Fig.5. Schematic presentation of the transformer
a) on-load tap-changer at the line inlet; b) on-load tap-changer at the neutral

V. Emergency Operating Conditions of the Transformer

Now, let us consider transients in the transformer taking place under phase-to-earth faults at different points of the supply network (points of phase-to-earth fault in Fig. 1).

In the first case, the phase-to-earth fault occurs close to the transformer (F1), just behind the supply cable line, in the second case (F2), the phase-to-earth fault occurs at a nearby substation. The oscillograms of voltages on the taps of the on-load tap-changer as well as the potential difference between them (ΔU in Fig. 5) taking place under the transient associated with phase-to-earth fault in the network have been obtained.

Figures 7 and 10 show the oscillograms of voltages on tap No. 6 of the on-load tap-changer for the case "a" and on tap No. 4 for the case "b" (Fig. 5). After phase-to-earth fault the overvoltage ratio affecting the tap of the on-load tap-changer is greater if it is located on the line inlet and totals 2.8. If the on-load tap-changer is at the neutral, the overvoltage ratio is 2.0.

The oscillograms of the potential difference between the tapes (ΔU) are shown in Figures 8 and 11 for the cases "a" and "b", respectively.

Oscillograms of voltages (Fig. 6, 7 and 8) under phase-to-earth fault near the transformer (point F1 in Fig. 1). The on-load tap-changer is at the line inlet.

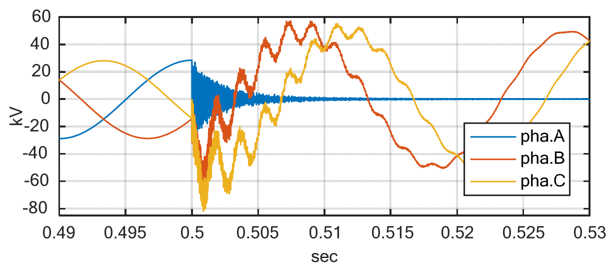

Fig. 6. Voltages on the line inlet of the transformer

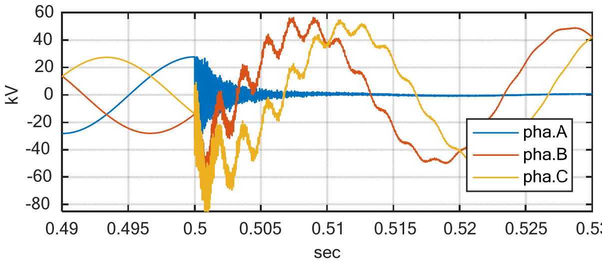

Fig. 7. Voltages on tap No. 6 of the transformer's on-load tap-changer

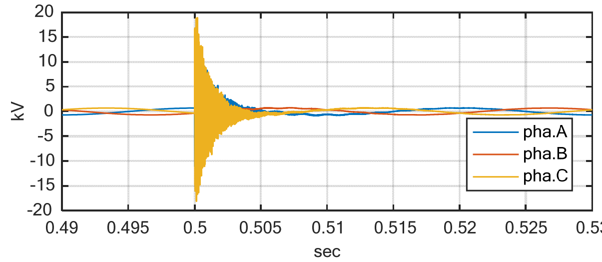

Fig. 8. The potential difference ΔU between the taps of the on-load tap-changer

Oscillograms of voltages (Fig. 9, 10 and 11) under phase-to-earth fault near the transformer (point F1 in Fig. 1). The on-load tap-changer is located at the neutral.

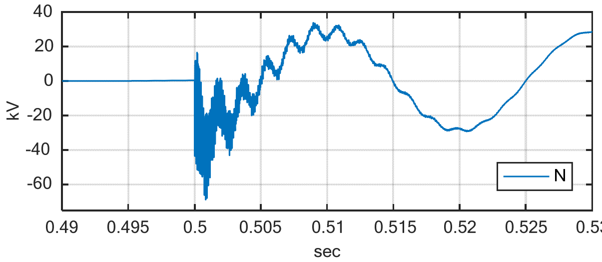

Fig. 9. Voltage at the transformer neutral

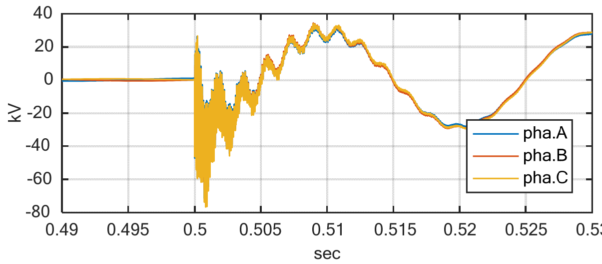

Fig. 10. Voltages on tap No. 4 of the transformer's on-load tap-changer

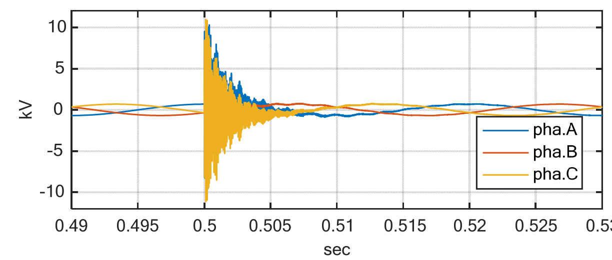

Fig. 11. The potential difference ΔU between the taps of the on-load tap-changer

Oscillograms of the voltages (Fig. 12, 13 and 14) under phase-to-earth fault on the neighboring substation (point F2 in Fig. 1). The on-load tap-changer is at the line inlet.

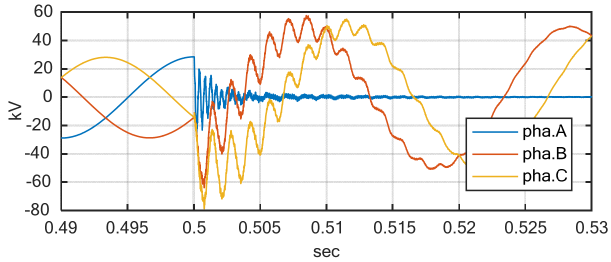

Fig. 12. Voltages on line inlet of the transformer

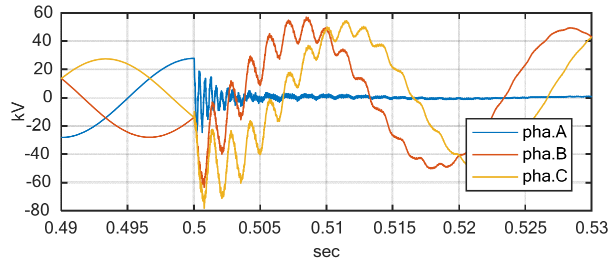

Fig. 13. Voltages on tap No. 6 of the transformer's on-load tap-changer

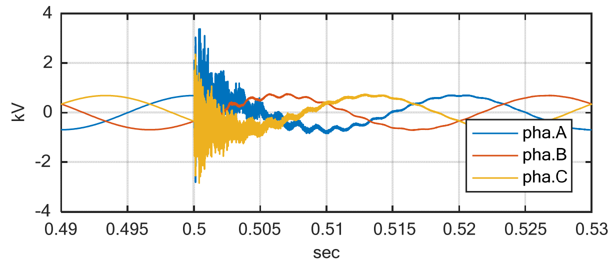

Fig. 14. The potential difference ΔU between the taps of the on-load tap-changer

Oscillograms of the voltages (Fig. 15, 16 and 17) under phase-to-earth fault on the neighboring substation (point F2 in Fig. 1). The on-load tap-changer is located at the neutral.

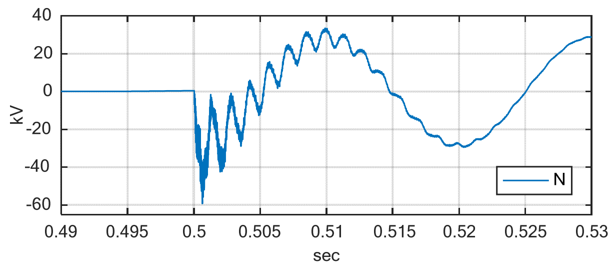

Fig. 15. Voltage at the transformer neutral

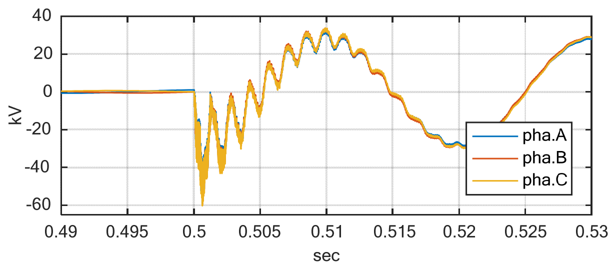

Fig. 16.Voltages on tap No. 4 of the transformer's on-load tap-changer

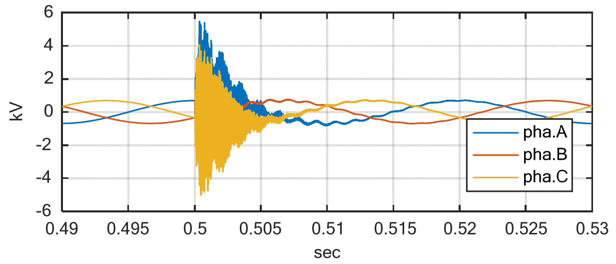

Fig. 17. The potential difference ΔU between the taps of the on-load tap-changer

The maximum permissible voltage between two taps of the on-load tap-changer declared by the manufacturer is 5 kV for one minute. According to the oscillograms of the potential difference (Fig. 8 and Fig. 11), the voltage between the control taps under the transient exceeds the maximum permissible value by factor of 4 if the on-load tap-changer is located at the line inlet and by factor of 2 if the on-load tap-changer is located at the neutral.

VI. Conclusion

The voltages applied to the insulation between the taps of the on-load tap-changer under the transient associated with phase-to-earth fault both near the transformer and at the neighboring substation exceed the maximum permissible (test) voltage of the tap stage, which may cause interturn flashover inside the transformer. It should be noted that the location of the on-load tap-changer at the neutral of the transformer significantly (by several times) reduces the voltage applied to the insulation of the tap stage both under steady-state and transient conditions.

TABLE II. THE COMPARISON OF VOLTAGE VALUES APPLIED TO THE ON-LOAD TAP-CHANGER INSULATION UNDER TRANSIENT

	The maximum voltage at the tap following the working tap, kV	**Maximum potential difference between working and neighbor tap, kV**
phase-to-earth fault at point F1, the on-load tap-changer at the neutral	78	11
phase-to-earth fault at point F1, the on-load tap-changer at the line inlet	90	20
phase-to-earth fault at point F2, the on-load tap-changer at the neutral	60	5
the phase-to-earth fault at point F2, the on-load tap-changer at the line inlet	80	3.5

It can be concluded basing on the specifics of transients that the most effective measure of overvoltage limitation on the taps of the transformer is the installation of an overvoltage suppressor in parallel to the taps of the on-load tap-changer. This has been confirmed by the oscillograms of Fig. 19-22 demonstrating satisfactory voltage level on the taps of the on-load tap-changer under the transient. At that, the values of the currents affecting the varistors of the overvoltage suppressor are relatively small.

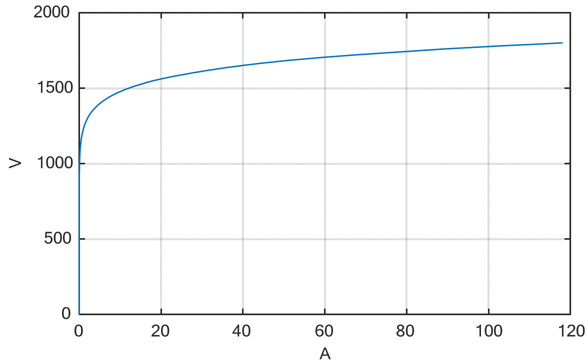

Fig. 18. Current-voltage characteristic of overvoltage suppressor

Oscillograms of the voltages (Fig. 19 and 20) under phase-to-earth fault near the transformer (point F1 in Fig. 1). The on-load tap-changer is located at the line inlet of the transformer; overvoltage suppressors with the characteristic presented in Fig. 18 are installed in parallel with neighboring taps of the tap-changer.

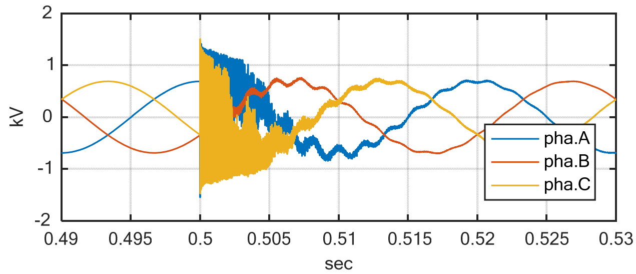

Fig. 19. The potential difference ΔU between the taps of the on-load tap-changer with the overvoltage suppressor installation

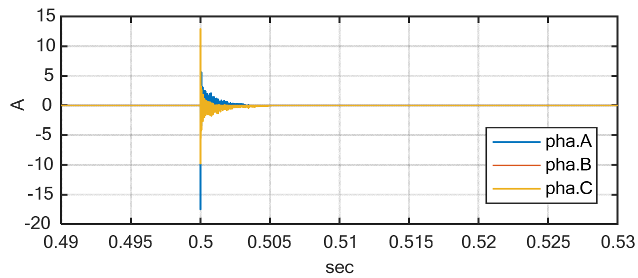

Fig. 20. Overvoltage suppressor currents

Oscillograms of the voltages (Fig. 21 and 22) under phase-to-earth fault near the transformer (point 1 in Fig. 1). The on-load tap-changer is located at the neutral of the transformer, overvoltage suppressors with the characteristic presented in Fig. 18 are installed in parallel with neighboring taps of the tap-changer.

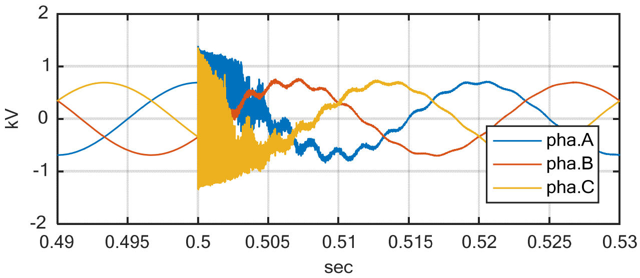

Fig. 21. The potential difference Δ*U* between the taps of the on-load tap-changer with the overvoltage suppressor installation

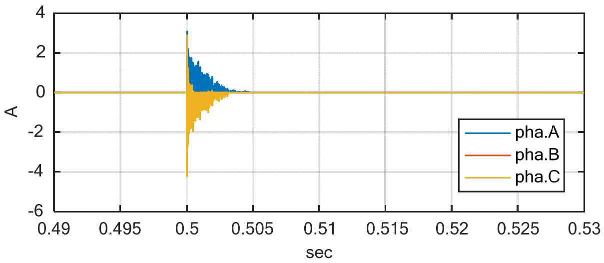

Fig. 22. Overvoltage suppressor currents

References

[1] Evdokunin G.A., Dmitriev M.V. *Modelirovanie perehodnih protsessov v elektricheskoy seti, soderzhaschei transformatory pri ychete configuratsii ih magnitnoi systemy* [Transient simulation in electrical grid containing transformers with account for magnetic system configuration], Izvestiya RAN. Energetika, no.2, 2009. pp. 37-48.

[2] Evdokunin G.A., Nikolaev R.N. *Modelirovanie I analiz perehodnih processov v transformatorah* [Simulation and analysis of transiens in transformers], Scientifically technical sheets SPbPU no. 4-1 (89), 2009., pp. 207-215.

[3] Selivanov V.N. *Ispolzovanie programmy pascheta elektromagnitnih perehodnih processov ATP-EMTP v ychebnom protsesse* [Using the ATP-EMTP electromagnetic transient calculation program in the education process], Vestnik MGTU, vol. 12 – 2009. no. 1., pp. 107-112.

[4] Demirchyan K.S., Butyrin P.A. *Modelirovnie I mashinyi raschet electricheskih tsepey: Uchebnoe posobie* [Modeling and computer simulation of electrical circuits: Studies. grant.], M.: Higher school., 1988.

[5] The COMSOL application gallery [Internet resource]. – Access mode: https://www.comsol.ru/models/acdc-module – Capacitance Matrix of Two Spheres.

[6] Evdokunin G.A. *Electricheskie sistemy I seti: Uchebnoe posobie* [Electrical systems and networks: studies. grant.],vol. 4., SPb.: Native Ladoga, 2016., 384 p.

[7] Demirchyan K.S., Neumann L.R., Korovkin N.V., Chechurin V.L. *Teoreticheskie osnovy electrotehniki: v trekh tomakh. Uchebnik dlya vyshih uchebnih zavedeniy* [Theoretical bases of electrical equipment: In 3 volumes. The book for higher education institutions.] vol. 3, SPb.: St. Peteesburg, 2003., 377 p.