

Considerations on Switching Capability of Circuit Breakers under Earth Fault in Electrical Grid

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Abstract - Circuit-breakers are essential for the safety and reliability of electrical power systems by interrupting fault currents under various conditions. Circuit-breakers must be capable of breaking single-phase short-circuit currents which can occur in two distinct scenarios. The first scenario involves effectively earthed neutral systems, where single-phase faults can generate high fault currents that the circuit-breaker must safely interrupt to prevent equipment damage and ensure personnel safety. The second scenario occurs in non-effectively earthed neutral systems, where double earth faults can appear on two separate phases, with one fault occurring on one side of the circuit-breaker and the other on the opposite side. Such conditions pose significant challenges for circuit-breaker design and operation, requiring careful consideration of their dynamic response and fault current interruption capacity. This paper presents the expected behavior of the circuit breakers and the real-life situations encountered during high-power testing of this type of equipment. Real-life testing reveals critical insights into performance limitations, transient phenomena, and operational reliability, providing valuable information for both equipment manufacturers and system designers. The study highlights the importance of accurate modeling, thorough testing, and adherence to standards to ensure that circuit-breakers perform reliably under all anticipated fault conditions. The most severe condition is identified as a double earth fault occurring under phase opposition. Although additional tests are planned to confirm this, preliminary assessment suggests that under normal operating conditions ($0^\circ < \varphi < 30^\circ$), the current at the final breaking pole should not exceed the generator's short-circuit current.

Cuvinte cheie: întreruptoare, defect de punere la pământ, mare putere, teste.

Keywords: circuit-breaker, earth fault, high power, tests.

I. INTRODUCTION

The switchgear operates correctly when it eliminates the short circuit in an optimal time without any consequences that endanger the system, defined by the type and class of the switchgear [1], [6]. The switching process is characterized by a number of physical phenomena that are determined by the type of switching device and its operating parameters. The switching characteristics of electrical devices are defined by the following parameters:

- Breaking capacity - defined as the highest value of the real or assumed current, measured as the effective value at the moment of contact separation, which can be in-

terrupted by the switchgear without damage, with explicit specification of the main parameters of the reference transient recovery voltage (characterized by the parameters of the power line) [2], [3];

- Rated Peak Withstand Current - defined as the highest value of current, measured as a peak value, that the switchgear can break at a given voltage without damage;

- The operating frequency recovery voltage (RV), in the event of a short circuit across the terminals, is the voltage value that appears between the contacts after the arc is extinguished [1], [7];

- Transient recovery voltage (TRV) consists of high frequency voltage oscillations. In the case of high power tests, in three-phase mode, the recovery voltage has the value $kU_n/\sqrt{3}$ in the case of the first phase that interrupts the current and $U_n/\sqrt{3}$ in the case of the other two phases that interrupt the arc, where k is the factor of the first pole and has the value 1.3 or 1.5, depending on how the neutral of the network is earthed (by resistance or inductance) or insulated. In the case of tests, the value of the recovery voltage is allowed to drop to 95% of the specified value during the test and must be maintained for a minimum of 300 ms in the case of circuit breakers. The transient recovery voltage wave has an aperiodic shape.

- The voltage applied to the circuit breaker terminals is the rated voltage of the system. The average applied voltage for each phase must be at least equal to the rated voltage $U_n/\sqrt{3}$ and must not exceed this value by more than 10%. For single-phase testing of a three-pole circuit breaker, the applied voltage shall be at least equal to the value of the phase voltage multiplied by 1.3 or 1.5, and for single-pole circuit breakers, the applied voltage shall be at least equal to the rated value.

- The power factor of the test circuit is standardized for circuit breakers $\cos\varphi \leq 0.15$ and can be determined from the time constant of the circuit or from the aperiodic component of the short-circuit current [6], [7].

II. SINGLE AND DOUBLE EARTH FAULT TESTS

A. Use Cases

In the laboratory, the single earth fault case consists of a single-phase test of one side pole of the circuit-breaker to interrupt the short-circuit current at rated value I_{sc} under the action of voltage $U_n/\sqrt{3}$.

The double earth fault situation occurs when the neutral of the system is isolated or not firmly earthed by the simultaneous earthing of two different phases, one upstream

and one downstream of the circuit-breaker, in the case of the earthing of two phases, one on the load side and one on the supply side, considered as a double earth fault.

Depending on the type of connection of the neutral of the system in which the circuit-breaker is used, its operating mechanism and the short-circuit test scheme (single-phase or three-phase) in the T100s sequence of the circuit-breaker, additional single-phase short-circuit tests must be carried out on the terminals according to Table 1.

The purpose of these tests is:

- to verify that the circuit-breaker is able to interrupt the fault current on a single pole with the parameters set;
- to verify that the opening action of the operating mechanism common to all poles is not affected by the high forces generated by the single-phase short-circuit current at that pole [4], [5].

TABLE I.
TEST PARAMETERS

Single-pole or three-pole circuit breaker with common mechanism for operating the poles		
Grounded neutral network $K_{pp}=1.0$ or 1.3		Resonant neutral grounding or isolated neutral network $K_{pp}=1.5$
Single earth fault test		Double earth fault test
The T100 test is single-phase	The T100 test is three-phase	Further tests are performed: $I = 0.87 I_{sc}$ $U = U_n$
No further testing	Further tests are performed: $I = I_{sc, nom}$ $U = U_n/\sqrt{3}$	

B. The Test Sequence

The test sequence consists of a single opening operation. The test should be carried out on the outer pole, which results in maximum stress on the actuating mechanism. The arcing time for this sequence must not be shorter than the value given by the relation: $t_a \geq t_{a, 100s} + 0.7 T/2$, where $t_{a, 100s}$ is:

- The minimum arcing time for the breaking pole after three opening operations in sequence T100s (if T100s is carried out in three-phase scheme);
- Minimum arcing time after a T100s sequence (if T100s is carried out in single-phase schemes);
- T - duration of the current.

Single earth fault tests shall be carried out on one of the side poles where the operating mechanism is subjected to maximum stress, and double earth fault tests may be carried out on either pole.

In the case of two tests in a single-phase scheme on a three-pole circuit-breaker with a common operating mechanism, they must be carried out on two different poles in order to avoid stressing a single pole.

C. The Test Voltage

The test voltage must be equal to the rated voltage of the circuit-breaker for the double earth fault test and $U_n/\sqrt{3}$ for the single earth fault test. The following TRV values shall be used:

a) for single earth fault:

- 2-parameter TRV:

$$u_{c,sp} = 1,4 \frac{U_n \sqrt{2}}{\sqrt{3}} \text{ (kV)}; t_{3,sp} = \frac{u_{c,sp}}{t_3} \text{ (\mu s)} \quad (1)$$

- 4-parameter TRV:

$$u_{1,sp} = 1,4 \frac{U_n \sqrt{2}}{\sqrt{3}} \text{ (kV)}; t_{1,sp} = \frac{u_{c,sp}}{t_1} \text{ (\mu s)} \quad (2)$$

$$u_{c,sp} = 1,4 u_{1,sp} \text{ (kV)}; t_{2,sp} = 3t_{1,sp} \text{ (\mu s)} \quad (3)$$

b) for double earth fault:

- 2-parameter TRV:

$$u_{c,sp} = 1,4 U_n \sqrt{2} \text{ (kV)}; t_{3,sp} = \frac{u_{c,sp}}{t_3} \text{ (\mu s)} \quad (4)$$

- 4-parameter TRV:

$$u_{1,sp} = 1,4 U_n \sqrt{2} \text{ (kV)}; t_{1,sp} = \frac{u_{c,sp}}{t_1} \text{ (\mu s)} \quad (5)$$

$$u_{c,sp} = 1,4 u_{1,sp} \text{ (kV)}; t_{2,sp} = 3t_{1,sp} \text{ (\mu s)} \quad (6)$$

D. The Test Current (I_{sc})

The test current (I_{sc}) for the single-phase double earth fault test according to IEC 62271-100 is 87% of the rated short-circuit breaking capacity at the terminals. The DC component of the interrupted current must not exceed 20% of the AC component [7], [8].

The test current for the single earth fault test is equal to the rated breaking capacity of the circuit-breaker.

III. SINGLE AND DOUBLE EARTH FAULTS IN POWER PLANTS

In power plant substations where the connection between the generator and the associated step-up transformer is made via generator busbars (IPB), three-phase faults occur very rarely. The most probable faults are single-phase phase-to-earth faults and phase opposition. Single earthing faults in a system with a firmly earthed neutral sometimes result in a secondary fault on another phase due to the high transient voltages that occur with this type of fault.

A generator together with its step-up transformer forms such a system: the neutral of the generator is normally earthed by a high ohmic resistor or preferably by a Petersen coil, or generally by a high impedance (including an insulated neutral), and the low voltage (LV) part of the step-up transformer is normally connected in delta [5], [11].

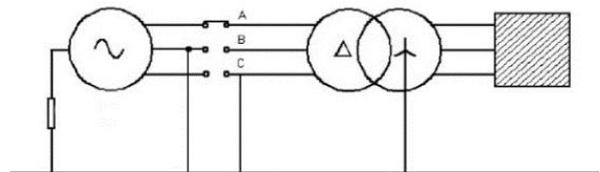


Fig. 1. Synchronous generator - circuit breaker - step-up transformer - high voltage circuit, double earthing on phases B and C.

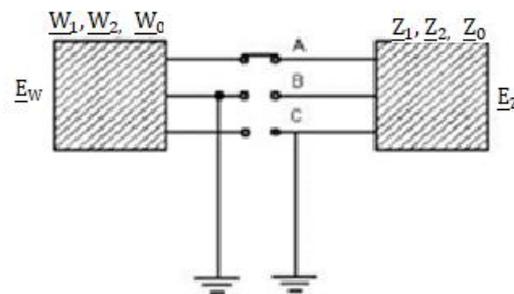


Fig. 2. Two systems connected by a circuit-breaker, double earth fault on phases B and C, current on the last pole interrupting the current.

If both faults are located on the same side of the circuit-breaker, we have a classic double earth fault with respect to the circuit-breaker. Fault currents, the current flowing through the circuit-breaker and the transient recovery voltage are defined in technical standards.

However, the load on the circuit-breaker is different if the earth faults are located on different parts of the circuit-breaker. Assuming that the pole of the circuit-breaker on the valid phase breaks last, it must interrupt a fault current under the influence of a transient recovery voltage composed of the voltage on the generator side plus the voltage on the transformer side.

Theoretically, we have two three-phase voltage sources (synchronous generator and high-voltage system) with their own impedances connected to one phase and through the earth fault to the other two (the streamlined diagram is shown in Fig.1).

Current Through The Last Interrupting Pole

The analysed situation is shown in Fig. 2. It should be noted that when poles A and B or A and C are closed, the currents flowing through these poles are different, so that interruption of phases B and C does not automatically mean interruption of phase A.

In Fig. 2, a W system (synchronous generator) is defined on the left and a Z system (high-voltage step-up transformer) on the right. Both systems are characterized by complex impedances in symmetrical components (the short-circuit impedances), in the following referred to as W_1, W_2, W_0 or Z_1, Z_2, Z_0 and the voltages E_W and E_Z .

It is assumed that the earth faults are on phase B on the W side and on phase C on the Z side, and that the B and C poles of the circuit-breaker are already open. The last phase to interrupt the current is therefore phase A.

The following conditions were defined:

$$\begin{aligned} I_{WA} &= -I_{ZA}; \\ I_{WC} &= I_{ZB} = 0; \\ U_{WA} &= U_{ZA}; \\ U_{WB} &= U_{ZC} = 0. \end{aligned}$$

Given $\alpha = e^{j120^\circ}$ and $\alpha^2 = e^{-j120^\circ}$, the sequence of currents is:

$$\begin{aligned} I_{W1} + I_{W2} + I_{W0} &= -I_{Z1} - I_{Z2} - I_{Z0}; \\ \alpha I_{W1} + \alpha^2 I_{W2} + I_{W0} &= 0; \\ \alpha^2 I_{Z1} + \alpha I_{Z2} + I_{Z0} &= 0; \end{aligned}$$

and the sequence of voltages:

$$\begin{aligned} U_{W1} + U_{W2} + U_{W0} &= U_{Z1} + U_{Z2} + U_{Z0}; \\ \alpha^2 U_{W1} + \alpha U_{W2} + U_{W0} &= 0; \\ \alpha U_{Z1} + \alpha^2 U_{Z2} + U_{Z0} &= 0. \end{aligned}$$

The relationship between the voltage sequence and the current sequence is given by the following equations:

$$\begin{aligned} U_{W1} &= E_W - W_1 I_{W1}; \\ U_{W2} &= -W_2 I_{W2}; \\ U_{W0} &= -W_0 I_{W0}; \\ U_{Z1} &= E_Z - Z_1 I_{Z1}; \\ U_{Z2} &= -Z_2 I_{Z2}; \\ U_{Z0} &= -Z_0 I_{Z0}. \end{aligned}$$

The system of equations can be solved by substitution and gives the values of the current and voltage sequences as functions of E_W, E_Z , and impedances. Retransforming to phase values gives the general expression of the current through the last interrupting pole [9], [10], [12].

$$I_{WA} = \frac{(1-\alpha)[E_Z(W_1+W_2+W_0)(\alpha^2 Z_1 - Z_0) + E_W(Z_1+Z_2+Z_0)(W_0 - \alpha^2 W_2)]}{(Z_1+Z_2+Z_0)(W_1 W_0 + W_2 W_0 + W_1 W_2) + (W_1+W_2+W_0)(Z_1 Z_0 + Z_2 Z_0 + Z_1 Z_2)} \quad (7)$$

For simplicity, the following assumptions are made:

- all impedances are predominantly inductive and have the same angle (same X/R ratio);
- positive and negative sequence impedances are equal;
- the absolute values for E_W and E_Z are equal ($E_W = E_Z e^{j\varphi}$);
- a realistic hypothesis for the configuration in Fig. 1 is that $W_0 = Z_0 \rightarrow \infty$.

Thus, we can define the simplified equation for the current in phase A:

$$\begin{aligned} I_{WA} &= \frac{\alpha - 1}{2} \frac{E_Z + \alpha^2 E_W}{W_1 + Z_1} = \frac{\alpha - 1}{2} \frac{E_Z (1 + e^{j(\varphi - 120^\circ)})}{W_1 + Z_1} \\ |I_{WA}| &= \frac{\sqrt{3}}{2} \left| \frac{E_Z}{W_1 + Z_1} \right| |(1 + e^{j(\varphi - 120^\circ)})| \\ &= \frac{\sqrt{3}}{2} \left| \frac{E_Z}{W_1 + Z_1} \right| |F(\varphi)| \quad (8) \end{aligned}$$

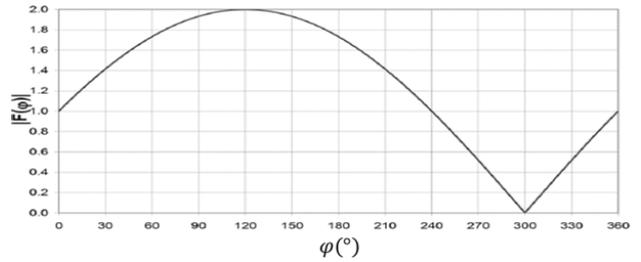


Fig. 3. Graph of $F(\varphi)$ function for $W_0 = Z_0 \rightarrow \infty$ and $E_W = E_Z e^{j\varphi}$.

Figure 3 shows $F(\varphi)$ as a function of angle φ . Note that for $\varphi = 0^\circ$, the generator is operating at no load. For the maximum of 2, the angle is 120° .

In power plants, the range of Z_1 is between $0.5 W_1$ and $1 W_1$. The phase A current on the I_{WA} supply side has the highest value when $Z_1 = 0.5 W_1$. In this situation, equation (8) is simplified:

$$|I_{WA}| = \left| \frac{E_Z}{W_1} \right| \frac{1}{\sqrt{3}} |F(\varphi)| \quad (9)$$

E_Z/W_1 is the synchronous generator short-circuit current.

Thus, under normal operating conditions ($0^\circ < \varphi < 30^\circ$), the current on phase A remains below the generator short-circuit current. In summary, this value is exceeded only under phase shift conditions (by a factor of $\frac{2}{\sqrt{3}} = 1.15$ at an angle of 120°).

IV. EXPECTED RESULTS

Using assisted simulation, predicted values were obtained for the single and double earth fault tests.

Figure 4 shows the circuit to obtain the expected values:

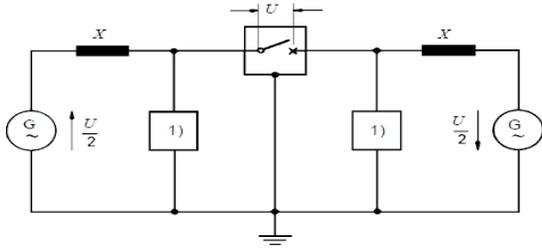


Fig. 4. The circuit used for the test simulation.

In the figure above, a single-phase test circuit is considered, consisting of two equivalent sources located on each side of the circuit breaker, denoted by G.

The elements denoted by X represent the equivalent reactances used for modeling the source-side networks.

The blocks marked 1 represent equivalent combinations of capacitors and resistors used to model the transient recovery voltage circuit.

To obtain the required values for the circuit breaker, the following values have been entered for the circuit elements:

- for a single earth fault: source voltage 9.7 kV with a current of 35 kA, 285 mΩ reactance, 2.14 transformer ratio, and to model the transient recovery voltage, a capacitance of 0.25 μF with a resistance of 50 Ω;
- for the double earth fault, the same assumed circuit was used, but the source voltage value was changed to 11.2 kV and 44 kA.

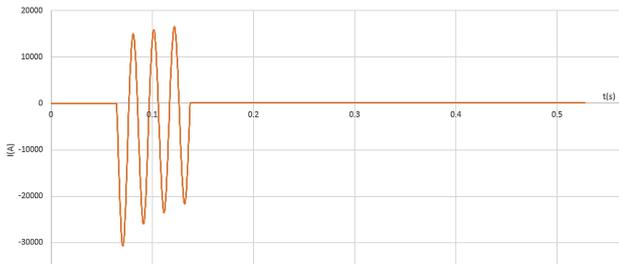


Fig. 5. The shape of the current obtained from the simulation.

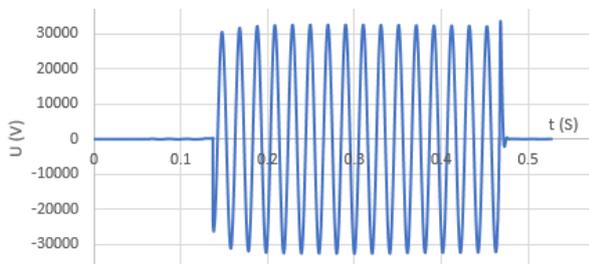


Fig. 6. The shape of the voltage obtained from the simulation.

Numerical simulations (fig.5 and fig. 6) were performed using the dedicated Micro-Cap software to obtain the predicted values for the single and double earth fault tests.

For the sake of simplicity, the arcing time of the circuit breaker was ignored and an opening operation of the switchgear was performed. A peak current of 31 kA was

obtained, with an rms value of 14 kA and a voltage of 34 kV for the double earth fault test.

This provides the peak current value required by the test standards.

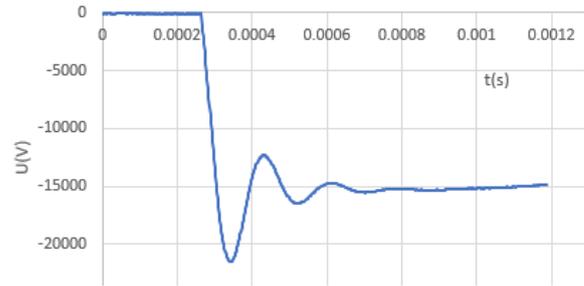


Fig. 7. Transient recovery voltage.

Because the impedance of transformers is generally higher than that of generators, the TRV value is significantly higher. So $t_3 = 60 \mu s$, and $U_C = 28 kV$. The TRV values are also required by IEC 62271-100 depending on the rated voltage of the circuit breaker. Figure 7 shows the assumed value for a 12 kV circuit breaker.

V. EXPERIMENTAL RESULTS

A 36 kV, 630 A, 16 kA, 630 A vacuum circuit breaker was used for single and double earth fault tests. The parameters of the single earth fault test were: $U = 36 kV / \sqrt{3} = 20.9 kV$, $I = 16 kA$ (rated breaking capacity),

$$u_{c,sp} = 1.4 \frac{U_n \sqrt{2}}{\sqrt{3}} = 61.4 (kV); t_{3,sp} = \frac{u_{c,sp}}{t_3} = 109 (\mu s);$$

The test circuit may be similar to that shown in Fig. 8, depending on laboratory capacity:

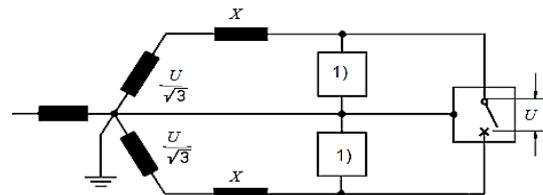


Fig. 8. Test circuit for testing phase opposition using two voltages phase-shifted by 120 electrical degrees ((1) - combinations of capacitors and resistors for TRV modelling).

A single-phase test with a Y_2 connection generator source was selected:

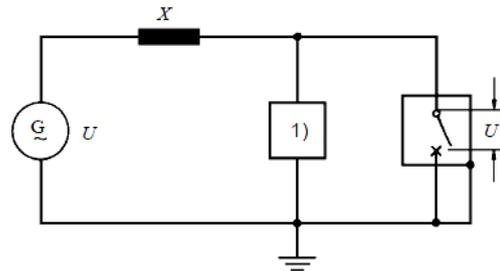


Fig. 9. The circuit used for experimental testing.

The circuit in Fig. 9 is grounded, and the oscillation factor k used in the transient recovery voltage calculations is 1.4. The test sequence consists of a single opening operation of the circuit-breaker, the test being performed on a side pole, thus placing maximum stress on the operating mechanism.

Prior to the single and double earth fault tests, the T100s test was performed to determine the minimum arcing time. This was used in the equation $t_a \geq t_{a100s} + 0,7T/2$, and by adjusting the opening command of the device in relation to the current zero crossing, the maximum arcing time value is obtained.

Figure 10 shows the oscillogram for the single earth fault test. During the test, the following parameters were recorded: circuit breaker control current (I_{C_IO}), recovery voltage (U), transient recovery voltage, short-circuit current (I), reference source voltage (U_G), contact stroke on the stroke sensor, time base (s).

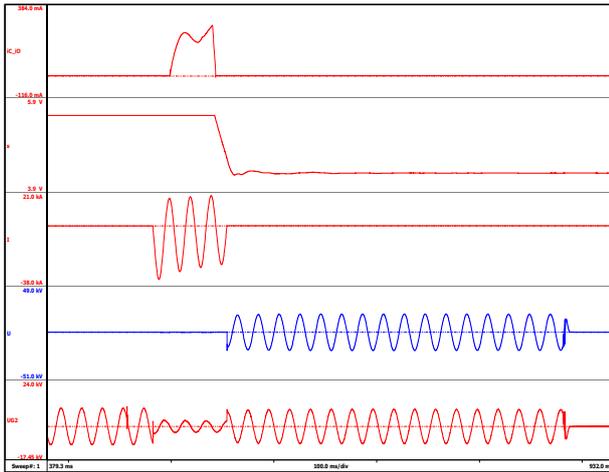


Fig. 10. Oscillogram obtained during the single earth fault test.

Values obtained: peak current value 34 kA; rms current value 16.1 kA; rms voltage value $36/\sqrt{3}$ kV.

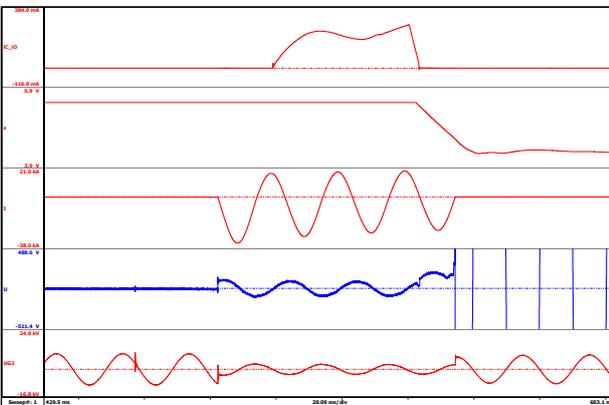


Fig. 11. Oscillogram obtained during the single earth fault test - details.

Figure 11 shows the same oscillogram, but zoomed in on the current sine wave to show the value of the 10.8 ms arc time.

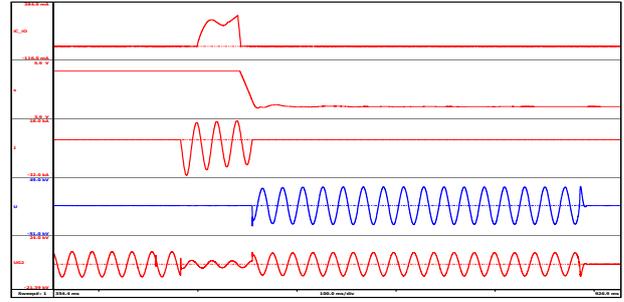


Fig. 12. Oscillogram obtained during the double earth fault test.

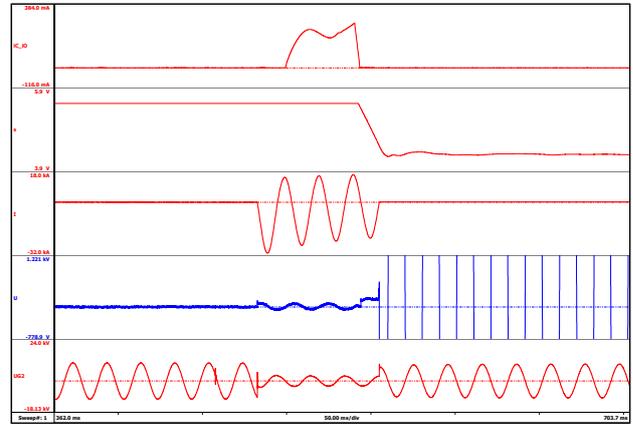


Fig. 13. Oscillogram obtained during the double earth fault test – details.

In the double earth fault test, a current of 30.7 kA peak, 14.1 kA rms and a voltage of 22.7 kV were obtained. Caption of the oscillogram: I_{C_IO} shows the control current through the circuit-breaker's closing or opening coil, recorded by means of a shunt; s - the curve of the motion sensor of the circuit-breaker's moving contacts.

To measure the arcing time, the level previously measured on the motion sensor at the moment of contact separation during no-load operation and at the moment of arc extinction (current passing through zero) and recovery of the industrial frequency voltage are taken into account. In this experiment, an arcing time value of 10.7 ms was obtained. The time measured between the occurrence of the opening command and the moment of contact separation is 44.7 ms, resulting in a total current interruption time of 55.4 ms.

VI. CONCLUSIONS

This article presents the most unfavourable situations encountered in the operation of circuit-breakers in the case of single and double earth faults. The case encountered in substations where the connection between the generator and the associated step-up transformer is made through generator bus bars (IPB) is studied and the current equation for the side interrupting pole is expressed.

The test results confirm the predicted values for voltage, current and transient recovery voltage.

The worst case is a double earth fault under phase opposition conditions. Further tests will be carried out to verify this, but it is estimated that under normal operating conditions ($0^\circ < \varphi < 30^\circ$) the current at the last breaking

pole should not exceed the short-circuit current of the generator.

Tests will be carried out on the test circuit shown in Figure 8 and it is expected that the magnitude will increase under phase opposition conditions (by a factor of $2/\sqrt{3}$ at an angle of 120°).

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Contribution of authors:

First author – 30%;

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Third coauthor – 15%;

Fourth coauthor – 15%.

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