OVERVOLTAGE AT THE TRANSFORMER WHEN DISCONNECTING CLOSE ASYMMETRICAL SHORT CIRCUITS

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Abstract

This article examines overvoltages at the inputs of high-voltage (HV) and low-voltage (LV) transformers rated at 110/6 kV and 110/10 kV, focusing on scenarios involving grounded and isolated neutrals during short circuits near the transformers. The study finds that with an isolated neutral, overvoltages resulting from a phase-to-ground short circuit reach the highest levels, as anticipated. However, the disconnection of all types of asymmetrical short circuits—whether with an isolated or grounded neutral—yields even greater, potentially excessive overvoltages. This occurs because the windings of undamaged transformer phases remain partially energized during disconnection, leading to significant currents being interrupted. The magnetic energy from these currents converts to electrical energy, resulting in substantial voltage increases, characterized as pulsed overvoltages lasting several microseconds. Implementing switches with shunt resistance can reduce these overvoltages considerably, though the remaining levels may still exceed acceptable thresholds. To mitigate the risk of such excessive overvoltages, installing surge arresters at the inputs of high-voltage transformers is recommended, ensuring that transformer input overvoltages remain within permissible limits.

Keywords: Overvoltages, short-circuit interruptions, surge arresters, asymmetrical short circuits, switches with shunt resistance.

I. Introduction

Overvoltages during line or load disconnections in electrical networks occur due to the conversion of magnetic energy from interrupted currents in inductances into electrical energy, leading to an increase in voltage. The greater the interrupted current, the more magnetic energy is converted, resulting in a higher voltage increase. Therefore, the disconnection of short-circuit currents (SC) can lead to significant overvoltages, as very high currents are being interrupted.

In single-phase circuits, there is no increase in voltage during short-circuit interruptions, as switches operate when the current passes through zero. At this moment, there is no magnetic energy available for conversion into electrical energy. In three-phase circuits, however, the currents across all three phases do not reach zero simultaneously during a short circuit. Consequently, when the switch operates, only one phase may have a zero current, while the other phases remain at non-zero values. The interruption of these currents can lead to substantial overvoltages [1, 13].

It is important to note that this phenomenon has not been extensively addressed in the existing literature, which primarily focuses on single-phase circuits [4,5].

In the event of short circuits occurring in close proximity to a transformer [6,9], this component is typically isolated through relay protection and is thus regarded as safely disconnected from the network. However, the behavior of the transformer—particularly given its significant inductance—

remains a critical area of inquiry, especially when it continues to carry operating phase currents in the windings of undamaged phases after disconnection. The interruption of these currents can lead to substantial overvoltages [12, 13].

II. Assessment of overvoltages when disconnecting short-circuit currents in transformers

The overvoltage when switching off short-circuit currents can be roughly estimated as follows. When current flows through the windings of transformers, corresponding magnetic energy is generated

$$W_M = \int_0^{\psi_M} id\ \psi_M \quad (1)$$

where, ψ_M – winding flux linkage. The rupture of a circuit containing inductance at a current value i different from zero must be accompanied by the conversion of this energy into other forms, in particular into the energy of an electric field, which explains, as stated above, the occurrence of overvoltages on inductive network elements when they are turned off - Fig. 1.

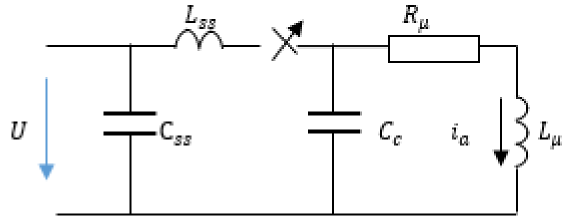


Figure1. Equivalent circuit for calculating overvoltages when the transformer is turned off

In the diagram in Fig. 1, L_μ и L_{ss} are the inductance of the transformer and the substation bus system, respectively, C_c and C_{ss} are the capacitance of the disconnected transformer and the busbar wires, respectively, R_μ is the active resistance of the transformer winding.

The amplitude U_{max} of voltage fluctuations on the capacitor is determined based on the equality of the energy of the magnetic field of the winding

$$W_M = \frac{1}{2} L_\mu i_a^2, \quad (2)$$

and the energy of the electric field of the capacitor

$$W_c = \frac{1}{2} C_c U_{max}^2 . \quad (3)$$

The equality of these two expressions can determine U_{max}.

$$U_{max} = i_a \sqrt{\frac{L_\mu}{C_c}} = i_a Z_{ch}, \quad (4)$$

where, Z_{ch} is the characteristic resistance of the $L_\mu - C_c$ circuit, which has a value of several tens of kilo-ohms.

This expression shows that when the inductance is turned off, the voltage across it can be tens of thousands of times greater than the short-circuit currents that are cut off by the switches when they are turned off.

The task posed is quite complex, since it contains two transient processes - the occurrence of a short circuit and its shutdown, and all this in a complex, nonlinear, three-phase circuit in which asymmetrical changes occur.

This was confirmed in the results of this article, which, due to the complexity of the network diagram, the presence of nonlinearity and the occurrence of two successive transient processes, was carried out by mathematical modeling using computer technology. The algorithmic language used was OrCAD 17.2.

III. Computational results

For instance, consider short circuits occurring within the differential protection zone of transformers. This article specifically examines the overvoltages that manifest in transformers during disconnection amid asymmetrical short circuits occurring nearby. The analysis is situated within a radial network operating at a nominal voltage of 110 kV. This voltage level was selected because 110 kV networks can function with both isolated and grounded neutrals, facilitating a thorough investigation of overvoltage phenomena across varying short circuit conditions [2, 3, 4].

It is understood that in grounded neutral systems, elevated currents from single-phase short circuits can induce a transition to an isolated or partially isolated neutral mode, aimed at mitigating single-phase short circuit currents. The electrical circuit under consideration is depicted in Fig. 2, comprising three substations—SS1, SS2, and SS3—and two lines, W_1 and W_2. Substations SS2 and SS3 are outfitted with transformers rated at 110/6 kV and 110/10 kV, each supplying loads S_2 and S_3, respectively. To safeguard against overvoltages, the bus systems at each substation are equipped with suitably rated surge arresters (SARs).

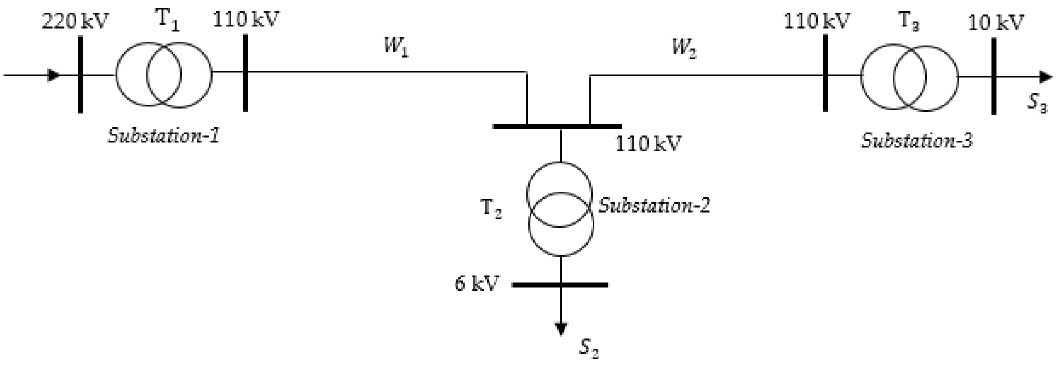


Figure 2. Schematic diagram of the electrical network under investigation.

Various short circuit scenarios—namely single-phase, two-phase, and two-phase-to-ground—were systematically executed at the junction between transformer T_2 and its associated switches within the high-voltage busbar system of substation SS-2. Both grounded and isolated neutral configurations of the network were evaluated. The results obtained from these experiments are summarized in Tables 1 to 3 and illustrated in Figures 2 to 9.

The results obtained are shown in Tables 1 - 3, as well as in Fig. 3 – 10.

As indicated in Table 1, under normal operating conditions, the maximum voltage values at the terminals of loads 1 and 2 were recorded at 4.9 kV and 7.6 kV, respectively.

The voltage calculations within the busbar systems of substations SS1 and SS2—covering the inputs of both HV and LV windings of the transformers as well as the terminals of the first load—are presented in Tables 1 and 2. These calculations were conducted under the assumption of a grounded neutral configuration for the transformers and reflect the conditions arising from the aforementioned short circuit scenarios, as depicted in Figures 3 to 7.

In the event of a single-phase short circuit (on phase A) at the aforementioned location, with the network configured for a grounded neutral, the voltage in the affected phase drops to zero, while the healthy phases experience a reduction from 91 kV to 77 kV. This short circuit also influences the voltage at substation SS3, where the high-voltage section sees an increase. The increase in voltage for the damaged phase is minimal, whereas the healthy phases can rise by approximately 15% (see Fig. 3). Similar voltage variations are also observed on the secondary sides of the transformers at substations SS2 and SS3.

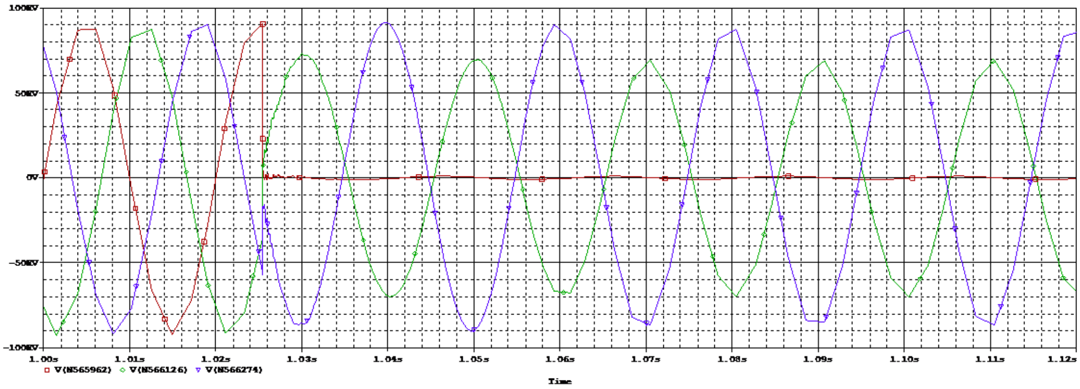
Table 1

The voltage calculation results

Neutral mode	Network mode	U_{S1A} kV	U_{S1B} kV	U_{S1C} kV	U_{T1A} kV	U_{T1B} kV	U_{T1C} kV	U_{T1a} kV	U_{T1b} kV	U_{T1c} kV
neutral is grounded	1	91,23	91,79	91,19	91,23	91,79	91,19	4,95	4,97	4,95
	2	0	76,83	76,74	0	76,83	76,74	0,61	4,28	4,44
	3	182	195	192	0	6903	6616	65,0	323	316
	4	226	128	200	0	195	199	6,26	10,38	10,40
	5	0	0	29,59	0	0	29,59	0,513	0,513	1,055
	6	222	226	238	0,078	0,066	29631	473	473	946
	7	226	229	240	0,082	0,063	240	3,77	3,76	7,52
	8	46,6	46,6	92,3	46,6	46,6	92,3	2,514	2,514	5,01
	9	187	190	102	3804	3804	7585	181	181	363
	10	162	191	191	187	187	192	5,94	5,94	11,82
		U_{S2A} kV	U_{S2B} kV	U_{S2C} kV	U_{T2a} kV	U_{T2b} kV	U_{T2c} kV	U_{N1a} kV	U_{N1b} kV	U_{N1c} kV
	1	85,12	85,37	85,24	7,719	7,742	7,737	4,89	4,91	4,89
	2	86,87	97,43	101	7,95	8,87	9,15	4,35	4,29	4,07
	3	169	120	112	15,41	10,97	10,23	0	14,09	14,16
	4	204	119	181	18,82	10,79	16,50	0,327	10,4	10,6
	5	87,89	36,61	60,72	8,04	3,38	5,56	4,12	1,89	2,32
	6	175	202	225	15,91	18,48	20,66	1,49	1,47	2,97
	7	183	203	225	16,56	18,56	20,71	1,55	1,53	3,08
	8	97,94	93,2	86,31	8,92	8,536	7,83	4,43 2,49	4,71 2,49	4,95
	9	142	147	104	12,87	13,34	9,48	8,12	8,11	16,22
	10	140	148	103	12,69	13,49	9,34	5,54	5,52	11,06

The maximum current values in the high-voltage windings, the neutrals of transformers T_1 and T_2, as well as in line 1, the switch, and the short-circuit current are presented in Table 2. The corresponding current curves are illustrated in Figure 3. Based on the data from Table 2 and the visual representation in Figure 4, the short-circuit characteristics of these currents are detailed in Figure 5.

The currents observed include those in the windings and the neutral of transformers T_1 and T_2, as well as in the switches and the short-circuit current itself.



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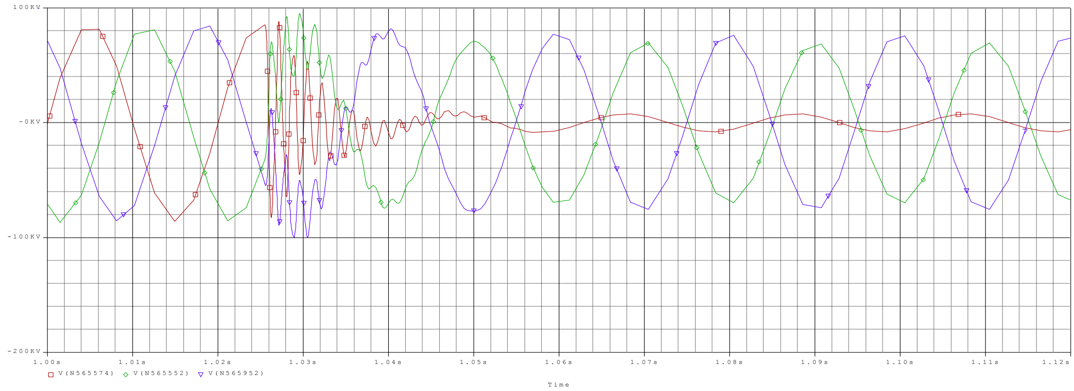


b)

Figure 3. Overvoltages in the busbar systems of high-voltage substations SS2 (a) and SS3 (b) during a single-phase short circuit in a network with a grounded neutral.

As illustrated in Table 2 and Figure 4, the short-circuit current flowing to ground is primarily routed through the neutrals of transformers T_1 and T_2, with only a small portion being transmitted through line capacitances. The predominant share of the short-circuit current (I_{NT_2}) enters transformer T_2 via its neutral and flows consistently through its three high-voltage windings (I_{T2A}, I_{T2B}, I_{T2C}).

Table 2.

The current calculation results

Type of short circuit	I_{T1A} A	I_{T1B} A	I_{T1C} A	I_{T2A} A	I_{T2B} A	I_{T2C} A	I_{cbA} A	I_{cbB} A	I_{cbC} A	I_{NT1} A	I_{NT2} A	I_{cs} A
1_{psc}	5280	2420	2370	2300	2330	2220	5410	2330	2220	790	6843	7648

The currents in phases B and C of transformer T_2 pass through the switch, while the currents in phases B and C of transformer T_1, along with a minor portion of the short-circuit current that reaches the neutral of T_1 from the short-circuit point (I_{NT_1}), return to the short-circuit location via phase A. The short-circuit pathways for these currents are depicted in Figure 5.

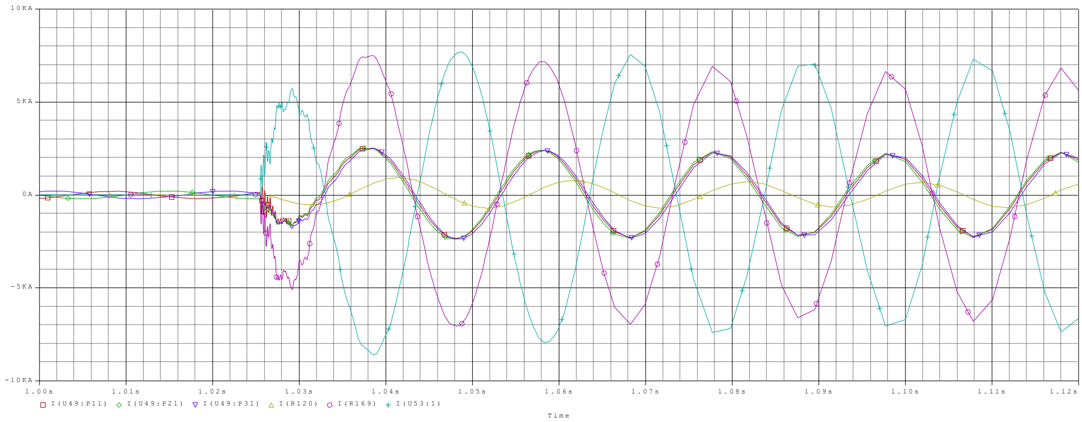


Figure 4. Currents in the windings and the neutral of transformers T_1 and T_2, as well as in the switches and the short-circuit current.

In figures 4 and 5, the currents in phases B and C of the switch exhibit the same direction and magnitude, while the current in phase A flows in the opposite direction. These currents do not cross zero simultaneously. If the switch operates precisely when the current in phase A is at zero, the currents in phases B and C are calculated to be approximately 200 A. The interruption of such currents is significant and can result in substantial overvoltages.

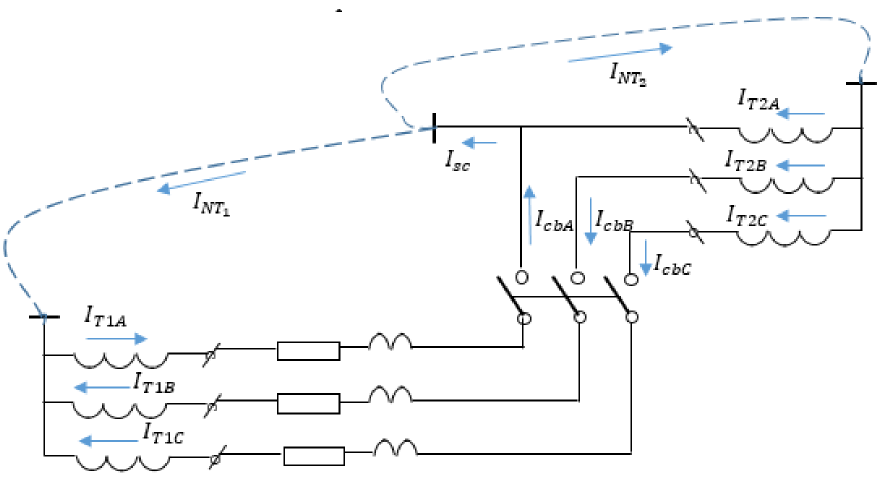


Figure 5. Diagram illustrating the short-circuit current

Figure 6 displays the overvoltage curves in the busbar systems of substation SS2 and at the HV inputs of transformer T_2 following the disconnection of a single-phase short circuit in the examined network [5, 13]. According to the data presented in Table 1 and illustrated in Figure 6, the voltages in the HV busbar systems of substation SS2 double upon disconnection of the single-phase short circuit. This significant increase is attributed to the presence of a surge arrester at this location (Figure 5a).

In the HV busbar systems of substation SS3, a similar doubling of voltage occurs only in phase A, while the increases in the other phases are minimal, particularly in phase C. At the inputs of the undamaged phases B and C of the high-voltage winding of transformer T_2—which has been isolated from the HV busbar system of substation SS2 by the tripping of the circuit breaker—there is a sudden voltage increase characterized by a surge with very high amplitude and extremely short duration.

This phenomenon results from the interruption of substantial inductive currents flowing through windings B and C of the transformer (Figures. 6b and 6c). The very large value of the ratio of the characteristic resistance and the active resistance of the transformer winding - Z_{ch}/R_w, also contributes to the creation of this form of this voltage.

Meanwhile, in phase A, the voltage remains at zero due to the ongoing short circuit in that phase.

Excessively high overvoltage values on the high-voltage side of transformer T_2 are transmitted to its low-voltage windings. Attempts to mitigate these overvoltages through the use of double-contact switches yielded limited success; while such switches reduced the overvoltages significantly, the resulting levels remained unacceptably high.

However, the installation of an overvoltage limiter directly on the HV inputs of transformer T_2 proved effective in bringing these overvoltages within permissible limits. With the overvoltage limiter in place, the overvoltage at the HV inputs is maintained below 200 kV, while at the low-voltage inputs, it remains around 11 kV, both of which are within acceptable thresholds.

In the case of two-phase short circuits to ground (in phases A and B), the voltage in the damaged phases of the HV busbar system at substation SS2 drops to zero, while the healthy phase experiences a reduction to one-third of its original voltage (Table 1). A similar short circuit affecting two phases on the high-voltage side of transformer T_2 results in a significant decrease in its secondary voltages, with voltages in phases A and B diminishing by nearly tenfold, and in phase C by approximately fivefold. This discrepancy in phase voltages on the secondary side of the transformer is attributed to the substantial reduction in currents flowing through the HV windings of the damaged phases.

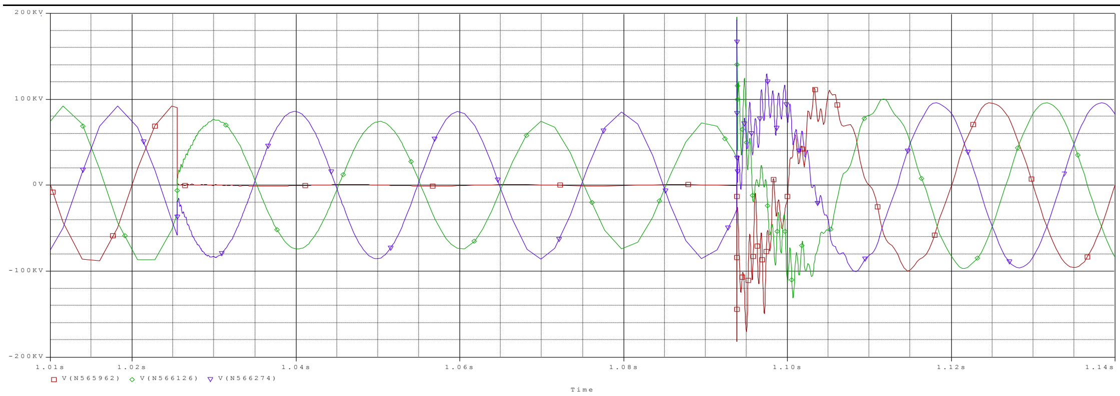
The disconnection of two-phase short circuits to ground results in a voltage increase in the HV busbar systems of substation SS2 by nearly 2.5 times—an increase even greater than that observed during the disconnection of single-phase short circuits. This phenomenon occurs because higher currents are interrupted in the two-phase scenario. At the HV inputs of transformer T_2, the voltage in the short-circuited phases remains at zero, while the voltage in the healthy phase escalates to an extraordinarily high value, significantly exceeding the increase associated with single-phase short circuits. Consequently, the voltages on the secondary side of the transformer also reach excessively high levels for this winding.

Figure 7a illustrates the current curves in the HV windings and the neutral of transformer T_2, as well as the neutral of transformer T_1 and the short-circuit currents. Meanwhile, Figure 7b presents the currents in the switches during two-phase short circuits to ground. As shown in Figure 7b, the currents in the switch phases are considerably more phase-shifted relative to each other compared to single-phase short circuits. Therefore, when one of these currents crosses zero, the others retain substantial values, leading to more pronounced overvoltages upon interruption.

The installation of an overvoltage protection device at the high-voltage inputs of transformer T_2 effectively reduces the overvoltages on its high-voltage and low-voltage sides to 240 kV and 8 kV, respectively. These values are significantly below the permissible overvoltage thresholds for voltage classes of 110 kV and 6 kV.

In the event of a two-phase short circuit (specifically between phases A and B), the voltages in phases A and B equalize, each becoming half the value of the voltage in phase C, which remains at its normal operating level [11]. This same ratio is observed in the secondary phase voltages of transformer T_2, aligning with theoretical expectations for this type of short circuit.

The disconnection of a two-phase short circuit results in a voltage increase in the HV busbar systems of substation SS2 by four times compared to the values during the short circuit, and by two times relative to the voltages in normal network operation (Table 1). Unlike the previously analyzed cases, this time excessively high overvoltages occur in all three phases of transformer T_2.



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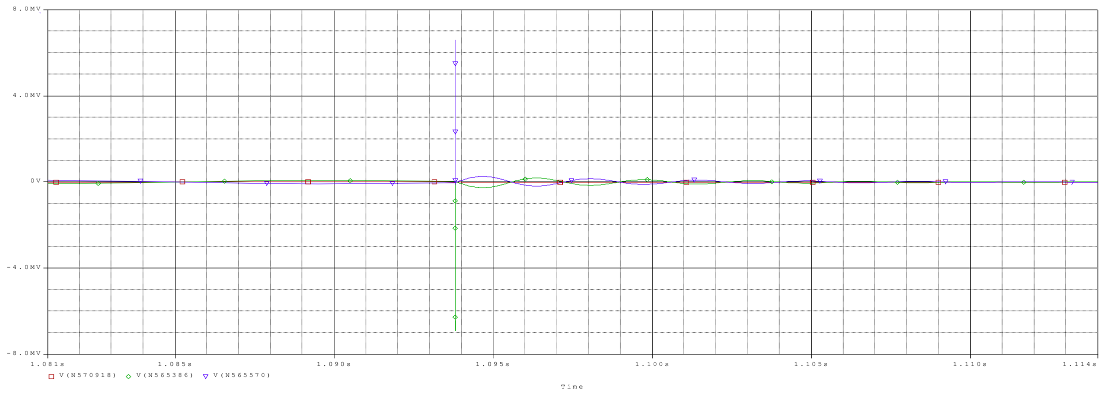

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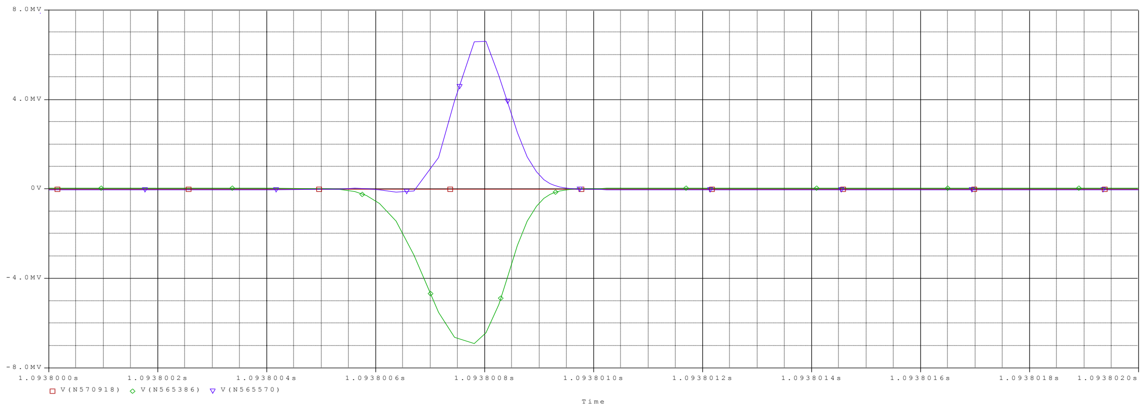
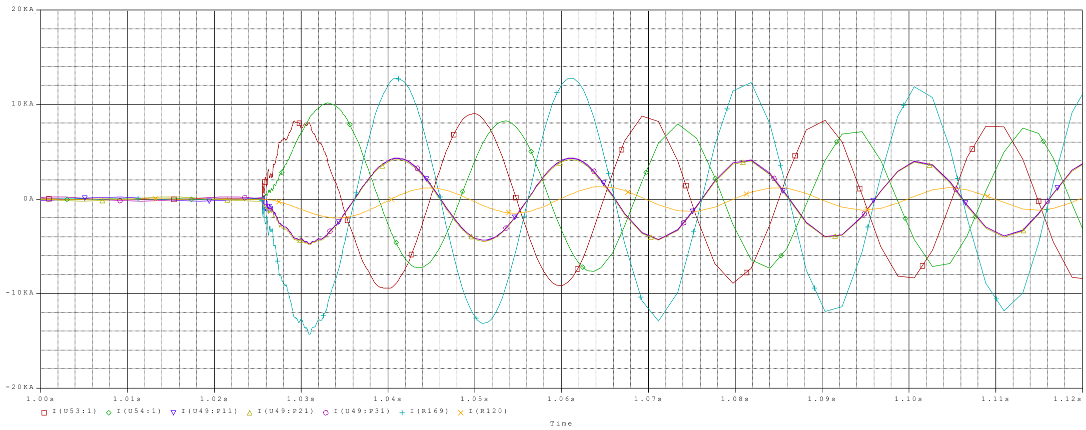


c)

Figure 6. Overvoltages in the HV busbar systems of substation SS2 (a), at the HV inputs of transformer T_2 (b), and the same presented in an open form (c) during the disconnection of a single-phase short circuit.

In this scenario, the installation of a surge protective device (SPD) at the HV inputs of transformer T_2 provides effective protection. The overvoltages on the high-voltage and low-voltage sides of the transformer are reduced to 190 kV and 12 kV, respectively, both of which fall within permissible limits.

An analysis of three-phase short circuits reveals that neither the occurrence nor the disconnection of this type of short circuit generates overvoltages in the network. In a three-phase short circuit, the voltages in all affected phases drop to zero, and the currents in all three HV windings of the transformer also fall to zero. As a result, there is no cutoff current to generate overvoltages.



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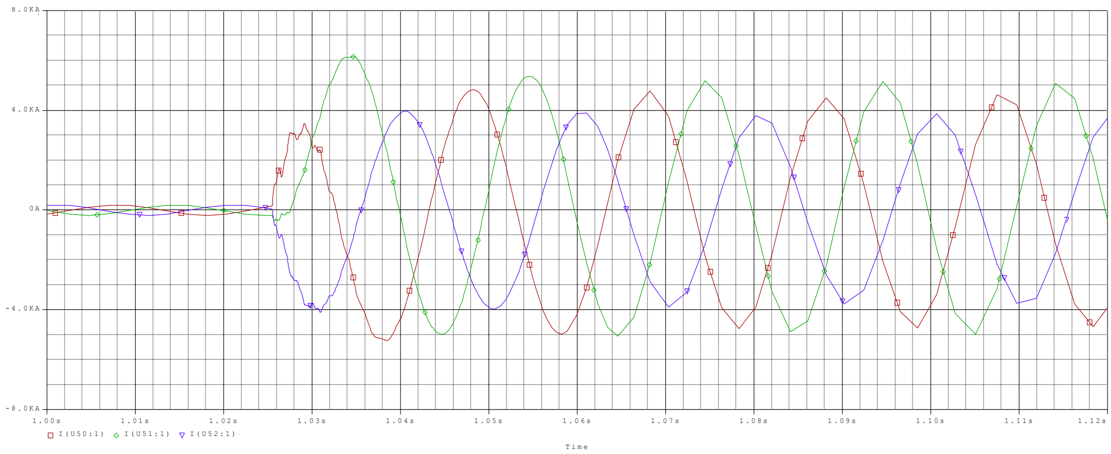


b)

Figure 7. Current curves in the HV windings and the neutral of transformer T_2, in the neutral of transformer T_1, and at the short-circuit point (a), and in the switches (b) during a two-phase short circuit to ground.

[12] The results of voltage calculations for the busbar systems of substations SS2 and SS3, as well as the HV and LV inputs of both transformers and the terminals of the first load, with the transformers' neutrals isolated from ground, are presented in Table 3 and illustrated in Figures 7-9.

From Table 3, it is evident that with the network's neutrals isolated from ground, a single-phase ground fault (short circuit of phase A) leads to the voltage of the damaged phase dropping to zero. In contrast, the voltages in the healthy phases increase significantly—from 92 kV to 166 kV in phase B and 188 kV in phase C, nearly doubling the values observed in the grounded neutral case. An increase in voltage is also noted on the secondary side of transformer T_2, where the voltage in the damaged phase rises by up to 20%, while the remaining phases experience only a slight increase. For transformer T_3, the voltage increase is even more pronounced, doubling in phase A and increasing by almost 25% in phases B and C.

In this scenario, the current flowing to ground is primarily channeled through the capacitances of both lines. When one phase is shorted to ground, the capacitive currents increase significantly, reaching up to 220 A. However, these currents quickly diminish, stabilizing at approximately 20 A in the steady state following the short circuit. An increase in capacitive currents is also observed upon disconnection of the emergency short circuit of one phase to ground (Figure 8).

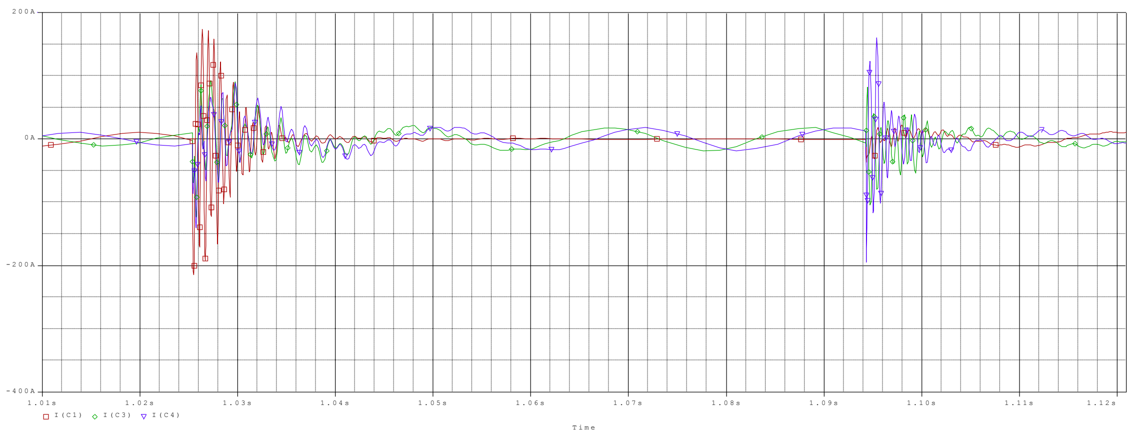


Figure 8. Currents in the first line capacities during a single-phase short circuit in a network with an isolated neutral

Tripping a single-phase ground fault in networks with an isolated neutral, similar to those with a grounded neutral, results in extremely high overvoltages on both the HV and LV sides of transformer T_2. This phenomenon is primarily due to the interruption of currents in the undamaged phases, as previously noted.

In networks with an isolated neutral, a single-phase ground fault does not significantly alter the phase currents. At the moment the circuit breaker trips—when the current of the faulted phase crosses zero—the currents in the other phases retain sufficiently large values (approximately $\pm I_m$ sin(120°)). The interruption of these currents contributes to the generation of remarkably high overvoltages.

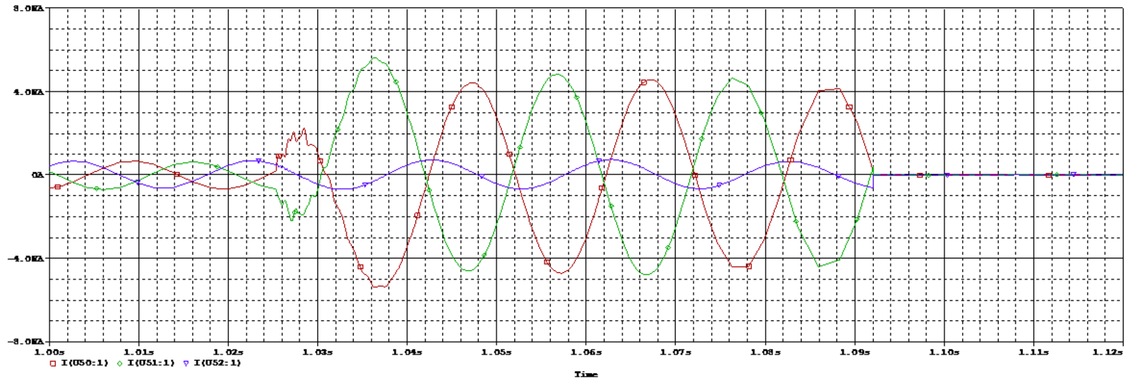
The voltages in the busbar systems of both substations also experience notable changes. At substation SS2, the voltage of phase A rises from zero to 163 kV, phase B increases from 166 kV to 195 kV, while phase C decreases from 188 kV to 171 kV. Compared to the nominal voltage values, the increases in phases A and B are 1.8 and 2.15 times, respectively, while phase C experiences an increase of 1.85 times. In substation SS3, phase A's voltage increases by 1.6 times, and the voltages in phases B and C rise by 2.25 times.

Protection against excessively high overvoltages is achieved by installing an overvoltage protection device at the high-voltage inputs of transformer T_2, as previously described [13].

In the case of a two-phase short circuit to ground (specifically in phases A and B), the currents in the damaged phases become oppositional due to the isolated neutral, while the steady-state values of the capacitive currents remain low (approximately 20 A). The minimum values of the currents in phases A and B coincide with nearly maximum values in phase C. The interruption of this current in phase C results in significantly elevated voltage levels in the network, particularly affecting transformer T_2 (Figure 9a).

In this type of short circuit, the currents in the damaged phases do not reach the corresponding windings of transformer T_2. For instance, the current from the damaged phase A is redirected into the other damaged phase B and returns to the network through phase B. Thus, the same current flows through both phases A and B, similar to a two-phase short circuit.

Only the current from phase C reaches the winding of phase C in the transformer, with half of this current flowing through winding B and the other half through winding C (Figure 8b). As illustrated in Figure 8b, the currents in the windings of phases A and B are identical, each being half of the current in winding C of transformer T_2. The halves of the phase C current passing through the windings of phases A and B, combined with the currents from the damaged phases, return to the network through phase B.



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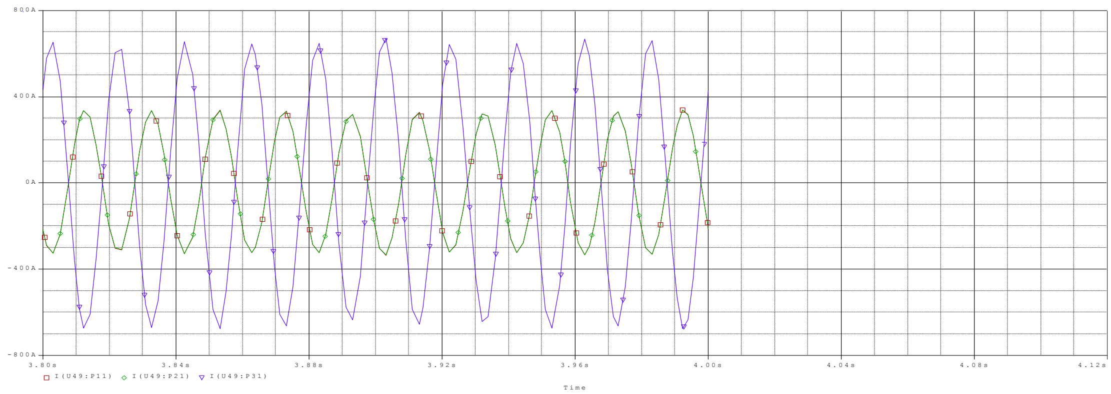

b)

Figure 9. Illustrates the currents during a two-phase short circuit to earth in the network under consideration.

The current curves presented in Figures 8a and 8b help identify the short-circuit paths for these currents, which are depicted in Figure 10.

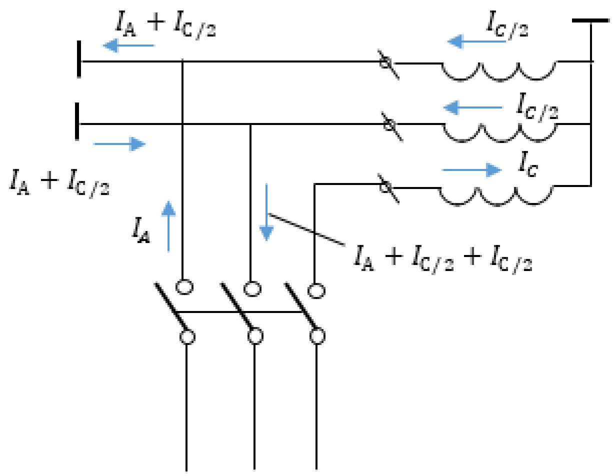

Figure 10. Illustrates the circuit diagram of the current short circuit in the high-voltage windings of transformer T_2 and in the switch during a two-phase short circuit to ground in the network under consideration

A two-phase short circuit to ground leads to a complete reduction of the voltages in the faulty phases to zero while causing an increase in the voltage of the healthy phase across all network elements. For instance, the voltage in phase C of the high-voltage winding of transformer T_2 increases by 1.6 times. On the secondary side of this transformer, the voltage in phase C is double that of phases A and B, as the currents in the high-voltage windings for phases A and B are identical and equal to half the current of phase C (refer to Figure 8b).

When a two-phase short circuit to ground is tripped, it results in even higher overvoltages within the network. While tripping a single-phase short circuit caused the voltages in the busbar systems of substations SS2 and SS3 to rise to 195 kV and 190 kV, respectively, a two-phase short circuit leads to voltages of 233 kV and 204 kV. On both the primary and secondary sides of transformer T_2, these voltages reach disproportionately high levels. The installation of surge arresters at the high-voltage inputs of transformer T_2 effectively limits these excessive overvoltages to 200 kV and 8 kV, respectively.

In the case of a two-phase short circuit (in phases A and B), the voltages of the damaged phases become equal at almost all points of interest. Unlike a two-phase short circuit to ground, this type of short circuit results in a reduction of voltage in substation SS2. While the reduction in the healthy phase is minimal, in the damaged phases it can reach up to two times lower than normal. On the secondary winding of transformer T_2, the voltages in phases A and B are also half that of phase C, reflecting a current distribution similar to that observed during a two-phase short circuit to ground (Figure 9). In substation SS3, there is a slight increase in the voltages of phases A and B.

The disconnection of a two-phase short circuit also differs from that of a two-phase short circuit to ground. Compared to a two-phase short circuit to ground, the voltage increase during the disconnection of a two-phase short circuit is less pronounced (Table 3). For instance, in the high-voltage busbar systems of substation SS2, the voltage in the damaged phases rises to 233 kV when disconnecting a two-phase short circuit to ground, while it reaches only 192 kV during a two-phase short circuit. The voltages in transformer T_2 also increase significantly, similar to other short circuit scenarios, necessitating the installation of an overvoltage limiter at the high-voltage inputs of transformer T_2 to ensure that these voltages remain within permissible limits.

IV. Conclusions

1. The study examines overvoltages at the high-voltage (HV) and low-voltage (LV) inputs of transformers with grounded and isolated neutrals during short circuits occurring nearby. It was found that with an isolated neutral, a single-phase ground fault can increase the voltage on the undamaged phases of the primary and secondary windings of the transformer by up to 2.2 times and 1.2 times, respectively. In the case of a two-phase ground fault, the increases are 1.6 times and 1.1 times.
2. The disconnection of all forms of short circuits, whether in transformers with grounded or isolated neutrals, results in excessively high overvoltages on the primary and secondary sides of the affected transformer. This phenomenon is exacerbated by the interruption of substantial currents in the undamaged phases at the moment the circuit breaker operates, as the three phase currents do not reach zero simultaneously. These overvoltages manifest as pulsed voltage surges with durations of several microseconds.
3. To mitigate these excessively high overvoltages, surge arresters should be installed at the high-voltage inputs of transformers. While the implementation of two-contact switches can reduce these overvoltages by a factor of 2 to 3, the resulting values still remain excessively high.

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