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Temporary Overvoltage in Case of Multiple Faults in Power Systems

Gheorghe Hazi[1], Aneta Hazi[1]
[1]*Department of Power Engineering, Faculty of Engineering, Vasile Alecsandri University of Bacău, Romania*

Abstract:
The paper presents a case of temporary overvoltage due to complex asymmetries (two-phase interruption and two-phase short-circuit) in a 110 kV power system. It presents the conditions in which such overvoltage can occur, the results of the calculations and of some measurements made and its particularly bad consequences. The causes that can generate such events are established and measures are proposed to avoid them.
Key Word*:Temporary overvoltage; Unsymmetrical faults; Experimental checks.*

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I. Introduction

Temporary overvoltages are usually due to asymmetric faults: single-phase or two-phase short-circuit with ground fault. Overvoltages can also be caused by operating regimes with an incomplete number of phases, overvoltages due to ferroresonance. The level of the overvoltages does not exceed the value of 1.4 pu [4], [7], [8]. The paper[1] presents a comprehensive analysis on Temporary Overvoltage caused Distributed Generation connected to the transmission Network via various Transformer tertiary connexion groups . The paper [2] shows the level of temporary overvoltages in long transport lines (2500 km). In this situation, the relative value reaches values of 2.2 for defects at distances between 1400-2500 km. For transmission networks with shorter lengths (260 km) the measured or calculated temporary overvoltages do not exceed 1.22 ur [3]. In Australia the level of these overvoltages has values between 1.15 and 1.25 ur. These values affect the network equipment if the duration of the overvoltage is higher [5]. There are also important effects on residential consumers, however they are less affected by temporary overvoltages as the value does not exceed1.3 ur for networks with grounded neutral [6].

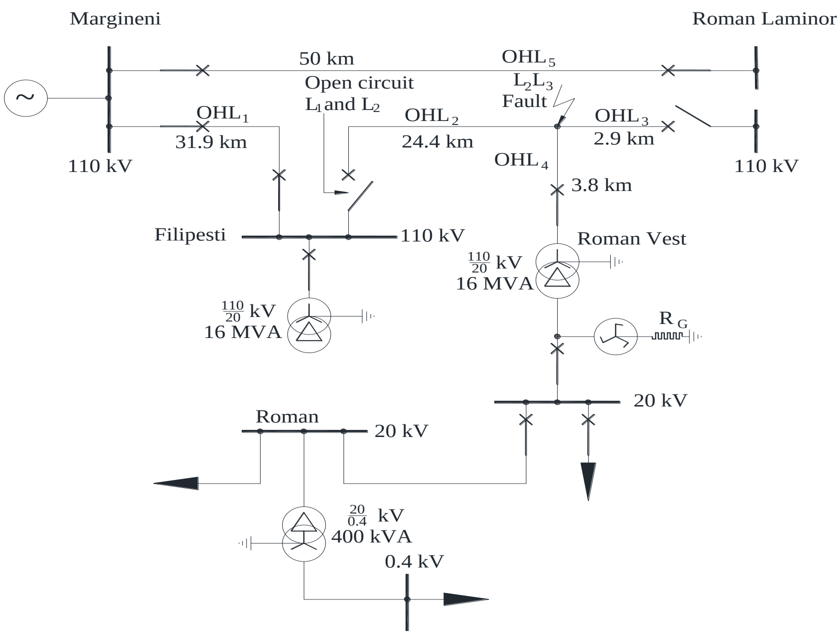

Figure 1. Power systemdiagram

Based on an incident that occurred in a 110 kV network, we will show that temporary over voltages may occur under other particular conditions. These over voltages are propagated in the Medium Voltage (MV) and Low Voltage (LV) networks, with important consequences for consumers connected to these networks.

Figure 1 shows the single line diagram of the 110/20 / 0.4 kV power system in which the incident took place.

In addition to the events marked in the figure, a single-phase short circuit on the L1 phase in the Filipeşti substation, on the Filipeşti-Roman circuit, took place in the network, by priming the surge arrester mounted on the line, at the industrial frequency overvoltage.

For a better understanding of the situation, we will briefly present how the final status of the network presented in the figure was reached :

- two-phase fault on Over Head Line (OHL) 110 kV Filipeşti-Roman Laminor, L2-L3 phases, near the Roman-Vest connection;
- auto reclose failed in both Roman_Laminor and Filipeşti;
- disconnecting OHL Roman in Filipeşti by non-correspondence (breaker operated by compressed air, each phase independently);
- refusal to operate the breaker on phase L3 in Filipeşti;
- start of line surge arrester, phase L1, on OHL 110 KV Roman, in Filipeşti;
- current fluctuations on OHL 110 KV Mărgineni-Filipeşti-Roman Vest and voltage fluctuations on phase L1 on OHL 110 KV Filipeşti-Roman_Vest;
- circuit breaker of transformer Roman_Vest trip with maximum current protection of 110 kV.

Due to temporary over voltages, hundreds of household appliances connected to the LV in the power loops of the Roman_Vest substation were destroyed.

II. Calculation temporary overvoltage

Equivalent sequence schemes for complex asymmetry are shown in Figures 2 and 3.The calculations were performed under the following assumptions:

• the power lines are modeled by equivalent schemes in π;

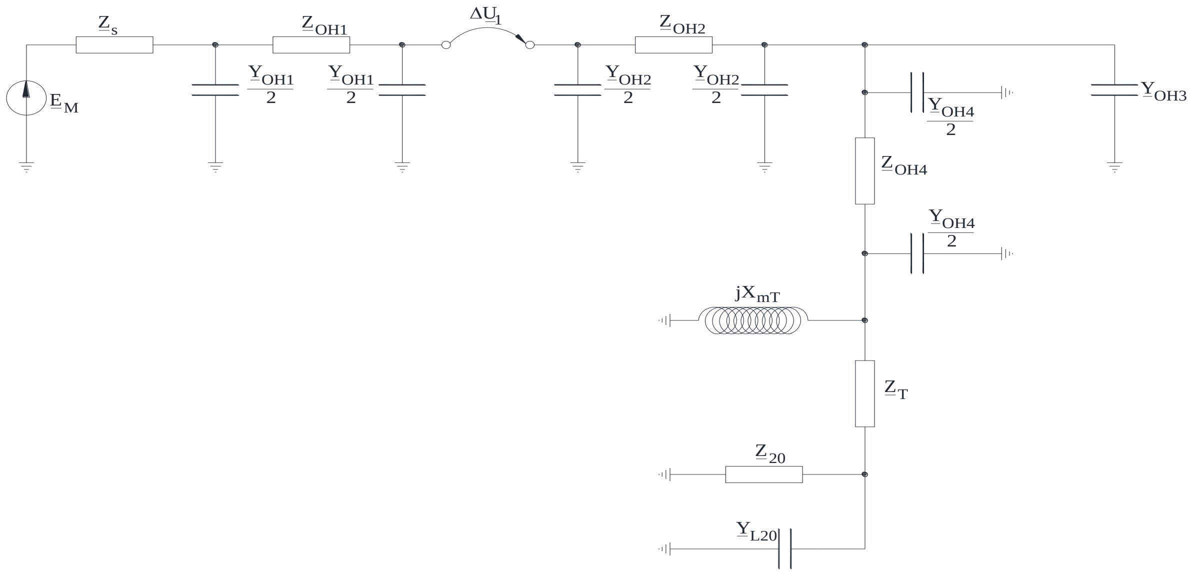

Figure 2. Positive sequence diagram

• the transformer from the Roman_Vest substation is modeled by an equivalent scheme in Γ, taking into account the magnetization reaction and the current operating tap;

• the total load on the 20 KV bars in the Roman_Vest substation is modeled by a constant impedance in the direct and reverse sequence scheme;

• 20 kV cable lines are considered in the sequence diagrams only by their capacitive admittance;

• the load from the Filipeşti substation is neglected;

• the 110/20 kV transformer from Filipeşti substation is considered only in the homopolar sequence scheme;

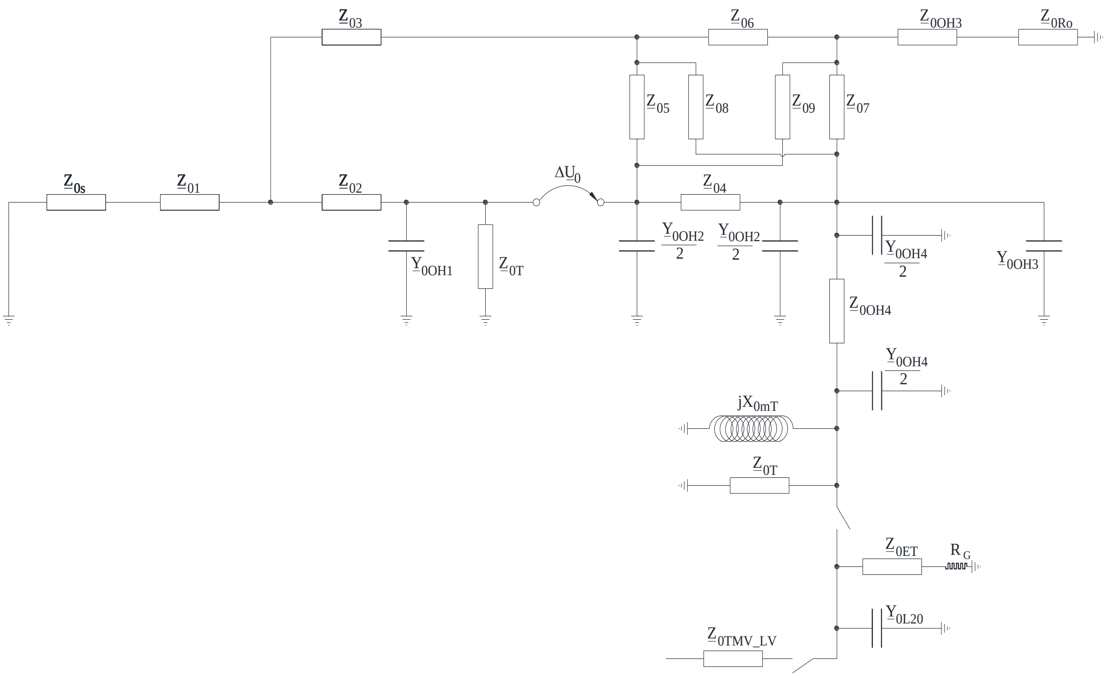

Figure 3. Zero sequence diagram

•the coupling between the 110 kV Mărgineni-Roman OHL and the 110 KV Mărgineni-Filipeşti-Roman OHL is considered in the zero sequence scheme but the coupling on the input - output connection Filipeşti of small length (4.7 km) is neglected;

• the surge arrester on phase L1 from Filipeşti substation (OHL 110 KV Roman) is modeled by a variable resistor R1 with a value of 5 Ω in case the voltage is high and with the value of 40000 Ω when the voltage is low (it was taken into account that the discharger gap of surge arrester was already pierced);

• The short circuit L2-L3 from Roman_Vest is considered by a resistance R2 = 10 Ω.

• it is considered as the power supply of the network the Mărgineni system substation, with EM=117/√3·ej0 KV (phase voltage).

As can be seen, equivalent schemes take into account the capacity of the line. This was due to the fact that, in the first phase, a possible ferroresonance was seen in the network.

The conditions in the asymmetry points result from figure 4.In figure 4 "Le" indices show the left side of the network (from Filipeşti to Mărgineni, including Filipeşti substation), indices "4" show line L4 (Roman-West connection), indices "2 + 3" show lines 2 and 3 faults in the connection node Roman_Vest, and the indices k refer to the two-phase short-circuit point.

The following local conditions result:

$$\underline{U}_{L1} = -R_1 \cdot \underline{I}_{L1} \quad (1)$$

$$\underline{I}_{L1Le} = 0 \quad (2)$$

$$\underline{I}_{L2Le} = 0 \quad (3)$$

$$\underline{I}_{L3Le} = \underline{I}_{L3} \quad (4)$$

$$\underline{I}_{L2} = 0 \quad (5)$$

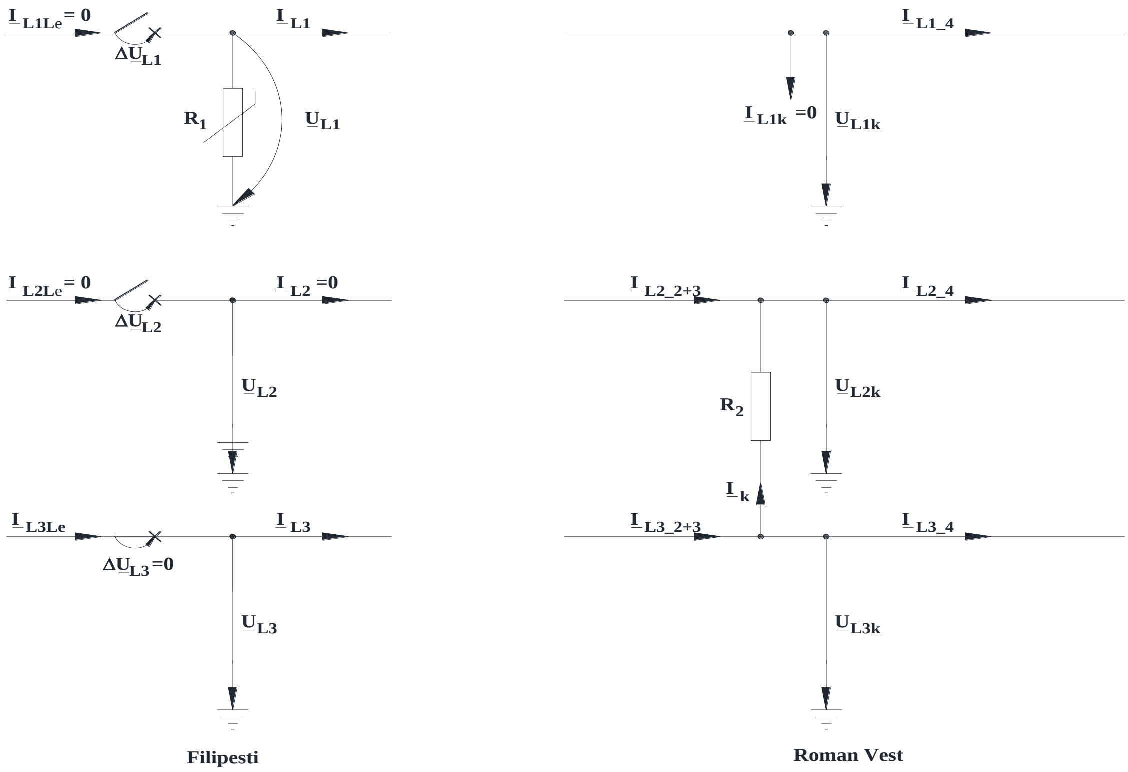

Figure 4. Local conditions, in phases, in asymmetry points

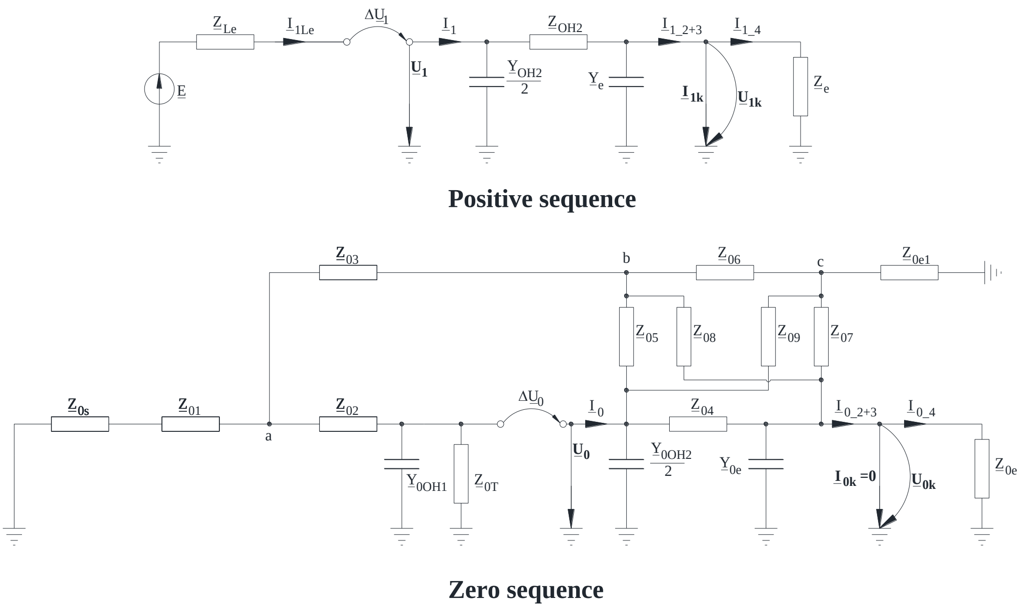

Figure 5. Equivalent sequence diagrams

$$\Delta\underline{U}_{L3} = 0 \qquad (6)$$

for Filipeşti substation and:

$$I_{L1k} = 0 \tag{7}$$

$$\underline{I}_{L2k} = -\underline{I}_{L3k} = -\underline{I}_k \tag{8}$$

$$\underline{U}_{L3k} - \underline{U}_{L2k} = R_2 \cdot \underline{I}_k \tag{9}$$

for the two-phase short circuit point (Roman_Vest connection).
By reducing the sequence schemes to the asymmetry points, the schemes in figure 5 are obtained. In this figure $\underline{Z}_e$, $\underline{Z}_{0e}$ represents the equivalent impedances of the Roman_Vest branch, $\underline{Z}_{0e1}$, the zero impedance of the Roman_Vest-Roman_Laminor branch, $\underline{Z}_{Le}$ the direct sequence impedance of the left branch of the scheme (Filipeşti-Mărgineni), and $\underline{Y}_e$, $\underline{Y}_{0e}$ the sum of the admittance from the admittance of line L2. The impedances $\underline{Z}_{01} \div \underline{Z}_{09}$ represent equivalent impedances in the zero sequence scheme calculated as follows:

$$\underline{Z}_{01} = \underline{Z}_{0mOH1} \qquad \underline{Z}_{02} = \underline{Z}_{03} = \underline{Z}_{0OH1} - \underline{Z}_{0mOH1} \tag{10}$$

$$\underline{Z}_{04} = \underline{Z}_{06} = \frac{\underline{Z}_{0OH2}^2 - \underline{Z}_{0mOH2}^2}{\underline{Z}_{0OH2}} \qquad \underline{Z}_{05} = \underline{Z}_{07} = \frac{\underline{Z}_{0OH2}^2 - \underline{Z}_{0mOH2}^2}{\underline{Z}_{0mOH2}} \tag{11}$$

$$\underline{Z}_{08} = \underline{Z}_{09} = -\underline{Z}_{05} \tag{12}$$

In the above relations, $\underline{Z}_{0mOH1}$, $\underline{Z}_{0mOH2}$ represent the mutual impedance of zero sequence between the two circuits of the 110 kV double circuit OHL Mărgineni-Filipeşti, respectively, Filipeşti-Roman.
From conditions (2), (3), (4), taking phase L3 as a special phase (reference), it results:

$$\underline{I}_{1Le} = \underline{I}_{2Le} = \underline{I}_{0Le} = \frac{1}{3} \cdot (\underline{I}_1 + \underline{I}_2 + \underline{I}_0) \tag{13}$$

and from the conditions (7), (8), (9) we will have:

$$\underline{I}_{2k} = -a \cdot \underline{I}_{1k} \qquad \underline{I}_{hk} = 0 \tag{14}$$

$$\underline{I}_k = (1-a) \cdot \underline{I}_{1k} \tag{15}$$

$$\underline{I}_{1k} = \frac{1}{R_2} \cdot \left[\underline{U}_{1k} + (1+a) \cdot \underline{U}_{2k}\right] \tag{16}$$

Writing the conditions (1), (5), (6) in sequence sizes, using Kirchhoff's theorems written for the sequence networks (fig. 4), taking into account the relations (13), (14) and (16) it result the following system of equations that allows the calculation of the asymmetric regime of the network:

$$\underline{U}_0 + a^2 \cdot \underline{U}_1 + a \cdot \underline{U}_2 = -\left(\underline{I}_0 + a^2 \cdot \underline{I}_1 + a \cdot \underline{I}_2\right) \cdot R_1 \tag{17}$$

$$\underline{I}_0 + a \cdot \underline{I}_1 + a^2 \cdot \underline{I}_2 = 0 \tag{18}$$

$$\Delta\underline{U}_1 + \Delta\underline{U}_2 + \Delta\underline{U}_0 = 0 \tag{19}$$

$$\underline{E} = \underline{Z}_{Le} \cdot \frac{1}{3} \cdot (\underline{I}_1 + \underline{I}_2 + \underline{I}_0) + \Delta\underline{U}_1 + \underline{U}_1 \tag{20}$$

$$0 = \underline{Z}_{Le} \cdot \frac{1}{3} \cdot (\underline{I}_1 + \underline{I}_2 + \underline{I}_0) + \Delta\underline{U}_2 + \underline{U}_2 \tag{21}$$

$$\underline{U}_1 = (\underline{I}_1 - \underline{U}_1 \cdot \frac{\underline{Y}_{OH2}}{2}) \cdot \underline{Z}_{OH2} + \underline{U}_{1k} \tag{22}$$

$$\underline{U}_2 = (\underline{I}_2 - \underline{U}_2 \cdot \frac{\underline{Y}_{OH2}}{2}) \cdot \underline{Z}_{OH2} + \underline{U}_{2k} \tag{23}$$

$$\underline{U}_{1k} = \underline{I}_{1\_4} \cdot \underline{Z}_e \tag{24}$$

$$\underline{U}_{2k} = \underline{I}_{2\_4} \cdot \underline{Z}_e \tag{25}$$

$$\underline{U}_{0k} = \underline{I}_{0\_4} \cdot \underline{Z}_{0e} \tag{26}$$

$$\underline{I}_1 - \underline{U}_1 \cdot \frac{\underline{Y}_{OH2}}{2} - \underline{U}_{1k} \cdot \underline{Y}_e - \frac{1}{R_2} \cdot [\underline{U}_{1k} + (1+a) \cdot \underline{U}_{2k}] = \underline{I}_{1\_4} \tag{27}$$

$$\underline{I}_2 - \underline{U}_2 \cdot \frac{\underline{Y}_{OH2}}{2} - \underline{U}_{2k} \cdot \underline{Y}_e + \frac{a}{R_2} \cdot [\underline{U}_{1k} + (1+a) \cdot \underline{U}_{2k}] = \underline{I}_{2\_4} \tag{28}$$

$$\frac{\underline{U}_{0a}}{\underline{Z}_{0s} + \underline{Z}_{01}} + \frac{\underline{U}_{0a} - \underline{U}_{0b}}{\underline{Z}_{03}} + \frac{\underline{U}_{0a} - \Delta\underline{U}_0 - \underline{U}_0}{\underline{Z}_{02}} = 0 \tag{29}$$

$$\frac{1}{3} \cdot (\underline{I}_1 + \underline{I}_2 + \underline{I}_0) = \frac{\underline{U}_{0a} - \Delta\underline{U}_0 - \underline{U}_0}{\underline{Z}_{02}} - (\Delta\underline{U}_0 + \underline{U}_0) \cdot (\underline{Y}_{0OH1} + \frac{1}{\underline{Z}_{0T}}) \tag{30}$$

$$\frac{\underline{U}_{0b} - \underline{U}_{0a}}{\underline{Z}_{03}} + \frac{\underline{U}_{0b} - \underline{U}_0}{\underline{Z}_{05}} + \frac{\underline{U}_{0b} - \underline{U}_{0k}}{\underline{Z}_{08}} + \frac{\underline{U}_{0b} - \underline{U}_{0c}}{\underline{Z}_{06}} = 0 \tag{31}$$

$$\frac{\underline{U}_{0c}}{\underline{Z}_{0e1}} + \frac{\underline{U}_{0c} - \underline{U}_{0b}}{\underline{Z}_{06}} + \frac{\underline{U}_{0c} - \underline{U}_0}{\underline{Z}_{09}} + \frac{\underline{U}_{0c} - \underline{U}_{0k}}{\underline{Z}_{07}} = 0 \tag{32}$$

$$\underline{I}_0 - \underline{U}_0 \cdot \frac{\underline{Y}_{0OH2}}{2} + \frac{\underline{U}_{0b} - \underline{U}_0}{\underline{Z}_{05}} + \frac{\underline{U}_{0c} - \underline{U}_0}{\underline{Z}_{09}} = \frac{\underline{U}_0 - \underline{U}_{0k}}{\underline{Z}_{04}} \tag{33}$$

$$\frac{\underline{U}_0 - \underline{U}_{0k}}{\underline{Z}_{04}} = \frac{\underline{U}_{0k} - \underline{U}_{0b}}{\underline{Z}_{08}} + \frac{\underline{U}_{0k} - \underline{U}_{0c}}{\underline{Z}_{07}} + \underline{I}_{04} + \underline{U}_{0k} \cdot \underline{Y}_{0e} \tag{34}$$

In the above relations a is the complex operator, $a = e^{j \cdot \frac{2\cdot\pi}{3}}$, $\underline{U}_{0a}$, $\underline{U}_{0b}$, $\underline{U}_{0c}$ are the voltages in points a, b, c of the zero sequence diagram in figure 5.

By solving the system (17)÷(34) the sequence sizes are obtained and then the phase sizes on each network element. The results obtained for the two limit values of resistance R_1 are given in tables 1 and 2.
In order to see better the influences of the surge arrester resistance in the process of oscillations of the voltages and currents as well as the influence of the resistance R_2 at the two-phase short circuit place, in Figures 6, 7, 8 and 9, the variation of the voltage on the surge arrester, U_{L1}, of the system flow current is presented. through the 110 kV OHL Mărgineni-Filipeşti, $I_{L3Măr}$, of the two-phase short-circuit current, I_k, and of the voltages at the low voltage terminals of a Roman 20 / 0.4 kV substation, connected in the Roman_Vest substation depending on the resistance value, R_1, of the surge arrester primed at the industrial frequency.

Table 1: The parameters in unsymmetrical regime, R_1 = 40000 [Ω], R_2 = 10 [Ω]
(surge arrester is not sparked)

Parameter	UM	Value	Parameter	UM	Value
Current phase L3, line OH1, in Mărgineni	A	67.06	Voltage phase L1, line OH2, in Filipeşti	kV	136.93
Filipeşti transformer input (zero sequence current per phase)	A	9.38	Voltage phase L2, line OH2, in Filipeşti	kV	67.09
Current phase L3, line, OH2 in Filipeşti	A	74.49	Voltage phase L3, line OH2, in Filipeşti	kV	67.58
Current phase L1, OH2 line in Filipeşti	A	3.42	Line voltage, U_{L1L2}, Roman_Vest transformer, part MV	kV	20.21
Two-phase short-circuit current, Roman_Vest	A	37.23	Line voltage, U_{L2L3}, Roman_Vest transformer, part MV	kV	20.31
Current phase L1, Roman_Vest transformer	A	10.32	Line voltage, U_{L3L1}, Roman_Vest transformer, part MV	kV	40.52
Current phase L2, Roman_Vest transformer	A	36.06	L3 phase voltage, LV terminals, TS 20 / 0.4 Roman	V	467.93
Current phase L3, Roman_Vest transformer	A	36.11	L1 phase voltage, LV terminals, TS 20 / 0.4 Roman	V	233.36
Zero sequence current on LEA 110 kV phase Mărgineni-Roman	A	6.72	L2 phase voltage, LV terminals, TS 20 / 0.4 Roman	V	234.57

Table 2: The parameters in unsymmetrical regime, R1 = 5 [Ω], R2 = 10 [Ω]
(surge arrester is sparked)

Parameter	UM	Value	Parameter	UM	Value
Current phase L3, line OH1, in Mărgineni	A	367.05	Voltage phase L1, line OH2, in Filipeşti	kV	1.07
Filipeşti transformer input (zero sequence current per phase)	A	52.01	Voltage phase L2, line OH2, in Filipeşti	kV	51.70
Current phase L3, line, OH2 in Filipeşti	A	423.36	Voltage phase L3, line OH2, in Filipeşti	kV	56.65
Current phase L1, OH2 line in Filipeşti	A	213.67	Line voltage, U_{L1L2}, Roman_Vest transformer, part MV	kV	5.34
Two-phase short-circuit current, Roman_Vest	A	211.59	Line voltage, U_{L2L3}, Roman_Vest transformer, part MV	kV	5.45
Current phase L1, Roman_Vest transformer	A	212.65	Line voltage, U_{L3L1}, Roman_Vest transformer, part MV	kV	10.78
Current phase L2, Roman_Vest transformer	A	214.33	L3 phase voltage, LV terminals, TS 20 / 0.4 Roman	V	124.46
Current phase L3, Roman_Vest transformer	A	214.66	L1 phase voltage, LV terminals, TS 20 / 0.4 Roman	V	61.68
Zero sequence current on LEA 110 kV phase Mărgineni-Roman	A	47.06	L2 phase voltage, LV terminals, TS 20 / 0.4 Roman	V	62.98

It is clear from the data presented that the overvoltages which appeared in the analyzed regime have important values reaching 2.15 u.r. in the 110 kV network and 2.03 u.r. in the LV. Obviously the values of the over voltages can have even higher values, they are influenced by the values of the voltages in the system, by the values of the taps at transformers as well as by the network load. In the analyzed case, the actual tap was considered at the 110/20 kV transformer (tap 1), and for the 20 / 0.4 kV transformers, it was considered to operate at the nominal tap. The phenomenon that generates the temporary overvoltage is the 110/20 kV transformer supply from Roman_Vest, the L2 and L3 phases with the L3 phase in the system. In this way, the fluxes on phases L2 and L3, of approximately equal values, are assembled, generating on phase L1 a voltage of double value and of opposite direction. This voltage propagates in the MV network (between phases L3 and L1 due to the Yn d11 connection) and then in the LV network (on the L3 phase due to the Dyn 5 connection).

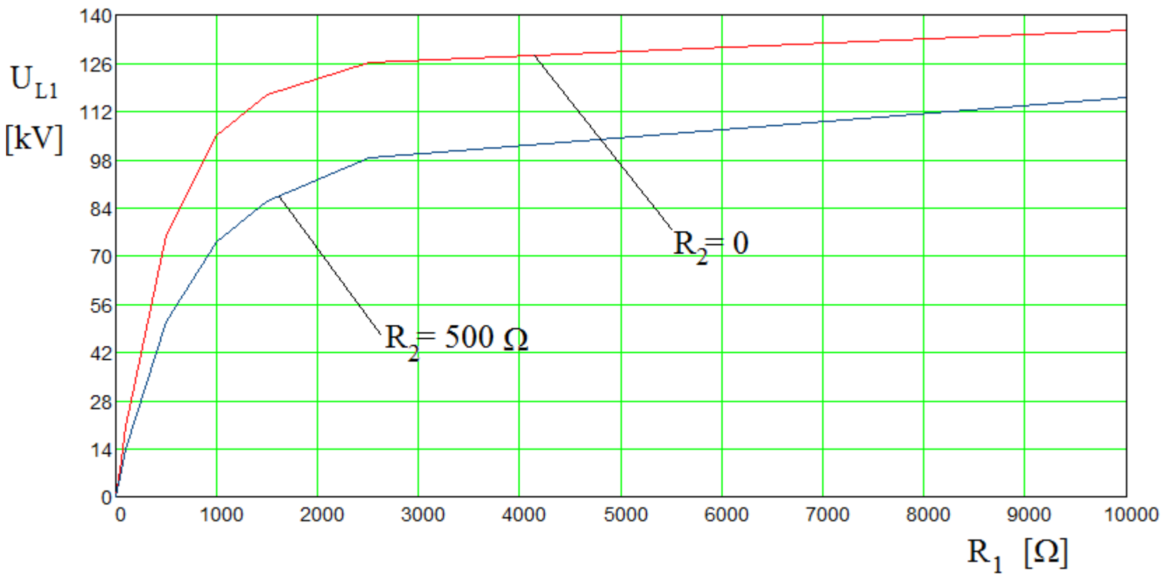

Figure 6. Variation of voltage on surge arester

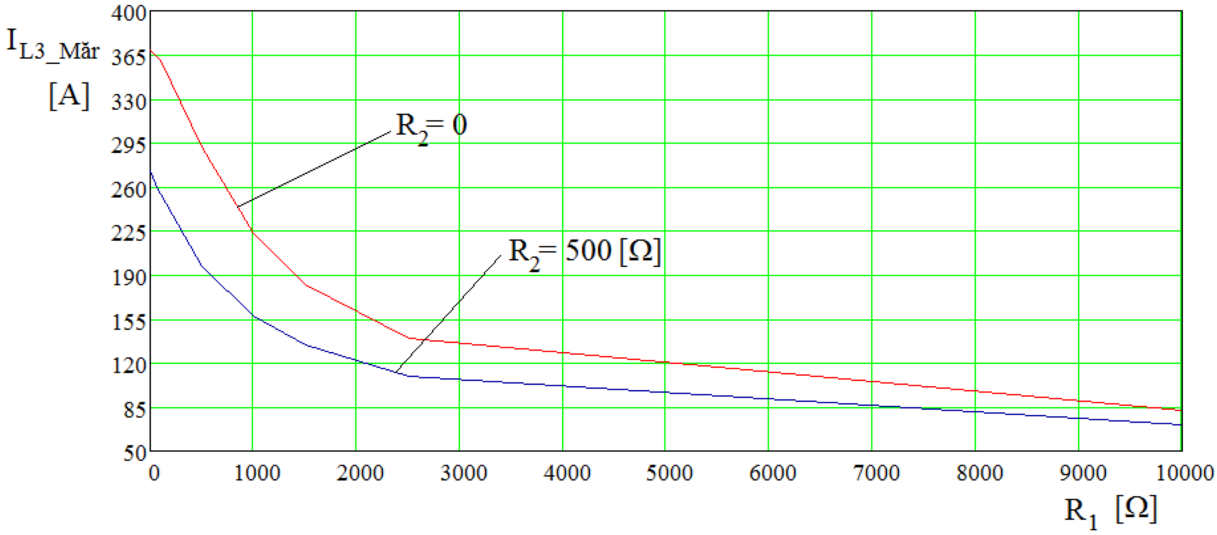

Figure 7. Current given by the system

The main reason that caused the phenomenon is the refusal of the circuit breaker to operate in the Filipeşti substation after failed Rapid Auto Reclose on incomplete number of phases. It is due to the poor performance of the circuit breakers with low oil level operated with compressed air. To eliminate future incidents, these circuit breakers need to be replaced with more efficient ones. From the analysis of the curves presented in Figures 6 and 9 it can be seen that the overvoltages have significant values regardless of the value of the resistance at the two-phase short circuit place, the extreme values considered (0 and 500 Ω) being covering for the practical cases. For higher values of the fault resistance, the overvoltages are lower, but they far exceed the values of the maximum permissible phase voltages (123/√3 at 110 kV, 24/√3 KV at 20 kV and 253 V at low voltage). Obviously, from the graphs presented in Figures 6 and 9, the values for high R_1 must be considered, and in our case, the break down of the surge arrester from phase L1 from Filipeşti substation is worsening the situation.

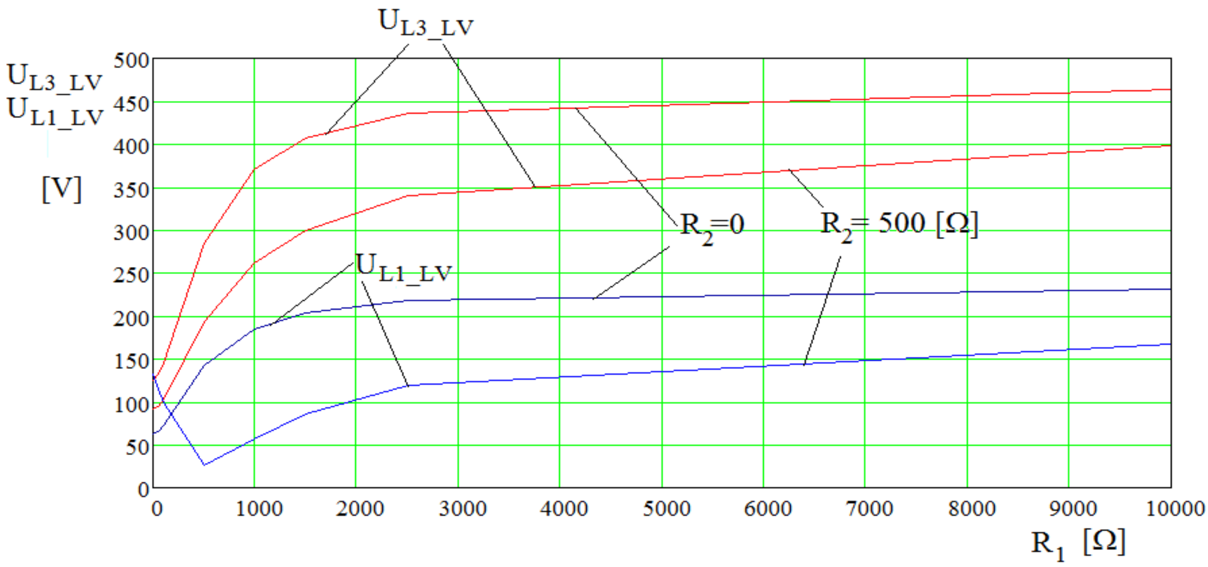

Figure 8. Two-phase short-circuit current

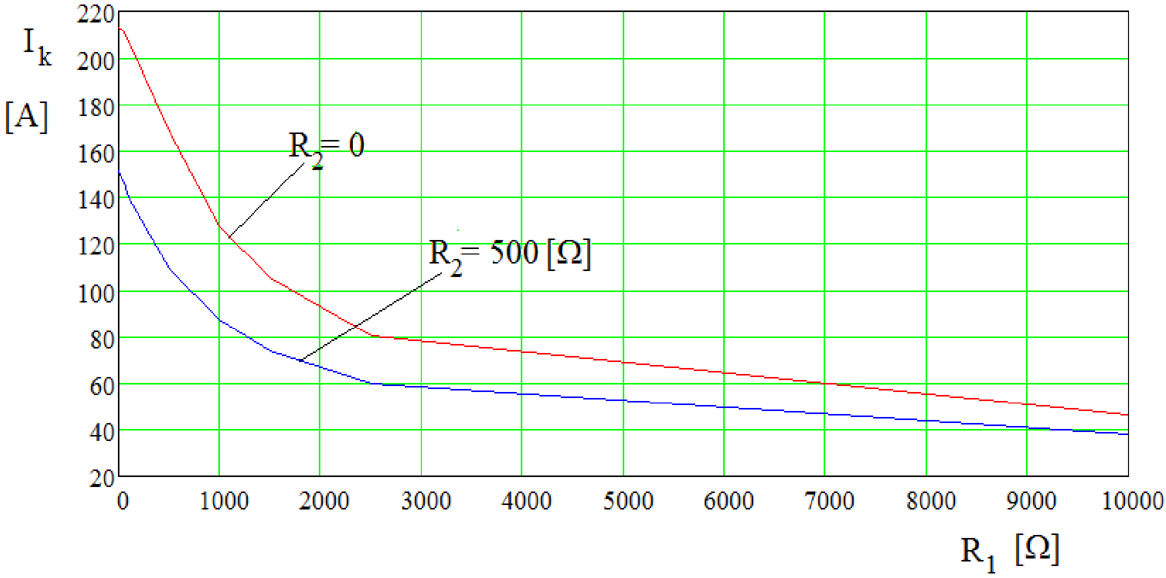

Figure 9. Voltages on the JT bar of the Roman transformation substations

Figures 7 and 8 show the variation of currents in the variable regime generated by the priming of the surge arrester. The failure of the surge arrester, VA 102 type with variable resistance , is explained by the value of the industrial frequency voltage to which it was subjected (130-140 kV) and by the fact that its gaps were already pierced. These were pierced due to commutation overvoltages to which it was subjected systematically, including those at the time of which the incident was analyzed. This last aspect was confirmed by the tests performed in the laboratory on the surge arrester on phase L2. This type of surge arrester has the maximum permissible voltage of 102 kV rms, and the starting voltage at the industrial frequency of 161 kV rms. There are variations of currents within wide limits (tens to hundreds of amps) to the variation of nonlinear resistance.

III. Experimental Results

For the verification of the hypotheses used as for the verification of the mathematical model, experimental checks were carried out on the network in question. Because testing in the actual conditions of the incident registered would have led to dangerous requests for the isolation of the equipment and installations, the supply of the network was made with a lower voltage obtained from a 110 / 27.5 kV transformer from the Rail Network at Filipeşti substation. The voltage was applied on phase L1 and had a value of 25.85 kV. The network was disconnected to the Mărgineni substation, and in the Roman area, only 110/20 kV transformer in the Roman_Vest substation and auxiliary transformer 100 kVA, 20 / 0.4 kV from the same substation, operated. The two-phase short circuit was also performed in the Filipeşti substation, between phases L1-L2, and phase L3 was left empty. The value of the measured data was verified via computer analysis. The comparative results are presented in table 3. Voltages at 0.4 kV were measured at the auxiliary transformer terminal, which has the Yzn5 connection.

Table 3: Results obtained from experimental checks

No.	Parameter	UM	Measured value	Calculated value	Error [%]
1.	Voltage phase L2 Filipeşti	kV	25.85	25.85	0.00
2.	Voltage phase L3 Filipeşti	kV	54.45	53.64	-1.49
3.	20 kV bar voltage U_{L2L3} Roman_Vest	kV	15.98	15.83	-0.96
4.	20 kV bar voltage U_{L1L2} Roman_Vest	kV	7.98	7.91	-0.84
5	20 kV bar voltage U_{L3L1} Roman_Vest	kV	7.98	7.91	-0.84
6.	Voltage phase L1, bar 0.4 KV own services Roman_Vest	V	87	87.02	0.02
7.	Voltage phase L2, bar 0.4 KV own services Roman_Vest	V	176	174.04	-1.14
8.	Voltage phase L3, bar 0.4	V	87	87.02	0.02

	KV own services Roman_Vest				

From the analysis of the results presented in table 3, a very good correspondence of the experimental data with the theoretical ones is found. The differences are up to 1.5%, a value that can be explained by the error introduced by the measuring devices.

IV. Conclusions

The following conclusions are drawn from the analysis of the data presented:

• The appearance of complex asymmetries can lead to temporary overvoltages of high values, exceeding the value of 2 ur, with important consequences on the insulation of the equipment and installations. Propagation of over voltages in LV networks leads to the destruction of household appliances and other equipment connected to these networks.

• The main cause of the occurrence of the phenomenon is the existence in the installations of the circuit breakers with low levels of oil actuated on single phase with compressed air, which leads to the possibility of operating lines with incomplete number of phases. The superposition of such an event over a two-phase defect in the case of lines that supply 110 / MV transformers, can generate high values of over voltages at industrial frequency. Avoiding such incidents in the future requires replacing these circuit breakers on the lines to which they are connected 110 / MV transformers.

• The differences between the results obtained experimentally and those established by calculation are insignificant (up to 1.5%), which confirms the viability of the model used.

• The procedure for calculating complex asymmetric regimes is relatively complicated if all the dimensions that influence the regime are taken into account. It can be simplified by accepting simplifying assumptions, such as:

- considering longitudinal and transverse asymmetries at the same point;
- neglecting the electromagnetic couplings with paralld lines;
- neglect transverse admittance of lines and transformers.

For the analyzed case, the neglect of the electromagnetic coupling between the 110 kV Mărgineni-Roman double circuit as well as the consideration of the two-phase short-circuit in Filipeşti leads to errors below 0.5% in the low current regimes (R_1 of high value) and to errors of about 3% in high current regimes (low value R_1). However, the number of equations to be solved is reduced from 18 to 3.

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