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Phenomena leading to asymmetry of phase–to–earth voltages in MV networks

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When analysing the earth–fault phenomena, the longitudinal impedance of individual elements is neglected, and the capacitances and conductivities of individual phases to ground are only taken into account. Such a procedure is well–founded for resonant earthed networks and the faults accompanied by a significant resistance at the disturbance's location (called high–resistance faults). However, in such a case, the possibility of occurrence of voltage differences between the network neutral point and the earth should be considered. The voltage is the effect of natural asymmetry in the network's phase admittances or in the supply voltages. Level of such a voltage asymmetry significantly affects the flawless of the earth–fault protections and the accurate tuning of Petersen coils in the earth–fault compensation process. In the paper, the results of research work on how different phenomena affect the level of the network phase voltage asymmetry are presented. The investigations have been carried out on the PSCAD software–based MV network model, and investigations take into account the relations between asymmetries in the phase capacitance and conductance of the network as well as the load asymmetry degree in the individual power lines.

KEYWORDS: earth–faults, MV network, voltage asymmetry, earth–fault protections

1. Introduction

The U_0 voltage zero–sequence component that presents the voltage between the network's neutral point and the earth when neglecting the longitudinal impedance of the line is the fundamental magnitude describing the network under the earth–fault [1, 2, 3, 4]. However, the level of the latter voltage is decided not only by the conditions at the earth–fault location but also by the asymmetry in the earth–fault capacitances and conductances as well as by the voltage–to–earth asymmetry in the power supply system [1, 2]. In particular, phenomena due to such asymmetries are visible in the compensated networks and have to be taken into account when defining the operating conditions of both the earth–fault protections and the earth–fault follow–up compensation controllers. Therefore, the theoretical analysis of disturbances following the asymmetry and earth–faults is mostly carried out basing on network equivalent scheme shown in Fig. 1.

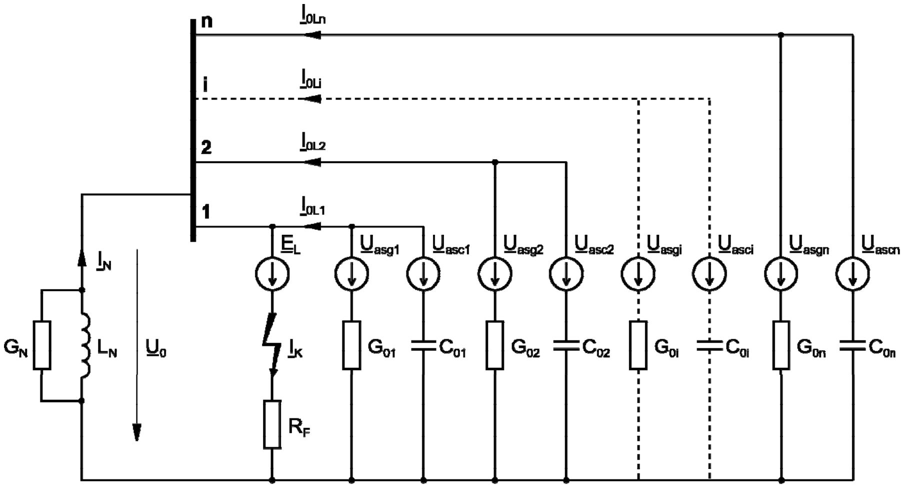

Fig. 1. Compensated MV network equivalent scheme for computations of the earth–fault magnitudes [1]

Elements and depictions implemented in Fig. 1 are: $\underline{E}_L$ – electromotive force of the earth–faulted phase, C_{0i} – phase capacitance of the ith line, G_{0i} – phase conductance of the i^{-th} line, $\underline{I}_{0i}$ – earth current of the ith line (resulting from C_{0i} *and* G_{0i}), R_F – transition resistance at the earth–fault location, L_N – reactance of Petersen coil installed at the network's neutral point, G_N – conductance of the network's neutral point grounding system,
and

$$\underline{U}_{asci} = \frac{\underline{E}_{L1}C_{0L1i} + \underline{E}_{L2}C_{0L2i} + \underline{E}_{L3}C_{0L3i}}{C_{L1i} + C_{L2i} + C_{L3i}} \tag{1}$$

$$\underline{U}_{asgi} = \frac{\underline{E}_{L1}G_{0L1i} + \underline{E}_{L2}G_{0L2i} + \underline{E}_{L3}G_{0L3i}}{G_{L1i} + G_{L2i} + G_{L3i}} \tag{2}$$

where: $\underline{U}_{asci}$ – voltage due to the asymmetry of the phase earth–fault capacitances of the ith line, $\underline{U}_{asgi}$ – voltage due to the asymmetry of the phase earth–fault conductance of the ith line, $\underline{E}_{L1}$, $\underline{E}_{L2}$, $\underline{E}_{L3}$ – electromotive force of individual phases (L1, L2 and L3) of the network, C_{0L1i}, C_{0L2i}, C_{0L3i} – earth–fault capacitance of individual phases (L1, L2 and L3) in the ith line, G_{0L1i}, G_{0L2i}, G_{0L3i} – earth–fault conductance of individual phases (L1, L2 and L3) in the ith line.

The $\underline{I}_N$ current flows in the neutral point grounding system, whilst the neutral point–to–ground voltage (further referred as zero–sequence component of network voltage) and the current at the fault location are depicted as $\underline{U}_0$ and $\underline{I}_K$, respectively. These magnitudes basically describe the basic features of the earth–fault phenomenon in MV network, and the $\underline{U}_0$ voltage is of special importance for the earth–fault–dedicated protective automatic devices. The relationships enabling to assess how the earth–fault asymmetry of the individual network lines affects the $\underline{U}_0$ and $\underline{I}_K$ depending on conditions of the earth–fault compensation s and the resistance value R_F are reported below.

2. Components of voltage U₀

According to the scheme in Fig. 1, the value of the U_0 voltage zero–sequence component is given by the dependency

$$\underline{U}_0 = \frac{\underline{E}_L + R_F j\omega \sum_{i=1}^{n} \underline{U}_{\mathrm{asci}} C_{0i} + R_F \sum_{i=1}^{n} \underline{U}_{\mathrm{asgi}} G_{0i}}{1 + R_F \cdot \omega \sum_{i=1}^{n} C_{0i} \left[\frac{G_N + \sum_{i=1}^{n} G_{0i}}{\omega \sum_{i=1}^{n} C_{0i}} + j\left(1 - \frac{1}{\omega^2 L_N \sum_{i=1}^{n} C_{0i}} \right) \right]} \tag{3}$$

where ω is the operating pulsation of network.

Assuming that

$$\frac{G_N + \sum_{i=1}^{n} G_{0i}}{\omega \sum_{i=1}^{n} C_{0i}} = d_0 \quad \text{and that} \quad 1 - \frac{1}{\omega^2 L_N \sum_{i=1}^{n} C_{0i}} = s \tag{4}$$

we receive

$$\underline{U}_0 = \frac{\underline{E}_L + R_F j\omega \sum_{i=1}^{n} \underline{U}_{\mathrm{asci}} C_{0i} + R_F \sum_{i=1}^{n} \underline{U}_{\mathrm{asgi}} G_{0i}}{1 + R_F \cdot \omega \sum_{i=1}^{n} C_{0i} \left[d_0 + js \right]} \tag{5}$$

where: d_0 – damping decrement of the network, s – earth–fault compensation detuning coefficient.

After having implemented the equations

$$\underline{U}_{\mathrm{asc}} = \frac{1}{C_{0s}} \sum_{i-1}^{n} \underline{U}_{\mathrm{asci}} C_{0i} \quad \text{and} \quad \underline{U}_{\mathrm{asg}} = \frac{1}{G_{0s}} \sum_{i-1}^{n} \underline{U}_{\mathrm{asgi}} G_{oi} \tag{6}$$

where

$$C_{0s} = \sum_{i-1}^{n} C_{0i} \quad \text{and} \quad G_{0s} = \sum_{i-1}^{n} G_{0i} \tag{7}$$

we obtain the expression for U_0 voltage in the form as follow:

$$\underline{U}_0 = \frac{\underline{E}_L + R_F j\omega C_{0s} \underline{U}_{\mathrm{asc}} + R_F G_{0s} \underline{U}_{\mathrm{asg}}}{1 + R_F \omega C_{0s} [d_0 + js]} \tag{8}$$

The formula as above shows that the network voltage zero–sequence component is decided by three phenomena: (i) phase–to–earth short–circuit, (ii) total asymmetry of the phase–to–earth capacitances and (iii) total asymmetry of the phase–to–earth conductance of the network. To any of these phenomena, the following form of the relationship can be assigned:

– for the phase–to–earth fault

$$\underline{U}_{0\mathrm{z}} = \frac{\underline{E}_{\mathrm{L}}}{1 + R_{\mathrm{F}}\omega C_{0s}[d_0 + js]} \tag{9}$$

– for asymmetry of the phase–to–earth capacitances of the network

$$\underline{U}_{0\mathrm{asc}} = \frac{R_{\mathrm{F}} j\omega C_{0s}\underline{U}_{\mathrm{asc}}}{1 + R_{\mathrm{F}}\omega C_{0s}[d_0 + js]} \tag{10}$$

– for asymmetry of the phase–to–earth conductance of the network

$$\underline{U}_{0\mathrm{asg}} = \frac{R_{\mathrm{F}} G_{0s}\underline{U}_{\mathrm{asg}}}{1 + R_{\mathrm{F}}\omega C_{0s}[d_0 + js]} \tag{11}$$

Thus, the network voltage zero–sequence component can be described by the equation

$$\underline{U}_0 = \underline{U}_{0\mathrm{z}} + \underline{U}_{0\mathrm{asc}} + \underline{U}_{0\mathrm{asg}} \tag{12}$$

The quantitative interpretation of individual components of the U_0 is more convenient when expressed in the relative values. Therefore, the both sides of expression (12) shall be divided by E_{L} and the voltage U_0 shall be transformed to the form of earth–fault coefficient β described by the relationship

$$\underline{\beta} = \frac{\underline{U}_0}{\underline{E}_{\mathrm{L}}} = \underline{\beta}_{\mathrm{z}} + \underline{\beta}_{\mathrm{asc}} + \underline{\beta}_{\mathrm{asg}} \tag{13}$$

where

$$\underline{\beta}_{\mathrm{z}} = \frac{1}{1 + R_{\mathrm{F}}\omega C_{0s}[d_0 + js]} \tag{14a}$$

$$\underline{\beta}_{\mathrm{asc}} = \frac{j\omega C_{0s} R_{\mathrm{F}}\underline{X}_{\mathrm{c}}}{1 + R_{\mathrm{F}}\omega C_{0s}[d_0 + js]} \tag{14b}$$

$$\underline{\beta}_{\mathrm{asg}} = \frac{G_{0s} R_{\mathrm{F}}\underline{X}_{\mathrm{g}}}{1 + R_{\mathrm{F}}\omega C_{0s}[d_0 + js]}, \tag{14c}$$

and $\underline{X}_{\mathrm{c}} = \frac{\underline{U}_{\mathrm{asc}}}{\underline{E}_{\mathrm{L}}} = X_{\mathrm{c}} e^{j\alpha_{\mathrm{c}}}$ as well as $\underline{X}_{\mathrm{g}} = \frac{\underline{U}_{\mathrm{asg}}}{\underline{E}_{\mathrm{L}}} = X_{\mathrm{g}} e^{j\alpha_{\mathrm{g}}}$ are the coefficients of the phase–to–earth capacitive and conductance–type asymmetries of the network.

The expressions presented above and their detailed discussion indicate and confirm that the assessment of the effects resulting from both the earth–faults and the voltage asymmetry phenomena is complex and requires the work–consuming calculations, even if some simplifications are introduced. Lack of the credible and current/updated data on differences in the phase admittances of the individual network phases and on the distribution of the phase voltages along successive line sections can be an additional trouble. Therefore, the investigations carried out on the computer–based models of the extended MV network structures can significantly facilitate the analysis of the asymmetry–born phenomena in the network. Results of simulation carried out in the PSCAD software environment are a good example.

3. Characteristics of MV network and modeled asymmetry phenomena

To perform the investigations, a model of the 15 kV compensated network with earth–fault capacitive current equal to 100 A has been developed. In the modeled network, the phenomena related to the asymmetry of the phase–to–earth capacitance and conductance occur and the distribution of the phase–to–earth voltages in the asymmetrically loaded lines is diversified. The model's scheme is shown in Fig. 2, and the locations of the modeled phenomena are depicted (denotations X_C, X_G, X_{ob} in line L1). In the modeled network (i) the way of operation of the neutral point can be defined, (ii) operation of the forced active component automatic devices (depicted as WPC and WAF circuit–breakers) can be taken into account and (iii) measurements of currents and voltages (phase values, zero–sequence components) can be carried out.

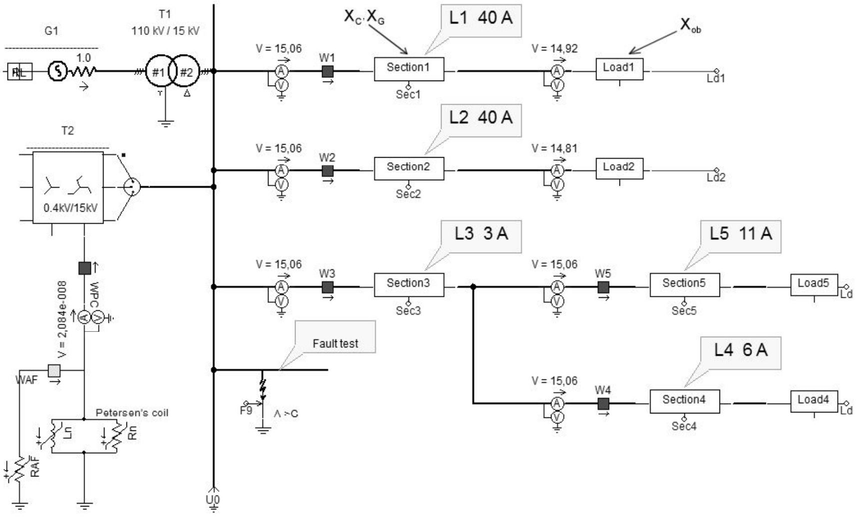

Fig. 2. Model of MV network used in research work

Below, chosen results of simulations are reported.

3.1. Voltage U_0 forced by the capacitive asymmetry

In the compensated MV network, the capacitive asymmetry of line of up to 5% is followed by a voltage zero–sequence component of significant value. Simulation results for the line L1 with the effective earth–fault capacitive current factor equal to 0.4 are presented in Fig. 3.

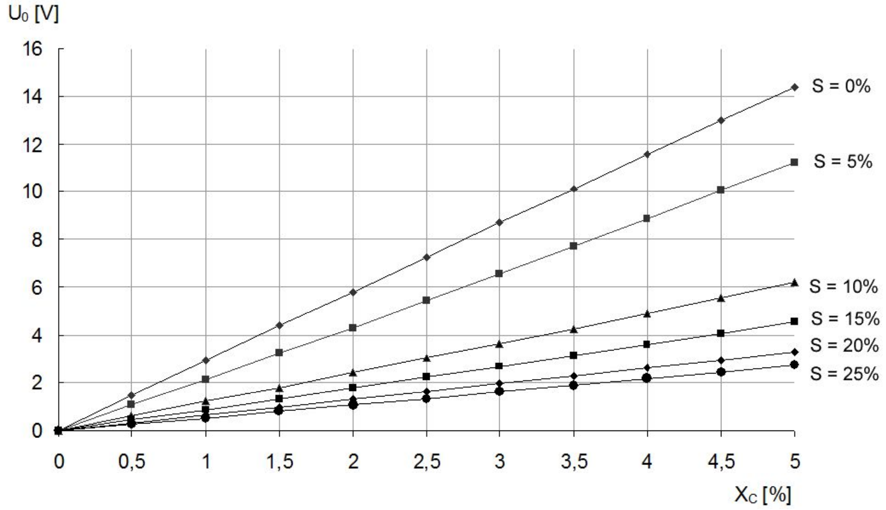

Fig. 3. Voltage U_0 forced by capacitive asymmetry X_C for different values of detuning coefficient of the earth–fault compensation *s*

The voltage zero–sequence component depends on the detuning coefficient of the earth–fault compensation *s* and reaches its highest values in the network highly compensated for the high capacitive asymmetries. In our investigations, the X_C factor value range limited by the network natural asymmetry values appearing in the true MV networks with the overhead lines or the overhead–cable lines has been considered. During investigations, the natural asymmetry voltage U_{0as} for the isolated neutral point network have also been found for successive X_C values. These values are reported in Table 1 (the raw marked by 1). In the compensated network, the measured U_0 values exceed many times the U_{0as} values forced by the same asymmetries of transversal elements of the considered line L1. During simulation, the earth–fault capacitive asymmetry does not occur in the other part of the network.

In the Polish MV network operation and maintenance, the natural asymmetry exceeding 0.2 – 0.3 V level occurs incidentally. During investigations conducted by the authors in 2015 in more than twenty compensated MV networks managed by one of the distribution companies, three times the natural asymmetry value was higher than 0.5 V.

In Fig. 4, the relation between U_0 and detuning coefficient of the earth–fault compensation s (negative values denote the uncompansated network) for chosen values of the capacitive asymmetries X_C has been shown.

Values U_0 forced by the capacitive asymmetry can reach the level of the set–up values of the earth–fault protections applied up to now in the Polish distribution networks working with the coil–earthed neutral point.

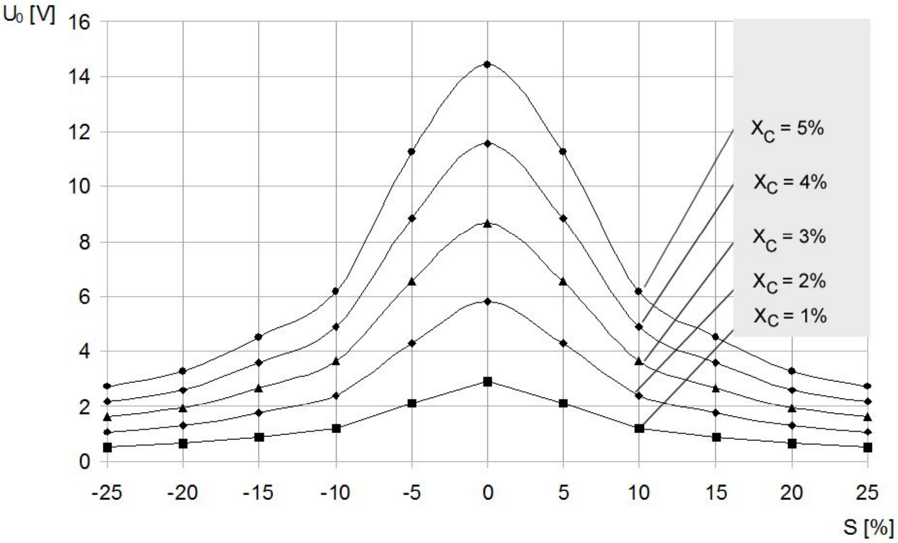

Fig. 4. Influence of detuning coefficient of the earth–fault compensation s on U_0 forced by the capacitive asymmetry X_C

The values fall mostly in the region from 10 V to 20 V.

Table 1. Influence of transversal asymmetries on zero–sequence component of voltage U_0

Lp.	X [%]	2	4	6	Notes	
1	U_0 [V]	0.26	0.53	0.79	U_{0as} *)	Capacitive asymmetry X_C
2		2.39	4.89	7.50	s = 10%	
3		5.80	11.56	17.24	s = 0%	
4		0.005	0.010	0.015	U_{0as} *)	Conductance–type asymmetry X_G
5		0.046	0.090	0.132	s = 10%	
6		0.112	0.220	0.324	s = 0%	

*) refers to network with isolated neutral point

In Table 2, simulation results reflecting the influence of conductance–type asymmetry on the voltage zero–sequence component are also reported. Due to the identical levels of the asymmetry, the occurring value of U_0 voltage is nearly 50 times smaller than that with capacitive asymmetry.

3.2. Voltage U_0 forced by the relatively high conductance–type asymmetry

Not but the significant differences in the values related to the earth leakage of individual phases are noticeable in the voltage zero–sequence component measurement; in particular, it refers to the networks with precise earth–fault compensation (see Fig. 5 and Fig. 6). For high conductance–type asymmetry values, the forced U_0 voltage did not exceed 2 V.

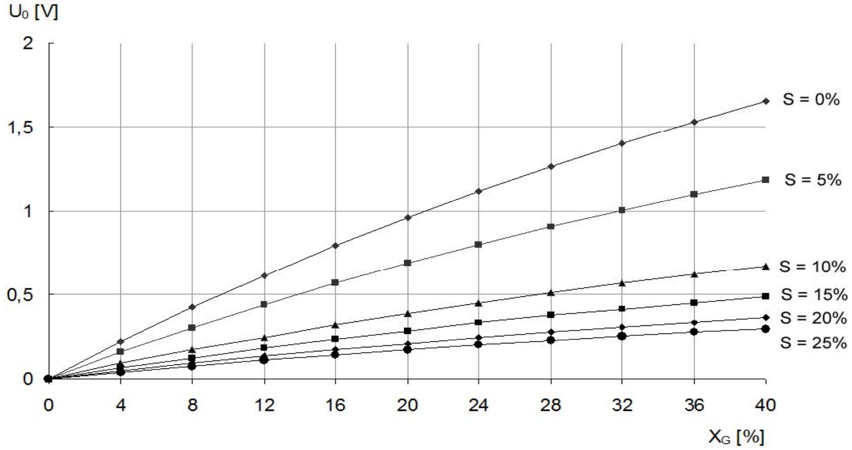

Fig. 5. Voltage U_0 forced by conductance–type asymmetry X_G for different values of detuning coefficient of the earth–fault compensation *s*

According to formula (12), a conductance–type asymmetry factor complements a more significant influence of the earth–fault capacitive asymmetry on the zero–sequence component value. In face of the recent years' practice of reducing the start–up values U_{0n} of the earth–fault protections, related, among others, to the questions of detection of the high–resistance single–phase earth faults, a negligence of the conductance–type asymmetry contribution to the voltage U_0 value is not justified.

For X_G coefficient equal to 40%, the network natural asymmetry voltage (measured in the network operating with isolated neutral point) was 0.075 V. Therefore, the occurrence of higher conductance–type asymmetries in the true MV networks can not be excluded. In the networks with prevailing cable sections characterized by a very good capacitive symmetry, the U_0 value is mainly forced by the time–variant conductive–type asymmetry.

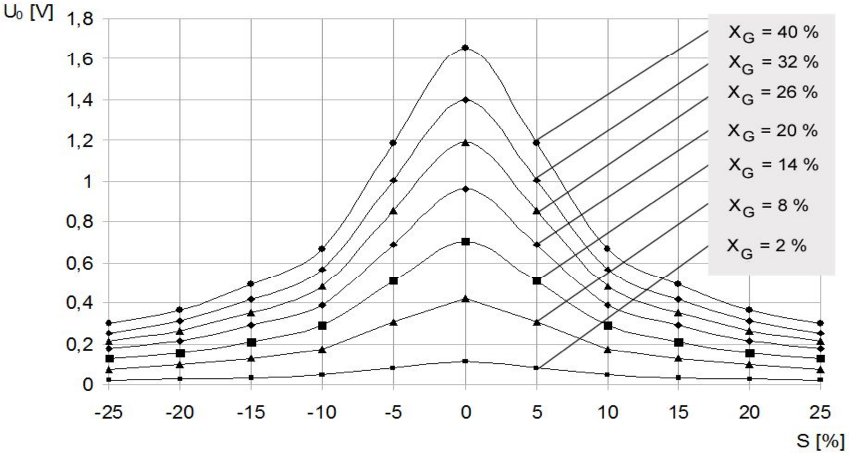

Fig. 6. Influence of detuning coefficient of the earth–fault compensation s on U_0 forced by the conductance–type asymmetry X_G

3.3. Voltage U_0 forced by the line loads' asymmetry

In the simulations, the X_{ob} coefficient defining the load asymmetry has been described according to the relationship

$$X_{ob} = \max\left\{\frac{I_{L1}-I_{L2}}{I_{L1}};\frac{I_{L2}-I_{L3}}{I_{L2}};\frac{I_{L3}-I_{L1}}{I_{L3}}\right\} \tag{15}$$

where: I_{L1}, I_{L2}, I_{L3} are currents of individual phases measured in the line L1.

In Table 2, the values of phase voltages, voltage zero–sequence component and the highest of the differences between phase voltages observed during simulation in the compensated network (coefficient s is equal to 0) are presented. The influence of the load–type asymmetry degree on the U_0 voltage value has not been noticed. The asymmetry is noticeable in the phase voltage variation values and. at the significant values, causes the occurrence of differences at the level of 100 V.

Table 2. Phase voltage value versus load asymmetry

Lp.	X_{ob}	U_{phL1}	U_{phL2}	U_{phL3}	U_0	$U_{phL1} - U_{phL2}$
	%	V	V	V	V	V
1	0	8669	8669	8669	0	0
2	10	8717	8637	8702	0	79
3	20	8732	8627	8712	0	104
4	30	8740	8621	8718	0	119
5	40	8747	8617	8722	0	130

Changes in the earth–fault compensation coefficient realized by the change in the coil current did not lead to the changes in the measured voltages.

4. Final remarks

The effectiveness of the earth–fault protections' operation in the MV networks is most often decided by the zero–sequence voltage component level. However, as mentioned in section 2, the voltage can be due to phenomena that are not directly related to the earth–fault disturbances. In the voltage U_0 components, the effect of the phenomena following the asymmetry of the earth–fault admittances of individual phases or of the differences in the levels of the phase power voltage can be distinguished

In the work, we have shown that it is convenient to analyze the influence of the asymmetry–related phenomena on the voltage U_0 using computer–based simulations on the suitable model. By implementing the low complex PSCAD–based models of network systems, the influence of different earth–fault asymmetries of the network on the U_0 voltage level can be assessed in a relatively simple way. The reported investigation results show that the effects of the network's earth–fault asymmetry are especially spectacular in the networks where the earth–fault compensation is being precisely applied. It has been shown that the U_0 voltage level may even exceed 15% of the phase voltage value. Moreover, the influence of the capacitive asymmetry is evidently higher than that of the conductance–type earth–fault asymmetry. Also, it has been shown that the asymmetry of the line's phase loads does not affect, in practice, the U_0 voltage level.

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