MV Network Operation Issues and Elimination of Phase Voltage Unbalance

František Žák

Analyst and Lecturer of the distribution network operation, České Budějovice, Czech Republic,
e-mail: *ee.zak@seznam.cz*

Abstract — **This article focuses on networks with great phase voltage unbalance. Formerly, it was necessary to operate these networks with an isolated neutral, resistance or solid grounding. The three-phase compensation system eliminates phase voltage unbalance and can substitute or complement the arc-suppression coil. This system enables a more effective operation of distribution networks with non-effectively grounded node, even in networks with a significantly high capacity unbalance.**

Keywords — phase voltage unbalance, earth-fault current, active part of earth-fault current, charging capacitive current, phase capacitive unbalance, island operation, voltage symmetrization system

I. Introduction

Regarding the types of neutral grounding, the greatest heterogeneity can be found in MV distribution networks. It is possible to operate these networks with a solidly grounded, isolated or non-effectively grounded neutral; both through resistance and inductive reactance. Continuously variable inductive reactance is called arc-suppression coil, or – after its inventor – Peterson coil, and it is mostly used for the resonant grounding netural. None of these types of grounding can be claimed “the best.” There are many reasons for and against in each case. The continuously variable arc-suppression coil is vastly used for neutral grounding in Europe. A significant disadvantage of such a type of neutral grounding is a problematic operation in the networks with high phase capacitive unbalance. This led to searching for a new solution of how to eliminate the phase capacitive unbalance.

II. The Causes of Phase Voltage Unbalance

According to the symmetrical components theory (Charles Legeyt Fortescue), the phase voltage in the network is given by the vector sum of positive, negative and zero sequence voltages as shown in (1).

$$\begin{bmatrix} U_{01} \\ U_{02} \\ U_{03} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ a & a^2 & 1 \\ a^2 & a & 1 \end{bmatrix} \begin{bmatrix} U_{(1)} \\ U_{(2)} \\ U_{(0)} \end{bmatrix} \tag{1}$$

Where:

U_{01}, U_{02}, U_{03} phase voltage
$U_{(1)}$ positive sequence voltage
$U_{(2)}$ negative sequence voltage
$U_{(0)}$ zero sequence voltage
a vector rotated by 120°, where:

$$a = -\frac{1}{2} + \mathrm{j}\frac{\sqrt{3}}{2}$$

a^2 vector rotated by 240°, where:

$$a^2 = -\frac{1}{2} - \mathrm{j}\frac{\sqrt{3}}{2}.$$

If the zero sequence voltage in the network changes, phase voltage values also change. Such a change does not influence the phase-to-phase voltage values. If the cross parameters of a network have the same values in the phases, the network is ideally balanced. In practice, however, these networks account for exception. The phase capacitive unbalance emerges especially in overhead lines. This unbalance is mainly influenced by the phase conductor configuration and the difference in capacity of each conductor against the ground.

For illustration, there is an easy example in Fig. 1 to demonstrate the influence of phase cross parameters unbalance on the phase voltage changes. The example thus contains some simplifaction without affecting its comprehensibility. The type of neutral grounding is also important.

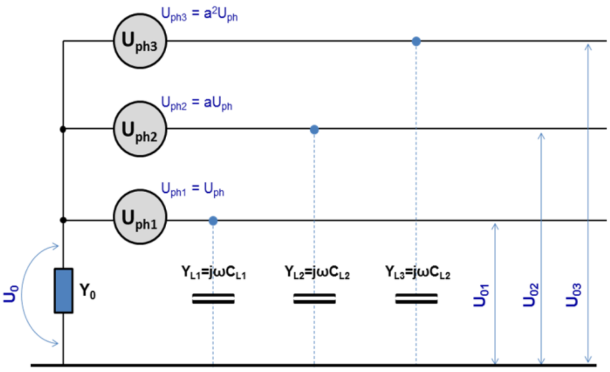

Fig. 1. A simplified diagram for the following calculation of the phase voltage in a network.

Zero sequence voltage U_0 in a simple circuit with an isolated netural (Y_0 = 0; Z_0 = ∞) may be expressed e.g. through the method of node voltage and vectors of shunt admittance according to (2).

$$U_0 = U_{ph} \frac{Y_{L1} + aY_{L2} + a^2 Y_{L3}}{Y_{L1} + Y_{L2} + Y_{L3}} \tag{2}$$

Where:

U_0 zero sequence voltage
U_{ph} phase voltage
Y_{L1}, Y_{L1}, Y_{L1}, shunt admittance L_1, L_2, L_3,

To make it easier, the shunt admittance is expressed only as capacitive susceptance $Y = \mathrm{j}\omega C$. Next, the phase shunt admittance Y_L is expressed as the sum of average value of the ground susceptance Y and its deviation from ΔY_L mean value (3).

$$Y_L = j\omega C + j\omega\Delta C = Y + \Delta Y_L \tag{3}$$

Where:

TELEN2017005
DOI 10.14311/TEE.2017.3.072

C	mean value of phase-to-ground capacity
Y	mean value of shunt admittance
ΔY_L	deviation from the mean value of the shunt admittance.

Using the simplification in (2), we get (4).

$$U_0 = U_{ph}\frac{Y(1+a+a^2)+(\Delta Y_{L1}+a\Delta Y_{L2}+a^2\Delta Y_{L3})}{3Y+\Delta Y_{L1}+\Delta Y_{L2}+\Delta Y_{L3}} \quad (4)$$

Eq. (4) can be further modified applying (5) and (6).

$$1+a+a^2=0 \quad (5)$$

$$Y+\Delta Y_{L1}+Y+\Delta Y_{L2}+Y+\Delta Y_{L3}=3Y \quad (6)$$

After the modification and insertion of the general impedance Y_0 between the neutral point and ground, we gain (7):

$$U_0 = U_{ph}\frac{((\Delta Y_{L1}+a\Delta Y_{L2}+a^2\Delta Y_{L3}))}{(3Y+Y_0)} \quad (7)$$

Where:

Y_0	admittance between the node and ground

Eq. (7) demonstrates the influence of several types of neutral grounding on the magnitude of the zero sequence voltage U_0. To simplify, we can presume that the value of the vector sum of the phase deviances ΔY_L is 0.5 % of Y. The magnitude of the nodal admittance is ideally $Y_0 = \infty$ ($Z_0 = 0$) for a solidly grounded neutral and thus the magnitude of the zero sequence voltage is (8).

$$U_0 = U_{ph}\frac{0{,}5\%\ Y}{3Y+\infty}=0 \quad (8)$$

As expected, the solidly grounded neutral has not any voltage between the neutral and ground. The phase voltage in the network is independent from the magnitude of the phase capacitive unbalance. Therefore, single- or two-phase lines can be used in a three-phase system.

In case of an isolated node, the value is $Y_0 = 0$ (without neutral-to-ground connection). The value of the zero sequence voltage, i.e. the voltage of a neutral against the ground, at the supposed phase capacitive unbalance of 0.5 % of Y is determined by (9) in this demonstrative case.

$$U_0 = U_{ph}\frac{0{,}5\%\ Y}{3Y}=0{,}16\% U_{ph} \quad (9)$$

In case of the low-resistance neutral grounding, it is recommended that the current flowing through the nodal resistor is higher than the earth capacitive current during a single-phase earth fault. This may be described by the equation: $/3Y/ \leq /Y_0/$. The nodal admittance Y_0 against the ground comprises of the conductivity of a nodal resistor: $Y_0 = G_0$. Presuming the earth capacitive current equals the nodal resistor current ($/Y_0$ $/=$ $/3Y/$), the nodal voltage against the ground is (10.1) and after calculation (10.2).

$$U_0 = U_{ph}\frac{0{,}5\%\ Y}{3Y+Y_0}=U_{ph}\frac{0{,}5\%\ Y}{\sqrt{9Y^2+9Y^2}} \quad (10.1)$$

$$U_0 = U_{ph}\frac{0{,}5\%\ Y}{\sqrt{18}\ Y}=0{,}118\% U_{ph} \quad (10.2)$$

From (10.2) follows that the magnitude of the zero sequence voltage for the resistance grounding neutral is lower than for the isolated neutral. For resonance grounding, the nodal admittance comprises of a real and imaginary component. The real component represents the replacement conductivity of an arc-suppression coil, which is influenced by losses in the arc-suppression coil, and the imaginary component represents the inductive susceptance of the arc-suppression coil.

$$Y_0 = G_{tl} - j\frac{1}{\omega L} \quad (11)$$

Where:

Y_0	admittance between the neutral and ground
G_{tl}	replacement conductivity of an arc-suppression coil
ω	network angular frequency
L	arc-suppression coil inductance.

Subsisuting (11) for (7) for the zero sequence voltage and breaking down shunt admittance, we get (12).

$$U_0 = U_{ph}\frac{(\Delta Y_{L1}+a\Delta Y_{L2}+a^2\Delta Y_{L3})}{3G_0+j3\omega C+G_{tl}-j\frac{1}{\omega L}} \quad (12)$$

Where:

G_0	network lead

Eq. (12) applies with an arc-suppression coil tuned exactly to the parallel resonance against ground capacity.

$$j3\omega C - j\frac{1}{\omega L}=0 \quad (13)$$

Presuming the real component of Y admittance is 2 % of the imaginary Y phase admittance component, the zero sequence voltage in a resonant grounded network with an ideally tuned arc-suppression coil can be illustratively determined as follows in (14):

$$U_0 = U_{ph}\frac{0{,}5\%\ Y}{2\%\ Y}=25\%\ U_{ph} \quad (14)$$

If the difference between each phase capacities against the gorund is greater than 0.1 %, evident changes already are in the zero sequence voltage and thus differences in the phase voltage during the arc-suppression coil tuning as well (Fig. 2).

Following the example, it is obvious that the zero sequence voltage U_0 depends on the accuracy of the arc-suppression tuning in the resonant grounded networks. The maximum value of the zero sequence voltages is reached just at the accurately tuned arc-suppression coil (15), where the denominator is of the least value. This quality is used in many automatics of the arc-suppression coil tuning.

$$U_0 = U_{ph}\frac{(\Delta Y_{L1}+a\Delta Y_{L2}+a^2\Delta Y_{L3})}{3G_0+G_{tl}} \quad (15)$$

The greatest difference in the phase voltage is reached just at the accurate tuning of the arc-suppression coil on the parallel resonance against the network phase-to-ground capacity. The arc-suppression coil eliminates the earth fault currents only and from the nature of its connection it cannot influence the charging currents. It functions only during an earth fault.

TELEN2017005
DOI 10.14311/TEE.2017.3.072

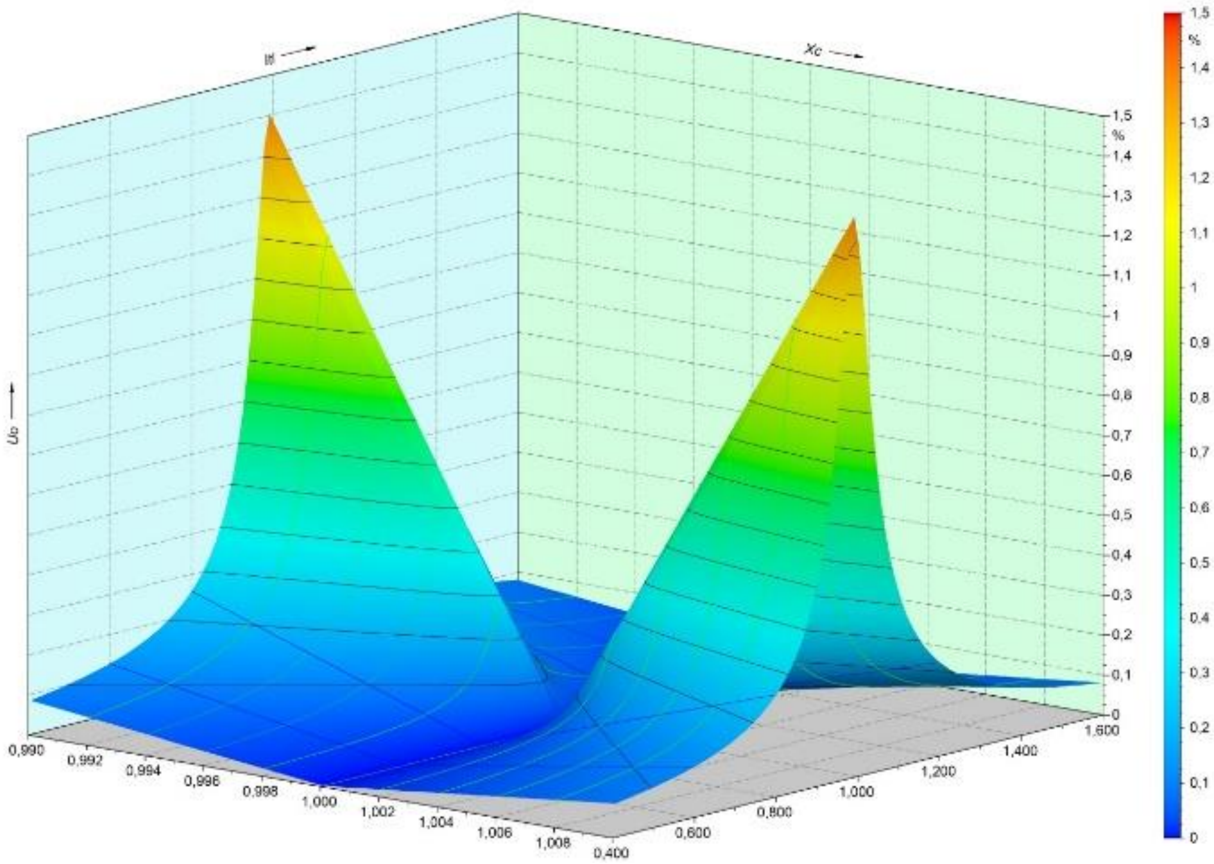

Fig. 2. Graph showing the impact of cross parameters X_C unbalance (ideally, a balanced network equals $X_C = 1$) and the impact of the arc-suppression coil tuning accuracy I_{tl} (in a resonant state $I_{tl} = 1$) on the zero sequence voltage U_0.

This implies that operating a classic arc-suppression coil in unbalanced networks causes a great phase voltage asymmetry. From (12) follows that there are some possibilities of partial elimination of the phase voltage asymmetry; however, with considerable limits. For instance, the denominator value can be increased by operating the network with an untuned arc-suppression coil or by intensifying the dumping.

In some distribution companies, small-scale consumers connect only through a single phase with primary winding of a single-phase transformer connected between two phases. Therefore, only two phases of a three-phase line are brought to these consumers and the transformer is connected between the two phases. This causes a significant phase-to-ground capacity asymmetry. The operation with an arc-suppression coil is very complicated or impossible in these networks. It is necessary to complement the arc-suppression coil with a system eliminating three-phase system of phase-to-ground capacity asymmetry or to substitute it with a three-phase system of the phase-to-ground capacitive current compensation if these networks are to be operated with resonant grounding.

III. Voltage Symmetrization System

The three-phase system of phase-to-ground capacitive current compensation – the Voltage Symmetrization System (VSS) – has several basic functions. It is used for the phase voltage asymmetry elimination in the network, earth fault current elimination and reduction of the charging current value and for the influence of the residual active earth fault current. The system was patented. For elimination of the phase voltage asymmetry only, the system can be operated with just a relatively low power. The patented principle of the system enables elimination of the phase cross parameters unbalance, or more precisely, elimination of the phase capacitive unbalance in the network according to (16).

$$\Delta Y_{L1} + a\Delta Y_{L2} + a^2\Delta Y_{L3} = 0 \qquad (16)$$

The basic three-phase system VSS connection is illustrated in Fig. 3. The magnitude of the phase capacitive unbalance can be controlled with this system (see Fig. 4).

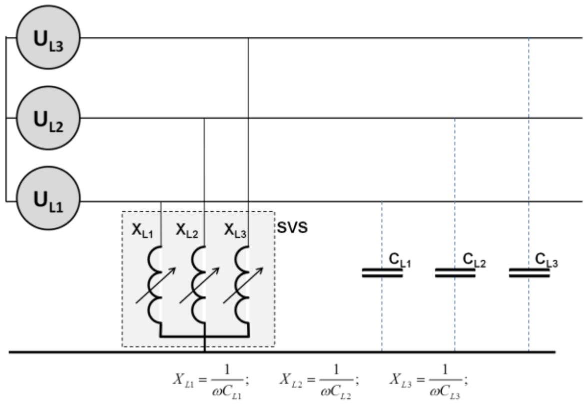

Fig.3. Basic diagram of VSS connection.

TELEN2017005
DOI 10.14311/TEE.2017.3.072

The VSS system comprises of three phase variable reactances connected between each phase and ground with the possibility to individually change the phase reactance. It is the phase reactance change through which the system influences the phase-to-ground capacity unbalance and thus eliminates the emeregence of the phase voltage unbalance. In the automatic mode, the system maintains the value of the zero sequence voltage within the range of assigned parameters. The range of the zero sequence voltage U_0 restriction varies typically between 1 % and 5 % of the phase voltage. With a moderate phase voltage unbalance, it is possible to maintain the functionality of all common systems of the arc-suppression coil tuning according to the value of the zero sequence voltage (Fig. 4).

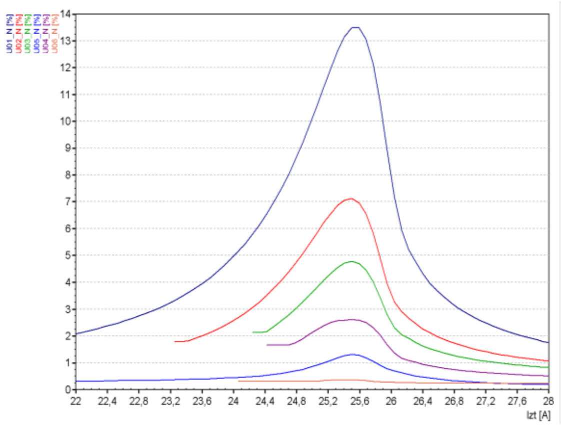

Fig.4. Controlling capacitive asymmetry in a network using the VSS system, changes in the zero sequence voltage during arc-suppression coil tuning.

The VSS system is especially used for the earth fault current elimination during a single-phase earth fault in cable lines, mostly in industrial networks. It fully substitutes the arc-suppression coil connected between the neutral and ground. The power of the system is designed regarding the value of the earth capacitive current. The advantage of the system is the fact it does not connect to the neutral to eliminate the earth fault currents. This is the reason why the VSS has been implemented mainly in networks with isolated neutral. In a faultless condition, the VSS system serves for elimination of the charging capacitive current. In single-phase cable lines, the VSS enables to eliminate the whole charging capacitive current thanks to the fact that the operational capacity comprises of the phase-to-ground capacity only. In three-phase cable lines or overhead lines, the operational capacity comprises of the phase-to-ground capacity and phase-to-phase capacity. With these lines, the VSS system eliminates a significant part of the charging capacitive current: typically, 60 % to 70 % of the whole line operational capacity as the system is not designated for the elimination of the phase-to-phase charging capacitive current of the line. Using the VSS system in cable lines in a faultless condition contributes to a significant reduction of the charging reactive power. The VSS system in a faultless condition is thus used for the voltage symmetrization and charging current elimination. For the charging current elimination it is not necessary to install a shunt reactor or it is possible to install the shunt reactor with a significantly lower power.

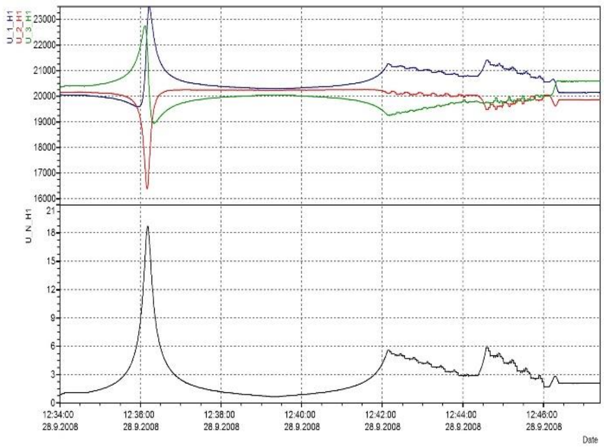

Fig.5. Tuning of an arc-suppression coil in an asymmetrical network with a blocked function of automatic voltage symmetrization (on the left) and with the unblocked function (on the right).

As mentioned above, in comparison with the arc-suppression coil the VSS can be operated even in networks with a major phase-to-ground capacity unbalance. During a single-phase earth fault, the VSS enables to eliminate the earth capacitive current similarly to the arc-suppression coil connected between the neutral and ground. The total inductive current of the phase inductive reactances is always rotated by 180° against the vector of the earth fault current (Fig. 6). Another possibility is to influence the value of an earth-fault current active component by a suitable change in the phase inductive reactances of a three-phase system during an earth fault.

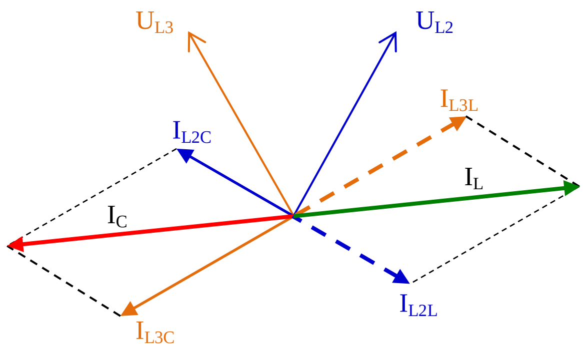

Fig.6. Earth fault current elimination in a network with a major phase-to-ground capacity unbalance with an earth fault in L_1 phase ($U_{L1} = 0$).

As the VSS system does not require a neutral for its connection, it is possible to connect it anywhere in the network. At the same time, it is possible to adjust its power for the earth fault current elimination of a certain part of the network only. This can be used especially in local distribution networks or in long feeders, feeders with a high value of charging current, alternatively in feeders with a high capacitive unbalance. The part of the network, in which the system is installed, does not further influence the earth fault current value in the whole network. The system is very beneficial in local distribution networks where an island operation is implemented in case of power supply failure. After separation from the supply network and creation of island operation, the source is not loaded by the charging capacitive current and the separated area is operated with the earth fault current compensation.

TELEN2017005
DOI 10.14311/TEE.2017.3.072

The system has been employed for more than ten years with broad experience. These systems are installed in industrial 6 kV networks (Fig. 7) as well as in standard distribution networks of up to 35 kV.

Fig.7. The VSS system of the three-phase earth fault current compensation, charging current elimination and phase voltage symmetrization in a 6 kV industrial network.

IV. Conclusion

A great advantage of the VSS system is that the installation of one VSS system into the electrical network enables to cover various functions. In the case without the VSS system we would have to use more devices such as an arc suppression coil, shunt reactor for the reactive power compensation; however, there is no other adequate device for voltage unbalance elimination.The benefit of an easy VSS system connection into any point of the network proves to be especially significant where the operation using isolated node transforms into the operation using resonant earthing. Installation of one device which covers more functions saves the funds. Network operation with the VSS system, where its features are used, contributes to the elimination of voltage transient and by this means, the system also contributes to decrease in the number of faults in the network.Operation experience proved that the VSS system can eliminate even an extremely grave phase-to-ground capacity unbalance without negative impact on the ground fault protection. Thanks to phase capacitive unbalance elimination, it is possible to reach an elevated level of the directional ground protection reliability even in high-resistance earth faults. During an earth fault, it is possible to influence the value of the residual active part of the current, and thus to increase it or decrease it. This feature can be also used for improvement in directional ground protection function and also for decreasing the current in the point of an earth fault. The possibility to operate the networks with exactly compensated earth fault currents contributes to higher safety of operation of such networks.

References

[1] F. Žák, *Device for Watt and Blind Current Component Compensation in the Earth Fault Point and Phase-to-ground Voltage Equalization Under Failure-free Network Condition*, EP1817829 B1; EPO Bulletin 2016/05.

[2] F. Žák, “Trends in the Development of Electricity Distribution Grids,” *Energie 21*, vol. 10, no. 3 (2017), ISSN 1803-0394, MK ČR E 18090, pp. 32-33.

TELEN2017005
DOI 10.14311/TEE.2017.3.072