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Analysis of the effect of symmetrical load on the value of negative voltage asymmetry factor in medium-voltage power networks

Streszczenie. *Zjawisko asymetrii napięciowej występuje powszechnie w sieciach elektroenergetycznych i jest powodem występowania szeregu niekorzystnych zjawisk występujących, takich jak wzrost strat mocy i energii, a także nieprawidłową pracę niektórych odbiorników. Do jednego z wielu czynników rzutujących na asymetrię napięciową w sieci elektrycznej zaliczyć można także wpływ symetrycznego obciążenia, jednak w przypadku sieci elektroenergetycznych średniego napięcia w literaturze wpływ ten się pomija. W artykule przedstawiono i oceniono wpływ zmian obciążenia symetrycznego mocą czynną i bierną pobieraną przez odbiorców na wartości wskaźników asymetrii przeciwnej napięć $\alpha_{U2\%}$ w sieciach elektroenergetycznych średniego napięcia z punktem neutralnym uziemionym przez dławik gaszący (cewkę Petersena). Z analiz teoretycznych przeprowadzonych przez Autorów wynika, że wraz ze wzrostem mocy czynnej rośnie wartość współczynnika asymetrii na końcu linii i zmiana ta – w całym analizowanym przedziale mocy – wynosi 47,3% wartości maksymalnej. W celu zweryfikowania poprawności opisu zjawisk zachodzących w układzie przez zaproponowany model matematyczny, przeprowadzone zostały badania terenowe w punkcie przyłączenia zakładu przemysłowego branży metalowej położonego w północno-wschodniej Polsce. Aproksymując uzyskane wyniki badań zależnością liniową otrzymano zależność wprost proporcjonalną pomiędzy zarejestrowanymi wartościami mocy biernej oraz współczynnika asymetrii przeciwnej. Jest to zgodne z zależnością uzyskaną na podstawie obliczeń analitycznych. (**Analiza wpływu symetrycznego obciążenia na wartość współczynnika asymetrii przeciwnej napięć w elektroenergetycznych sieciach średniego napięcia**).*

Abstract. *The phenomenon of voltage asymmetry is common in electricity networks and is the cause of several unfavourable phenomena occurring, such as an increase in power and energy losses, as well as the abnormal operation of specific loads. One of the many factors impinging on voltage asymmetry in the electrical network is the influence of symmetrical loading, which is ignored in the literature for medium-voltage power networks. This paper presents and evaluates the influence of changes in the symmetrical load of active and reactive power consumed by consumers on the values of negative voltage asymmetry factor in medium-voltage power networks with the neutral point earthed by arc-suppression reactor (Petersen's coil). The authors' theoretical analyses show that as the active power increases, the value of the negative asymmetry factor at the end of the line increases, and this change - in the whole analysed power range - amounts to 47.3% of the maximum value. In order to verify the correctness of the description of the phenomena occurring in the system by the proposed mathematical model, field tests were carried out at the connection point of a metal industry plant located in north-eastern Poland. A directly proportional relationship was obtained between the recorded reactive power values and the negative asymmetry factor by approximating the test results with a linear relationship. It is consistent with the relationship obtained from the analytical calculations.*

Słowa kluczowe: asymetria napięcia, składowa przeciwna, sieć elektroenergetyczna.
Keywords: voltage asymmetry, negative component, power grid.

Introduction

Voltage asymmetry occurs when voltages are unequal across phases or angles between consecutive voltages. Asymmetrical voltage systems are decomposed into symmetrical components [1-4]:

$$\underline{U}_0 = \frac{1}{3}\cdot\left(\underline{U}_{L1}+\underline{U}_{L2}+\underline{U}_{L3}\right)$$
(1)
$$\underline{U}_1 = \frac{1}{3}\cdot\left(\underline{U}_{L1}+a\cdot\underline{U}_{L2}+a^2\cdot\underline{U}_{L3}\right)$$
$$\underline{U}_2 = \frac{1}{3}\cdot\left(\underline{U}_{L1}+a^2\cdot\underline{U}_{L2}+a\cdot\underline{U}_{L3}\right)$$

or in matrix form:

(2)
$$\begin{bmatrix}\underline{U}_0\\ \underline{U}_1\\ \underline{U}_2\end{bmatrix}=\frac{1}{3}\begin{bmatrix}1 & 1 & 1\\ 1 & a & a^2\\ 1 & a^2 & a\end{bmatrix}\begin{bmatrix}\underline{U}_{L1}\\ \underline{U}_{L2}\\ \underline{U}_{L3}\end{bmatrix}$$

where: U_0 , U_1 , U_2 - the composite values of the voltages symmetrical components of the zero, positive and negative sequence, U_{L1} , U_{L2} , U_{L3} - the composite values of the phase voltages, *a* - the rotation operator described by the equation:

(3)
$$a = e^{j\frac{2\pi}{3}}$$

Asymmetry in the system of supply voltages results, among other things, in the appearance of symmetrical components of the negative order, which is described by the negative voltage asymmetry factor $\alpha_{U2\%}$ [5,6]:

(4)
$$\alpha_{U2\%} = \left|\frac{\underline{U}_2}{\underline{U}_1}\right|\cdot 100\%$$

There are two basic types of asymmetry in electricity networks:

- the internal asymmetry of individual network components (e.g. power lines, transformers) caused by impedance imbalances in individual phases,
- external asymmetry:
  - at the supply points - the three-phase voltage at these points is asymmetrical,
  - at consumption points locally - the loads connected at individual points on the network have different capacities in each phase,
  - at spatial consumption points, single-phase loads are connected to the network at different points.

The leading cause of voltage asymmetry in electricity networks is non-uniform voltage drops in individual phases caused by load asymmetry (unequal distribution of single-phase consumers) [7,8]. In the case of medium-voltage networks, unequal ground capacitances (mainly in overhead lines) and mismatch of the arc-suppression reactor (in networks operating with the neutral point earthed by a Petersen's coil), leading in some cases to resonance [9, 10]. Nowadays, more and more photovoltaic power plants [11-14] and wind power plants [15-17] appear in electricity systems, significantly affecting power quality parameters, including negative voltage asymmetry. Other potential sources of voltage asymmetry are electric car charging stations [18,19] and energy storage facilities [20, 21].

The adverse effects resulting from the occurrence of voltage asymmetry in MV supply networks include, in particular [22, 23]:

- increased power and energy losses occurring in power lines, MV/LV transformers and capacitor banks;
- faster wear and tear on induction motors - the rotating magnetic field takes on an elliptical shape instead of a circular one, resulting in faster wear and tear on the machine's bearings and an additional increase in temperature in the rotor;
- unwanted tripping of earth fault protection;
- an increase in the pulsation of the rectified voltage and a reduction in the allowable DC power of the converter systems.

The permissible value of negative voltage asymmetry factor $\alpha_{U2\%}$ in medium-voltage power systems have been set in Polish law [24-26] at 2 % (for 95 % of the aggregated 10-minute values recorded during the week).

The electricity network can operate with the neutral point isolated or earthed [27, 28]:

- directly,
- through a resistor whose resistance value is selected so that the earth fault current does not exceed 600 A;
- through a arc-suppression reactor (Petersen's coil), whose inductance value is selected based on the earth capacitance in all the lines connected to the same busbar section.

Poland has no medium-voltage distribution power grids with the neutral point directly earthed. The most common mode of operation of the neutral point is earthing through a reactor or resistor. In networks with an isolated neutral point, the circuit of the symmetrical zero component is not closed, as the zero impedance is theoretically equal to infinity. However, in natural systems, the closure of the earth (neutral component) circuit is achieved through the existing transverse conductances (capacitances and leakage) in the network [29].

An inductive current can compensate for the capacitive earth current when one phase is short-circuited to earth in an isolated neutral point system. This compensation is achieved by earthing the neutral point of the system with an inductive coil, called a Petersen's coil [2]. To incorporate the quenching coil, an additional earthing transformer is installed in the medium-voltage switchgear, to whose neutral point the coil is connected. In order to reduce overvoltages occurring in ground faults, the neutral point of the network is earthed via a resistor. The resistor's resistance value should allow the earth fault current to flow with a value ensuring the correct operation of the earth fault protectors installed in the network. Phenomena related to voltage asymmetry are particularly evident in networks earthed through a Petersen's coil and must be considered, among other things, when determining the operating conditions of earth fault protections [30]. The voltage is usually more symmetrical in networks with predominantly cable lines than overhead lines [31].

A general schematic of a medium-voltage (MV) power network supplied from an HV/MV substation operating with the neutral point earthed through a arc-suppression reactor is shown in Figure 1. The HV/MV power transformer is usually made with windings in the YNd (star-delta) arrangement, the MV/LV earthing and own-needs transformer operate in the ZNyn (zigzag-star) arrangement, while the MV/LV consumer transformers operate in the Dyn (delta - star) arrangement [32, 33].

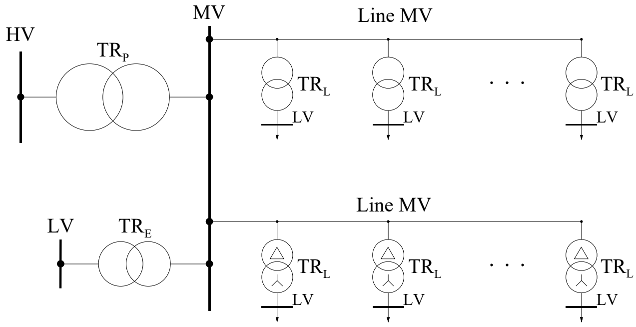

Fig 1. General diagram of MV power network supplied from HV/MV substation. HV - high voltage, MV - medium voltage, LV - low voltage, TR_P - power transformer, TR_E - earthing and auxiliary transformer, TR_L - load transformer (own elaboration).

The general network diagram in Figure 1 will correspond to the surrogate model shown in Figure 2.

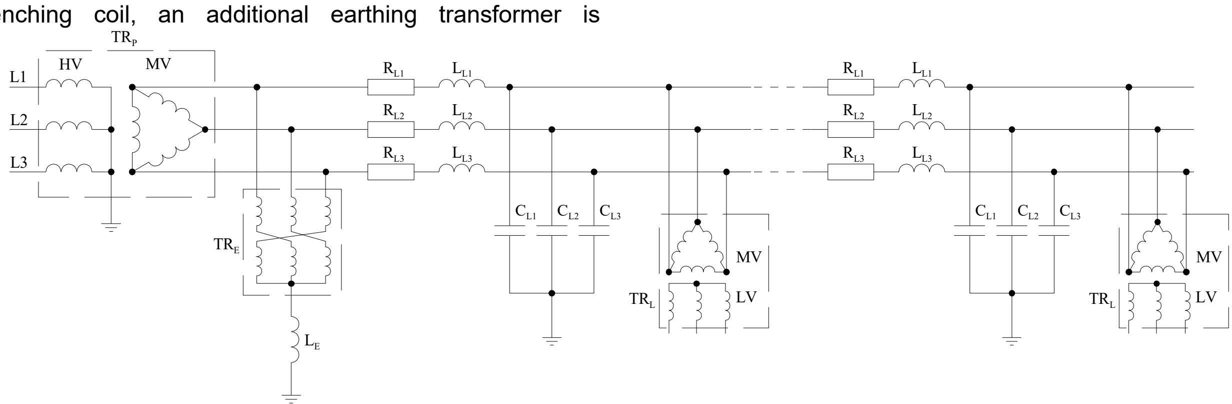

Fig 2. Equivalent model of an MV power network with the neutral point earthed by a arc-suppression reactor (earth fault compensation). L_E - arc-suppression reactor, R_{L1} , R_{L2} , R_{L3} - MV line longitudinal resistances, L_{L1}, L_{L2}, L_{L3} - MV line longitudinal reactances, C_{L1}, C_{L2} , C_{L3} - MV line earth capacitances (own elaboration).

Most often in the literature, when identifying the causes of voltage asymmetry in the electricity network, load asymmetry is taken as the main reason. On the other hand, it is believed that a symmetrical load (especially one connected in delta) does not affect negative voltage asymmetry, or this effect is so tiny that it can be neglected [34]. As shown by preliminary analyses carried out by the authors [16, 17], the value of this factor is affected not only by the active power flowing through the line but also by the value of the reactive power transmitted through it. Therefore, it was decided to take a closer look at this issue. The mathematical analyses and field tests aimed to determine the influence of symmetrical active and reactive power flowing through power lines on the value of the negative voltage asymmetry factor at the end of the line.

Material and methods

In order to determine the influence of the symmetrical load on the value of the negative voltage asymmetry, a symmetrical load was attached to the simplified equivalent diagram from Figure 2, which was illustrated by interfacial impedances ($\underline{Z}_{L12}$, $\underline{Z}_{L23}$, $\underline{Z}_{L31}$) of equal values through which the load currents flow ($\underline{I}_{L12}$, $\underline{I}_{L23}$, $\underline{I}_{L31}$) - Figure 3. The voltage vector system corresponding to the analysed loaded network is shown in Figure 4.

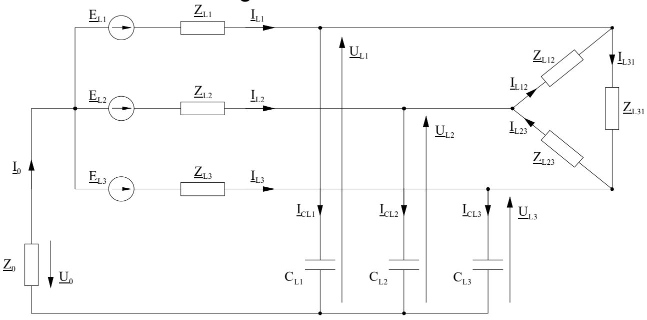

Fig 3. Equivalent diagram of the MV power network taking into account symmetrical line loading (own elaboration).

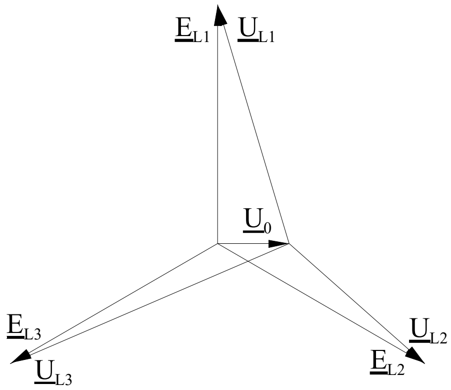

Fig 4. Voltage vector system for the diagram in Figure 3 (own elaboration).

The relationship between the voltages for the diagram considering the line loads in Figure 3 can be converted by equations using the nodal potential method:

(5)
$$\begin{cases} -\underline{Y}_0\underline{U}_0-\underline{Y}_{L1}\underline{E}_{L1}+\underline{Y}_{L1}\left(\underline{U}_0-\underline{U}_{L1}\right)-\underline{Y}_{L2}\underline{E}_{L2}-\underline{Y}_{L2}\left(\underline{U}_0-\underline{U}_{L2}\right)-\underline{Y}_{L3}\underline{E}_{L3}+\underline{Y}_{L3}\left(\underline{U}_0-\underline{U}_{L3}\right)=0 \\ \underline{Y}_{L1}\underline{E}_{L1}+\underline{Y}_{L1}\left(\underline{U}_0-\underline{U}_{L1}\right)-\underline{Y}_{C1}\underline{U}_{L1}-\underline{Y}_{L12}\left(\underline{U}_{L1}-\underline{U}_{L2}\right)-\underline{Y}_{L31}\left(\underline{U}_{L1}-\underline{U}_{L3}\right)=0 \\ \underline{Y}_{L2}\underline{E}_{L2}+\underline{Y}_{L2}\left(\underline{U}_0-\underline{U}_{L2}\right)+\underline{Y}_{L12}\left(\underline{U}_{L1}-\underline{U}_{L2}\right)-\underline{Y}_{L23}\left(\underline{U}_{C2}-\underline{U}_{C3}\right)-\underline{Y}_{C2}\underline{U}_{L2}=0 \\ \underline{Y}_{L3}\underline{E}_{L3}+\underline{Y}_{L3}\left(\underline{U}_0-\underline{U}_{L3}\right)+\underline{Y}_{23}\left(\underline{U}_{L2}-\underline{U}_{L3}\right)+\underline{Y}_{L31}\left(\underline{U}_{L1}-\underline{U}_{L3}\right)-\underline{Y}_{C3}\underline{U}_{L3}=0 \end{cases}$$

and then

(6)
$$\begin{cases} -\left(\underline{Y}_0+\underline{Y}_{L1}+\underline{Y}_{L2}+\underline{Y}_{L3}\right)\underline{U}_0+\underline{Y}_{L1}\underline{U}_{L1}+\underline{Y}_{L2}\underline{U}_{L2}+\underline{Y}_{L3}\underline{U}_{L3}=\underline{Y}_{L1}\underline{E}_{L1}+\underline{Y}_{L2}\underline{E}_{L2}+\underline{Y}_{L3}\underline{E}_{L3} \\ \underline{Y}_{L1}\underline{U}_0-\left(\underline{Y}_{L1}+\underline{Y}_{C1}+\underline{Y}_{L12}+\underline{Y}_{L31}\right)\underline{U}_{L1}+\underline{Y}_{L12}\underline{U}_{L2}+\underline{Y}_{L31}\underline{U}_{L3}=-\underline{Y}_{L1}\underline{E}_{L1} \\ \underline{Y}_{L2}\underline{U}_0+\underline{Y}_{L12}\underline{U}_{L1}-\left(\underline{Y}_{L1}+\underline{Y}_{L12}+\underline{Y}_{L23}+\underline{Y}_{C2}\right)\underline{U}_{L2}+\underline{Y}_{L23}\underline{U}_{L3}=-\underline{Y}_{L2}\underline{E}_{L2} \\ \underline{Y}_{L3}\underline{U}_0+\underline{Y}_{L31}\underline{U}_{L1}+\underline{Y}_{L23}\underline{U}_{L2}-\left(\underline{Y}_{L3}+\underline{Y}_{L23}+\underline{Y}_{L31}+\underline{Y}_{C3}\right)\underline{U}_{L3}=-\underline{Y}_{L3}\underline{E}_{L3} \end{cases}$$

After transformation to matrix form, equation (6) can be represented as follows:

(7)
$$\begin{bmatrix} -\underline{Y}_0-\underline{Y}_{L1}-\underline{Y}_{L2}-\underline{Y}_{L3} & \underline{Y}_{L1} & \underline{Y}_{L2} & \underline{Y}_{L3} \\ \underline{Y}_{L1} & -\underline{Y}_{L1}-\underline{Y}_{C1}-\underline{Y}_{L12}-\underline{Y}_{L31} & \underline{Y}_{L12} & \underline{Y}_{L31} \\ \underline{Y}_{L2} & \underline{Y}_{L12} & -\underline{Y}_{L1}-\underline{Y}_{L12}-\underline{Y}_{L23}-\underline{Y}_{C2} & \underline{Y}_{L23} \\ \underline{Y}_{L3} & \underline{Y}_{L31} & \underline{Y}_{L23} & -\underline{Y}_{L3}-\underline{Y}_{L23}-\underline{Y}_{L31}-\underline{Y}_{C3} \end{bmatrix}\begin{bmatrix} \underline{U}_0 \\ \underline{U}_{L1} \\ \underline{U}_{L2} \\ \underline{U}_{L3} \end{bmatrix}=\begin{bmatrix} \underline{Y}_{L1}\underline{E}_{L1}+\underline{Y}_{L2}\underline{E}_{L2}+\underline{Y}_{L3}\underline{E}_{L3} \\ -\underline{Y}_{L1}\underline{E}_{L1} \\ -\underline{Y}_{L2}\underline{E}_{L2} \\ -\underline{Y}_{L3}\underline{E}_{L3} \end{bmatrix}$$

Using Cramer's method, the end-of-line phase voltages UL1 , UL2 , UL3 were determined from the system of equations 7:

(8)
$$\underline{U}_{L1}=\frac{\begin{vmatrix} -\underline{Y}_0-\underline{Y}_{L1}-\underline{Y}_{L2}-\underline{Y}_{L3} & \underline{Y}_{L1}\underline{E}_{L1}+\underline{Y}_{L2}\underline{E}_{L2}+\underline{Y}_{L3}\underline{E}_{L3} & \underline{Y}_{L2} & \underline{Y}_{L3} \\ \underline{Y}_{L1} & -\underline{Y}_{L1}\underline{E}_{L1} & \underline{Y}_{L12} & \underline{Y}_{L31} \\ \underline{Y}_{L2} & -\underline{Y}_{L2}\underline{E}_{L2} & -\underline{Y}_{L1}-\underline{Y}_{L12}-\underline{Y}_{L23}-\underline{Y}_{C2} & \underline{Y}_{L23} \\ \underline{Y}_{L3} & -\underline{Y}_{L3}\underline{E}_{L3} & \underline{Y}_{L23} & -\underline{Y}_{L3}-\underline{Y}_{L23}-\underline{Y}_{L31}-\underline{Y}_{C3} \end{vmatrix}}{\begin{vmatrix} -\underline{Y}_0-\underline{Y}_{L1}-\underline{Y}_{L2}-\underline{Y}_{L3} & \underline{Y}_{L1} & \underline{Y}_{L2} & \underline{Y}_{L3} \\ \underline{Y}_{L1} & -\underline{Y}_{L1}-\underline{Y}_{C1}-\underline{Y}_{L12}-\underline{Y}_{L31} & \underline{Y}_{L12} & \underline{Y}_{L31} \\ \underline{Y}_{L2} & \underline{Y}_{L12} & -\underline{Y}_{L1}-\underline{Y}_{L12}-\underline{Y}_{L23}-\underline{Y}_{C2} & \underline{Y}_{L23} \\ \underline{Y}_{L3} & \underline{Y}_{L31} & \underline{Y}_{L23} & -\underline{Y}_{L3}-\underline{Y}_{L23}-\underline{Y}_{L31}-\underline{Y}_{C3} \end{vmatrix}}$$

(9)
$$\underline{U}_{L2}=\frac{\begin{vmatrix} -\underline{Y}_0-\underline{Y}_{L1}-\underline{Y}_{L2}-\underline{Y}_{L3} & \underline{Y}_{L1} & \underline{Y}_{L1}\underline{E}_{L1}+\underline{Y}_{L2}\underline{E}_{L2}+\underline{Y}_{L3}\underline{E}_{L3} & \underline{Y}_{L3} \\ \underline{Y}_{L1} & -\underline{Y}_{L1}-\underline{Y}_{C1}-\underline{Y}_{L12}-\underline{Y}_{L31} & -\underline{Y}_{L1}\underline{E}_{L1} & \underline{Y}_{L31} \\ \underline{Y}_{L2} & \underline{Y}_{L12} & -\underline{Y}_{L2}\underline{E}_{L2} & \underline{Y}_{L23} \\ \underline{Y}_{L3} & \underline{Y}_{L31} & -\underline{Y}_{L3}\underline{E}_{L3} & -\underline{Y}_{L3}-\underline{Y}_{L23}-\underline{Y}_{L31}-\underline{Y}_{C3} \end{vmatrix}}{\begin{vmatrix} -\underline{Y}_0-\underline{Y}_{L1}-\underline{Y}_{L2}-\underline{Y}_{L3} & \underline{Y}_{L1} & \underline{Y}_{L2} & \underline{Y}_{L3} \\ \underline{Y}_{L1} & -\underline{Y}_{L1}-\underline{Y}_{C1}-\underline{Y}_{L12}-\underline{Y}_{L31} & \underline{Y}_{L12} & \underline{Y}_{L31} \\ \underline{Y}_{L2} & \underline{Y}_{L12} & -\underline{Y}_{L1}-\underline{Y}_{L12}-\underline{Y}_{L23}-\underline{Y}_{C2} & \underline{Y}_{L23} \\ \underline{Y}_{L3} & \underline{Y}_{L31} & \underline{Y}_{L23} & -\underline{Y}_{L3}-\underline{Y}_{L23}-\underline{Y}_{L31}-\underline{Y}_{C3} \end{vmatrix}}$$

(10)

$$\underline{U}_{L3}=\frac{\begin{vmatrix} -\underline{Y}_0-\underline{Y}_{L1}-\underline{Y}_{L2}-\underline{Y}_{L3} & \underline{Y}_{L1} & \underline{Y}_{L2} & \underline{Y}_{L1}\underline{E}_{L1}+\underline{Y}_{L2}\underline{E}_{L2}+\underline{Y}_{L3}\underline{E}_{L3} \\ \underline{Y}_{L1} & -\underline{Y}_{L1}-\underline{Y}_{C1}-\underline{Y}_{L12}-\underline{Y}_{L31} & \underline{Y}_{L12} & -\underline{Y}_{L1}\underline{E}_{L1} \\ \underline{Y}_{L2} & \underline{Y}_{L12} & -\underline{Y}_{L1}-\underline{Y}_{L12}-\underline{Y}_{L23}-\underline{Y}_{C2} & -\underline{Y}_{L2}\underline{E}_{L2} \\ \underline{Y}_{L3} & \underline{Y}_{L31} & \underline{Y}_{L23} & -\underline{Y}_{L3}-\underline{Y}_{L23}-\underline{Y}_{L31}-\underline{Y}_{C3} \end{vmatrix}}{\begin{vmatrix} -\underline{Y}_0-\underline{Y}_{L1}-\underline{Y}_{L2}-\underline{Y}_{L3} & \underline{Y}_{L1} & \underline{Y}_{L2} & \underline{Y}_{L3} \\ \underline{Y}_{L1} & -\underline{Y}_{L1}-\underline{Y}_{C1}-\underline{Y}_{L12}-\underline{Y}_{L31} & \underline{Y}_{L12} & \underline{Y}_{L31} \\ \underline{Y}_{L2} & \underline{Y}_{L12} & -\underline{Y}_{L1}-\underline{Y}_{L12}-\underline{Y}_{L23}-\underline{Y}_{C2} & \underline{Y}_{L23} \\ \underline{Y}_{L3} & \underline{Y}_{L31} & \underline{Y}_{L23} & -\underline{Y}_{L3}-\underline{Y}_{L23}-\underline{Y}_{L31}-\underline{Y}_{C3} \end{vmatrix}}$$

On this basis, the value of the negative voltage asymmetry factor $\alpha_{U2\%}$ can be described as follows:

(11)

$$\alpha_{U2\%}=\left|\frac{\underline{U}_{L1}+\underline{U}_{L2}\cdot e^{-j\frac{2\pi}{3}}+\underline{U}_{L3}\cdot e^{j\frac{2\pi}{3}}}{\underline{U}_{L1}+\underline{U}_{L2}\cdot e^{j\frac{2\pi}{3}}+\underline{U}_{L3}\cdot e^{-j\frac{2\pi}{3}}}\right|\cdot 100\%$$

In order to observe the effect of symmetrical loading on the value of the negative voltage asymmetry factor, an example medium-voltage (15 kV) power system was modelled using the equivalent diagram in Figure 3, for which the values of the voltages U_{L1}, U_{L2}, U_{L3} and the negative voltage asymmetry factor $\alpha_{U2\%}$ at the end of the line were then determined.

A power line made in a flat system with bare steel-aluminium ACSR conductors with a nominal cross-section of 70 mm^2 was adopted for the calculations

The line operates at 15 kV and has a length of 5 km. The following equivalent line parameters were adopted for the calculations:

Z_{LA} = 0.488 + j0.7674 Ω/km
Z_{LB} = 0.488 + j0.7692 Ω/km
Z_{LC} = 0.488 + j0.7674 Ω/km
C_{LA} = - j0.0093 μF/km
C_{LB} = - j0.0103 μF/km
C_{LC} = - j0.0093 μF/km

no. 073645, issued by the Research and Calibration Laboratory in Swidnica, was used to record changes in the values of electrical quantities. The analyser records network parameters in accordance with class A of the EN 61000-4-30 standard. Values were recorded for one week, with an interval of one second. Based on the recorded values, the dependence of the negative voltage asymmetry factor as a function of the active and reactive power of the load was determined.

Results and discussion

As a result of analytical calculations, using the equivalent model (Figure 3) and relations (8 - 11), the values of the negative voltage asymmetry factor as a function of the load power were obtained. Figures 5 and 6, in order, show the determined dependence of

the reverse voltage asymmetry factor $\alpha_{U2\%}$ as a function of the active power P and reactive power Q of the symmetrical load.

When analysing the values shown in Figure 5, a clear rectilinear relationship between the value of the negative voltage asymmetry factor and the active power of the line load is noticeable. As the active power increases, the value of the negative voltage asymmetry factor at the end of the line increases and this change - over the entire power range analysed - is 47.3% of the maximum value.

Analogous calculations were carried out for the system loaded with reactive power, and the results obtained are presented in Figure 6. The analysis of the values contained therein shows that with the increase in reactive power, the negative voltage asymmetry coefficient's value increases,

The line is supplied with symmetrical voltage with the following values:

$E_{L1} = 8660\ e^{j0^\circ}$ V
$E_{L2} = 8660\ e^{-j120^\circ}$ V
$E_{L3} = 8660\ e^{j120^\circ}$ V

It was assumed that a symmetrical load connected in a triangle with active power in the 0 to 4 MW range and reactive power in the range of - 1 to 1 Mvar (from capacitive to inductive character) would be connected at the end of the line. The relationships described by equations (8) and (9) were used for the calculations.

In order to verify the correctness of the description of the phenomena occurring in the analysed system by the proposed mathematical model, field tests were carried out. These tests were carried out at the point of connection of a metal industry industrial plant in north-eastern Poland. Most of the equipment installed in the plant under study was three-phase, so it could be assumed (according to the recorded active power values) that load it was a symmetrical. The plant was supplied by an overhead cable line consisting of the following sections:

- overhead line with bare conductors ACSR 70 mm^2 with a length of 4.2 km,
- cable line made with cable type NA2XS(F)2Y 70 mm^2 with a length of 0.55 km.

A portable SONEL PQM-701 power quali

ty analyser, with serial number 960060, holding calibration certificate

similarly to the load with active power. In this case - in the whole analysed power range - the change in the value of the coefficient $\alpha_{U2\%}$ amounts to 53.4%, and this is an approximately linear relationship.

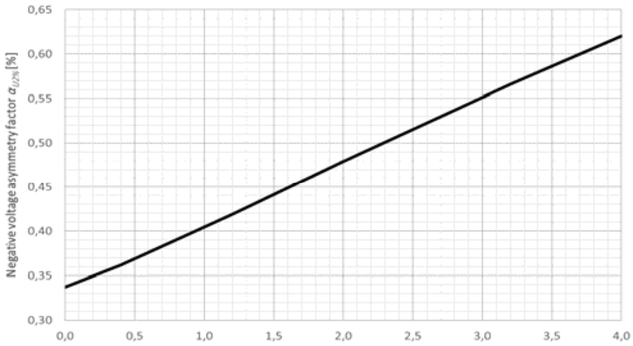

Fig 5. Dependence diagram of the negative voltage asymmetry factor $\alpha_{U2\%}$ as a function of the active power of the load P, determined using the analytical method (own elaboration).

In order to verify the results obtained using the analytical method, field tests were carried out to determine the dependence of the negative voltage asymmetry factor on the active load power. The dependencies obtained from the measurements are presented in Figure 7. A rather significant scatter of the measured values is noticeable, resulting from the fact that multiple values of the negative voltage asymmetry factor $\alpha_{U2\%}$ were recorded for one load power value. This is mainly due to the fact that the actual operating conditions of the grid at a given point are the resultant of the operation of the entire power system, in which a number of processes and phenomena take place. The analytical system is simplified according to the assumptions made.

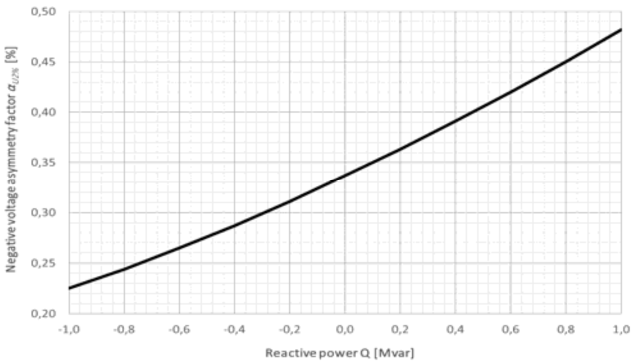

Fig 6. Diagram of the dependence of the negative voltage asymmetry factor $α_{U2\%}$ as a function of the reactive power of the load Q, determined using the analytical method (own elaboration).

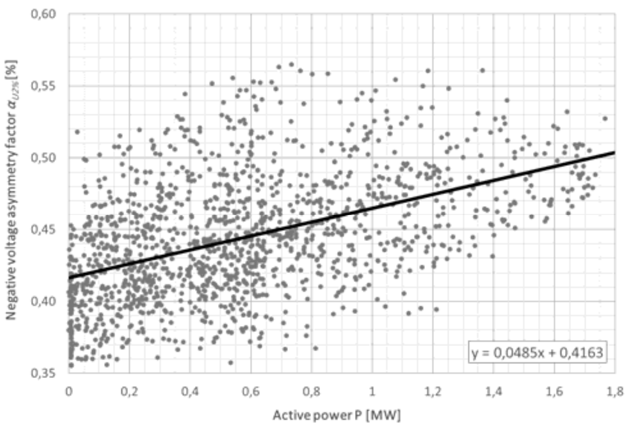

Fig 7. Dependence diagram of the negative voltage asymmetry factor $α_{U2\%}$ as a function of active load power P, determined during field tests (own elaboration).

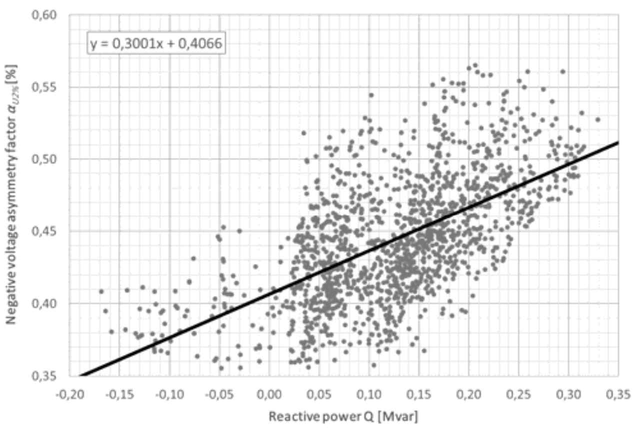

Fig 8. Dependence diagram of the negative voltage asymmetry factor $α_{U2\%}$ as a function of reactive load power Q, determined during field tests (own elaboration).

Adding a trend line to the values obtained, with a correlation of 48.5%, it can be seen that the relationship between active power and voltage asymmetry is analogous to that obtained analytically. The value of the negative voltage asymmetry factor increases with an increase in the active power of the load. This change is significant over the entire power range analysed and amounts to more than 17.4 %. It is worth highlighting that loads in the 0 to 1.8 MW range were recorded during the field tests. In the analogous power range, for the analytical model, the calculated increase in the value of the negative voltage asymmetry factor was 27.3 %. The discrepancy between these values is mainly due to the non-idealities of the power system under study - first of all, there was no equality of load power in individual phases (the recorded values were only close to each other, and the difference between them, at any time, did not exceed 4.3 %)

The dependence of the negative voltage asymmetry factor as a function of the reactive power load was measured similarly to before. The recorded values are shown in Figure 8. As in the case of active power, the scatter of the recorded values is also noticeable here, although it is smaller than in Figure 7.

By approximating the results obtained with a linear relationship (with a correlation of nearly 59.6 %), a directly proportional relationship was obtained between the reactive power of the load and the value of the negative voltage asymmetry factor. It is also consistent with the relationship obtained from the analytical calculations. Analogously, as before, it can be seen that the values of the negative voltage asymmetry factor increase with increasing reactive power (from capacitive to inductive). This change is significant over the entire power range analysed and amounts to more than 32.6%. In the plant analysed, reactive power loads varied during the recording period from -0.17 Mvar (capacitive in nature) to 0.33 Mvar (inductive in nature). In such a range of reactive power changes for the analytical model, the increase in the value of the negative voltage asymmetry factor was 18.4%

Conclusions

The leading cause of voltage asymmetry in electricity networks is the unequal loading of the different phases, resulting mainly from operating single-phase loads or sources. Voltage asymmetry can lead to various problems, such as malfunctioning electrical equipment and an increase in its temperature, which in extreme cases can lead to damage. Many articles can be found in the literature on this issue. However, when determining the negative voltage asymmetry factor, none of the authors considered the effect of a symmetrical load. This article shows that for MV electricity networks with the neutral point earthed by a reactor (Petersen's coil), voltage asymmetry occurs in power lines even with a symmetrical power source and a uniform load. As can be seen from the authors' studies and analyses, the values of the negative voltage asymmetry factor $α_{U2\%}$ depend strictly on the value of the load power - they are directly proportional to both the active and reactive power of the load. These conclusions are analogous to the model analysed analytically and are derived from the field tests carried out by the authors in one of the industrial plants. The recorded changes are pretty significant, as they exceed 17 % in each case (the increase in the negative voltage asymmetry factor $α_{U2\%}$ as a function of changes in active power was 27.3 % for the theoretical analysis and 17.4 % from the field tests. The change in $α_{U2\%}$ as a function of reactive power was 18.4 % and 32.6 %, respectively). These changes are significant and should be considered primarily in the design process of natural power systems. Therefore, in the detailed analyses of system stability and the quality of electricity transmitted through power grids, according to the authors, the nature and the value of the load occurring in the studied system should be considered when determining the value of the negative voltage asymmetry factor.

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REFERENCES

[1] Kochura D., Tsivilyov I., Sarin L., *Influence of arc-suppression method on voltage unbalance in 10 kV network with cable lines and overhead lines*. Electric Power Quality and Supply Reliability Conference (PQ), (2014) pp. 359-362,
[2] Hołdyński G.; Skibko Z. *Wpływ sposobu pracy punktu neutralnego na asymetrię napięć w sieci elektroenergetycznej SN*. Przegląd Elektrotechniczny, No. 9/2013 (2013) pp. 190-192,
[3] Holdyński G., Skibko Z., Borusiewicz A., *Analysis of the Influence of Load on the Value of Zero-Voltage Asymmetry in Medium-Voltage Networks Operating with Renewable Energy Sources*. Energies, (2023) 16(2), 580.
[4] Hanzelka Z., *Jakość dostawy energii elektrycznej. Zaburzenia wartości skutecznej napięcia*. Wydawnictwa AGH, Kraków (2013).
[5] Robak S., Pawlicki A., Pawlicki B., *Asymetria napięć i prądów w elektroenergetycznych układach przesyłowych*, Przegląd Elektrotechniczny 07/2014 Str. 23
[6] Olczykowski Z., *Electric Arc Furnaces as a Cause of Current and Voltage Asymmetry*. Energies, 14, (2021) 5058.
[7] Zajkowski K., Duer S., Paś J., Pokorádi L., *Cooperation of a Nonlinear Receiver with a Three-Phase Power Grid*. Energies, 16, (2023) 1418.
[8] Jagieła K., Gała M., *Nomograficzna metoda wyznaczania współczynnika asymetrii w trójfazowych sieciach elektroenergetycznych*, Przegląd Elektrotechniczny 01/2004 Str. 21-26
[9] Möller F., Meyer J.: *Survey of voltage unbalance and unbalanced power in German public LV networks*. 20th International Conference on Harmonics & Quality of Power (ICHQP), Naples, Italy, 29 May 2022 - 01 June (2022).
[10] Paranavithana P., Perera S., Koch R., Emin Z., *Global Voltage Unbalance in MV Networks Due to Line Asymmetries*. IEEE Transactions On Power Delivery, Vol. 24, No. 4, October (2009).
[11] Al-Shetwi A.Q., Hannan M.A., Jern K.P., Alkahtani A.A., Abas A.E., *Power quality assessment of grid-connected PV system in compliance with the recent integration requirements*. Electronics, 9, (2020) 366.
[12] Antić T., Capuder T., Bolfek M. A., *Comprehensive analysis of the voltage unbalance factor in pv and ev rich non-synthetic low voltage distribution networks*. Energies, 14, (2021) 117.
[13] Püvi V., Lehtonen M., *Convex Model for estimating the single-phase photovoltaic impact on existing voltage unbalance in distribution networks*. Appl. Sci., 10, (2020) 8884.
[14] Islam M., Nadarajah M.N, Hossain J., Shah R., *Dynamic voltage stability of unbalanced distribution system with high penetration of single-phase PV units*. Journal of Engineering, (2019) 4074-4080.
[15] Skibko Z.; Hołdyński G.; Borusiewicz A., *Impact of Wind Power Plant Operation on Voltage Quality Parameters - Example from Poland*. Energies, 15, (2022) 5573.
[16] Suproniuk M., Skibko Z., Stachno A.: *Diagnostyka wybranych parametrów energii elektrycznej produkowanej w elektrowniach wiatrowych*. Przegląd Elektrotechniczny nr 11 (2019), str. 105-108.
[17] Hołdyński G., Skibko Z., Skliński R.: *Analiza wpływu pracy elektrowni wiatrowych na asymetrię napięć w sieciach elektroenergetycznych średniego napięcia* Wiadomości Elektrotechniczne Nr 5, (2013). 11-14.
[18] Rodríguez-Pajarón P., Hernández A., Jovica V., Milanović J.V., *Probabilistic assessment of the impact of electric vehicles and nonlinear loads on power quality in residential networks*. International Journal of Electrical Power & Energy Systems, 129, (2021) 106807.
[19] Nour M., Chaves-Ávila J.P., Magdy G., Sánchez-Miralles A., *Review of positive and negative impacts of electric vehicles charging on electric power systems*. Energies, 13, (2020) 4675.
[20] Held L., Mueller F., Steinle S., Barakat M., Suriyah M.R., Leibfried T., *An optimal power flow algorithm for simulating energy storage systems in unbalanced three-phase distribution grids*. Energies, 14, (2021) 1623.
[21] Bozalakov D., Mnati M.J., Laveyne J., Desmet J., Vandevelde L., *Battery storage integration in voltage unbalance and overvoltage mitigation control strategies and its impact on the power quality*. Energies, 12, (2019) 1501.
[22] Jayatunga U., Perera S., Ciufo P., Agalgaonkar A. P., *Voltage Unbalance Emission Assessment in Interconnected Power Systems*. IEEE Transactions On Power Delivery, Vol. 28, No. 4, October (2013). 2274659
[23] Ciontea C. I., Iov F., *A Study of Load Imbalance Influence on Power Quality Assessment for Distribution Networks*. Electricity, 2(1), (2021) pp. 77-90.
[24] Rozporządzenie Ministra Gospodarki z dnia 4 maja 2007 r. w sprawie szczegółowych warunków funkcjonowania systemu elektroenergetycznego (Dz. U. z 2007 r., Nr 93, poz. 623).
[25] PN-EN 50160:2010 *Parametry napięcia zasilającego w publicznych sieciach rozdzielczych*.
[26] Instrukcja Ruchu i Eksploatacji Sieci Dystrybucyjnej, PGE S.A. wrzesień 2013 r.
[27] Taiwo O. P., Tiako R., Davidson I. E., *Investigation of voltage unbalance in low voltage electric power distribution net-work under steady state mode*. IEEE 3rd International Conference on Electro-Technology for National Development (NIGERCON), Owerri, Nigeria, 07-10 November (2017).
[28] Kahingala T. D., Perera S., Agalgaonkar A. P., Jayatunga U., *Determining the Impact of Line Asymmetries on Network Voltage Unbalance based on Balanced Load Flow Studies*. Australasian Universities Power Engineering Conference (AUPEC), Auckland, New Zealand, 27-30 November (2018).
[29] Soljan Z., Holdyński G., Zajkowski M.. *CPC-Based Minimising of Balancing Compensators in Four-Wire Nonsinusoidal Asymmetrical Systems*. Energies, 14(7), (2021) 1815.
[30] Lorenc J., Staszak B., *Modelling phenomena leading to the asymmetry of the phase voltages in mv networks*. Electrical Engineering, Poznan Universit of Technology Academic Journals, No. 86, (2016) pp. 117-127,
[31] Toman P., Drapela J., Orsagova J., *Solution of voltage asymmetry and reduction of outage time in MV compensated net-works*, 13th International Conference on Harmonics and Quality of Power, (2008) pp. 1-7,
[32] Musierowicz K., Lorenc J., Marcinkowski Z., Kwapisz A., *A fuzzy logic-based algorithm for discriminating damaged lines during intermittent earth faults*. 2008 IEEE Russia Power Tech, (2008)
[33] Lorenc J., Musierowicz K., Kwapisz A., *Detection of the intermittent earth faults in compensated MV network*. 2003 IEEE Bologna Power Tech Conference Proceedings, (2003) pp. 6 Vol.2
[34] Toman P., Paar M., Orsagova J., *Possible Solutions to Problems of Voltage Asymmetry and Localization of Failures in MV Compensated Networks*. 2007 IEEE Lausanne Power Tech, (2007) pp. 1758-1763,