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Passive automatic voltage balancer in medium voltage power networks

Pasywny automatyczny symetryzator napięcia w sieciach elektroenergetycznych średniego napięcia

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Abstract: The paper presents the concept of an automatic passive balancer designed to continuously balance (symmetrize) both line-to-ground and line-to-line voltages in a medium-voltage electric power grid by connecting in parallel an appropriate system of capacitors connected in a star or delta configuration. This solution aims to reduce the natural capacitive asymmetry of power lines, thereby limiting the zero sequence component U0 and the negative sequence component U2 of the voltage during normal grid operation. The paper also presents the results of simulation analyses confirming the efficiency of the proposed solution.

Keywords: voltage unbalance, MV power networks, voltage balancing, automatic passive voltage balancer.

Streszczenie: W artykule przedstawiono koncepcję automatycznego symetryzatora pasywnego, którego zadaniem jest nadążne wyrównywanie (symetryzacja) zarówno napięć fazowych, jak i międzyfazowych w sieci elektroenergetycznej średniego napięcia, poprzez równoległe przyłączanie odpowiedniego układu kondensatorów połączonych w gwiazdę lub trójkąt. Rozwiązanie to ma na celu zmniejszenie naturalnej asymetrii pojemnościowej linii, a tym samym ograniczenie wartości składowej zerowej U0 i przeciwnej U2 napięcia w stanie normalnym pracy sieci. W artykule przedstawione zostaną także wyniki analiz symulacyjnych, potwierdzające skuteczność proponowanego rozwiązania.

Słowa kluczowe: asymetria napięć, sieci elektroenergetyczne SN, symetryzacja napięcia, automatyczny symetryzator pasywny.

Introduction

Medium voltage electric power networks usually operate with an inefficiently grounded neutral point. In Poland, this is most often achieved by low resistance or, more commonly, by inductance (Petersen coil) [1, 2, 3]. The most important operational issue in such systems is the occurrence of voltage asymmetry, which manifests itself mainly in the presence of a zero sequence voltage component U_0 [4, 5, 6]. This phenomenon, although often overlooked in analyses of normal operating conditions, has an important impact on the functioning of protection systems, the accuracy of ground fault location, and the quality of electricity transmitted through the electric power network [7, 8]. One of the main sources of this asymmetry in medium voltage networks is the natural capacitive asymmetry of power lines (especially overhead lines), resulting from the actual conditions of conductor arrangement [9, 10, 11]. Although power lines are designed as three-phase and symmetrical, in practice their capacities for each phase differ from each other, which leads to voltage unbalance. In networks with earth fault compensation, where the impedance for the zero sequence is high, the effect of capacitive asymmetry is particularly noticeable through the appearance of significant values of the zero sequence voltage U_0 [12, 13, 14].

Passive compensators (balancers) known in the literature may consist of passive components (capacitance and inductance) and be available in two configurations: star or delta. As shown in [15, 16], voltage asymmetry can be compensated using a passive balancer consisting of passive components (coils and capacitors). The analysis shows that a star-connected balancer is better for minimizing the zero sequence voltage, while a delta-connected balancer is better for reducing the negative sequence component. Examples of passive compensator configurations are shown in Figure 1.

However, the use of passive components with fixed parameters does not produce the desired results

in practice. This is due to changes in voltage unbalance in real electric power networks as a function of load (even symmetrical load), as proven in [17, 18]. Therefore, a passive voltage balancer should be able to adjust to changing operating conditions of the electric power network. Many symmetrizing circuits have been developed in the literature, whose parameters can be calculated based on knowledge of the electric power network parameters and load. For this purpose, among other things, the theory of Currents' Physical Components (CPC) can be used [19]. However, according to this theory, a balancer consists of inductive and capacitive elements, which would make it very difficult to calculate and select the parameters of individual elements in real time.

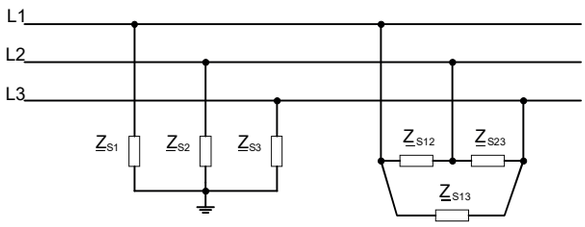

Figure 1. Schematic diagram of passive compensators consisting of impedances connected in a star and delta configuration, connected directly to the phase conductors of the line. Z_{S1}, Z_{S2}, Z_{S3} – balancer impedances connected in a star configuration, Z_{S12}, Z_{S23}, Z_{S13} – balancer impedances connected in a delta configuration

Therefore, the author undertook to develop an automatic passive balancer that would adapt to the operating conditions of the electric power network and use only capacitive elements (capacitors). Furthermore, for its proper operation, no information about the parameters of the electric power network would be needed, only voltage measurements at the balancer connection point. Such a device could then operate in different networks without the need for adjustment or calibration.

The implementation of a direct automatic passive balancer, where individual capacitive elements (capacitors) would be connected directly to the phase conductors of the medium voltage (MV) line, would be very expensive and difficult to implement. This is mainly due to the high cost of capacitors designed for network voltage (e.g., 15 kV) and the control devices used (e.g., MV contactors). For this reason, it was decided to use low-voltage capacitors (0.4 kV) connected via an MV/LV transformer. A generalized diagram of such a passive balancer is shown in Figure 2.

Material and methods

Based on many years of research and analysis carried out in medium voltage electric power networks with a neutral point grounded by inductance (Petersen coil), it has been found that the main cause of network disturbances (e.g., incorrect operation of earth fault protection) is the zero sequence voltage U_0. Therefore, in most cases, the priority should be to minimize the zero sequence voltage.

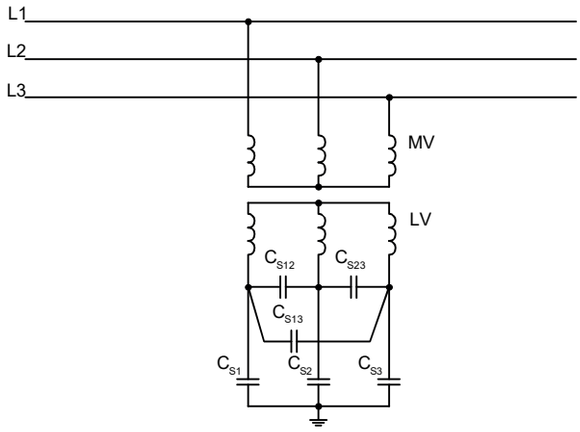

Figure 2. Generalized diagram of a passive symmetrizer consisting of capacitors connected in a star and delta configuration, connected via a MV/LV transformer with a Yy winding connection system. MV – medium voltage, LV – low voltage, C_{S1}, C_{S2}, C_{S3} – balancer capacities connected in a star configuration, C_{S12}, C_{S23}, C_{S13} – balancer capacities connected in a delta configuration

For this reason, two balancer configurations have been developed: a balancer consisting of capacitors connected in a star configuration, which would only minimize the zero sequence voltage, and a balancer consisting of capacitors connected in a star and delta configuration, whose task would be to minimize both the zero sequence U_0 and the negative sequence U_2 voltage.

In both cases, the idea behind the balancer is to switch-on capacitor elements to individual phases of the system in sequence. In the case of a balancer with capacitors connected in a star configuration, line-to-ground capacitors are connected between the phase conductor and ground, while in the second case, additional capacitors are connected between individual phase conductors. The capacitors are switched on or off by contactors controlled by a regulator based on the measurement of voltages in individual phases and the zero sequence and negative sequence voltages. These values are obtained on an ongoing basis from the electric power grid using a voltage transformer. Figures 3 and 4 show diagrams of individual passive balancer configurations.

In the case of a balancer with capacitors connected in a star configuration, minimizing the zero sequence voltage, the control concept is based on sequentially switching-on of line-to-ground capacitors to the phase with the lowest voltage (balancing the line-to-ground voltages) until the zero sequence voltage value falls be-

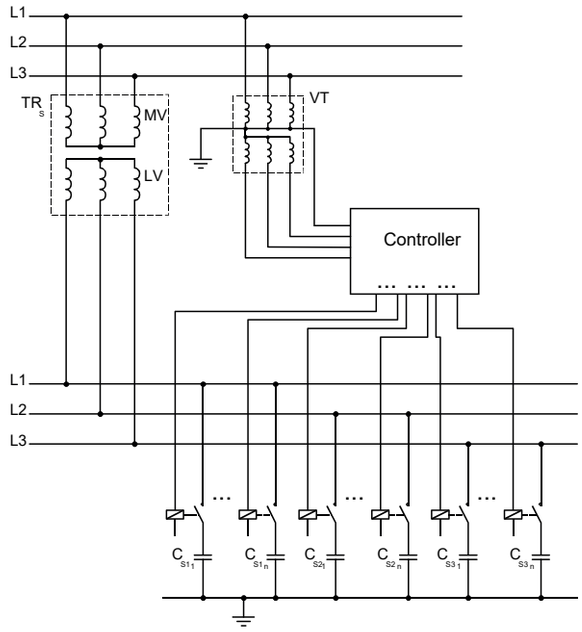

Figure 3. Diagram of a balancer with capacitors connected in a star configuration. TRS – power supply transformer, VT – voltage transformer, CT – balancer controller, $C_{S11} \div C_{S3n}$ – capacitive elements of the balancer

low the set (required) value. The system then monitors the zero sequence voltage values until they exceed the set value. If this happens, the capacitors in the phase with the highest voltage are switch-off one by one. If the number of capacitors switched on in a given phase is equal to 0 and there is a need to reduce the voltage in this phase by disconnecting another capacitor, the capacitors in all phases are switch-off and the algorithm starts from the beginning. A simplified diagram of the control algorithm for a balancer with capacitors connected in a star configuration is shown in Figure 5.

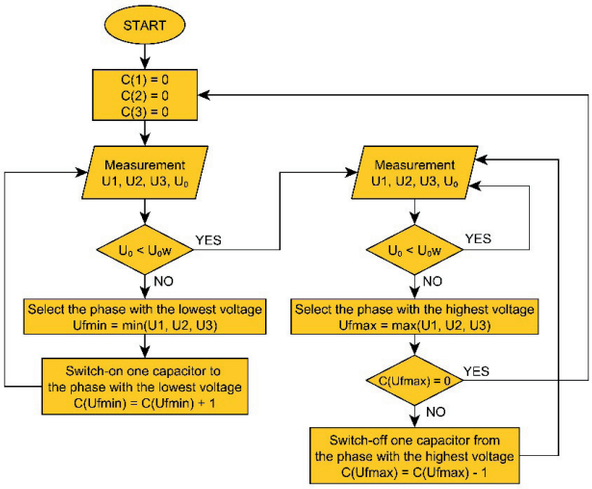

Figure 5. Simplified control algorithm for a balancer with capacitors connected in a star configuration. C (1), C (2), C (3) – number of capacitor elements switched on to the individual phases, U1, U2, U3 – phase voltages, U_0 – zero sequence voltage, U_{0W} – set (required) value of the zero sequence voltage

In the case of a balancer with capacitors connected in a star and delta configuration, minimizing the zero sequence and negative sequence voltage, the control idea is to primarily switch-on the capacitors between

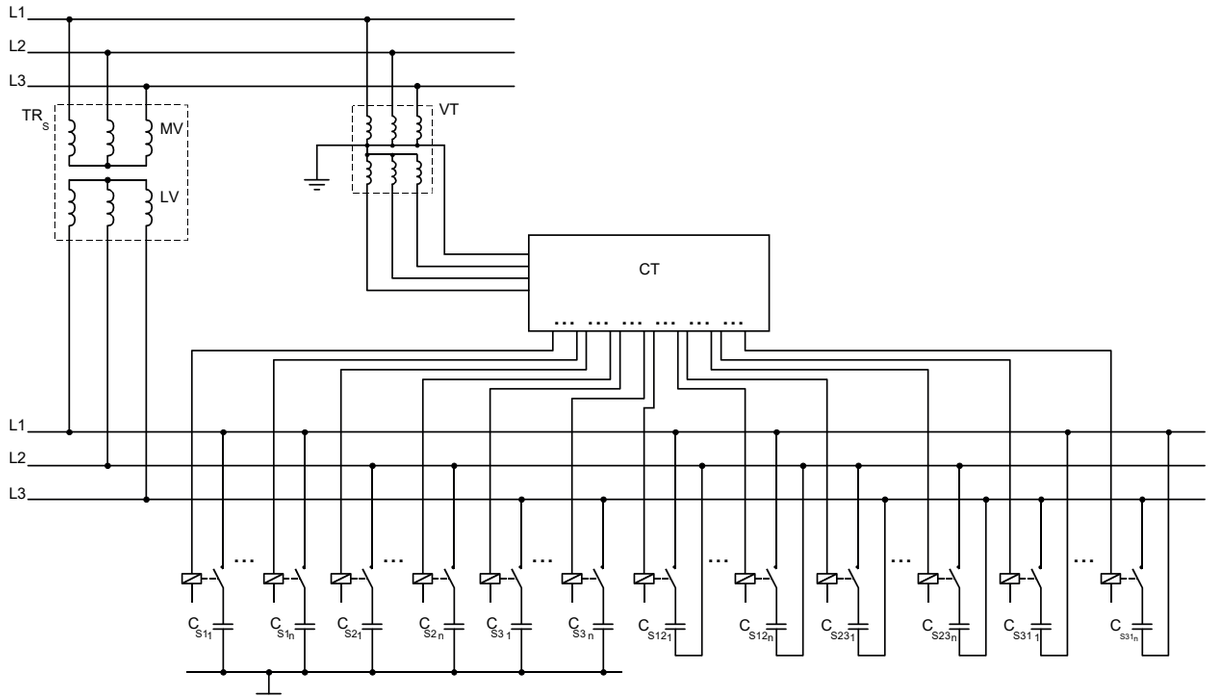

Figure 4. Diagram of a balancer with capacitors connected in a star and delta configuration. TR_S – power supply transformer, VT – voltage transformer, CT – balancer controller, $C_{S11} \div C_{S31n}$ – capacitive elements of the balancer.

the phases where the voltage is lowest (balancing the line-to-line voltages). This operation can be repeated sequentially until the negative voltage component falls below the set value. After completing this procedure, the system proceeds to minimize the zero sequence voltage (balancing the line-to-ground voltages) in the same way as in the case of a balancer with capacitors connected in a star configuration. After voltage balancing, the system monitors the zero and negative sequence voltage values until they exceed the set values. If this happens, line-to-ground or line-to-line capacitors are switched off in sequence, depending on whether the zero or negative voltage component increases. If the number of capacitors switched on in any of the banks is equal to 0 and there is a need to switch it off, the algorithm is reset and starts from the beginning. In each case, it should be remembered that a given capacitor can only be switched on again after the time necessary for it to discharge. A simplified diagram of the algorithm controlling the balancer with capacitors connected in a star and delta configuration is shown in Figure 6.

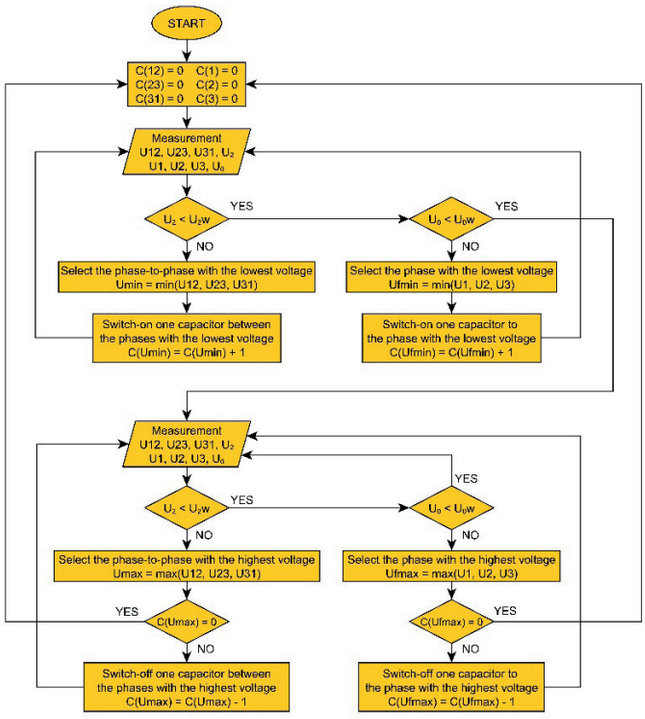

Figure 6. Simplified control algorithm for a balancer with capacitors connected in a star and delta configuration. C (12), C (23), C (31) – number of line-to-line capacitor elements switched on between the individual phases, U12, U23, U31 – line-to-line voltages, U_2 – negative sequence voltage, U_{2W} – set (required) value of the negative sequence voltage

Results and discussion

In order to verify the correct operation of the developed passive balancers, a model of a sample section of a medium voltage (15 kV) electric power network was created using NEPLAN software. The analysis took into account a medium voltage electric power network supplied from a primary substation (PS) equipped with a 110/15 kV transformer with a rated power of 16 MVA. A 15 kV overhead line with bare conductors in a flat configuration with a length of 120 km is led from the transformer station. The line uses three ACSR steel-aluminum conductors with a cross-section of 70 mm^2. Every 10 km along the line, receiving stations with MV/LV transformers with a power of 100 kVA have been connected. Each station on the low voltage side is symmetrically loaded with 60 kW (total 720 kW) with a power factor cosφ = 0.93 of inductive character. Three variants of balancer connection were taken for the calculations: at the beginning of the line (to MV busbars in the PS), in the middle of the line (60 km) and at the end of the line (120 km). The computer model diagram is shown in Figure 8.

Simulations of balancer operation were carried out on two configurations: a balancer consisting of capacitors connected in a star configuration and a balancer consisting of capacitors connected in a star and delta configuration.

In this paper, two asymmetry factors are taken as measures of voltage asymmetry in electric power networks. The first is the inequality of line-to-ground voltage values or angles is described by the zero sequence asymmetry factor $\alpha_{U2\%}$ [20]:

$$\alpha_{U0\%} = \left|\frac{\underline{U}_0}{\underline{U}_1}\right| \cdot 100\% \tag{1}$$

In the second case, the negative asymmetry factor $\alpha_{U2\%}$, which describes the inequality of line-to-line voltage values or angles [20]:

$$\alpha_{U2\%} = \left|\frac{\underline{U}_2}{\underline{U}_1}\right| \cdot 100\% \tag{2}$$

where: $\underline{U}_0$, $\underline{U}_1$, $\underline{U}_2$ – complex values of symmetrical components of zero, positive and negative voltage sequences.

The First, simulation tests were carried out for a balancer consisting of capacitors connected in a star configuration, switched on sequentially at the beginning, in the middle, and at the end of the tested MV power line. The calculations yielded values of the zero asymmetry factor $\alpha_{U0\%}$ and the negative asymmetry factor ($\alpha_{U2\%}$) of the voltage at all nodes of the model. Figures 8 and 9 show the values of the $\alpha_{U0\%}$ factor (Figure 8) and the $\alpha_{U2\%}$ factor (Figure 9) for individual nodes of the analyzed network without a balancer and with a balancer connected at successive points of the line.

By analyzing the waveforms shown in Figure 8, it can be concluded that in the absence of a balancer, a systematic increase in the zero asymmetry factor

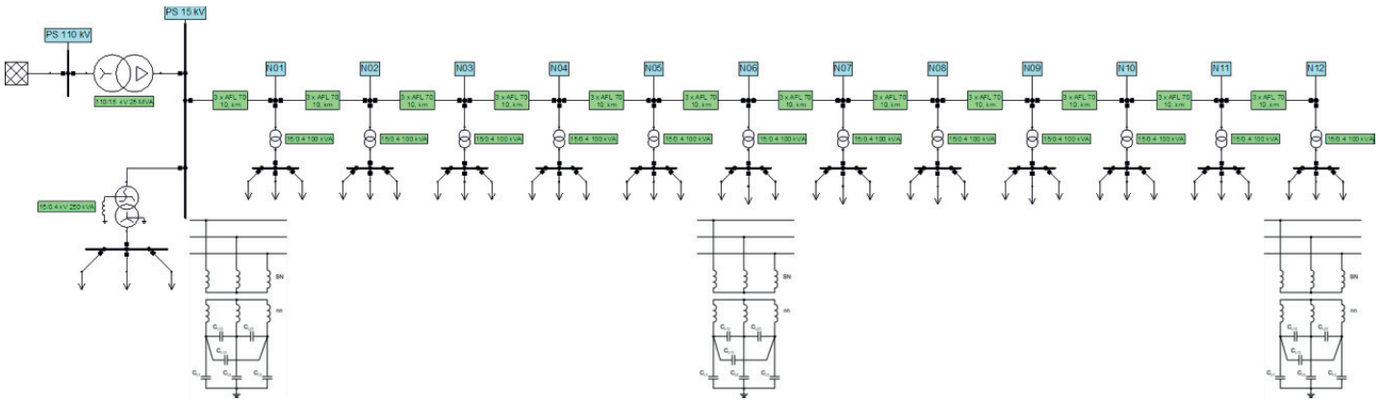

Figure 7. Simulation model of the tested medium-voltage power network in Neplan software with the locations of balancers marked

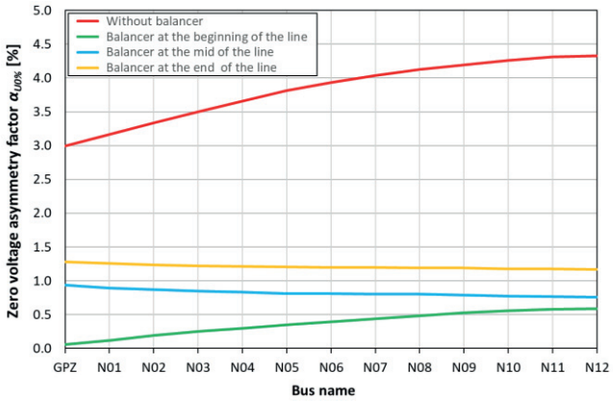

Figure 8. Graph of the zero voltage asymmetry factor ($\alpha_{U0\%}$) in individual network nodes with a balancer with capacitors connected in a star configuration

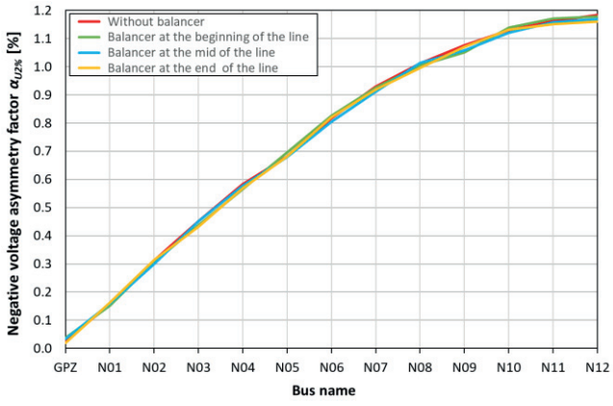

Figure 9. Graph of the negative voltage asymmetry factor ($\alpha_{U2\%}$) in individual network nodes with a balancer with capacitors connected in a star configuration

$\alpha_{U0\%}$ from 3.0% at the PS to approximately 4.3% at the end of the line (node N12) is observed. The introduction of a balancer significantly improves voltage quality. When the balancer is installed at the beginning of the line, the $\alpha_{U0\%}$ value on the PS busbars drops to only 0.06%. In subsequent nodes, the asymmetry gradually increases, reaching approximately 0.6% at the end of the line (N12). Although these values are higher than in the initial nodes, they are still significantly lower than in the absence of a balancer. Even in this case, the connection of a balancer reduces the asymmetry by more than 86.4%. When the balancer is installed in the middle of the line, the $\alpha_{U0\%}$ factor values are approximately constant throughout the network and vary between 0.76 and 0.94%. In this case, the greatest reduction in asymmetry, 82.5%, is achieved at the end of the line (N12). This distribution indicates that placing the balancer in the middle results in uniform but less efficient balancing. On the other hand, placing the balancer at the end of the line results in the lowest balancing efficiency (maximum reduction of 72.9%).

As opposed to zero asymmetry, the effect of the balancer on the negative asymmetry factor is practically negligible regardless of its location, as shown in Figure 9. In each of the three connection variants (at the beginning, in the middle, and at the end of the line), the curves almost coincide with the curve without a balancer. In practice, this means that in the analyzed system, the balancer mainly reduces the zero sequence voltage component, while its effectiveness in limiting the negative sequence component is negligible.

The second phase of the analysis, similar simulation tests were carried out for a balancer consisting of capacitors connected in a star and delta configuration. Figures 10 and 11 show the values of the $\alpha_{U0\%}$ factor (Figure 10) and the $\alpha_{U2\%}$ factor (Figure 11) for individual nodes of the analyzed network without a balancer and with a balancer connected at successive points of the line.

Compared to the previously analyzed case, the use of a balancer consisting of capacitors connected in a star and delta configuration results in a significantly better reduction of both the zero asymmetry factor and the negative asymmetry factor along the entire length of the line, as shown in Figures 9 and 10. In the case of the zero asymmetry factor (Fig. 9), for the

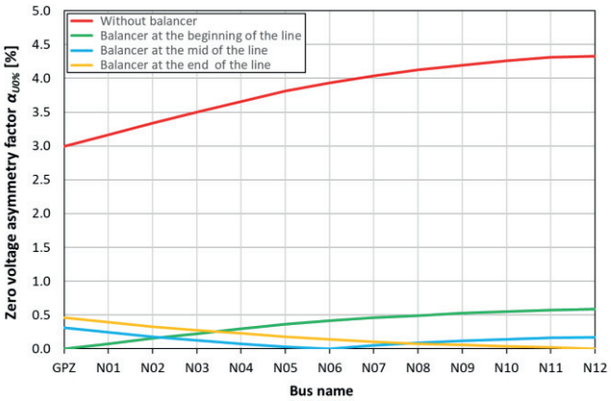

Figure 10. Graph of the zero voltage asymmetry factor ($\alpha_{U0\%}$) in individual network nodes with a balancer with capacitors connected in a star and delta configuration

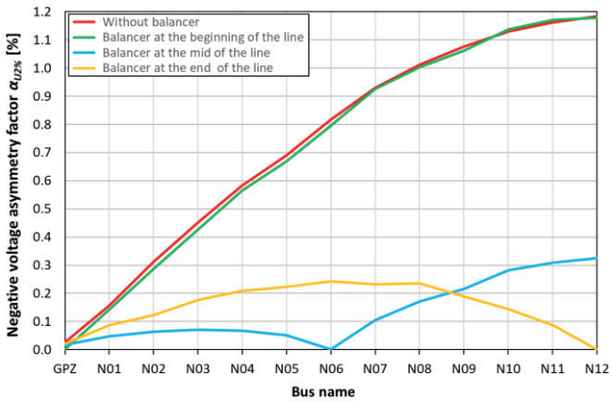

Figure 11. Graph of the negative voltage asymmetry factor ($\alpha_{U2\%}$) in individual network nodes with a balancer with capacitors connected in a star and delta configuration

variant in which the balancer is located at the beginning of the line, the $\alpha_{U0\%}$ factor on the busbars in the PS is 0%, which indicates complete elimination of the zero sequence voltage. As the distance from the device installation point increases, this coefficient rises slightly, reaching approx. 0.6% at node N12, which is comparable to the previous case. When the balancer is switched on in the middle of the line, there is a complete reduction of asymmetry for node N06 and a slight increase in the $\alpha_{U0\%}$ factor both towards the beginning of the line (to 0.31%) and towards the end of the line (to 0.17%). This distribution indicates a very effective reduction of asymmetry over the entire length of the line, with a particular improvement in its middle and end sections. On the other hand, the variant with the device at the end of the line initially leads to slightly higher values of the $\alpha_{U0\%}$ factor (0.45% in PS), but this factor quickly decreases towards the end of the line and, starting from node N06, falls below 0.15%, reaching 0% at the end of the line (N12). Observing all three variants of the balancer consisting of capacitors connected in a star and delta configuration, a significantly higher reduction in asymmetry can be observed than in the previous configuration, which indicates much better balancing efficiency.

In the case of reduction of the negative asymmetry factor $\alpha_{U2\%}$ (Fig. 10), the use of a balancer consisting of capacitors connected in a star and delta configuration results in a significant increase in balancing efficiency. This is particularly evident when the balancer is connected in the middle and at the end of the line. Placing the balancer in the middle of the line results in a complete reduction of the $\alpha_{U2\%}$ coefficient at this node (N06) and a significant reduction at other points in the network, not exceeding 0.33%. When the balancer is installed at the end of the line, the greatest benefits are observed at the end (0% for N12) and at the beginning of the line (0.02% for PS). The maximum value of the $\alpha_{U2\%}$ coefficient in this variant is 0.24% and occurs in the middle of the line (N06). For a balancer installed at the beginning of the line, there is no effect on the distribution of the $\alpha_{U2\%}$ coefficient along the line. The figures show that the best solution for improving voltage quality throughout the network is to locate the balancer at the end of the line.

In the context of the designed balancer, it is worth considering the potential risk of resonance (series or parallel) and ferroresonance phenomena. It should be emphasized that the proposed solution is based exclusively on capacitive components – it does not contain any inductive or nonlinear components, which are crucial for the occurrence of classic ferroresonance states. In addition, the capacitors are switched on sequentially, with voltage parameter control, which significantly reduces the risk of accidentally putting the system into resonance. It can therefore be concluded that in the presented device configuration, the risk of undesirable resonance phenomena is low. Nevertheless, further development work is planned to analyze transient states and conduct experimental studies taking into account possible resonance effects in the presence of unusual network configurations.

Conclusions

Based on the results and analyses presented in this paper, the following conclusions can be drawn:

- It is possible to build a properly functioning passive voltage balancer in a medium-voltage electric power network consisting exclusively of capacitive elements (capacitors).
- The simulations showed that low-voltage capacitors connected via an MV/LV transformer can be used to build a balancer, but proper balancing efficiency was only achieved for a transformer with a star-star (Yy) connection.

- The use of a balancer consisting only of capacitors connected in a star configuration allows for a significant (but not complete) reduction of the zero sequence voltage component, while no effect on the negative sequence component was observed. The use of a balancer in a star configuration effectively minimizes voltage asymmetry only on the busbars in the PS, while complete voltage balancing deep in the network is possible with a balancer containing both star-connected and delta-connected capacitors.
- The efficiency of the balancer is greatly influenced by its location in the electric power network. When using a star-connected balancer, the best results were obtained by connecting it to the MV busbars of the power supply station (PS). When using a star-delta connected balancer, the best connection point is halfway along the line.
- The use of a balancer completely eliminates voltage asymmetry only at the point of connection of the device. At other points in the network, balancing will not be complete but significantly lower than without the use of a balancer.

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REFERENCES

[1] Lorenc J., Łowczowski K.: Grounding methods in medium voltage networks. Electric Power Networks (EPNet), Szklarska Poreba, Poland, 2016, pp. 1–6.
[2] Olejnik B.: Adaptive Zero-Sequence Overcurrent Criterion for Earth Fault Detection for Fault Current Passage Indicators in Resistor Grounded Medium Voltage Networks. IEEE Access, vol. 9, 2021, pp. 63952–63965.
[3] Lorenc J., Staszak B., Borucki R., Torbus M.: Criteria for the regulation of follow-up earth fault compensation in medium voltage networks. Przegląd Elektrotechniczny, No. 10/2018, pp. 28.
[4] 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).
[5] Toman P., Drapela J., Orsagova J. Solution of voltage asymmetry and reduction of outage time in MV compensated networks, 2008 13th International Conference on Harmonics and Quality of Power, 2008, pp. 1–7.
[6] Toman P., Paar M., Orsagova J.: Possible Solutions to Problems of Voltage Asymmetry and Localization of Failures in MV Compensated Networks. IEEE Lausanne Power Tech, Lausanne, Switzerland, 2007, pp. 1758–1763.
[7] Lorenc J., Handke J.: Assessment of the degree of tuning of the Petersen coil based on measurement of the natural frequency of the circuit. Przegląd Elektrotechniczny, No. 08/2010, pp. 57.
[8] 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.
[9] Ciontea C. I., Iov F.: A Study of Load Imbalance Influence on Power Quality Assessment for Distribution Networks. Electricity 2021, 2 (1), 77–90.
[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]]Dziendziel A., Kocot H.: Methods to Minimize the Effects of Geometric Asymmetry of Multi-Circuit, Multi-Voltage Overhead Lines on Transmission Network Operation. Energies 2023, 16, pp. 7611.
[12]]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. 2018 Australasian Universities Power Engineering Conference (AUPEC), Auckland, New Zealand, 27–30 November 2018.
[13] Andruszkiewicz J., Lorenc J., Torbus M., Dziura J., Skowron M.: Limiting the effects of capacitive earth asymmetry in compensated MV networks. Przegląd Elektrotechniczny, No. 11/2024 pp. 270–272,
[14] Kochura D., Tsivilyov I., Sarin L., Influence of neutral grounding method on voltage unbalance in 10 kV network with cable lines and overhead lines. 2014 Electric Power Quality and Supply Reliability Conference (PQ), 2014, pp. 359–362.
[15] Czarnecki L. S.: Currents' Physical Components (CPC) – based Power Theory A Review. Part II: Filters and reactive, switching and hybrid compensators. Przegląd Elektrotechniczny, No. 04/2020, pp. 1–11.
[16] Pasko M., Dębowski K.: Symmetrization of asymmetrical three-phase load supplied from asymmetrical non-ideal voltage source with periodic nonsinusoidal waveforms. Przegląd Elektrotechniczny, No. 11/2008, pp. 248–252.
[17] Hołdyński 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.
[18] Hołdyński G., Skibko Z., Firlit A., Borusiewicz A.: Analysis of the effect of symmetrical load on the value of negative voltage asymmetry factor in medium-voltage power networks. Przegląd Elektrotechniczny, No. 07/2024, pp. 289.
[19] Sołjan Z., Hołdyński G., Zajkowski M.: CPC-Based Minimizing of Balancing Compensators in Four-Wire Nonsinusoidal Asymmetrical Systems. Energies 2021, 14 (7), 1815.
[20] Hołdyński G., Skibko Z.: Influence of neutral point work on the voltage asymmetry in MV power network. Przegląd Elektrotechniczny, No. 09/2013, pp. 190.