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ENERGY LOSSES' REDUCTION IN METALLIC SCREENS OF MV CABLE POWER LINES AND BUSBAR BRIDGES COMPOSED OF SINGLE-CORE CABLES

OGRANICZANIE STRAT ENERGII W ŻYŁACH POWROTNYCH LINII I MOSTÓW KABLOWYCH ŚREDNIEGO NAPIĘCIA WYKORZYSTUJĄCYCH KABLE JEDNOŻYŁOWE*

The growing share of medium voltage cable lines in distribution networks challenges distribution network operators in terms of proper mode of operation of these lines. It is related to the reduction of energy losses in cable conductors and metallic cable screens. The article focuses on energy losses in metallic cable screens of cable lines and substation busbar bridges composed of single-core cables with metallic screens and possible ways of their reduction. Simulation and measurement analysis of the level of energy losses in the metallic screens of cables is presented together with the economic analysis of various variants of losses reduction through the change of the way these screens are operated in relation to the traditional bilateral earthing at both ends of cable. Technical problems and threats connected with the use of considered modifications of metallic screens operation during earth fault disturbances in distribution networks are also presented.

Keywords: *cable lines, medium voltage network, energy losses, metallic cable screen.*

Rosnące skablowanie linii średniego napięcia w sieciach dystrybucyjnych stawia przed operatorami tych sieci wyzwanie prawidłowej eksploatacji linii kablowych. Powiązane jest to z redukowaniem strat energii w żyłach roboczych i powrotnych kabli. W artykule skupiono się na stratach energii w żyłach powrotnych linii oraz mostów kablowych wykonanych przy wykorzystaniu kabli jednożyłowych z metalicznymi żyłami powrotnymi oraz możliwych sposobach ich ograniczania. Przedstawiono analizę symulacyjną i pomiarową poziomu strat energii w żyłach powrotnych kabli wraz z analizą ekonomiczną różnych wariantów ich redukcji poprzez zmianę sposobu pracy tych żył w stosunku do tradycyjnego obustronnego ich uziemienia. Przedstawione zostały również problemy techniczne oraz zagrożenia związane z zastosowaniem rozważanych modyfikacji pracy żył powrotnych podczas zakłóceń zwarciowych w sieciach dystrybucyjnych.

Słowa kluczowe: *linie kablowe, sieć średniego napięcia, straty energii, żyła powrotna.*

1. Introduction

SAIDI (System Average Interruption Duration Index), which is characterizing the reliability of electricity supplies from the medium voltage distribution network, is significantly greater in Poland than in other European countries, which are the leaders in these statistics. One of the important reasons for this state is the relatively low share of cable lines in medium voltage (MV) network, not exceeding 25% in Poland [4]. The expected profits from converting the MV network into the cable one can be assessed by comparing average SAIDI values in Polish distribution network and in foreign networks having the high share of cable lines. The SAIDI of distribution networks in Switzerland, Denmark, Luxembourg, Germany and the Netherlands, basically operating a cable network, reach the level several times lower than in the case of networks with a significant share of overhead power lines in the MV network, as illustrated in Fig. 1.

In order to improve this situation in Poland, a broad plan for replacing the overhead lines by cables in the sections of the network characterized by high statistical damage indicators, usually passing

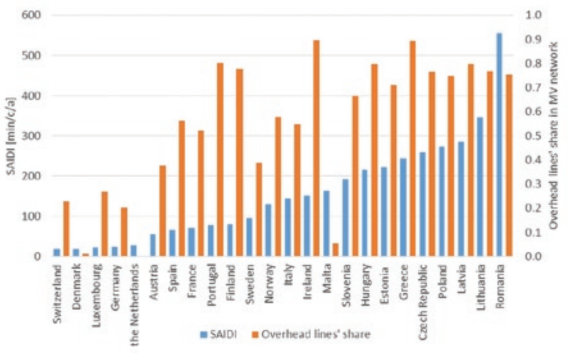

Fig. 1. SAIDI in comparison with the share of overhead lines in the total length of the medium voltage distribution network in various countries based on [4]

the forests or supplying wooded areas, is being prepared. In the coming twenty years, one should therefore expect a

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** significant increase in the MV cable network at the level of 40 000 km [40]. Replacement of existing overhead lines by cable lines will allow to eliminate the impact of severe climatic conditions and increase the operational reliability of these sections [17, 29]. Moreover, cable lines have lower impact on the landscape and are more easily accepted by the public [49].

In the last two decades, there have also been significant changes in cable line technology. Practically, the most common insulating material used is crosslinked polyethylene, and for the construction of cable lines, single-core cables with a metallic screen are used to ensure effective earth fault short-circuit current discharge and enable rapid operation of the damaged cable line protection system to prevent long-term effects of this current on insulation layers of other phases of a cable and its surroundings [37, 43]. In case of the absence of a cable metallic screen in the vicinity of short circuit event, significant electrical risks could occur as well. Detailed requirements in terms of protection against electric shock in MV networks are presented in [14-16].

The presented circumstances prompt to undertake research on the correct operation of the medium voltage distribution network containing an increasing share of cable line sections constructed in the new technology using three single-core cables with metallic screens. The problem presented in this article concerns the energy losses in cable metallic screens resulting from the use of their earthing at both ends and the ways to prevent such losses by modification of the traditionally used mode of metallic screens operation. The advantages and drawbacks of the proposed modifications are discussed as well. Considered issue is presented using computer simulations of cable line operation, which were verified by measurements conducted in existing sections of MV cable lines in the network of one of the Polish distribution system operators. The presented issue is in line with global trends in reducing energy losses in distribution networks [7].

Energy losses in cables are associated with the occurrence of a core conductor, insulation and metallic cable screens or other metallic layers of the cable. A distinction can be made between losses in the core conductor due to its resistance, dielectric losses related to the cable capacitance and insulation parameters as well as losses in the metallic cable screen related to the current flow through these layers and eddy currents [2, 35]. Losses associated with eddy currents are usually much lower in the cable screens than losses related to the current flow induced in the screen's circuit by load currents and do not depend on the circuit arrangement [37].

Energy losses in cable lines depend on the nominal cross-section of the conductor and of the metallic screen, way of laying the cable (flat or trefoil formation), but also to a large extent, on the connection and earthing system of the cables' metallic screens [32, 34, 38, 52]. The greater the distance between single-core cables, regardless of the thickness of individual conductors, the greater losses in these cable systems are observed, hence much greater losses will occur in the case of cables in a flat formation than in a trefoil formation [20, 37]. If there is more than one cable system, for example two three-phase cables side by side, energy losses will also depend on the phase sequence in individual single-phase cables [38].

The most popular in MV networks in Poland is both end bonding and earthing of metallic screens of a cable line section. In such systems, under normal load operation, there are negligibly low voltages in metallic screens, but significant currents induced by currents flowing in the cable core conductors, which cause additional losses in the cable metallic screens and may reduce the nominal current carrying capacity of the cable line. Losses in cable metallic screens, caused by induced currents, depend on the coupling impedances of the core conductors and metallic screens of the cable [52]. For standard medium voltage cables, additional losses in the metallic screens constitute 2-10% of the total losses in the cable [20]. Due to the large number of factors determining the losses in the metallic screens, in the most unfavourable cases, the loss in the metallic screens may be greater than the losses in the core conductor [18]. Reduction of losses occurring in metallic screens is possible by modification of operation mode of cable metallic screens including their earthing system, such as single-point metallic screen earthing applied in the case of high voltage cables [6, 11, 52] associated with the use of surge arresters at the unearthed screen end [20, 30], cable metallic screen intersection and cross-bonding [6, 11, 21, 33] or cross-bonding and transposition of the load carrying wires as well [44], inserting additional resistances or inductances at the place of cable metallic screens earthing or at cable joints' earthing [24, 32, 46] or reducing the cross-section of cable metallic screen, which are very often oversized [3, 27, 28, 50]. However, these solutions are rarely used in medium voltage networks due to the fear of electric shock hazards or overvoltage of screen insulation [11, 20] and expected problems with detecting cable line operation distortions due to the modified metallic cable screens connection systems [10, 23] and the possibility of damages in additionally introduced cable cross bonding joints or boxes [48]. In this study, a new task is undertaken to determine the cost-effectiveness of the proposed measures to reduce losses in metallic cable screens, and this cost-effectiveness is evaluated in real energy market conditions depending on the load of the line and the method used to decrease losses in the metallic screens.

The proposed methods of reducing losses in the metallic cable screens also require analysis during fault states. The analysis of electric shock hazards in cable networks [41] should take into account the influence of the number of MV/LV substations operating in the considered MV grids and their earthing as well as the resistance of the cable layers on the flow of ground fault current. The distribution of short-circuit current in the earthing system is also the subject of analysis in [42], where the influence of metal elements in the ground is taken into account. In [5], the influence of parameters of cable layers and earthing system on the earth fault current distribution and the hazards associated with its flow are analysed. The new approach presented in this paper concerns simulations and site studies of earth fault current distribution in different cases of earthing of the metallic screens in order to identify the risk of electric shock.

An important element of cable analysis in fault cases are also overvoltages, which may occur at the unearthed ends of the cable screens. Overvoltage issues are most often analysed for high voltage lines [6, 20, 48], less frequently for medium voltage lines [19], but their analysis is extremely important to ensure proper condition of metallic cable screens' insulation. In this article, attention was drawn to the possible occurrence of overvoltages when using the proposed methods of reducing losses in the metallic cable screens.

The article addresses this issue in order to develop proposals for the operation of cable lines built in the presented technology allowing for reduction of losses in cable metallic screens in economically justified cases when simultaneously surge protection requirements concerning the screen insulation and electric shock protection requirements at MV/LV transformer substations are met. For this purpose extensive simulation tests of medium voltage networks with cable sections have been conducted as well as tests on models containing sections of real cable lines and measurements on sections of cables operating in the distribution network, which are described below.

2. Cable lines' modelling

The analyzed sections of cable lines operating in the distribution network were modelled using the DIgSILENT PowerFactory software. In the cable lines modelling procedure, firstly a single-core cable is created, based on which a three-phase cable is composed. The input data applies to all conductive, insulating and semi-conductive layers that occur. All geometric parameters defining the cross-section and data defining the properties of all component materials are also entered.

Using the defined cable type, it is possible to create a simulation model of the cable system used in distribution networks as shown in Fig. 2. Input data considered for this purpose are: the type of single-core cable used to build the cable system, the position of each cable line in relation to the ground level, the position of each single-core cable line in relation to the remaining ones, as well as the cable laying environment (earth, air), frequency, soil resistivity, or the number of parallel cable systems.

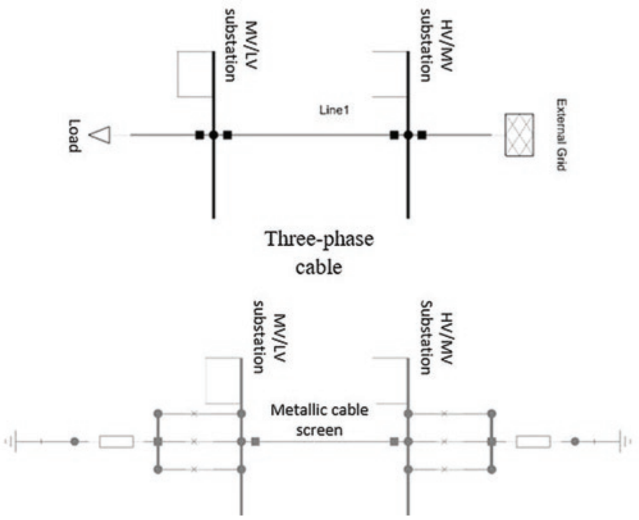

Fig. 2. Cable system model

The calculations for a cable system created with three single-core cables are conducted on the basis of solving matrix differential equations that bind the currents in the cable core conductor and metallic screen with voltages along the conductive layers of the cable [2, 8, 9]. Such calculation method enables the operation of the cable system's simulation in terms of currents and voltages in the conductor and in the metallic screen, in steady and transient conditions during normal operation and short-circuits. The model shown in Fig. 2 allows to simulate the cable operation considering different ways of connecting metallic screens with each other and with the ground and to include various values of earthing electrode resistances. In the case of busbar bridges, a cable system was modelled as consisting of three or four cable bundles connected in a parallel between the HV/MV transformer and the busbars of the MV substation. In the considered case, cables and busbar bridges were modelled in accordance with the MV distribution cable network standard presented in [12].

3. Load and energy losses modelling in MV cable lines

The purpose of this study was to determine the losses in the conductors and metallic screens for the registered loads in selected existing sections of MV cables in order to propose technical solutions to reduce losses in the metallic cable screens. In an urban network, two cable routes were selected which output power from HV/MV substations, consisting of three cable sections connected in series in trefoil formation. For the HV/MV substation bay, to which cable sections were directly connected, actual values of load currents were registered and provided by the Distribution Management System (DMS) controlling the operation of HV/MV substations, for the selected days of 2017 in winter, spring, summer and autumn for periods from Wednesday to Sunday. On the basis of relative changes in energy consumption in particular weeks of the year, the annual load profile for the tested facility was determined. The annual energy demand profile of the analysed cable section created for the maximum load case of 2,0 MVA is shown in Fig. 3.

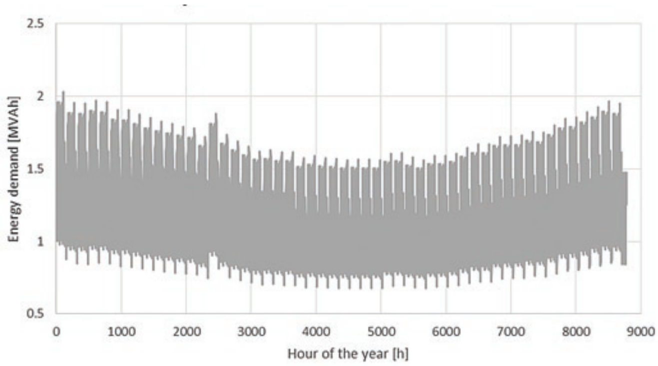

Fig. 3. Annual load profile for the considered cable line bay

The illustrated load profile applies only to the cable section that is connected to the substation bay with the conductor cross-section of 3x240mm^2 and 50 mm^2 for the metallic screens. For the following cable sections, the conductors' cross-section decreased to 3x120 mm^2, due to the reduced load because of additional outflows in the following MV/LV substations, while the same cross-section of the metallic screens was maintained. Taking into account the number and power of MV/LV transformers on a selected line, it is possible to determine the relative load of subsequent cable line sections, assuming an even load of MV/LV distribution transformers proportional to their rated power. In this way, the load on the second section was determined at the level of 72% of the first section load. Similarly, taking into account the next power stations, the third section was loaded at 63% of the first section load. With the progress of balancing meters installation at MV/LV substations, being the component of AMI (Advanced Metering Infrastructure) system, more precise estimation of cable section load will be possible, based on the values registered by the meters, but such data was not available at the time of the presented study.

For the first of the cable lines considered, due to the large differences in the length of the cable sections, the losses in section II and III were much smaller than in section I. Losses in individual sections of the considered cable system indicate seasonal variability, according to the variation of the load modelled in Fig. 3. The conducted analyses allow to determine losses in the metallic screen of the cable, which are presented in the form of a graph in the Fig. 4 as the absolute annual values in kWh and as a share in total energy losses in the cable for the analysed sections. The results of the analysis indicate that the average share of energy losses in metallic screens constitutes 3,5% of the total losses in the cable line.

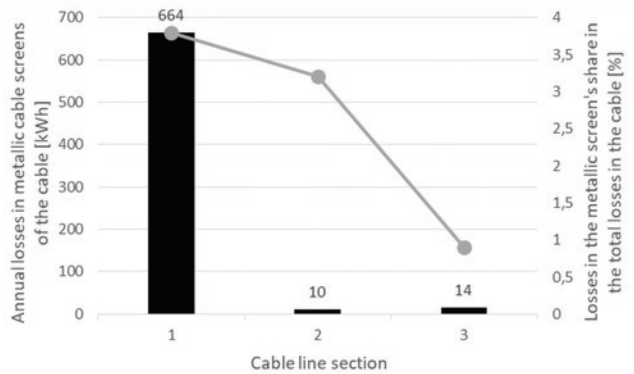

Fig. 4. Energy losses in the metallic screens of analysed cable line's sections

The similar simulations were performed for the second tested cable line. The maximum annual power output of this cable line was significantly lower and reached only 0,8 MV with the same cross-section of the cables in the analysed sections as for the first cable line analysed. The second section of the considered line was loaded at the same level as the first one, but the third section was loaded at 88% of the first section load. Due to the lower load on the second tested cable line, the absolute values of losses in the metallic screens of the cable are lower and for the entire line they amount to approx. 40 kWh per year. The share of losses in metallic screens in the total losses in individual sections of cables equals 2,3% for the first section, 1,1% for the second one and 0,5% for the third section, with the average of 1,5%.

Losses in metallic screens were also analysed in case of a busbar bridge composed of three sections of three-phase cables 3x3x240/50 mm^2 operating in parallel with a length of 23 m. The laying scheme of particular single-core cables in the tested busbar bridge is shown in Fig. 5. It is worth noting that similar cable systems can be found in lines that lead power out of large local power plants [19]. The maximum load of the bridge connected to the 25 MVA transformer was 13 MVA. After taking into consideration seasonal load changes, annual losses in metallic screens, based on computer simulation, reach the level of 150 kWh, which constitute approx. 6,7% of the total losses in the considered busbar bridge.

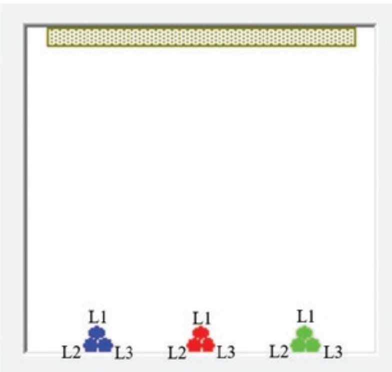

Fig. 5. Construction scheme of a busbar bridge

4. Measurement verification of simulation results

In order to verify simulation results, a series of measurements in existing MV cable lines and in a busbar bridge composed of three single-core cables were performed. The aim of the verification was to assess the discrepancy level between measured and simulated current values in metallic cable screens. Simulations were carried out using DigSILENT PowerFactory software.

Verification measurements were performed at three sections of MV cable lines in a trefoil formation and at a busbar bridge, at the substations where access to cable screens was easy. For each of the analysed cable sections, current values in core conductors and metallic screens of the cable were measured. In the measurements, the following equipment was used:

- power quality analyser Fluke 435 equipped with Rogowski coils installed on cable cores – 2% measuring accuracy,
- current clamp meters BRYMEN BM135s installed on cable screens – 5% measuring accuracy,
- in case of busbar bridges, cable core current values were recorded with four significant digit accuracy by the DMS system.

Discrepancy level was calculated with the following formula:

$$\delta I_{cs} = \frac{I_{m\_cs} - I_{s\_cs}}{I_{m\_cs}} \cdot 100\% \qquad (1)$$

where: I_{m_cs} – measured one-minute average cable screen current, I_{s_cs} – cable screen current obtained from PowerFactory simulations for the same loading conditions.

Recorded cable screen and core currents were analysed for particular load states, determined with the sampling frequency of the true RMS values recorded by the meters. Exemplary measurement results are presented in Fig. 6.

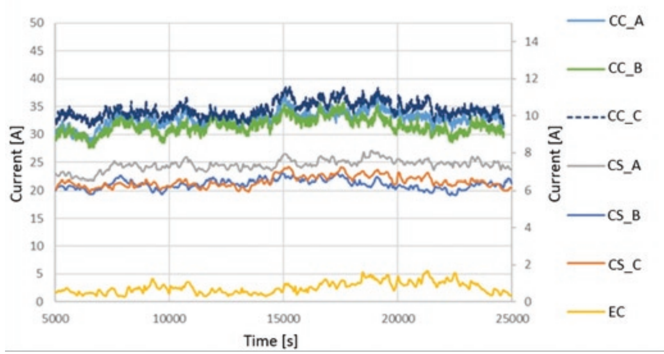

Fig. 6. Cable currents obtained from measurements (CC – cable core, CS – cable screen, EC – earth electrode current)

Significant discrepancy level between measurement and simulation results is observed for the analysed cables – measured cable screen current values are approximately +20 to +35% higher than simulation ones.. Taking into account the measurement verification of computer simulations of cable screen currents and measurement accuracy of the meters, in further considerations regarding the cost-effectiveness of the measures applied to reduce the losses in metallic screens, it is assumed that the currents flowing in the metallic cable screens are 25% higher than calculated based on computer simulations. The increased values of losses compared to the simulated ones summarized for the cable lines considered in chapter 2, presented in Fig. 7, are obtained in result of the assumption that real cable screen currents are higher by 25% than the simulated ones (for the cable line section analysed in Fig. 3).

One of the reasons for discrepancies could be harmonics content in the cable core current, transferring into cable screen current decomposition presented in Fig. 8 and not included in the PowerFactory simulation. Additional reason for discrepancies between simulation and measurement results may be the current flowing through screens, resulting from potential differences between substations' earthing installations connected by the analysed cable. The current flowing through the earth electrode, presented in Fig. 6, is the sum of above-mentioned screen currents and contains the harmonic currents as well.

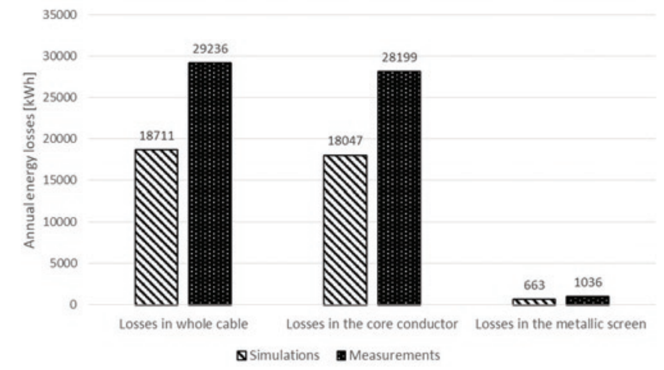

Fig. 7. Comparison of summed cable screen annual losses in investigated cable sections obtained from simulation and measurement results

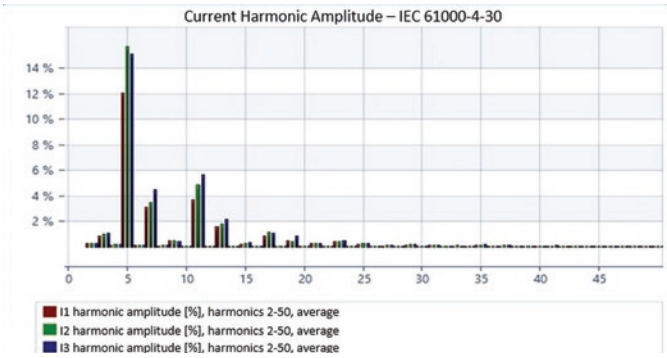

Fig. 8. Average one-month harmonic decomposition of cable screen currents in one of the analysed cables

5. Cross section selection and modifications of earthing method of metallic cable screens leading to the reduction of active power losses

The losses in metallic screens of cable line sections can be reduced by the following methods:

- cross bonding,
- one-sided earthing,
- the use of a lower cross-section compared to the standard one.

The first of the mentioned methods, when applying two cross bonding connections in one third and two thirds of the cable length, ensures reduction of losses practically to the negligible values at non-distorted currents. However, it requires the use of special cross bonding joints or the construction of cable boxes for cross bonding the screens, which is expensive. In the case of cable cross bonding the network operator's maintenance service is also expecting difficulties in conducting periodically performed cable line diagnostics.

One sided earthing of cable screens reduces losses, but requires analysis and confirmation of the admissibility of possible overvoltages of cable screen insulation at the unearthed ends of the cable screens in the case of short-circuit currents flowing through the cable cores. In addition, earthed metallic screens are used to limit the earth current flowing through the earthing installation of MV/LV substations powered by cable lines, which contributes to the limiting of possible dangerous touch voltages at these substations. Thus, in the case of cable lines operating with some of the screens earthed at one side, it is necessary to verify the values of possible touch voltages present during earth faults on these objects are within the permissible limits.

A smaller cross-section of cable screens, which is a technical solution to be applied at the stage of new cable line construction, leads to significant savings of investment expenditures. In addition, the higher resistance value of the metallic screen reduces the induced current in the both-end earthed screens, which leads to a reduction in losses. The screens with reduced cross-section may be exposed to inadmissible temperature rise during the double-phase short-circuits through the ground in the section outputting power from HV/MV substations [26]. However, to prevent this harmful thermal effect, it is possible to install instantaneous overcurrent protection for this cable section.

The use of one of the above-mentioned ways to reduce energy losses in cable screens should be economically efficient. The level of losses to which the savings can be calculated is the value of losses occurring in the cable with standard both ends earthing of screens. The proposed modification is reasonable if savings achieved thanks to the applied measure of the screen operation, exceed the investment expenditure for the cable operation modernisation during the lifetime of the cable, which can be expressed by the following relationship:

$$\Delta E_{Lmd} - V_i > 0 \tag{2}$$

where: ΔE_{Lmd} – discounted savings achieved due to modification of the cable screens operation for the considered time of cable line exploitation, V_i – value of expenditures to implement the chosen measure of the cable screens operation.

The process of decision making concerning the choice of a specific method of reducing losses in cable screens should be justified by simplified economic analyses using relatively easily available data characterising the analysed cable line. In order to evaluate the possible savings on losses in the cable screens, computational simulations of losses in these screens were performed in the function of cable loading for the considered loss reduction methods, such as cross bonding, single-sided screen earthing and the use of reduced screen cross-section. The values of cable screen current calculated in computer simulations were corrected according to the results of measurement verification of simulation results, which revealed an average increase of 25% in current values flowing in the screens operating within the distribution network, in relation to the values obtained in computational simulations. This can be translated into the following increase in losses in real metallic screens (3):

$$\Delta P_{re} = I_{re}^2 \cdot R = (1,25 \cdot I_{sim})^2 \cdot R = 1,5625 \cdot I_{sim}^2 \cdot R = 1,5625 \cdot \Delta P_{sim} \tag{3}$$

where: ΔP_{sim} – value of power losses obtained from simulation, I_{sim} - current in the cable screens obtained from simulation, R - cable resistance, I_{re} – measured current in the cable screens, ΔP_{re} - actual losses in the cable screens.

When cable screen cross bonding is applied, the losses in screens are negligible. For other cases analysed, the obtained results showing values of losses in the cable screens in relation to the losses in the core conductors for selected cable and screen cross sections are presented in Fig. 9. The visible shaded range of losses values for individual cable types results from different lengths of analysed cable sections in the range from 0,1 to 1 km. It was found, as the overall result of simulations conducted, that the share of losses in cable screens in the losses in the core conductors of the analysed cable systems is constant in the range from 5 to 100% of the rated current load, which is illustrated in Fig 9.

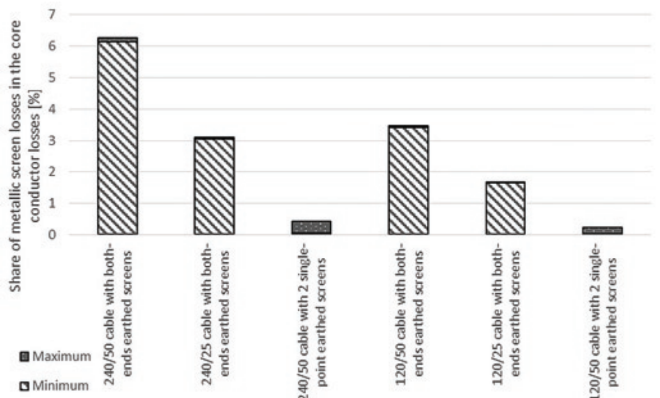

Fig. 9. The share of power losses in cable screens in the losses in core conductors analysed for cases of various cable screen operation and cross section

In the case of short sections of cable lines operating in substation cable bus bar bridges, cross bonding is not applicable, however, single point earthing of cable screens is rational since cable screens operation mode does not influence the electrical shock hazards at the HV/MV after cable screen proper insulation at the unearthed ends. The shares of power losses in cable screens in core conductor losses in busbar bridges for various cable screen connection configurations obtained on the basis of the measurement corrected simulation of the considered busbar bridges operation at various loads are shown in Fig. 10.

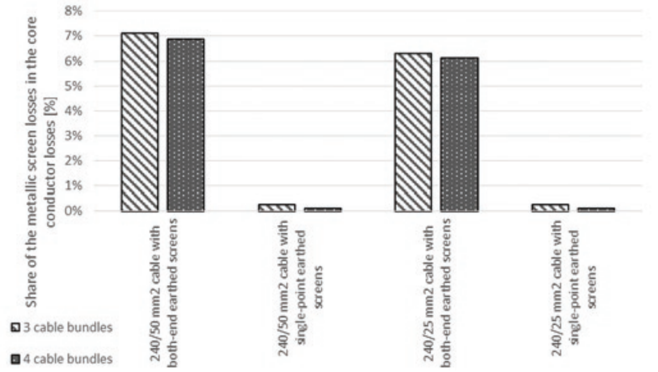

Fig. 10. The share of power losses in cable screens in core conductor losses in cable busbar bridges for various cable screen connection configurations and cable busbar bridges composed of 3 or 4 cable bundles

The presented results can be used to estimate the annual savings resulting from the change in the method of cable screens operation in accordance with the following procedure.

A. Determining the maximum losses P_{max} in the cable core conductors (4):

$$P_{\max} = 3 \cdot I_{\max}^2 \cdot \frac{l}{\gamma \cdot s} \tag{4}$$

where: I_{max} - current in the core conductor of the analysed cable section, l - length of the section [m], γ - conductivity of the cable core [m/(Ωmm^2)], s - cross-section [mm^2].

The load data of the analysed sections can be obtained in the case of power line bays in HV/MV substations from the registered values by the distribution network management system (DMS); for cable sections situated down the power line, when measured load values are not available, the approximate load can be calculated by multiplying the power leaded out from a given line bay of HV/MV substation, registered by DMS, by the share of the sum of rated power of MV/LV transformers supplied from a given section of cable line in the summed rated power of all transformers supplied from the power line supplied by the given bay in the analysed substation.

B. Determining the annual savings in energy losses $\Delta E_{l(BEB-m)i}$ in cable screens during a year as a result of the change in the way cable screen operation from both end earthing (*BEB*) system to the new modernised way (*m*):

$$\Delta E_{l(BEB-m)i} = (\Delta P_{lBEB\%} - \Delta P_{lm\%}) \cdot P_{\max} \cdot \tau_{\max} \cdot \left(1 + \frac{\Delta P_a}{100}\right)^i \tag{5}$$

where: $\Delta P_{lBEB\%}$; $\Delta P_{lm\%}$ - values of power losses in cable screens as percentage of the total cable power losses for the considered ways of cable screen operation presented as samples in Fig. 9 and 10; P_{max} - losses in the core conductors of the cable line according to the equation (4), τ_{max} - annual duration of maximum losses in the analysed cable section, ΔP_a - annual increase of losses due to the average increase in annual load of the section in [%].

In order to determine the power flows in individual sections of cable lines P_{max}, one may use the method of load distribution based on rated power of supplied transformers, load distribution based on monthly readings of cable section energy flow, analysis of load profiles or use of data recorded by smart meters (AMI, Advanced Metering Infrastructure) [1]. It is widely assumed that the use of data from the AMI system allows to achieve the most accurate results [25, 47], however due to the fact that the AMI system does not achieve full functionality, the data based on standard load profiles [22] are often used in the analyses.

The annual durations of maximum losses τ_{max} for segments of the distribution network in Poland can be found in the bibliography and according to [36], for bus bar bridges and cable sections leading out power from HV/MV substation bays, their value range is 1248 - 4449 h with an average value of 2525 h and a standard deviation value of 510 h. Selection of the right duration time of maximum losses depend on the types of loads supplied, greater for industrial loads and smaller for residential ones. For sections situated down the line, loaded with MV/LV substations, the range of considered duration times lies in the value range from 788 to 2444 h with an average value of 1662 h and standard deviation of 801 h. For power lines supplying individual MV/LV substations deep in the distribution network, when the results of load measurement are not available, it will be rational to adopt the values from the given range of values in proportion to the summed rated power of MV/LV substations supplied from a given section in relation to the total summed rated power of substation transformers supplied from the analysed line taking into account the types of loads supplied as well.

C. Discounted value of losses for cable line lifetime ΔE_{lmd}

In order to determine the value of discounted losses saved ΔE_{lmd}, the annual savings resulting from modernization, after discounting their values to the initial year level, should be summed up for the cable lifetime considered using the following relationship:

$$\Delta E_{Lmd} = \sum_{i=1}^{25}\left[\Delta E_{l(BEB-m)i} \cdot C_{ee0} \cdot \left(1 + \frac{\Delta C_a}{100}\right)^i \cdot \left(1 + \frac{R_d}{100}\right)^{-i}\right] \tag{6}$$

where: $\Delta E_{l(BEB-m)i}$ - annual savings in energy losses given by (5), C_{ee0}, ΔC_a - market price of electric energy in the year zero [PLN/kWh] and its expected annual growth in [%], R_d - annual discounting rate used in [%] to determine the value of losses in initial year.

The discount period was assumed to be 25 years, i.e. slightly above the accounting depreciation period of the cable lines in Poland amounting to 22,5 years [45].

Investment expenditure value V_i for the modernization of the cable screens operation ways, presented in inequality (2), depend on the solution applied. The cheapest solution is to isolate the cable screens at one end, which is related to the costs of a service brigade operation carrying out such insulation and the rather low equipment costs. The use of cross bonding is definitely more expensive, because it requires the purchase and installation of cross bonding joints or cable boxes for the implementation of this solution. The use of a metallic screen with a smaller cross-section compared to that considered as standard solution leads to significant savings in investment expenditure, the more important the longer the analysed section of the cable is and the limitation of the loss level as well. However, this can only be implemented at a stage of the cable line construction because the replacement for a cable with a smaller cross-section of metallic screen would not be economically efficient, due to the high investment costs close to the initially spend value for the construction of the cable line.

Numerous analyses of the cost-effectiveness of limiting losses by applying the above-mentioned modernization ways of cable screen operation have been carried out. The cost of losses were discounted to the sample initial investment year i.e. 2017 using two discount rates: a low value of 2,85% used in calculating the value of public assistance applied for example in the distribution of due payments in instalments and a higher having value of 5,633% being the return rate of capital cost obtained by distribution system operators in Poland. An increase in the annual cable line load was assumed to be 0,5% and an annual increase in electricity prices to cover losses at the level of 2,5% annually in relation to the 2017 price. The results of economic analyses performed lead to the following conclusions:

- lack of profitability of cable screens cross bonding for currently observed cable power line loads in the distribution network supplying residential and commercial customers due to the low value of discounted savings on energy losses reduction which for the analysed line segments amount up to approximate sum of PLN 3 000 over the period of 25 years,
- the cost-effectiveness of applying the one single-point earthing for two out of 3 cable screens of cable power line loaded with maximum power greater than 2 MVA for residential consumers,
- lack of profitability of applying single side earthing of cable screens in existing cable bus bar bridges due to the low value of discounted losses saved in these bridges, which results from their small length, despite their significant load,
- profitability of using 25 mm^2 cable screens in place of 50 mm^2 used as standard so far in new cable power lines and considering the profitability of applying single side earthing of 2 out of 3 cable screens in such cables depending on the results of simplified economic analysis,
- profitability of using 25 mm^2 cable screens in cable bus bar bridges and the application of single point earthing of all of their metallic cable screens in the case of new investments.

6. Risks resulting from cable screens operation with single point earthing

Single point earthing of some or all cable screens is the most interesting way of reducing cable screen losses. Unfortunately, some risks resulting from the single point earthing of cable screens are identified and presented below.

6.1. Risk of electrical electrocution in MV/LV substations

Single point earthing of cable screens has impact on earthing currents flow and contact voltage, which occur in MV/LV substations under phase to earth fault conditions and in LV circuits supplied from these substations [41, 42]. Earth fault current I_{k1} is divided into two paths – current flowing through earthing system of MV substation I_e and return current flowing through cable screens I_{cs}:

$$I_{k1} = I_e + I_{cs} \tag{7}$$

Only I_e component causes increase of contact voltage in substations. Decrease of the earthing current I_e due to the current flowing partially through the cable screen is presented by the value of reduction factor r, causing reduction of the earthing current I_e:

$$I_e = r \cdot I_{k1} \tag{8}$$

The reduction factor of a cable line consisting of three single core cables is usually calculated with the formula:

$$r = 1 - \frac{Z_M}{Z_{CS}} = \frac{Z_{CS} - Z_M}{Z_{CS}} \tag{9}$$

where: Z_M – mutual coupling impedance between cable core with phase to earth fault current and cable screens; Z_{CS} – self impedance of cable screen.

Formula (9) is fully valid in case of neglecting the earthing resistance of three cable screens. Taking into account the resistance of earthing systems [5], the resulting earth fault current flow is presented in Fig. 11, for the case of earth fault at the end of the cable line at MV/LV substation, supplied directly from HV/MV substation.

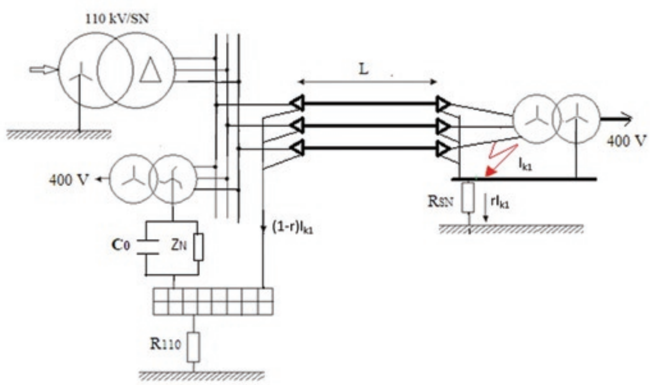

Fig. 11. Phase to earth current flow during the earth fault at MV/LV substation, including cable screens of the cable, as well as resistance of earthing systems of both substations; Z_N – impedance of MV neutral point earthing (resistor or Petersen's coil), C_0 – earth fault network capacitance, I_{k1} – earth fault current, R_{110} – earthing resistance of the HV substation, R_{MV} – earthing resistance of the MV substation, L – length of the considered cable line [km]

Voltage difference between earthing systems of HV/MV substation and MV/LV substation can be described by the following formula:

$$(1-r)I_{k1}Z_{CSu} - I_{k1}Z_{Mu} \cdot L = rI_{k1}(R_{110} + R_{MV}) \tag{10}$$

where: Z_{Mu} and Z_{CSu} - unit impedances [Ω /km], r – reduction factor, R_{110} – *earthing resistance of the HV substation*, R_{MV} – *earthing resistance of the MV substation*, L - cable length [km].

After conversion of (10), the formula describing the earthing current is obtained:

$$I_e = I_{k1} \cdot \frac{(Z_{CSu} - Z_{Mu}) \cdot L}{(R_{110} + R_{MV}) + Z_{CSu} \cdot L} \tag{11}$$

Due to the fact that most often $R_{110} << R_{MV}$, in the calculations only the earthing resistance of the supplied substation R_{SN} is taken into account.

It can easily be noticed that formula can be transformed to the following version:

$$I_e = r \cdot I_{k1} \cdot \frac{Z_{CSu} \cdot L}{R_{MV} + Z_{CSu} \cdot L} \tag{12}$$

or

$$I_e = r_{re} \cdot I_{k1} \tag{13}$$

where:

$$r_{re} = r \cdot K_{cor} \tag{14}$$

and the correction factor K_{cor}:

$$K_{cor} = \frac{Z_{CSu} \cdot L}{R_{MV} + Z_{CSu} \cdot L} \tag{15}$$

Table 1. Change of reduction factor values resulting from single point earthing of cable screens as multiplicity of reduction factor for both-end earthed screens under assumption that impedances Z_{CS} and the sum of earthing resistances (R_{110}+R_{MV}) are comparable.

No.	Growth rate of r value according to measurement results	Growth rate of r value according to analytical calculations	Growth rate of r value according to PF simulations results	Remarks
1	1,20	1,28	1,20	for one single point cable screen earthed in substation HV/MV
2	1,70	1,79	1,75	for two single point cable screens earthed in substation HV/MV

Correction factor K_{cor} presented in the formula (15) is valid for cables in which three cable screens are earthed. After single point earthing of one or two cable screens in MV/LV substation, value of that factor is changed because impedance Z_{CS} is changed. Expected variation range of the reduction factor values for such cases is presented in the table 1 for three different ways of determining the value of correction factor:

- measurement results on real cable line supplied with 230/400 V,
- simplified analytical calculations, which include cable formation and cable parameters influence,
- computer simulations using PowerFactory software.

When assessing the earthing electrode currents flow in MV substations supplied by cable lines, the impact of the substation earthing electrode resistance should also be taken into account in the calculation of the reduction factor. For the assumed sum of earthing resistances (R_{110}+R_{MV}) in range 0 – 5 Ω, the correction factor of the reduction factor values change can be illustrated by the curve depicted in Fig. 12. In order to determine the resistance of the earthing electrodes of the actual MV/LV substation, measurements should be taken in accordance with [13, 14].

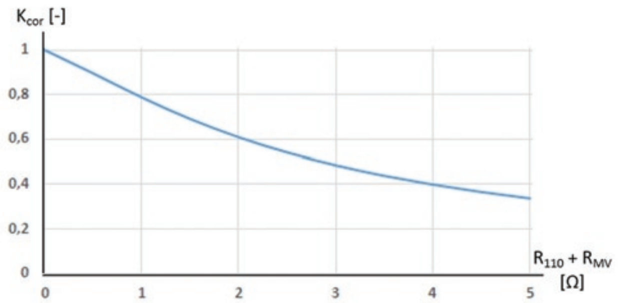

Fig. 12. Changes of reduction factor correction coefficient in function of the sum of earthing resistances of cable screens

Simulation and measurement results on cable line supplied with the reduced voltage showed that reduction factor increases when cable screens are unearthed. For the analysed case, the value of reduction factor equals 0,5 for both-end earthed cable and 0,6 when one cable screen is single point earthed or 0,85 when two cable screens are single point earthed. Permissibility of cable screen single point earthing operation should be therefore verified based on acceptable touch voltage level, which depend also on earth electrodes' resistance values at substations connected by the cable screens. Data for such analysis can be obtained by simulating earth fault current flow for the actual neutral point impedance, the mode of cable screens operation and earthing resistance of cable screens involved.

In case of cable bus bar bridges earthing at both ends or single point earthing does not have significant impact on a change of current flowing through earthing system of the HV/MV substation and therefore does not have a significant impact on risk of electric shock during earth faults at this substation.

6.2. Overvoltages at the end of cable line with single point earthed cable screens

Single point earthing of cable screens does not result in overvoltages under normal loading conditions. Hazard is created during phase to earth faults and phase to phase faults in MV cables, where, as it appears in simulation, peak value of transient overvoltage at the unearthed end of cable screen can be in range of over a dozen kV, which could be dangerous to cable sheath insulation. Not only does the value of transient overvoltages have influence on a risk of cable sheath damage, but also a frequency of fault occurrence in cable line. The most frequent faults can be observed in MV lines composed of several cable and overhead line sections, because of big intensity of faults in overhead lines. As a result, negative cumulative aging effect of cable screen insulation can be expected [31, 39]. In case of single point earthing of two cable screens, it could be beneficial, in order to reduce transient overvoltages, to bond those two unearthed screen ends, which should decrease the change in surge impedance of the screen and possibly result in the reduced overvoltages, but at the same time, it causes losses' increase in the connected screens.

According to simulation results, both side earthed screens reduce transient and steady-state overvoltages at the remaining single point earthed screens in comparison with the overvoltages in case of single-point earthing of all of cable screens. It can be supposed that both side earthed screen act in a similar way as ECC cable laid in proximity of HV cable lines applied there for reducing overvoltages [51, 52].

Application of cable screen single point earthing in MV cable lines requires further investigations in terms of transient overvoltages under phase to earth fault conditions and analysis of efficiency of overvoltage reduction methods, as well as the impact of overvoltages on cable screen insulation.

Simulation results indicate that overvoltages in cable bus bar bridges under phase to earth fault taking place in cable feeders are characterized by relatively low peak value, however the occurrence of overvoltages is more frequent, i.e. they occur during every short circuit in a network supplied by a given HV/MV substation. Theoretically cable bus bars could be safely unearthed because peak transient overvoltages values are below 2 kV even during phase to phase short-circuits through the earth and therefore is below 5 kV used under their DC voltage acceptance tests.

7. Conclusions

The growing share of cable lines, composed of single-core cables with metallic screens, in the overall length of medium voltage power distribution network, encourages the analysis of feasibility of possible changes of their standard operation with the aim to find the optimal solutions. In particular the choice of operation mode preventing excessive losses in the cable metallic screens seems to be important. In the presented analysis the value of losses in metallic screen of cable lines and bus bar power bridges with both side earthing of their screens was investigated in function of the loading carried for residential and commercial load profile. The computer simulations of cable line sections operation were performed and their results were verified concerning the energy losses in cable screens by measurements in real objects.

This verification indicated a 25% underestimation of the currents induced in the cable metallic screens obtained in computer simulations. One of the reasons for higher losses may be the content of harmonic distortions of currents in conductors.

The conducted simulations, corrected in result of measurement verification, can be the basis for the assessment of financial losses resulting from the both side earthing of cable metallic screens during the cable lifetime operation. The level of economic losses assessed for such standard operation of cable screens may lead to a modification of the way these screens are operated by applying remedial measures such as cross bonding, single side earthing or the use of a smaller cross-section of cable screens. The simplified methodology for assessing the economic value of reduction of losses possible to be achieved is proposed in this article, based on relationships enabling to calculate the savings on losses in 25 years of cable operation. The value of losses is obtained by discounting annual values to the initial year of analysis assuming a specific annual increase in energy prices and of cable loading rate over the analysed period. The determined savings constitute the basis for making a decision about implementation of possible modification of cable screens operation mode or for the proper choice of cable screens cross section.

The basic conclusion from the conducted analysis is the recommendation to limit the cross-section of cable metallic screens to 25 mm^2. At the current load level of cable lines in the distribution network supplying residential and commercial facilities, the level of discounted losses does not justify the use of quite costly remedies in the form of cable screens cross bonding.

A relatively simple remedy is the operation of cable screens with single point earthing. Application of this solution is recommended for all cable screens in the case of new installations of bus bar cable bridges made of single-core cables. In the case of cable lines, in cases demonstrating the profitability of limiting losses by applying single point earthing of one or two cable screens, such a solution can be conditionally applied leaving always one earthed screen on both ends to ensure the possibility of short-circuit current reduction.

The article describes the problem of the reduction of earth fault current following the single point earthing of metallic cable screens. The results of the reduction of current flowing to the ground through earth electrodes based on analytical equations are presented, as well as computer simulations and tests of cables laid in the ground supplied with reduced voltage. Procedures for determining the distribution of short-circuit currents should take into account the resistances of cable screen conductor and the resistances of earthing installations in the substations to which the cable screen conductors are bonded. In urban areas where earthing systems can be considered as forming the integrated earthing installations, the limited reduction of short circuit currents should not be an obstacle in applying the analysed remedy to reduce losses.

Computer simulations of overvoltages of the metallic screen outer cable insulation in cases of single point earthing of metallic screens that may occur during short-circuits are performed. Methods that can limit the values of such overvoltages are proposed for further research purposes. With two single side earthed screens, it is proposed to short-circuit the single point earthed screens at the unearthed end, resulting in the unchanged screen impedance for overvoltage waves, but for the price of increased losses similar to the case of one single point earthed screen. An alternative solution may be leaving two screens both side earthed, which can result in similar overvoltage's reduction as observed in high voltage cable equipped with ECC wire.

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