

Article

Novel Earth Fault Protection Algorithm Based on MV Cable Screen Zero Sequence Current Filter

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Abstract: This paper presents novel zero sequence current filter and earth fault protection relay, which utilize cable screens earthing current in protection algorithm. Different problems connected with state of the art of zero sequence current filters and protection relays are presented and compared with the proposed solution. The presented concept is verified in PowerFactory simulation software, experiment concerning modeling the earth fault current flow in medium voltage (MV) cable supplied from the low voltage (LV) network and measurements in the MV network in the Polish distribution system. The proposed solution is characterized by higher sensitivity and reduced number of erroneous trips. The presented solution is suitable for any MV cable lines. Biggest advantages are observed in power output lines from renewable energy sources, which are often operated under no-load conditions.

Keywords: cable screen; earthing system; zero sequence filters/transformers; protection relays; current measurement

1. Introduction

Experience in the operation of distribution system networks indicates that among all electrical disturbances, approximately 70% are earth faults [1]. Their intensity is relatively high and the average number of earth faults is 10–20 per 100 km over a year [2,3]. Earth faults are connected with different phenomena, which have an unfavorable impact on power quality and reliability of supply, as well as on the risk of overvoltages and electrical shocks. Overvoltages accompanying earth faults have a negative impact on insulation. Intermittent earth faults, characterized by unstable electric arc are a source of particularly dangerous phase to ground overvoltages, which can lead to insulation degradation [4] and further failures, which can transform into two phase to earth faults [5–7]. Phase to earth faults can lead to dangerous touch voltages. Current flow during the phase to earth fault is connected with the voltage drop across conductive elements. As a result of voltage drop, dangerous contact voltage can be generated. The risk is particularly high in the vicinity of phase to earth fault site, however, in some cases, the dangerous voltage can be transferred to the low voltage network through a common earthing system [8]. If a fragment of the network affected by phase to earth fault is not disconnected and dangerous operation conditions remain sustained, power lines and devices may be destroyed [9].

Lack of effective neutral point earthing results in low amplitude of phase to earth fault current. As a result, effective operation of phase to earth fault protection relays is more difficult [10]. In extreme cases, amplitudes of measurands are comparable with noise measurement. The noise is a result of imperfect production of instrument transformers and natural phase to earth asymmetry. The presented phenomenon acquires a great significance in compensated networks with neutral point earthed via Petersen coil. High resistance at the fault location, measuring error, zero sequence asymmetry, harmonic distortion, intermittent faults are common in compensated networks [11–14].

Many different protection algorithms against earth faults are developed in countries, in which neutral point of distribution system network is insulated from earth. A particularly big number of protection algorithms are developed for compensated networks. Protection algorithms can be divided into two groups: The first group which is based on steady-state components and second group, which is based on transient signal analysis [15]. Different directional criteria or harmonic based criteria are often based on steady-state analysis [16]. In case of transient signal, attention is typically paid to the moment of phase to earth fault occurrence.

New criteria of earth fault detection were developed in the 80s and 90s last century in Institute of Electrical Power Engineering of Poznan University of Technology. Criteria are based on analysis of average zero-sequence admittance, conductance and susceptance or analysis of increments of zero sequence admittance during operation of active current forcing resistor [17–19]. The protection algorithm utilizes zero sequence voltage measurement and is blocked when the zero sequence voltage is below the threshold. Thousands of protection relays equipped with admittance based criteria were installed in Polish distribution system networks. Operational experience confirms that sensitivity under bolted and intermittent faults is relatively high [20]. The great advantage of admittance based criteria is versatility—admittance based criteria can be utilized in networks with different neutral point earthing methods. Thanks to the versatility admittance based relays are effective also after the failure of neutral point earthing transformer.

Despite of many new solutions, the effectivity of earth fault protection relays is not always satisfactory, in particular in case of unstable electric arc or high impedance faults [21]. It is, therefore, necessary to develop new protection criteria, which would ensure higher sensitivity and increase the effectivity of nowadays protection relays. Results of scientific research indicate, that the wide utilization of medium voltage (MV) cables with screens, which are common in distribution system network, create the possibility of using screens current measurements during the earth faults to increase the efficiency of protection relays operation. This paper presents simulation results and measurements result, which confirm the validity of simulation results. Moreover, the protection algorithm, which is based on current values flowing in the earthing circuits containing cable screens was developed and is presented. Innovative earth fault protection criteria ensure high sensitivity of earth fault detection and help to avoid unwanted tripping due to erroneous settings. The idea of utilization cable screen currents is presented in a few papers, but to the best authors knowledge, no paper presents a detailed protection algorithm, which utilizes cable screen earthing current in protection algorithm [22–24]. This paper also presents a novel zero sequence current filter, which allows for installation of accurate current sensors. The biggest advantage is achieved under low load or no-load conditions of protected feeder, where conventional solutions are characterized by big measuring errors. It is believed that presented zero sequence current filter could also be used for detection of phase to phase short circuits and, therefore, has the potential to be an independent protection relay, which utilizes only one current input that could greatly simplify the protection relay hardware since the number of current inputs could be reduced. Another innovation presented in the paper is the possibility to distinguish if earth fault occurred in the cable or overhead line of mixed—cable overhead feeder. Zero sequence earthing current measurements allows for identification of erroneous connections in two-point bonded cables, as well as cross-bonded cable lines and, therefore, functionality of proposed protection algorithm could be increased [25–27]. The earthing screen current can also be used for detection of cable sheath damages, in differential protection relays and auto-reclosing blocking algorithms [24,28]. Analysis of cable screen current flow is also used for assessment of safety against electric shock or assessment of stray current flow [29,30].

In further paragraph state of the art methods of zero sequence current measurement are presented and analyzed. Various cable screen current sources are presented and analyzed in the context of the protection algorithm. Simulation and measurement results are presented to validate the proposed solution and to analyze the impact of different factors on the earth fault screen current. One before last paragraph presents proposed solutions—zero sequence filter and developed algorithm. General

flowchart of the developed algorithm is presented in Figure 1. The paragraph is finished with a comparison of the developed criterion with conventional solutions. Finally, the main conclusions and outline of further work are presented.

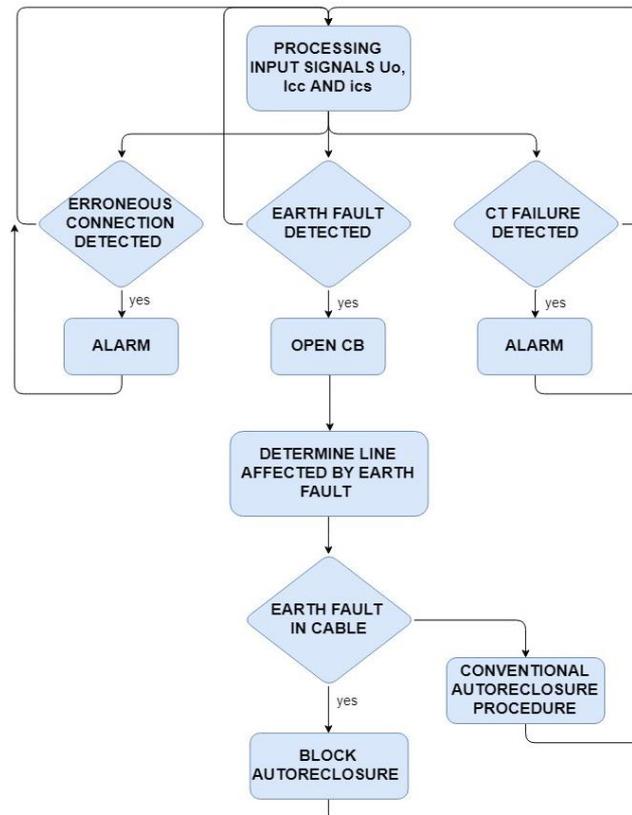


Figure 1. Flowchart of the proposed solutions (CB—circuit breaker).

2. Zero Sequence Current Measurement

Selection of protection relay setting is based on the calculation of a range of applicable settings and selection of activating setting form the calculated range. Selection of values from the lower range results in higher sensitivity of protection relays, but at the same time, a risk of unwanted tripping increase. Selection of setting from the upper range is connected with reduced sensitivity, but a risk of unwanted trips is smaller. Operational experiences show, that often, higher settings are chosen to minimize the risk of unwanted tripping. Additionally, protection relays are equipped with $U_0 >$ overvoltage criterion, i.e., earth fault is detected when secondary U_0 voltage exceeds a certain threshold, i.e., 15 V (on the secondary side of zero sequence voltage filter).

The sensitivity of earth fault detection is affected by the zero sequence current filter. Measuring error is defined for the secondary side and its value is in the range 10–50 mA [31]. Earth fault current filter should not saturate under load conditions because under saturation conditions current is strongly distorted [32]. To avoid saturation transformer ratio needs to be high, i.e., 300:5. One can easily observe that the higher the primary current is, the higher the measuring errors on the secondary side are. At the same time, sensitivity of protection relay is lower. Accuracy of conventional zero sequence filter is further reduced due to the incorrect position of cables inside the filter and size of core balance current transformer (CBCT)—i.e., measuring error is 30 mA for 85 mm diameter and 500 mA for 130 mm diameter [33]. Position of cables inside a measuring window of CBCT transformer is particularly important in the case of parallel lines made of many cables. CBCT transformers are constructed to fulfill requirements of norms, i.e., IEC61869, it is, however, noted that for protection transformer, the error is specified only for nominal loading conditions. Measuring error under loading

below nominal is not specified. Measuring error in lower loading range can be in the range of tens of percent, i.e., 20% [34]. Operational experience shows that often additional errors, which result from incorrect installation, can be observed. Among the installation errors of Ferranti current transformer (CT) one can mention following errors: Incorrect pulling of cable screens through measuring window, to small distance between the Ferranti CT placement and the cable end, inaccurate connection of open core CT or dirt on the surface of open core type CT [35].

It is possible to buy CBCT transformer, which fulfills the requirement of 0.2s class in the lower range and 5p protection class in the higher range [36]. Special CBCT transformers are, however, more expensive and replacement of these transformers is a complex procedure—the bay needs to be de-energized. Another example of a conventional zero sequence current transformer is residual CT connection (Holmgreen), which is created by connecting 3 CT together. Holmgreen filter measures zero sequence accurately if all CTs have the same amplitude-phase characteristics. Deviation from the similar characteristics results in zero sequence current flow. The current increases when load increases and, therefore, protection relay could be erroneously tripped if the current exceeds the threshold [37].

Proposed alternative—installation of Rogowski coil on the earthing system of a cable is simple and can be performed on energized cable. Because earthing current flows only through one metallic element, dimensions of the sensor can be greatly reduced and errors due to displacement are greatly reduced. Measuring range of Rogowski coil can be changed via modification of sensitivity factor (mV/A) and, therefore, measuring range can be adaptively adjusted to zero sequence current amplitude, i.e., due to the expected fault resistance or modification of neutral point impedance. An additional advantage of Rogowski coil is practically negligible measuring angle error and no burden errors [38]. It has to be, however, noted that signal cable is an integral part of Rogowski coil and cannot be modified or replaced with different cable [39]. Despite sensitivity factor and measuring error, one should analyze resonance band of Rogowski coil [40]. An alternative for Rogowski coil is an optical current transformer to monitor cable screen current flow [41].

3. Cable Screen Earthing Current

Figure 2 present cable screen current sources, which can force the earthing current flow resulting from cable screen currents summation. Other current sources can be observed in power lines composed of many cable sections or mixed cable-overhead lines, however, the mentioned, complex lines go beyond the scope of the study.

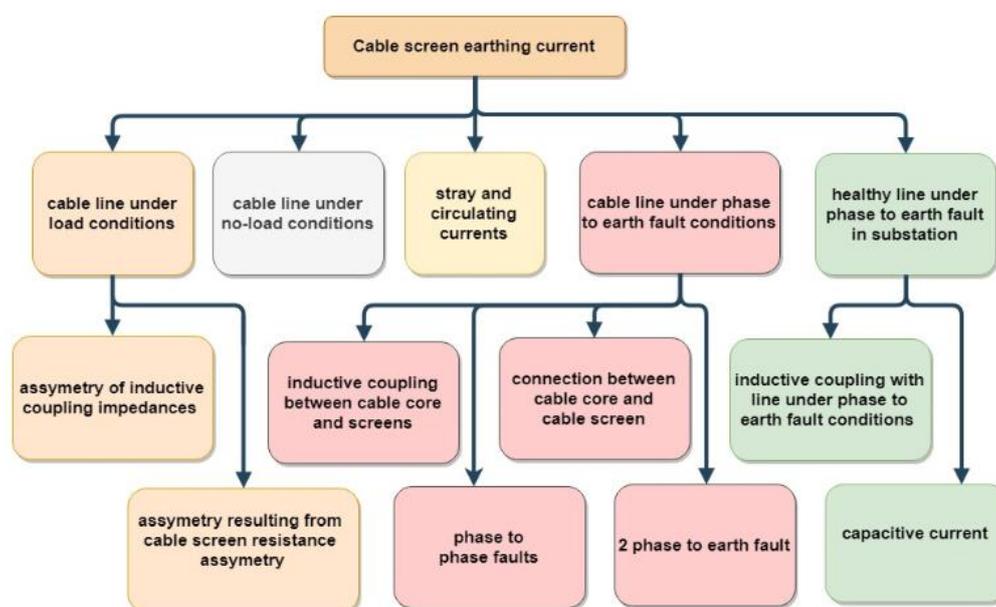


Figure 2. Current sources in two-point bonded cable lines (one section).

Earthing current flow under load conditions is a result of coupling impedance asymmetry or asymmetry of cable screen resistance, i.e., due to erroneous cable screen connection. Earthing current under no-load conditions is a result of cable screen resistance asymmetry [25].

Besides load and no-load earthing current one can observe circulating current, which is a result of the voltage difference between two earthing systems at both cable ends. It is, however, noted that the earthing system voltage changes drastically under earth fault conditions and in such case, the circulating current can be neglected.

The earthing current can be a result of stray currents. Stray currents can have high amplitudes if the cable is laid in the vicinity of traction loads. In order to reduce stray current flow, some cables are reconfigured and single point bonding is used. Cable screen voltage limiters are installed at the unearthed side of the cable in order to reduce expected contact voltage to safe values required by norms and to protect the cable sheath from overvoltages [42].

Earthing current can also be a result of inductive coupling between another power line or conductive, metallic installation, through which flows zero sequence current [43]. If zero sequence current flows through the line, which is connected to different substation or section and is coupled with the analyzed line, then the cable screen earthing current would have higher amplitude than zero sequence current measured in cable cores. If zero sequence current flows through the line, which is supplied from the same substation, one can observe phase shift between zero sequence current in cable screens and cable cores because the capacitive current in cable screens is affected by induced current. An analogical phenomenon can be observed in high voltage (HV) and extra-high voltage (EHV) overhead lines, where counterpoise conductor is used to minimize the amplitude of the current flowing through the earthing system of substation [44].

Another reason for earthing current flow are two or three phase to phase faults in the protected line or open phase conditions (single phasing) of the supplied transformer [45]. The amplitude of the earthing current during the disturbances strongly depends on cable line parameters, mainly on cable formation and on phases involved in short circuit. The earthing current under phase to phase fault is high in the case of cable line phase circuits laid in the flat formation and is very low in the case of cables laid in trefoil configuration. It is, however, noted that under phase to phase fault zero sequence voltage does not increase. Zero sequence voltage is present under two phase to earth fault conditions, however, the ratio of zero sequence current and zero sequence voltage is significantly higher than under phase to earth fault conditions. Presented relations allows for distinguishing different types of faults in cable line.

The earthing screen current is also a result of earth fault in other lines supplied from the same substation. In that case, earth current is a capacitive current, so zero sequence current leads the zero sequence voltage. Capacitive current flow both in cable cores and cables screens because of capacitances between cable core and screen as well as cable screen and earth.

Finally, the current in cable screens can be a result of the connection between cable screen and cable core. Earth fault can be easily distinguished from other disturbances because of zero sequence voltage or neutral point current, which increase at the moment of an earth fault. Earth fault in cable line can be categorized as earth faults in cable line itself, in cable joints or in cable terminations. In some cases, it is possible to distinguish the faulted element, which could reduce downtime significantly [46]. In order to detect intermittent earth faults, waveform analysis tools are used, i.e., CNN convolutional neural network [47]. An alternative for the detection of damages in cables is the utilization of partial discharge sensors. In the case of medium voltage (MV) cables with cross-linked polyethylene (XLPE) insulation, the time between detection of first partial discharge (PD) to permanent failure with 50% confidence level is approximately 12 days [48].

Earth faults inside a substation can be treated as earth faults in cable lines because all metallic constructions are connected to the same earthing system as cable screens in order to avoid voltage difference between different elements [49]. Probability of earth faults inside a substation is typically low, however, the probability can increase due to dirt and moisture [50].

The presented cable screens current sources have a different impact on the earthing current flow, depending on cable parameters, cable formation, and bonding method [51]. Table 1 presents an overall assessment of the cable screen bonding method on cable screen earthing current.

Table 1. Impact of cable formation and bonding on the screen earthing current.

	2 Points Bonded Laid in Flat Formation	2 Points Bonded Laid in Trefoil Formation	Single Point Bonded	2 out of 3 Phases Unearthed
Load current dependency	Average	No	No	Average
Dependency on erroneous connection	High	High	No	Present
Reduction factor of 110/15 station	High	High	High	Reduced
Vulnerability on stray current flow	High	High	No	Reduced
Inductive coupling with other lines	Possible	Possible	No	Reduced
Vulnerability on circulating current flow	High	High	No	Reduced

Reduction factor describes a ratio of current value flowing through the earthing system and the total value of earth fault current. In the paper, attention is paid to the earthing system of 110/15 substation and reduction factor of 110/15 substation is given by Formula (1)

$$RF_{110/15} = \frac{3I_{0cs}}{3I_{0cc}} \quad (1)$$

where $3I_{0cs}$ —part of earth fault current, which return through cable screens to 110/15 substation, $3I_{0cc}$ —earth fault current flowing through cable core (total earth fault current).

The screen earthing current is a result of inductive coupling and conductive connection of cable screen and core [52]. Bibliography often presents a reduction factor in the context of high voltage and extra high voltage lines, where earthing resistance is negligible. In the case of MV lines, however, the impact of earthing resistance on reduction factor is strong and cannot be neglected. This paper presents research results, which present a strong impact of earthing resistance on the cable screens current flow.

4. Cable Screen Earthing Current Analysis

4.1. Simulation

In order to analyze the earthing screen current under earth fault conditions, a model of the network and cable line was developed in PowerFactory software. Attention was paid to steady-state analysis. In order to analyze transient phenomena, one should use advanced cable line model, with cable line represented by distributed parameters [53]. The developed model is presented in Figure 3 and consist of ZNyn11 earthing transformer, power transformer, neutral point impedance, cable lines with total earth fault current equals 100 A and loads [54].

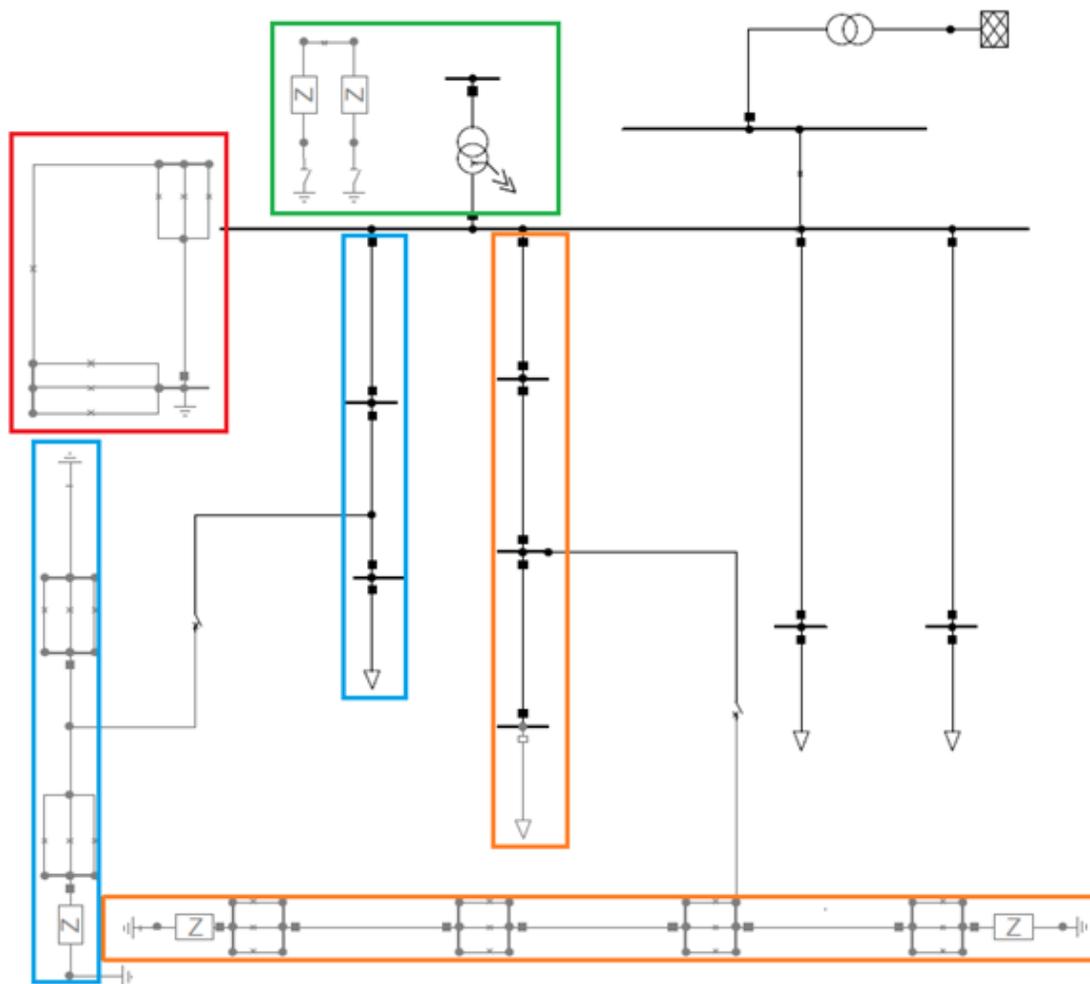


Figure 3. Model of analyzed distribution network.

All cable screens at the supply side are bonded and connected with the earthing system of 110/15 substation. Because the earth fault current flows through a metallic connection of neutral point impedance to the earthing installation, to which cable screens are bonded, the resistance of this connection is negligible. It is, however, worth noting that erroneous connection or aging of connection can result in a significant rise of connection resistance. In the case of another cable screen current sources, the current is flowing through an earthing system of the substation, which in Poland is typically in the range of $0,1 \Omega$ due to extensive lattice earthing electrodes. All results presented in the paragraph are based on following assumptions: Resulting earthing resistance of MV station is 4Ω , cable type is 3x YHAKXS 150/25 laid in trefoil configuration and the soil resistivity is $200 \Omega\cdot\text{m}$.

Figure 4 presents a current flow forced by different current sources. The decision about earthing of 110/15 YNd11 transformer is based on earth fault factor defined in IEC 604-03-06, however, one has to underline that regardless of earthing of Y winding, zero sequence current does not flow through Yd transformer. Different sources are marked with colors as in Figure 2: Orange—load conditions, gray—no-load conditions, yellow—stray and circulating currents, green—capacitive current and —part of zero sequence earth fault current. Attention is paid to the earth fault current.

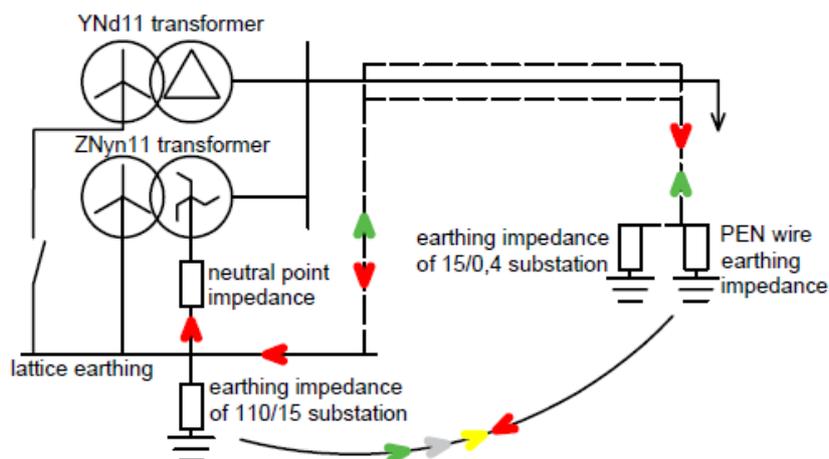


Figure 4. Cable screen currents flow.

As can be observed in Figure 5, in the case of single point bonding, a reduction factor of 110/15 ($RF_{110/15}$) station equals one since all currents flow in one direction and is practically independent of cable line parameters. $RF_{110/15}$ also equals one in the case of bonding type two out of three, however, only when earth fault occurs in phases with unearthed screens. When earth fault occurs in the phase with the earthed screen, $RF_{110/15}$ is lower than in the case of two-point bonding. Decrease of $RF_{110/15}$ is the bigger, the bigger cable length is. Simulation results indicate that $RF_{110/15}$ in cross bonded lines is similar to two-point bonded cable lines.

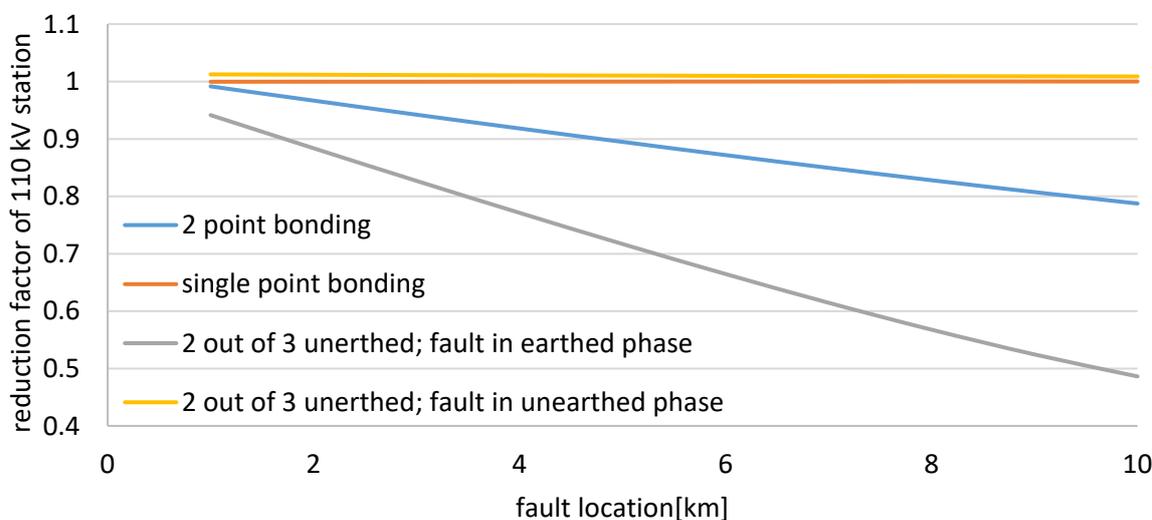


Figure 5. Impact of cable screen bonding method on $RF_{110/15}$.

As is presented in Figures 6 and 7, $RF_{110/15}$ clearly changes with the location of the fault along the cable line and the longer the cable line is, the bigger is the change of $RF_{110/15}$. Lower values of $RF_{110/15}$ can be observed for two out of three bondings, whereas higher values for conventional two-point bonding. The relationship can be used to pre-locate the fault along the cable line. In case of earth fault inside substation at the receiving end of the cable, the $RF_{110/15}$ will be the smallest.

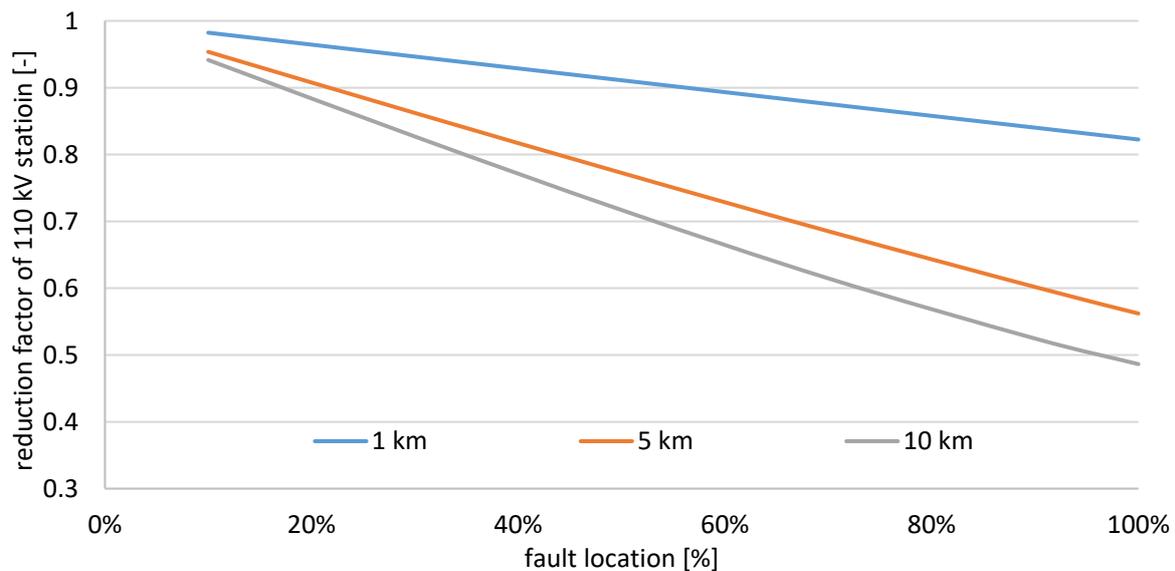


Figure 6. Impact of fault location on $RF_{110/15}$ in two out of three bonding configurations.

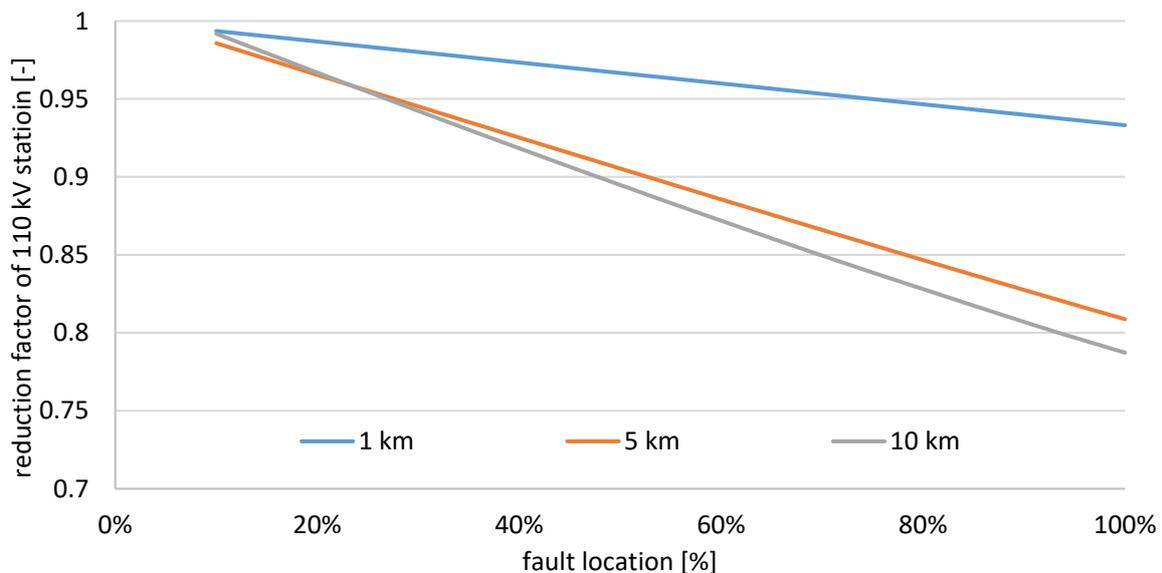


Figure 7. Impact of fault location on $RF_{110/15}$ in two-point bonded cable line.

In old type XLPE cables in Poland 50 mm^2 cross-section cable screens were used. Nowadays, cables are optimized in order to reduce losses and investment cost. Cross-section of the cable screen is selected based on short circuit power [55]. The smallest cross-section is 16 mm^2 when short circuit power is below 70 MVA, 25 mm^2 when short-circuit power is below 110 MVA, 35 mm^2 when short-circuit power is below 150 MVA and 50 mm^2 when short circuit power is below 220 MVA. Cross-sections were calculated based on the assumption that two phase short circuit is switched off during 1,5 s. Cable screen resistance has a big impact on $RF_{110/15}$, which is presented in Figure 8. The higher the resistance of the cable screen is, the lower the $RF_{110/15}$ is.

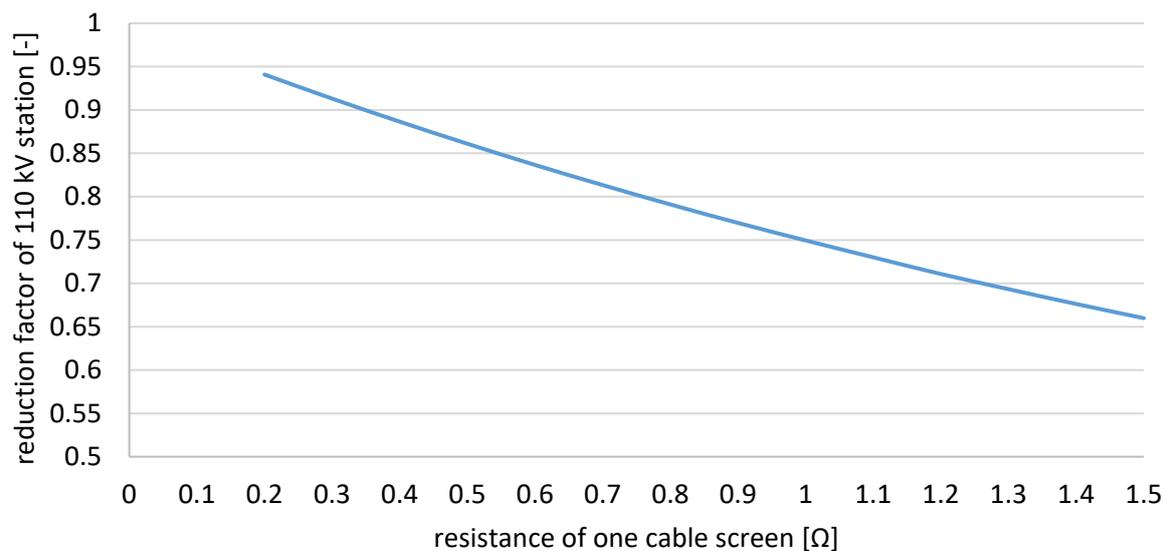


Figure 8. Impact of cable screen resistance on $RF_{110/15}$ in two-point bonded cable line.

According to simulation results, soil resistivity has a negligible impact on $RF_{110/15}$, at the same time, however, soil resistivity has a big impact on earthing resistance, which in turn has a big impact on cable screen current flow. Seasonal variation of earthing system resistance has to be analyzed in order to select proper settings of the proposed protection relay, particularly in the case of long cable lines. As is presented in Figure 9 $RF_{110/15}$ for 10 km 150/25 line can be changed in wideband: 0,38 up to 0,88.

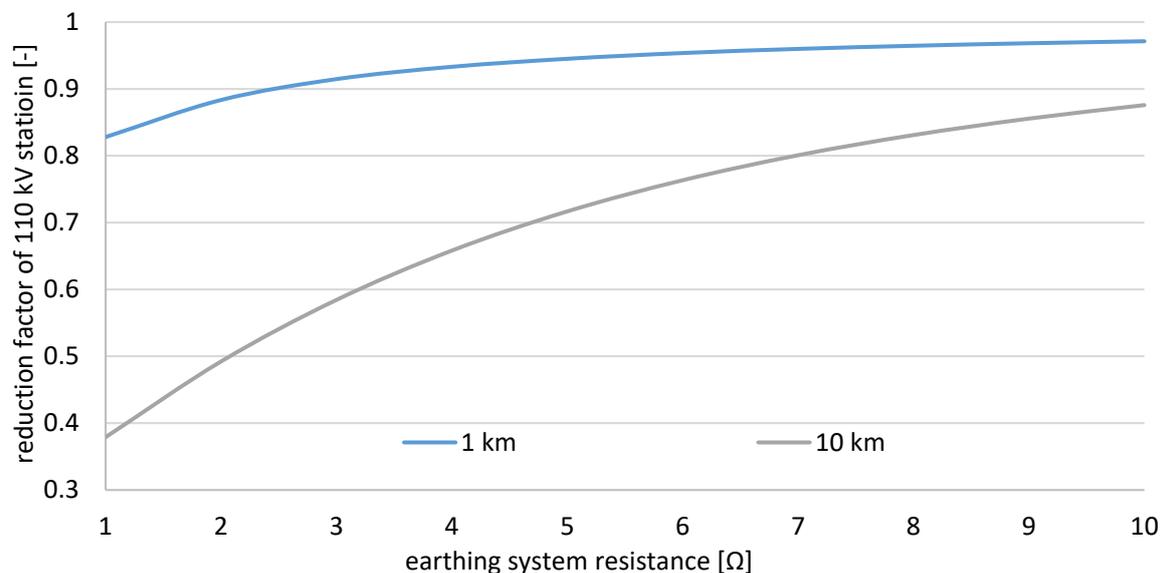


Figure 9. Impact of earthing resistance at load side (medium voltage (MV) station) on $RF_{110/15}$ in two-point bonded cable line.

4.2. Network Experiment

In order to validate the simulation results, an experiment in a power system network was performed. The experiment was performed on NA2XS(F)2Y 150/25 12/20 kV cable line (1,5 km) supplied with low voltage winding of the earthing transformer. Currents in cable cores and screens were measured via A class waveform recorders and $RF_{110/15}$ was calculated [56,57]. The same cable line was modeled in PowerFactory software and comparison of simulation $RF_{110/15}$ factor with the measured $RF_{110/15}$ was made.

As can be seen in Table 2, simulation error is satisfying, below 10%, which confirms relations presented in the chapter above. Measured $RF_{110/15}$ is always higher than simulated $RF_{110/15}$. Results are repeatable and independent from the unearthed phase. The difference is a result of simulation simplification of the model and lack of precise information about some parameters of cable. i.e., earth resistivity.

Table 2. Comparison of measurement and simulation results.

Number of Earthed Cable Screens	Zero Sequence Core Current ($I_{0_{cc}}$)	Zero Sequence Screen Current ($I_{0_{cs}}$)		$RF_{110/15}$	
	Measured	Measured	Simulated	Measured	Simulated
3	9,1	8,7	7,7	0,96	0,85
1	8,8	6,6	6,1	0,75	0,69
2	8,9	7,9	7,1	0,88	0,80

Accuracy of measuring equipment [14].

During the test, cable was under no-load conditions. It is, however, observed that due to stray currents and voltage difference, earthing current was constantly flowing through the analyzed cable. It is, however, noted that under fault conditions the circulating and stray currents are practically invisible, which is a result of rapid change of earthing system voltages under phase to earth fault conditions.

When the screens of cable line are single-point bonded, the measured earthing current is only the earth fault current. Earthing current resulting from load conditions is practically eliminated in two-point bonded cable lines laid in trefoil configuration. Unfortunately, in the case of other bonding methods, the earthing current measured under fault conditions could be affected by other current sources. To avoid erroneous measurement filtering method was developed. The filtering is particularly important in networks with a neutral point connected to the ground through Petersen coil because of the low amplitude of the earthing current. On the other hand, filtering is theoretically not necessary in case of low impedance earthing.

In this study attention is focused on cable lines, one can, however, imagine that line is extended with an overhead section at the end of the cable line. Measurements of zero sequence cable core and cable screen currents allow for the identification of line type affected by phase to earth fault. This statement is valid only for the cable overhead line. In the case of complex lines, i.e., cable 1, overhead and cable 2 one can only conclude if a fault occurred in cable 1 or in the remaining part composed of overhead line and cable 2. Detection of line type affected by phase to earth fault is based on the relation of $I_{0_{cs}}$ and $I_{0_{cc}}$ as well as on phase shift between $I_{0_{cs}}$ and $I_{0_{cc}}$. According to laboratory experiments on the MV network model, experiment on MV cable supplied with low voltage (LV)—230/400 V one can observe the following relations. In case of phase to earth faults in cable line, the phase shift between $I_{0_{cs}}$ and $I_{0_{cc}}$ in ideal conditions is 180° assuming polarization presented in Figure 11 and negligible impact of induced current. In case of phase to earth fault in overhead line phase shift between $I_{0_{cs}}$ and $I_{0_{cc}}$ is 90° . 180° phase shift is a result of galvanic connection and the opposite direction of current flow through current sensors. 90° phase shift is a result of inductive coupling between cable core and screens. Majority of earth fault current returns through earth since the earthing resistance of cable termination is in the range of ohms, in PL approximately 10Ω [58], whereas the resistance of earth is negligible [59]. Presented relations are also confirmed by MV recording taken by authors presented in Figure 10. Figure 10 presents raw waveform of $3I_{0_{cc}}$ and I_{cs} (earthing screen current) recorded under phase to ground fault in one of the Polish distribution networks in cable overhead lines. Cable length is a few hundred meters and cable type is YHAKXS 3x120/50. As can be seen, in case of earth fault outside of the cable line one can observe the phase shift between measured currents. After digital filtering of waveforms and obtaining fundamental components (50 Hz) of currents, the 45° phase shift between the currents is measured. It is, however, noted that accurate measurement of phase shift in real networks is difficult since high angle errors can occur if conventional zero sequence filter is used. It is believed that because of conventional current transformers the angle

error is so big. RMS currents are: $I_{cs} = 1,7$ A and $3I_{0cc} = 24$ A, therefore, $RF_{110/15}$ is 0,07. Similar $RF_{110/15} = 0,07$ was measured during the experiment in Austria [60]. The results are clearly out of scope presented in Section 4.1 and, therefore, one can conclude that earth fault occurred outside of the cable line and, therefore, the concept is proved. Despite the problems authors believe that detection of line type affected by fault is possible and is very interesting and further research activities are planned. Identification of line affected by fault allows to shorten repair time of affected line and allows to restore power to consumers not affected by fault as fast as possible.

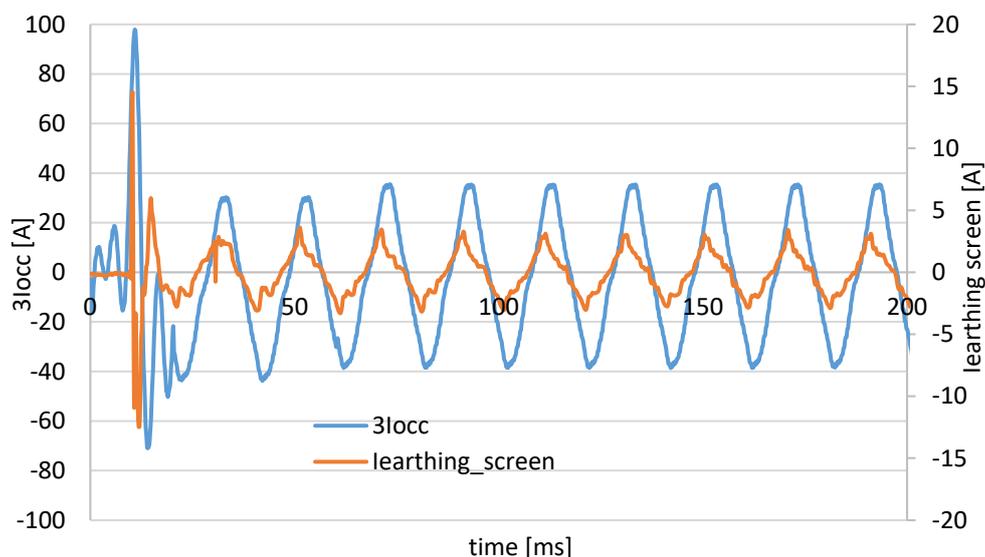


Figure 10. Waveforms recorded under phase to earth fault conditions in overhead section of cable overhead line.

5. Results

5.1. Filtering Method

There are two possibilities of measurement of the earthing screen current. It is possible to install a current sensor in place A and B presented in Figure 11. The recommended solution is place B since errors resulting from the incorrect position of cables screens in the measuring window are practically eliminated. All earth current sources can force the flow of fundamental component—50 Hz of current, which is the same as the frequency of earth fault current. It is, therefore, difficult to filter earth fault current using conventional band-pass filters. To avoid the impact of earth current resulting from load conditions it is possible to subtract earthing current before earth fault occurs from earthing current after the occurrence of the fault. In order to detect an earth fault, the increase of zero-sequence voltage is used. Zero sequence voltage is also used to calculate phase shifts of earthing current before and after the fault. In order to calculate the phase shift between U_0 and the earthing current before the fault, the zero-sequence voltage is artificially extended before fault occurrence. In order to properly calculate earth fault current, fixed (steady-state) earth fault current has to be utilized. Experiments performed in PF software indicate that the presented method can fully eliminate the impact of load conditions.

Subtraction of current before and after the fault occurrence is justified because the dynamics of load variation is a few orders of magnitude lower than earth current. It is also true in the case of power cable deriving power from renewable energy sources—high variable photovoltaic (PV) panels change power in the range of 0,6 pu/min [61].

An alternative way of removing the impact of other current sources is the utilization of the analogous zero-sequence screen current filter. The filter is built via bonding cable screens at both ends. In order to build the filter, cable sheath has to be notched at a short distance and then cable screens at both ends are bonded. In order to ensure safety of personnel, the filter is single point bonded. The filter

is presented in Figure 3 and marked with red color. Stray and circulating currents cannot flow in the filter, whereas zero-sequence current resulting from load dependencies can be removed. Alternatively, the filter can be laid in trefoil configuration, which naturally eliminates load dependencies. It has to be underlined that load asymmetry does not affect the filter. On the other hand, flat configuration offers additional benefits like detection of single-phasing and phase to phase fault. If filter consists of two transposed cable sections, it is believed that it is possible to detect phase to phase fault and single phasing independently of affected phases. Created zero-sequence current filter ensures even more effective fault detection than state of the art solutions, however, have limited auxiliary capabilities—it is not able to detect erroneous connection in cable screen or indicate fault location. Another problem with the proposed zero-sequence filter is the difficulty of creation since in case of existing cable lines the filter would have to be manufactured and calibrated locally. Moreover, the filter could be susceptible to electromagnetic fields inside of substation and appropriate screening would have to be developed. Despite difficulties, it is believed that concept is interesting and further research activities are planned. It is planned to connect the filter to the physical MV network model in order to further investigate the presented concept. Zero sequence current in the filter depends mostly on cable screen cross-section.

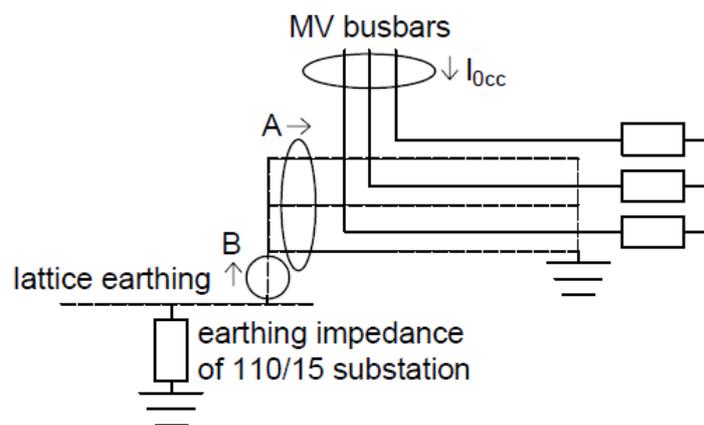


Figure 11. Installation of the current sensor on a cable screen earthing system.

5.2. Protection Algorithm

The developed I_{0cs}/I_{0cc} criterion is valid for MV networks with single-point grounded neutral point and isolated network. Among neutral grounding (neutral point treatment methods) one can mention resistor, coil, a coil with an active current forcing resistor, parallel connection of coil and resistor or isolated neutral point [31]. I_{0cs}/I_{0cc} criterion utilizes measurement of cable screen current, therefore, is valid for cables equipped with cable screen, which is required for any cables developed for a grid above 1 kV [62]. Attention is focused on single-core cables, however, the criterion can be adopted to different cable types, i.e., three-phase cable or cables equipped with additional armor [63].

Neutral point of LV networks is typically directly grounded through the local earthing system, however, LV cables are not equipped with cable screens, therefore, I_{0cs}/I_{0cc} criterion cannot be used. An exception is LV cable line equipped with cable armor, which main task is to ensure high mechanical strength [64]. It is, however, noted that current flow is observed in the armor and that current sources are the same as in cable screens.

Neutral point impedance is commonly used in distribution system networks, industrial networks and in microgrids [65]. The criterion is valid in conventional radial networks as well as new active networks, which consist of renewable energy sources, energy storage or energy hub and, therefore, the potential range of application is wide [66,67]. The developed filter, which ensures high measuring accuracy, can be applied in any power network. It is believed that the proposed filter could be manufactured as short cable lines with short-circuited cable screens and that the filter could be connected to any power line, i.e., overhead or LV cables without cable screens.

Earthing current can be used as independent earth fault protection of cable lines, however, can also be used in cooperation with conventional earth fault relays and it is recommended solution since the utilization of zero sequence current measured in cable cores I_{0cc} and screens I_{0cs} will allow for the reduction of a number of unwanted trips and higher sensitivity. In order to reduce the risk of erroneous trips, the consideration of $RF_{110/15}$ values should be added to conventional relays algorithm. Earth fault is detected only when $RF_{110/15}$ is in the appropriate range, which mostly depends on cable length, cable screen resistance, and bonding method. The value of $RF_{110/15}$ alone is, however, not sufficient because similar $RF_{110/15}$ values could be observed in the cable if earth fault occurs in other lines in the substation. In order to distinguish such fault types, it is possible to measure the direction of earth fault current. An alternative way is to compare measured I_0 and U_0 with $I_0 = f(U_0)$ characteristic. If the measured point is out of the band of the capacitive current, earth fault is detected in the protected line.

The values of $RF_{110/15}$ can, however, give erroneous results when loading of the line is below minimum, i.e., 4 A [68]. Protection relay should recognize that zero sequence current is measured with big error and block operation of conventional zero-sequence current algorithms when loading of zero sequences current sensor is below the minimum. In this case, the zero-sequence currents measured in cable screens should be used to detect earth faults.

It is believed that presented algorithms could be applied in lines, which are often operated under no-load conditions and capacitive current of the line is below the minimum current range of the current sensor. As a result, high measuring accuracy would be ensured. An example could be a power line, which derives the power from renewable energy sources.

Protection algorithm is presented in Figure 12. The earthing screen current, zero sequence current measured in cable core I_{0cc} , zero-sequence voltage U_0 and loading of current sensor— I_{load} are input quantities measured in a substation where protected cable line is installed. The earthing screen current is filtered in order to get zero-sequence current measured in cable screen I_{0cs} . Admittances Y_{0cc} (I_{0cc}/U_0) and Y_{0cs} (I_{0cs}/U_0) are calculated based on the measured values. Y_{0cc} is calculated and analyzed in conventional admittance earth fault protection relay. Y_{0cs} and Y_{0cc} are used to calculate the ratio of Y_{0cs} and Y_{0cc} ($RF_{110/15}$), which is further compared with the setting value. If measured $RF_{110/15}$ is within setting range, conventional admittance earth fault algorithm detects an earth fault and loading of the current sensor is above minimum high signal is sent to gate OR. The logical gate OR can be also stimulated by Y_{0cs} within a defined range and under low loading of the current sensor in cable core. Further verification of cable screen earthing current is made. If the earthing screen current is not within a band of the capacitive current measured in cable screens an earth fault is detected and the timer is started. In order to avoid unnecessary complexity of the algorithm, the description of the timer is not included in the paper. Comparison of different timers may be found in [69]. Earth fault protection algorithm should be blocked when post-earth fault oscillation is detected [70].

Developed protection algorithm is compared with other earth fault algorithms in Table 3. Comparison is based on the methodology presented in [71]. Developed solutions are compared with conventional earth fault protection methods—residual voltage and ground fault directional current. All presented algorithms can be operated online, however, it is also possible to use offline analysis in order to detect the erroneous connection of cable screens or indicate line affected by the fault.

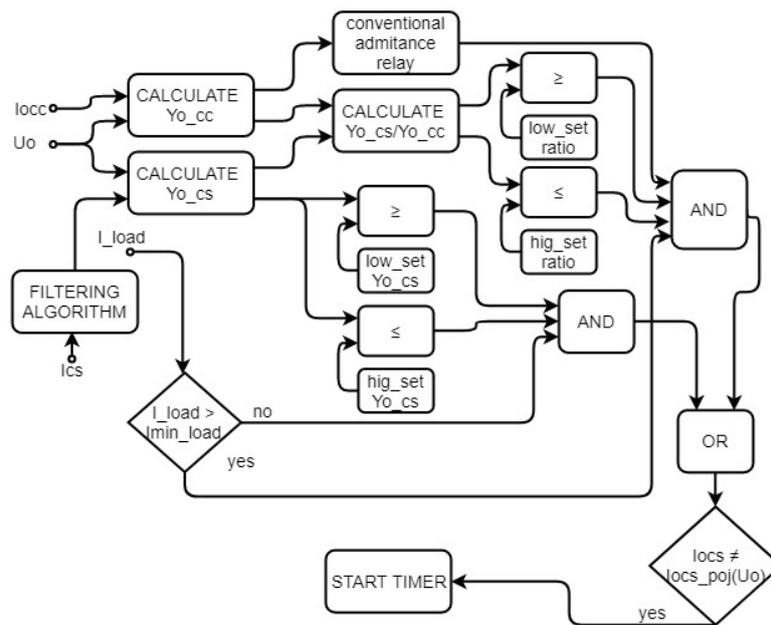


Figure 12. Developed protection algorithm.

Table 3. Table 3. Comparison of protection algorithms.

Criterion	Protection Algorithm				
	ANSI 59N ¹⁾	ANSI 67N ²⁾	I_{0cs}/I_{0cc} Criterion	I_{0cs}	I_{0cs} Filter
Check wiring polarity of voltage transformer (VT) to protection system	no	yes	yes	yes	yes
check wiring polarity of CT's to protection system	no	yes	yes	yes	yes
check tripping angle between I_0 and U_0	no	yes	no	yes	yes
Selective tripping	no	yes	yes	yes	yes
Easy to set in operation	yes	no	yes ³⁾	yes ³⁾	yes ³⁾
Cost of the protection system	low	high	high	low	low ⁴⁾
Time to put the protection system into operation	short	long	long	long	long
Primary injection needed to test its functionality	no	yes	yes	yes	yes
Detection of erroneous connection of cable screen	no	no	yes	yes	no
Sensitive for reconfiguration of network	no	yes	no	yes	yes
Impact of neutral point treatment	high	high	reduced	reduced	reduced
impact of line loading on accuracy	high	high	reduced	reduced	reduced
operation in case of CT failure	CT not required	no	Reduced performance	no	no
Identification of line affected by fault	no	no	yes	no	no
Risk of erroneous tripping	yes	yes	reduced	reduced	reduced

¹⁾ Residual voltage, ²⁾ ground fault directional overcurrent, ³⁾ on energized cable if safety rules are followed, ⁴⁾ potential for optimization and further cost reduction.

Erroneous connections are monitored via comparing measured values with a defined characteristic. Measured earthing current and positive sequence load current is saved as x and y coordinates and compared with load defined load characteristic. If the threshold is exceeded an alarm is activated.

Conventional earth fault protection relays are set based on the capacitive current of power lines. The capacitive current can change when feeder or part of the feeder is reconfigured and, therefore, the sensitivity of the relays is affected.

Developed I_{0cs}/I_{0cc} criterion remains operational, after the failure of neutral point impedance since the relation I_{0cs}/I_{0cc} remain the same, whereas conventional protection algorithm is not able to detect faults in case of neutral impedance failure. In order to mitigate risks, new grounding impedances are monitored, and failure can be recognized quickly, which significantly reduces the risk of erroneous operation of earth fault protection relays. It has to be, however, noted that earth fault could occur before the neutral impedance is repaired, which could lead to erroneous operation and dangerous situations.

The I_{0cs}/I_{0cc} criterion utilizes two zero-sequence current measurements, which is a potential problem since typical protective relays are equipped with four current inputs. However, one has to notice that some new generation protection relays are equipped with five current inputs [72]. The current generation of protection relays is able to obtain zero-sequence current in two ways—via measurement of I_0 or via digital summing of phase currents it is therefore possible to replace analog zero sequence current measurement with the digital summing and to measure I_{0cs} . Presented configuration allows for performing additional functions presented in Table 3. Moreover, protection relay remains operational after the failure of one current source— I_{0cs} or I_{0cc} filter and is able to fulfill the basic function – earth fault protection. Proposed solutions can be used to improve earth fault protection in the case of conventional zero-sequence current sensor failure or wrong sizing of CT since it is possible to install the filter on energized cables assuming that safety rules are fulfilled.

Occurrence of erroneous tripping is reduced thanks to additional criteria of distinguishing between line affected by the fault and healthy line. It is proposed to compare measured I_{0cc} current with fault characteristic $I_{0cc} = f(U_0)$.

Both proposed solutions – I_{0cs}/I_{0cc} criterion and novel zero-sequence current filter ensure higher sensitivity of earth fault detection, which in turn. reduces a risk that undetected earth fault will evolve into two phase to ground fault. Two phase to ground faults are dangerous because of high current amplitude which could damage components of the distribution system network and create an electrocution hazard. Another advantage of the proposed solution is the possibility of analyzing earthing current in the context of abnormal loading resulting from, i.e., abnormally high potential difference between substations. Finally, it is believed that settings of developed criteria would be much simpler since information about cable type and grounding is sufficient to predict the reduction factor.

Developed criteria are universal and can be used in all power networks, however, the biggest increase of effectiveness is observed in power lines operated under low load and no-load conditions. As an example, one can mention lines connected with renewable energy sources, i.e., photovoltaic power plants or industrial load operated only part of a day. I_{0cs}/I_{0cc} provide additional mechanisms against unwanted tripping, therefore, is particularly interesting for important loads, which require high reliability of supply. I_{0cs} criterion and I_{0cs} filter can be used as a replacement of conventional zero-sequence current sensors. It is believed that presented solutions could be used as stand-alone protection relay (1 current input for I_{0cs} criterion or I_{0cs} filter or two current inputs for I_{0cs}/I_{0cc} criterion), however, further research work is needed. Thanks to high accuracy in low loading conditions, proposed solutions could be also used in microgrids.

6. Conclusions

The presented analysis results show that utilization of cable screen earthing current is possible and allows for the improvement of the effectiveness of protection relay algorithms. Among the biggest advantages, one can mention higher sensitivity, independence of measuring error on line loading and reduced risk of unwanted tripping.

The cable screen earthing current can be utilized to detect different types of disturbances in power network, i.e., for detection of phase to phase fault or open phase conditions (single phasing). It has to be, however, underlined that detection of some disturbances is possible only for some cable

configuration and screen bonding types. The protection function can, therefore, be used as support to existing conventional protection algorithms. Measurement of the screens earthing current and calculation of $RF_{110/15}$ value allows for pre-localization of phase to earth fault, which, in consequence, allows to reduce the time of energy supply interruption.

This paper presents a new concept of zero sequence filter. The current filter is built via short-circuiting cable screens at both ends. In order to build the filter, cable sheath has to be notched, and then cable screens at both ends are bonded. Theoretically the filter could be produced as prefabricated element.

The presented criteria were developed for one section cable lines—with only two earthing systems at the beginning and the end of the cable line. Further work will be focused on the adaptation of criteria to complex distribution feeders, which consist of many cable and overhead segments.

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