# Utilization of Cable Screen Earthing Current for Detection and Location of Earth Faults in Medium Voltage Networks

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**Abstract**

The paper presents issues related with detection and location of earth faults in medium voltage (MV) networks. Attention is paid on cable and cable-overhead lines. The criterion value – cable screen earthing current is presented. Afterwards, the method of utilization of the cable screen earthing current for detection and location of earth faults is described. The next part of the paper presents the results of simulation research for different variants of earth faults in cable and cable-overhead lines. The presented relations are the basis of the developed algorithm of detection and localization of earth faults. The presented considerations were confirmed by an experiment performed in the MV network.

**Keywords:** earth faults; medium voltage network; protection relay; earth fault location; cable screen.

## 1. Introduction

Identification and localization of disturbances is the research topic since the very beginning of electrical power system development. Despite of the passage of many years, the effectiveness of the earth fault detection is limited – it is estimated that the effectiveness is in range of 90 – 95 %, what necessitates further research in the field of earth fault detection. Each earth fault creates a risk of electrocution and increases risk of insulation failure because of the voltage rise under phase to earth fault conditions. Because of that every earth fault has to be successfully detected. Limited effectiveness of the earth fault detection is a particularly serious problem because earth faults account for approximately 70-80% of disturbances in MV network e.g. 72% in Portugal [1]. One can expect a few earth faults in cable lines per 100 km of lines and approximately 20 earth faults in overhead lines per 100 km over year.

Location of earth fault is a more severe problem. Among many solutions presented in the literature [3]-[8] only earth fault current indicators and switches in depth of the network – reclosers have been installed in distribution system networks on a larger scale. Unfortunately, the installation of measuring equipment and remote switches is connected with high investment costs and operational problems e.g. difficult installation or technical constraints, connected with the operation of additional devices, and problems with coordination of protection relays.

The paper presents a concept of earth fault protection, which is based on the measurement of the cable screen earthing current. It is proposed to use the current measurement to detect and locate earth faults in MV networks.

## 2. Cable screen earthing current

Typically, cable lines consist of 3 single-core cables laid in trefoil or flat formation. Cable screens of the cables are short-circuited at both sides of the cable lines and connected with earthing system, which aims to limit

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overvoltages occurring in transient states and during normal operation to safe levels [9]. The scheme of earthing of the cable screen bonding is presented in Fig. 1
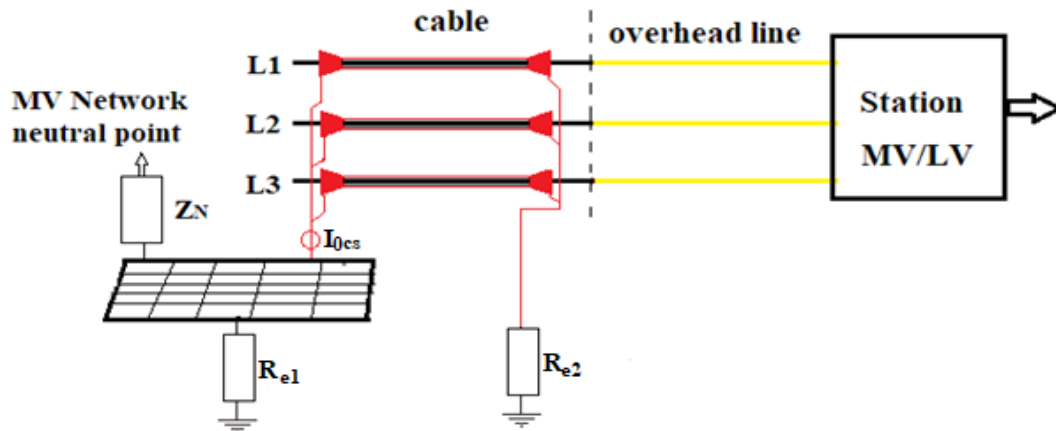


Fig. 1. Cable screen bonding ($I_{0cs}$ – cable screen earthing current; $R_{e1}$, $R_{e2}$ – earthing system resistance at both cable ends, ZN – impedance of the neutral point).

With some simplification, it can be assumed that in the event of an earth fault in the cable line, the cable screens and core are galvanically connected. Under these circumstances, the greater part of the current is flowing through the cable screens and returns to the neutral point of the earthing transformer. The smaller part of the current is flowing through earthing systems. The amount of current flowing through the earthing systems depend on earth system resistance, cable screen impedance and inductive coupling between cable screen and core.

In the case of earth fault in overhead section of the cable-overhead line, the great majority of earth fault current is flowing through earth, not the cable screen, because the earth resistance is about ~0.05 ohm/km, whereas the earthing system resistance is about a few ohms. Zero sequence current flowing through cable screens is the result of inductive coupling between cable core affected by earth fault, and cable screens.

Additionally, each earth fault, regardless of the place of its occurrence, causes the current flow in the cable core. The current flow is a result of the phase to earth capacitances. The capacitive current flows to the cable line from two sides, but due to the low resistance of the earth electrodes in the 110/15 substation in relation to the resistance of the earthing system at the load side, the big part of the capacitive cable screen current is flowing through earthing system at the side of 110/15 substation.

One has to however underline, that cable screen earthing current may be a result of different sources, which are not directly connected with phase to earth fault. As is presented in [11], one can eliminate or greatly reduced the impact of the different sources using appropriate methods of signal filtering.

The case of earth fault in cable line can be presented using the equivalent circuit diagram shown in Fig.2.
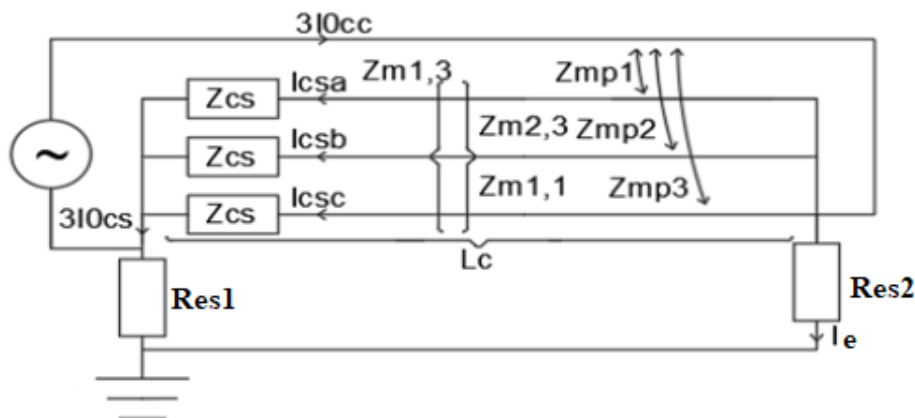


Fig. 2. Equivalent circuit of cable line under phase to earth fault conditions.

The relations presented in Fig. 2. allow for the formulation of a set of equations describing the earth fault current flow in the cable line.

$$a_{11}I_{csa} + a_{12}I_{csb} + a_{13}I_{csc} = b_1 I_{0cc}, \tag{1}$$

$$a_{22}I_{csb} + a_{21}I_{csa} + a_{23}I_{csc} = b_2 I_{0cc}, \tag{2}$$

$$a_{33}I_{csc} + a_{31}I_{csa} + a_{32}I_{csb} = b_3 I_{0cc}, \tag{3}$$

$$I_{gr} = 3I_{0cc} - (I_{csa} + I_{csb} + I_{csc}), \tag{4}$$

where

$$a_{ii} = (R_{es1} + L_c z_c + R_{es2}); \qquad i \in [1,3] \tag{5}$$

$$a_{ij} = (R_{es1} + L_c z_{mi,j} + R_{es2}); \qquad i \neq j \tag{6}$$

$$b_i = (R_{e1s} + L_c z_{mp,i} + R_{es2}); \qquad i \in [1,3] \tag{7}$$

After solving the system of equations using the substitution method, one obtains the formula describing the value of the cable screen earthing current on the 110/15 substation side.

$$3I_{0cs} = 3I_{0cc}\left(1 - \frac{3R_{es1} + L_c\left(z_{cs} - z_{mp,1}\right)}{L_c\left(z_{m1,2} + z_z\right) + 3R_{es1} + 3R_{es2}}\right). \tag{8}$$

Analysis of the formula allow us to conclude, that cable screen current is a part of the cable core zero-sequence current. The complex numbers in the formula show that there is a phase shift between the zero sequence components of the currents. The phase shift depends on the parameters of the cable line.

Based on the formula (8), two criterion quantities are proposed - the $RF_{110/15}$ coefficient describing the ratio of the zero-sequence current in cable screens and cable cores, and the angle α - describing the phase shift between the zero-sequence current in cable screens and cable cores.

## 3. Simulation results

### 3.1. General information

In order to investigate the possibilities of using the proposed values – $RF_{110/15}$ and the angle α for the detection and location of earth faults, simulation research in PSCAD software was performed. The model consists of cable lines modeled using the library Cable System. The cable line under analysis are: 120/25, 150/25, 150/50 cable lines laid in trefoil formation. Attention was paid on cable length and earthing system resistance because of performed sensitivity analysis, the parameters have the biggest impact on earth fault current flow.

### 3.2. Earth faults in cable line

Fig. 3. presents the changes in a value of $RF_{110/15}$ under phase to earth fault conditions along the cable line. Cable lines with a length of 1, 5 and 10 km were analyzed and the fault location was described as the relative length between the 110/15 substation and the fault location. The presented results allow to conclude that the values of $RF_{110/15}$ decrease with increasing distance of the fault location from the 110 / MV station, which can be used to initially determine the fault location in the cable line, and therefore shorten the repair time. In order to increase the accuracy of the fault location, it is advisable to use an additional value - angle α, which increases with the distance to the fault location – Fig. 4.
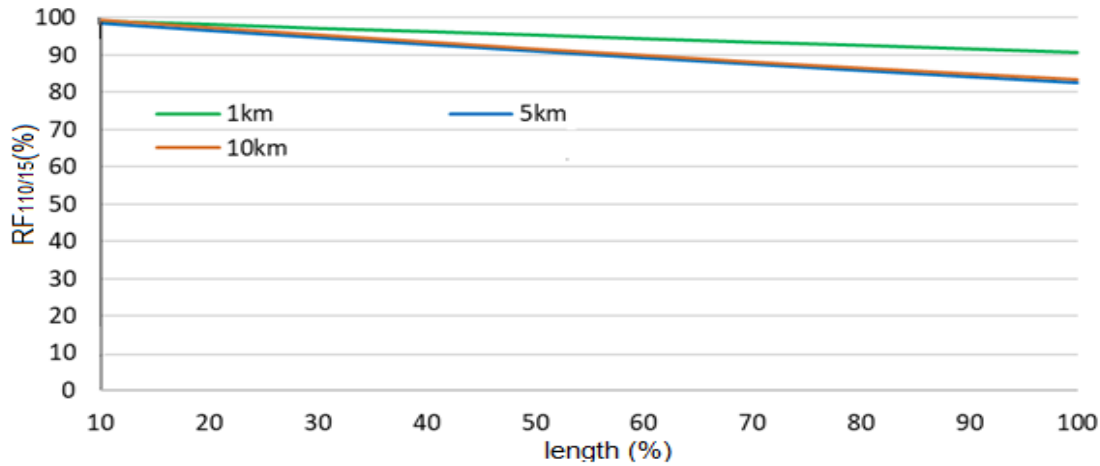
Fig. 3. $RF_{110/15}$ as a function of fault location in 120/25 cable line ($R_{es}$ = const = 2 Ω).



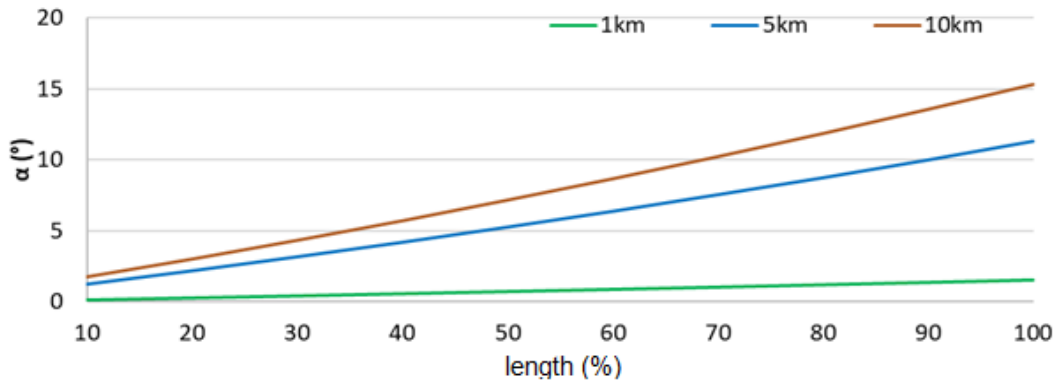Fig. 4. The angle α as a function of fault location in 120/25 cable line ($R_{es}$ = const = 2 Ω).

### 3.3. Earth faults in overhead section of cable-overhead line

In the next part of the research, waveforms of electrical quantities under earth fault conditions in cable line, which is a part of mixed - cable overhead line are analyzed. Attention is paid on $RF_{110/15}$ and angle α. In the next part of the research, waveforms of electrical quantities under earth fault conditions in cable line, which is a part of mixed - cable overhead line are analyzed. Attention is paid on $RF_{110/15}$ and angle α.

Based on the research result, presented in Fig. 5 and Fig. 6 one can simply conclude, that a value of $RF_{110/15}$ is rising with the rise of cable length, what is a result of inductive coupling between cable core, in which the earth fault current is flowing, and cable screens. The induced voltage depends on cable length whereas the current is limited by earthing system resistance, which is held constant during simulations. At the same time, the angle α decreases because the ratio of the amount of power dissipated on the earthing system resistance and the total source power increases with the rise of the length of the cable line. One can clearly state, that both $RF_{110/15}$ and the angle α strongly depend on the length of the cable line and the resistance of the earthing system resistance.
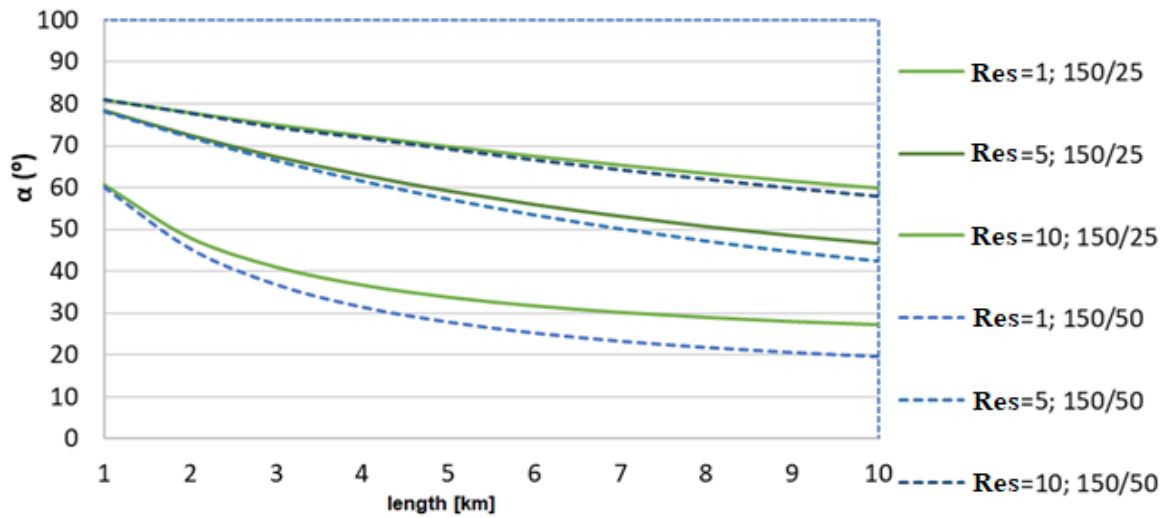
Fig. 5. The angle α as a function of cable length and earthing resistance under phase to earth fault conditions in the overhead section of the cable-overhead line.
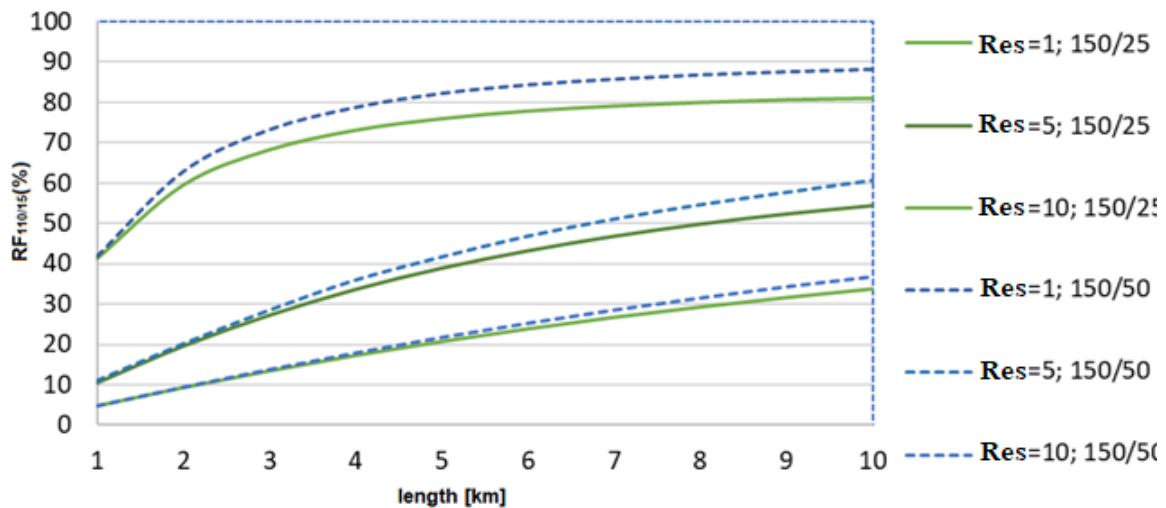


Fig. 6. $RF_{110/15}$ a function of cable length and earthing resistance under phase to earth fault conditions in the overhead section of the cable-overhead line.

Next figures – 7 and 8 presented a case of earth faults at the end of the cable line because, as is shown earlier (Fig. 3 and Fig. 4), earth faults at the end of the cable line are characterized by the smallest value of $RF_{110/15}$ and the biggest value of angle α. Therefore the faults at the end of the cable line have the greatest similarity to faults in the overhead section. As can be noticed in Fig. 7, the $RF_{110/15}$ for earth faults in cable line is in the range of 80-100%. The high value of $RF_{110/15}$ is a result of 2 sources of earthing current – galvanic connection and inductive coupling. The earthing current resulting from galvanic connection, measured at the side of 110/15 substation, decreases with the rise of cable length because a growing part of the current is returning to the substation neutral point through the earthing system at the load side. At the same time, when the current resulting from galvanic connection is decreasing, the current resulting from inductive coupling is rising.
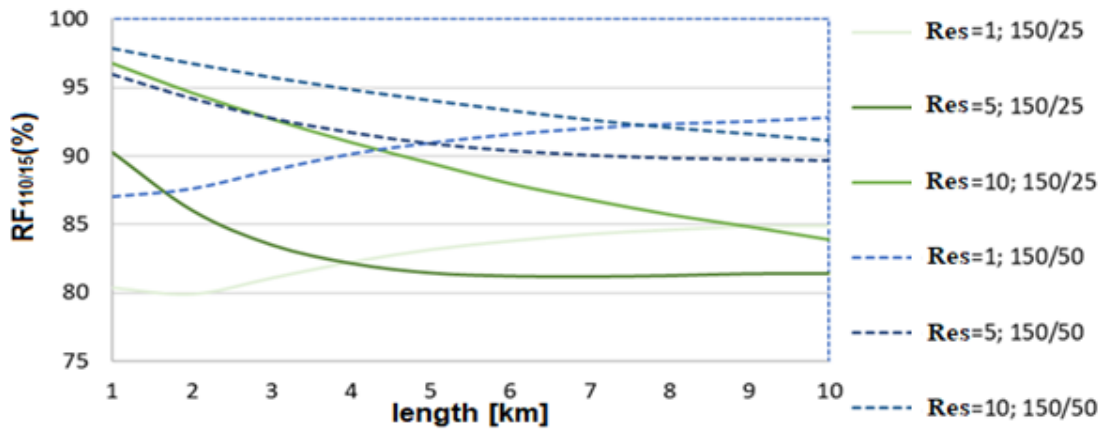
Fig. 7. $RF_{110/15}$ a function of cable length and earthing resistance under phase to earth fault conditions in the overhead section of the cable-overhead line.
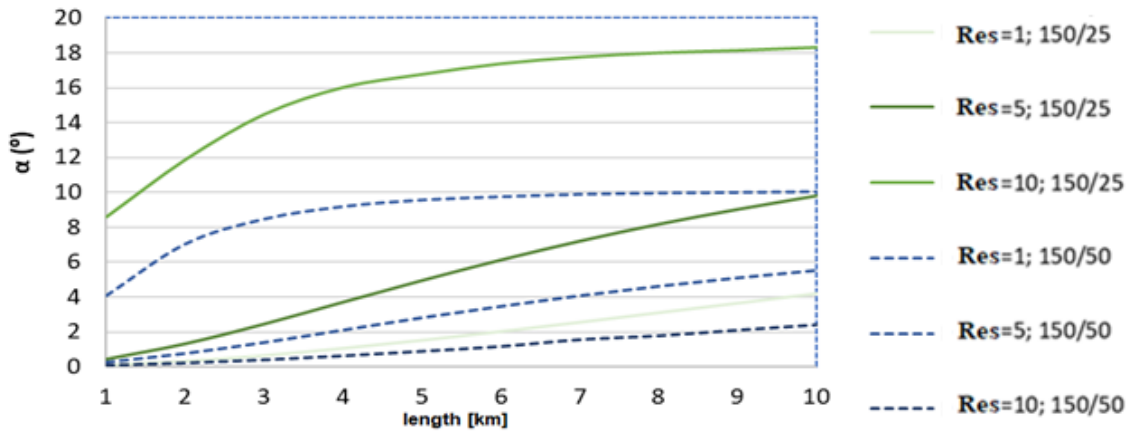


Fig.8. The angle $\alpha$ as a function of cable length and earthing resistance under phase to earth fault conditions in the overhead section of the cable-overhead line.

### 4. Earth fault protection algorithm

Simulation results presented above allow us to notice, that based on $RF_{110/15}$ and $\alpha$, it is possible to identify line type under phase to earth fault conditions. In order to improve the readability of results, the $RF_{110/15}$ is combined with angle $\alpha$, as a result, a function $RF_{110/15} = f(\alpha)$ is obtained – Fig. 9. As can be seen, comparators can be used to identify if earth fault parameters lay in the area of the cable or overhead earth faults.

In order to detect and identify line type under earth fault conditions, the protection algorithm was developed – Fig. 10. The algorithm starts with processing the input quantities – filtration of $I_{0cs}$ and $U_0$ (removing harmonics) and removing of the background. Background removal is based on the process of subtraction – the $I_{es}$ after identification of earth fault is subtracted from $I_e$ before the earth fault occurrence. The subtraction is made in relation to $U_0$, which is artificially extended to the moment before the earth fault. The angle $\alpha$ is obtained based on the measured currents $I_{0cs}$ and $I_{0cc}$, further, the $\alpha$ is compared with the set $\alpha$ (yellow block) in order to identify the line type affected with the earth fault. Then, in parallel, the admittance values are determined as ratio of the currents $I_{0cc}$ and $I_{0cs}$ and the voltage $U_0$ (green blocks in Fig. 10). The calculated values of $Y_{0cc}$ and $Y_{0cs}$ are compared with the corresponding settings (yellow blocks) in order to identify the line type affected with the earth fault. If an earth fault in a cable line is detected, the short time setting is used because the cable is permanently damaged, whereas in the case of earth faults in the overhead section one can use longer time settings because there is a relatively big probability that the reason of earth fault is temporary and the fault will disappear.
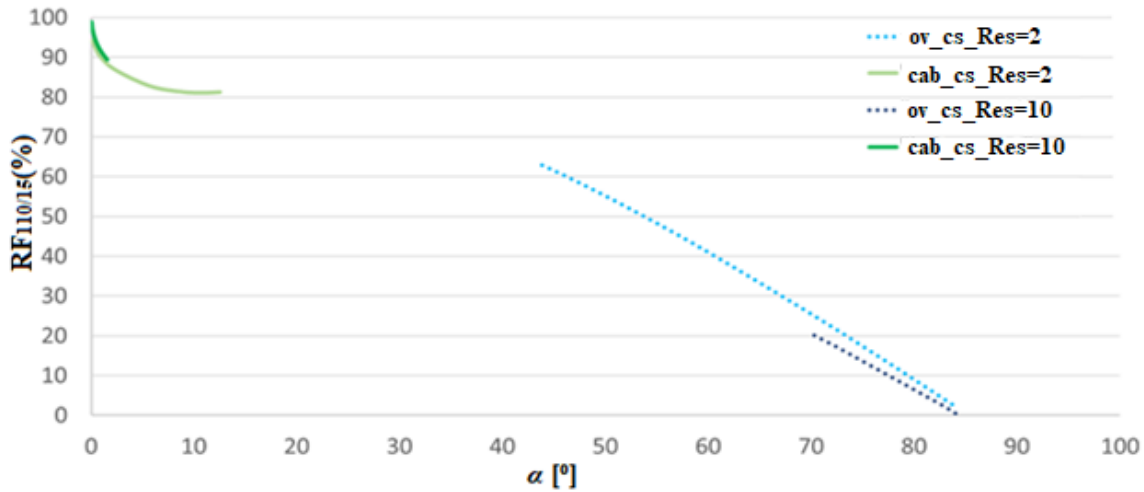
Fig.9. $RF_{110/15}$ as a function of angle $\alpha$.

Moreover, identification of line type allows blocking the auto-reclose relays in case of earth fault in cable line. The algorithm considers the measuring error of Ferranti transformers, which can be as high as 20% in unloaded lines, what practically eliminates the possibility of effective utilization of $I_{0cc}$ [12]. If unfavorable conditions for Ferranti filter are identified, the algorithm block utilization of $I_{0cs}$ and the earth fault is detected solely based on the modification of conventional admittance protection relay - $Y_{0cs}$, which is calculated as ($I_{0cs}/U_0$) [13]. If the earth fault persists for a set time, the circuit breaker is opened.



Fig.10. The developed protection algorithm.
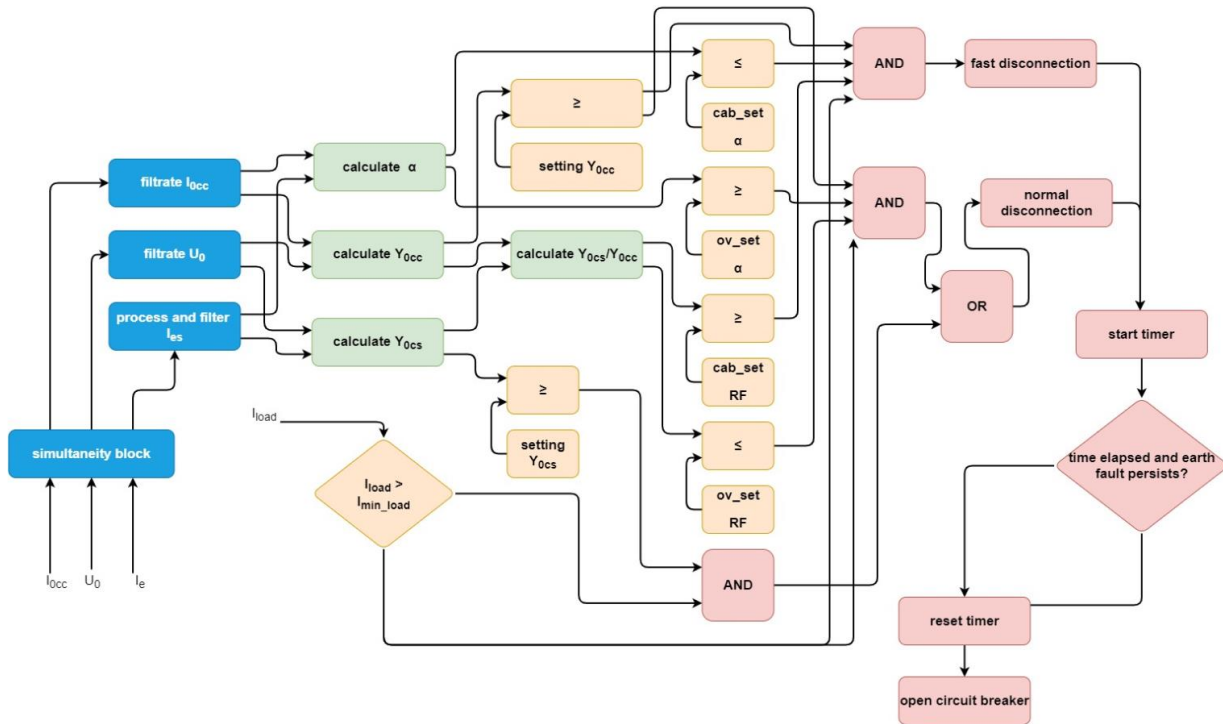
### 5. Network experiment

In order to verify the correctness of the simulation results, a network experiment is carried out in the actual MV distribution network with the neutral point earthed by the Petersen coil ($Z_N = j\omega L$) with a compensation degree in the range of 1.1 - 1.2. With the help of employees of the distribution system operator, a cable-overhead line, in which

earth faults were made, was selected. Currents flowing through cable cores and screens, as well as zero-sequence voltage that occurred during the experiment, were recorded. A simplified diagram of the test system is shown in Fig. 11, the tested cable line is marked in red and the overhead line is marked in yellow.
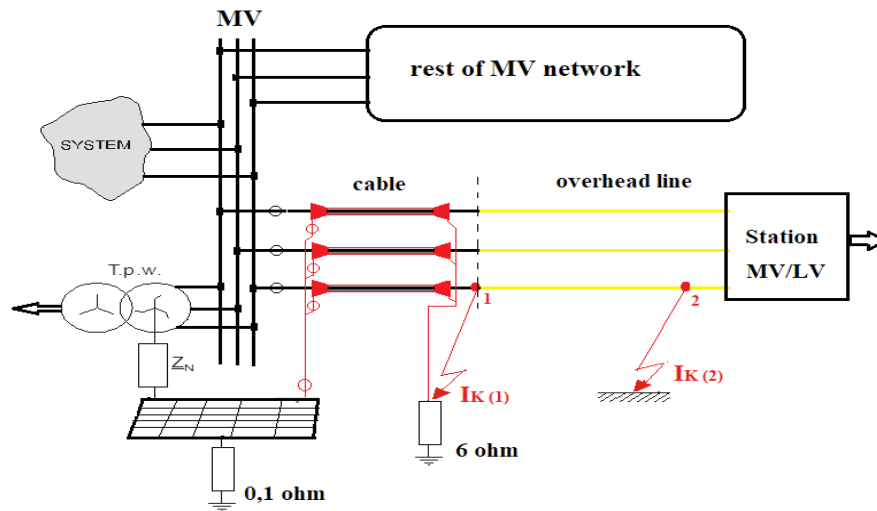


Fig.11. Scheme of the measurement system during network experiments T.p.w - auxiliary transformer (earthing), 1 - the earth faults in the cable line, 2 - the earth faults in overhead line, ⊖ - places of recorded currents in the cables core, ⊖ - places of recorded currents in the screen cables and in their earthing circuit.

Table 1 presents measurement and simulation results. Different cable screen bonding methods were analyzed and it was confirmed that simulation results are consistent with the measurement results. Moreover, simulation errors are small. Results presented in Table 1 confirm the possibility of using the developed algorithms in engineering practice.

Table 1. Characteristics of individual network experiments.

| No. | Measurements in the MV network | | | | Connection of cable screen to the ground* | | | Simulation research | | | Simulation errors | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $I_{0cc}$ | $I_{0cs}$ | $\alpha_m$ | $RF_{110/15\text{-}m}$ | A | B | C | $I_{0cs}$ | $\alpha_s$ | $RF_{110/15\text{-}s}$ | $\delta RF_{110/15}$ [%] | $\Delta RF_{110/15}$ [-] | $\delta\alpha$ [%] |
| 1 | 44.03 | 42.71 | 1.75 | 97 | 1 | 1 | 1 | 43.38 | 0.03 | 98.5 | 1.59 | -0.68 | -1.91 |
| 2a | 44.07 | 41.81 | 1.62 | 94.9 | 1 | 0 | 1 | 43.13 | 0.14 | 97.9 | 3.12 | -1.31 | -1.64 |
| 2b | 42.67 | 40.21 | 2.7 | 94.2 | 1 | 0 | 1 | 41.76 | 0.14 | 97.9 | 3.89 | -1.55 | -2.84 |
| 3a | 34.87 | 33.35 | 1.98 | 95.6 | 0 | 0 | 1 | 33.40 | 0.29 | 95.8 | 0.21 | -0.05 | -1.88 |
| 3b | 33.39 | 31.28 | 1.44 | 93.7 | 0 | 0 | 1 | 31.99 | 0.29 | 95.8 | 2.25 | -0.71 | -1.28 |
| 4a | 33.40 | 31.02 | 3.35 | 92.9 | 0 | 1 | 1 | 31.17 | 0.04 | 93.3 | 0.44 | -0.15 | -3.68 |
| 4b | 31.81 | 29.63 | 2.79 | 93.1 | 0 | 1 | 1 | 31.17 | 0.04 | 98 | 5.23 | -1.54 | -3.06 |
| 5 | 31.60 | 0.68 | 86.9 | 2.14 | 1 | 1 | 1 | 0.89 | 81.84 | 2.8 | 31.75 | -0.21 | -5.62 |
| *0 – no connection to the ground; 1 – connection to the ground | | | | | | | | | | | | | |

### 6.  Conclusion

The developed algorithm is able to detect and locate earth faults using the cable screen earthing current and the zero-sequence voltage. The algorithm is also able to detect and locate earth faults based on relations between cable screen earthing current and zero sequence cable core current. In the proposed solution, the criterion values are $RF_{110/15}$ coefficient, which describes the ratio of the zero-sequence current in cable screens and zero-sequence current in cable cores, and the value of the phase shift between the zero-sequence current in cable screens and cable cores (angle $\alpha$). The utilization of the proposed values for earth fault detection allows to improve the efficiency of earth fault detection and to reduce the risk of unnecessary protection operation (unwanted tripping). The location tools allow to:

- define the approximate place of failure in the cable line,

- define the type of line affected by the earth fault [14],
- indicate the line branches in which possibly the earth fault was occurred [15].

The correctness of the presented solutions is confirmed by the network experiment in the actual MV distribution network. The solution which is proposed can be operated as the independent earth fault protection algorithm or be operated as a complementary algorithm with the existing protection relays.

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# Використання струму заземлення екрану кабелю для виявлення та локалізації замикань на землю у мережах середньої напруги

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**Анотація**

У статті представлені питання, пов'язані з виявленням та локалізацією замикань на землю у мережах середньої напруги (СН). Приділено увагу кабельним та кабельно-повітряним лініям. Представлено значення критерію – струм заземлення екрану кабелю. Описано спосіб використання струму заземлення екрану кабелю для виявлення та локалізації замикань на землю. У наступній частині статті представлено результати імітаційних досліджень для різних варіантів замикань на землю в кабельних та кабельно-повітряних лініях. Представлені залежності є основою розробленого алгоритму виявлення та локалізації замикань на землю. Теоретичні розрахунки були підтверджені експериментом, проведеним у мережі СН.

**Ключові слова:** замикання на землю; мережа середньої напруги; реле захисту; місце замикання на землю; екран кабелю.