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Overcurrent protection against multi-phase faults in MV networks based on negative and zero sequence criteria

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ABSTRACT

Adequate power system protection plays crucial role in ensuring reliability of electricity supply, thus it is a key challenge for distribution system operators to increase the effectiveness of protection schemes operation and protection equipment itself. The main goal of the paper is presenting a multi-criteria protection algorithm that may boost effectiveness of power lines' short-circuit overcurrent relays in medium voltage networks in case of various two phase faults. The idea of enhancing protection performance is based on fault current symmetrical components' analysis and specifically on using negative and zero sequence currents as criterial values for overcurrent line protection used against such faults. The paper describes in detail the proposed solution and analyses its performance based on medium voltage network simulations carried out using DIgSILENT PowerFactory software. Promising simulation results can be observed for definite time overcurrent protection relays used in reactance-earthed networks, as introduction of the proposed method proved to increase the zone of effective operation twice comparing to the traditional phase current based solutions. Moreover, in the proposed solution, coordination of protection settings for small earth-fault current values, which are identified by other protection relays, is not necessary. The proposed solution may complement the traditional algorithms for short-circuit protection (I≫) used in modern protection relays monitoring the level of negative and zero sequence current, and therefore may significantly improve the effectiveness of detecting various phase-to-phase faults in the considered MV line protection zone.

1. Introduction

Proper operation of distribution networks determines the quality and reliability of electricity supply to final customers. To ensure reliability of the network's operation it is crucial to provide quick and adequate protection relays' operation in case of short-circuits in the medium voltage (MV) lines. As the MV networks are constantly developing, accurate protection is becoming a bigger challenge for the distribution system operators specifically in case of increasing number of local renewable energy sources connected to the network [1–6]. That is why it is extremely important to improve the effectiveness of MV protection both in terms of modification of protection algorithms and proper adjustments of protection settings.

Still however, the majority of MV faults are single line-to-earth short-circuits, often referred to as earth-faults [7]. In actual practice, there are two methods used for earth-faults' identification, which depend on the earthing system of the neural point of the MV network [8–9]. In case of solidly-earthed or resistance-earthed networks with low resistance earthing of MV neutral point, line-to-earth or line-to-line short-circuits lead to the flow of significant currents, which can be detected by overcurrent protection relays, operating based on the level of phase fault currents [9–10]. Such neutral point earthing mode, ensuring high values of earth fault currents and creating favourable conditions for earth fault identification, is applied in the USA and in many other countries in cable networks [10–12]. In case of long sections of overhead lines with in-line reclosers, the coordination of operating conditions of protection relays mounted in various points of the feeder during various types of short-circuits is then required. For numerous cases of more sophisticated network configurations, such coordination becomes extremely difficult and overcurrent protection based on phase currents is not sufficient to ensure proper network operation [13–16]. Then other protection solutions involving symmetrical components analysis [16–20], discussed in

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detail in section 2, should be considered.

In MV networks with insulated neutral point or with neutral point earthed through a resistance or a reactance (e.g. Petersen coil), the protection against the effects of low-current earth faults constitutes a separate, independent protection system (earth-fault protection), in which the most frequently used criteria are based on the relations between symmetrical zero components of the current and voltage. The earth-fault protection require separate coordination of protection settings, independent of high-current faults, and enables arc self-extinguishing in case of earth faults in the overhead power lines. Such operation mode is applied in Germany, France, Italy, Poland and many other European countries in order to allow self-healing of the overhead network with no brakes in the network operation [21–24]. Earthing the network's neutral point through a reactance aims to compensate the capacitive earth-fault currents. In such cases, single line-to-earth faults are characterised by the flow of small currents, often smaller than the load currents, therefore the faults cannot be detected by the phase overcurrent protection relays. For identification of such short-circuits in case of unsuccessful self-extinguishing, dedicated protection devices should be used with the operation criteria based on the zero sequence components of phase currents and network voltages. A very effective solution turns out to be protection based on zero sequence admittance of a line or its components [25–27]. Although in the MV networks with insulated neutral point, zero sequence overcurrent protection is often a sufficient solution, it may well be improved by the additional use of negative sequence current criteria [28–29].

Moreover, earth faults in the MV networks with high impedance earthing of the neutral point may initiate other faults, which are caused by the voltage increase in the phases not involved in the earth fault almost to the value of phase-to-phase voltage and the resulting insulation puncture possibly at the place distant from the initial fault. Such faults are often referred to as double or cross-country faults and they are also widely analysed in terms of providing adequate protection of the power network [14,30–31]. Protection against cross-country faults is a considerable challenge to network operators [32] and therefore different approaches are used to detect such disturbances, which include distance protection [33], differential protection [34], wide-area backup protection scheme [35] or even artificial neural networks [36] depending on the voltage level in the considered network. Various modifications of traditional overcurrent criteria are also described, such as using improved phase selection logic to detect cross-country faults [37].

Usually multi-phase fault protection in the networks with low earth-fault currents is implemented using time independent overcurrent systems based on phase currents only. Coordination of their settings within the network does not require analysing their coordination with the earth-fault protection relays as they operate on different criteria. However, the overcurrent protection should operate both in case of three phase faults and two phase faults and as the fault currents for the two phase faults are smaller than for three phase faults, the protection reach for two phase faults is substantially lowered. One of interesting possibilities of its improvement is the application of fault current symmetrical components as criterial values for the case of multi-phase faults, similarly to the earth-fault protection, and the advantages of such solution should be investigated.

Although negative sequence current has been widely used throughout the years primarily for the purposes of protecting synchronous generators against the effects of asymmetrical load [38], recent analyses prove its value may be used for other protection functions as well [18–19,39–41]. The increased interest in negative sequence current may also be explained by the rapid developments in the digital measurement and decision-making techniques for power system protection, which facilitate and simplify the acquisition of complete information about the level of symmetrical components. It is highlighted also in [42], where the possibilities of using negative sequence current to improve sensitivity and operation coordination of two-phase fault protection is described.

The aim of the paper is providing a novel multi-criteria solution for improving overcurrent protection performance and extending the protection reach for two phase faults in MV networks with insulated neutral point or with the neutral point earthed through a reactor, including cross-country faults. Section 2 describes the protection systems applied for multi-phase faults in Polish distribution networks so far, emphasizing the unsatisfactory effects of their operation during two phase faults in lines equipped with reclosers. Section 3 describes the methods used for phase fault currents' analysis using symmetrical components in terms of short-circuit protection performance, while Section 4 presents in detail the proposed multi-criteria phase fault protection algorithm based on the negative and zero sequence current criteria, which boosts the protection effectiveness in case of two-phase or cross-country faults. In Section 5 the results of simulation analyses are presented, while Section 6 discusses the advantages of the proposed solution and its effectiveness. Finally, Section 7 summarises the benefits of using the negative and zero sequence currents criteria in the protection systems against two phase faults encountered in MV networks.

2. Effectiveness of multi-phase fault protection operation in reactance-earthed MV networks

For the purpose of multi-phase fault protection in MV lines in Poland, the overcurrent protection criterion with set current threshold and time independent operation on fault current value is used most often. Usually there are installed two protection relays of such type. The current setting of the first protection, playing the role of the time-delay short-circuit and overload protection marked with the I > symbol, needs to fulfil the following conditions:

$$I_{Kmin} > I_{pr} > I_{dop} \tag{1}$$

where: $I_{K\text{min}}$ – minimum short-circuit phase current of the line equipped with I > protection, I_{pr} – set threshold value of the overcurrent protection, I_{dop} – steady state component of the highest load current of the line.

Such protection relays react only to phase current values and they are mostly definite minimum time (DMT) overcurrent relays set according to selectivity requirements. In the case of several reclosers along the line, their time settings are the lowest at the far end of the line and increase towards the feeder supply point. The main drawback of such protection is that short-circuits close to the substation busbars are tripped with the longest time delays while having the highest current values. Additionally, such operation of protection relays limits the effectiveness of FDIR (Fault Detection, Isolation, Restoration) systems which are becoming more and more popular in Poland, as they increase the reliability of electricity supply and simultaneously reduce the values of System Average Interruption Duration Index (SAIDI) that need to be registered for DSO regulation purposes [43–44].

For these reasons, the second overcurrent protection is introduced, marked with the I≫ symbol, which is instantaneous protection of a line section, often referred to as short-circuit instantaneous protection. It should be clearly noted that, according to Eq. (2a), the short-circuit protection threshold I≫ is set to the maximum short-circuit current value recorded at the end of the protected line section (for three-phase short-circuits) and therefore the protection may react only partly to high-current faults, which occur in the considered section. The Eq. (2a) should be supplemented with Eq. (2b) determining the value of $I_{K(l)}$ current, as follows:

$$I_{K(l)} > I_{pr(zz)} > I_{Kmax} \tag{2a}$$

$$I_{K(l)} = \frac{nU_f}{m(Z_s + Z_l)} \tag{2b}$$

where: $I_{K(l)}$ - short-circuit current of the protected line section at a distance of l, $I_{pr(zz)}$ - short-circuit protection threshold (I≫), $I_{K\text{max}}$ -

maximum value of the short-circuit current at the end of the protected line section, U_f – supply phase voltage, Z_S – equivalent impedance of the supplying power system, Z_l – line impedance from the protection point I≫ to the fault point; $n = 1$, $m = 1$ for three-phase faults, $n = \sqrt{3}$, $m = 2$ for two-phase faults.

The introduced criterion protects only a certain length of the line section. Therefore, the effectiveness of the I≫ criterion depends on the short-circuit type and on the sum of the impedances Z_S and Z_l. The operational practice of Polish MV networks indicates that MV substations are characterised by short-circuit power values above 100 MVA, which corresponds with $Z_l > Z_S$ and therefore strong dependence of the short-circuit current value from the fault location in the line.

Time delay of the I≫ protection tripping is very small and it usually results only from the own operation times of the systems implementing measurement-decision algorithms and usually amounts to 50 – 100 ms. An example of cooperation of the I > and I≫ protection relays is shown in Fig. 1. The MV line is supplied from the substation bay (with a circuit-breaker *Wa*) and there are reclosers mounted further along the line (*Rb* and *Rc*). All the circuit-breakers are equipped with I > protection relays, while the *Rb* recloser and *Wa* circuit-breaker are additionally controlled with I≫ protection. Time setting values of the time-delay protection I > are selected according to condition (1) in the network points A, B and C. The current settings of the I≫protection ($I_{pr(zz)}$) are different in the points A and B and for the purpose of their proper selection, the maximum short-circuit currents in points B (for the protection setting in point A) and in point C (for the protection setting in point B) must be determined.

It should be clearly noted that according to the condition (2a), operation of the short-circuit protection I≫ is only possible if the fault at a location within the protected section results in current value exceeding the protection threshold. In case of supply substations with relatively low short-circuit power values, the equivalent impedance of the power system is greater than the impedance of the line sections, resulting in a weak dependence of the short-circuit current on the fault location along the line, which is however is not the case frequently encountered in Polish MV distribution networks as described earlier.

Another factor influencing the effectiveness of I≫ protection is the length of the protected line section. For line sections of several kilometres (e.g. 4–5 km), using I≫ protection for tripping multi-phase faults close to the substation terminals is justified. An example of a relatively high effectiveness of I≫ protection is presented in Fig. 2. It presents changes of the short-circuit currents values along the 15 kV line, in which the I≫ protection devices are located at its beginning (cooperating with the *W* circuit-breaker) and further down the network at the beginning of the line supplied from B substation (cooperating with the *R* recloser). The $I_{K(\max)}$ curve refers to the maximum short-circuit current values during three phase faults while the $I_{K(\min)}$ curve refers to the minimum short-circuit current values resulting from two phase faults. The I≫ protection reach at the beginning of the line, with a properly selected $I_{pr(zz)}$ threshold of 3 kA, reaches 87% of the AB line section (5100 m) during three phase faults (3F) and 55% in the case of two phase faults (2F).

Such a high effectiveness of the I≫ protection, regardless of the type of short-circuit, mainly concerns identification of short-circuits occurring close to the feeding substation. The further the fault location from the feeding substation, the lower the protection effectiveness, as for the first AB line section the zone of undetected two phase faults reaches even 45%. In case of the second line section between substations B and C, the I≫ protection effectiveness is definitely weaker. As shown in Fig. 2, the protection zone covers 57% of the BC line section length only during three phase faults, while the protection is completely ineffective during two phase faults in the considered section.

Poor effectiveness of I≫ protection against two phase faults in MV lines may be the reason for using other more complex solutions for protection of the MV networks, such as:

- protection with time-delayed operation dependent on the short-circuit current value,
- independent I≫ protection for two phase faults blocked during three phase faults,
- distance (under-impedance) protection reacting to phase short-circuits in the protected zone,
- differential protection covering the protected line section.

The first solution, i.e. relays with inverse time-delayed operation dependent on the short-circuit current value are usually not easy to implement because they require proper selection and adjustment of operation characteristic $t = f(I)$. According to [16–20] using the negative sequence symmetrical current component I_2 as the criterial value enables effective protection against line-to-line as well as line-to-earth short-circuits, thus they can be applied in the MV networks with high values of earth-fault current. Such solutions are practically not used in MV networks with insulated neutral point or MV networks with the neutral point earthed through a Petersen coil, and instead, instantaneous definite minimum time protection against multi-phase faults is used more often.

The second solution, which is the separate protection for two phase faults, requires differentiation of the fault type. If the phase current measurements for three phases are available, the system shown in Fig. 3 can be used, comprising four amplitude comparators and a simple logic system. According to the presented diagram, the first three comparators compare the current values of the individual phases with the protection setting value for two phase faults *F2nast*. Simultaneous activation of three comparators clearly indicates a three phase fault and the short-circuit protection will trip based on the value of one of phase currents and the threshold value resulting from the *F3nast* setting. Lack of

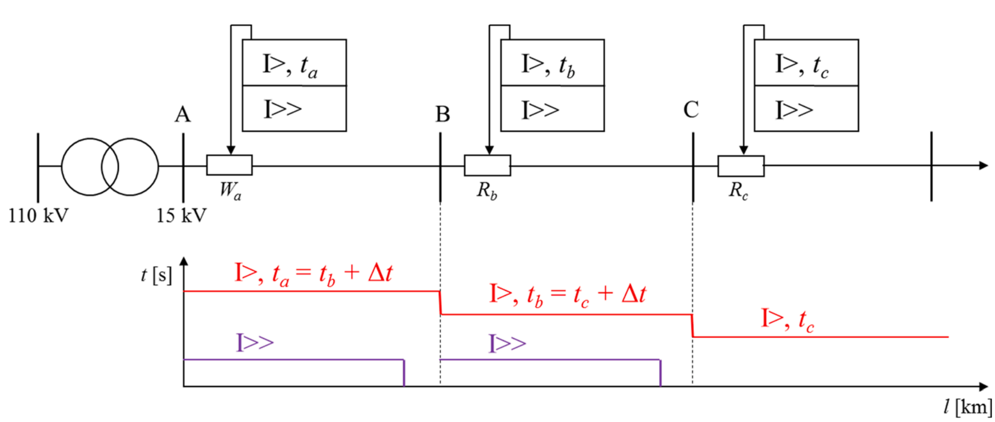

Fig. 1. Coordination example of I > time-delay overcurrent protection relays' settings with appropriate current settings of I≫ short-circuit protection in MV lines.

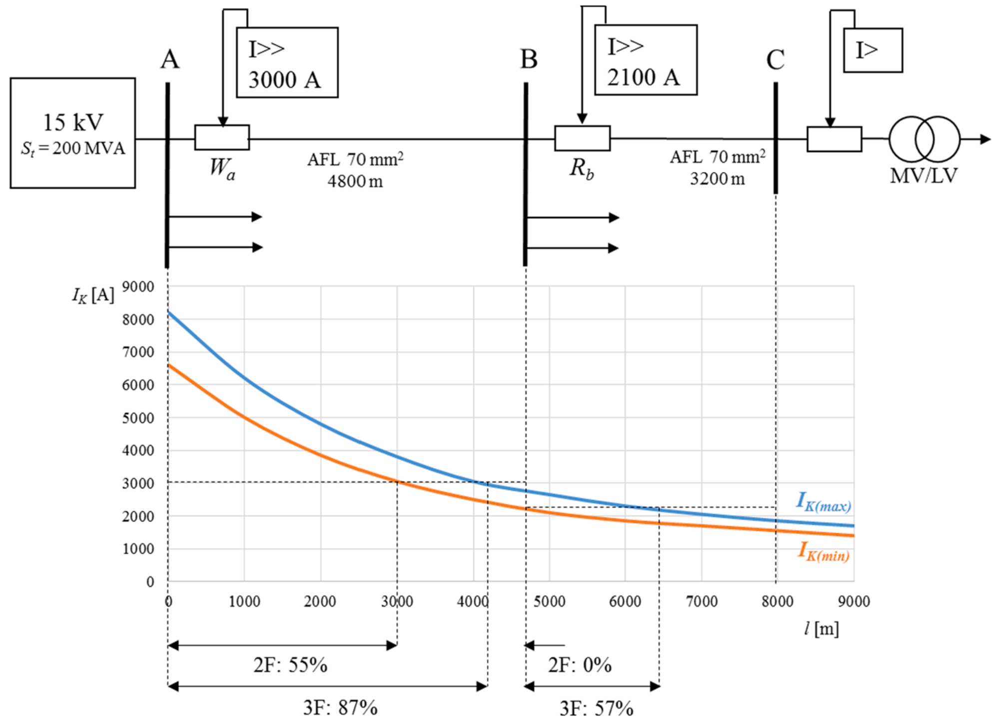

Fig. 2. I≫ protection operation zones installed in A and B substations during three phase ($I_{K(\max)}$) and two phase ($I_{K(\min)}$) short-circuits in a 15 kV line supplied from a substation with a short-circuit power $S_t = 200$ MVA.

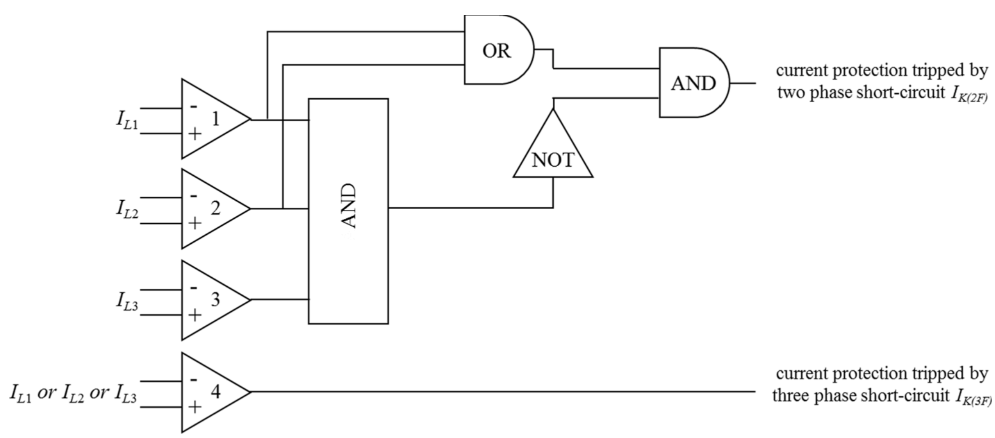

Fig. 3. Diagram for short-circuit type differentiation. Comparators 1, 2 and 3 are set for two phase short-circuits (*F2nast*) and comparator 4 is set for three phase short-circuits (*F3nast*).

simultaneous excitation of the three phase comparators may be used for initialising operation of the two phase fault protection.

The remaining solutions, i.e. distance or differential protection, require extending the protection components with additional elements such as voltage measurement units for the case of distance (under-impedance) protection or additional set of current measuring devices and communication link in the case of differential protection. An alternative solution that does not require expansion of control and measurement devices is presented in the following section.

3. Short-circuit protection performance analysis based on negative and zero sequence currents

Negative and zero sequence fault current components may also be applied as criteria in the short-circuit overcurrent protection I≫ of power lines. The value of negative sequence current could be decisive for distinguishing between two phase and three phase short-circuits and such solution could significantly improve the effectiveness of phase fault protection. Moreover, zero sequence current component could be useful for detection of double phase faults. The analysis concerning symmetrical components in relation to phase fault currents and protection performance is presented below.

In case of symmetrical load, as well as in case of three phase short-circuits, the negative sequence current is not present, but it occurs during unbalanced loads, and it is highly noticeable during two phase faults. Therefore, it may be assumed that in the case of a two phase fault, the phase currents have the following values:

$$I_{\_L1} = I_{K(2F)}; I_{\_L2} = -I_{K(2F)}; I_{\_L3} = 0 \quad (3)$$

where $I_{K(2F)}$ is a two phase fault current. Then the negative sequence current I_2 may be expressed as

$$I_{\_2} = \frac{1}{3} I_{K(2F)} (1 - a_{\_}{}^2 + 0) \quad (4)$$

and it may be further transformed as follows:

$$a\_^2 = -\frac{1}{2} - j\frac{\sqrt{3}}{2} \tag{5}$$

$$I\_{_2} = \frac{1}{3}I_{K(2F)}\left(\frac{3}{2} + j\frac{\sqrt{3}}{2}\right) \tag{6}$$

The absolute value of the negative sequence current may be determined as:

$$I_2 = \frac{1}{\sqrt{3}}I_{K(2F)} \tag{7}$$

If the two phase short-circuit concerns other phases, e.g. L2 and L3 or L1 and L3, then only the argument of the negative sequence current $\underline{I_2}$ changes, but its absolute values always comply with formula (7). Then, the relationship between the values of three phase ($I_{K(3F)}$) and two phase ($I_{K(2F)}$) short-circuit currents in the same short-circuit loop may be described according to the equation [45]:

$$I_{K(3F)} = \frac{2}{\sqrt{3}}I_{K(2F)} \tag{8}$$

By analysing the negative-sequence current occurring during a two-phase short-circuit at a specific network point in relation to the three-phase short-circuit current value at the same network point, by combination of Eqs. (7) and (8) it may be reasoned that the absolute value of the negative sequence two phase short-circuit current may be expressed as half the value of the three phase short-circuit current at that point, which is presented by the following relationship:

$$I_2 = \frac{1}{\sqrt{3}}I_{K(2F)} = \frac{1}{2}I_{K(3F)} \tag{9}$$

Such relationship between the currents I_2 and $I_{K(3F)}$ makes it very simple to implement negative sequence criterion in the short-circuit over-current protection, making it possible to set the same protection reach for three phase faults and for two phase faults. The current threshold value of such protection is indirectly determined by the relationship (9), setting it at the level of half of the threshold value adopted for three phase faults. Such criterion can be described as:

$$I_2 > \frac{1}{2}I_{pr(zz)} \tag{10}$$

It should be noted, however, that the relationship (9) is correct when the protection measurement system covers both phases affected by a two phase short-circuit. Fig. 4 shows four examples of phase faults considered in the study, including two phase faults occurring at one network point (Fig. 4a and 4b) as well as double phase-to-earth faults, occurring in different phases and different network location within one line, i.e. cross-country faults (Fig. 4c and 4d). Such disturbances are considered as they also concern faults within two phases of a line.

If the I≫ protection that controls the AB line section is installed at point A, it will be able to monitor the currents in both faulted phases in case of short-circuits at one line point, i.e. two phase faults (Fig. 4a and 4b). In the networks with neutral point earthed by a Petersen coil, the fault currents' values in both cases are of similar values as the contact of the faulted phases with earth changes the currents only by several or several dozen amperes. In case of double phase-to-earth faults and the protection measurement system located at point A, two following situations can be distinguished:

a. both fault points are located within the protected line section (Fig. 4c),
b. one fault point is located upstream of the protection relays (e.g. supply substation busbars) and the second one is within the protected section (Fig. 4d).

For the former case (Fig. 4c), the protection system registers the short-circuit current in both phases and the negative sequence current determined according to the formula (7) is transformed to:

$$I_2 = \frac{1}{\sqrt{3}}I_{K(2FZ)} \tag{11}$$

where $I_{K(2FZ)}$ is the two phase short-circuit current resulting from the zero sequence line impedance of the section a between fault points present in the current flow loop, as it is depicted in Fig. 5.

Assuming with certain approximation that the zero sequence unit impedance of the MV overhead line is four times greater than its positive sequence unit impedance and neglecting the influence of the earth-fault

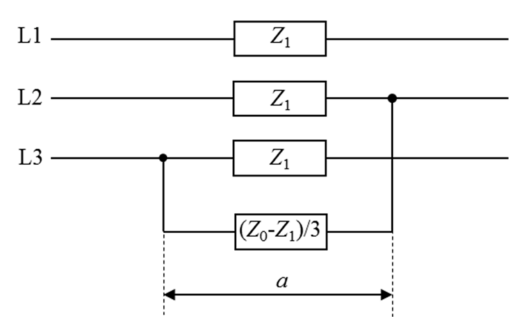

Fig. 5. Part of the fault current circuit loop related to a cross-country fault occurring between phases L2 and L3 within the a distance.

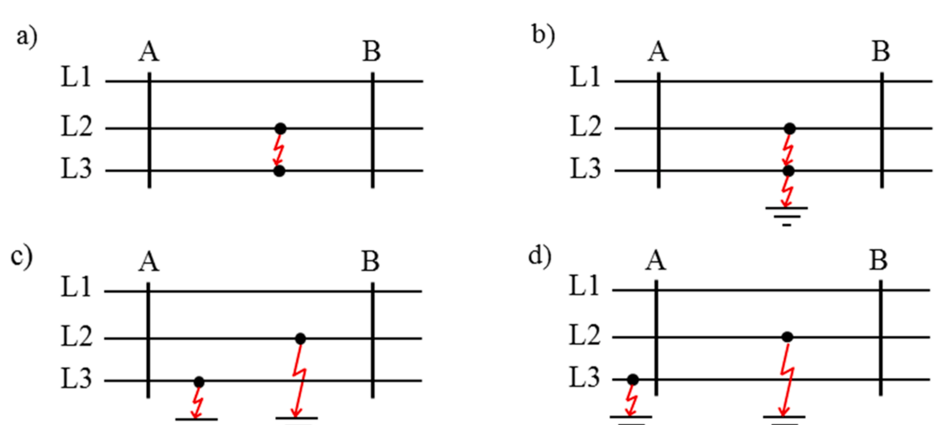

Fig. 4. Examples of various two phase or double phase-to-earth faults in MV power lines.

resistance, the current $I_{K(2FZ)}$ is of similar value to the short-circuit current in case of a two phase fault $I_{K(2FZ)} = I_{K(2F)}$. Therefore, it can be assumed that the response of the I≫ protection at point A to such a double phase-to-earth fault is practically the same as to a two phase fault.

For the latter fault case shown in Fig. 4d, the measurement system of the I≫ protection registers the short-circuit current only in one phase, which results in the following negative sequence current measurement according to formulas (3) and (4):

$$I_2 = \frac{1}{3} I_{K(2FZ)} \tag{12}$$

The current is then $\sqrt{3}$ times lower than for the previously analysed short-circuits and may significantly reduce the possibility of using the I_2 component as an operation criterion of the I≫ short-circuit protection. Such phenomenon may however be detected by the protection measurement system in order to enhance its effectiveness. For this purpose, it would be enough to use the zero sequence current I_0, which in such case is equal to the negative sequence current I_2:

$$I_0 = I_2 = \frac{1}{3} I_{K(2FZ)} \tag{13}$$

In MV networks with the neutral point earthed by a reactance used to compensate the high level of the zero sequence line current, the zero sequence current may occur only in the case of such double phase-to-earth faults and thus it may constitute a very effective decision information. The measurement of a high value of the I_0 current may be used as another criterion implemented in the overcurrent protection to include detection of described double faults. The threshold level determined by Eq. (10) should then be reduced to a $\sqrt{3}$ times lower value. Taking into account the possible level of zero-sequence current I_0 determined by (13) and maintaining the requirements applicable to the I≫ protection in the line section protection zone, the I_0 criterion should operate with the following condition:

$$I_0 > \frac{1}{2\sqrt{3}} I_{pr(zz)} \tag{14}$$

4. Operation algorithm of I≫ protection using the I_2 and I_0 criteria

The principle of operation of the proposed I≫ protection, which has already been implemented in the prototype protection relay, is shown in Fig. 6. The decisive elements of the system are digital negative and zero sequence current filters, which performs the following tasks:

- simultaneous current sampling from three phases (L1, L2 and L3) with 6000 Hz frequency,
- creating data buffers for individual phases from the samples for each measurement period (for 50 Hz frequency it fits 120 samples in each buffer with angular resolution of 3 degrees),
- determining the n^{th} sample of the zero $I_{0(n)}$ and negative sequence component $I_{2(n)}$ with buffers being continuously filled up; for the case of negative sequence current according to the following relationship:

$$I_{2(n)} = \frac{1}{3}\left(I_{L1(n)} + I_{L2(n-40)} + I_{L3(n-80)}\right) \tag{15}$$

or using the relation $I_{L3(n\text{-}80)} = -I_{L3(n\text{-}20)}$ and applying the following formula to speed up calculations:

$$I_{2(n)} = \frac{1}{3}\left(I_{L1(n)} + I_{L2(n-40)} - I_{L3(n-20)}\right) \tag{16}$$

On the basis of the collected samples in the considered time range, e.g. 20 ms, the effective value of the negative sequence I_2 current is determined.

As in the traditional short-circuit protection solutions against three phase faults, the proposed protection reacts to an increase in the phase current above the threshold value (K3 comparator) set according to the selectivity conditions for three phase faults ($I_{pr(zz)3F}$). For two phase faults, the operation of the protection is based on the result of comparing the I_2 current value with the value set at 50% of the $I_{pr(zz)3F}$ setting (K2 comparator). In case of double phase-to-earth faults, the operation of the protection is based on the result of comparing the I_0 current value with the value set according to (14) based on the $I_{pr(zz)3F}$ setting (K1 comparator). In practical terms, a major advantage of such solution is the necessity to determine only one setting value in accordance with condition (2) as it was done so far for protection settings' selection purposes.

The protection is supplemented with a system of zero sequence current filter and additional logic elements, the task of which is to detect double cross-country phase-to-earth faults presented in Fig. 4d, in case of which the protection measurement point is located between the fault points involved. Therefore, two phase short-circuits will be detected primarily according to the basic criterion implemented in the K2 comparator and, in specific cases, according to the criterion implemented in the K1 comparator. The activation thresholds of both comparators (K1 and K2) are automatically calculated after setting the basic

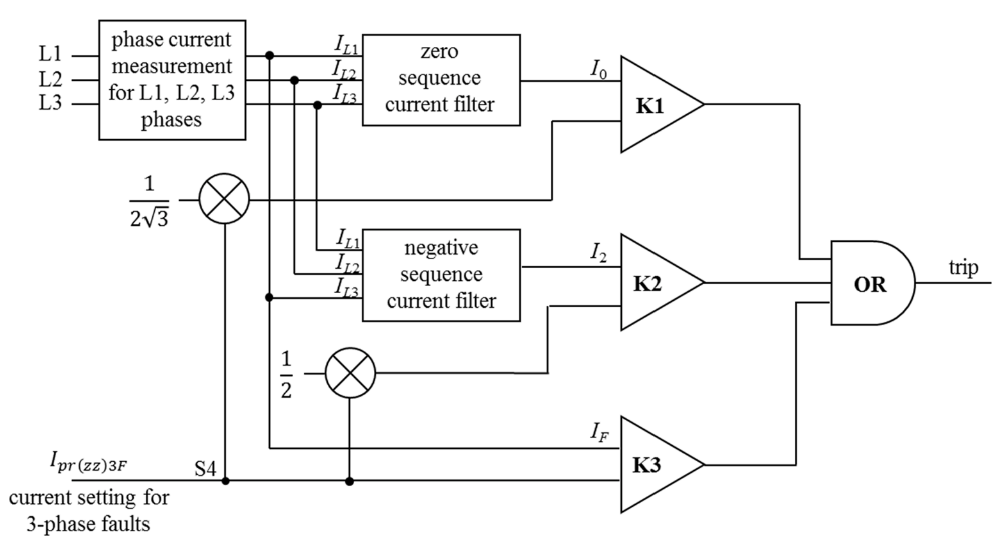

Fig. 6. Operation principle of the overcurrent protection against multi-phase faults including negative and zero sequence current criteria.

current threshold $I_{pr(zz)}$ consistent with the condition (2) for three phase short-circuits. Additional implementation of the I_0 protection criterion allows for detecting double cross-country faults with the same effectiveness as for the other two phase disturbances. The final decision function of the presented I≫ protection, which effectively protects a specific line section against three phase faults and various cases of two phase faults, can be described as follows:

$$I_{L1} > I_{pr(zz)3F} \cup I_2 > \frac{1}{2} I_{pr(zz)3F} \cup I_0 > \frac{1}{2\sqrt{3}} I_{pr(zz)3F} \quad (17)$$

5. Simulation results

Performance of the proposed protection solution was analysed in a series of simulations modelling the short-circuit events in the MV network using DIgSILENT PowerFactory software package. The model system chosen for simulation purposes was selected from a set of MV lines operating in the actual distribution network in Poland. The influence of the surrounding network was considered by the level of short-circuit power at individual points of the tested line and the resulting changes to the traditional I≫ criterion settings. A test model consisting of a six-kilometre long overhead line of 15 kV was adopted for simulations. The model includes a circuit-breaker P1 at the beginning of the line installed at the feeder bay of the HV/MV substation and a recloser located at half of the line length close to a MV/LV substation. The P1 circuit breaker and the R1 recloser are equipped with I≫ short-circuit overcurrent protection operating without additional time delays and with I > protection, for which time delay settings were selected in accordance with the coordination needs. The load is modelled with two MV/LV transformer substations, which are equipped with circuit-breakers and cooperating I > protection at the MV side. The diagram of the modelled system is shown in Fig. 7 and the relevant input data is presented in Table 1.

To verify the operation of the proposed solution, different short-circuit simulations were performed for the analysed network. The threshold settings of the I≫ protection installed at P1 and R1 chosen for a modelled line according to (17) are presented in Table 2.

One of the main goals of the simulation analysis was determination of steady-state values of two phase short-circuit phase current values and the corresponding values of negative sequence current. Fault points were selected with a step of 100 m for both line sections (L_{AR} and L_{RB}). The obtained results were compared with the short-circuit protection threshold values, which were selected using selectivity conditions (1), (2a) and (2b). A final stage of the analysis was determination of the sensitivity coefficients' value for the short-circuit overcurrent protection I≫, which is defined by the formula:

$$k_c = \frac{I_{Kpom}}{I_{pr(zz)}} \quad (18)$$

Table 1
Input data for the implementing the MV line model using DIgSILENT PowerFactory software.

Parameter	Symbol	Value	Unit
Rated voltage	U_n	15	kV
Short-circuit power at 15 kV busbar	S_k	155	MVA
Line length between substation A and recloser R1	L_{AR}	3	Km
Line length between recloser R1 and substation B	L_{RB}	3	Km
Unit line resistance at 20 °C	R	0.434	Ω/km
Unit line reactance	X	0.369	Ω/km

Table 2
Overcurrent protection settings thresholds for selected criteria including traditional overcurrent, negative and zero sequence criteria.

Protection location	Traditional phase current criterion setting $I_{pr\ (zz)}$	Negative sequence current criterion setting	Zero sequence current criterion setting
P1 (A busbar)	3600 A	1800 A	1040 A
R1 (R busbar)	2200 A	1100 A	640 A

where: I_{Kpom} –measured short-circuit current value, $I_{Kpom} = I_{K(2F)}$ for two phase short-circuits and $I_{Kpom} = I_{K(3F)}$ for three phase short-circuits, $I_{pr\ (zz)}$ - short-circuit protection threshold (I≫).

Simulation results comparing the traditional phase current I≫ protection and protection with incorporated negative sequence current are presented below. Table 3 presents the sensitivity coefficient values for the traditional phase current I≫ criterion, while Table 4 presents the results for the protection reacting to negative sequence current values. The resulting formulas for determining the sensitivity coefficient in each case are presented in the table.

The simulation tests also analysed the reaction of the I≫ protection to the effects of cross-country double phase-to-earth faults, assuming

Table 3
Sensitivity coefficients' values for traditional phase current I≫ protection for two phase faults modelled at different points of the line.

No.	Fault point [%] from the line section beginning	Sensitivity coefficient $k_c = I_{K(2F)}/I_{pr(zz)}$	
		A-R section	R-B section
1	0	1.52	1.22
2	16.5	1.31	1.13
3	35	1.15	1.04
4	36	1.14	1.00
5	50	1.00	<1.00
6	55	<1.00	<1.00

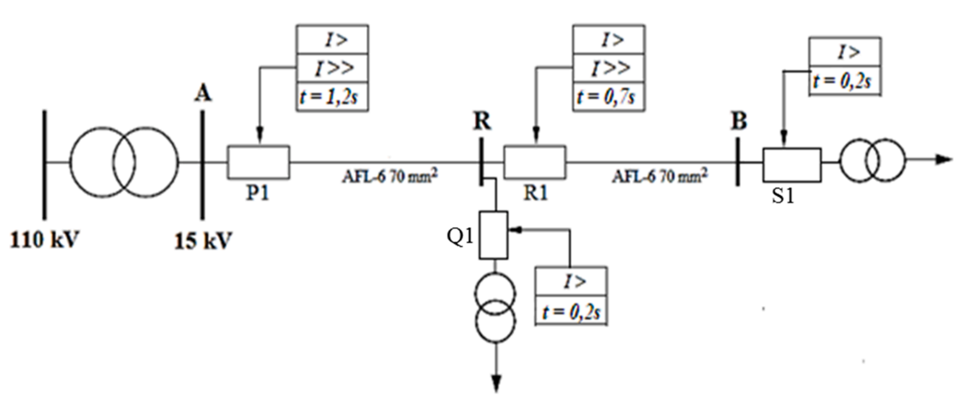

Fig. 7. Diagram of the 15 kV test system adopted for simulations.

Table 4
Sensitivity coefficients' values using the negative sequence current protection criterion for two phase faults modelled at different points of the line.

No.	Fault point [%] from the line section beginning	Sensitivity coefficient $k_c = 2I_2/I_{pr(zz)}$	
		A-R section	R-B section
1	0	1.78	1.42
2	16.5	1.52	1.30
3	33	1.32	1.20
4	50	1.20	1.12
5	66	1.05	1.06
6	73	1.00	1.00
7	75	<1.00	<1.00

that one of the earth-faults occurred either at the distribution supply substation busbars or at the beginning of the MV line, and the other at the distant point of the network lines. Such short-circuit is influenced by positive and negative sequence impedances, as well as by zero sequence line impedance of the line section between the earth-faulted phases. Equivalent diagram of such a double phase-to-earth fault, assuming that $Z_1 = Z_2$, is shown in Fig. 8.

In the performed analysis, the influence of the a distance between the fault points on the symmetrical components' currents I_2 and I_0 was assessed, neglecting the resistance at the fault locations. The effectiveness of the I≫ protection criteria, reacting to the I_2 and I_0 currents, was also checked according to the conditions specified in the algorithm proposed in Fig. 6. The tests were carried out for the 15 kV line operated in an earth-fault current compensated network without considering load influence for the following double phase-to-earth fault cases:

- L3 phase fault at point A at the substation busbars and L2 phase fault at the a distance from the substation (fault points 1 and 3 according to Fig. 8); protection I≫ operated at the feeder bay of the A substation,
- L3 phase fault at point A at substation busbars and L2 phase fault within the RB line section, (fault points 1 and 5 according to Fig. 8); protection I≫ operated at the point of R recloser installation,
- L3 phase fault at the beginning of the AR line section and L2 phase fault along the line section at a distance (fault points 2 and 3 according to Fig. 8); protection I≫ operated in the feeder bay of the A substation,
- L3 phase fault at the beginning of the RB line section and L2 phase fault along the line section at a distance (faults points 4 and 5 according to Fig. 8); protection I≫ operated in the point R of recloser installation.

In case of the latter two cross-country faults considered, one of the faults is outside reach of the traditional overcurrent protection, as presented in Fig. 4d, whereas the two latter cases concern faults within one protection zone as presented in Fig. 4c. The test results are presented in Tables 5 to 8.

6. Discussion

The effectiveness of the I≫ short-circuit protection can be determined by comparing the length of the protected zone of a line to its overall length by analysing the k_c sensitivity coefficient values for various individual fault points in the considered network. It may be assumed that the short-circuit identification zone defined by the instantaneous tripping of a circuit-breaker or a recloser reaches the distance for which the sensitivity coefficient values are greater than or at least equal to one. Sensitivity coefficient values lower than one clearly indicate that the I≫ protection will not operate at a given fault point and tripping of the P1 circuit-breaker or R1 recloser (as presented in Fig. 7) will be controlled only by the I > protection operating with a certain delay.

The I≫ protection operation zones are presented in Tables 3 and 4 as a percentage of length of the protected line section. Thus, it may be noticed that traditional phase current short-circuit protection effectively protects against the two phase short-circuits only half of the modelled AR section (50%) and only 36% of the RB section. The situation changes significantly when a criterion responding to the negative sequence component is introduced. Such protection operates effectively in case of two phase faults within 70% of the section length of both AR and RB sections. In practice, short-circuit relays are expected to operate with sensitivity above 1 (e.g. 1,1), which means that protected zones of the traditional phase current short-circuit protection does not exceed 40% of the AR section's length and 20% of the length of the RB section. When comparing the obtained results, it may be noticed that implementing the I_2 current criteria doubles the protection reach.

Table 5
Current I_2 and I_0 values and operation of the K1 and K2 comparators during simulated double phase-to-earth faults of the L3 phase at point A at substation busbars and of the L2 phase within the line section at a distance from the A substation, fault points 1 and 3 according to Fig. 8.

a distance between fault points [m]	Fault current I_2 component [A]	Fault current I_0 component [A]	K2 trip	K1 trip
250	1616	1620	no	**yes**
500	1520	1526	no	**yes**
750	1435	1440	no	**yes**
1000	1357	1361	no	**yes**
1250	1287	1292	no	**yes**
1500	1222	1227	no	**yes**
1750	1164	1168	no	**yes**
2000	1110	1116	no	**yes**
2250	1060	1065	no	**yes**
2500	1015	1020	no	no
2750	975	980	no	no
3000	930	935	no	no

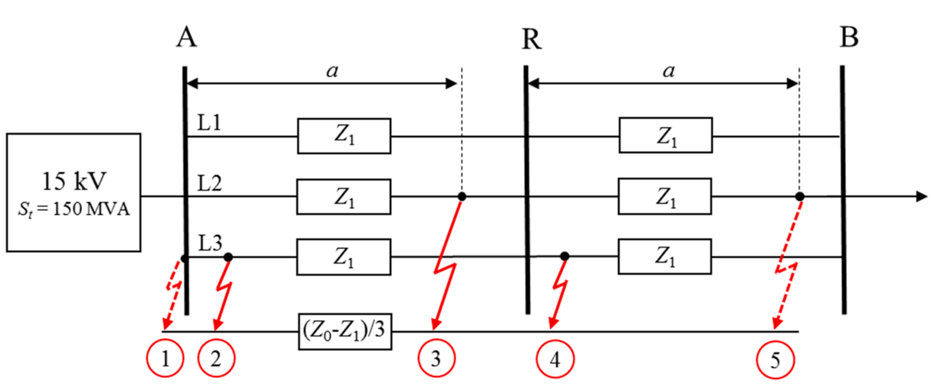

Fig. 8. Equivalent diagram of various cases of tested double phase-to-earth faults.

Table 6
Current I_2 and I_0 values and operation of the K1 and K2 comparators during simulated double phase-to-earth faults of the L3 phase at point A at substation busbars and of the L2 phase within the RB section of the line section, faults points 1 and 5 according to Fig. 8.

a distance between fault points [m]	Fault current I_2 component [A]	Fault current I_0 component [A]	K2 trip	K1 trip
3250	866	870	no	**yes**
3500	833	836	no	**yes**
3750	806	810	no	**yes**
4000	779	783	no	**yes**
4250	753	757	no	**yes**
4500	730	734	no	**yes**
4750	705	709	no	**yes**
5000	685	689	no	**yes**
5250	666	670	no	**yes**
5500	645	650	no	**yes**
5750	630	634	no	no
6000	717	722	no	no

Table 7
Current I_2 and I_0 values and operation of the K1 and K2 comparators during simulated double phase-to-earth faults of the L3 phase at the beginning of the AR line section and of the L2 phase along the line section at *a* distance, faults points 2 and 3 according to Fig. 8.

a distance between fault points [m]	Fault current I_2 component [A]	Fault current I_0 component [A]	K2 trip	K1 trip
250	2980	<10	**yes**	no
500	2805	<10	**yes**	no
750	2638	<10	**yes**	no
1000	2489	<10	**yes**	no
1250	2345	<10	**yes**	no
1500	2232	<10	**yes**	no
1750	2120	<10	**yes**	no
2000	2018	<10	**yes**	no
2250	1915	<10	**yes**	no
2500	1840	<10	**yes**	no
2750	1760	<10	no	no
3000	1690	<10	no	no

Table 8
Current I_2 and I_0 values and operation of the K1 and K2 comparators during simulated double phase-to-earth faults of the L3 phase at the beginning of the RB line section and of the L2 phase along the line section at *a* distance, faults points 4 and 5 according to Fig. 8.

a distance between fault points [m]	Fault current I_2 component [A]	Fault current I_0 component [A]	K2 trip	K1 trip
250	1560	<10	**yes**	no
500	1505	<10	**yes**	no
750	1445	<10	**yes**	no
1000	1390	<10	**yes**	no
1250	1350	<10	**yes**	no
1500	1307	<10	**yes**	no
1750	1266	<10	**yes**	no
2000	1227	<10	**yes**	no
2250	1190	<10	**yes**	no
2500	1156	<10	**yes**	no
2750	1123	<10	**yes**	no
3000	1040	<10	no	no

The results of the simulation tests confirm high efficiency of the proposed algorithm (Fig. 6) also in the case of double cross-country faults. Additional decision support in the form of the I_0 component implies that, regardless of the location of double phase-to-earth faults, the protected zones of the AR and RB sections range from 75% to 85% and may even be larger during three phase faults. It should be emphasized that the effectiveness of I≫ protection during two phase faults is of immense practical significance, as the recorded disturbances in MV overhead lines prove that high-current faults are primarily two phase short-circuits taking place both at a single location or as cross-country faults and occurring 3–4 times more often than three phase faults.

Protection devices are currently constructed using solely the digital microprocessor techniques, so determination of the negative sequence current components is only related to implementation of simple calculation procedures with no need to introduce additional measurement elements. The proposed criterion does not require additional settings either, as its threshold value is automatically determined as half of the setting value determined for three phase faults, similarly to the traditional phase current solutions.

It should be emphasized that the proposed solution improves effectiveness of the I≫ short-circuit protection during two phase short-circuits by extending range of the protected zone up to the protection reach of three phase short-circuits. Further research on the use of the I_2 criterion should focus on the possibilities of further extension of the effective line protection zones, also in cases of relatively low values of short-circuit powers at the protection mounting points. That concerns mainly line points distant from the HV/MV substation and line sections with flattened short-circuit current characteristics. Determination of the I≫ protection threshold currents, which in such cases is based only on the three phase faults analysis that constitute only 5% of all faults, is rather inappropriate and may result in the protection being inactive or shrinking the protection zones to several percent of the line length. Future analyses should aim at proving that using time independent protection relays using symmetrical negative and zero sequence overcurrent criteria may solve this problem to a large extent.

The operating conditions of the proposed protection were tested based solely on the values of primary currents in the analysed network. Errors concerning the processes of transforming these currents by current transformers and the transformers' saturation or additional signal processing may affect the final effectiveness of the protection operation. In particular, the problem may apply to the case of three-phase faults near the supply substations with high short-circuit power values. However, the increasing use of Rogowski coils in reclosers or the corrections implemented in digital signal processing significantly reduce and sometimes even eliminate the negative impact of such phenomena.

Connecting renewable energy sources, as well as any changes to the supply network configuration result in different values of short-circuit power at various network points in the analysed MV line. In the provided simulation, for the purposes of maintaining protection selectivity, the maximum short-circuit power values were considered (the protection setting according to $I_{K(3F)\max}$ current), which may be increased by generation connected to the substation A or upstream. The case of distributed generation connected to the substations R or B was not analysed, as their influence should be mitigated by adding directional protection criteria to the overcurrent protection used.

7. Conclusions

In order to improve the fault location process in MV power lines and to reduce the power outage duration times (SAIDI), the circuit-breakers in the vicinity of MV/LV substations with adequately quick protection are used more and more often in order to trip almost instantaneously during short-circuits occurring within a specific line section. The results obtained by such costly investments depend on the effectiveness of the protection relays controlling the circuit-breakers' operation, which can be improved by widening the zones covered by the I≫ short-circuit overcurrent protection. Traditional protection solutions based on phase current measurements are often unsatisfactory due to their relatively narrow protection zones. Poor protection performance applies specifically to the cases of two phase faults, which occur more frequently than three phase faults.

The article proposes a simple and easy-to-implement solution in which two phase faults are identified on the basis of the negative sequence current value. The use of the I_2 current as a criterion value, supplemented by a filter controlling the I_0 current level for the cases of double phase-to-earth faults, increases the degree of detection of two phase faults to the level obtained during three phase faults. A significant advantage of the proposed solution is the fact that it does not require changes in the protection method or protection settings' values. The operating conditions of the suggested criteria resulting from negative and zero sequence currents are selected automatically based on the three-phase short-circuit criterion.

The results of the simulation analyses prompted the authors to carry out initial study on the implementation of the proposed solution to measurement and control algorithms implemented in controllers cooperating with circuit breakers in MV substation bays and with reclosers protecting particular network sections.

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CRediT authorship contribution statement

Jerzy Andruszkiewicz: Validation, Resources. **Józef Lorenc:** Conceptualization, Methodology, Validation, Investigation, Writing – original draft. **Bogdan Staszak:** Conceptualization, Software. **Agnieszka Weychan:** Methodology, Resources, Writing – review & editing. **Beata Zięba:** Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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