IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received April 12, 2021, accepted April 24, 2021, date of publication April 27, 2021, date of current version May 4, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3076022

Adaptive Zero-Sequence Overcurrent Criterion for Earth Fault Detection for Fault Current Passage Indicators in Resistor Grounded Medium Voltage Networks

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This work was supported by the Poznan University of Technology under Grant 0711/SBAD/4455.

ABSTRACT Earth faults are the most common disturbances in medium voltage networks. They cause threats to equipment and people, and reduce the quality and reliability of electricity supply. Detection and localization of earth faults is a key challenge to network operators, therefore it is important to constantly develop criteria that allow for an unequivocal assessment of the current network state. This article focuses analysis of effectiveness of classic zero-sequence overcurrent criterion and on modification of the zero-sequence overcurrent criterion applied in fault current passage indicators, which are the devices used to effectively detect and locate earth faults. Two new adaptation criteria for networks with resistor grounded neutral point have been proposed, which enable significant improvement of the effectiveness of earth faults detection, in particular high impedance ones. The effectiveness of the criteria was verified computationally and in simulations. In certain situations, the proposed solutions may be over 40% more effective than the classic criterion. The value of detected transition resistance R_F also increases significantly. All the above-mentioned advantages make their potential use in practice very beneficial.

INDEX TERMS Adaptive criterion, earth fault, earth fault passage indicator, medium voltage network, resistor grounded neutral point, zero-sequence current.

NOMENCLATURE

$\underline{U}_0$	Zero-sequence voltage
$\underline{\beta}$	Earth fault coefficient
$\underline{U}_L$	Phase-to-earth voltage
I_{k1}	Fault current at the fault location
C_s	Network ground capacity (equivalent)
d_0	Damping decrement of the network
s	Earth fault compensation detuning coefficient
R_F	Transition resistance between the phase conductor and earth at the fault location
ω	Voltage pulsation
G_n	Network ground conductance
G_L	Earthing coil conductance
R_{np}	Resistance in neutral point of network
I_R	Active current in neutral point during a metallic earth fault
I_{CS}	Capacitive current of a network
I_{CL}	Capacitive current of a line
I_L	Rated earth fault current of the compensating coil
I_{kb}	Fault current as the beginning of the line (in switchgear)
I_{kZ}	Fault current in a given point of the line
a	Relative value of the capacitive current of a line in the capacitive current of a network
a_i	Relative value of the share of the line capacitive current behind the given point in the capacitive current of the network
k_s	Protection safety factor
k_{rr}	Protection return ratio
$\Delta I_{0\mu}$	Current error of the zero sequence current filter
k_{sens}	Protection sensitivity factor

The associate editor coordinating the review of this manuscript and approving it for publication was Siqi Bu.

I_{0set}	Zero-sequence overcurrent protection setting value
E	Electromotive force of the source equal to the nominal voltage of the network
$\underline{U}_0, \underline{U}_1, \underline{U}_2$	Phasors for zero, positive and negative sequence voltage
$\underline{Z}_0, \underline{Z}_1, \underline{Z}_2$	Zero, positive and negative sequence short-circuit impedance
U_n	Nominal network voltage
U_0	Zero-sequence voltage in the place of installation of fault current passage indicator (RMS)
k_{a1}, k_{a2}	Adaptation coefficients

I. INTRODUCTION

In modern MV distribution networks, about 75% of all faults are earth faults [1]–[4]. Of all earth faults, 85% are self-extinguishing ones [5]. Their intensity is relatively high, as on average, there are 10 to 20 earth faults for every 100 km of lines per year [6], [7].

Earth faults are associated with various phenomena that have a negative impact on the quality and reliability of electricity supply. In addition, earth faults often cause overvoltages [8], [9], which are a threat to devices installed in the network, especially to cable insulation. Particularly dangerous are overvoltages caused by intermittent earth faults, which may lead to complete degradation of the equipment insulation. This, in turn, may transform a single phase fault into two phase to earth fault or a phase to phase fault [10].

Another danger resulting from the occurrence of earth faults is the risk of electric shock. It can occur not only in the MV network, but also transfer to the low-voltage transformer side through the common earthing system, which is extensively described in [11], [12].

Lack of solidly earthed neutral point results in low amplitude of phase to earth fault current. The short-circuit current is at most close to the value of the load current. As a result, effective operation of phase to earth fault protection relays is more difficult [13]. In many cases, amplitudes of measurands are comparable with noise measurement. The presented phenomenon acquires a great significance in compensated networks with neutral point grounded by Petersen coil [14].

Many different protection algorithms against the effects of earth faults are developed in countries, where the neutral point of distribution networks is isolated from earth and the case of detection and localization of earth faults in compensated networks is particularly popular [15]–[20].

The basic criterion of earth fault detection in MV networks earthed through a resistor is zero-sequence overcurrent protection. Since this type of earthing is less common (in comparison with compensated networks), there are much fewer publications related to the development of earth fault criteria. New criteria of earth fault detection were developed in the 80s and 90s in the Institute of Electric Power Engineering at Poznan University of Technology. These criteria are based on the analysis of average zero-sequence admittance, conductance and susceptance [13], [21]. The great advantage of these admittance based criteria is their versatility, as they may be used in networks with different neutral point earthing methods. Due to their versatility, the admittance based relays are effective also after the failure of a neutral point earthing transformer [20].

Currently, the greatest challenges of the earth fault criteria are related to the detection of intermittent (IF) and high-impedance faults (HIF).

There are two main types of HIFs encountered in practice. The first one is broken live wire touching the ground directly, while the other type is indirect contact with ground, e.g. through nearby trees or failed insulation. HIFs do not cause severe adverse impacts on the normal operation of the power network, but the fallen live wires pose a serious hazard to people and properties nearby [22]. The parameter related to HIF is the transition resistance R_F at the fault location.

In [23] the Authors propose to use the discrete form of the Continuous Wavelet Transform for the HIFs' detection. It is emphasized that the algorithm responds adequately to HIFs and remains stable to other rapid changes in the network, regardless of the network neutral point earthing mode. The admittance criteria mentioned above are also characterized by high efficiency in terms HIF detection [24].

Apart from earth fault detection, location of the fault must also be considered. It is advantageous to use fault current passage indicators (FCPI) for this purpose. FCPIs are digital devices that detect the short-circuit current flow in the point of the power system where they are installed, while they can be powered by batteries or by the grid voltage using small auxiliary transformers [25]. They can detect both phase faults and earth faults. The FCPI equipment is often used by dispatchers for the operation of medium voltage networks both in normal and emergency states, and they are also important elements of smart FDIR (Fault Detection, Isolation and Restoration) systems [26], [27]. In case of earth faults, FCPIs operate mostly by measuring only the zero-sequence current I_0 [28]–[30].

In order to improve the detection efficiency of HIF in a network with a resistor grounded neutral point by FCPI, this article proposes two new adaptive zero-sequence overcurrent criteria.

The differences between them are in the method of determining the value of the adaptation coefficient. One of the methods is based on change of phase-to-earth voltages after the occurrence of an earth fault with simultaneous analysis of the value of the short-circuit current in FCPI installation site. The second one is based on the change of the value of the zero-sequence voltage in the place FCPI installation site.

The analysis of the work of both criteria was carried out computationally and with the use of the PSCad simulation environment, and the results are presented later in the article.

The article is organized as follows. Section 2 presents the key theoretical aspects of earth faults in the networks with the neutral point grounded by a resistor. This section also presents an extensive analysis of the effectiveness of the classic zero-sequence overcurrent criterion. Section 3 presents the idea of an adaptive zero-sequence overcurrent criterion, with two methods of adapting the criterion setting proposed. The effectiveness of both adaptation methods is verified in Section 4, where the results of simulation tests are presented. Section 5 summarizes the presented analysis. Additionally, there are two appendices at the end of the paper. They include tables presenting selected results of simulation tests and calculations.

II. EFFICIENCY OF THE ZERO-SEQUENCE OVERCURRENT CRITERION IN THE DETECTION OF EARTH FAULTS

A. GENERAL INFORMATION ABOUT MV NETWORK

The medium voltage network is an electricity grid with phase-to-phase voltage ranging from 1 kV to 60 kV. These types of networks are used to distribute electricity over medium and short distances. It is also used for the direct supply of electricity to small and medium-sized industrial plants.

The medium voltage grid is connected to the high voltage grid in primary substations using a HV/MV power transformer (see Fig. 1). The structure of the MV network depends mainly on the topographic conditions and the requirements of the recipients - usually the networks are radial or connected into a ring with the possibility of cutting it [31].

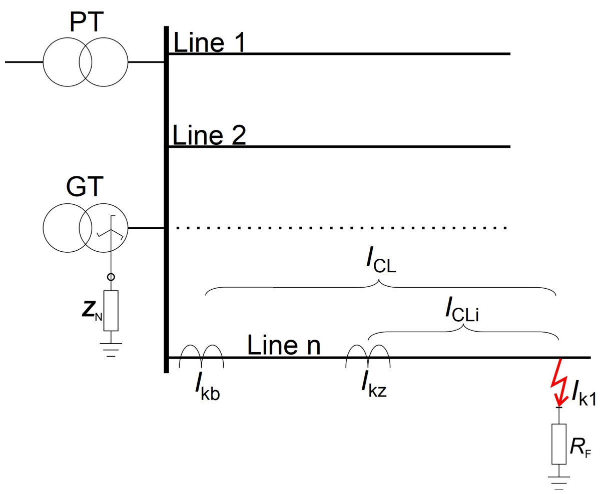

FIGURE 1. Earth fault current at the fault location and at selected points on the line; PT - power transformer (HV/MV), GT - grounding transformer.

The operation mode of network neutral point has the greatest impact on the phenomena occurring in the network during earth faults. Generally this point can be insulated from earth or grounded - directly or indirectly. One of the possibilities of network operation with an indirectly earthed neutral point is to ground the neutral point through a resistor. In this type of networks, high short-circuit currents occur during earth faults, which in turn determine the total inability of the network to extinguish arc faults. Earth-fault overvoltages are very small, hence this type of neutral point operation is often found in networks with a predominance of cables or purely cable. It is stated that the protection of the network with the neutral point earthed by the resistor is quite easy and the protection itself - simple [32].

Another common way of operating the neutral point of an MV network is to ground it using a Petersen coil (compensated network). In this case, the greatest advantage of the network is the possibility of self-extinguishing the electric arc, but there are difficulties with the implementation of earth-fault protection, which must be more complicated than in a network with a resistor [33], [34].

B. ANALYSIS OF THE EFFECTIVENESS OF THE ZERO-SEQUENCE OVERCURRENT CRITERION

In order to analyze the effectiveness of the zero-sequence overcurrent criteria in the detection of earth faults in the MV network by FCPIs, it is necessary to calculate the characteristic quantities related to the earth fault current.

The most common relationships describing the earth fault values in MV networks with ineffectively grounded neutral point do not take into account the longitudinal impedances of the power system components [35], [36]. Although such a procedure is not fully justified, these relationships ensure sufficient accuracy and can be successfully used to calculate the settings of various types of protection. The relationships that ignore the longitudinal impedances are presented in the formulas [13], [21]:

$$\underline{U}_0 = \underline{\beta} U_L \tag{1}$$

$$\underline{I}_{k1} = \underline{\beta} U_L C_S (d_0 - js). \tag{2}$$

The earth fault coefficient $\underline{\beta}$ can be calculated from the relationship:

$$\underline{\beta} = \frac{1}{1 + R_F \omega C_s (d_0 - js)}. \tag{3}$$

Damping decrement of the network d_0 can be calculated using formula:

$$d_0 = \frac{G_n + G_L + \frac{1}{R_{np}}}{\omega C_s} \approx \frac{1}{R_{np} \omega C_s} \approx \frac{I_R}{I_{CS}}. \tag{4}$$

The nominal value of the earth fault current of the earthing resistor (in the network with the neutral point earthed by the resistor, several hundred amps) or, for compensated networks, the value of the current forced on the primary side by the Active Current Forcing Automation (ACFA - several amperes) system can be assumed as I_R.

Detuning coefficient s is given by the formula:

$$s = \frac{I_L - I_{CS}}{I_{CS}}. \tag{5}$$

The value of the earth fault current flowing through the current transformer (CT) installed at the beginning of the line (in the switchgear) can be calculated according to the formula:

$$\underline{I}_{kb} = \underline{\beta} I_{CS} \sqrt{{d_0}^2 + (s + a)^2}. \tag{6}$$

The value of the a coefficient is calculated from the formula (see Fig. 1):

$$a = \frac{I_{CL}}{I_{CS}}. \tag{7}$$

The value of the earth-fault current flowing through a given point of the line (e.g. the place of installation of the protection, recloser or fault current passage indicator) can be calculated according to the formula:

$$\underline{I}_{kZ} = \underline{\beta} I_{CS} \sqrt{d_0{}^2 + (s + a_i)^2} \tag{8}$$

The relative value of the share of the capacitive current I_{CLi} behind the considered point in the capacitive current of the network I_{CS} is calculated using formula:

$$a_i = \frac{I_{CLi}}{I_{CS}}. \tag{9}$$

Formulas 1-9 are universal and can be used in a compensated network as well as in a network with a resistor grounded neutral point. In the latter case, $s = -1$ should be assumed.

For the purpose of computational analysis of the effectiveness of the zero-sequence overcurrent criteria in the network with the neutral point grounded by the resistor, it was assumed that the network capacitance current $I_{CS} = 120$ A. Because in this type of systems it is assumed that in order to maintain the desired properties of this type of neutral point grounding, the damping decrement factor d_0 should be approximately $d_0 = 1.5$. Therefore the value of the rated earth fault current of the resistor was assumed equal to $I_R = 180$ A. At the nominal network voltage of 15 kV gives its nominal resistance equal to $R_{np} = 48.11\Omega$.

The most desirable properties of grounding the network through a resistor are [37]–[40]:

- slight earth fault overvoltage,
- low probability of restriking faults,
- small natural voltage asymmetry of the three-phase system,
- no tendency to ferroresonance.

In table 1 the values of the earth fault coefficients $\underline{\beta}$ and fault current at the fault location I_{k1} are presented. The calculations were carried out for according to the formula (3) for different transition resistances $\underline{R}_F$. The network parameters were as given above.

TABLE 1. Values of the earth fault coefficients and fault currents at the fault location and their modulus for various R_F in the MV network with the neutral point grounded by a resistor.

R_F (Ω)	$\underline{\beta}$	β	$\underline{I}_{k1}$ (A)	I_{k1} (A)
1	0.979-0.012i	0.979	177.6+115.3i	211.8
10	0.820-0.085i	0.824	157.8+83.1i	178.3
100	0.280-0.113i	0.302	64.0+13.3i	65.3
200	0.158-0.076i	0.175	37.6+5.3i	37.9
500	0.068-0.037i	0.077	16.7+1.5i	16.7
1000	0.035-0.020i	0.040	8.7+0.6i	8.7
2000	0.017-0.010i	0.020	4.3+0.2i	4.3
5000	0.007-0.004i	0.008	1.7+0.1i	1.7

The table 2 presents the calculated values of the earth fault current I_{kb} in switchgear. Their values were calculated according to the equation (6). Different values of the line capacitance behind the protection installation site are assumed. The table also shows the values of the a factor.

In order to assess the effectiveness of the zero-sequence overcurrent criterion in the network with the neutral point grounded by the resistor, the earth fault protection setting should be calculated from the formula:

$$I_{0set} = \frac{k_s I_{CLi}}{k_{rr}} + \Delta I_{0\mu}. \tag{10}$$

In equation 10 the following coefficients were assumed: $k_s = 2$, $k_{rr} = 0.98$ [32].

The zero-sequence current criterion setting must also meet the second condition:

$$k_{sens} = \frac{I_{CS}\sqrt{d_0{}^2 + (1 - a_i)^2} - \Delta I_{0\mu}}{I_{0nast}}. \tag{11}$$

The protection sensitivity factor k_{sens} for the selected I_{0nast} setting should be greater than 1.2 and preferably greater than 2 [32].

Problems with the proper selection of the current setting of the zero-sequence current criterion result mainly from the fact that these criteria, in systems with FCPI, obtain signals from atypical filters. These can be three series-connected Rogowski coils, three current transformers with through-going construction (in silicone insulation) [25]. There are also other non-standard solutions, such as measurement coils made in PCB HDI technology [41].

The value of the current error of the zero sequence current filter, depending on formulas (10) and (11), should be given on the primary side of the filter, because the FCPI current setting is calculated on the primary side. Currently, it can be assumed that the value of this error (for Holmgreen filter) is equal to $\Delta I_{0\mu} = 0.5$ A [32]. It is stated in [42] that this value is higher for non-standard zero sequence current filters. However, in further analyzes the value of $\Delta I_{0\mu} = 0.5$ A will be assumed with the hope that it is correct, and certainly taking into account the continuous development and improvement of the quality of measuring instruments.

Table 3 includes the current settings I_{0set} calculated according to the dependence (10) and rounded up to full units. The same table also shows the value of the sensitivity factor k_{sens} for a given setting.

Figure 2 show the values of the earth fault current I_{kz} at the FCPI installation site for different values of the transition resistance R_F at the fault location. They are compared with the setting values. The intersection of the lines in the graphs shows the value of the R_F above which the classically zero-sequence overcurrent criterion will not work.

The maximum detected values of the transition resistance R_{Fmax} at the fault location during single-phase earth faults in the network with the previously set parameters are, for different I_{CLi} values, show in the Figure 3.

It is clearly visible that in a situation where the capacitive current of the line downstream of the FCPI installation site is

TABLE 2. Calculated values of the earth fault current I_{kb} in the place of the protection installation.

I_{CLi} (A)	a	R_F (Ω)							
		1	10	100	200	500	1000	2000	5000
1	0.01	211.4	177.5	63.9	36.9	16.2	8.4	4.3	1.7
5	0.04	209.2	175.7	63.3	36.5	16.0	8.3	4.2	1.7
10	0.08	206.6	173.5	62.5	36.0	15.8	8.2	4.2	1.7
15	0.13	204.1	171.4	61.7	35.6	15.6	8.1	4.1	1.7
20	0.17	201.7	169.4	61.0	35.2	15.4	8.0	4.1	1.6
25	0.21	199.4	167.4	60.3	34.8	15.3	7.9	4.0	1.6
30	0.25	197.1	165.5	59.6	34.4	15.1	7.8	4.0	1.6

TABLE 3. Current settings and the corresponding sensitivity factors - neutral point grounded through a resistor.

I_{CLi} (A)	a	I_{0set} (A)	k_{sens}
1	0.01	3	52.9
5	0.04	11	15.7
10	0.08	21	7.9
15	0.13	31	5.0
20	0.17	41	3.6
25	0.21	52	2.7
30	0.25	62	2.2

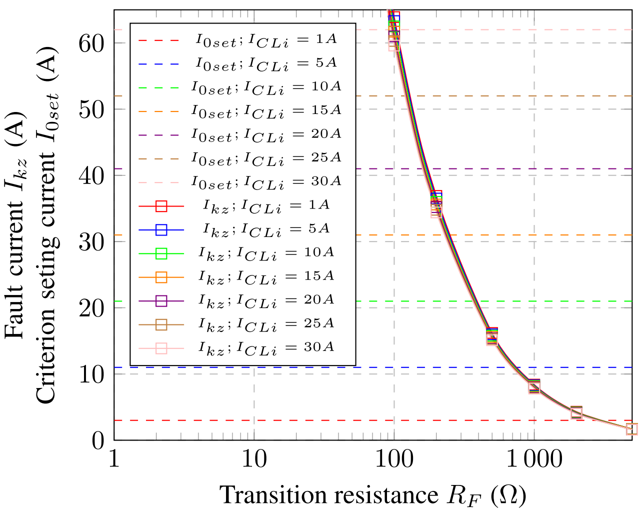

FIGURE 2. The values of the fault current I_{kz} and criterion setting current I_{0set} in the network with the neutral point grounded by the resistor for different I_{CLi} values.

small, i.e. in practice there is only an overhead line behind the signaling device, the effectiveness of the zero-sequence overcurrent criterion is quite high. Short-circuits with a transition resistance of up to a few kΩ can be detected. An increase in I_{CLi} (see Fig. 2) does not cause a significant decrease in the value of the zero-sequence current at the FCPI installation site of the I_{kZ}, however, in order to avoid unnecessary trips, its setting should be increased. As a result, in lines with higher capacitive current downstream of the installation of the FCPI, the zero-sequence overcurrent criterion has a very limited effectiveness.

It should be remembered that in the case of a setting for which the sensitivity coefficient is calculated according to the formula (11), it will be lower than 1, the FCPI will not detect any short-circuit, even a metallic one.

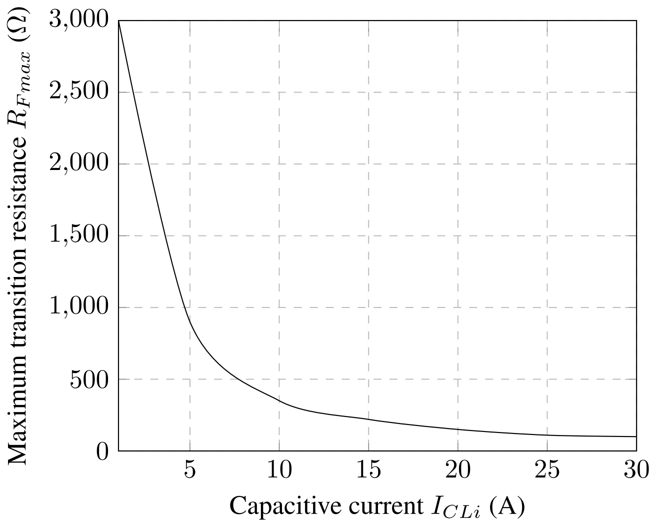

FIGURE 3. The maximum detected values of the transition resistance R_{Fmax} at the fault location during single-phase earth faults in the network with the previously set parameters, for different I_{CLi} values.

III. ADAPTIVE ZERO-SEQUENCE CURRENT CRITERION FOR MV NETWORK WITH A RESISTOR GROUNDED NEUTRAL POINT

A. GENERAL INFORMATION

In order to improve the effectiveness of earth fault detection in the MV network with the neutral point grounded by the resistor, it is proposed to adapt the criterion setting to the existing conditions using:

1) change of phase-to-earth voltages after the occurrence of an earth fault with simultaneous analysis of the value of the short-circuit current in FCPI installation site,
2) change of the value of the zero-sequence voltage in the place FCPI installation site.

In the first adaptation variant, it is therefore necessary to measure the phase-to-earth voltage. In the second one, the value of the zero sequence voltage should be measured.

Assuming that a non-metallic fault occurred in the network in phase L1, the values of the phase-to-earth voltages at the fault location will be calculated using equations (12), (13) and (14):

$$\underline{U}_{L1} = \underline{U}_0 + \underline{U}_1 + \underline{U}_2 = \frac{3R_F}{\underline{Z}_0 + \underline{Z}_1 + \underline{Z}_2 + 3R_F}\underline{E} \quad (12)$$

TABLE 4. Phase-to-earth voltages during an earth fault in the medium voltage network with the neutral point grounded by a resistor, U_n = 15 kV, d_0 = 1.5.

R_F (Ω)	$\underline{U}_{L1k}$ (V)	$\underline{U}_{L2k}$ (V)	$\underline{U}_{L3k}$ (V)	U_{L1k} (V)	U_{L2k} (V)	U_{L3k} (V)
1	176+j103	-12811-j7394	-12811+j7605	205	14792	14899
10	1559+j730	-11428-j6767	-11428+j8232	1722	13282	14085
50	4765+j1188	-8223-j6310	-8223+j8689	4911	10366	11964
100	6234+j6518	-6754-j6518	-6754+j8481	6311	9387	10843
250	7539+j563	-5449-j6936	-5449+j8063	7561	8821	9732
500	8092+j321	-4917-j7327	-4917+j7821	8079	8701	9239
1000	8359+j172	-4630+j7327	-4630+j7672	8361	8668	8961
2000	8508+j89	-4482+j7410	-4482+j7589	8509	8661	8841

$$\begin{aligned}\underline{U}_{L2} &= \underline{U}_0 + a^2\underline{U}_1 + a\underline{U}_2\\ &= \frac{3R_F}{\underline{Z}_0+\underline{Z}_1+\underline{Z}_2+3R_F}\\ &\quad \cdot[(a^2-a)\underline{Z}_2+(a^2-1)\underline{Z}_0+3a^2R_F] \qquad (13)\end{aligned}$$

$$\begin{aligned}\underline{U}_{L3} &= \underline{U}_0 + a\underline{U}_1 + a^2\underline{U}_2\\ &= \frac{3R_F}{\underline{Z}_0+\underline{Z}_1+\underline{Z}_2+3R_F}\\ &\quad \cdot[-(a^2-a)\underline{Z}_2+(a-1)\underline{Z}_0+3aR_F] \qquad (14)\end{aligned}$$

where $a = e^{j\frac{2}{3}\pi}$.

The phase-to-earth voltages during earth faults characterized by different values of the transition resistance in the network with the neutral point grounded by the resistor and with the damping decrement factor $d_0 = 1.5$, calculated using formulas (12)-(14) are shown in Table 4.

The value of the line capacitive current I_{CLi} downstream of the FCPI installation site, according to the dependencies (12)-(14), has no effect on the phase-to-earth voltage values at the fault location after the fault occurs.

It is understandable that in a short-circuit with a very low transition resistance, the phase-to-earth voltage approaches zero, while the voltage of the healthy phases increases almost to the value of the phase-to-phase voltage. With an increase in R_F, the disproportions between individual voltages decrease - for high-resistance short-circuits, the phase-to-earth voltages are close to the nominal.

B. AN ADAPTIVE ZERO-SEQUENCE CURRENT CRITERION THAT USES THE VARIABILITY OF PHASE-TO-EARTH VOLTAGES AFTER THE OCCURRENCE OF AN EARTH FAULT

After an earth fault occurs in the network, the phase-to-earth voltages change, e.g. as shown in Table 4. It is proposed to use this voltage variation to adapt the setting of the time-delay overcurrent protection. It is assumed that to fulfill the criterion it is necessary to measure only one phase-to-earth voltage. It should be noted that:

- the voltage of the earthed phase in relation to the ground decreases after the failure occurs,
- the voltage of healthy phases in relation to the ground increases (asymmetrically) after the failure.

Therefore, the adaptation of the zero-sequence current criterion should be active in a situation when:

1) the relative change of the phase-to-earth voltage is in the range from -60% to -5% (condition 1),
2) relative change in phase-to-earth voltage is in the range from $+2\%$ to $+60\%$ (condition 2),
3) the value of the zero-sequence current measured by the FCPI with the use of an appropriate measuring system meets the relationship $I_{kZ} > 5\Delta I_0$ (condition 3).

The change of the zero-current criterion setting value should occur when the following logical expression is fulfilled:

$$[(condition1) \vee (condition2)] \wedge (condition3) \qquad (15)$$

The values of the ranges under the conditions 1-3 were selected on the basis of experience and observation of the variability of voltages and currents during short-circuits. The ranges for conditions 1 and 2 must not be too narrow (then the adaptation gain would be small) or too wide (it may result in maloperations).

Condition 1 can be met when the voltage measurement necessary for the criterion to operate will be carried out in the phase in which the earth fault occurred. Condition 2 can be met when the voltage measurement is performed in the healthy phase. Condition 3 is very important for the criterion because it allows to distinguish between short-circuit and voltage fluctuations in the network. In this condition, ΔI_0 denotes the zero-sequence current measurement error introduced by the zero-sequence current filter.

To determine changes in the RMS value of the phase-to-earth voltage, the nominal voltage of the network should be used, i.e. for each i-th phase-to-earth voltage, the change in its RMS value after an earth fault occurs:

$$U_{Li\%} = \frac{U_{Li-k}}{U_{Ln}} \qquad (16)$$

The expression defining the setting of the adaptive zero-sequence current criterion for networks with the neutral point grounded by a resistor in a situation where the adaptation uses the phase-to-earth voltage variation is as follows:

$$I_{0set-a1} = k_{a1}\frac{k_s I_{CLi}}{k_{rr}} + \Delta I_{0\mu}. \qquad (17)$$

In formula (17) safety factor k_s is equal to 2, return ratio k_{rr} is equal to 0.98, current error of the zero sequence current filter $\Delta I_{0\mu}$ assumed equal to 0.5 A.

The value of the adaptation coefficient each of the formula (17) should be equal:

- 0.55, if the condition determined by the relation (15) is met, i.e. the criterion and setting adaptation is active,

- 1, if the condition (15) is not met and the criterion works as a classic zero-sequence current criterion.

Logical values of the conditions and pick-up as well as the settings of the adaptive zero-sequence current criterion for earth faults in the network with the neutral point grounded by a resistor ($d_0 = 1.5$) for different values of the a_i coefficient are presented in table 5. In this table the designation "×" refers to a situation in which a given condition is not met or there is no adaptive zero-sequence current criterion pick-up. If the cell is marked with "✓", it means that the given condition is met for a short-circuit with a given transition resistance R_F or the criterion is started.

TABLE 5. **Logical quantities and current settings of the adaptive zero-sequence current criterion for MV networks with the neutral point grounded by a resistor, $U_n = 15$ kV, $d_0 = 1.5$, $I_{CS} = 120$ A.**

R_F (Ω)	condition 1?	condition 2?	condition 3?	adaptation?	a = 0.01		a = 0.05		a = 0.1		a = 0.2	
					$I_{0set-a1}$ (A)	pick-up?	$I_{0set-a1}$ (A)	pick-up?	$I_{0set-a1}$ (A)	pick-up?	$I_{0set-a1}$ (A)	pick-up?
1	×	×	✓	×	3	✓	13	✓	26	✓	51	✓
10	×	✓	✓	✓	1.8	✓	7.2	✓	14	✓	27.4	✓
50	✓	✓	✓	✓	1.8	✓	7.2	✓	14	✓	27.4	✓
100	✓	✓	✓	✓	1.8	✓	7.2	✓	14	✓	27.4	✓
250	✓	×	✓	✓	1.8	✓	7.2	✓	14	✓	27.4	✓
500	×	×	✓	✓	1.8	✓	7.2	✓	14	✓	27.4	×
1000	×	×	✓	×	3	✓	13	×	26	×	51	×
2000	×	×	✓	×	3	✓	13	×	26	×	51	×
4000	×	×	×	×	3	×	13	×	26	×	51	×

The advantage of applying the adaptive zero-sequence current criterion for networks with the neutral point grounded by a resistor, which uses the change in the value of phase-to-earth voltages to adapt the setting, is obtained for FCPI installed in places of the network where the MV line is relatively large. For the participation coefficient $a_i = 0.01$ and $a_i = 0.05$, no increase in the effectiveness of the adaptation criterion is noted.

The mentioned benefit is apparently small, but it should be added here that in a network with a neutral point grounded by a resistor, the transition resistance values at the fault location are much smaller compared to the compensated network. It is related to the relatively high value of the current flowing at the fault location.

C. AN ADAPTIVE ZERO-SEQUENCE CURRENT CRITERION THAT USES THE VARIABILITY OF THE ZERO-SEQUENCE VOLTAGE IN THE PLACE OF INSTALLATION OF THE FCPI

Table 6 shows the RMS values of the zero-sequence voltage in the network with the neutral point grounded by the resistor for different values of the rated earth fault current of the resistor, and thus also the network damping decrement factor d_0.

According to the dependencies (1) and (3), the RMS value of the zero-sequence voltage in the network does not depend on the a_i coefficient (see formula (9)).

The setting of the zero-sequence current criterion using the RMS value of the zero-sequence voltage for adaptation

TABLE 6. **RMS values of the zero-sequence voltage in the MV network with the neutral point grounded by a resistor with different damping decrement factors, $U_n = 15$ kV, $I_{CS} = 120$ A.**

R_F (Ω)	U_0 (V)		
	d_0 = 1,5	d_0 = 2	d_0 = 2,5
1	8484	8428	8373
10	7138	6767	6436
50	4071	3548	3145
100	2616	2212	1913
250	1254	1036	878
500	670	549	462
1000	347	283	237
2000	176	143	120
4000	89	72	60

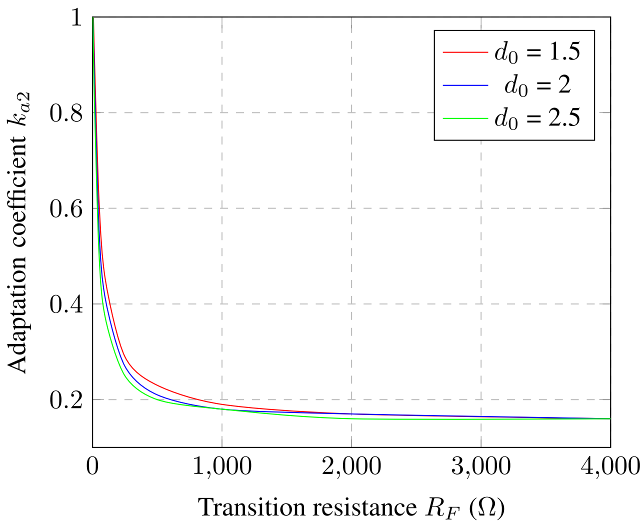

FIGURE 4. **The values of the adaptation coefficient k_{a2} for MV networks with the neutral point grounded by a resistor with different decrement damping factors d_0, $U_n = 15$ kV, $I_{CS} = 120$ A.**

should be determined from the dependence:

$$I_{0set-a2} = k_{a2} \frac{k_s I_{CLi}}{k_{rr}} + \Delta I_{0\mu}, \tag{18}$$

and the value of the adaptation coefficient k_{a2} from the formula:

$$k_{a2} = \frac{0,3 + \frac{2\sqrt{3}U_0}{U_n}}{2}. \tag{19}$$

The relationship (19) was developed on the basis of the author's experience related to the analysis of many cases of real short-circuits.

For such a defined adaptation coefficient k_{a2} of its value for the MV network with the neutral point grounded by a resistor, for which the RMS values of U_0 during various short-circuits are presented in Table 6, the adaptation coefficients shown in Figure 4 are obtained.

The current values I_{kZ} at the installation site of the FCPI, the settings of the adaptive zero-sequence current criterion using the RMS value of the zero-sequence voltage $I_{0set-a2}$ and information about the criterion pick-up are presented in Table 7. Various values of the coefficient a_i are taken into account with a damping decrement coefficient of $d_0 = 1.5$.

TABLE 7. Short-circuit current values in the place of installation of FCPI, settings of the adaptation criterion and information about the pick-up of the criterion in the network with the neutral point grounded by a resistor, U_n = 15 kV, I_{CS} = 120 A.

R_F (Ω)	I_{kZ} (A)	a = 0.01		a = 0.05		a = 0.1		a = 0.2	
		$I_{0set-a2}$ (A)	pick-up?	$I_{0set-a2}$ (A)	pick-up?	$I_{0set-a2}$ (A)	pick-up?	$I_{0set-a2}$ (A)	pick-up?
1	204.55	3.4	✓	14.7	✓	29.4	✓	57.6	✓
10	172.11	2.9	✓	12.6	✓	25.2	✓	49.5	✓
50	98.20	1.9	✓	8.1	✓	16.1	✓	31.6	✓
100	63.10	1.4	✓	5.9	✓	11.7	✓	23.0	✓
250	30.24	0.9	✓	3.8	✓	7.5	✓	14.8	✓
500	16.16	0.7	✓	3.0	✓	6.0	✓	11.7	✓
1000	8.36	0.6	✓	2.5	✓	4.9	✓	9.7	×
2000	4.25	0.5	✓	2.2	✓	4.4	×	8.7	×
4000	2.15	0.5	✓	2.1	✓	4.2	×	8.2	×

The adaptive zero-sequence current criterion, which uses the RMS value of the zero-sequence voltage may be very effective in a network with a neutral point grounded by a resistor. For FCPI, installed in short lines, earth faults with a transition resistance equal to $R_F = 4$ kΩ can be detected.

The effectiveness of the criterion decreases with an increase in the value of the capacitive current of the line downstream of the FCPI, however, the R_F limit values are always, for the criterion with this type of adaptation, higher than with conventional protections.

IV. SIMULATION TESTS OF ADAPTATION CRITERIA

A. GENERAL INFORMATION

Most of the research work carried out today is based on the results of experiments performed in various simulation environments. As the operation of the adaptation criteria was analyzed computationally and the results of these calculations were satisfactory, it was decided to build a simulation model of the MV network. As a rule, the model reflects the earth-fault phenomena with the maximum possible accuracy, the scale of the model is adequate to the size of the actual network. In addition, the model is highly expandable for future research.

The simulation environment was PSCad ver. 4.2.1.

B. SIMULATION MODEL

The general view of the model is shown in Fig. 6.

The model represents a HV/MV substation powered by a transformer with a YNd11 connection group with a rated power of $S_{tr} = 25$ MVA.

The value of no-load losses of transformer was assumed to 14 kW, and the load losses equal to 130 kW. The transformer's short-circuit voltage is 12 %. All these values, although unnecessary from the point of view of earth fault calculations, are typical for transformers with the assumed power.

The short-circuit power of the HV power system is 1500 MVA, although this power has no effect on the ground fault calculation. It is given for complementary purposes.

The nominal voltage of the modeled MV network is equal to $U_n = 15$ kV, which gives the nominal voltage of the phase-to-earth voltage equal to $U_{nL} = 8660$ V.

The modeled network can work with the neutral point:

- grounded through a resistor of any rated resistance value,
- grounded by a Petersen coil of any compensating current value, without active current forcing automation (ACFA),
- grounded through the compensating reactor as above, but with ACFA,
- grounded by a parallel system of a reactor and a resistor,
- isolated.

The earthing transformer is modeled as a device with the ZNyn11 connection group and has a compensation power $S_{tre} = 400$ kVA.

The model can simulate a network with any value of capacitive earth fault current I_{CS}, whereby the entire value of this current is divided into two lines:

- line powered from the Y bay, which consists of 5 sections, with the possibility of making a short-circuit at the end of each section and with measurement of electrical quantities at the beginning of each section. The sections are numbered from 1 to 5 (gray rectangles with arrows),
- line powered from the X bay, which consists of one section that is to represent the rest of the network not covered by the short-circuit. The line powered from the X bay is the so-called network background.

Each segment of the network is constructed as a mirror Γ-network. In the longitudinal branch of the Γ-network, resistance and inductance are simulated, while in the transverse branch - capacitance and conductance related to line leakage. The internal structure of the LINE block is shown in Fig. 5.

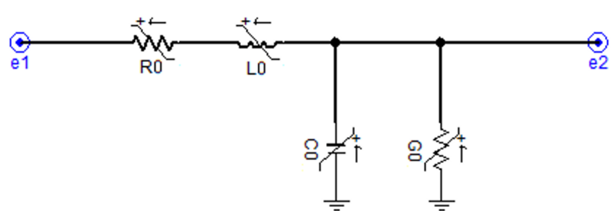

FIGURE 5. Internal structure of the LINE block.

The parameters of individual elements of the LINE block are determined in separate calculation modules, while the line resistance and inductance, which have a slight impact on the earth-fault processes, are declared as constant values corresponding to the line with resistance $R0 = 0.5$ Ω and inductive reactance $X0 = \omega L0 = 0.05$ Ω. The earth capacitance C0 of the line assumes a value depending on the value of the declared capacitive current of a given line section, while the value of the conductance G0 reflects the natural leakage of the line.

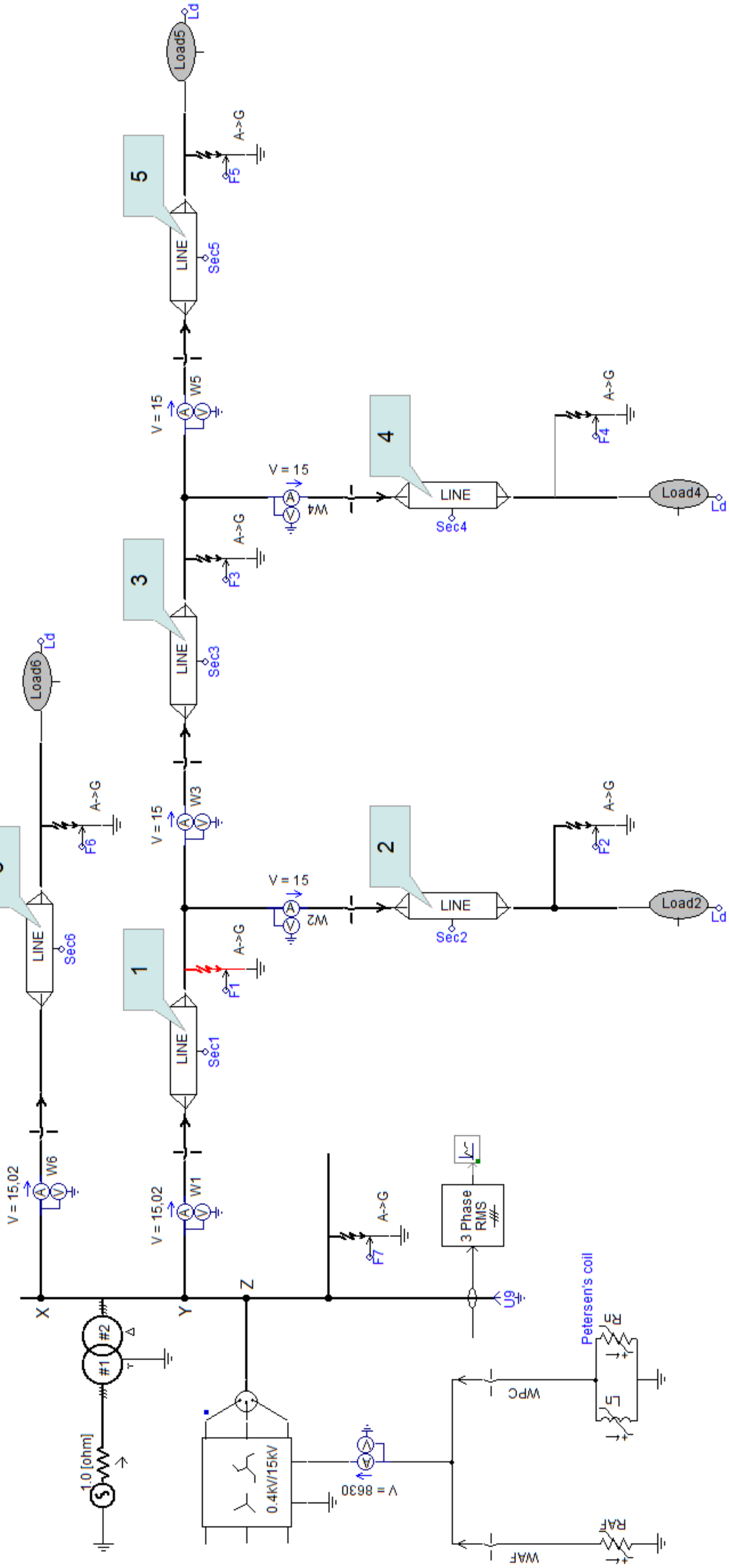

FIGURE 6. MV network model used during simulation tests.

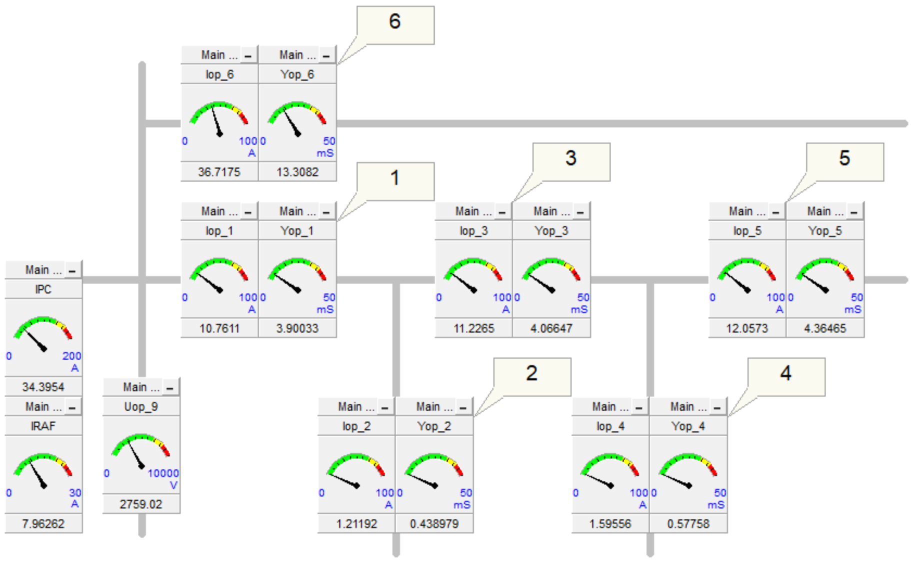

FIGURE 7. General view of the measuring module.

During the simulation tests, the following values of capacitive currents I_{CLi} for individual sections of the line powered from Y bay were adopted:

- section 1: 1.2 A,
- section 2: 4.8 A,
- section 3: 6.0 A,
- section 4: 6.0 A,
- section 5: 6.0 A.

The value of the capacitive current of section 6 (network background) was selected so that the total capacitive current during all tests was equal to $I_{CS} = 120$ A.

The length of the line or section is not given - for estimation purposes, it can be assumed that 1 km of an overhead line has a capacitive current value of 0.05 A. In the case of a cable line, the capacitive current (per 1 km) depends on the rated voltage of the cable and its cross-section - it can be assumed 2.5 A/km.

The modeled earth-fault can be characterized by any adjustable R_F resistance , but in any situation the short-circuit is made between the L1 phase and the ground. The location of the fault can be selected by the user using the appropriate control element from among 7 locations:

- point 1: behind the section 1 of the line powered from Y bay,
- point 2: after the section 2 of the line powered from the Y bay,
- point 3: after the section 3 of the line powered from Y bay,
- point 4: after the section 4 of the line powered from Y bay,
- point 5: after the section 5 of the line powered from Y bay,
- point 6: behind the section 6 of the line powered from X bay,
- point 7: short-circuit on the busbar.

After sections 2, 4, 5 and 6, the line load is modeled in the form of three resistors connected in a triangle with a resistance $R_{load} = 1$ MΩ.

The simulation results are visualized in the measurement module, the view of which is shown in Figure 7. It is possible to read directly:

- RMS value of zero-sequence voltage on busbar,
- RMS value of zero-sequence current at the beginning of each line segment 1-6,
- zero-sequence admittance values at the beginning of each line segment 1-6,
- earthing reactor current IPC,
- grounding resistor current IRAF.

In addition, a report is generated for a text file and a CSV file, which in addition to the above-mentioned sizes provides, among others:

- RMS values of zero-sequence voltage at the beginning of each line segment 1-6,
- RMS values of phase-to-earth voltages at the beginning of each segment 1-6,
- RMS values of phase currents at the beginning of each segment 1-6.

C. SIMULATION PROCEDURE

In section III two adaptive zero-sequence current criteria are presented, which are to be implemented in FCPI in the network with the neutral point grounded by a resistor. Both methods were verified during the same simulation calculations.

Simulation procedure:

1) assumptions: $I_{CS} = 120$ A, $I_R = 180$ A,
2) n-times start of the simulation for different I_{CLi} values, i.e. for different values of the capacitive current of the line after the FCPI installation site,
3) aggregation of the phase-to-earth voltage values of all phases, i.e. U_{L1-k}, U_{L2-k}, U_{L3-k}, zero-sequence voltage U_{0-s} and zero-sequence current U_{0-s} at the

location of the FCPI, assuming that this may be the beginning of any section 1-6,

4) determining of the value of the k_{a1} adaptation coefficient,
5) determining the value of the k_{a2} adaptation coefficient (in the spreadsheet),
6) calculating the settings of both criteria, i.e. $I_{0set-a1}$ and $I_{0set-a2}$,
7) checking the starting condition of the criteria and assessing the possibility of its operation under given conditions.

The criteria pick-up condition is given by the appropriate dependencies:

$$I_{0set-a1} \leq I_{0-s} \tag{20}$$

$$I_{0set-a2} \leq I_{0-s} \tag{21}$$

During all tests, it was taken into account that the current error on the primary side of sequence current filter is equal to $\Delta I_{0\mu} = 0.5$ A.

D. SIMULATION RESULTS

Table 9, included in Appendix A, summarizes the results of simulations carried out with the use of the constructed MV network model. The results relate to the zero-sequence current criterion using the U_{Li-k} and I_{0-s} values for adaptation. Table 10 in appendix B shows the simulation results for the zero-sequence current criterion, which uses the RMS value of the zero-sequence voltage to determine the adaptation factor k_{a2}.

The effectiveness of the criteria was checked using the dependencies (20) and (21). For this purpose, the settings of the adaptation criteria $I_{0set-a1}$ and $I_{0set-a2}$ were calculated. The results of the calculations are presented in the table 8. It also contains an analysis of the work of adaptation criteria.

The zero-sequence current criterion, which use the U_{Li-k} and I_{0-s} values for adaptation, is in Table 8, for simplicity, called "a1 criterion". The zero-sequence current criterion, which uses the RMS value of the zero-sequence voltage to determine the adaptation factor k_{a2} is in Table 8 called "a2 criterion".

In the table 8, the criterion start-up is marked with a "✓", and the "×" - no start-up. Moreover, marking in green means the pick-up of a given adaptive criterion in the absence of a pick-up of the classic criterion. The blue color indicates the pick-up of the "a2" criterion in the absence of the "a1" criterion.

In total, simulations were performed for 30 earth faults cases with different transition resistances R_F and with different a_i coefficient values. The classic zero-sequence current criterion made it possible to detect 13 short-circuits, which constitutes approx. 43% of all simulated faults.

The zero-sequence current adaptive criterion, which for adaptation uses the RMS phase-to-earth voltage the RMS value of the zero-sequence current, was picked-up during 16 of the simulated earth fault cases, which accounts for approximately 53% of all failures. The criterion is therefore about 10% more effective than the classic zero-sequence current criterion.

TABLE 8. **Results of simulation and analytical calculations related to the zero-sequence current criteria and logical values related to the pick-up of these criteria in the network with the neutral point grounded by a resistor, I_{CS} = 120 A, I_R = 180 A.**

R_f (Ω)	a_i	I_{0-s} (A)	classic criterion		a1 criterion		a2 criterion	
			I_{0set} (A)	pick-up?	$I_{0set-a1}$ (A)	pick-up?	$I_{0set-a2}$ (A)	pick-up?
	0.01	63.12	3.0	✓	1.8	✓	1.3	✓
	0.05	63.11	13.1	✓	7.2	✓	5.8	✓
100	0.10	63.10	25.8	✓	14.0	✓	11.4	✓
	0.15	63.09	38.4	✓	20.7	✓	16.9	✓
	0.20	63.08	51.0	✓	27.4	✓	22.4	✓
	0.01	30.25	3.0	✓	1.8	✓	0.9	✓
	0.05	30.24	13.1	✓	7.2	✓	3.8	✓
250	0.10	30.24	25.8	✓	14.0	✓	7.5	✓
	0.15	30.24	38.4	×	20.7	✓	11.1	✓
	0.20	30.24	51.0	×	27.4	✓	14.8	✓
	0.01	16.16	3.0	✓	1.8	✓	0.7	✓
	0.05	16.16	13.1	✓	7.2	✓	2.9	✓
500	0.10	16.16	25.8	×	14.0	✓	5.7	✓
	0.15	16.16	38.4	×	20.7	×	8.4	✓
	0.20	16.16	51.0	×	27.4	×	11.2	✓
	0.01	11.02	3.0	✓	3.0	✓	0.6	✓
	0.05	11.02	13.1	×	13.1	×	2.6	✓
750	0.10	11.02	25.8	×	25.8	×	5.2	✓
	0.15	11.02	38.4	×	38.4	×	7.7	✓
	0.20	11.02	51.0	×	51.0	×	10.2	✓
	0.01	8.36	3.0	✓	3.0	✓	0.6	✓
	0.05	8.36	13.1	×	13.1	×	2.5	✓
1000	0.10	8.36	25.8	×	25.8	×	4.9	✓
	0.15	8.36	38.4	×	38.4	×	7.3	✓
	0.20	8.36	51.0	×	51.0	×	9.7	×
	0.01	4.25	3.0	✓	3.0	✓	0.5	✓
	0.05	4.25	13.1	×	13.1	×	2.2	✓
2000	0.10	4.25	25.8	×	25.8	×	4.4	×
	0.15	4.25	38.4	×	38.4	×	6.5	×
	0.20	4.25	51.0	×	51.0	×	8.7	×

The zero-sequence current adaptive criterion, which uses the RMS value of the zero-sequence voltage for adaptation, was picked-up at 26 simulated short-circuits, which corresponds to about 87% of all failures. Therefore, the criterion is about 44% more effective than the classic zero-sequence overcurrent criterion.

The results of simulations and calculations show that the zero-sequence current adaptive criterion using the RMS value of the zero-sequence voltage for adaptation is characterized by a significantly higher earth fault detection efficiency than the criterion based on the adaptation using RMS value of phase-to-earth voltage and zero-sequence current. The differences are especially visible in the situation where there is a longer cable section behind the FCPI, characterized by a relatively high value of the capacitive current I_{CLi}. For such lines, the better of the proposed criteria allows to detect a short-circuit with a transition resistance $R_F = 750$ Ω. If there is a short section of a cable line or an overhead line after the FCPI installation site, the proposed adaptive criteria are equally effective and do not have any advantage over the classic zero-sequence overcurrent criterion.

TABLE 9. The results of simulation and analytical calculations related to the adaptive zero-sequence current criterion using for adaptation the value of the RMS voltage of one phase-to-earth voltage and the value of the zero-sequence current, I_{CS} = 120 A, I_R = 180 A.

R_F (Ω)	I_{CLi} (A)	a_i	U_{L1-k} (V)	U_{L2-k} (V)	U_{L3-k} (V)	I_{0-s} (A)	k_{a1}
100	1.2	0.01	6312	9387	10843	63.12	0.55
	6	0.05	6311	9387	10843	63.11	0.55
	12	0.10	6310	9387	10843	63.10	0.55
	18	0.15	6309	9387	10843	63.09	0.55
	24	0.20	6308	9387	10843	63.08	0.55
250	1.2	0.01	7561	8821	9732	30.25	0.55
	6	0.05	7561	8821	9732	30.24	0.55
	12	0.10	7560	8821	9733	30.24	0.55
	18	0.15	7560	8822	9733	30.24	0.55
	24	0.20	7559	8822	9733	30.24	0.55
500	1.2	0.01	8079	8701	9239	16.16	0.55
	6	0.05	8079	8701	9239	16.16	0.55
	12	0.10	8079	8701	9239	16.16	0.55
	18	0.15	8078	8701	9239	16.16	0.55
	24	0.20	8078	8701	9239	16.16	0.55
750	1.2	0.01	8265	8677	9056	11.02	1
	6	0.05	8265	8677	9057	11.02	1
	12	0.10	8265	8677	9057	11.02	1
	18	0.15	8265	8677	9057	11.02	1
	24	0.20	8265	8677	9057	11.02	1
1000	1.2	0.01	8361	8668	8961	8.36	1
	6	0.05	8361	8668	8961	8.36	1
	12	0.10	8361	8668	8962	8.36	1
	18	0.15	8361	8668	8962	8.36	1
	24	0.20	8361	8668	8962	8.36	1
2000	1.2	0.01	8509	8661	8814	4.25	1
	6	0.05	8509	8661	8814	4.25	1
	12	0.10	8508	8661	8814	4.25	1
	18	0.15	8508	8661	8814	4.25	1
	24	0.20	8508	8661	8814	4.25	1

V. CONCLUSION

For the medium voltage networks working with the neutral point grounded by a resistor, it was proposed to adapt the zero-sequence current criterion setting using the change of the phase-to-earth RMS voltage and using the zero-sequence voltage RMS value.

The advantage of using the adaptive zero-sequence current criterion, using a change in the value of phase-to-earth voltage to adapt the setting, is obtained for FCPIs installed in such network points where the MV line has relatively high value of the capacitive current I_{CLi}. For the a_i not greater than 0.05, there is no increase in the effectiveness of the adaptation criterion. It should be noted that the increase in the detected transition resistance R_F is by several hundred ohms, which is a significant value in a network with the neutral point grounded by a resistor.

The advantage of the method is also the fact that there is no need to carry out complex and resource-consuming calculations related to, for example, the wavelet transform or the Fourier transform. Thanks to this, the method can be implemented in inexpensive devices such as FCPI.

Of course, adaptive methods also have the disadvantage of having to feed the FCPI signals related to the voltage measurement at the FCPI installation site. For the presented methods, it is necessary to provide the values of the phase-to-earth RMS voltages or the zero-sequence voltage. Measurement can be performed locally with the use of voltage transformers or sensors. The literature also provides another possibility - remote transmission of information about U_0 from the MV switchgear [28]. This solution seems to be the most advantageous, provided that high-speed data transmission technology is used.

The zero-sequence current criterion with an adaptive function, which uses the RMS value of the zero-sequence voltage to change the criterion setting value, can be very effective. For FCPIs installed in short taps, earth faults with a transition resistance equal to R_F = 4 kΩ can be detected. The effectiveness of the criterion decreases with an increase in the value of the capacitive current of the line downstream of the FCPI, however, the R_F limit values for the criterion with such adaptation type are always higher compared to the classic zero-sequence overcurrent criterion.

In order to verify the effectiveness of the criteria, simulation tests were carried out. The simulation environment was PSCAD software.

The results of simulations and calculations carried out for the zero-sequence overcurrent criteria with the adaptation function for networks with a neutral point grounded by a resistor show that the criterion using the RMS value of the zero-sequence voltage for adaptation is characterized by a significantly higher efficiency of earth fault detection than the criterion based on adaptation which uses the measurement of phase-to-earth voltage and zero-sequence current. For such lines, the better of the proposed criteria allows to detect a short-circuit with a maximum transition resistance R_{Fmax} = 750 Ω in cases where the classical overcurrent

TABLE 10. The results of simulation and analytical calculations related to the adaptive zero-sequence current criterion using for adaptation the value of the zero-sequence voltage, I_{CS} = 120 A, I_R = 180 A.

R_F (Ω)	I_{CLi} (A)	a_i	U_{0-s} (V)	k_{a2}
100	1.2	0.01	2488	0.44
	6	0.05	2489	0.44
	12	0.10	2489	0.44
	18	0.15	2489	0.44
	24	0.20	2489	0.44
250	1.2	0.01	1184	0.29
	6	0.05	1184	0.29
	12	0.10	1185	0.29
	18	0.15	1185	0.29
	24	0.20	1185	0.29
500	1.2	0.01	631	0.22
	6	0.05	631	0.22
	12	0.10	631	0.22
	18	0.15	631	0.22
	24	0.20	632	0.22
750	1.2	0.01	430	0.20
	6	0.05	430	0.20
	12	0.10	430	0.20
	18	0.15	430	0.20
	24	0.20	430	0.20
1000	1.2	0.01	326	0.19
	6	0.05	326	0.19
	12	0.10	326	0.19
	18	0.15	326	0.19
	24	0.20	326	0.19
2000	1.2	0.01	8509	8661
	6	0.05	166	0.17
	12	0.10	166	0.17
	18	0.15	166	0.17
	24	0.20	166	0.17

criteria would not operate. This value applies to FCPI installed in line with any value of capacitive current. In situations more typical for FCPI, i.e. when the I_{CLi} value is small, it is possible to detect short-circuits with a transition resistance above 2 kΩ.

Comparing the effectiveness of the proposed methods to other protection criteria, it can be concluded that it is similar to the most sensitive methods so far. In [43], the Authors state that the admittance criteria Y_0> and G_0> are able to detect a short circuit with a transition resistance up to 4 kΩ, which can also be found in [44]. The effectiveness of the wattmetric criteria ends at 1.5 kΩ. It is worth mentioning, however, that all these values apply to protections installed in MV switching stations, where there is access to accurate and precise measurements, in particular zero-sequence voltage. Moreover, the authors do not analyze the influence of the value of the line capacitive current. The proposed method is therefore competitive with the others and applicable to FCPI.

Finally, it is worth adding that all of the above conclusions are valid for a network with damping decrement d_0 from the network equal to 1.5. In such a network, all the desired features of the network with the neutral point grounded by a resistor are preserved, but at the same time the operating conditions of the earth-fault protection are the most difficult.

APPENDICES

In the table A1, I_{CLi} denotes the capacitive current of the i-th line segment after the FCPI, and this is the share of the capacitive current of the line section after the FCPI in relation to I_{CS}. U_{L1-k}, U_{L2-k} and U_{L3-k} are the simulated RMS values of phase-to-earth voltages in the place of installation of the FCPI. I_{0-s} denote the value of the zero-sequence current at the fault location. The k_{a1} column contains the calculated values of the adaptation coefficient.

Table 10 shows the simulation results for the zero-sequence current criterion, which uses the RMS value of the zero-sequence voltage to determine the adaptation factor k_{a2}. In the table U_{0-s} is the RMS value of zero-sequence voltage at the place of installation of the FCPI, k_{a2} is an adaptation coefficient determined from the dependence 19.

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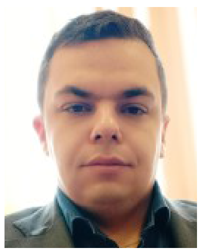

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