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Simulation of earth faults in parallel lines in mine medium voltage networks

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Abstract. The paper focuses on the phenomenon of earth faults in mine medium voltage networks with an isolated neutral system. Simplified network models with parallel lines have been considered. The article presents the zero-sequence current in places where in normal conditions earth fault protections relays are installed. For this purpose, the tCad program was used to simulate these networks. Research is preliminary.

1. Introduction

In the Polish mining industry, medium voltage networks (eg 3.3 kV or 6 kV) with an isolated neutral system are used to transport energy and power electrical equipment. These networks are extremely extensive and complicated (particularly in the case of 6kV networks, as the 3,3kV network configurations are quite simple). In addition, they are often rebuilt. These types of networks are particularly vulnerable to failures. This increases the risk of failure. The most frequent failure in medium-voltage mining networks is a single-phase earth fault [1,2]. In the case of a network with an insulated neutral point the earth fault has a small short circuit current value in comparison to other short circuit types. However, even in this case, this network fault bring a risk of thermal, fire, shock and explosive hazard [3]. This hazard is characteristic for the Polish mining industry due to the prevalence of methane [4]. It is also worth noting that the earth fault increases the risk of line-to-line short-circuit.

The purpose of this article is to better understand the phenomenon of earth faults in mine medium voltage networks on the basis of the example of simple models. The results obtained by this method can be used to create a more accurate network model. This model will be compared in further publications with fault transient data recorded by digital relays at real mining networks.

Earth fault protection can be used for signaling, but in most mines it is used as an instantaneous protection due to the risk of methane and coal dust explosion. This limits the selectivity of protection operations. In networks with an isolated neutral system, only three types of protection are used: zero-voltage, overcurrent, admittance (susceptance). They can be also set as directional ones in order to limit the protection zone and increase their reliability.

Zero-sequence voltage protection measures the voltages in the entire whole galvanically connected network. Their main disadvantage is that they cannot be used to determine a particular earth-faulted line. They are often used to cooperate with other protection. The overcurrent protections relays measure the value of the zero-sequence current component at the beginning of the protected line and when the relay setting value is exceeded they open the contactors. They can be used only if the condition [5] is met:



$$k_{nz}I_{cx} \leq I_n \leq \frac{I_c - I_{cx}}{k_c} \quad (1)$$

where:

- k_{nz} – reliability coefficient ($k_{nz} \geq 4$),
- k_c – sensitivity coefficient ($k_c \geq 2$),
- I_{cx} – capacitive current of the protected line,
- I_c – capacitive current of the entire network in which the protected line works.

Admittance protections measure the so-called zero-sequence admittance. It is the ratio of the zero-sequence current at the beginning of the protected section to the zero-sequence voltage. The directional protection, on the other hand, uses the property of earth fault current phase difference in the insulated neutral system, consisting in the return of the zero-sequence current at the beginning of the damaged section in comparison to the healthy sections.

2. Methodology of research

In the insulated neutral system, there is always a capacitive coupling between the conductors and the earth, which causes capacitive currents to flow in the system. Typically, these capacities, to simplify the earth fault current value calculation, are grouped together as one (lumped) capacitor for each phase. The zero-sequence current component value, calculated as the sum of the all the load currents, in the absence of a earth fault is zero. When one phase is connected to the ground, the line-to-earth voltages in the other phases increase $\sqrt{3}$ times (the line-to-line voltage values remain the same). The current in the damaged line flows from the transformer through the ground fault resistance (which in the case of a metallic ground fault is zero), earth, earth capacities of healthy lines and through healthy lines returns to the transformer (figure 1). The zero-sequence current component value is much smaller than the load current value.

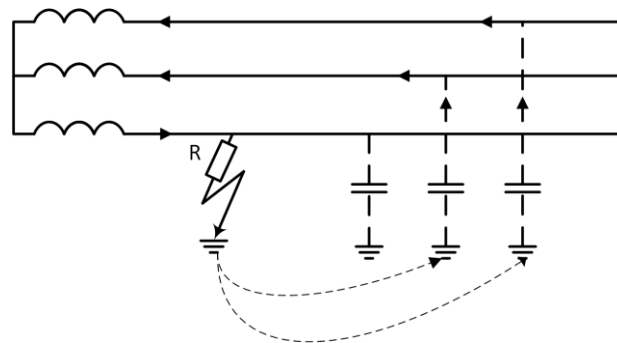


Figure 1. Model of an isolated neutral system in the event of an earth fault.

In the mining industry, earth faults have been an extensive topic of scientific research due to the complexity of the phenomenon and the continuing lack of a comprehensive and versatile solution [6-8]. In this paper, earth fault simulations will be carried out for three simple mining network models (figure 2). Each system was simulated in two configurations: no additional line - 'a' series and with additional lines from the RG switchgear - 'b' series. The results of the simulation are preliminary and are an introduction to the further research on earth faults.

As part of the simulation, it was assumed that all sections of cable lines are modelled as the series connection of 10 RC subcircuits. Each subcircuit as a part of the cable line consists of a series resistance acting as a wire resistance and a capacitor acting as a line-to-ground insulation capacitance. There have been also adopted additional assumptions as:

- the impact of the SUPO system [9] was neglected – a zero value of the protective conductor resistance,
- the conductance of the insulation has been neglected,
- the inductance of the wires has been neglected,
- the earth fault was assumed metallic and the rise time of it was infinitesimally short.

The cable parameters are listed in table 1. It was assumed that the earth fault occurred at a distance of 750 m from the RG in the K1 cable.

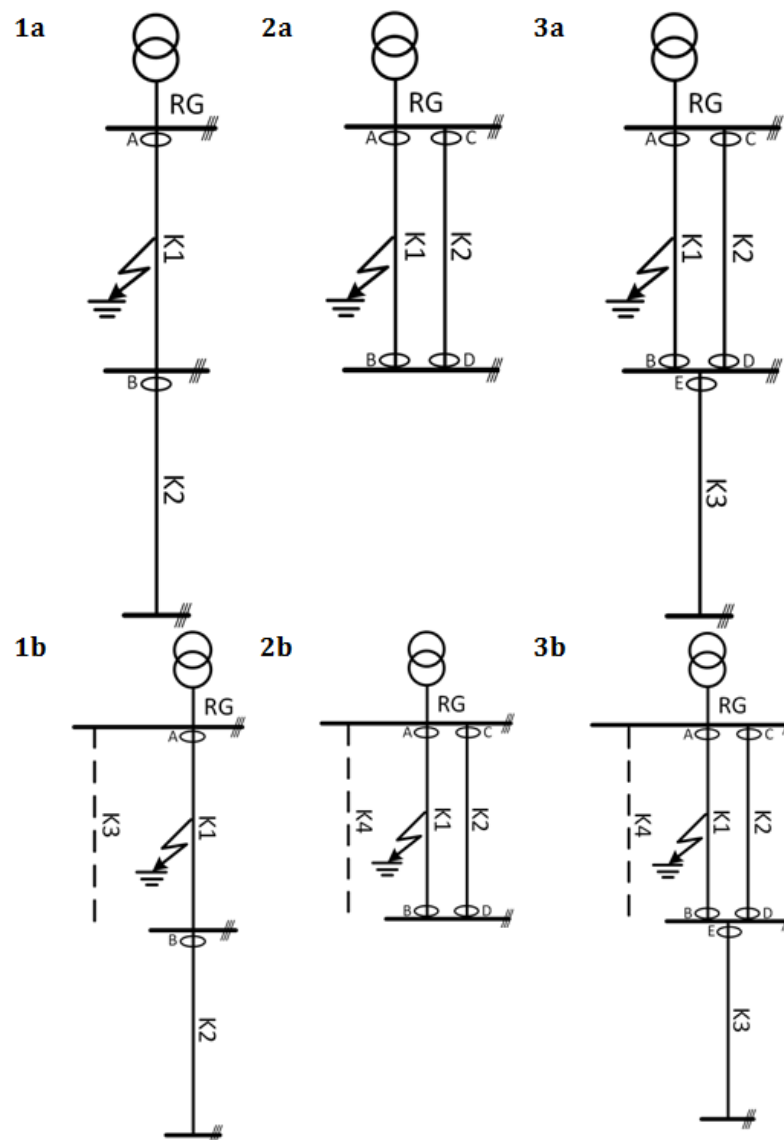


Figure 2. Layouts of simulated networks with marked earth fault locations and zero-sequence current component measurement locations

The data from table 1 concern both the 'a' and the 'b' cases. An additional cable K3 or K4 in the 'b' series networks marked with a broken line serves as the sum of outgoing cables from distribution board RG. The runs of these outgoing cables will not be measured. They were introduced in order to

show a significant impact of the remaining network capacitance on the filter measurement values. The total capacitive current for additional outgoing cables is 3.15 A for each system.

The tCad program was used for simulation tests. This is a software written by employees of the Gdańsk University of Technology. In calculations he uses the nodal analysis. It was chosen because of the simple interface and the speed of calculation.

Table 1. Cable parameters included in the simulations.

Circuit configuration	Cable name	Cable length (km)	Resistance of conductor (Ω)	Ground capacitance (μF)	Capacitive current of the whole cable (A)
1	K1	1,5	0,1131	0,81	3,09
	K2	1,0	0,0754	0,54	2,06
2	K1	1,5	0,1131	0,81	3,09
	K2	1,5	0,1131	0,81	3,09
	K1	1,5	0,1131	0,81	3,09
3	K2	1,5	0,1131	0,81	3,09
	K3	1,0	0,0754	0,54	2,06

3. Results

In situation 1a, the earth fault has occurred in a line that has only one outgoing cable and no other outgoing line has been connected to the transformer. At the moment of earth fault, the phase voltage of the damaged line drops to 0, while the voltages of healthy phases increase $\sqrt{3}$ times (figure 3). The zero-sequence voltage component after a ground fault is different from zero (figure 4). Exactly the same situation happens in other models, that is why the phase voltage waveforms for the 1b, 2a, 2b, 3a and 3b systems will be omitted. The article focuses on states of steady-state values of zero sequence currents. Transient situations occurring at various points in the network at the moment of earth fault will not be considered.

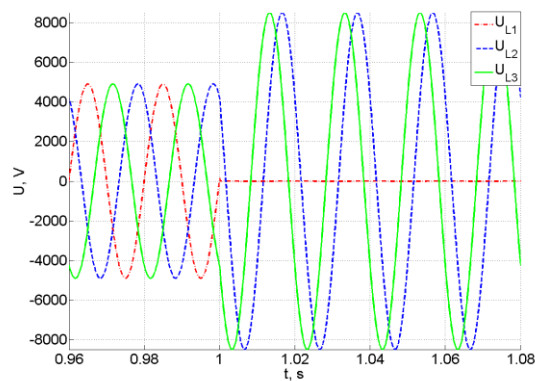


Figure 3. Waveforms of phase voltage for circuit 1a.

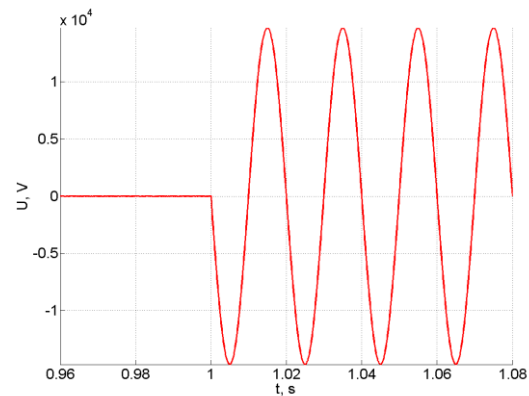


Figure 4. Waveform of zero-sequence voltage for circuit 1a.

A slightly different situation takes place in the case of earth fault current (figures 5, 7, 9, 11, 13, 15). The earth fault current depends directly on the sum of capacitive currents of all lines included in the galvanically connected network. In order to validate the correctness of the simulation results, theoretical values of steady-state earth fault currents were calculated and compared to the simulation results. The results are presented in table 2.

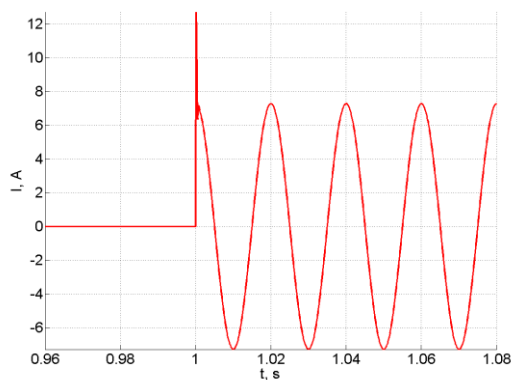
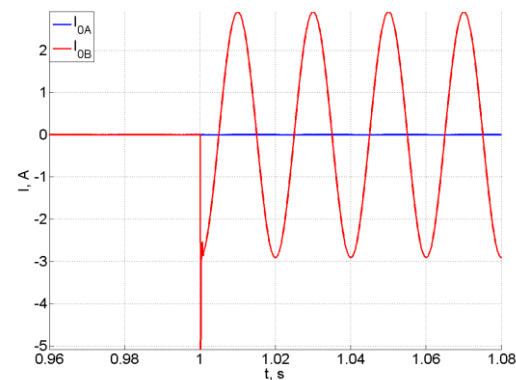
After analyzing table 2, it can be concluded that the simulation results are correct.

Table 2. Comparison of ground faults with theoretical simulations.

Circuit configuration	tCad		Theoretical
	Maximum value of earth fault current (A)	The effective value of earth fault current (A)	The effective value of earth fault current (A)
1a	7,276	5,160	$3,09 + 2,06 = 5,15$
1b	11,721	8,288	$5,15 + 3,15 = 8,30$
2a	8,7319	6,193	$3,09 + 3,09 = 6,18$
2b	13,152	9,300	$6,18 + 3,15 = 9,33$
3a	11,645	8,259	$3,09 + 3,09 + 2,06 = 8,24$
3b	16,112	11,393	$8,24 + 3,15 = 11,39$

3.1. Circuit 1

In the case of circuit 1a, the measurement of the zero-sequence current component at the points A and B (figure 6) differs significantly from each other, but considering the phenomenon of earth fault will confirm the above results. Earth fault caused an increase in the value of current flowing in the damaged wire 3 times, while the current in the other wires increased $\sqrt{3}$ times. The earth fault current will flow into healthy wires through ground capacities, however, the zero-sequence filter A will not detect this, because all capacitances galvanically connected to each other are located behind the filter.

**Figure 5.** Waveform of earth fault current for circuit 1a.**Figure 6.** Waveforms of zero-sequence current components at measurement the points for circuit 1a.

The situation is slightly different in the case of the point B. Because the earth fault occurred before this point, the current of the damaged wire will flow only to the fault location via this line. Due to the fact that in the point B the faulted phase current equals to zero, the zero-sequence current component in this place will be reversed by 180° against the earth fault current.

The above situation occurs if only one cable is supplied from the transformer. In practice, this situation does not happen. The appearance of additional outgoing cables (figure 8) causes the earth fault current to dissipate also to the phases of additional healthy lines. This will cause the zero-sequence current component to appear at the point A, which is consistent with the earth fault current. The effective value of this current is greater than the effective value of the zero-sequence current component at the point B. The capacitance of additional outgoing lines has no influence on the value of the zero-sequence current at the point B.

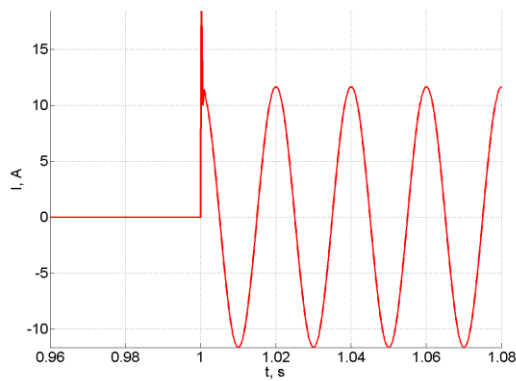


Figure 7. Waveform of earth fault current for circuit 1b.

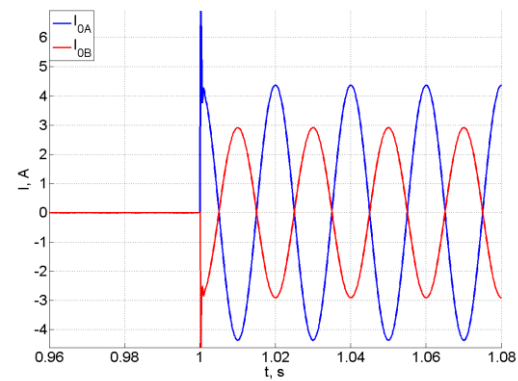


Figure 8. Waveforms of zero-sequence current components at measurement the points for circuit 1b.

3.2. Circuit 2

In the case of the second system, the matter gets complicated because the network is not a radial one. Parallel lines are quite a complex layout and a detailed analysis of such a line goes beyond the scope of this paper. In circuit 2a, the earth fault current path closes through the capacitance of both damaged and healthy lines, hence the zero-sequence current value measured by the filter A can no longer be zero.

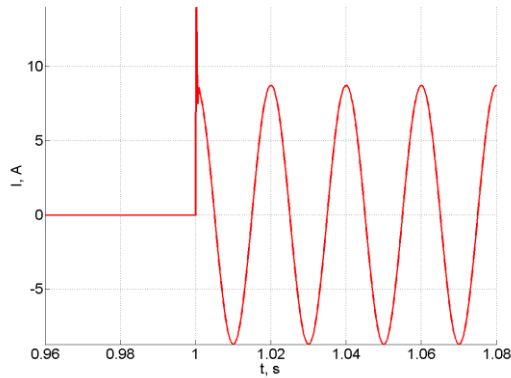


Figure 9. Waveform of earth fault current for circuit 2a

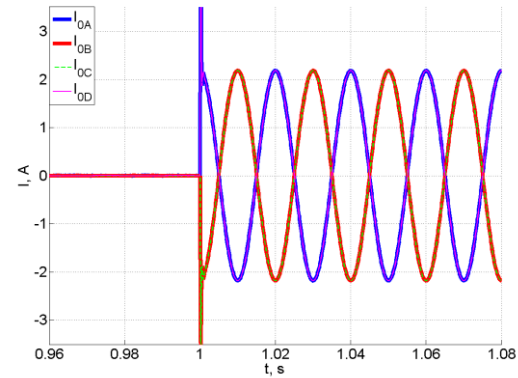


Figure 10. Waveforms of zero-sequence current components at measurement the points for circuit 2a.

In the point A (figure 10), a part of the current dissipated by ground capacities flows into the K2 cable. Therefore, the zero-sequence current will have a value between 0 and the earth fault current value and will be in phase with earth fault. In the K2 cable at the point C, the currents of healthy phases will be increased by the value of the current flowing into this cable through its capacitance. In this case, the L1 phase current will be lower than the other phases. The zero-sequence current phase of such a system will be reversed by 180° in relation to the earth fault current phase.

In such a network, if there is no load at the end of both power cables, the currents should be zero. However, in the event of an earth fault, the earth fault current is also supplied via the K2 cable, so that the current in accordance with the grounding phase flows in phase L1. Therefore, the zero-sequence current at the point D is consistent with the earth fault phase. For the same reason, the zero-sequence current phase at the point B is reversed by 180° in comparison to the earth fault current phase.

Including additional outgoing lines, as in the 2b system, causes a variation of the results (figure 12). The zero-sequence current component for the filter placed at the beginning of the damaged line increases significantly. The zero component of the current at the point C decreases. This is due to the fact that the part of the earth fault current which in the circuit 2a returned to the system by the earth capacities of healthy phases of the K2 line in this system returns through the earth capacitances of the healthy phases of the lines included in K4. Phase shifts, despite the additional lines, do not differ from the circuit 2a.

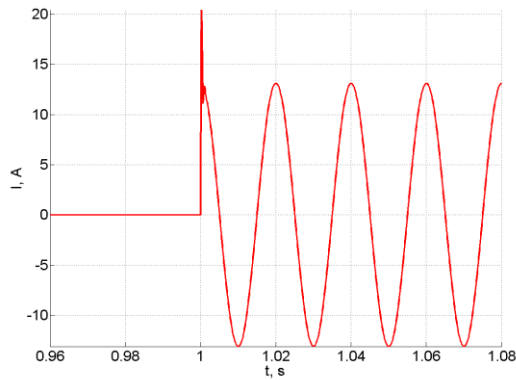


Figure 11. Waveform of earth fault current for circuit 2b.

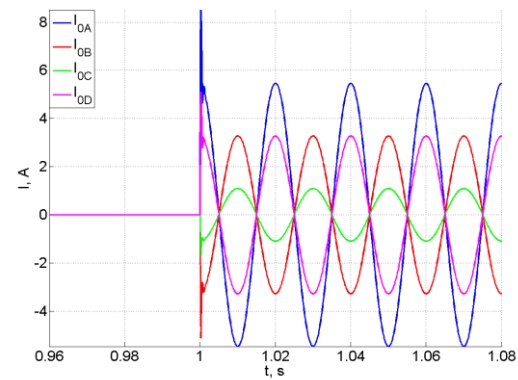


Figure 12. Waveforms of zero-sequence current components at measurement the points for circuit 2b.

3.3. Circuit 3

In the case of circuit 3 (figures 14 and 16), the situation is very similar to that of the system 2. In the points A and C there are identical phenomena as in the case of the point A and C of the system 2. The difference is at the end of cables K1 and K2. Here, the current supplying the K3 cable flows through the L2 and L3 phases. However, the values of these currents are so small that the zero components in filters B and D assume similar shapes as in the case of the points B and D in the case of circuit 2.

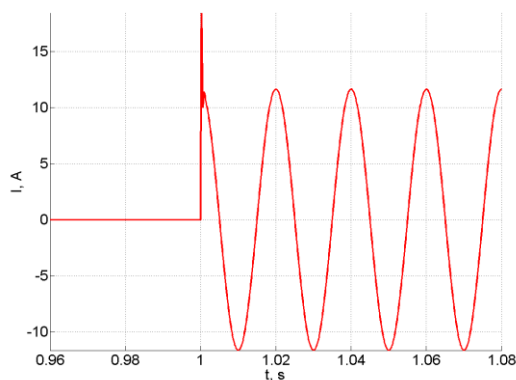


Figure 13. Waveform of earth fault current for circuit 3a.

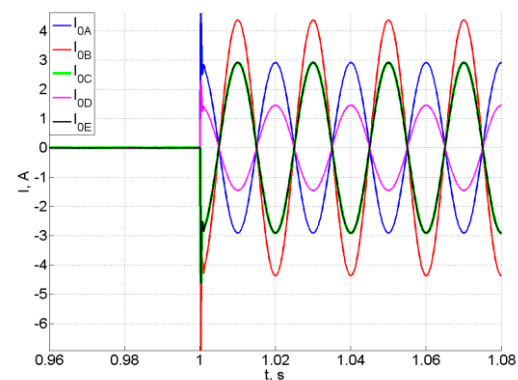


Figure 14. Waveforms of zero-sequence current components at measurement the points for circuit 3a.

The K3 line in this system behaves in a similar way to the K2 line in the system 1. Only currents in healthy phases flow through the E filter, while in the damaged phase the current value is zero. This is why, the zero-sequence current at this point is opposite in phase to earth fault. Additional outgoing

lines in the RG switchgear affect the values of zero-sequence current components at the measuring points. A larger number (and length) of additional feeder lines from the RG switchgear increases the values of the zero current components at both measuring points of the damaged line.

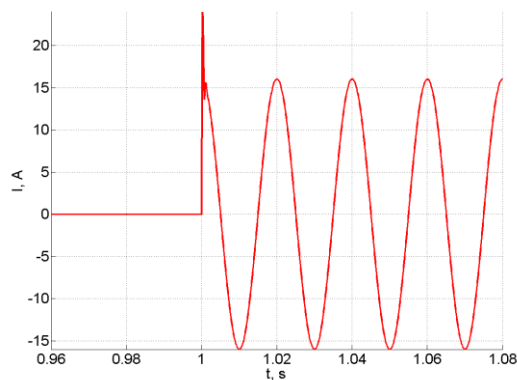


Figure 15. Waveform of earth fault current for circuit 3b.

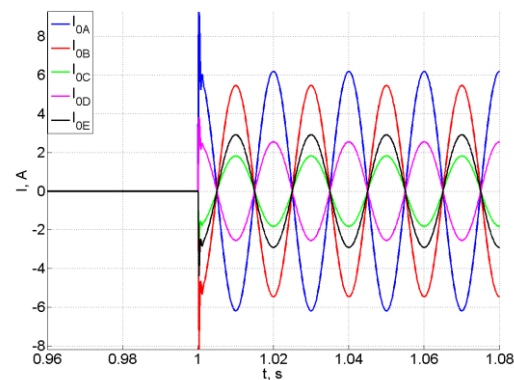


Figure 16. Waveforms of zero-sequence current components at measurement the points for circuit 3b.

4. Conclusions

Simulation analyses conducted for several cases of apparently simple networks with an isolated neutral system brings can reveal a number of interesting results. First of all, it can be concluded that the tCad program does all the calculations correctly and can be used for further analysis of earth fault phenomena. In addition, it can be noticed that if the earth fault parameters were not known, then it would not be possible to determine unequivocally which particular cable has been damaged on the basis of zero-sequence current values based on the results in circuit 2a and 3a. In the case of two lines, the phases of zero-sequence current components of both lines are opposite to each other, but this fact alone does not give us information which particular line is faulted. For this purpose, min. 3 lines must be analyzed and the decision can be reached on basis of the majority principle..

If the phases of the zero-sequence currents in particular cables are compared to the phase of the zero sequence voltage (the same for the whole network) it can be seen that $\varphi = 90^\circ$ for the beginning of the damaged line regardless of the situation. At the beginning of a healthy line $\varphi = -90^\circ$. These values have not changed, regardless of the circuit network configuration. The next step of the research will be to extend the network model by including the distributed model of the SUPO system and further testing the resulting cases. Finally, the research aims at the possibility of the most accurate simulation of various types of earth faults in the mine medium voltage network with an isolated neutral system.

5. References

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