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Intermittent earth fault passage indication in compensated distribution networks

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ABSTRACT An intermittent or restriking earth fault is a special type of earth fault that is common mostly in compensated cable networks. A great deal of effort has gone into protection against this type of fault. However, locating this fault has not received much attention. Therefore, there is a need to have a reliable method for locating this fault to repair the damaged cable. In this paper, the principles of a new method developed for locating transient intermittent earth faults on distribution networks are presented. The proposed method employs negative and zero sequence currents, and no voltage measurement is required, which means the proposed method has the potential to reduce cost when implemented in practice. It is intended mainly for typical intermittent earth faults in cable distribution networks where the typical fault resistance is in the range of a few ohms. Real data obtained from practical field tests is used to explain the phenomenon. A series of disturbance recordings obtained from field tests validate the proposed method.

INDEX TERMS Fault passage indication, intermittent earth fault, symmetrical sequence currents.

I. INTRODUCTION

Uninterruptable power supply is essential in today's networks. Distribution system operators (DSOs) always try to improve their System Average Interruption Duration Index (SAIDI) using various solutions. Overhead lines are prone to faults and disruptions, especially because of storms, lightning, etc. As a result, in many countries, DSOs have started to replace overhead lines massively with underground cables in urban and rural areas [1]–[3]. Despite the benefits this transition from overhead lines to cables provides, it brings about a new challenge to fault management systems, i.e., a special type of earth fault called an intermittent or restriking earth fault. These types of faults occur mainly in compensated cable networks. An intermittent or restriking earth fault is a special type of earth fault. It can be characterized as a series of cable insulation breakdowns in which a sudden electric discharge to the ground occurs. This type of fault is repetitive, and it ignites and self-extinguishes in irregular time intervals, which causes short current spikes. Because of these irregular current waveforms, conventional directional protection relays may fail to operate correctly.

The cause of intermittent earth faults on cables is the deterioration of the cable insulation layer. Many reasons can cause insulation deteriorations. For instance, it could be from the penetration of impurities and moisture because of chemical

reactions caused by insulation material aging or impurities originating from the cable manufacturing process, etc. [4].

Intermittent earth faults will eventually develop into permanent faults, where the fault current flows continuously if they are left to ignite for long enough. Most earth faults on cabled and compensated medium voltage (MV) distribution networks are intermittent ones [1], [5]. Almost all earth faults in compensated cable networks start as intermittent faults and then instantly or gradually evolve into short circuits or cross country faults [1]. Therefore, they are perhaps the most important type of fault to locate. In general, fault location and detection can be classified into three categories:

1) Feeder identification: Only the faulted feeder is determined; this function is normally an integral part of feeder protection implemented into modern protection relays.

2) Fault Passage Indication (FPI): The faulted segment, i.e., the faulted cable segment connecting two consecutive secondary substations, is pinpointed. The function of FPI is to issue an indication signal when a fault current passes the location at which the FPI device is mounted. If enough FPI devices are used in the network, any faulted segment can be identified.

3) Distance estimation: The exact fault location, i.e., the fault distance from the primary substation, is estimated.

For permanent (continuous) single-phase to ground faults, several fault location methods are proposed or already in use that fall into the second or third categories defined above. These methods include injection-based methods [6], [7], traveling wave-based methods [8], [9], impedance-based methods [10], [11]. A comprehensive review of permanent earth fault location methods in distribution networks is presented in [12]. However, when it comes to intermittent fault location, it appears that the majority of the efforts are focused only on faulted feeder identification, which is necessary to have properly functioning feeder protection. Therefore, there is a need for a cost-effective method that gives more accurate information on the fault location than only identifying the faulted feeder.

In this paper, the principles of a new FPI method to identify the faulted segment in compensated distribution networks are presented. The proposed method utilizes the concept introduced in [13], which is targeted for locating permanent earth faults but adapts it for intermittent earth faults.

In Section II, we discuss the intermittent earth fault phenomenon, its characteristics, and why it is problematic for conventional relays using disturbance recordings obtained from field tests. The state-of-the-art methods proposed in the literature to remedy the shortcomings of conventional relays are reviewed. The principles of operation of the proposed new method are presented in Section III. The effectiveness of the method is validated through the simulations in Section IV, and recordings obtained from field tests in Section V. Some implementation aspects of the method are discussed in Section VI. Conclusions are drawn in Section VII.

II. PROBLEM FORMULATION

Compensated networks with underground cables are prone to intermittent earth faults. Intermittent earth faults are usually caused by damage to the insulation of a cable. The damaged spot on the cable has a reduced insulation level so that when the faulted phase voltage rises, a sudden discharge of current occurs through that damaged spot. This is due to the discharge current of faulty phase capacitances and the charge current of the capacitances of healthy phases. These sudden charge and discharge currents cause spikes in phase currents in faulted and healthy feeders. If the faulted phase is not in direct contact with the ground, the fault is likely to self-extinguish in compensated networks as the fault current is low in these types of networks. However, as the damaged spot has a lower insulation level, discharges occur again every time the voltage of the faulty phase reaches a high enough value. This pattern repeats again and again and the result is what is known as an intermittent earth fault [14].

Fig. 1 shows the data from a disturbance recording obtained from a field test on a compensated distribution network in the event of an intermittent fault. For the purpose of comparison, the faulted phase voltage and current are shown in the same

figure. The measurements are made at the beginning of the faulted feeder with 10 kHz sampling rates. The fault is initiated when the phase voltage exceeds a certain value at the point where the insulation level is reduced. The fault extinguishes itself in one of the first zero crossings of the transient fault current. After the fault has been extinguished, the faulty phase's phase-to-earth voltage starts to recover, but not immediately.

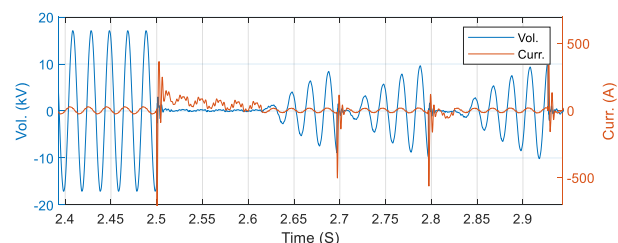


FIGURE 1. The faulty phase current and voltage were obtained from the field test recording, courtesy of Emtele Oy.

The behavior of the zero-sequence current I_0 measured at the beginning of the faulty feeder, along with the zero-sequence voltage U_0 (the residual voltage measured across the Petersen coil), is shown in Fig. 2. Similarly, the zero-sequence current extinguishes rapidly, whereas the zero-sequence voltage attenuates slowly, as can be seen from the figure.

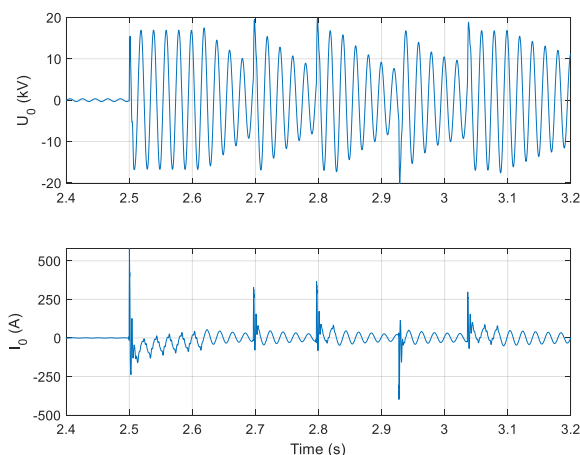


FIGURE 2. The field test recording of U_0 and I_0 was obtained from a faulted feeder in the case of an intermittent fault, courtesy of Emtele Oy.

Conventional earth fault protection is fundamentally aimed at detecting permanent faults [15]. The essential difference between permanent earth faults and intermittent earth faults is in the waveforms of residual voltages and currents. Permanent faults have almost a fundamental frequency in measured quantities, and the residual current and residual voltage waveforms are sinusoidal. In the case of an intermittent earth fault, the problem is that because of irregular waveforms of the residual current, conventional directional earth fault protection relays (DE/F) often fail to

detect this type of earth fault. Because of the more stabilized waveform of U_0 , residual overvoltage relays (RO/V relays) are more likely to detect the fault condition. As a result, intermittent earth faults could cause non-selective tripping of the substation's back-up protection. This situation eventually leads to an outage with substantial costs to a wide area.

Several methods have been put forward to overcome the problem of conventional relays [16]–[22]. The patented method presented in [16] requires the Petersen coil voltage (neutral to ground voltage) and zero sequence current of each feeder. The first-order derivative of the measured voltage is calculated. This derivative is correlated to each of the feeder zero sequence currents. The feeder with the highest correlation is determined to be the faulted feeder. It is, however, unclear how this method differentiates intermittent types of faults from regular earth faults. It appears that the intermittent characteristics of phase currents are not specifically considered in this method. In [17] and [18], another patented method for identifying the direction of intermittent earth faults is presented. It is based on measuring the residual current and voltage and then calculating the instantaneous active and reactive powers using Hilbert's transform. The method also keeps a count of current spikes to identify the event type, i.e., intermittent faults or transient events and noises. Another patented method is presented in [19]. The method requires two-phase currents and the ZSC (zero-sequence current). It is partly based on the assumption that the ratio of the magnitude of the NSC (negative sequence current) to the magnitude of the ZSC is high on the faulty feeder and low on healthy feeders. However, this assumption is not always valid. On the faulted feeder, both zero and negative sequence currents could be high in such a way that

their ratio is not necessarily high. In [20], a method is proposed based on calculating the zero sequence admittance for each feeder using a centralized residual voltage (measured across the Petersen coil) and zero sequence currents. The direction of the fault on a specific feeder is determined based on the sign of the real part of the calculated zero-sequence admittance so that a negative admittance means reverse (faulty) and a positive value indicates forward (healthy). In [21], a concept of cumulative phasor summing introduced in [22] is used to improve the zero sequence admittance method and remedy the shortcoming of the method presented in [20]. Ref. [23] reports on the results of experimenting with this method as FPI on a compensated distribution network.

The presented methods ([16]–[22]) deal with faulted feeder identification (in the event of intermittent earth faults) and not FPI. On the other hand, these methods (except for [19]) require voltage measurement. Therefore, even if these methods are used as FPIs, voltage measurement will be required at every point where the FPI device is installed, leading to extra cost. The method proposed in [24] attempts to avoid these costs by using the voltage measurements ordinarily available on the low-voltage side of distribution transformers. The drawback is the difficulties with practical implementation as the measurements need to be accurately time-synchronized. Therefore, what is missing is a reliable FPI method, which offers the potential to reduce the cost of implementation by eliminating the need for voltage measurement. The main characteristics of the reviewed methods are summarized in Table I to facilitate comparison.

TABLE I
STATE-OF-THE-ART METHODS FOR PROTECTION AGAINST INTERMITTENT FAULTS

Method	Requirements	Principles	Advantages	Disadvantages
Ref. [16]	Neutral voltage measurement and zero-sequence current	Correlation between $\frac{dU_0}{dt}$ and I_0	ZSC sufficient as opposed to three phase currents	Oscillatory characteristics of intermittent faults not well addressed, and voltage measurement required
Ref. [17]	Voltage measurement and zero sequence current	Instantaneous powers P and Q and counting current spikes	ZSC sufficient as opposed to three phase currents	Voltage measurement at every measurement point required for FPI applications
Ref. [19]	Two phase currents and zero-sequence current	Comparison of phase current magnitudes and directions	No need for voltage measurement	The assumption on the ratio of NSC to ZSC not always valid
Ref. [20]	Zero-sequence voltages and currents	$\frac{\Delta I_0}{\Delta U_0}$	ZSC sufficient as opposed to three phase currents	Voltage measurement at every measurement point required for FPI applications
Ref. [21]	Zero-sequence voltages and currents	$\frac{\sum I_0}{\sum U_0}$	Oscillatory characteristics of intermittent faults well addressed	Voltage measurement at every measurement point required for FPI applications
Ref. [24]	The voltage on the LV side with time synchronization	Correlation between voltages on LV side and currents on MV side	Utilizing voltage measurements normally available in the LV side of the network	Difficulty with practical implementation as accurate time synchronization required

III. PROPOSED METHOD

The proposed method combines the ZSC with the NSC to locate the intermittent earth fault. The trigger of the process at each measurement point is the rise in the magnitude of ZSC. The proposed method falls into the category of fault passage indication, i.e., the fault indication is performed locally. Therefore, there is no need for synchronization of the measurements from various locations.

In [13], a method based on the steady-state value of the negative sequence current at the fundamental frequency is proposed for locating permanent earth faults. It is based on a theoretical analysis of symmetrical sequence components, which shows that the negative sequence current at healthy feeders is insignificant. In contrast, it is significant on the faulty feeder from the beginning of the feeder up to the fault point. After the fault point, it is again negligible. In addition, the paper argues that sequence currents of measurement points located on the healthy feeder and points after the fault location behave similarly. They are both considered to be located off the fault passage.

The measured currents in a compensated network during an earth fault contain the following components [25]:

- fundamental frequency components of the fault and load currents as well as their harmonics
- charging and discharging transient components
- decaying DC-transient component originating from the Petersen coil circuit
- interline compensating transient component

Transients caused by charging the line to ground capacitances of the healthy feeders and discharging the line to ground capacitances of the faulty feeder occur simultaneously but with different durations. For a compensated network with full compensation, the fault location's fundamental frequency fault current is completely compensated [26]. The frequency of the transients is typically in the range of 100 to 800 Hz, and their amplitudes could be much larger than the fundamental frequency component, although decaying rapidly [25]. An intermittent earth fault can be described as a series of self-extinguishing faults. The time interval between two consecutive fault re-occurrences is typically in the range of few tens of milliseconds. Intermittent earth faults have typically broad frequency content [23]. This broad frequency content, or in other words harmonics, originates from the oscillatory nature of these types of faults.

The method presented in [13] is largely based on utilizing the negative sequence current's fundamental frequency, primarily developed for permanent faults. If it is used in its original form for intermittent earth fault location purposes, there will be a risk that the FPI device installed on the fault passage misses the fault. The method presented in [13] and, in general, methods based on fundamental frequency quantities may fail to operate correctly when the measured quantities have significant transient characteristics or harmonics. Earth faults of the intermittent type normally

have significant transient characteristics and harmonics and therefore problematic for fundamental frequency-based methods. Therefore, there is a need for a method that overcomes the challenges caused by transients and harmonics of intermittent earth faults. The newly proposed method utilizes a wider range of frequencies to address the oscillatory characteristics of intermittent faults. It employs harmonics of NSC in addition to its fundamental frequency. This way, the harmonic content in the measured currents work in favor of the FPI functionality.

A. THEORY

By definition [27], the phasor of the NSC of phase "a" $\bar{I}_2^{(a)}$ is obtained using the following equation:

$$\bar{I}_2^{(a)} = \frac{1}{3} (\bar{I}_a + a^2 \bar{I}_b + a \bar{I}_c) \quad (1)$$

Where, \bar{I}_a , \bar{I}_b and \bar{I}_c are the phasors of the phase currents of phases a, b, and c, respectively, and the operator $a = 1 \angle 120^\circ$. By definition, the phasors of the negative sequence currents calculated for each phase are equal in magnitudes. Only they are 120-degree phase shifted. The following relations are valid between the phasors and their magnitudes.

$$\begin{aligned} \bar{I}_2^{(b)} &= a \bar{I}_2^{(a)} \\ \bar{I}_2^{(c)} &= a^2 \bar{I}_2^{(a)} \\ I_2^{(a)} &= I_2^{(b)} = I_2^{(c)} \end{aligned} \quad (2)$$

Where $\bar{I}_2^{(b)}$ and $\bar{I}_2^{(c)}$ are the NSC phasors of phases b and c, respectively and $I_2^{(a)}$, $I_2^{(b)}$ and $I_2^{(c)}$ are the magnitudes of the phasors. As the proposed method is based on the magnitude of the phasor of the NSC and not the phasor itself, there is no need to know the faulted phase when implementing the method. The idea of phasor summation is introduced to adapt (1) for intermittent earth faults, i.e., harmonic components of the NSC are added to the fundamental frequency expressed in the following equation. This adaptation is based on the discussion presented earlier.

$$I_{2i} = \left| \sum_{n=1}^m \bar{I}_{2i}^n \right| \quad (3)$$

Where \bar{I}_{2i}^n is the phasor of the NSC at the n^{th} harmonic at measurement point i .

The calculation process is triggered at each measurement point once a rise (greater than a pre-defined value) in the ZSC is detected. The ZSC phasor for any phase is obtained as follows:

$$\bar{I}_0 = \frac{1}{3} (\bar{I}_a + \bar{I}_b + \bar{I}_c) \quad (4)$$

$$I_0 = |\bar{I}_0| \quad (5)$$

B. FAULT LOCATION PROCEDURE

Installing more FPI devices provides more visibility to the network. Every secondary substation must be equipped with an FPI device to achieve full visibility to every segment connecting two consecutive secondary substations. The faulted segment can be pinpointed as follows.

- 1- The procedure at measurement points is triggered once the magnitude of the ZSC is above a certain value.
- 2- The phase currents at measurement points (ideally at all of the secondary substations) are measured, and the magnitudes of the negative sequence currents using (3) are calculated.
- 3- The magnitude of the NSC over a certain period is calculated. If the calculated value rises above a predetermined value, a fault indication signal is issued to the system operator.
- 4- The faulted section is determined as the one between the last measurement point from which the fault indication signal is received and the first measurement point from which no signal is received.

As the magnitude of the NSC is negligible on healthy feeders, choosing a threshold is relatively straightforward. For the simulated and field tests results presented in this paper, the threshold for the zero and negative sequence currents is chosen to be 5.5 A. This choice has been made based on studying the values obtained from field tests measurements. The parameter m in (3) is chosen to be 3.

The proposed method is based on monitoring the NSC and especially the peak magnitude of it. The maximum value of NSC is detected. Every time the fault condition is met, i.e., NSC exceeds the thresholds, a peak occurrence is detected. The number of peaks over a certain period is counted, and the fault indication signal is issued based on that. The choice of the certain period is concerned with the method's sensitivity. The user can set it according to the desired sensitivity. The reason for counting peaks and issuing the fault signal based on multiple peaks and not only one is to avoid having fault indication signals when other types of events are temporarily causing spikes in the phase currents. Similarly, setting the number of peaks is a sensitivity issue. It is up to the network operator to set the desired number of peaks when utilizing the method.

The threshold for I_2 , i.e., 5.5 A, has been obtained experimentally through studying a series of simulations and the field tests results. Like overcurrent and earth-fault protection settings, no universal value for the threshold can be given. The reason is that the NSC depends on the network's symmetry, length of the feeders, the line types, the transformers impedances, etc. However, as the NSC of healthy feeders and points off the fault passage is

significantly lower than the NSC of the faulted feeder and points off the fault passage, it is possible to set a proper threshold with which points on and off the fault passage can be differentiated. The development of tools for finding practical threshold settings is beyond the scope of this paper.

IV. SIMULATION RESULTS

The effectiveness of the proposed method is investigated using simulations carried out in the PSCAD/EMTDC environment. The network shown in Fig. 3 is a compensated cable MV distribution network consisting of multiple feeders with a faulted feeder and a healthy feeder shown in the figure. A 110 kV high voltage network supplies a 20 kV medium-voltage network through a 40 MVA transformer. The feeder under study is 5.4 km long, consisting of AHXAMK-W underground cables, and has five secondary substations. Three faults at three locations are examined. The first intermittent earth fault occurs at 3 km from the HV/MV transformer on phase "a". The intermittent fault is simulated so that whenever the voltage exceeds a certain level, the cable's insulation level at the fault spot breaks down and the fault current starts to flow. The fault current flow stops as soon as it reaches a zero crossing. The insulation breakdown is modeled by a specific logic controlling the regular fault block in PSCAD. Some degraded insulation level is given to start. This insulation level is then compared with the instantaneous phase to ground voltage measured at the fault location. If the voltage is above the insulation level, the fault block is turned on, resulting in a phase-to-ground fault. The fault current, which starts with large transients, is monitored and as soon as there is the first zero crossing of the current, the fault block is turned off, stopping the fault current. The description of the simulation parameters is given in Appendix.

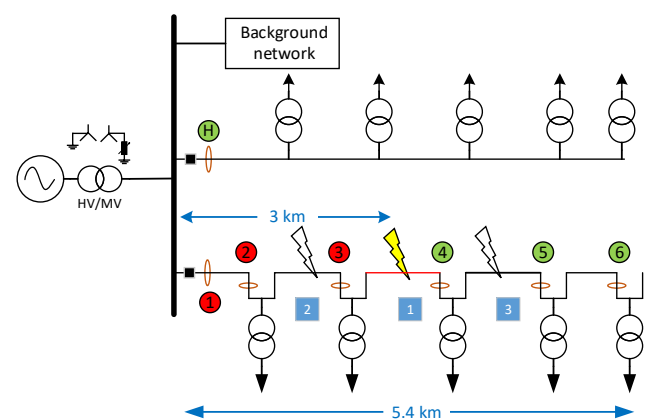


FIGURE 3 Intermittent earth fault on a compensated MV distribution network consisting of multiple underground cable feeders under three fault condition scenarios.

Phase currents and sequence currents (magnitudes) using (3) and (5) are shown in Fig. 4 and Fig. 5 for points 3 and 4, respectively. For Point 3, which is located behind the fault point, both sequence currents exceed the thresholds, and

hence the proposed method correctly identifies this point to be on the fault passage.

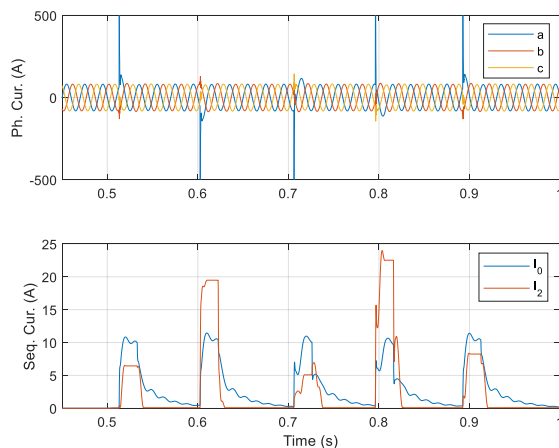


FIGURE 4 Phase currents and corresponding sequence currents under an intermittent earth fault condition, before fault point (Point 3), on fault passage.

On the contrary, for Point 4, which is located after the fault point, only the zero-sequence current is significant (around 4 A). Therefore, the proposed method correctly identifies this point to be off the fault passage.

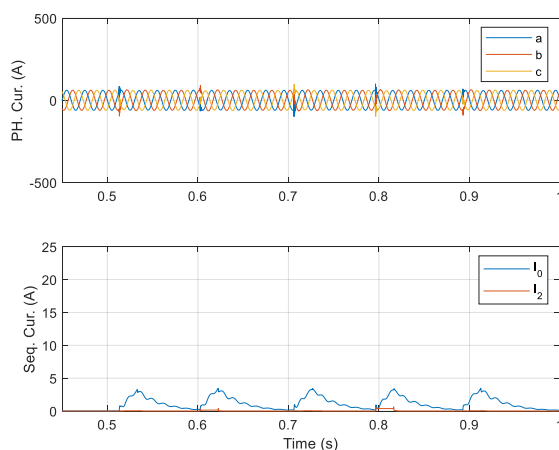


FIGURE 5. Phase currents and corresponding sequence currents under an intermittent earth fault condition, after fault point (Point 4), off fault passage.

The calculated zero and negative sequence currents (magnitudes) at various measurement points for faults 1, 2 and 3 are presented in Table II. The measurements are taken from five points on the faulted feeder and the adjacent healthy feeder's beginning. The values presented in the table are the maximum values of the calculated zero and negative sequence currents in the period between $t = 0.45 \text{ s}$ and $t = 0.9 \text{ s}$. Each measuring point is identified correctly to be on or off the fault passage using the proposed method. Subsequently, the faulted segments can be identified successfully.

TABLE II
SEQUENCE CURRENTS AT VARIOUS MEASUREMENT POINTS FOR THREE FAULTS AT THREE LOCATIONS

Points	Fault	On/off	I_0 (A)	I_2 (A)
1	1	on	8.4	24.3
2	1	on	10.4	24.2
3	1	on	10.7	24.1
4	1	off	3.4	0.6
5	1	off	1.7	0.4
H	1	off	7.1	0.7
1	2	on	8.7	17.5
2	2	on	10.5	17.4
3	2	off	5.3	0.7
4	2	off	3.6	0.4
5	2	off	1.8	0.3
H	2	off	7.2	0.7
1	3	on	8.1	24.4
2	3	on	10.5	24.4
3	3	on	10.9	24.3
4	3	on	11.4	24.2
5	3	off	1.7	0.4
H	3	off	7.2	0.7

To highlight the advantage that utilizing harmonics provides, the new proposed method is contrasted with the method presented in [13], by way of example. Consider Fault 2 when the fault resistance increases to 150 ohms. The phase currents and corresponding negative sequence currents for Point 2, which is located on the fault passage, are plotted in Fig. 6. The method presented in [13] is largely based on using the fundamental frequency of the NSC. In the figure, the NSC is calculated once only based on the fundamental frequency component excluding harmonics (method [13]) and once including harmonics (the newly proposed method).

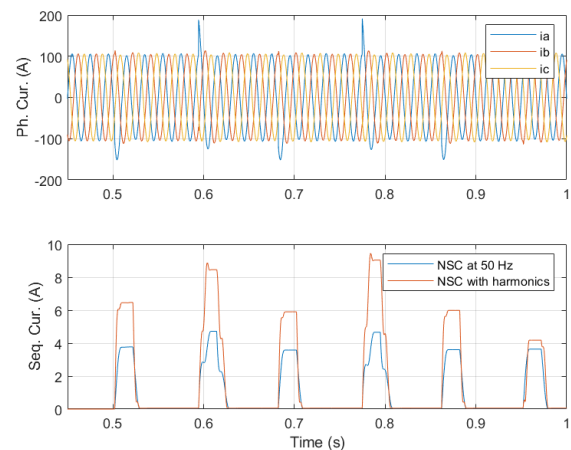


FIGURE 6. The proposed method utilizes harmonics and fundamental frequency components versus the method presented in [13].

The NSC at 50 Hz is below the pre-set threshold and therefore, the method [13] incorrectly identifies Point 2 to be

located off the fault passage. The phasor diagrams of the fundamental frequency, second and third harmonics along with their summation for the second spike which occurs at $t = 0.6 \text{ s}$ are illustrated in Fig. 7.

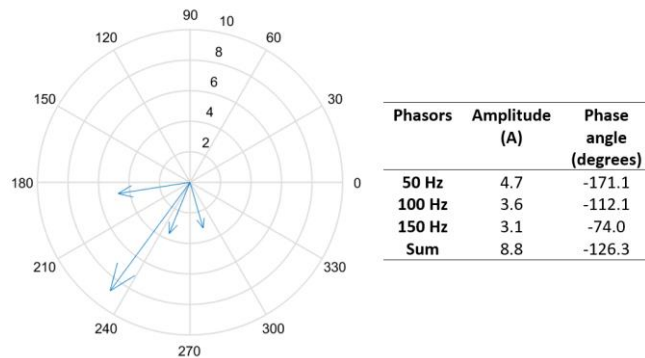


FIGURE 7. Phasors of NSC at the fundamental frequency and its harmonics.

V. FIELD TEST VERIFICATION

The proposed method has been examined using a series of disturbance recordings obtained from field tests carried out by DSOs in cooperation with network automation system providers in Finland. In this section, the results of two sets of recordings obtained from field tests are presented. The simplified diagram of the network on which the tests were performed is shown in Fig. 8.

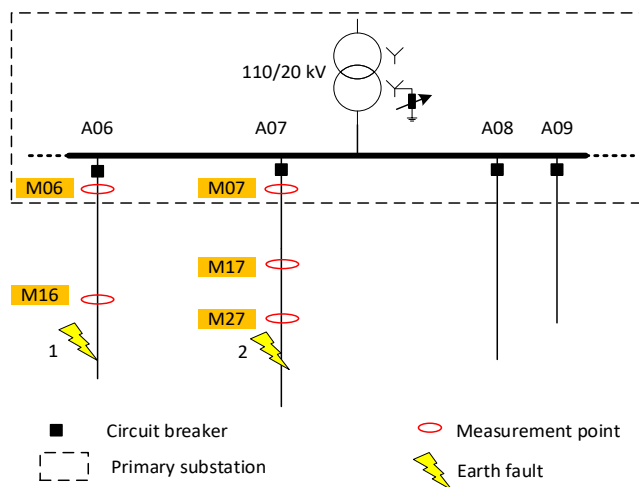


FIGURE 8. The compensated network used in field tests for fault studies.

The network consisted of several feeders and a 110/20kV primary substation. The feeders consisted of cables and overhead lines, so that they left the primary substation as cables and ended as overhead lines. The measurements were taken from the beginning of each feeder (M06 and M07), as well as one secondary substation on feeder A06 (M16) and two secondary substations on feeder A06 (M16 and M26). Intermittent earth faults were implemented on feeders A06

and A07 using special techniques and dedicated test equipment (Fig. 9). Two fault location scenarios are studied.



FIGURE 9. Earth fault field tests (photo credit: Jukka Rinta-Luoma).

A. SCENARIO I

The intermittent earth fault (Fault 1 in Fig. 8) occurs on feeder A06, which means measurement points M06 and M16 are located on the fault passage and M07, M17 and M27 off the fault passage. The fault occurs at $t = 0.76 \text{ s}$ on phase "a" and the network under study is under-compensated with the compensation degree of 95%. The phase-to-ground voltages, along with the zero-sequence voltage measured at the primary substation, are illustrated in Fig. 10.

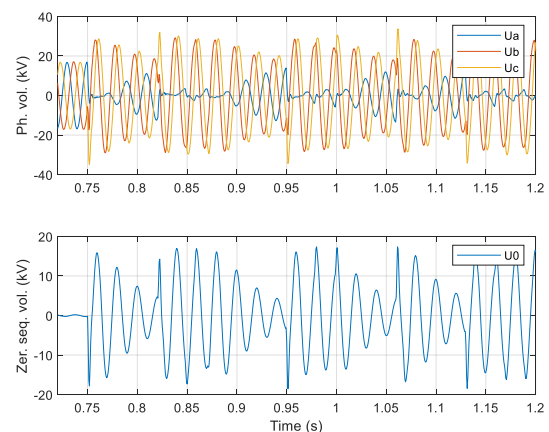


FIGURE 10. The phase-to-ground and zero-sequence voltages under intermittent fault condition, courtesy of ABB.

Phase currents and their corresponding negative and zero sequence currents (magnitudes) calculated using (3) and (5) are presented in Fig. 11 and Fig. 12 for measurement points M06 and M16, respectively. Both measurement points are correctly identified to be located on the fault passage using the proposed method. Both sequence currents exceed the pre-set threshold of 5.5 A.

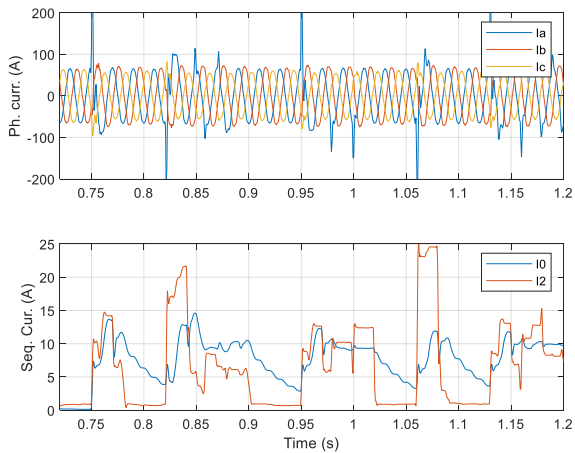


FIGURE 11. Phase currents and their corresponding zero and negative sequence currents (magnitudes) were measured at M06.

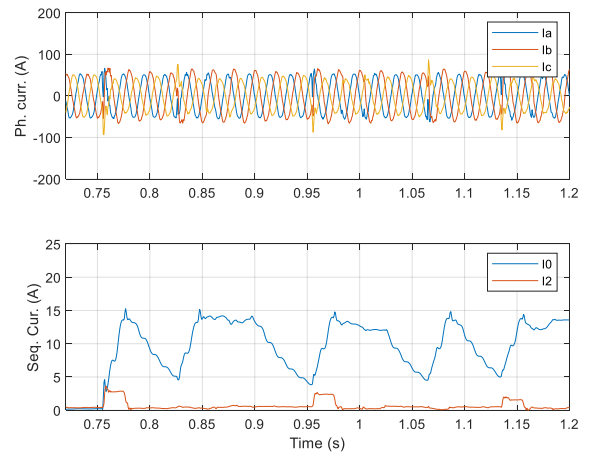


FIGURE 13. Phase currents and their corresponding zero and negative sequence currents (magnitudes) were measured at M07.

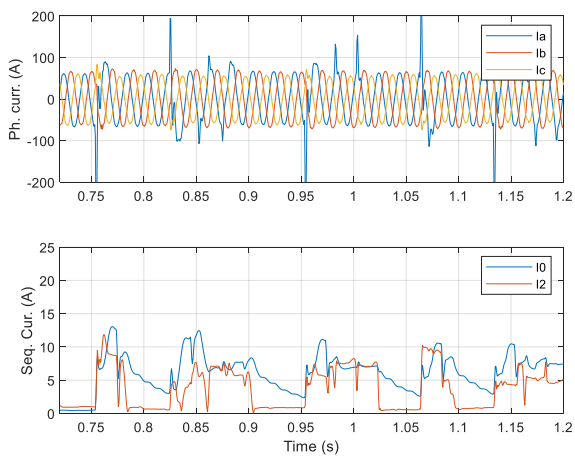


FIGURE 12. Phase currents and their corresponding zero and negative sequence currents (magnitudes) were measured at M16.

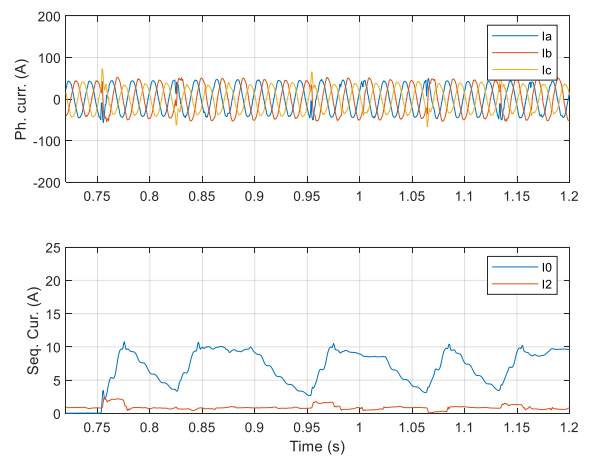


FIGURE 14. Phase currents and their corresponding zero and negative sequence currents (magnitudes) were measured at M17.

Similarly, phase currents and their corresponding negative and zero sequence currents (magnitudes) calculated using equations (3) and (5) are presented in Fig. 13, Fig. 14 and Fig. 15 for measurement points M07, M17 and M27, respectively.

For these measurement points, which are located on the healthy feeder, although the ZSC magnitude is significant, the NSC magnitude is negligible. According to the proposed method, this indicates that the measurement points in question are located off the fault passage.

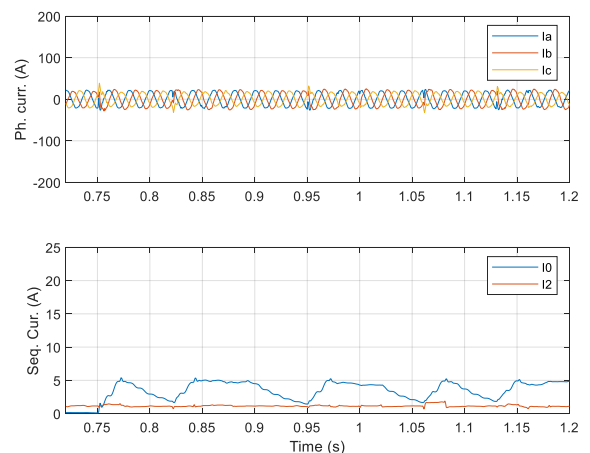


FIGURE 15. Phase currents and their corresponding zero and negative sequence currents (magnitudes) were measured at M27.

B. SCENARIO II

To further investigate the effectiveness of the proposed method in the case of different fault locations, Fault 2 is studied, which occurs on A07. Phase-to-ground voltages along with the zero-sequence voltages measured at the primary substation are illustrated in Fig. 16. Phase currents and their corresponding sequence currents for all measurement points are presented in Fig. 17 to Fig. 21. All the points on and off the fault passage can be identified successfully using the proposed method.

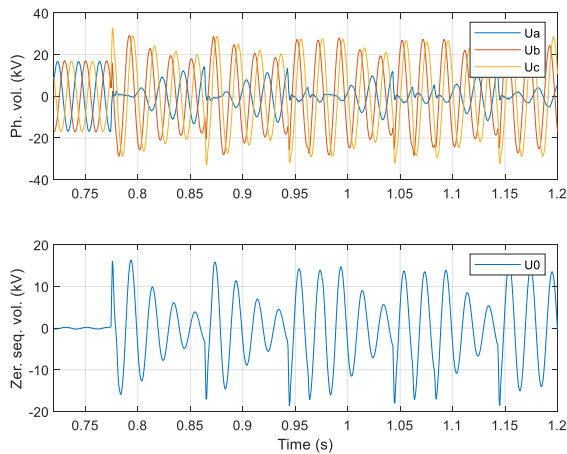


FIGURE 16. The phase-to-ground and zero-sequence voltages under intermittent fault condition, courtesy of ABB.

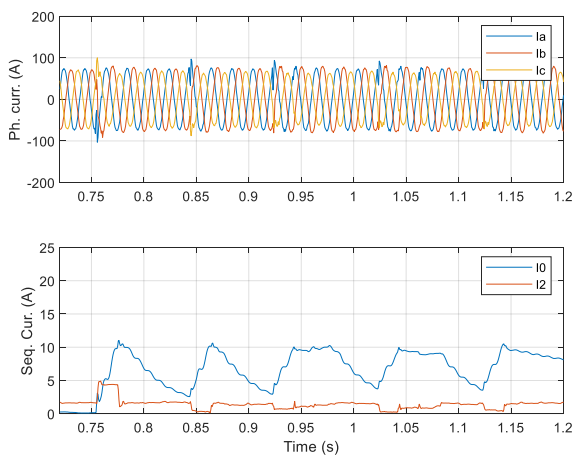


FIGURE 17. Phase currents and their corresponding zero and negative sequence currents (magnitudes) were measured at M06.

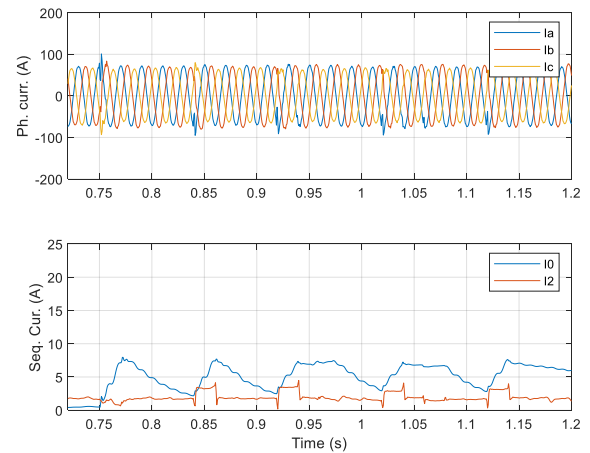


FIGURE 18. Phase currents and their corresponding zero and negative sequence currents (magnitudes) measured at M16.

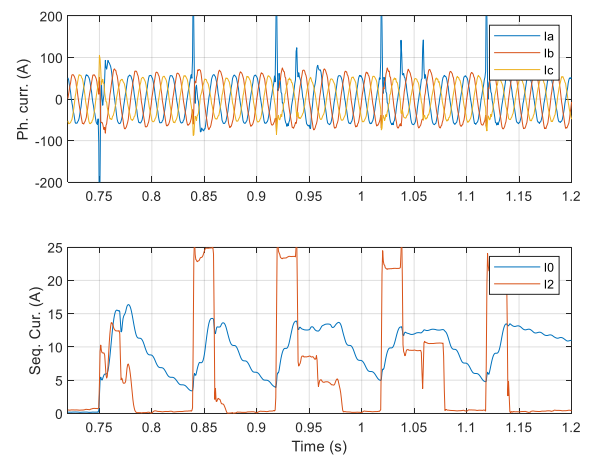


FIGURE 19. Phase currents and their corresponding zero and negative sequence currents (magnitudes) measured at M07.

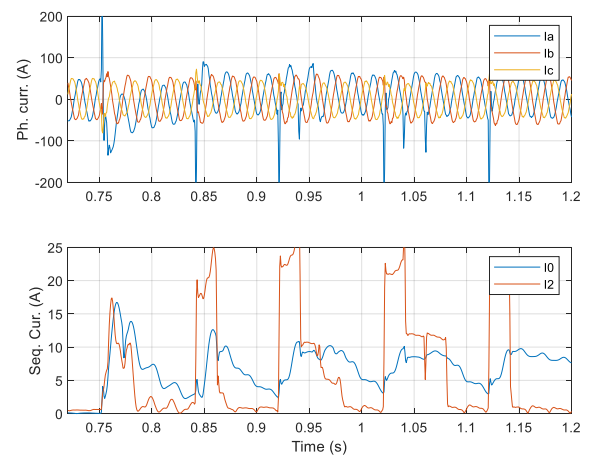


FIGURE 20. Phase currents and their corresponding zero and negative sequence currents (magnitudes) were measured at M17.

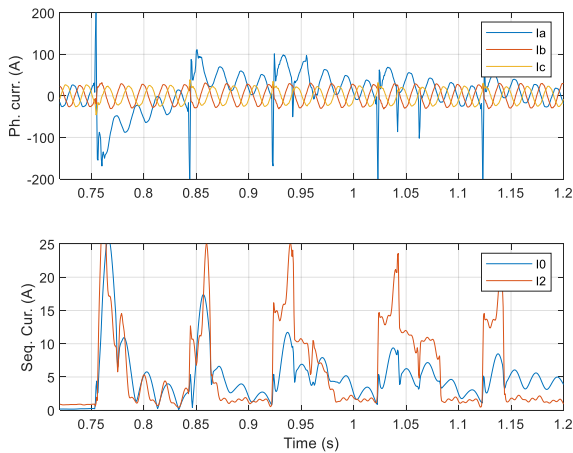


FIGURE 21. Phase currents and their corresponding zero and negative sequence currents (magnitudes) were measured at M27.

It should be noted that in both scenarios and in all measurement points, which are either on or off the fault passage, the zero sequence currents exceed the pre-set threshold. This result reveals the fact that the simple zero-sequence threshold method is insufficient for FPI applications.

All the measurement points can be successfully identified using the proposed method, as summarized in Table III. In the table, the maximum values are presented.

TABLE III
MAXIMUM VALUES OF SEQUENCE CURRENTS

Measuring point	Fault	I_0 (A)	I_2 (A)	On/off fault passage
M06	1	14.6	25.4	on
M16	1	13.1	19.8	on
M07	1	16.2	3.6	off
M17	1	11.5	2.4	off
M27	1	5.7	1.9	off
M06	2	11.9	5.0	off
M16	2	8.6	5.0	off
M07	2	16.4	27.2	on
M17	2	16.7	28.9	on
M27	2	25.9	33.2	on

As the results show, it is sufficient for the data used in this study to consider the second and third harmonics. If higher harmonics are considered, i.e., $m > 3$, then the threshold for I_2 must be determined accordingly. For comparison purposes, negative sequence currents are calculated for $m = 7$ and shown in Table IV. Using the same threshold of 5.5 A for I_2 leads to a false fault indication as I_2 at M16 for Fault 2 is 10 A. Therefore, a new threshold for I_2 must be set. The choice for setting a proper threshold is narrower now. In this particular case, 11 A would be a proper threshold with which points on and off the fault passage can be differentiated. The more harmonics considered in the method, the higher the value of the threshold for I_2 will have to be as NSC increases for points located off the fault passage. The relationship

between the number of harmonics considered in the method and the predetermined threshold for I_2 depends on the distribution network's characteristics.

TABLE IV
MAXIMUM VALUES OF SEQUENCE CURRENTS FOR $m = 7$

Measuring point	Fault	I_0 (A)	I_2 (A)	On/off fault passage
M06	1	14.6	55.1	on
M16	1	13.1	13.6	on
M07	1	16.2	3.2	off
M17	1	11.5	3.2	off
M27	1	5.7	3.5	off
M06	2	11.9	5.1	off
M16	2	8.6	10.0	off
M07	2	16.4	57.9	on
M17	2	16.7	55.9	on
M27	2	25.9	47.9	on

VI. DISCUSSION

In practice, phase currents can be measured using Rogowski coils which have the advantage of being suitable for retrofit installations. The measured phase currents or the computed sequence currents, following a fault occurrence, are sent from the measuring points (secondary substations) to the control room. The SCADA system or DMS (Distribution Management System) analyzes the data to visualize the fault location on a map to the operator or perform an automatic FLIR (fault location, isolation and restoration) switching sequence.

As seen earlier, the magnitude of the ZSC alone cannot determine the fault passage as it could be high in both faulty and healthy feeders. However, in this method, it is used as an auxiliary indication i.e. the fault location procedure is triggered when the zero-sequence current exceeds a threshold. In an ideal symmetrical network, no negative or zero sequence currents exist in the network under normal condition. However, in some cases in practice, some level of NSC could exist even when there is no actual earth fault, for example, due to asymmetry of loads. This result would lead to a false indication of an earth fault if the NSC was used alone. However, that is not a concern in the proposed method for the following reason. Typically, the connection type of MV/LV transformers is D/Y. This means that the unbalanced loads on the LV side do not cause zero sequence currents on the MV side (because the primary side is a delta connection). Therefore, the problem of false indication is avoided if the ZSC is used in combination with the NSC in the manner proposed in this paper.

Intermittent earth faults are most often of low resistances, in the range of a few ohms. This range of resistance causes a high negative sequence current, as seen in sections IV and V. The proposed method could also be used for permanent earth faults provided the resulting NSC is high enough. However, the proposed method is not intended for earth faults with high resistances. The reason is that the NSC is so tiny that it is unusable in practice.

VII. CONCLUSION AND FUTURE WORK

The principles of a new FPI method for identifying the faulted segment in compensated MV distribution networks in case of intermittent earth faults were presented. The proposed method was based on only current measurement with no voltage measurement required, which would be a significant advantage from a cost point of view. The proposed method utilized the magnitude of the summation of negative sequence currents calculated for the fundamental frequency and multiple harmonics. In addition, the zero-sequence current was used as an auxiliary tool to determine the fault passage. It was shown that the zero-sequence current alone would not be enough as it could be significant in both faulty and healthy feeders. The operation principles were presented, and it was pointed out that if enough FPI devices are installed in the network, any faulted segment can be identified. The method's effectiveness was investigated using simulations and a series of field tests that provided strong preliminary validation of the method.

Investigating the performance of the method in networks with decentralized compensation units and the impact of the fault initial phase angle with respect to the phase angle of voltage will be the subject of future studies. Moreover, wider tests with measurement points located both at the beginning and various points along the feeders, especially after the fault point, are needed. In addition, developing a method for setting the proper threshold for I_2 for any given distribution network needs further investigation. Finding an accurate relationship between the number of harmonics that has to be considered in the method and the predetermined threshold for I_2 is an open question that is one of the subjects of future work. Eventually, the implementation of the method with all the apparatus (current sensors, etc.) will be in future work.

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APPENDIX

SIMULATION PARAMETERS

Petersen coil	
Compensation degree	0.95 under-compensated (1 = fully-compensated)
Resistance of the parallel resistor	2309 Ω
Inductance of the Petersen coil	0.248511 H
Line parameters	
Positive sequence resistance	0.15 [ohms/km]
Positive sequence inductive reactance	0.110 [ohms/km]
Positive sequence capacitive reactance	0.01061033 [Mohms*km]
Zero-sequence resistance	0.954 [ohms/km]
Zero-sequence inductive reactance	0.44 [ohms/km]
Zero-sequence capacitive reactance	0.01082532 [Mohms*km]

Main transformer parameters

3 phase transformer MVA	40 MVR
Base operation frequency	50 Hz
Winding 1 voltage line to line (RMS)	110 kV
Winding 2 voltage line to line (RMS)	20 kV
Winding #1 type	Y
Winding #2 type	Y
Positive sequence leakage reactance	0.1 [pu]
Eddy current losses	0.0006 [p.u.]
Copper losses	0.0037 [p.u.]
Intermittent earth fault resistance	more than 10 Ω

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