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Elina Määttä S93545

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INTERMITTENT EARTH FAULT PROTECTION

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Supervisor Kimmo Kauhaniemi

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SYMBOLS AND ABBREVIATIONS

Symbols

φ_j	Phase angle difference of faulted feeder
φ_v	Phase angle difference of healthy feeder
f	Frequency
$3\underline{I}_0$	Residual current
I_{0j}	Zero sequence current of faulted feeder
I_{0v}	Zero sequence current of healthy feeder
$\underline{I}_0$	Zero sequence current
I_{L1}, I_{L2}, I_{L3}	Phase currents in phases 1,2, and 3
$\underline{E}_{CPS}$	Cumulative phasor sum
$\underline{U}_0$	Neutral point displacement voltage
t_{end}	End time
t_{start}	Start time
t	Time
$\underline{Y}_{0sum\_CPS}$	Cumulative phasor summing neutral admittance phasor
$\underline{Y}_{0sum}$	Fundamental frequency neutral admittance phasor
$\underline{Y}_0^1$	Neutral admittance phasor of the fundamental frequency
$\underline{Y}_0^n$	Neutral admittance phasor of the n^{th} harmonic frequency

Abbreviations

AC	Alternating Current
CPS	Cumulative Phasor Summing
DFT	Discrete Fourier Transform
DNO	Distribution Network Operator
MV	Medium Voltage
OHL	Overhead Line
UGC	Underground Cabling
XLPE	Cross-linked Polyethylene

1 INTRODUCTION

Nowadays, uninterruptable quality of electricity supply is very important. However, recent storms, which have damaged medium voltage (MV) distribution networks and related long outages to customers, and new quality of supply regulations, have contributed building more reliable and weatherproof MV distribution networks. Therefore, distribution network operators (DNO)s have started to replace overhead lines (OHL)s by underground cables also in rural areas. However, increased cabling isn't a trouble-free issue; a problem with a special, very short and repetitive type of fault, an intermittent earth fault is noticed. There have been existed intermittent earth faults in networks, but particularly recently they have risen in attention. Therefore, intermittent fault and its protection scheme in MV distribution networks are in the scope of this work. (Mäkinen 2001:1–2; Altonen, Mäkinen, Kauhaniemi & Persson 2003.)

For ensuring reliable electricity supply in MV distribution networks, faults have to be removed with selective relay operations, which limit the faulted network part as small area as possible, and prevent stress situations to the network equipment. When relay protection is reliable and selective, these problems can be avoided, and longer operating life for network equipment and underground cables will be achieved. (Mäkinen 2001:1–2.)

During an intermittent earth fault, regular or irregular waveforms and spikes arise. Conventional earth fault protection is incapable of detecting these kinds of faults. Relay may not be able to trip the faulted feeder and situation can lead to unselective operation. In the worst case a whole substation could be disconnected due to back-up protection, which observes neutral point displacement voltage growth. Outages in wide area and related costs could be significant. In normal conditions this neutral point displacement voltage, which is the voltage between earth and system's neutral point, is almost zero. Consequently, intermittent earth fault protection has to be implemented in other methods, and some of these methods are introduced in this work. (Mäkinen 2001:1–2; Altonen et al. 2003; Altonen, Kuisti, Svensson & Isaksson 1999; Kumpulainen 2008.)

2 INTERMITTENT EARTH FAULT

2.1 General

An intermittent earth fault or restriking fault is special, low impedance, transient type of earth fault, and repeated in very short time intervals, only a few milliseconds. Intermittent earth fault ignites and vanishes alternately, and it is caused by a series of cable insulation breakdowns or deterioration of insulation due to diminished voltage withstand. At the fault place, where cable insulation has become weaker, the phase-to-earth voltage arises and makes a spark. Nonetheless, when current reaches its zero point for the first time, fault may experience a self-extinguishment. (Kumpulainen 2008; Vamp 2009; Altonen et al. 2003.)

Fig. 1 shows a typical intermittent earth fault situation in a substation, where zero sequence current peaks and neutral point displacement voltage waveform at the faulted and healthy feeders are illustrated. Residual current, i.e. zero sequence current, which is the sum of three phase currents, can be measured by either each phase current via a separate current transformer or directly by a cable current transformer, which is connected around all three phases (Altonen et al. 2003; Mäkinen 2001:1–2; Dlaboratory Sweden Ab. 2012.) The amplitudes of the measured residual current spikes can be very high, several hundred amperes. Intermittent earth fault is problematic both with healthy feeders and faulted feeder. Relays aren’t able to detect fault reliably at the faulted feeder, where the tripping should be executed. On the other hand, healthy feeders might trip falsely or possibly the main supply might be disconnected, because neutral point displacement voltage stays in high values long enough. (Wahlroos 2012.)

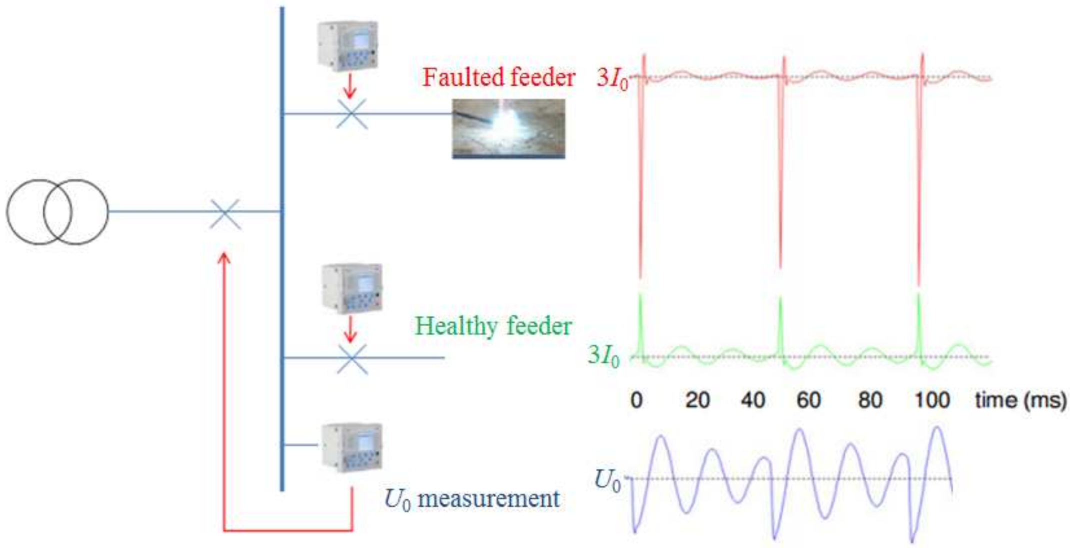

Figure 1. Residual currents of faulted and healthy feeders and neutral point displacement voltage waveform in intermittent earth fault situation. (Wahlroos 2012.)

An intermittent fault is very typical fault in compensated systems consisting of underground cables. Moreover, rural area networks consisting both OHLs and underground cables are relative susceptible for restriking faults. Thus, probability of earth fault density is greater due to overhead line parts. (Altonen et al. 2003.)

Usually, insulation levels of cables, cable terminal boxes or joints are damaged somehow as a result of cable ageing, material failure or mechanical stress situations in the long run. Also, moisture, dirt or unintentional accidents or human errors, e.g. excavation work can lead to intermittent faults. (Altonen et al. 2003.)

2.2 Fault initiation

During an intermittent earth fault, the phase-to-earth voltage reduces in the faulted phase and the phase-to-earth voltages increase in the healthy phases. The capacitanceto-earth of the faulted phase start to discharge i.e. produce discharge current transient and the healthy feeder phase-to-earth capacitances start to charge, which produce charge current transients. Charge transient frequency, *f* varies between 200 Hz and 1000 Hz. Discharge transient frequency is 4–20 times bigger compared to charge transient frequency. After succeeded extinguishment, phase-to-earth voltage of the faulted phase is recovering and the residual voltage declines waiting for next breakdown, which can be seen in Fig. 2. (Altonen et al. 2003.)

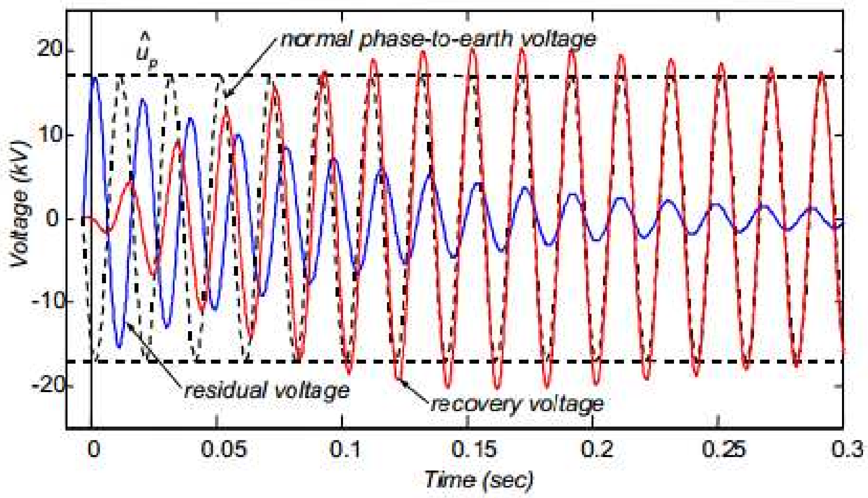

Figure 2. Recovery and residual voltages after an extinguishment of the fault. (Altonen et al. 2003.)

2.3 Types of intermittent earth faults

Next, three different types of intermittent earth faults are presented. The examples were recorded by a high performance fault recorder at the transformer station (130/20 kV) in Sweden. Fig. 3 shows the first type of intermittent earth fault, where five spikes arise in 10 seconds. It is peculiar to this long fault duration between each spike, which means that all quantities reach their zero value before next re-ignition. There isn't overlapping between spikes. Also, the neutral point displacement voltage reaches its zero value, and reset the timers for neutral point displacement voltage relay. Therefore, malfunctions can be avoided. (Dlaboratory Sweden Ab. 2012.)

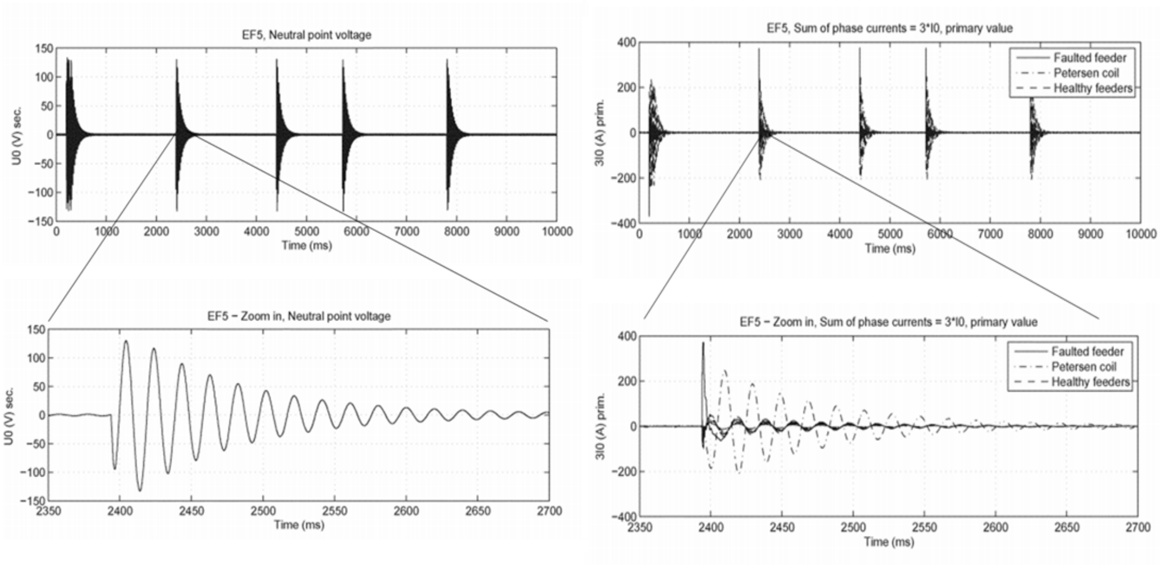

Figure 3. Neutral point voltage and sum of phase currents and close-ups in 10 seconds time interval. (Dlaboratory Sweden Ab. 2012.)

The second intermittent earth fault type, which is illustrated in Fig. 4 with close-ups, contains five spikes during less than one second. It is typical for this second intermittent earth fault type very short time between spikes. Hence, voltage transient is reduced before the next spike, and it is overlapping. In this case, neutral point displacement voltage stays at the high level, as long as the fault continues. In worst case, this type of intermittent fault can lead to an unselective relay operation and disconnection of all feeders in the whole substation. Neutral point displacement voltage doesn’t reduce and particular time delay of the protection is reached, which leads to tripping. Fig. 5 shows a real situation, where the relay operation tripped the supply of the substation due to U_0-measurement. In the third intermittent earth fault type example, which is presented in Fig. 6, there exists multitude high frequency current peaks during one second recording time. Typical for this kind of intermittent fault type is the high frequency content in the residual current. This is because of very short distance between fault and recording place. (Dlaboratory Sweden Ab. 2012.)

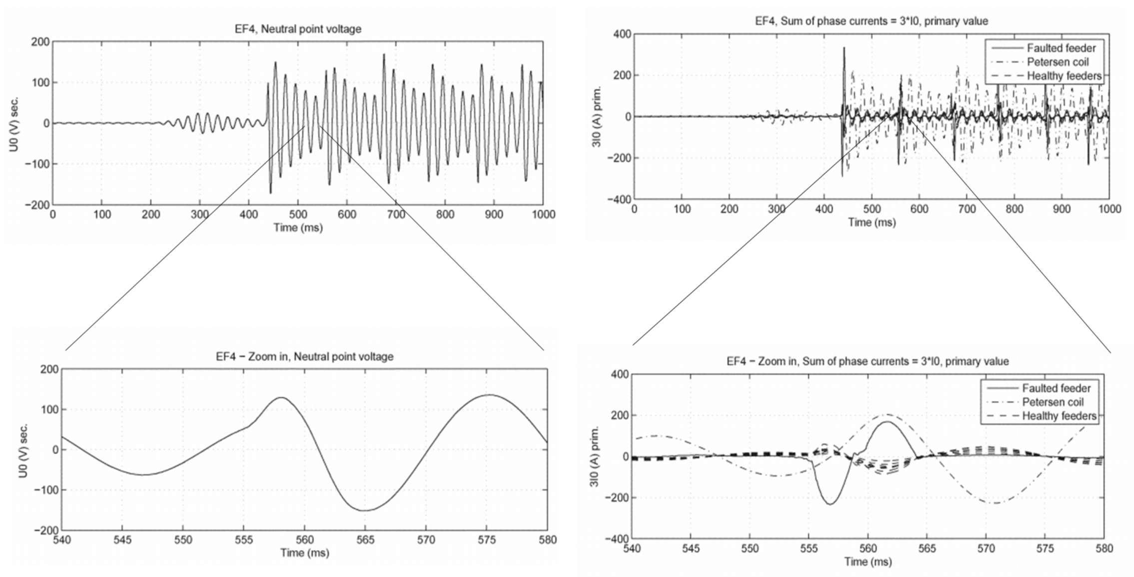

Figure 4. Neutral point displacement voltage, residual current, and close-ups in 1 second time interval. (Dlaboratory Sweden Ab. 2012.)

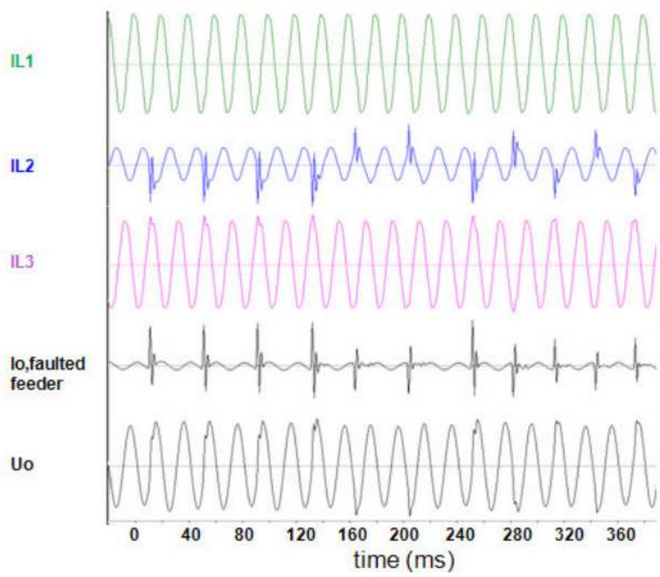

Figure 5. Phase currents, zero sequence current at the faulted feeder and neutral point displacement voltage from a real situation, which led to substation disconnection. (Wahlroos 2012.)

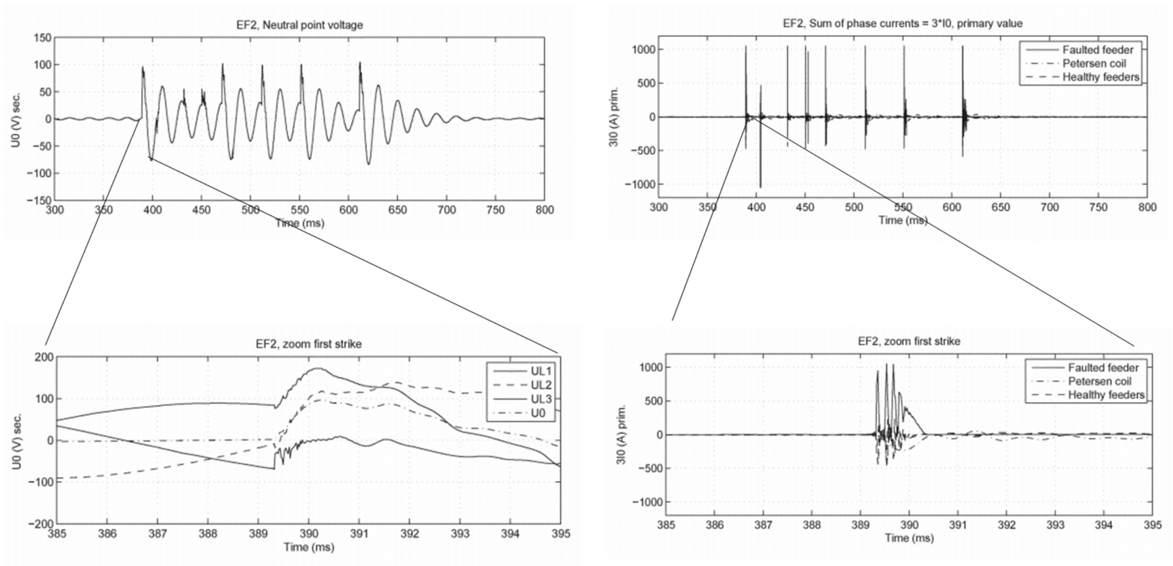

Figure 6. Neutral point voltage and sum of phase currents and close-ups in 0.8 second time interval. (Dlaboratory Sweden Ab. 2012.)

2.4 Water treeing

Water treeing, which leads to intermittent earth fault situation with XLPE-cables, is phenomenon due to, e.g. impurities in material, alternating current (AC)-electric field and penetrating water. Water plays a major role considering insulation breakdowns. XLPE-insulated cables are more vulnerable to restriking faults than paper-insulated cables. Water is penetrated to dielectric material and it contributes creating holes to the insulation. These holes are filled with water, which evaporates, and creates a recurring intermittent fault. Between sparks, the holes are dried due to arc, which is continuing until the next breakdown occurs. That’s why it seems fault is disappeared for a while. In order to avoid water penetrating to insulation material of cables, armoured cables should be used. (Mäkinen 2001:21–23; Kuisti et al. 1999.)

3 DETECTION AND PROTECTION METHODS

3.1 Conventional earth fault protection and related problems

The purpose of the earth fault protection scheme is to be reliable, sensitive, and make sure that protection is valid during and after every earth fault situation. The conventional earth fault protection is based on detecting permanent earth faults, which follow almost fundamental frequency and sinusoidal waveforms of residual current and neutral point displacement voltage. Because the behaviour of intermittent fault is rather different compared to permanent earth behaviour, which can be seen in Fig. 7, detection of it is very challenging. It has to be remembered that the precise fault mechanism of intermittent earth fault isn't known, and some fault modes can occur in unexpected circumstances. (Kuisti et al. 1999; Lorenc, Musierowicz & Kwapisz 2003.)

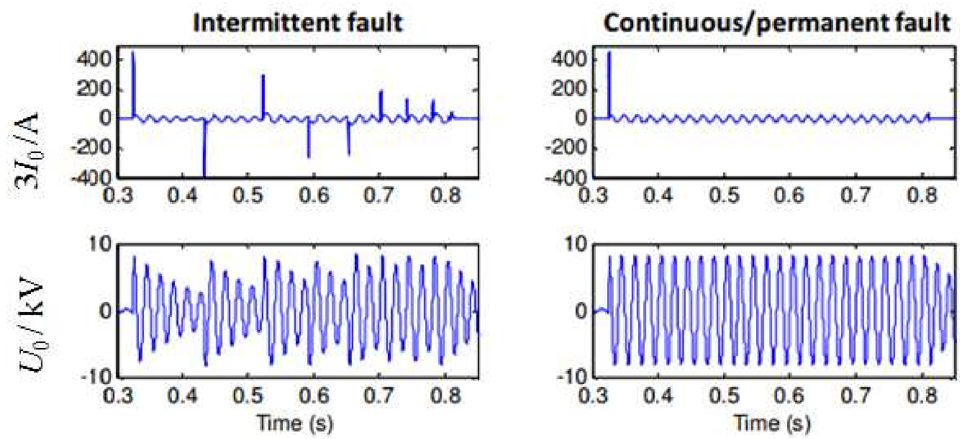

Figure 7. Comparison of intermittent erath fault waveforms and permanent earth fault waveforms. (Wahlroos et al. 2011.)

As can be seen in Fig. 7, very irregular current and voltage waveforms in case of intermittent earth fault are noticed. Therefore, conventional earth fault protection relays are incapable of detecting this kind of fault reliably and hence, more dedicated solutions for detection and removing intermittent earth faults are needed. One possible solution to improve the traditional protection is to design analog filters of relays so that the current peaks can be transformed into fundamental frequency signals. In order to achieve this, hardware and the algorithm should be fine-tuned. (Altonen et. al. 2003; Kuisti et al. 1999.)

Intermittent earth faults can cause the disconnection of the substation and interrupt power supply for a large amount of customers. This is caused by U_0-back-up protection relay tripping, because in compensated networks, where a compensation coil is connected to transformer's neutral point either centrally or locally to cancel the capacitive earth fault current almost entirely, U_0 attenuates slowly between insulation breakdowns. In compensated networks, there is also a parallel resistor connected to coil to increase resistive earth fault current for selective relay operation. However, the parallel resistor affects the probability of intermittent earth faults. The probability of an intermittent earth fault is evident, when the resistance increases. Increased resistance decreases also the magnitude of fault current. On the other hand, the higher resistance affects by the probability of intermittent earth fault by slowing the voltage rise at the faulted phase. Therefore, the probability of the next breakdown after the previous one is decreased. (Altonen et. al. 2003; Kuisti et al. 1999.)

3.2 Detection methods

There are few methods for detecting intermittent earth faults. Next, they are introduced briefly. Spike detection method is based on certain polarity of residual current spikes. Fig. 8 shows the residual current at the healthy feeder (marked with red) and at the faulty feeder (marked with blue). False trippings can be minimized by using counters. The drop-off time should be set at least longer than the time period between successive breakdowns, which can be several cycles. Timer characteristic enables the resetting of the operating timer between fault pulses, and also the protection function in time is guaranteed.

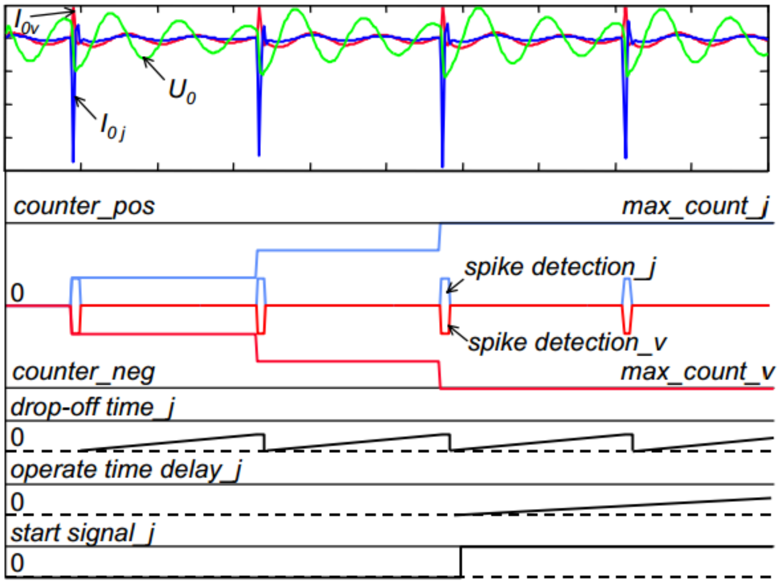

Figure 8. Residual currents and voltage of sampled and filtered in scope of spike detection method. *_j* and *_v* means faulty and healthy feeders. (Altonen et al 2003.)

In Fig. 9, the phase angle criterion for intermittent earth fault detection is presented. Fig. 9 shows phase angle difference between zero sequence current and voltage phasors. Faulted feeder is marked by blue and healthy feeder by red. The operation is achieved, when the phase angle difference is in the operating sector and the magnitudes of residual current and neutal point displacement voltage exceed the threshold values. Normally the operating sector is set to ± 80° or ± 88°, but in this case extended operating sector, (± 120 °) to achieve correct directional sensing of the protection is used. It is also possible to utilize frequency adaptive phasor calculation, which affects the accuracy of the phasor estimation between fault pulses. There is also a settable drop-off timer. There have been already done some field tests of above mentioned approaches. According to field tests performed by spike detection and extended phase angle criterion, intermittent earth faults were dependably detected, but the overall security will require improvements, especially with few false starts occurred. (Altonen et al 2003.)

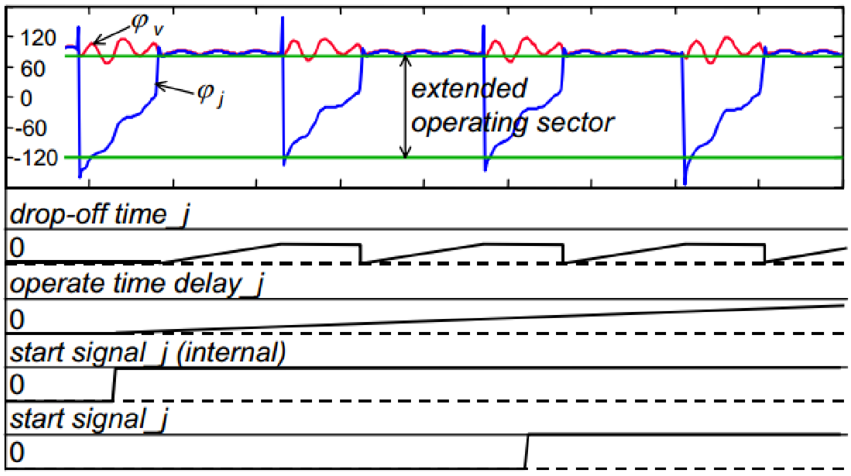

Figure 9. Phase angle difference of sampled and filtered residual current and voltage. *_j* and *_v* means faulty and healthy feeders. (Altonen et al 2003.)

The wavelet analysis according to Lorenc et al. (2003.) is also a method for detecting intermittent earth faults. It is based on specific dynamics of the signal, which are measured during intermittent earth fault situation. Filtering and proper algorithm for iteration processes are utilized. According to analysed examples of the damaged line and undamaged line, it was possible to separate the typical characteristics of the protected line and hence, facilitate intermittent earth fault clearing.

3.3 Intermittent transient earth fault protection

This method is used for detecting short restriking transient earth faults in compensated cabled networks. It is based on intelligent filtering of measured signals. Transient method is based on signs of the spikes. The spike of the residual current of faulted feeder has opposite sign compared to sign of the spike of the neutral displacement point voltage. Also, there isn't a phase angle difference between them. Transient fault makes a pick-up according to the direction of the fault, but doesn't trip if the time isn't long enough between two faults to release and reset the operation timer. If faults occur often enough, the intermittent timer characteristic can be used for clearing intermittent earth faults. Relay is tripped, when the counter reaches the set value. In practise this will happen after a few fault current spikes. Fig. 10 shows the transient method with intermittent and operation times. In case one, tripping doesn’t happen, because intermittent time is set to 0 ms, and it is exceeded. In the second case, where the intermittent time setting is defined to 120 ms, the first transients are ignored, but after several spikes, the tripping happens, and the relay operation is achieved at t = 0.87 ms. Intermittent transient earth fault protection have to be always used with fundamental frequency earth fault protection, because transient protection doesn’t detect permanent earth faults (Sauna-Aho 2013; Vamp 2009.)

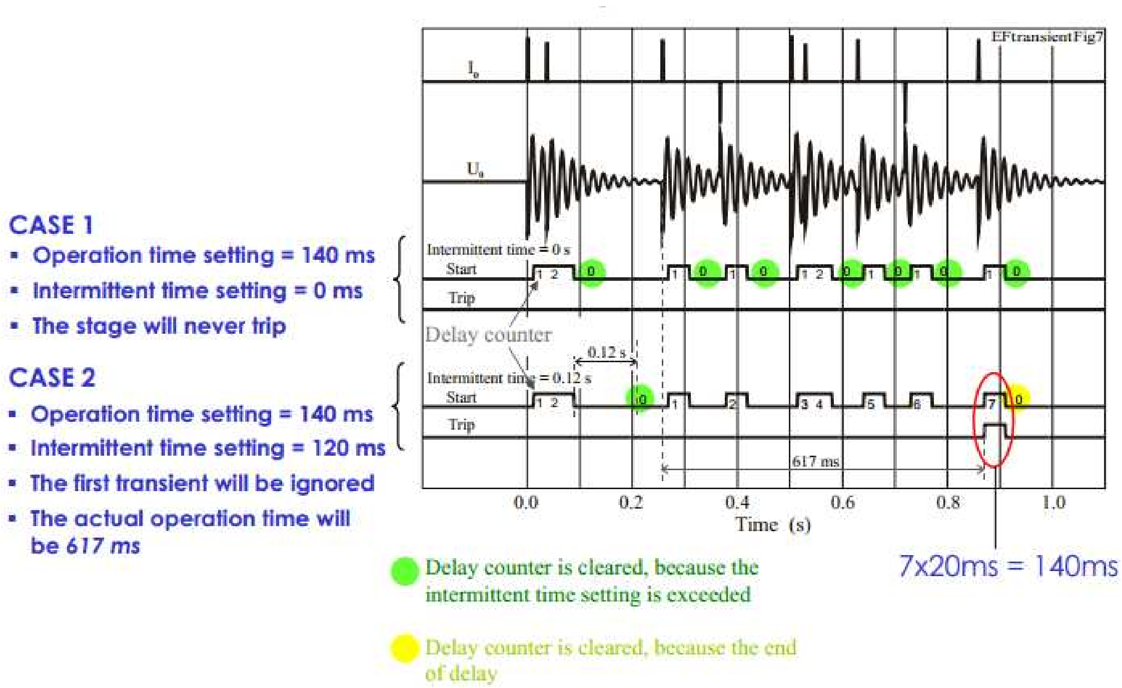

Figure 10. Intermittent and operation time in two cases. (Kumpulainen 2008; Sauna-Aho 2013.)

Figures 11–12 show field test data from faulty- and healthy feeders, where the transient method for detecting intermittent earth faults was used. Fig. 11 presents the faulted feeder. The relay is picked up correctly, only the lowest zero sequence sum current spikes are ignored. Fig. 12 illustrates the healthy feeder data recordings. The relay operates selectively, i.e. doesn’t pick-up. In case of healthy feeder, it is more important to avoid false relay trippings than trip the faulted feeder.

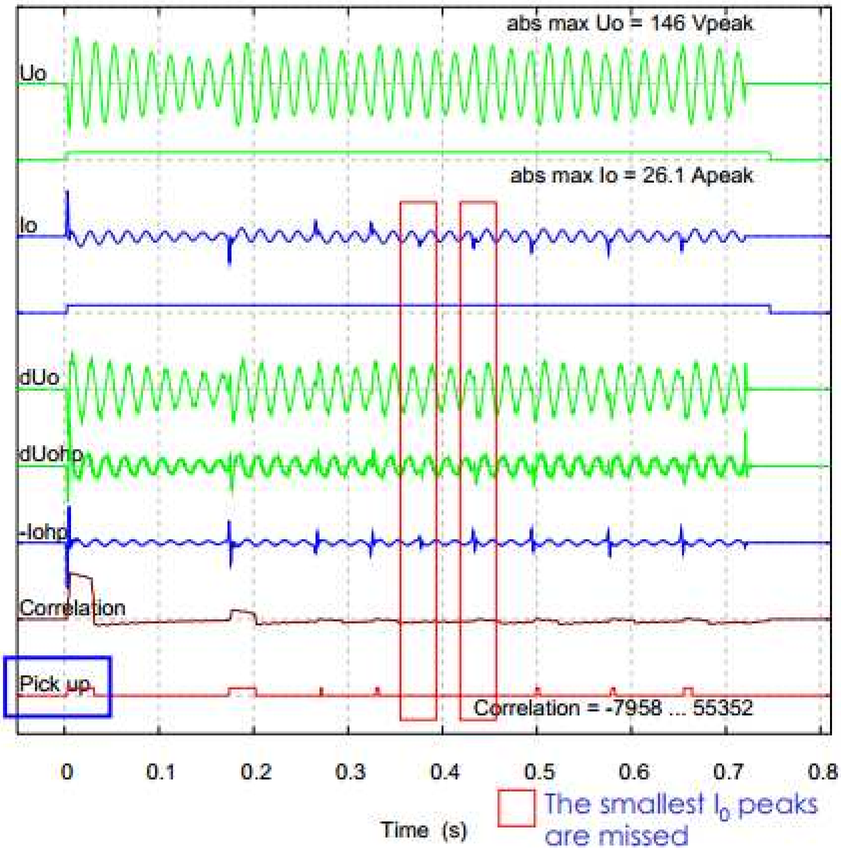

Figure 11. Field test data of faulty feeder. (Kumpulainen 2008.)

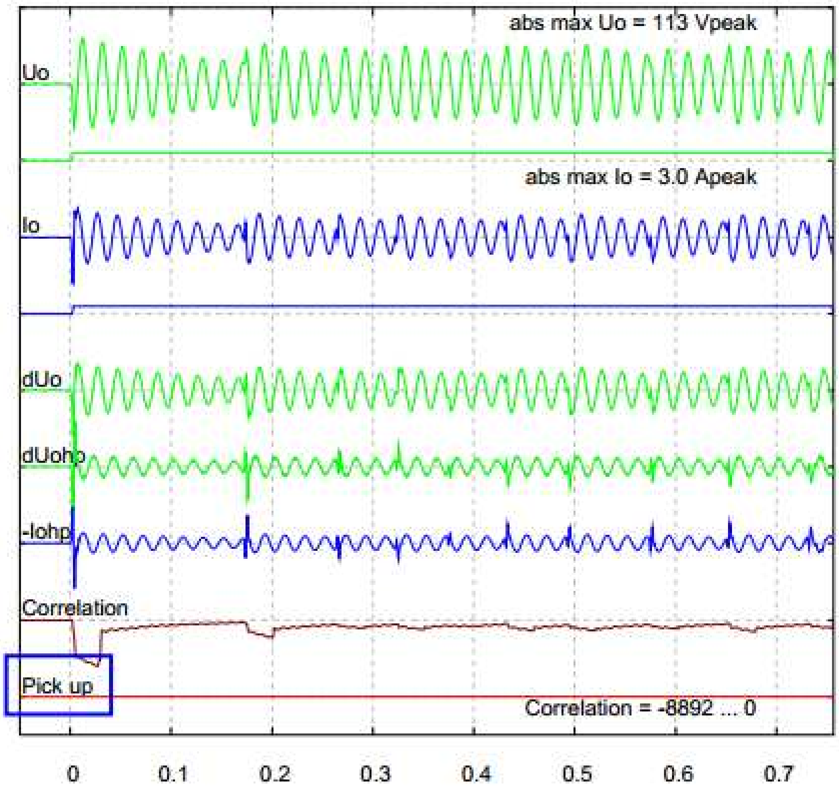

Figure 12. Field test data of healthy feeder. (Kumpulainen 2008.)

3.4 Novel admittance criterion

Novel admittance based earth fault protection is a novel algorithm for earth fault protection in compensated MV distribution networks. There is combined "optimal transient and steady-state performance into one function". The method is based on multi-frequency admittance measuring, where the direction of the accumulated fault phasor points towards the fault direction. Especially, it is proven to give accurate measurement results despite the fault resistance, and fault type. Moreover, the type of fault can be permanent, transient or an intermittent earth fault; earth fault protection function nonetheless reliably. (Wahlroos, Altonen, Uggla & Wall 2013.)

The fundamental admittance frequency phasor, which ensures the sensitivity of protection, can be calculated as follows:

$$\underline{Y}_{0\text{sum}} = \text{Re}[\underline{Y}_0^{\,1}] + j\cdot\text{Im}[\underline{Y}_0^{\,1} + \textstyle\sum_{n=2}^{m} \underline{Y}_0^{\,n}], \tag{3.1}$$

where

$\underline{Y}_0^{\,1} = 3\underline{I}_0^{\,1}/\text{-}\underline{U}_0^{\,1}$ is the neutral admittance phasor of the fundamental frequency,

$\underline{Y}_0^{\,n} = 3\underline{I}_0^{\,n}/\text{-}\underline{U}_0^{\,n}$ is the neutral admittance phasor of the n^{th} harmonic frequency.

Harmonics, which are accounted for loads, transformers, compensation coils, and the type of fault, improve the directional determination security of earth fault. Because the harmonics are significant by earth fault protection point of view, they are utilized. Directional determination of earth fault is very simple; the protection is based on the sign of the imaginary part of the operate quantity phasor. Operation characteristic can be seen in Fig. 13, and it is valid for isolated and compensated networks. (Wahlroos et al 2013.)

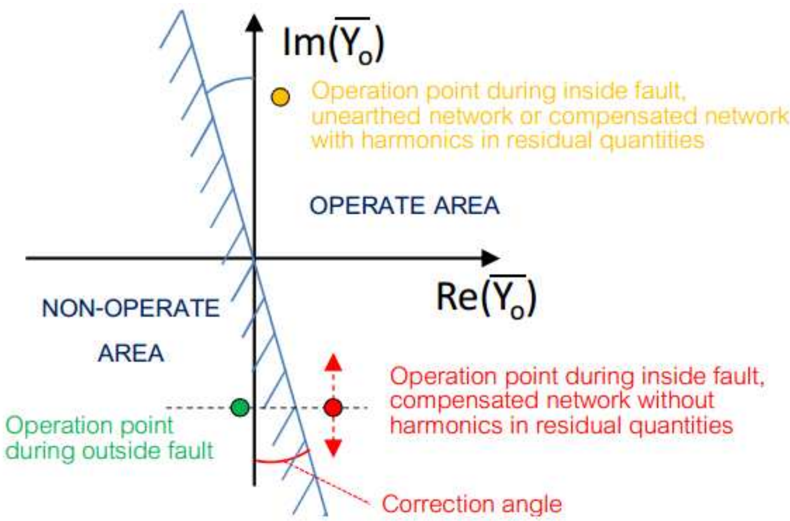

Figure 13. Operation characteristic for multi-frequency admittance protection method. (Wahlroos et al. 2013.)

However, the origin of harmonics, harmonics share and amplitudes might have large variation in time. Therefore, operation might be uncertain, and the calculation process of threshold settings might turn out problematic. If attenuation of higher frequency components due to fault resistance is occurred, the harmonic protection is reliable only in case of very low-ohmic earth faults. (Wahlroos et al 2013.)

Problems related to the traditional fundamental frequency, transients, and harmonic-based methods for earth fault protection can be avoided by using Cumulative Phasor Summing (CPS). It is a method, which utilizes discrete Fourier transform (DFT) calculation, but is still accurate in case of measured signals are temporary, distorted or are containing other frequency components than fundamental or have non-periodic components. CPS is a simple method, which is easy to implement and realize. (Wahlroos et al 2013.)

The cumulative phasor schema is presented in Fig. 14. Into the result, values of measured complex DFT phasors in phasor format from start time to end time are added. Cumulative phasor sum can be calculated according to equation (Wahlroos et al 2013.)

$$\underline{E}_{\mathrm{CPS}} = \sum_{i=t_{\mathrm{start}}}^{t_{\mathrm{end}}} \underline{E}(i) = \sum_{i=t_{\mathrm{start}}}^{t_{\mathrm{end}}} \mathrm{Re}[\,\underline{E}(i)] + j\cdot\sum_{i=t_{\mathrm{start}}}^{t_{\mathrm{end}}} \mathrm{Im}[\,\underline{E}(i)], \tag{3.2}$$

where

$\mathrm{Re}[\underline{E}(i)]$ = real part of phasor $\underline{E}$,

$\mathrm{Im}[\underline{E}(i)]$ = imaginary part of phasor $\underline{E}$.

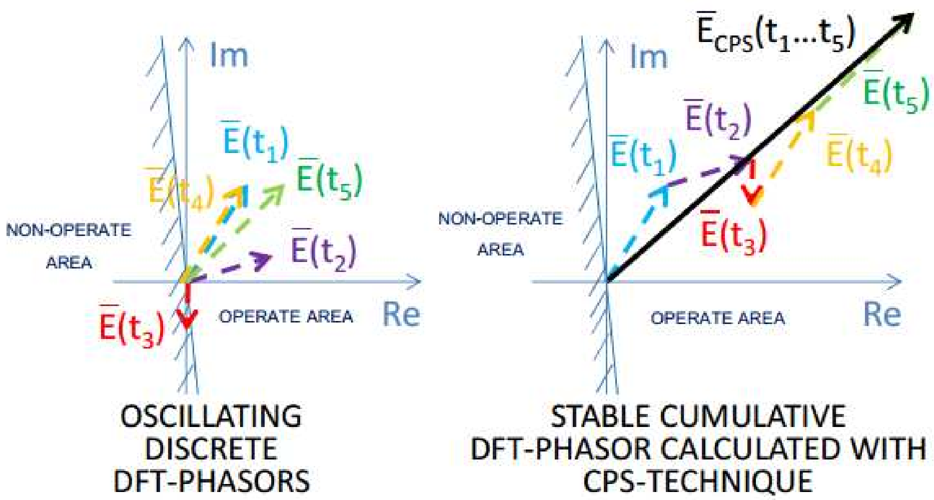

Figure 14. CPS summing concept. (Wahlroos et al. 2013.)

$\underline{E}_{\mathrm{CPS}}$ phasor can be, e.g. current, power, impedance or admittance phasor. The sufficient time interval between the phasor accumulation considering fault transients can be, e.g. 2.5 ms. And, when admittance measurement is used, CPS can be defined as follows:

$$\underline{Y}_{0\mathrm{sum\_CPS}} = \sum_{i=t_{\mathrm{start}}}^{t_{\mathrm{end}}} \mathrm{Re}[\underline{Y}_0^{\,1}(i)] + j\cdot\sum_{i=t_{\mathrm{start}}}^{t_{\mathrm{end}}} \mathrm{Im}[\underline{Y}_0^{\,1}(i) + \sum_{n=2}^{m} \underline{Y}_0^{\,n}(i)], \tag{3.3}$$

This technique is very valid and reliable, because the accumulated phasor is directioned clearly into the operating sector. CPS method also produces a sufficient amplitude estimation of the operation quantity. This patented solution is valid in case of transient and intermittent faults, when high distortions of residual quantity, non-fundamental frequencies or non-periodic components are occurred. (Wahlroos et al 2013.)

4 CONCLUSIONS

The aim of this work was to study intermittent earth faults and their protection methods in MV distribution networks. Intermittent fault is a special type of fault, which is caused by series cable insulation breakdowns or deterioration due to diminished voltage withstand. There have been existed intermittent earth faults in networks, but particularly recently they have risen in attention. This is because of increased UGC and more demands on uninterruptable power supply. A problem with intermittent faults is that traditional earth fault protection is incapable of detecting such irregular and non-periodic waveforms. Therefore, earth fault protection against intermittent earth faults is rather challenging. In the worst case, the whole substation might be interrupted. This would cause naturally, long outages for customers and considerable costs for DNOs. Consequently, earth fault protection from intermittent faults in MV distribution networks has become very important, because it seems the general trend is going towards increased use of UGC. Also in future, the natural ageing of the existing cables will probably increase the amount of intermittent earth faults.

First, there were introduced the main ideas of the detection methods for intermittent earth faults. However, according to field tests of spike detection and wider phase angle criterion, these two methods detected intermittent earth faults dependably, but the overall security will require improvements. Therefore, more field tests are needed, especially eliminating fault starts in case of healthy feeders. Wavelet analysis showed to be capable of separating the signal characteristics of the protected feeder and hence, facilitate damaged line discrimination and fault clearing. Next, the intermittent earth fault protection methods against intermittent earth faults were studied. At the moment there exist a few methods in addition to improvements in traditional methods to protect distribution network from intermittent earth faults. These methods are transient-based protection and novel admittance cumulative phasor summing (CPS). Transient based protection method is based on intelligent filtering of measured signals utilizing counter and the signs of fault spikes. In this method careful placing of intermittent and operation time is needed to make the selective relay tripping. Novel multi-frequency admittance criterion for earth fault protection is also a very promising method. It is based on multi-frequency admittance measuring, which points the fault direction clearly and facilitates the protection considerably. It is proven to give accurate measurement results despite the fault resistance, and fault type.

In order to achieve reliable and selective earth fault protection in case of intermittent earth faults, further field tests are definitely needed with these protection methods. When earth fault protection is reliable in MV distribution networks, longer operating life for network equipment and underground cables will be achieved. It has to be also remembered that the fault mechanism of this kind of special fault isn’t yet completely known. Therefore, at this point it is difficult to say precisely what kind of actions should be taken to minimize supply failures due to intermittent earth faults.

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