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TESTING OF THE PERFORMANCE OF NOVEL ADMITTANCE CRITERION FOR INTERMITTENT EARTH FAULT PROTECTION

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SYMBOLS AND ABBREVIATIONS

Symbols

f	Frequency
$3\underline{I}_0$	Residual current
I_{0Bg}	Zero sequence current of the background network
I_{0Fd}	Zero sequence current of the protected 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
R_f	Fault resistance
$\underline{U}_0$	Zero sequence voltage
t_{end}	End time
t_{start}	Start time
U_a, U_b, U_c	Phase-to-earth voltages in phase a, b, and c
$\underline{Y}_{0sum\_CPS}$	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
BG	Background
CPS	Cumulative Phasor summing
DFT	Discrete Fourier Transform
DNO	Distribution Network Operator
MV	Medium Voltage
OHL	Overhead Line
PSCAD	Power System Computer Aided Design, a simulation software
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 to build more reliable and weatherproof MV distribution networks. Therefore, distribution network operators (DNOs) have started to replace overhead lines (OHLs) by underground cables also in rural areas. However, increased cabling is not a trouble-free solution. 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. (Mäkinen 2001:1–2; Altonen, Mäkinen, Kauhaniemi & Persson 2003.)

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 false relay operation. In the worst case a whole substation could be disconnected due to back-up protection, which observes zero sequence voltage growth, i.e. neutral point displacement voltage measured at the substation. Outages in wide area and related costs could be significant. In normal conditions this zero sequence voltage, which is the voltage between earth and system’s neutral point, is almost zero. (Altonen et al. 2003.) Consequently, intermittent earth fault protection has to be implemented by other methods. Therefore, the aim of this work was to study the performance of the novel admittance criterion for detecting intermittent earth faults in MV distribution networks. (Wahlroos, Altonen, Uggla & Wall 2013.)

The most important thing in intermittent earth fault protection is that the relay observes only the fault in the faulted feeder (Arcteq 2014: 3). The novel admittance criterion for detecting intermittent earth faults, which is based on cumulative phasor summing (CPS), was studied more thoroughly in the simulations. The novel admittance criterion is proven to give accurate measurement results despite the fault resistance and fault type. (Wahlroos et al. 2013.) The simulation model for studying intermittent earth faults with defined two fault scenarios was carried out by PSCAD network modelling tool.

The structure of this work consists of five chapters. After the introduction, Chapter 2 summarizes the basics of intermittent earth faults. Chapter 2 is based on my seminar work Määttä (2014). Chapter 3 introduces the novel admittance criterion for intermittent earth fault protection. Part of the Chapter 3 is also based on my earlier seminar work. Chapter 4 presents the empirical part of this work, which is implemented by creating a typical MV distribution network model by PSCAD network modelling tool with two defined intermittent earth fault scenarios. Based on the simulation results, conclusions are made, and which can be found in Chapter 5.

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. The intermittent earth fault ignites and vanishes alternately. An intermittent fault is caused by a series of cable insulation breakdowns or deterioration of insulation due to diminished voltage withstand. 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 earth faults. 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. (Altonen et al. 2003; Mäkinen 2001: 1–2.)

Intermittent fault is very typical fault in compensated systems consisting of underground cables. Especially 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. 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. (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 zero sequence 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 are not 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 zero sequence voltage stays in high values long enough. (Wahlroos 2012.)

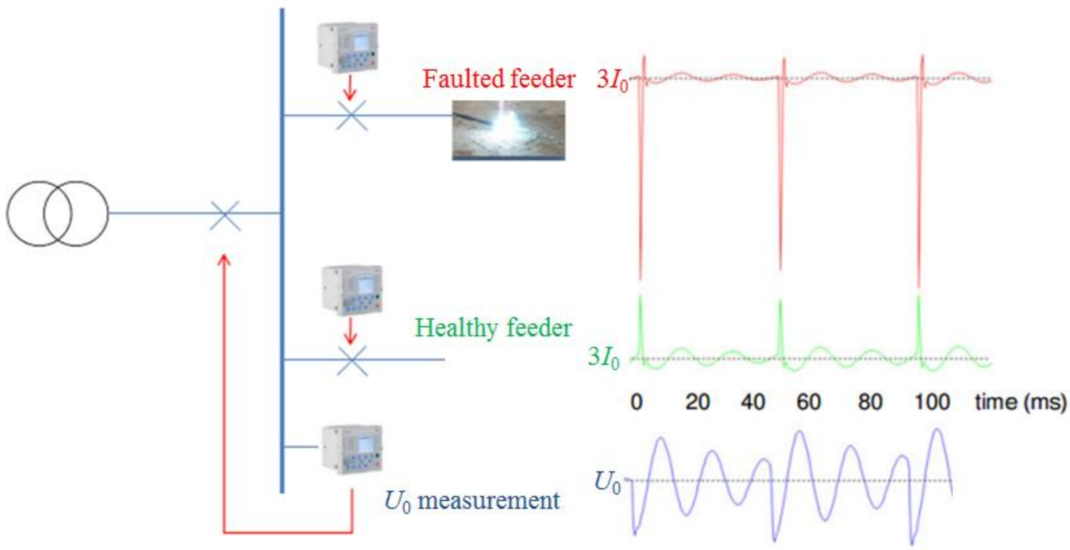

Figure 1. Residual currents of faulted and healthy feeders and zero sequence voltage waveform in intermittent earth fault situation. (Wahlroos 2012.)

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 capacitance-to-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.)

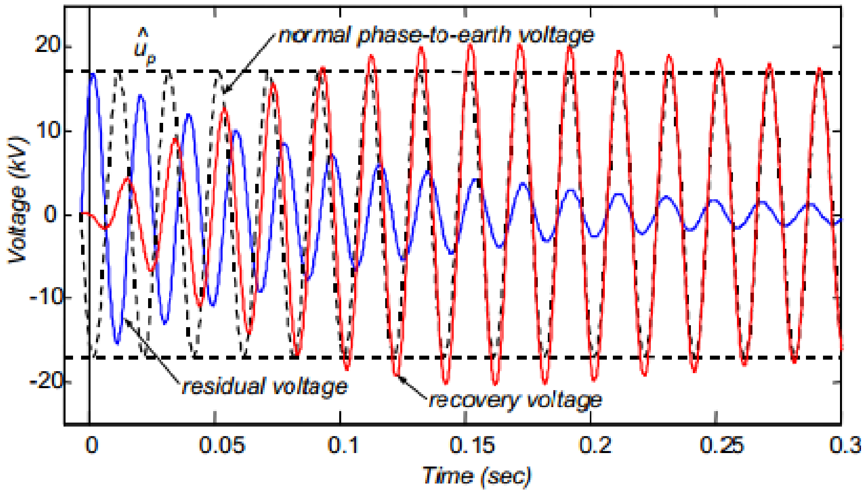

Figure 2. Recovery and residual voltages after an extinguishment of the fault. (Altonen et al. 2003.)

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 (130/20 kV) at the transformer station 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 is not overlapping between spikes. Also, the zero sequence voltage reaches its zero value, and reset the timers for zero sequence voltage relay. Therefore, malfunctions can be avoided. (Dlaboratory Sweden Ab. 2012.)

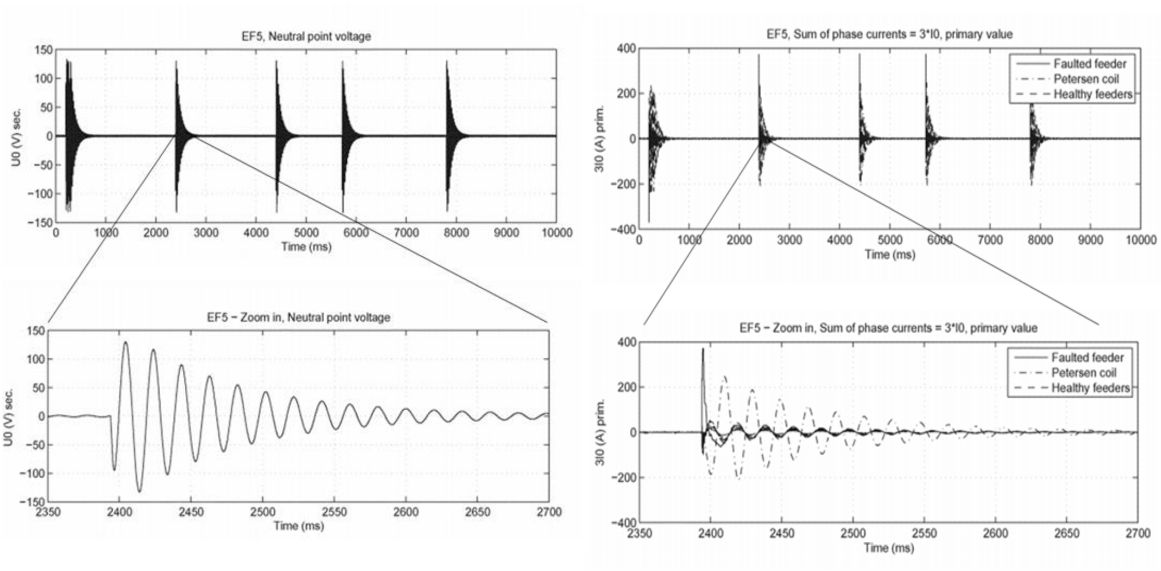

Figure 3. Zero sequence voltage and sum of phase currents and close-ups in 10 seconds time interval. (Dlaboratory Sweden Ab. 2012.)

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, zero sequence 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. Zero sequence voltage does not reduce and particular time delay of the protection is reached, which leads to relay operation. In the third intermittent earth fault type example, which is presented in Fig. 5, 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.)

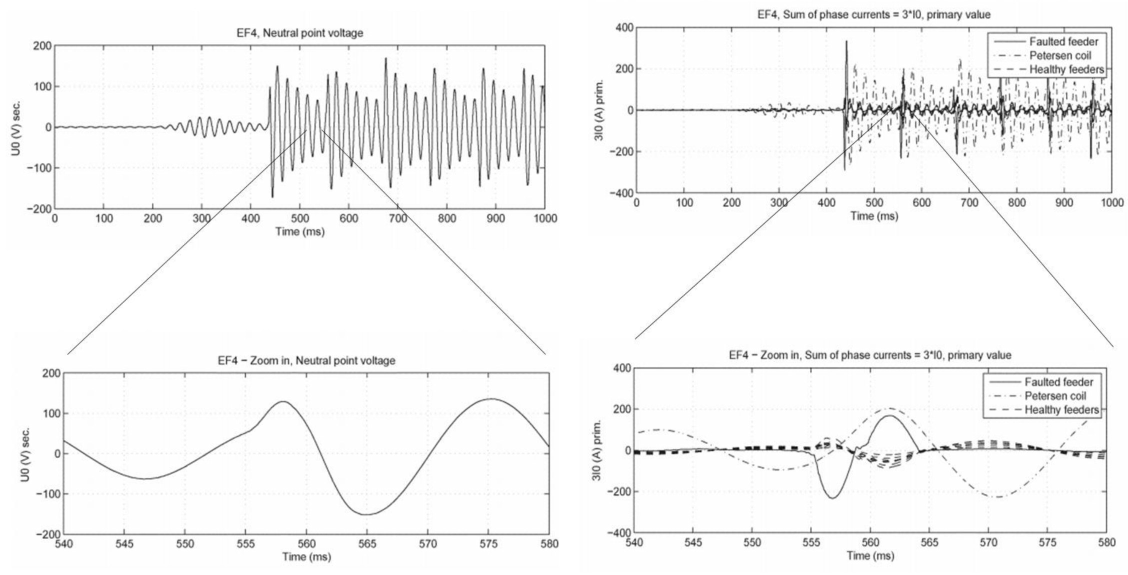

Figure 4. Zero sequence voltage, residual current, and close-ups in 1 second time interval. (Dlaboratory Sweden Ab. 2012.)

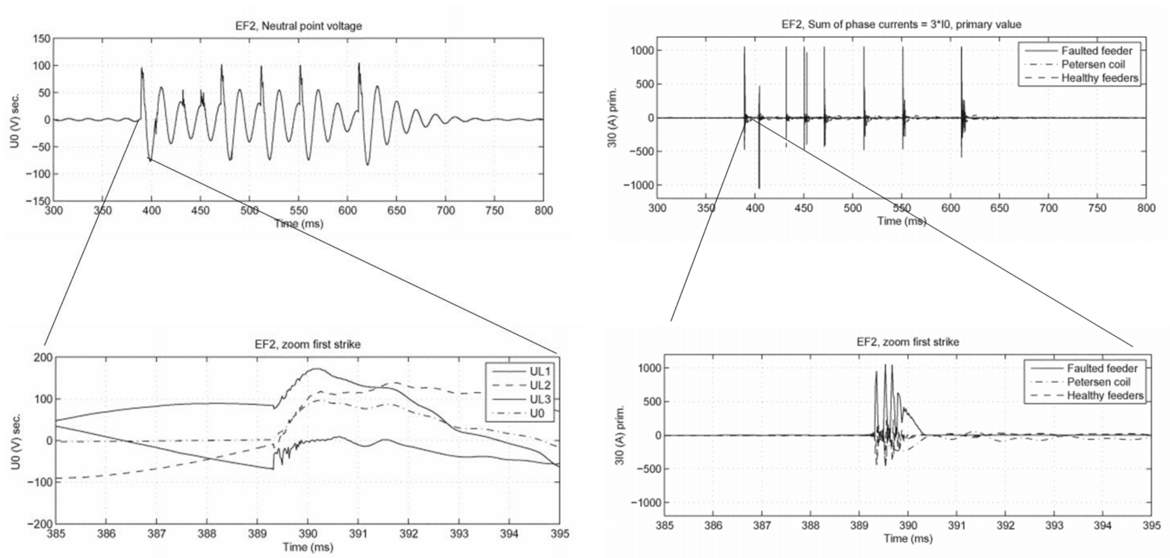

Figure 5. Zero sequence voltage and sum of phase currents and close-ups in 0.8 second time interval. (Dlaboratory Sweden Ab. 2012.)

3 PROTECTION METHODS

3.1 Conventional earth fault protection and related problems

The purpose of the earth fault protection scheme is to be selective, 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 zero sequence voltage. Because the behaviour of intermittent fault is rather different compared to permanent earth fault behaviour, which can be seen in Fig. 6, detection of it is very challenging. It has to be remembered that the precise fault mechanism of intermittent earth fault is not known, and some fault modes can occur in unexpected circumstances. (Kuisti et al. 1999; Lorenc, Musierowicz & Kwapisz 2003.)

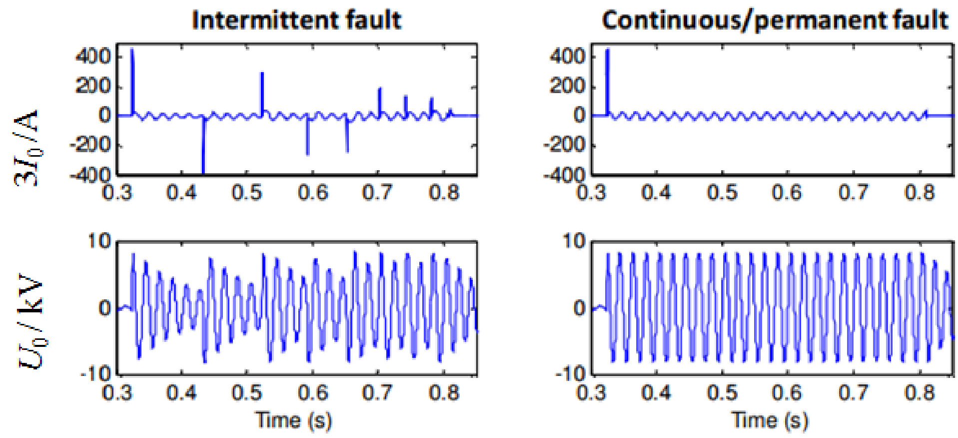

Figure 6. Comparison of intermittent earth fault waveforms and permanent earth fault waveforms. (Wahlroos et al. 2011.)

As can be seen in Fig. 6, 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. (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 decentrally 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. Alternatively, 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 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. Because of this solution is proven to be very reliable and other protection functions for detecting, e.g. permanent earth faults, are not needed. (Wahlroos et al. 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. 7, and it is valid for isolated and compensated networks. (Wahlroos et al. 2013.) According to Fig. 7, the left side of the operation characteristic represents the non-operate area, and the right side of the operation characteristic represents the operate area. The set correction angle, i.e. operation characteristic angle, separates these two areas. The proper angle can be, e.g. 5°. (Wahlroos et al. 2013.)

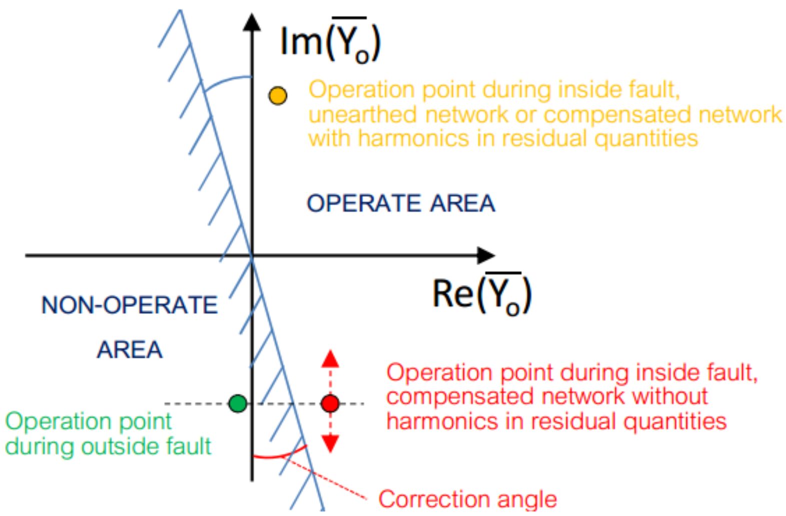

Figure 7. Operation characteristic of admittance criterion. (Wahlroos et al. 2013.)

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. 8. 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.)

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

where

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

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

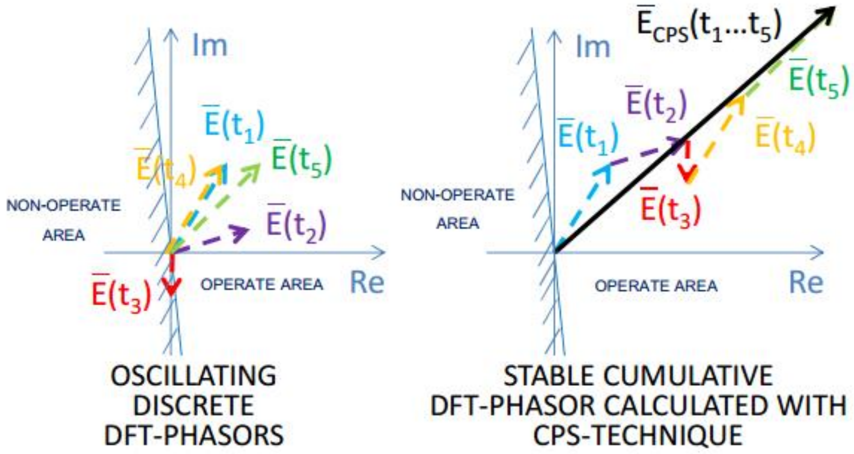

Figure 8. CPS concept. (Wahlroos et al. 2013.)

$\underline{E}_{\text{CPS}}$ 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:

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

This technique is very valid and reliable, because the accumulated phasor is pointing towards the fault direction. CPS method also produces a sufficient amplitude estimation of the operation quantity. This 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. The method is already used in ABB *REF615* IEDs, where the first version of the algorithm is utilized. (Wahlroos et al 2013.)

3.3 Relay operation time settings and coordination with busbar protection

It is clear that in pursuance of setting the intermittent earth fault protection, zero sequence voltage protection of the busbar has to be coordinated in the right way. The faulted feeder should be always disconnected before the operation of the busbar protection with sufficient margin. However, intermittent earth faults can cause stress for network, and therefore the operation of the protection should be done relative fast. It is recommended that the proper reset time of an intermittent earth fault stage would be 500 ms, calculated from the first occurred spike. The value should not be lower than 450 ms. In this case the operation requires at least two spikes to be noticed, which is a typical situation in compensated networks, because in these networks spikes occur less frequently. If the busbar protection is set to very fast, under 1 s, it should be revised. The back-up protection should not be faster than intermittent earth fault operation time with added circuit operate time and reset time of the zero sequence voltage protection. (Arcteq 2014: 4–5.)

4 SIMULATIONS

Intermittent earth fault protection was studied by novel admittance criterion based on CPS. The intermittent earth fault model was based on the calculation of the accumulated phasor sum of DFTs at fundamental frequency. In this work, the purpose was to simulate the performance of the admittance criterion in case of intermittent earth faults in two different situations. And also to find out how well the novel admittance criterion can detect intermittent earth faults in compensated cabled MV distribution network, when the time between spikes was short and long. In the first simulated situation in this work, the time between spikes was shorter (50 ms) compared to the second case, where the time between spikes was considerably longer (500 ms).

The simulations were created by PSCAD network modelling tool. The network model, which was used, was created by Jaakkola (2012). The model was modified partly to achieve the desired intermittent earth fault scenarios. The intermittent earth fault control segment was added to model to simulate intermittent earth faults in network. The intermittent earth fault model was created originally by Olavi Mäkinen, and it was also used in his Licentiate thesis: Mäkinen (2001). The simulation results in case of defined fault scenarios were created by a multi-run block and saved to separate files. The results were transferred into Excel for essential calculations. Finally, the results were transferred into Matlab®, where the protection graphs were created. In the next sections, the main parts of the simulation model and the performance of the protection in each case using novel admittance criterion for detecting intermittent earth faults are introduced.

4.1 Simulation model

Because intermittent earth faults occur mostly in compensated cabled networks, the protected feeder was totally cabled. The network model consisted of 110 kV main supply, 110/20 kV main transformer, parallel resistor, which was adjusted to produce 5 A resistive current, centralized compensation coil, and a busbar, which consisted of four feeders (2 OHLs and 2 cables) and their load, according to Fig. 9. The load in the background (BG) network was 8 MW and in the protected feeder, 2 MW or 2 MW per feeder.

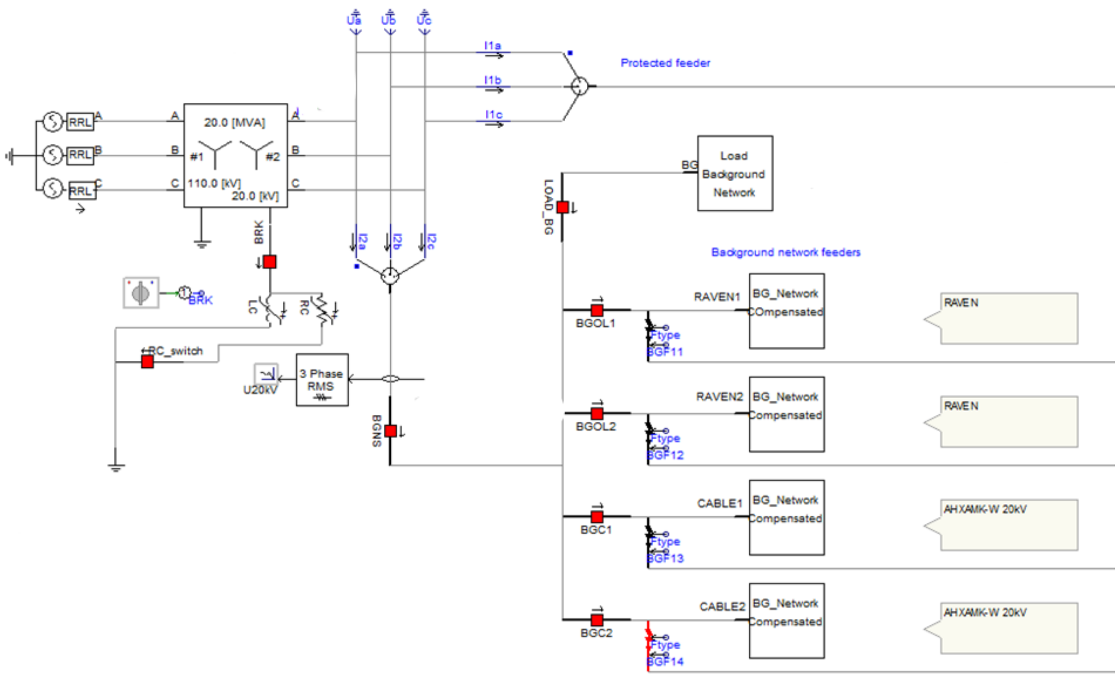

Figure 9. Main supply, 110/20 kV main transformer, protected feeder, BG network and the load of the BG network.

The central coil compensated 10 km from the beginning of each feeder, and the decentralized coils compensated the rest of the feeders. The cable feeders were decentrally compensated in every 5 km, and only one compensation coil compensated each OHL feeder. The coils at the OHL feeders located in the middle of the OHL feeders.

Figure 10 shows the protected feeder and its load with decentrally installed compensation coils. Loads were continuously connected, and the resistances of loads were delta-connected. The healthy state U_0 was adjusted to be 2 % of the main voltage, which was created by star-connected resistances referrering to shunt conductances. 2 % was an estimation of the typical asymmetry of a real network. The cable type AHXAMK-W

3·185+35, and the OHL type Raven 54/9 were used. The feeder sections were created by pi-sections. The length of each trunk line pi-section was 5 km, and branch line 2.5 km. The total length of the network was 220 km.

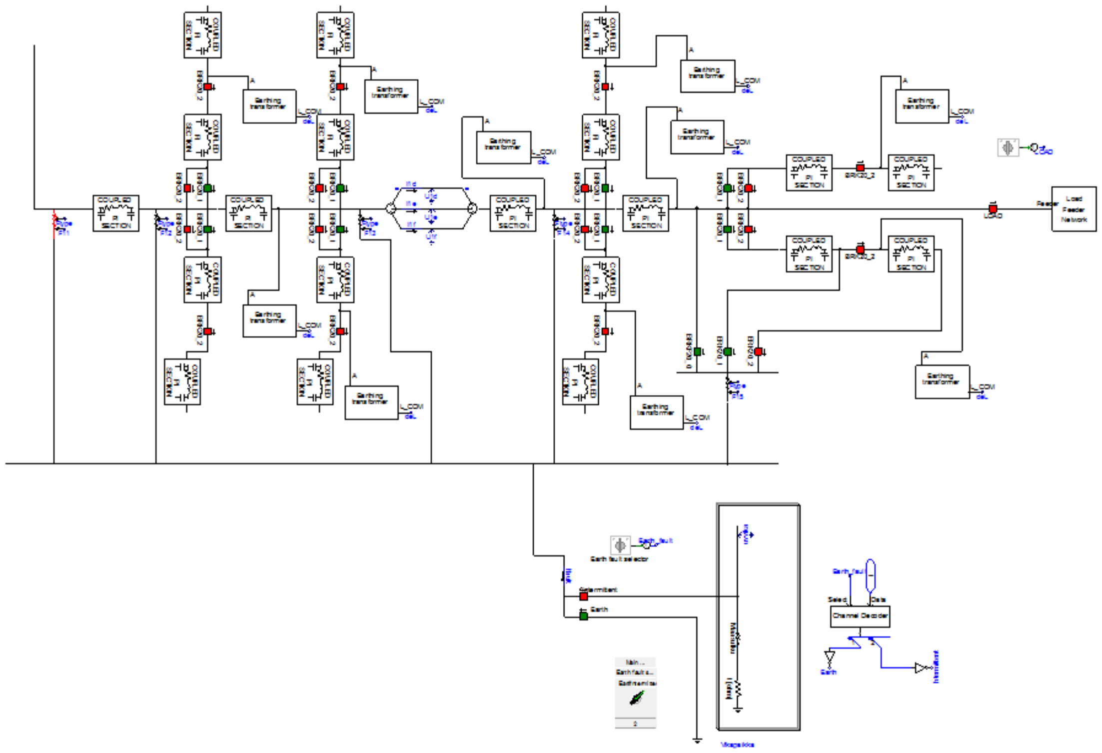

Figure 10. Protected feeder and its load, decentrally installed compensation coils, and intermittent earth fault section.

Intermittent earth fault phenomenon to network model was created, which can be seen in Fig. 10 below the protected feeder. Figure 11 shows the control segment for intermittent earth fault. It was possible to adjust ON and OFF delays of the intermittent earth fault, fault resistance, insulation level, intermittent earth fault start time, and fault duration time. In both cases the fault duration time was 1 s, and the fault start time was set to 0.2 s. For the protection method based on the cumulative phasor sum of the admittances from the protected feeder and BG network, multi-run block saved the instantaneous results at every 2.5 ms (Wahlroos et al 2013). The samples were taken during 1 s, i.e. between 0.2 s and 1.2 s. Some variation to the intermittent earth fault signal was created by a random number generator, which modified the set insulation level. The random number generator produced a new number, whenever the input timer signal changed. However, the probability was adjusted to 1 %, which meant that the number was varied only between 99 % and 100 %. It can be concluded that the variation of produced number was negligible. When the set insulation level was reached, the fault was switched on. And after the set time delay, which was set to 20 ms, the fault was allowed to switch off at the next zero crossing of the fault current.

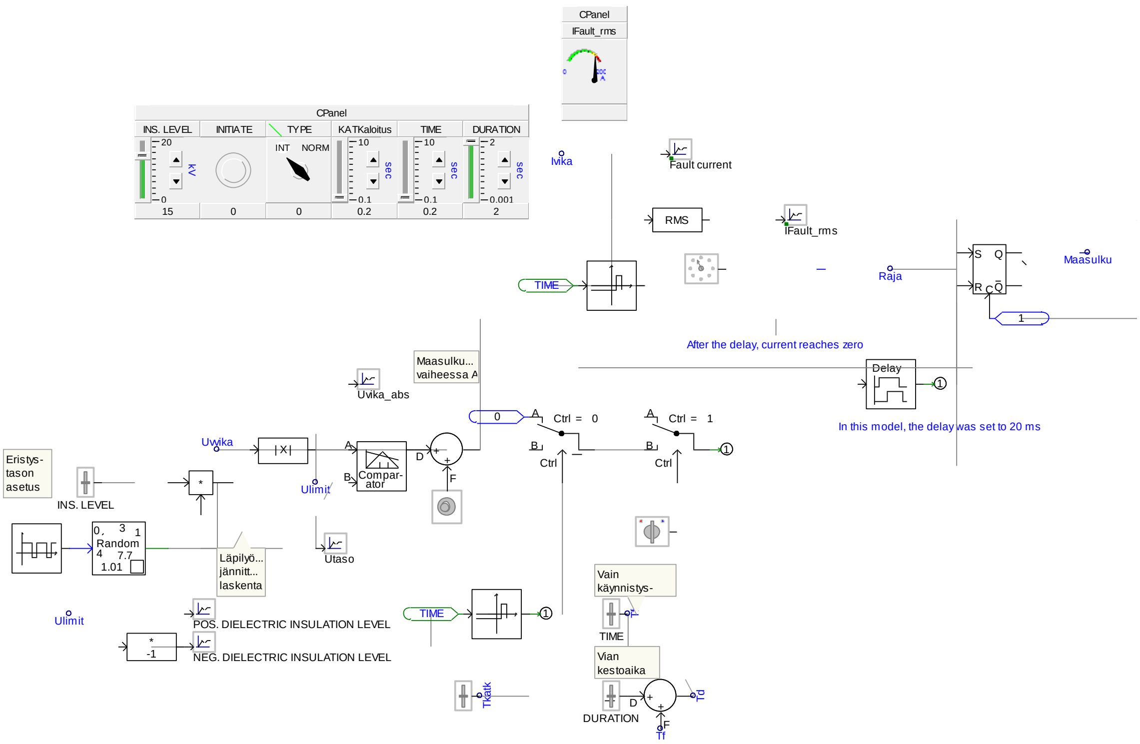

Figure 11. The control segment for intermittent earth fault.

4.2 Simulation parameters and constant values

In this model, the cable and OHL parameters were constant and can be found in Table 1. It was possible to adjust different factors, but only fault location, insulation level, and OFF delay were varied. The fault locations were at the beginning and at the end of the protected feeder, and also in the BG network. Compensation degree was kept at 0.95.

Fault resistance, R_f was 2 Ω, and parallel resistance was continuously connected. The length of the protected feeder was 60 km, and the intermittent earth fault was in phase a.

Table 1. Constant parameters for cable and OHL.

CABLE: 3*185+35 AHXAMK-W 20 kV		OVERHEAD LINE: RAVEN 54/9	
K_R1	0.22 Ω/km	O_R1	0.543 Ω/km
K_XL1	0.113 Ω/km	O_XL1	0.372 Ω/km
K_XC1	0.0122 MΩ·km	O_XC1	0.3238 MΩ·km
K_R0	0.882 Ω/km	O_R0	0.691 Ω/km
K_XL0	0.365 Ω/km	O_XL0	1.891 Ω/km
K_XC0	0.0119 MΩ·km	O_XC0	0.7267 MΩ·km

4.3 Simulation results

The results of the simulations are presented in the next sections. The protection graphs were created by Matlab® via scripts, which can be found in Appendix 1. Because the time interval between samples was adjusted to 2.5 ms, the simulation produced 400 results in each case. Therefore, the amount of data became substantial, and it was not attached to appendix. However, the waveforms of the different quantities in all situations were recorded, and presented in each case. The results of the simulations can be found in the created protection graphs. The protection graphs contain the calculated CPS admittances in case of protected feeder faults being either at the beginning or at the end of that feeder. They were marked by cyan, and BG network faults were marked by red during one second recording time.

The correction angle was drawn by dashed black line in the protection graphs. The angle was adjusted to 5° according to Wahlroos et al. (2013). The direction of the calculated total CPS admittances was marked in the graphs with bolded lines depending on whether the fault was at the protected feeder or in the BG network. The accumulated admittance phasors from 0.2 s to 1.2 s were marked by crosses. As it was mentioned earlier about the operation time of the relay, the adequate time could be 0.5 ms calculating from the first spike. In these simulations the first spike occurred at 0.2 s. Consequently, relay should operate at 0.7 ms. Therefore, the accumulated admittance phasor at 0.7 s was marked by black crosses in the graphs. This showed where the accumulated admittance phasor was located at that time.

4.3.1 Short time interval between spikes

In this case the insulation level was 10 kV, R_f was 2 Ω, ON delay was 20 ms, and OFF delay was 50 ms. The time between spikes was adjusted to be short, 50 ms.

Intermittent earth fault at the beginning of the protected feeder

Fig. 12 shows the typical waveforms of the phase-to-earth voltages U_a, U_b, U_c, zero sequence voltage U_0, zero sequence currents of the protected feeder I_{0Fd}, and healthy feeders I_{0Bg} measured at the substation, when the fault located at the beginning of the protected feeder. In this case the time between spikes was adjusted to be relative short (50 ms), which can be seen in Fig. 12. Phase-to-earth voltage U_a in the faulted phase a, reduced, and recovered between the short spikes due to fault. Respectively, healthy phase-to-earth voltages increased during the fault. Zero sequence current at the protected feeder contained relative high current peaks. In this case, zero sequence voltage behaved almost in the same way as in case of permanent earth fault situation. This means that, when spikes occur often enough, earth fault protection can detect the intermittent earth faults easier, and the operation of the back-up protection can be avoided.

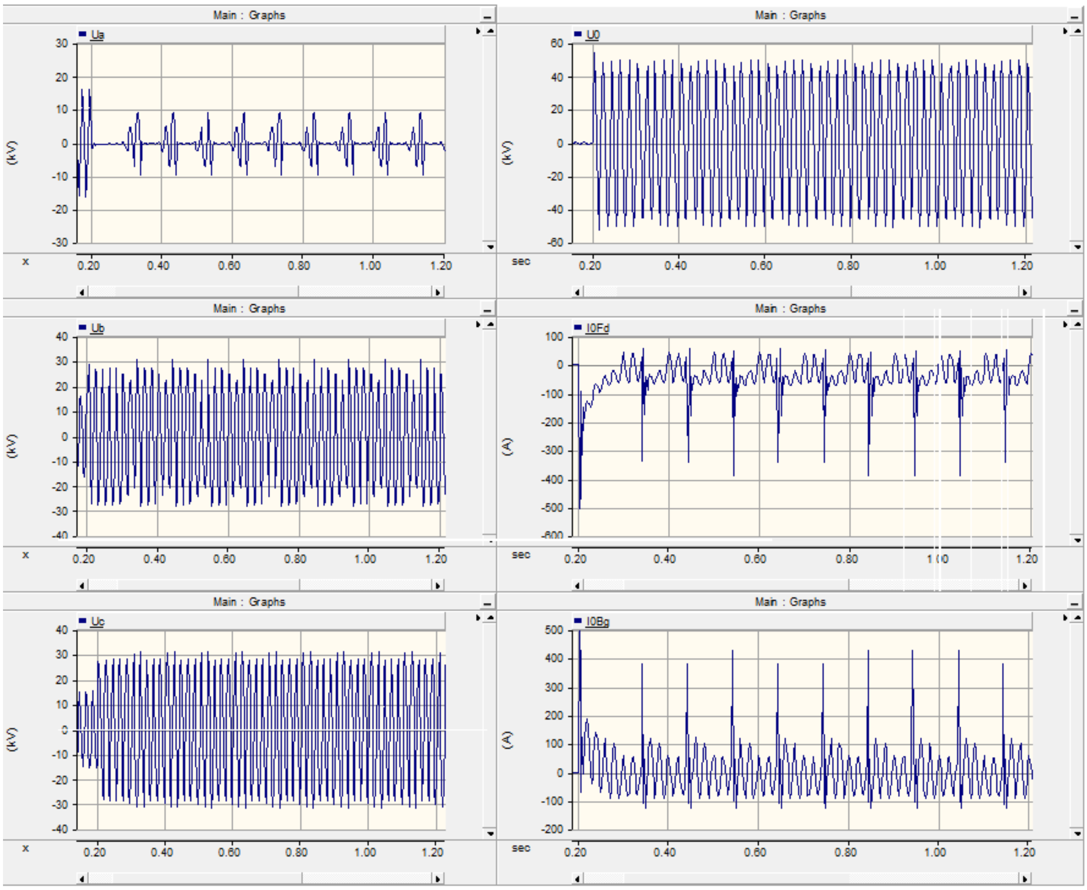

Figure 12. Waveforms of the U_a, U_b, U_c, U_0, I_{0Fd} and I_{0Bg} in case of fault located at the beginning of the protected feeder with short time interval between spikes.

Figure 13 shows the instantaneous admittances of the protected feeder and the BG network, and Fig. 14 the performance of the novel admittance criterion using CPS in case of intermittent earth fault at the beginning of the protected feeder. The left side in the graphs represented the non-operate area and the right side represented the operate area. The total CPS admittance of the BG network pointed to the non-operate area, even though the most of the instantaneous admittances were located very near the boundary line. Instantaneous admittances at the protected feeder were located more clearly in the operating area. Calculated total CPS admittance of the protected feeder was clearly pointing towards operating area, which meant that protection operated correctly in this case, and there was a sufficient margin to boundary line. It referred that protection with this method was reliable and selective. Accumulated admittance phasor of the protected feeder at 0.7 ms located correctly in the operating area.

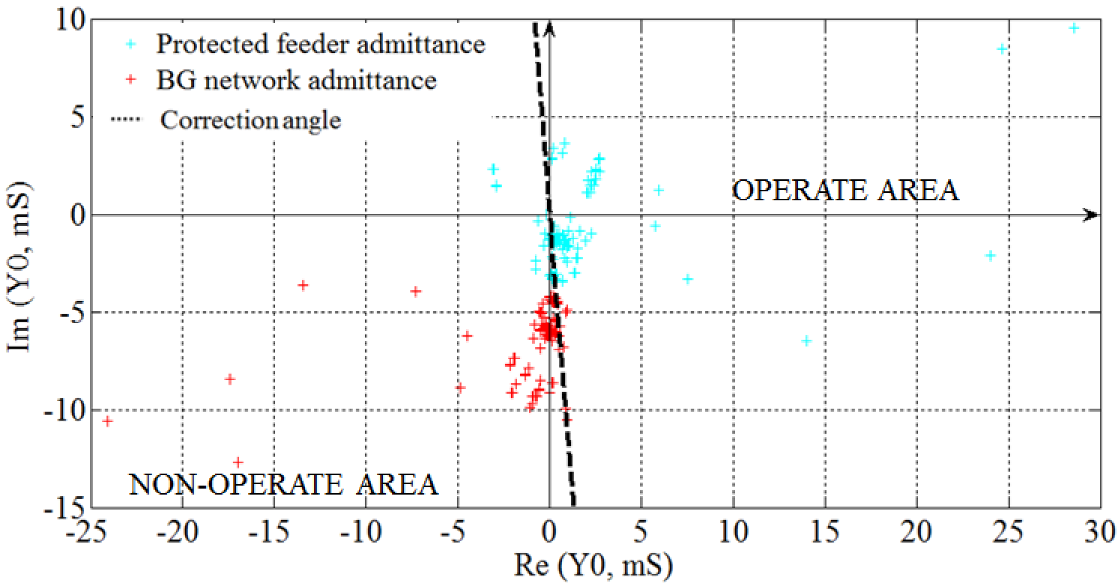

Figure 13. Instantaneous admittances, when fault located at the beginning of the protected feeder with short time interval between spikes.

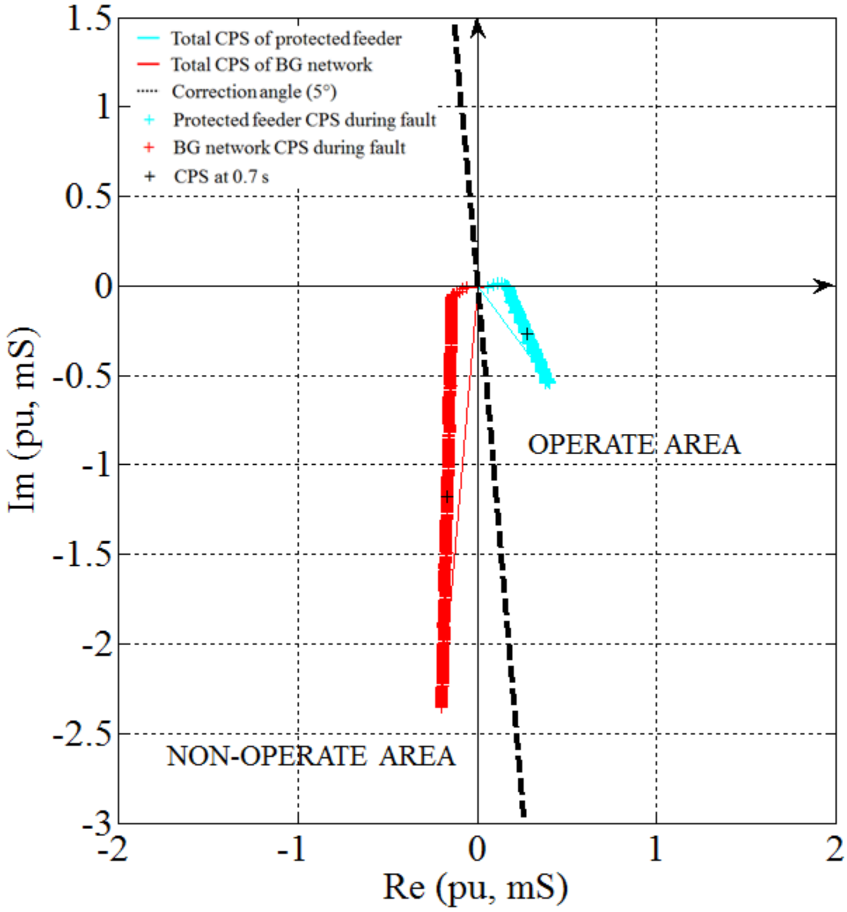

Figure 14. Calculated CPS admittances in case of intermittent earth fault at the beginning of the protected feeder with short time interval between spikes.

Intermittent earth fault at the end of the protected feeder

Fig. 15 shows the typical waveforms in this case. It can be seen in Fig. 15 that the waveforms did not change much compared to situation above, see Fig. 12. However, in the faulted phase according to Fig. 15, it can be seen that the voltage between spikes varied more compared to situation in Fig. 12.

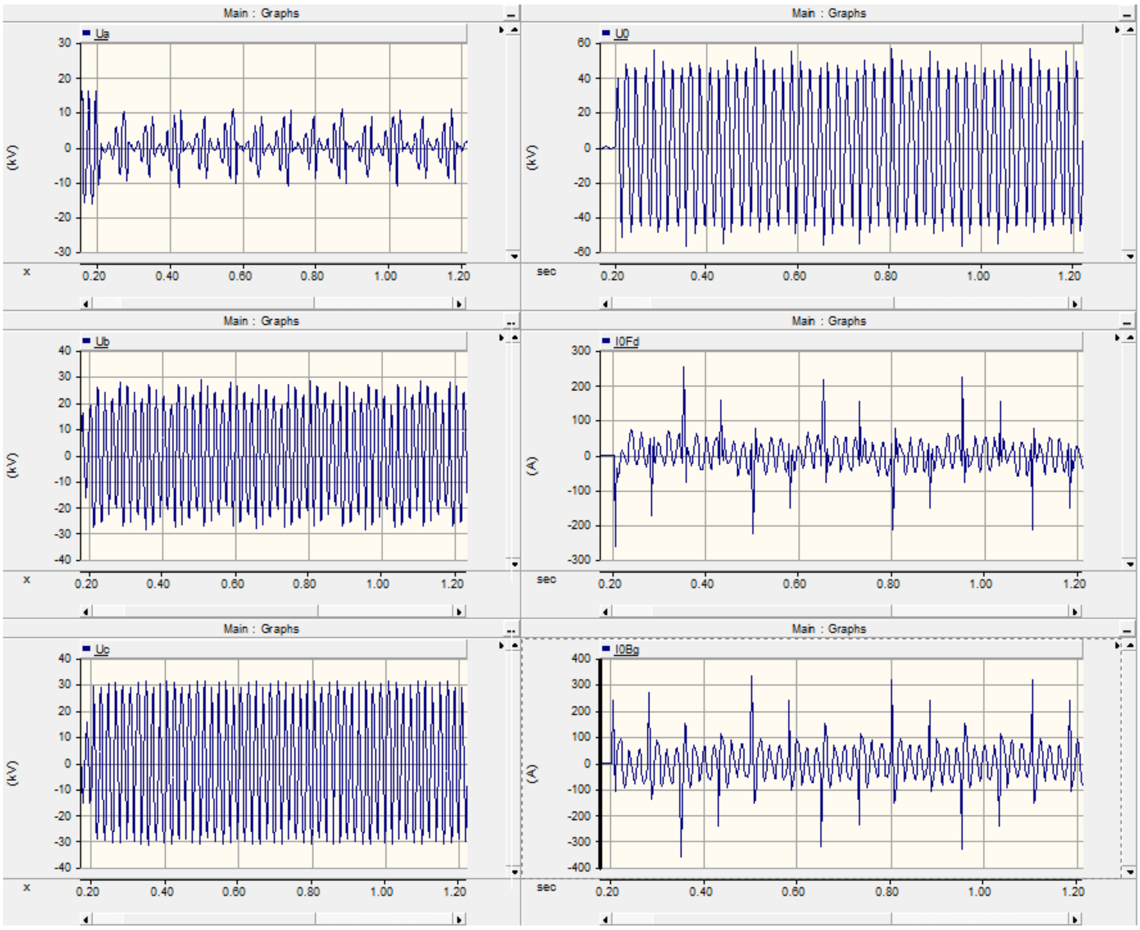

Figure 15. Waveforms of the U_a, U_b, U_c, U_0, I_{0Fd} and I_{0Bg} in case of fault located at the end of the protected feeder with short time interval between spikes.

Fig 16 shows the instantaneous admittances and Fig. 17 the performance of the novel admittance criterion using CPS in this case. The total CPS admittance of the BG network was pointing correctly to the non-operating area. Most of the instantaneous admittances at the protected feeder located correctly in the operating area. When calculating the total CPS admittance of the protected feeder, it was pointing towards the operating area. Accumulated admittance phasor at 0.7 ms guaranteed the correct functioning of the protection.

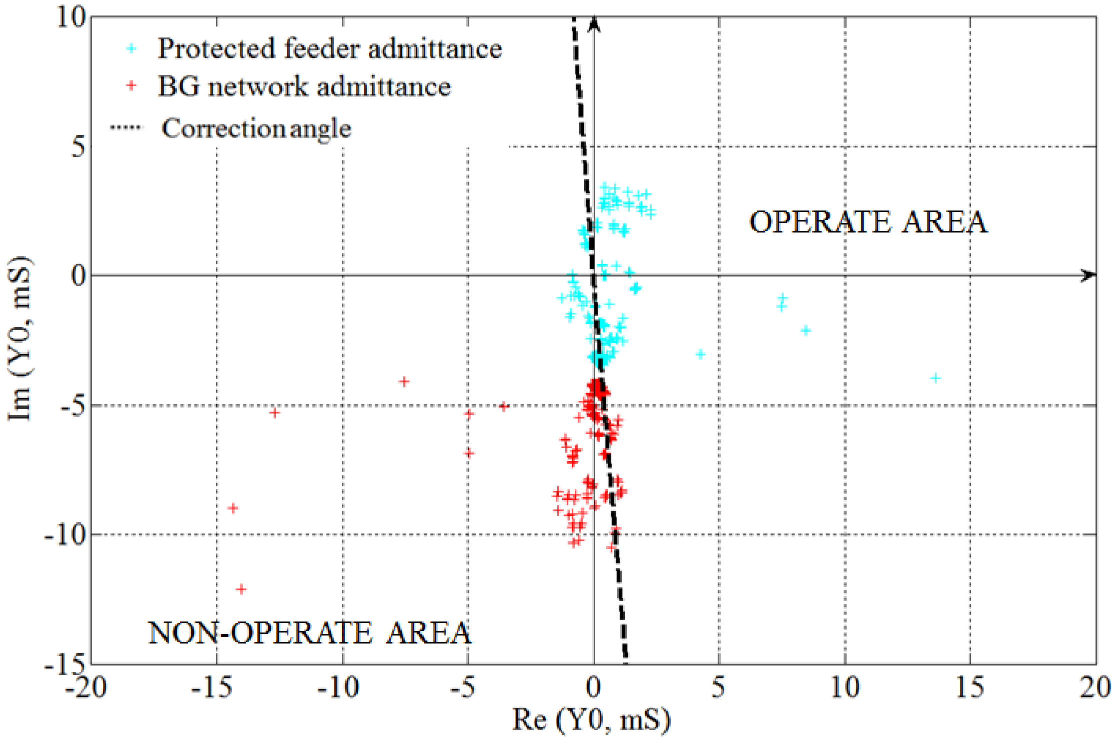

Figure 16. Instantaneous admittances, when fault located at the end of the protected feeder with short time interval between spikes.

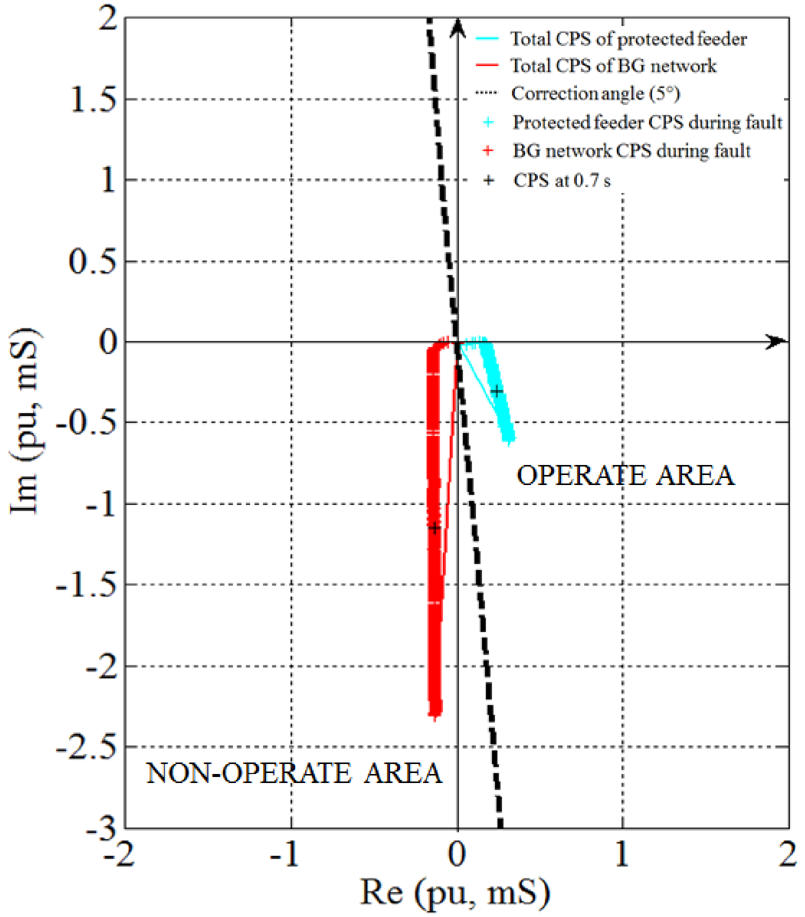

Figure 17. Calculated CPS admittances in case of intermittent earth fault at the end of the protected feeder with short time interval between spikes.

Intermittent earth fault in the BG network

Fig. 18 shows the waveforms of phase-to-earth voltages, zero sequence currents of the protected feeder and the BG network, and zero sequence voltage. It can be seen that the waveforms did not change much compared to situations, where fault was located at the beginning and at the end of the protected feeder.

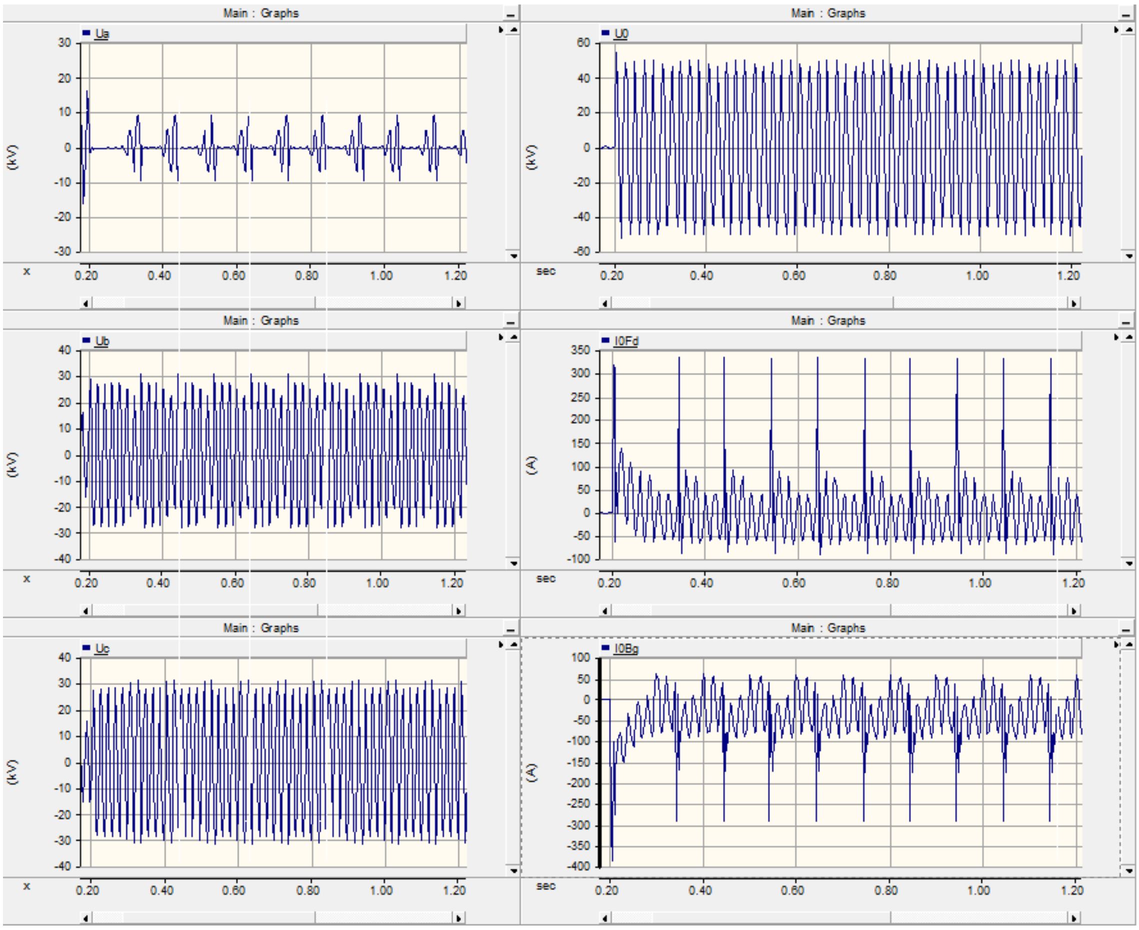

Figure 18. Waveforms of the U_a, U_b, U_c, U_0, I_{0Fd} and I_{0Bg} in case of fault located in the BG network with short time interval between spikes.

Fig. 19 shows the instantaneous admittances and Fig. 20 the accumulated admittance phasors during the fault. In case of intermittent earth fault located in the BG network, the most instantaneous admittances measured from the BG network located now in the operating area according to Fig. 19. The direction of all CPS admittances of the BG network located also in the operating area, including the accumulated admittance phasor at 0.7 s. Respectively, the accumulated admittance phasors of the protected feeder were pointing towards the non-operate area. Consequently, protection was selective also in this case despite the fault located in the BG network.

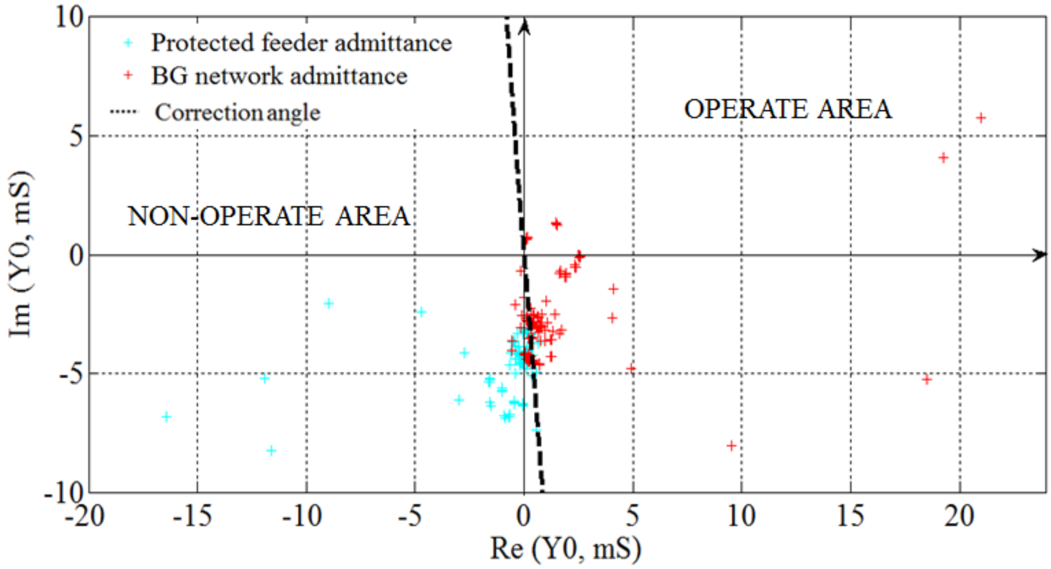

Figure 19. Instantaneous admittances, when fault located in the BG network with short time interval between spikes.

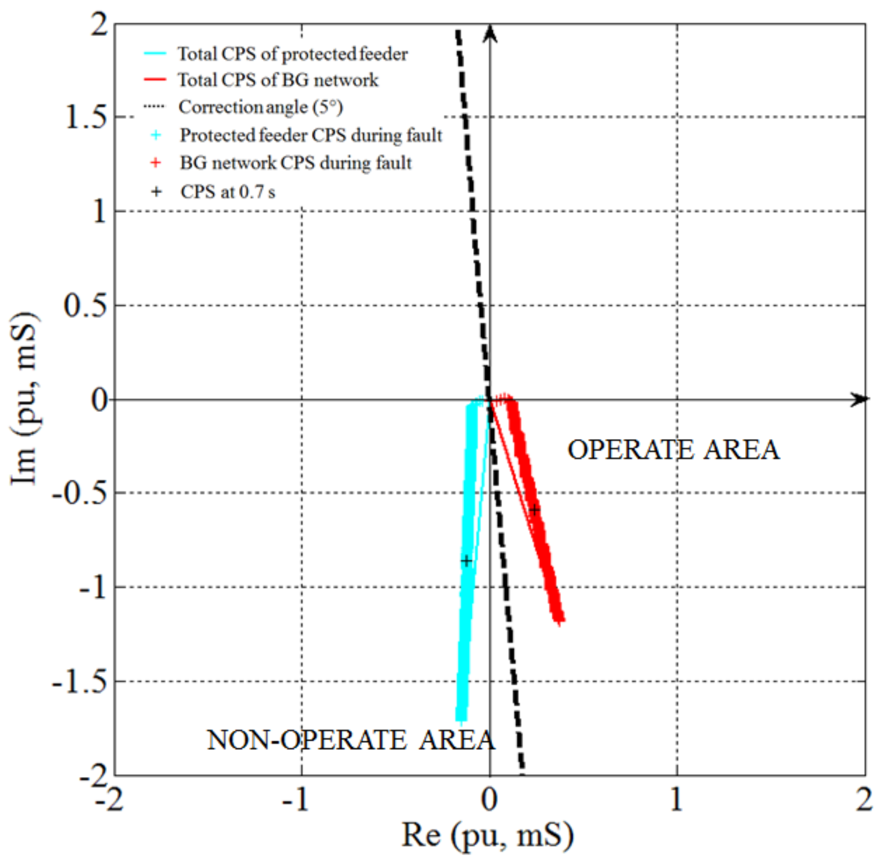

Figure 20. Calculated CPS admittances in case of intermittent earth fault in the BG network with short time interval between spikes.

4.3.2 Long time interval between spikes

Because the simulated network was large, the proper time interval between spikes was adjusted to be 500 ms in the second case. Therefore, the next simulations were created by using this time interval, where the spikes occurred less frequently. The insulation level in this case was 15 kV, R_f was 2 Ω, ON delay was 20 ms, and OFF delay was 500 ms, which was now longer compared to the previous simulation case.

Intermittent earth fault at the beginning of the protected feeder

In the second simulation case, the waveforms of phase-to-earth voltages, zero sequence currents of the protected feeder and the BG network, and zero sequence voltage can be found in Fig. 21. The waveforms of zero sequence voltage and zero sequence current to test simulation case according to Arcteq (2014: 18) were compared. Network was in close to resonance point, and fault was located 3 km from the substation. The network, which was simulated according to Arcteq (2014: 18.), was large (~100 A). On the other hand, the created network model in this work produced apprx. 400 A. Simulated zero sequence voltage and current waveforms examples can be found in Fig. 22. It can be seen that the waveforms correspond quite a lot to simulation case according to Figs. 21 and 22, even though the created network was larger, and compensation degree and fault locations were a bit different.

During the simulation time according to Fig. 21, there existed two spikes. Voltage at the faulted phase recovered, and the voltages at the healthy feeders increased, when fault occurred, but started to decrease after that. Zero sequence voltage decreased after the fault appeared, but it started to increase again, when the second spike occurred. Zero sequence voltage did not have time to reach zero before the next spike. Two high spikes in zero sequence currents were noticed.

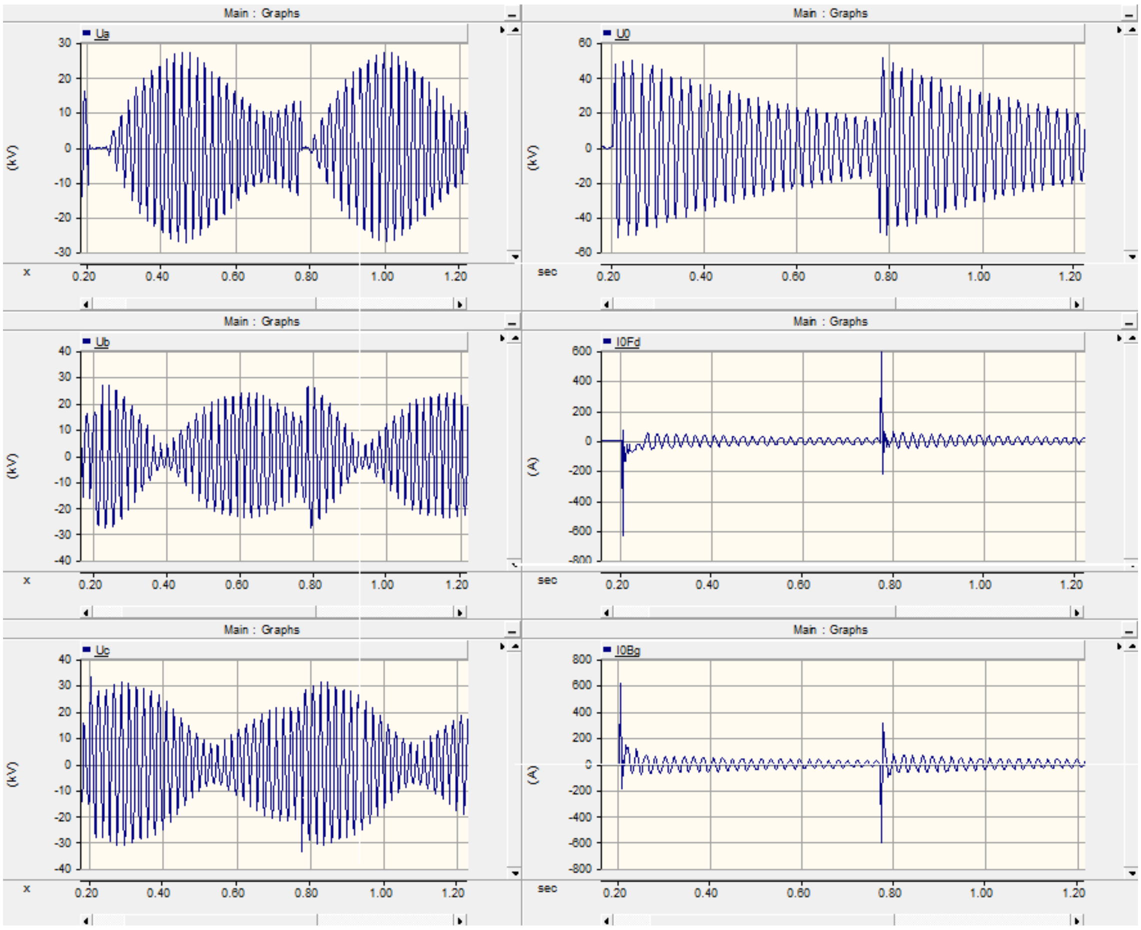

Figure 21. Waveforms of the U_a, U_b, U_c, U_0, I_{0Fd} and I_{0Bg} in case of long time interval between spikes, and fault located at the beginning of the protected feeder.

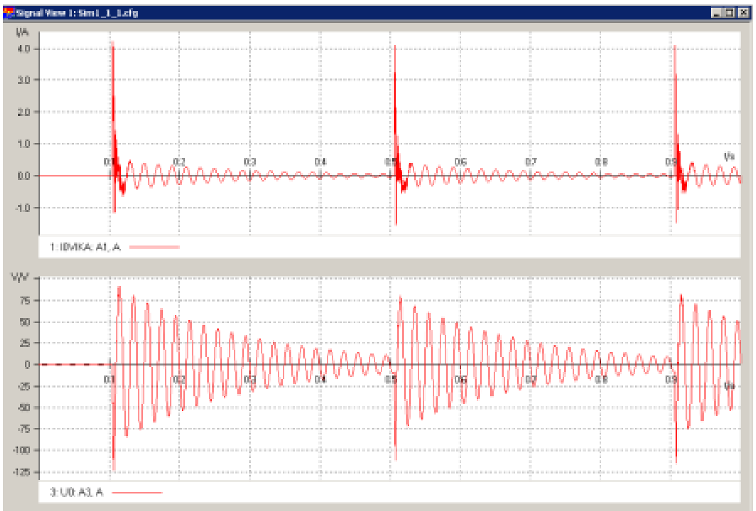

Figure 22. U_0 and I_0 waveforms of the example simulation case, where the large network was close to resonance point, and fault located 3 km from substation. (Arcteq 2014: 18.)

Fig. 23 shows the instantaneous admittances and Fig. 24 the accumulated admittance phasors of the protected feeder and BG network in case of fault located at the beginning of the protected feeder. When the time between spikes was now longer, the most instantaneous admittances of the BG network located very near the boundary line according to Fig. 23. However, the calculated total CPS admittance in this case located correctly in the non-operating area. The total accumulated admittance phasor of the protected feeder located very near the boundary line, but in the operating area. The accumulated admittance phasor of the protected feeder at 0.7 ms, was also located in the right area. It meant that the relay operation would operate correctly at that time. However, the margin to the boundary line was clearly smaller compared to situation, when the time between spikes was shorter. In this case, the probability of errors could impact on the operation of the protection. Moreover, the correction angle was in all situations adjusted to 5°. If it had been e.g. in this case 10°, malfunctions of protection would have probably occurred. Therefore, the set correction angle (5°) was accurate.

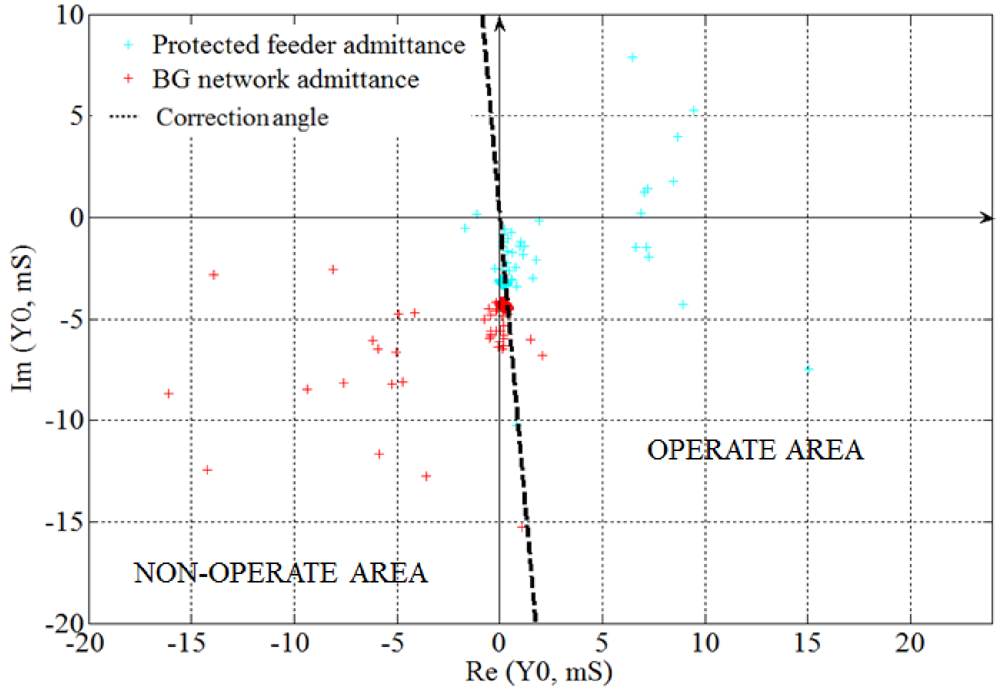

Figure 23. Instantaneous admittances, when fault located at the beginning of the protected feeder with long time interval between spikes.

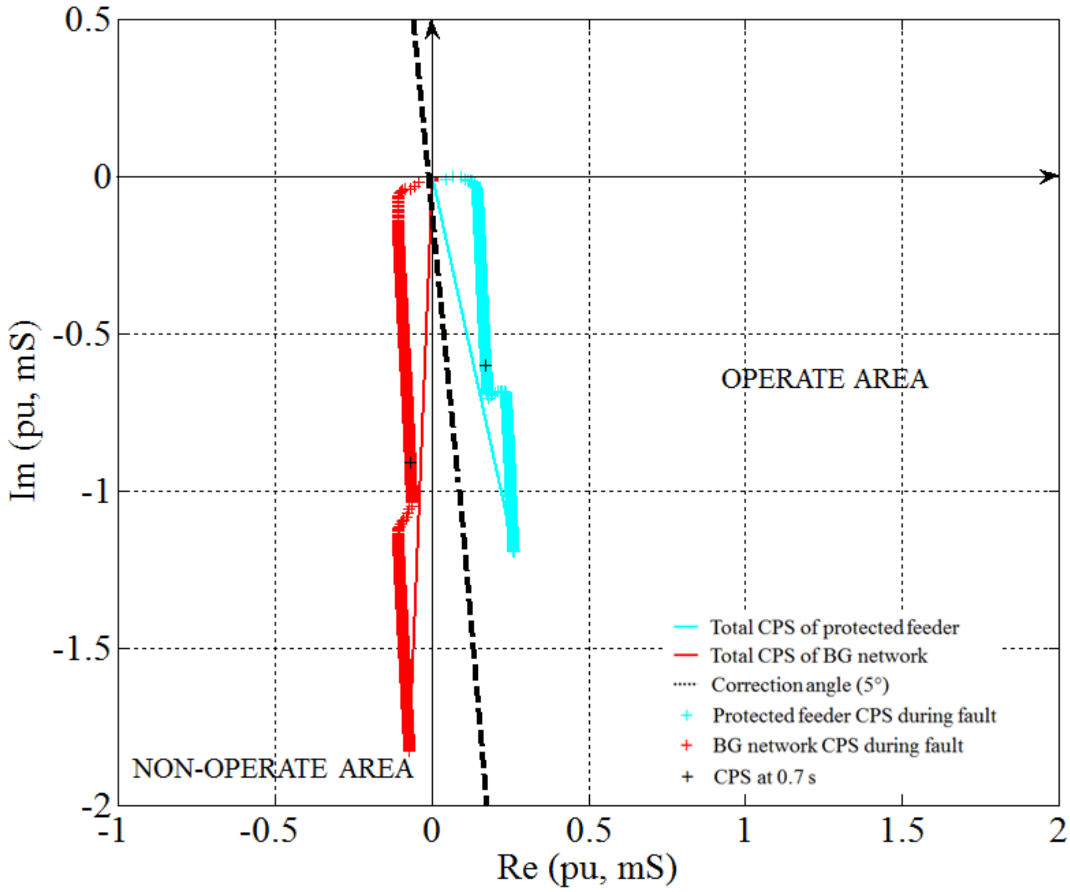

Figure 24. Calculated CPS admittances in case of intermittent earth fault at the beginning of the protected feeder with long time interval between spikes.

Intermittent earth fault at the end of the protected feeder

When fault located at the end of the protected feeder, the waveforms recorded in this case can be found in Fig. 25. The waveforms seem to be relative similar also in this case compared to situation introduced in Figs. 21 and 22.

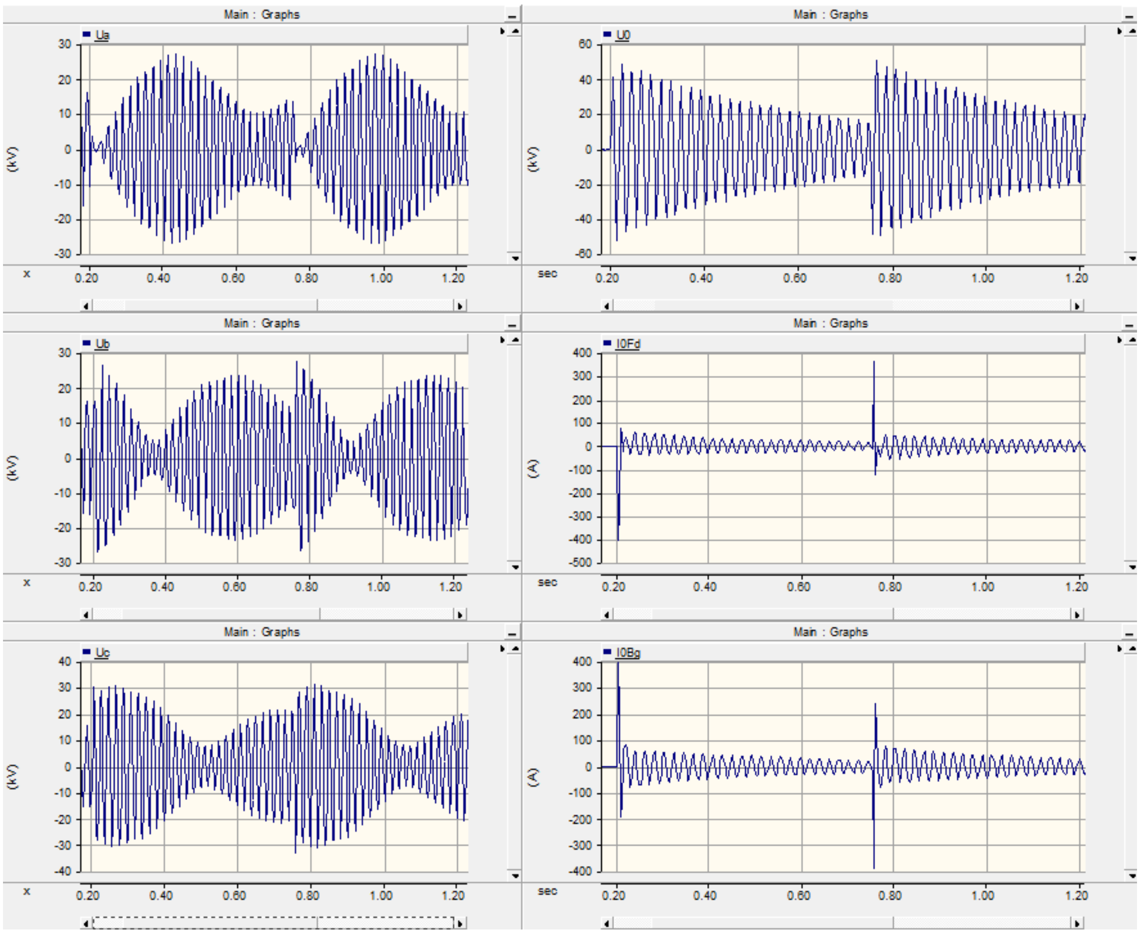

Figure 25. Waveforms of the U_a, U_b, U_c, U_0, I_{0Fd} and I_{0Bg} in case of long time interval between spikes, and fault located at the end of the protected feeder.

Fig. 26 shows the instantaneous admittances and Fig. 27 the accumulated admittance phasors measured from the BG network and protected feeder in case of long time interval between spikes, and fault located at the end of the protected feeder. The performance of the protection did not change considerably compared to situation above according to Fig. 27. The total CPS admittance of the protected feeder located in the same way in the operating area, and the total CPS admittance of the BG network located in the non-operating area. In this case, the margin to the boundary line was also small. If the applied relay operation time was used, the protection would have operated correctly.

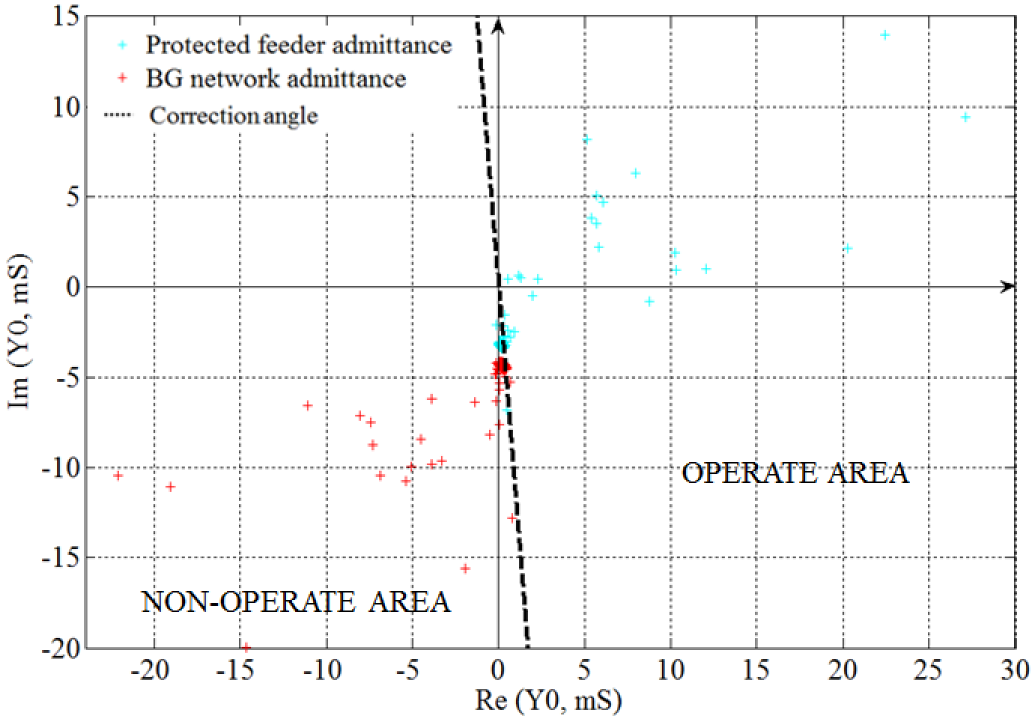

Figure 26. Instantaneous admittances, when fault located at the end of the protected feeder in case of long time interval between spikes.

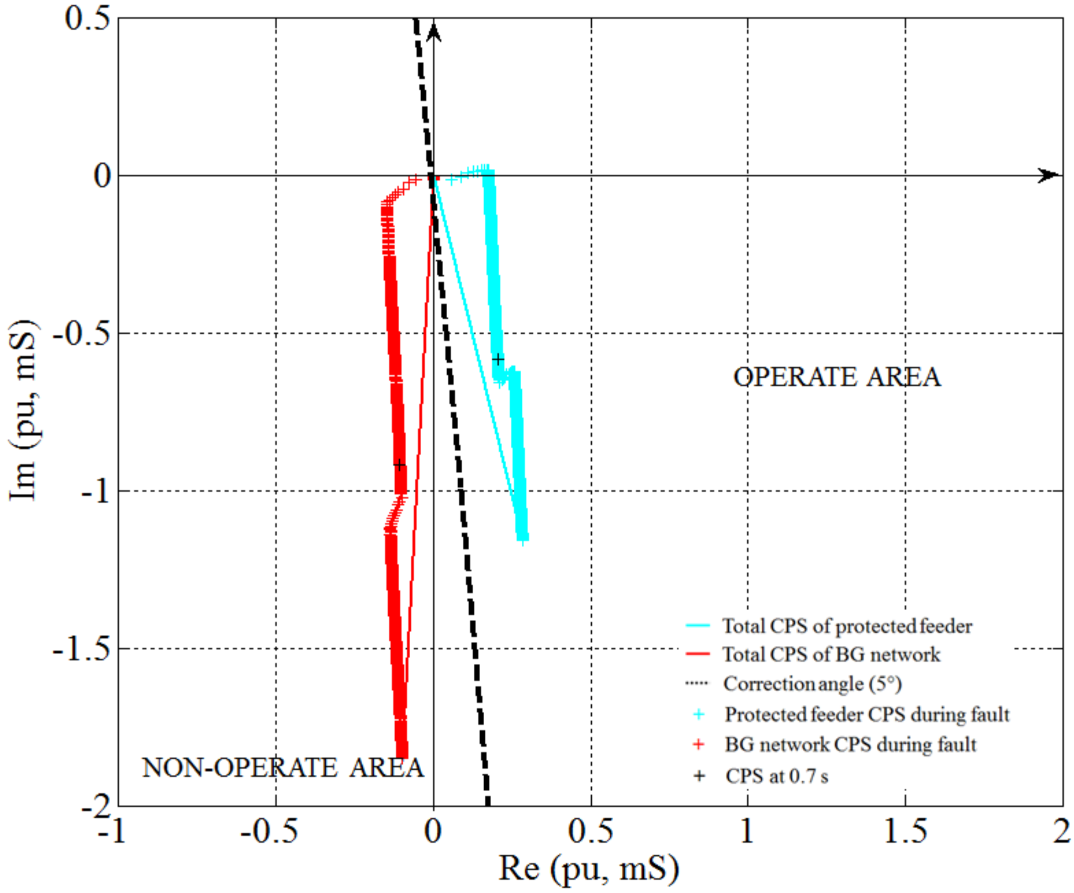

Figure 27. Calculated CPS admittances in case of intermittent earth fault at the end of the protected feeder with long time interval between spikes.

Intermittent earth fault in the BG network

In case of intermittent earth fault located in the BG network, the recorded waveforms in this case can be found in Fig. 28. Also in this case, the waveforms seemed to behave in the same way, as in the previous cases, where the fault located at the beginning and at the end of the protected feeder.

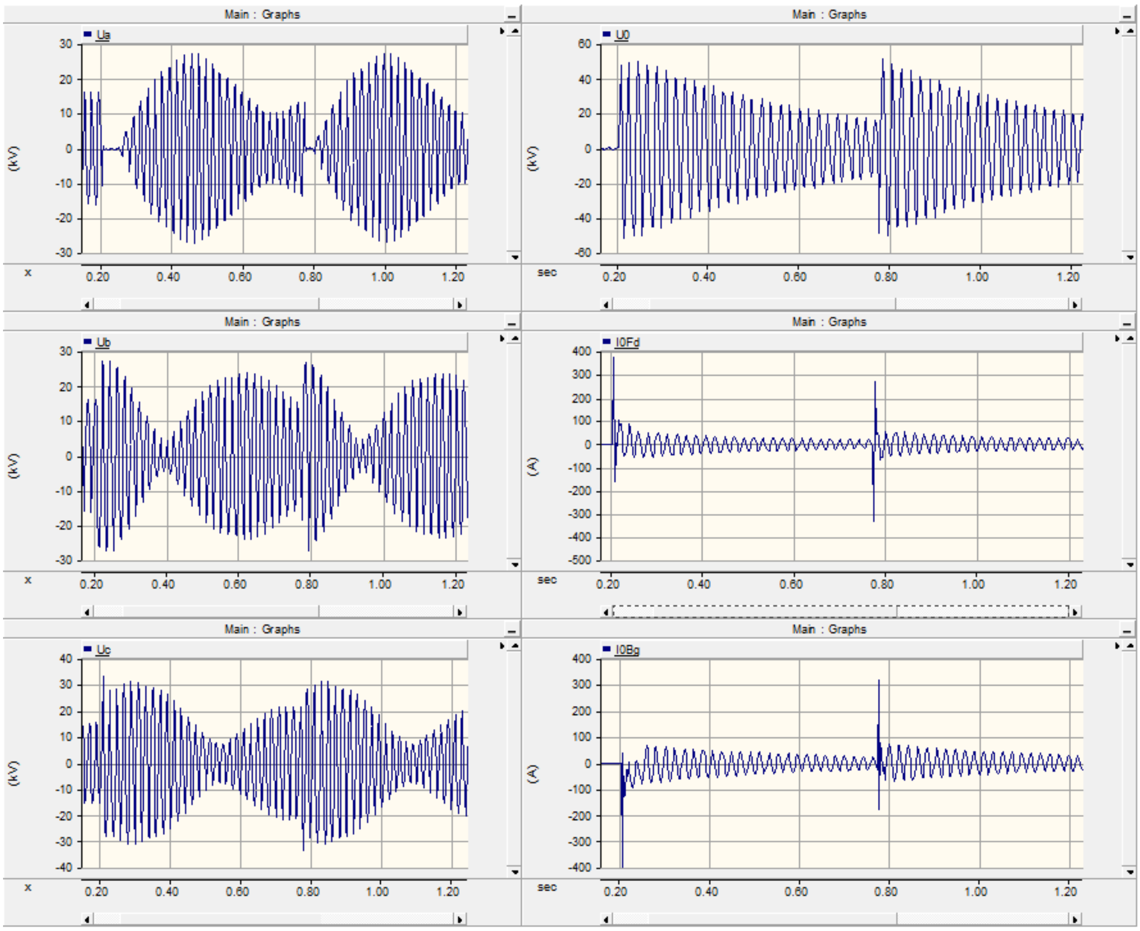

Figure 28. Waveforms of the U_a, U_b, U_c, U_0, I_{0Fd} and I_{0Bg} in case of long time interval between spikes, and fault located in the BG network.

Fig. 29 shows the instantaneous admittances and Fig. 30 the accumulated admittance phasors during fault in case of fault located in the BG network. The total CPS admittance and the accumulated admittance phasor at 0.7 s of the BG network located correctly now in the operating area, but the distance to set boundary line was very small. This was accounted for the instantaneous admittances, most of which located very near the boundary line and the non-operate area. In this case, errors of protection quantities should be considered carefully. The total CPS admittance of the protected feeder located in the non-operate area. Consequently, even though both CPS admittances located near the boundary line, protection should operate correctly. In this case the effect of possible errors in protection quantity measurements should be also considered.

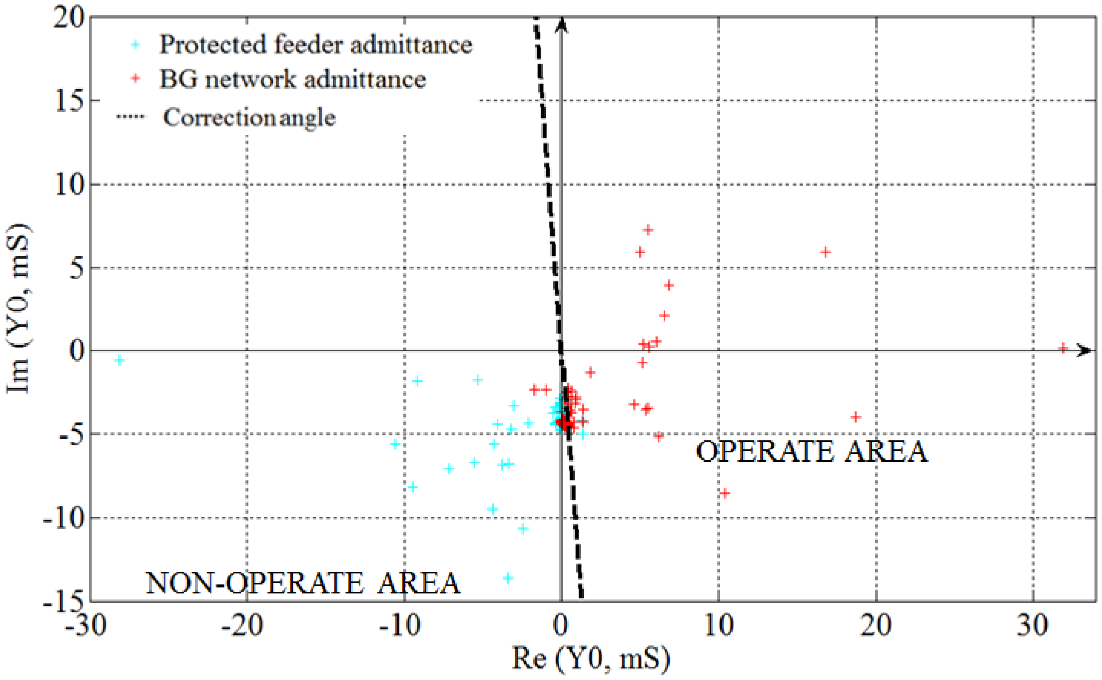

Figure 29. Instantaneous admittances, when fault located in the BG network in case of long time interval between spikes.

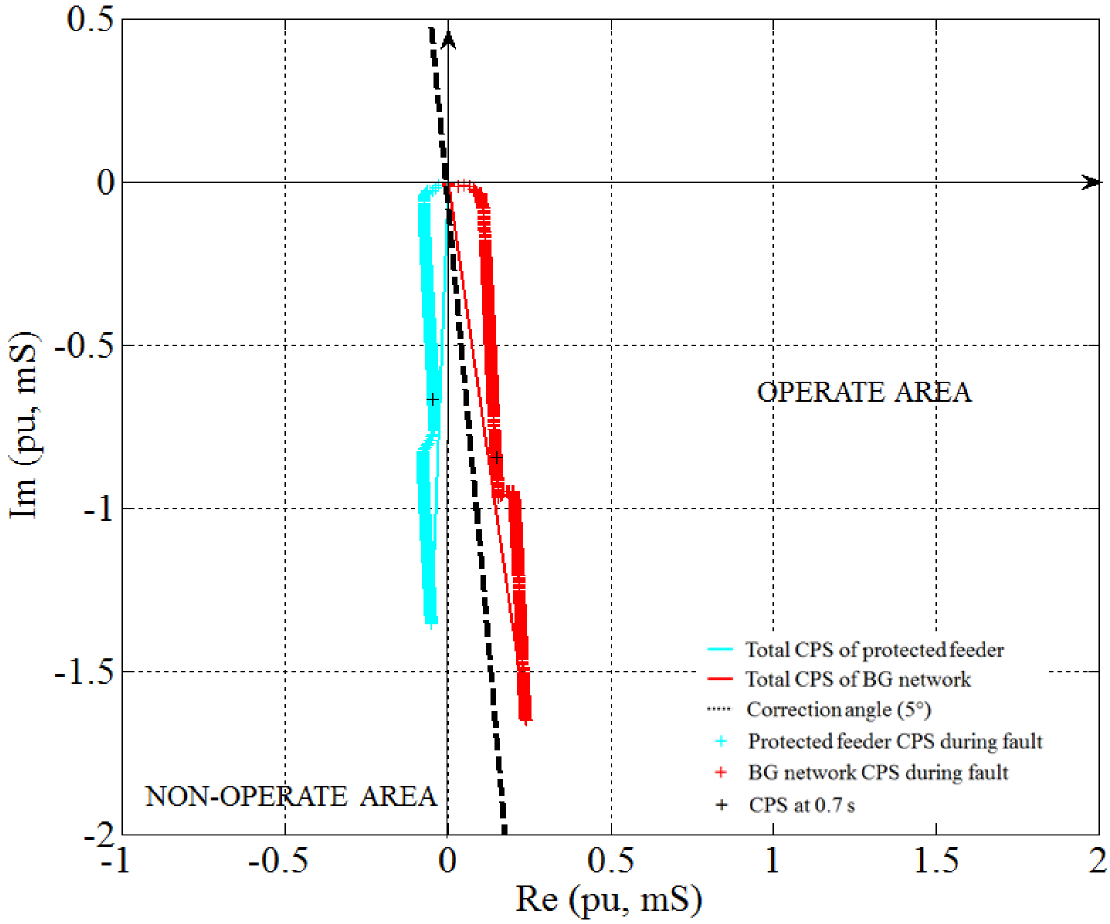

Figure 30. Calculated CPS admittances in case of intermittent earth fault in the BG network with long time interval between spikes.

5 CONCLUSIONS

The aim of this work was to study the performance of the novel admittance criterion for detecting intermittent earth faults 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 demanded uninterruptable power supply. A problem with intermittent earth 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 UGC. Also in future, natural ageing of the existing cables will probably increase the amount of intermittent earth faults.

At the moment there exist few methods to protect MV distribution network from intermittent earth faults. One of these methods is novel admittance criterion, which is based on cumulative phasor summing (CPS). This method was studied more thoroughly in this work. This novel criterion was studied in two different cases via PSCAD simulations. The novel admittance criterion facilitates the protection considerably, because the accumulated admittance phasor points the fault direction clearly. Admittance criterion is proven to give accurate measurement results despite the fault resistance and fault type. Therefore, other protection functions for detecting, e.g. permanent earth faults, are not needed, and intermittent earth faults can be detected reliably. However, relay operation time settings should be done carefully, and make sure that the coordination with busbar protection, i.e. zero sequence voltage setting, is done in the right way.

According to simulations in this work, the novel admittance criterion based on CPS detected the intermittent earth faults in both cases. When the time interval between spikes was shorter (50 ms), the admittance criterion was more reliable, because there existed more margin to set boundary line. On the other hand, when the time between spikes was longer (500 ms), the protection was capable of detecting the faults correctly, but now the accumulated admittance phasors were located more near the boundary line. In this case, the possible errors, which were not analysed in this work, should be also considered. The set correction angle seems to be accurate according to simulations. For example, if it was set to 10°, the problems would have probably occured in case of long time interval between spikes. It is also important to set accurate relay operation time. In these simulations, it was assumed to be 0.5 s, which meant that relay should operate at 0.7 s from the start of the simulation. The value seem to be accurate according to simulations in both cases, but especially when the network is large, spikes arise less frequently. Thus, the coordination with the busbar protection should be done in the right way. It is recommended that the proper time should not be lower than 1 s.

Consequently, the simulations of this work proved that the novel admittance criterion is very promising method for detecting intermittent earth faults in case of defined time intervals between faults. However, the protection quantity calculations in the created model were based on fundamental frequency signals. Therefore, the results may not be as accurate as possible, because multi-frequency signals were not considered. In future, these should be also considered and studied. In this work, only two different intermittent earth fault cases were studied. Moreover, intermittent earth faults and this novel admittance criterion are studied still fairly little. More field tests and simulations in different network topologies in order to be completely sure that this method operates correctly are needed. For example, in this work, the protected feeder was totally cabled, but intermittent earth faults occur also in networks, which consist of OHL feeders. Moreover, variations of different compensation degrees and fault resistances should be studied. When earth fault protection is reliable also in case of intermittent earth faults in MV distribution networks, longer operating life for network equipment and underground cables will be achieved, and unnecessary supply interruptions can be avoided.

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APPENDIX

Appendix 1. Matlab® scripts

Instantaneous admittances

```
I=A(:,1);
ang=A(:,2);
plot(I,ang,'c+');
hold on;

I=A(:,3);
ang=A(:,4);
plot(I,ang,'r+');
hold on;

lineLength = 30;
angle = (-85);
x(1) = cosd (-85);
y(1) = sind (-85);
x(2) = x(1) + lineLength * cosd(angle);
y(2) = y(1) + lineLength * sind(angle);
plot(x, y, 'k');
hold on;

lineLength = 30;
angle = (95);
x(1) = cosd (95);
y(1) = sind (95);
x(2) = -x(1)+ lineLength * cosd(angle);
y(2) = y(1) + lineLength * sind(angle);
plot(x, y, 'k');
hold on;

axis equal;
grid on;
```

CPS admittances

```
I=A(:,1);
ang=A(:,2);
plot(I,ang,'c+');
hold on;

I=A(:,3);
ang=A(:,4);
plot(I,ang,'r+');
hold on;

I=A(:,5);
```

```
ang=A(:,6);
plot(I,ang,'c-');
hold on;

I=A(:,7);
ang=A(:,8);
plot(I,ang,'r-');
hold on;

I=A(:,9);
ang=A(:,10);
plot(I,ang,'k+');
hold on;

I=A(:,11);
ang=A(:,12);
plot(I,ang,'k+');
hold on;

lineLength = 30;
angle = (-85);
x(1) = cosd (-85);
y(1) = sind (-85);
x(2) = x(1) + lineLength * cosd(angle);
y(2) = y(1) + lineLength * sind(angle);
plot(x, y, 'k');
hold on;

lineLength = 30;
angle = (95);
x(1) = cosd (95);
y(1) = sind (95);
x(2) = -x(1)+ lineLength * cosd(angle);
y(2) = y(1) + lineLength * sind(angle);
plot(x, y, 'k');
axis equal;
hold on;
grid on;
```