

## NEW METHOD FOR HIGH-IMPEDANCE FAULT DETECTION

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### ABSTRACT

*Correct detection of high-impedance faults (HIFs) is crucial because they produce a serious threat for humans, livestock and property. HIF currents, typically with fault resistances between 10 and 100 kΩ, cannot be detected with traditional protection functions and they behave randomly consisting of unstable and unpredictable dynamic fluctuations in the amplitude, harmonic levels etc. One main challenge is to reliably separate HIFs from normal network load and other switching events. In this paper, new HIF detection method is proposed based on extensive PSCAD simulation studies and tests with real-life HIF measurements. The proposed method is applicable to different MV networks with different grounding practices. Depending on the grounding type, HIF detection is based on the use of zero sequence current  $I_0$  or negative sequence current  $I_2$ . Method works in both 50 and 60 Hz networks and doesn't need voltage measurement. It also works as tripping protection function with sufficiently short operation time, is simple/flexible and has good usability from end user point of view.*

### INTRODUCTION

HIFs often occur when an energized overhead line falls to the ground, creating a major public danger for people, livestock and environment. Energized downed or broken conductors can, for example, ignite fires. HIFs are usually defined as single-phase faults that do not produce enough fault current to be detectable by traditional protection functions. Typical HIF fault resistance varies between 10 and 100 kΩ. HIF currents also behave randomly, mainly due to the changing resistivity of the contact surface, consisting of unstable and unpredictable dynamic fluctuations in the amplitude, harmonic levels and waveform asymmetry from cycle to cycle. In many previous HIF detection methods techniques like frequency or wavelet analysis, calculation of variations in the amplitude, or the study of the wave distortion of current have been used to extract information regarding HIF characteristics described above. One main challenge in HIF detection method is to separate them from normal network load and other switching events in order to avoid false detections. Therefore, previous HIF detection methods also have been based on adaptation and learning of the algorithms as well as on multiple algorithms and voting schemes. Also many of these previous HIF algorithms are not suitable to tripping operation and can be only used for alarming HIF detection due to rather slow or complex decision logics and sensitivity to false detections. [1], [2]

In this paper, new straightforward HIF detection method is proposed based on tests with real-life HIF measurements as well as on extensive PSCAD simulation studies in which behavior of different possible parameters for HIF detection from faulty and healthy MV feeders were investigated. In following proposed new HIF detection method is presented. After that study system and results from simulations and tests with real-life field measurement data are shown followed by discussion and conclusions.

### NEW METHOD FOR HIF DETECTION

#### HIF Detection Parameters

Behavior of multiple different possible parameters, like for example phase/zero sequence current and voltage nominal and harmonic components related, for HIF detection from faulty and healthy MV feeders were investigated in PSCAD simulations with MV networks with different grounding methods. Based on the simulations and on available faulty feeder  $I_0$  real-life field measurements most suitable parameters, depending on the MV network grounding practice, for HIF detection were found to be  $\Delta\text{Sum\_Io\_1}$  (1) and  $\Delta\text{Sum\_I2\_1}$  (2).  $\Delta\text{Sum\_Io\_1}$  is based on calculation of changes in magnitude of zero sequence current  $I_0$  ( $I_0 = (I_a + I_b + I_c)/3$  i.e. not  $3 \cdot I_0$ ) nominal frequency component  $\text{Io\_1}$  and  $\Delta\text{Sum\_I2\_1}$  on calculation of changes in magnitude of negative sequence current  $I_2$  nominal frequency component  $\text{I2\_1}$  at pre-defined time instants ( $t$ ). Alternatively also  $\text{Io\_rms}$  or  $\text{I2\_rms}$  values could be used as HIF detection function input parameters. Time instants to calculate  $\text{Sum\_Io\_1}$  or  $\text{Sum\_I2\_1}$  for (1) and (2) can be made user configurable. This makes the HIF detection algorithm flexible and enables the possibility to emphasize utilization of e.g. time instants with very short and/or longer time differences etc. In this paper, initially chosen most potential time instants to determine  $\text{Sum\_Io\_1}$  or  $\text{Sum\_I2\_1}$  are presented.

$$\Delta\text{Sum\_Io\_1} = (\text{MA over 200 ms of } \text{Sum\_Io\_1} / n_{\text{ti\_Sum\_Io\_1}}) - \text{Sum\_Io\_ave\_delay} \quad (1)$$

where  $\text{Sum\_Io\_1} = (|I_{0\_1(t)} - I_{0\_1(t-2.5\text{ms})}| + |I_{0\_1(t)} - I_{0\_1(t-5\text{ms})}| + |I_{0\_1(t)} - I_{0\_1(t-10\text{ms})}| + |I_{0\_1(t)} - I_{0\_1(t-50\text{ms})}| + |I_{0\_1(t)} - I_{0\_1(t-100\text{ms})}| + |I_{0\_1(t)} - I_{0\_1(t-200\text{ms})}| + |I_{0\_1(t)} - I_{0\_1(t-15\text{s})}| + |I_{0\_1(t)} - I_{0\_1(t-22\text{s})}| + |I_{0\_1(t)} - I_{0\_1(t-25\text{s})}| + |I_{0\_1(t)} - I_{0\_1(t-27\text{s})}|)$ ,  $n_{\text{ti\_Sum\_Io\_1}} = 10$  ( $n_{\text{ti\_Sum\_Io\_1}}$  = number of time instants to calculate  $\text{Sum\_Io\_1}$ ) and MA is moving average.

$$\Delta\text{Sum\_I2\_1} = (\text{MA over 200 ms of } \text{Sum\_I2\_1} / n_{\text{ti\_Sum\_I2\_1}}) - \text{Sum\_I2\_ave\_delay} \quad (2)$$

where  $\text{Sum\_I2\_1} = (|I2\_1(t) - I2\_1(t-2.5\text{ms})| + |I2\_1(t) - I2\_1(t-5\text{ms})| + |I2\_1(t) - I2\_1(t-10\text{ms})| + |I2\_1(t) - I2\_1(t-50\text{ms})| + |I2\_1(t) - I2\_1(t-100\text{ms})| + |I2\_1(t) - I2\_1(t-200\text{ms})| + |I2\_1(t) - I2\_1(t-750\text{ms})|)$  and  $n_{\text{ti\_Sum\_I2\_1}} = 7$  ( $n_{\text{ti\_Sum\_I2\_1}}$  = number of time instants to calculate  $\text{Sum\_I2\_1}$ ).

$$\text{Sum\_Io\_1\_ave\_delay} = (\text{Sum\_Io\_1\_ave}(t-9.5\text{s}) + \text{Sum\_Io\_1\_ave}(t-10.0\text{s}) + \text{Sum\_Io\_1\_ave}(t-10.5\text{s})) / 3 \quad (3)$$

$$\text{Sum\_I2\_1\_ave\_delay} = (\text{Sum\_I2\_1\_ave}(t-9.5\text{s}) + \text{Sum\_I2\_1\_ave}(t-10.0\text{s}) + \text{Sum\_I2\_1\_ave}(t-10.5\text{s})) / 3 \quad (4)$$

In general,  $\Delta\text{Sum\_Io\_1}$  and  $\Delta\text{Sum\_I2\_1}$  tries to see the increased (within cycle & after few and more cycles i.e. not just over few cycles) variation in  $I_{o1}$  or  $I2_1$  due to HIF and fault resistance  $R_f$  randomness.  $\Delta\text{Sum\_Io\_1}$  also takes into account longer time scale changes from seconds to tens of seconds.

Also use of harmonics, like THD or certain specific harmonics like 3<sup>rd</sup> or harmonic bands based on wavelet analysis, have been often proposed and used for HIF detection. However, based on literature these parameters are sensitive to false operations due to different current distorting fluctuating loads. In addition it was found in simulations that, for example, comparison of moving average (MA) over 150 ms of  $I_{o3}$  (magnitude of zero sequence current 3<sup>rd</sup> harmonic component) values between healthy and faulty MV feeders cannot be used for HIF detection, because in some cases the  $I_{o3}$  value was higher on the healthy MV feeder. Therefore use these harmonic based parameters was not further investigated. In principle, also other parameters calculated from phase currents  $I_a$ ,  $I_b$ ,  $I_c$  could be potentially used as input parameters for HIF detection like, for example,  $I_{\text{beta}}$  (from alpha-beta-transformation),  $I_q$  (from dq0-transformation) or  $I_1$  (positive sequence current). However, use of  $\Delta\text{Sum\_Io\_1}$  or  $\Delta\text{Sum\_I2\_1}$  for HIF detection seemed to be very well applicable to different cases.

### Proposed HIF Detection Method and Initial Settings

The proposed new HIF detection method (Fig. 1) works in both 50 and 60 Hz networks and doesn't need voltage measurement. It also works as tripping protection function with sufficiently short operation time and is simple when compared to many previously developed HIF algorithms. For example, the proposed new method (Fig. 1) does not need adaptation and learning. There is also possibility for two-stage, low and high, settings (Fig. 1) for HIF indication and operation/tripping purposes. Different settings depending on the grounding practice like, for example, low-resistance grounded, solidly uni-/multi- (single-/multiple-point) grounded, compensated (resonant grounded) and isolated, should be used. Initially proposed settings for  $\Delta\text{Sum\_Io\_1}$  and  $\Delta\text{Sum\_I2\_1}$  are shown in Table 1. However, with some grounding methods certain input parameter  $I_{o1}$  ( $\Delta\text{Sum\_Io\_1}$ ) or  $I2_1$  ( $\Delta\text{Sum\_I2\_1}$ ) based should be chosen. For example, in compensated networks use of  $I2_1$  ( $\Delta\text{Sum\_I2\_1}$ ) or  $I2_{\text{rms}}$  is the only feasible way and also with some other grounding types  $I2_1$  ( $\Delta\text{Sum\_I2\_1}$ ) has some advantages when compared to  $I_{o1}$

( $\Delta\text{Sum\_Io\_1}$ ) or  $I_{o_{\text{rms}}}$ . However,  $\Delta\text{Sum\_Io\_1}$  based start should be used in all cases with  $\Delta\text{Sum\_I2\_1}$  based HIF indication/detection in order to guarantee selectivity in other network events like load switchings (Fig. 1).  $\Delta\text{Sum\_I2\_1}$  based HIF indication/detection is confirmed only if also  $\Delta\text{Sum\_Io\_1}$  remains above low-stage setting of it during  $\Delta\text{Sum\_I2\_1}$  operation time delay (Fig. 1, Table 1). Only in multiple-point solidly grounded networks there is no advantage from  $\Delta\text{Sum\_Io\_1}$  based start. Use of upper limit (Fig. 1) setting with  $\Delta\text{Sum\_Io\_1}$  could enable the possibility to separate HIF cases from traditional fault cases (in addition to operation time delay based selectivity). One alternative could also be use of blocking from traditional earth-fault functions. Also during Petersen coil tuning in compensated networks, blocking signal from coil controller could be utilized to prevent false HIF function starting based on  $\Delta\text{Sum\_Io\_1}$ .

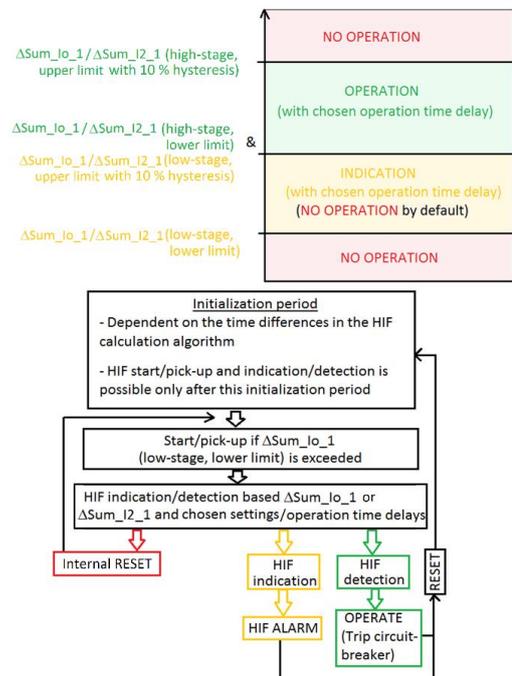


Figure 1. Principle of the proposed new HIF detection method.

Table 1. Initial settings for the proposed HIF detection method (Fig. 1) in networks with different grounding practices.

	$\Delta\text{Sum\_Io\_1}$ <sup>(o)</sup>		$\Delta\text{Sum\_I2\_1}$	
	low-stage	high-stage	low-stage	high-stage
Setting (A)	0.02 <sup>*)</sup> 0.03 <sup>**)</sup>	0.075	0.02 <sup>*)</sup> 0.04 <sup>**)</sup>	0.065
Operation Time Delay $t_{\text{op\_delay}}$ (s)	1.0	1.0	1.75	1.75
<b>Solidly uni-grounded (single-point)</b>				
Setting (A)	0.025 <sup>*)</sup> 0.04 <sup>**)</sup>	0.075 <sup>*)</sup> 0.1 <sup>**)</sup>	0.02 <sup>*)</sup> 0.028 <sup>**)</sup>	0.045
$t_{\text{op\_delay}}$ (s)	1.0	1.0	1.75	1.75
<b>Solidly multi-grounded (multiple-point)</b>				
Setting (A)	0.12	0.22	0.025	0.05
$t_{\text{op\_delay}}$ (s)	1.0	1.5	1.75	1.75
<b>Compensated (resonant grounded)</b>				
Setting (A)	0.035 <sup>**)</sup>	-	0.038 <sup>**)</sup>	0.075 <sup>**)</sup>
$t_{\text{op\_delay}}$ (s)	-	-	1.75	1.75
<b>Isolated</b>				
Setting (A)	0.031 <sup>**)</sup>	-	0.035 <sup>**)</sup>	0.07 <sup>**)</sup>
$t_{\text{op\_delay}}$ (s)	-	-	1.7	1.7

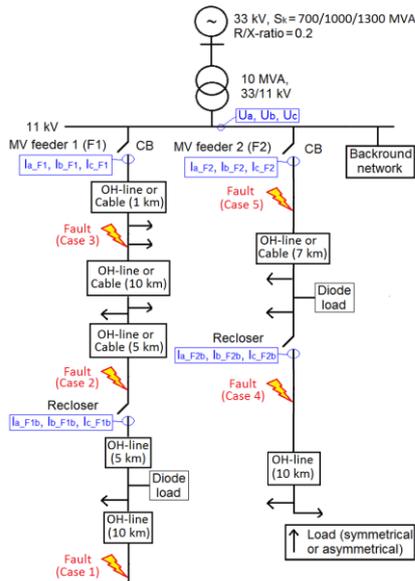
<sup>\*)</sup> Overhead (OH) lines, <sup>\*\*)</sup> Mixed (OH + cable) lines, <sup>(o)</sup> ( $I_o$ , not  $3 \cdot I_o$ )

If continuous calculation of  $\Delta\text{Sum\_Io\_1}$  for HIF function start purposes wants to be avoided,  $\Delta\text{Io\_1} = (|\text{Io\_1}_{(t)} - \text{Io\_1}_{(t-1.0s)}|)$  could be used instead e.g. with 0.05 A setting. Also (if available) zero voltage change  $\Delta\text{Uo}$ -based start using sensitive setting could be another possibility. The proposed new HIF detection method can be made flexible from end customer point of view. Flexibility and user configurable calculation also means that there could be, for example, 50 or more points (instead of 7 or 10 used in (1) and (2)) which could be chosen by the user to be included in the calculation of  $\Delta\text{Sum\_Io\_1}$  (1) or  $\Delta\text{Sum\_I2\_1}$  (2). Also comparison time to calculate (3) or (4) could be user settable (default could be e.g. average from 9.5, 10 and 10.5 s old values use in this paper) as well as window for calculating moving average in (1) and (2) could be user settable between 20 and 500 ms (default 200 ms). In general, the algorithm should be also such that it could adapt to chosen settings and comparison times (e.g. regarding to initialization period in Fig. 1).

## STUDIED SYSTEM

Studied system used in PSCAD simulations is presented in Fig. 2. Network with 50 or 60 Hz frequency was simulated using overhead (OH) lines or mixed (OH and cable) lines (Fig. 2) and different grounding practices.

(50 or 60 Hz, overhead (OH) or mixed (OH & cable) lines, low-resistance (33 ohm), solidly uni-/multi-grounded, compensated or isolated)



Simulation Cases

Case	Phase	Fault resistance $R_f$	HIF *)	Non-Random HIF (Stable EF)
1	A	Between 0.1 and 75 k $\Omega$		1 $\Omega$
2	B	Between 0.215 and 90 k $\Omega$		1 k $\Omega$
3	C	Between 0.5 and 100 k $\Omega$		5 k $\Omega$
4	A	Between 0.2 and 50 k $\Omega$		10 k $\Omega$
5	B	Between 0.175 and 80 k $\Omega$		50 k $\Omega$

\*) Varying  $R_f$  values were chosen so that fault currents remained very small, between 0.3 – 5 A (before broken conductor)

Simulation Sequence

Time (s)	Event
40.5	Connection of 3-phase diode load on MV feeder 1 (21 km from the beginning of the MV feeder)
43.0	Downed conductor (HIF / Non-HIF)
45.0	Broken conductor (HIF / Non-HIF at the same location and phase where HIF / Non-HIF and downed conductor)
47.0	End of HIF / Non-HIF
50.0	End of simulation

Figure 2. Simulated study system, fault locations, cases and simulation sequences.

Different HIF and non-random HIF (stable earth-faults) cases were simulated with above mentioned network types and grounding practices (Fig. 2). Used simulation sequences, line lengths, voltage levels and loads are also shown in Fig. 2.

## HIF Model for PSCAD Simulations

Chosen HIF modelling approach is shown in Fig. 3 which enables simulation of HIFs with randomly variable (duration and magnitude) fault resistance  $R_f$  (in certain limits) in PSCAD, but there is no exact equation or model for the HIF  $R_f$  randomness.

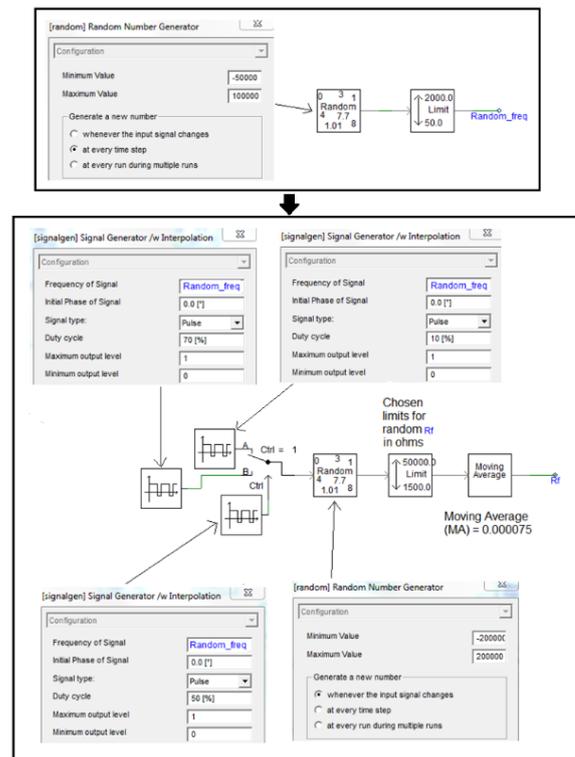


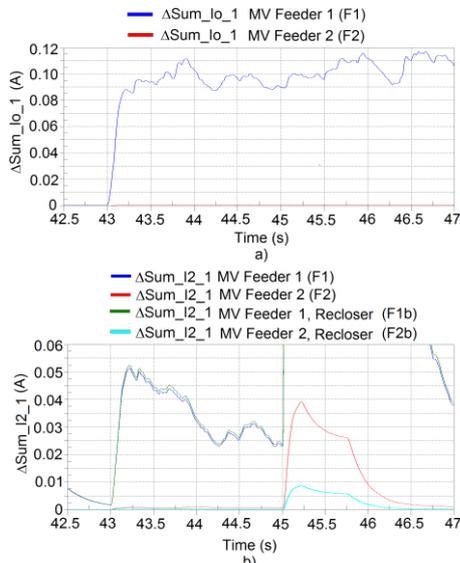
Figure 3. HIF modeling principle with random fault resistance  $R_f$  duration and magnitude used in PSCAD simulations.

## RESULTS FROM SIMULATIONS AND REAL-LIFE DATA TESTS

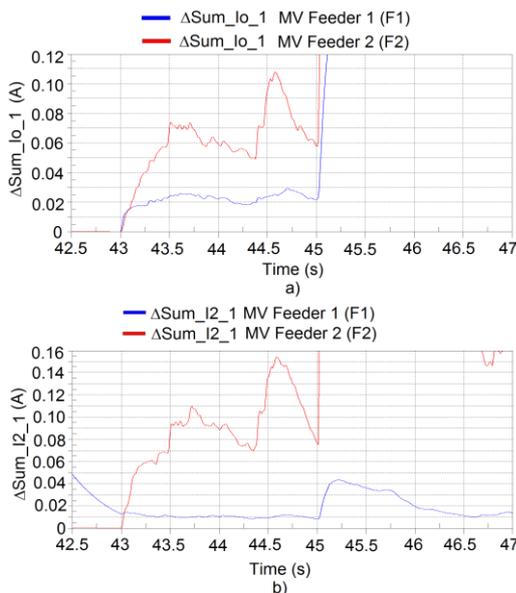
In the following chosen simulation results from Fig. 2 HIF and non-random HIF (stable earth-faults, EFs) cases with different grounding practices and field data test results will be presented.

### Low-Resistance Grounded Network – Simulation Results

In Fig. 4a) simulation results for  $\Delta\text{Sum\_Io\_1}$  and in Fig. 4b) for  $\Delta\text{Sum\_I2\_1}$  from Case 1 with HIF and OH-lines are presented (Fig. 2). Respectively, in Fig. 5  $\Delta\text{Sum\_Io\_1}$  and  $\Delta\text{Sum\_I2\_1}$  from Case 5 with HIF and mixed lines are shown (Fig. 2). With Table 1 settings for low-resistance grounded networks it can be seen that in Case 1 (Fig. 4) HIF can be detected with  $\Delta\text{Sum\_Io\_1}$  based method and indicated with  $\Delta\text{Sum\_I2\_1}$  based method. Respectively, in Case 5 (Fig. 5) HIF can be indicated with  $\Delta\text{Sum\_Io\_1}$  and detected with  $\Delta\text{Sum\_I2\_1}$ .



**Figure 4.** Simulation results for a)  $\Delta\text{Sum}_{Io_1}$  and b)  $\Delta\text{Sum}_{I2_1}$  from Case 1 with HIF and OH-lines with symmetrical load (see Fig. 2).



**Figure 5.** Simulation results for a)  $\Delta\text{Sum}_{Io_1}$  and b)  $\Delta\text{Sum}_{I2_1}$  from Case 5 with HIF and mixed lines with symmetrical load (see Fig. 2).

### Low-Resistance Grounded Network – Test Results with Field Data

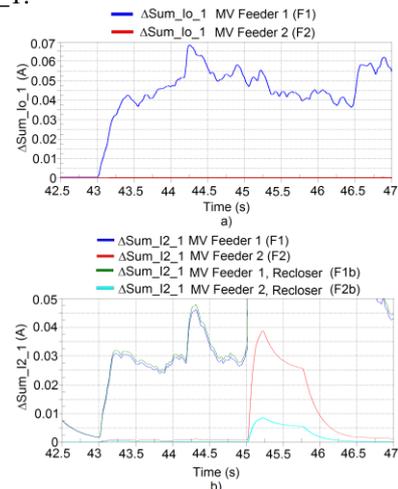
The proposed new HIF detection method was tested with real-life HIF measurements from low-resistance grounded 60 Hz network with OH-line settings and operation time delays (Table 1). In Table 2 summary from four test cases is presented regarding HIF indication / detection capability with  $\Delta\text{Sum}_{Io_1}$ . Table 2 shows that HIFs can be indicated/detected in all studied cases.

**Table 2.** HIF indication/detection of  $\Delta\text{Sum}_{Io_1}$  in low-resistance grounded (60 Hz) real-life test cases.

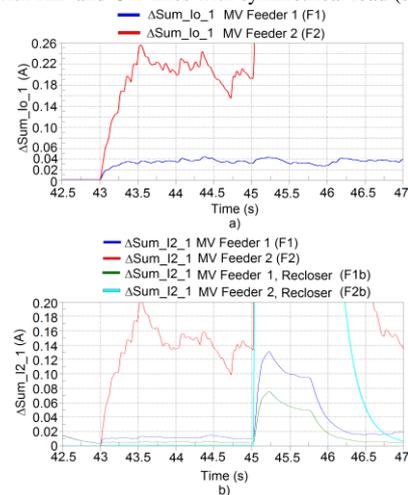
Case	$\Delta\text{Sum}_{Io_1}$		Surface
	HIF Indication	HIF Detection	
1	YES	YES	Sand
2	YES	YES	Semi-rocky
3	YES	YES	Semi-rocky
4	YES	NO	Semi-rocky

### Solidly Uni-Grounded – Simulation Results

Fig. 6 shows  $\Delta\text{Sum}_{Io_1}$  and  $\Delta\text{Sum}_{I2_1}$  from Case 1 with HIF and OH-lines (Fig. 2). Respectively, in Fig. 7  $\Delta\text{Sum}_{Io_1}$  and  $\Delta\text{Sum}_{I2_1}$  from Case 5 with HIF and mixed lines are presented (Fig. 2). With Table 1 settings for solidly uni-grounded networks one can see that in Case 1 (Fig. 6) HIF can be indicated with both  $\Delta\text{Sum}_{Io_1}$  and  $\Delta\text{Sum}_{I2_1}$  based methods. In Case 5 (Fig. 7) HIF can be detected with both  $\Delta\text{Sum}_{Io_1}$  and  $\Delta\text{Sum}_{I2_1}$ .



**Figure 6.** Simulation results for a)  $\Delta\text{Sum}_{Io_1}$  and b)  $\Delta\text{Sum}_{I2_1}$  from Case 1 with HIF and OH-lines with symmetrical load (see Fig. 2).



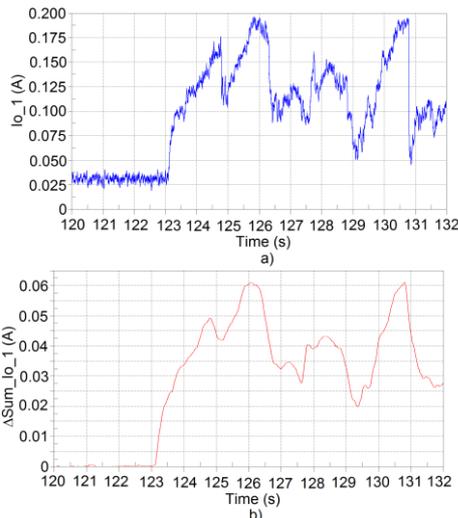
**Figure 7.** Simulation results for a)  $\Delta\text{Sum}_{Io_1}$  and b)  $\Delta\text{Sum}_{I2_1}$  from Case 5 with HIF and mixed lines with symmetrical load (see Fig. 2).

### Solidly Uni-Grounded – Test Results with Field Data

New HIF detection method was also tested with real-life HIF cases from solidly uni-grounded 50 Hz network with Table 1 OH-line settings and operation time delays. In Table 3 summary from seven test cases is shown regarding HIF indication / detection capability with  $\Delta\text{Sum}_{Io_1}$ . Table 3 shows that HIFs can be indicated/detected in all studied cases. In Fig. 8 waveforms of  $I_{o_1}$  and  $\Delta\text{Sum}_{Io_1}$  during  $t = 120-132$  s from Case 2 (Table 3) are presented. Fig. 8b) shows only HIF indication moment and the HIF will be detected later (not shown in Fig. 8).

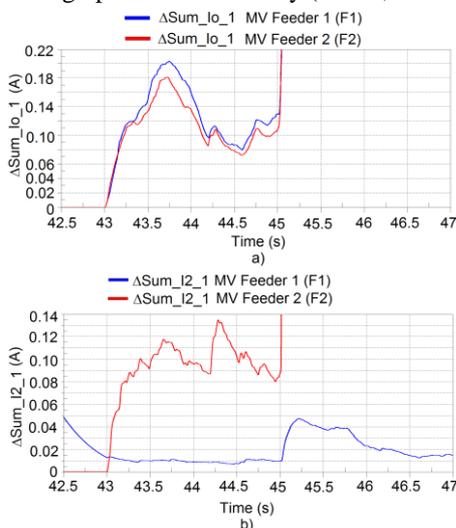
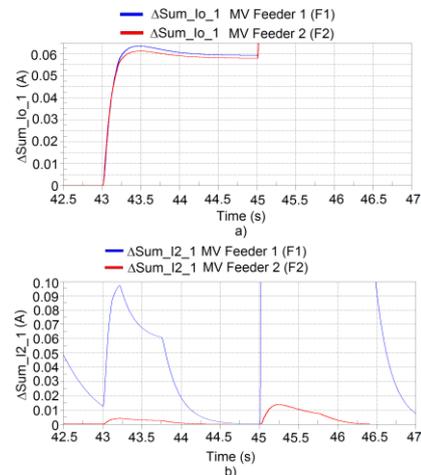
**Table 3.** HIF indication/detection of  $\Delta\text{Sum}_{Io\_1}$  in solidly ungrounded (50 Hz) real-life test cases.

Case	$\Delta\text{Sum}_{Io\_1}$	
	HIF Indication	HIF Detection
1	YES	YES
2	YES	YES
3	YES	YES
4	YES	NO
5	YES	NO
6	YES	YES
7	YES	YES


**Figure 8.** Waveforms of a)  $I_{o\_1}$ , b)  $\Delta\text{Sum}_{Io\_1}$  during  $t = 120-132$  s from real HIF Case 2 (Table 3).

### Compensated Network – Simulation Results

In Fig. 9  $\Delta\text{Sum}_{Io\_1}$  and  $\Delta\text{Sum}_{I2\_1}$  from Case 5 with HIF and mixed lines (Fig. 2) is presented. Fig. 10 shows  $\Delta\text{Sum}_{Io\_1}$  and  $\Delta\text{Sum}_{I2\_1}$  from Case 3 with non-random HIF and mixed lines (Fig. 2). With Table 1 settings for compensated networks it can be seen that in Case 5 (Fig. 9) HIF can be detected with  $\Delta\text{Sum}_{I2\_1}$  based method. In Case 3 (Fig. 10) non-random HIF / stable earth-fault will not be detected by  $\Delta\text{Sum}_{I2\_1}$  due to chosen long operation time delay (1.75 s, Table 1).


**Figure 9.** Simulation results for a)  $\Delta\text{Sum}_{Io\_1}$  and b)  $\Delta\text{Sum}_{I2\_1}$  from Case 5 with HIF and mixed lines with symmetrical load (see Fig. 2).

**Figure 10.** Simulation results for a)  $\Delta\text{Sum}_{Io\_1}$  and b)  $\Delta\text{Sum}_{I2\_1}$  from Case 3 with non-random HIF (stable earth-fault) and mixed lines with symmetrical load (see Fig. 2).

If the interest would be only in non-random HIFs or in traditional intermittent faults then more appropriate time instants and settings for the calculation of  $\Delta\text{Sum}_{I2\_1}$  and  $\Delta\text{Sum}_{Io\_1}$  could be chosen.

### DISCUSSION AND CONCLUSIONS

This paper proposed new, simple and flexible HIF detection method which is applicable to different 50 or 60 Hz MV networks with different grounding practices. Depending on the grounding type, HIF detection is based on the use of zero sequence current  $I_o$  or negative sequence current  $I_2$  and doesn't need voltage measurement. Based on the simulations with different grounding practices and field data test results, the proposed method seems to be very promising for detecting also very challenging HIF cases.

Effect of distributed generation (DG) on  $I_2$  values was also studied in simulations. Based on the simulations the effect of DG on  $I_2$  value is very small. It also depends on the DG unit type (e.g. synchronous generator or converter based) and potentially on the control method of the converter-based DG unit during faults (e.g. negative sequence current feeding during unsymmetrical faults).

Based on the simulations even higher sensitivity without risk of false detection or maloperation of MV healthy feeders could be achieved with centralized / multi-feeder HIF detection. In addition, in ring operated MV networks centralized (or decentralized) communication and comparison of  $\Delta\text{Sum}_{I2\_1}$  values based HIF detection method could be potentially feasible, because it is difficult to find generally applicable settings for standalone (local measurements based) HIF detection. However, further studies regarding ring operated MV networks and centralized HIF detection are needed.

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