APPLICATION OF MULTI-FREQUENCY ADMITTANCE-BASED FAULT PASSAGE INDICATION IN PRACTICAL COMPENSATED MV-NETWORK

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ABSTRACT

This paper introduces a novel fault passage indicator function and device for compensated MV-networks. The operation is based on multi-frequency neutral admittance measurement together with a cumulative phasor summing technique. With this methodology, high-level requirements for indication sensitivity and selectivity can be fulfilled during all types of earth faults that may be encountered in practical MV-networks.

The first commercial installation to apply the new fault passage indicator devices was implemented and field-tested at the end of 2016, in close co-operation with the second-largest utility in Finland, Elenia. This pilot project included several compact secondary substations and one pole-mounted load-break switch installed along feeders of a rural compensated 110/20kV substation, applying both centralized and distributed compensation. Followed by an extensive field test, the performance of the fault passage indicator devices was evaluated.

The results verified the highly dependable operation of fault passage indication based on the multi-frequency admittance criterion. All trial faults were correctly detected, even up to 7.5kΩ in terms of fault resistance. However, a special challenge of "local over-compensation" owing to distributed compensation coils was recognized due to which some false indications were obtained from certain line sections located upstream from distributed coils.

Based on the test results, the new fault passage indicator device truly enables and enhances the location of earth faults in compensated MV-networks. Additionally, distributed compensation coils must be taken into account in such networks when implementing FPI-schemes and setting FPI-devices.

INTRODUCTION

In today's numerical protection relays, fault location has become an important part of functionality. When faults are located with reliable and accurate techniques, fault clearance times can be reduced and supply quality improved. Typical solutions are based on computational fault distance estimation and Fault Passage Indication (FPI) information from dedicated FPI-devices.

The most commonly applied method for computational fault distance estimation is to calculate the fundamental frequency reactance from the measuring point to fault location. The physical fault distance can then be derived by converting the calculated reactance value to kilometers using the set conductor reactance values (Ω/km). For short-circuit faults, reactance-based solutions have been available for many years with very good practical performance resulting in typical inaccuracies in the range of only 1% of the total line length. On the contrary, regardless of the several years of research, computational location of earth faults in compensated networks using the impedance based methods, is still very challenging. This is mainly due to the multitude character of earth faults in practice. Thus, its applicability so far has mainly been limited to relatively low-ohmic permanent earth faults [1]. For earth faults the expected inaccuracy could be even ten times higher compared to short-circuits [1]. Therefore, in the field of earth-fault location a need for better performance and fault type coverage exists.

An FPI-device derives its operating quantities based on the available local measurements, for example in secondary substations (MV/LV) installed along the MV-lines. The basic purpose of the FPI is to point out whether the fault current has passed the location in question. This indication can be complemented with directional information (forward/reverse) depending on the operating principle of the FPI. The indications are then sent to upper level systems such as SCADA and DMS, and visualized in the single-line diagram or map view of the network. The faulted line section is identified, and manual or automatic fault isolation and supply restoration can be initiated. Accurate and reliable fault location information is the key to effective fault isolation and supply restoration. This implies that a fault should be isolated with minimum number of switching operations, so that the disconnection is strictly limited to the faulted line section only. Also thanks to high-quality fault location information, the field-personnel can instantly direct repair works to the right spot, which then also speeds up the supply restoration for the faulted line section [2].

Many manufacturers have been developing dedicated FPI-devices to solve the challenge of locating earth faults, especially in compensated networks. One of such is the new *Multi-frequency admittance* (MFA)-based FPI-function and device, which is implemented into the ABB RIO600 device.

MULTI-FREQUENCY ADMITTANCE-BASED FAULT PASSAGE INDICATION

Fault passage indication in compensated networks is a very challenging task. Due to the compensation effect of the Arc Suppression Coil (ASC), the residual current magnitude itself cannot be used for the indication of the fault current passage. Furthermore, the reactive component of the residual current can have the same direction in healthy and faulty feeders. This implies that a fault indicator must evaluate both magnitude and direction in order to operate dependably and securely. Attention should also be paid to intermittent earth faults, i.e. a special fault type that is often encountered in compensated cable networks. As a solution for these challenges, multi-frequency admittance (MFA)-based earth-fault criterion was applied to fault passage indication. The MFA-function consists of two main elements: the directional element and the current magnitude supervision element, which are described in the following.

Directional element of MFA

In MFA, the broad frequency spectrum of measured residual signals (Uo, Io) is utilized. In addition to the fundamental frequency, the harmonic components in fault signals are utilized in the form of harmonic admittances by adding them to the fundamental frequency neutral admittance in phasor format. The resulting sum admittance phasor applied in directional estimation is, ***Eq. 1*** [3]:

$$\overline{Y}_{osum} = \mathrm{Re}\left[\overline{Y}_o^1\right] + j\cdot\mathrm{Im}\left[\overline{Y}_o^1 + \sum_{n=2}^{m}\overline{Y}_o^n\right] \qquad (1)$$

Where $\overline{Y}_o^1 = \overline{I}_o^1 / -\overline{U}_o^1$ is the fundamental frequency neutral admittance phasor, $\overline{Y}_o^n = \overline{I}_o^n / -\overline{U}_o^n$ is the n^{th} harmonic frequency neutral admittance phasor.

In order to secure the validity of directional estimation during restriking earth faults as well, the new concept of *Cumulative Phasor Summing (CPS)* was introduced in reference [3]. In CPS-calculation, values of the complex sum admittance phasors are added together in phasor format starting at time t_{start} and ending at time t_{end}, ***Eq. 2***:

$$\overline{Y}_{osum\_CPS} = \sum_{i=t_{start}}^{t_{end}} \mathrm{Re}\left[\overline{Y}_{osum}(i)\right] + j\times\sum_{i=t_{start}}^{t_{end}} \mathrm{Im}\left[\overline{Y}_{osum}(i)\right] \qquad (2)$$

The start criterion for the CPS-calculation is obtained from internal residual overvoltage condition (Uo>), which defines the basic sensitivity of the MFA-function. The benefit of CPS-calculation is the unique filtering effect to the oscillating discrete DFT-phasors. It enables secure fault direction evaluation regardless of the fault type – even the direction of restriking earth faults can be indicated reliably.

Another improvement on traditional earth-fault protection functions is the shape of the directional characteristics of the MFA-function. It uses an "extended" operation sector, which makes it valid both in compensated and unearthed networks, ***Fig. 1***. This is a great practical advantage in secondary substation applications as the connection status of the ASC is typically not available.

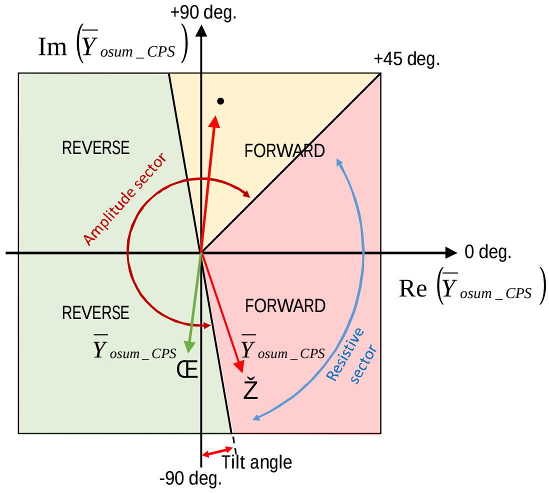


Fig. 1 *Illustration of the directional characteristics of the MFA-function.*

Current magnitude supervision element of MFA

In order to ensure correct directional indication, the directional element of MFA is additionally supervised by a unique current magnitude supervision element. With this element, the correct current magnitude (50Hz) can be obtained regardless of fault type or fault resistance value. This is achieved by calculating the quotient of cumulative phasors of fundamental frequency residual current and residual voltage; the result represents the "stabilized" neutral admittance, ***Eq. 3*** [3]:

$$\overline{Y}^1_{o\,stab} = \frac{\overline{I}^1_{oCPS}}{-\overline{U}^1_{oCPS}} = \mathrm{Re}\left[\overline{Y}^1_{o\,stab}\right] + j\cdot\mathrm{Im}\left[\overline{Y}^1_{o\,stab}\right] = G_{ostab} + j\cdot B_{ostab} \qquad (3)$$

This "stabilized" admittance value can be converted into the corresponding current value by multiplying it with the system nominal phase-to-earth voltage value, ***Eq. 4***:

$$\overline{I}^1_{o\,stab} = (G_{ostab} + j\cdot B_{ostab})\times\frac{U_n}{\sqrt{3}} = I^1_{oCosstab} + j\cdot I^1_{oSinstab} \qquad (4)$$

The estimated current value given by ***Eq. 4*** matches the correct steady-state information with a unique feature: it does not depend on the fault type or fault resistance value, i.e. the estimated current magnitude is the same regardless of fault type or whether the fault is solid, low-ohmic or high(er)-ohmic. Another unique feature of MFA is that the estimated current value applied to current threshold supervision is automatically adapted to the fault type and network compensation degree: depending on the phase angle of the accumulated sum admittance phasor either amplitude or the resistive part of the "stabilized" current phasor is used in the comparison, ***Fig. 1***. The phase angle sectors for this purpose are depicted in ***Fig. 1*** together with the accumulated sum admittance phasors used as an example. Phasor • depicts the direction of the accumulated sum admittance phasor if an earth fault occurs outside the protected feeder (i.e. in reverse direction). Phasor , depicts the direction of the accumulated sum admittance phasor if an earth fault occurs inside the protected feeder (i.e. in a forward direction) regardless of the fault type, when the network is unearthed. The result is also valid in compensated networks when there are harmonics present in the fault quantities. Phasor *f* depicts the direction of the accumulated sum admittance phasor if a resistive earth fault occurs inside the protected feeder without harmonics in the fault quantities, when the network is compensated. This self-adaptive feature of MFA enables operation in unearthed networks as well, and even without the parallel resistor in compensated networks if there are plenty of harmonics present, e.g. during restriking earth faults.

Indication scheme for earth faults

An example of one field-tested multiple feeder CSS (ABB SafeRing/SafePlus RMU) and its simplified single-line diagram with the novel earth-fault indication functionality is shown in ***Fig. 2***.

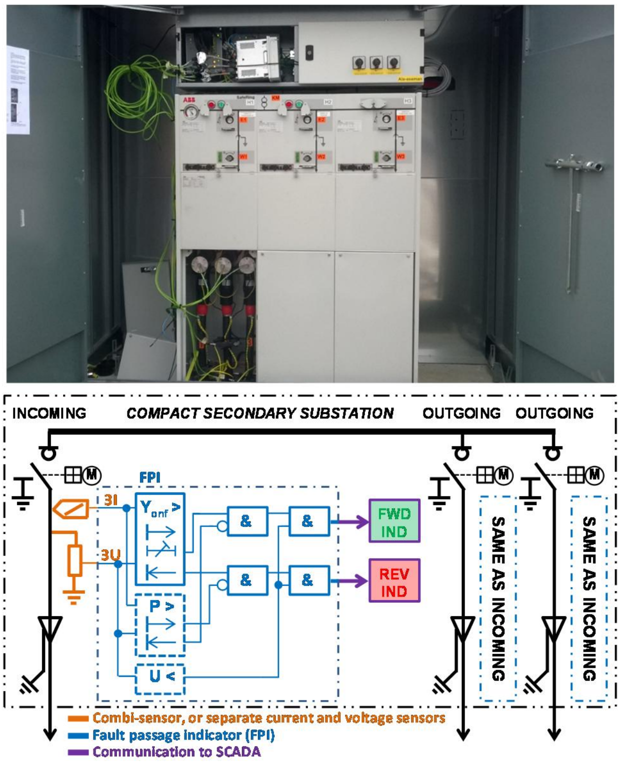


Fig. 2 *Field-tested CSS and its simplified single-line diagram with the novel earth-fault indication functionality.*

The phase currents (3I) and voltages (3U) are measured with sensors from which the residual current (Io) and voltage (Uo) are calculated. Similar functionality can be implemented into a pole-mounted load-break switch (ABB SECTOS) used in overhead line networks.

In the proposed solution, one stage of MFA set in forward direction is applied in each cubicle of a CSS, ***Fig. 2***. The MFA-stage displays a forward indication (FWD_IND) if the fault current flows from the busbar towards the line. If the fault current flows from the line towards the busbar, a reverse indication (REV_IND) is displayed. These indications may be further filtered with optional Directional Power Supervision (DPS) logic and the supply interruption condition (U<). The basic principle of the DPS-logic is that it enables indication only when the direction of the active power flow coincides with the direction of the fault. The DPS-logic is needed to secure correct operation when FPI utilizes an "extended" operation sector as in case of the MFA-function. The supply interruption condition ensures that indications are only obtained from the faulty feeder after the feeder breaker has tripped at the primary substation, and the measured voltages of the disconnected feeder have therefore dropped to zero. The advantage is that all events with lower priority during an earth fault such as reverse fault indications from healthy feeders are blocked, reducing the communication burden and the amount of events in the control room. Directional indications are then sent to an upper level system such as SCADA, using LTE/3G/GPRS gateway devices and a commercial mobile network.

ORIVESI FPI PILOT PROJECT: FIELD TESTING AND EXPERIENCE

The performance of the first prototype of the MFA-based indicator device (ABB RIO600) was validated with a small-scale field test at the end of 2015. The excellent results showed that this function provides truly universal and reliable earth-fault detection [4]. After this field test, a more extensive pilot project was initiated in co-operation with the Finnish utility Elenia to obtain further user experience and performance evaluation. In this pilot project, 10 CSSs and one SECTOS with the latest version (v1.7) of the novel FPI-device were installed along four feeders of the Orivesi 110/20kV substation. An extensive field test was conducted to evaluate the performance of these FPI-devices on a large scale. The total number of cubicles with full FPI-functionality was 26 which all were monitored during the test. The trial fault spots were selected so that they were located in front of as many CSS as possible at the time. As a result, a total of three network configurations and two fault spots were selected. A simplified single-line diagram of the network with the trial fault spots is shown in ***Fig. 3***. The network presents a large (I_c=226A, 20kV) mixed rural network with both long cable feeders and overhead line sections. The earth-fault current compensation is done by applying both centralized (tunable ASC) and distributed compensation (fixed 5-15A ASCs). The earth fault related network parameters are presented in ***Table 1***. Based on this information, the required settings for the MFA-function were easily determined. The selected settings are summarized in ***Fig. 4.*** We emphasize that these settings are valid when the network is compensated, but also when the network is unearthed (central ASC disconnected).

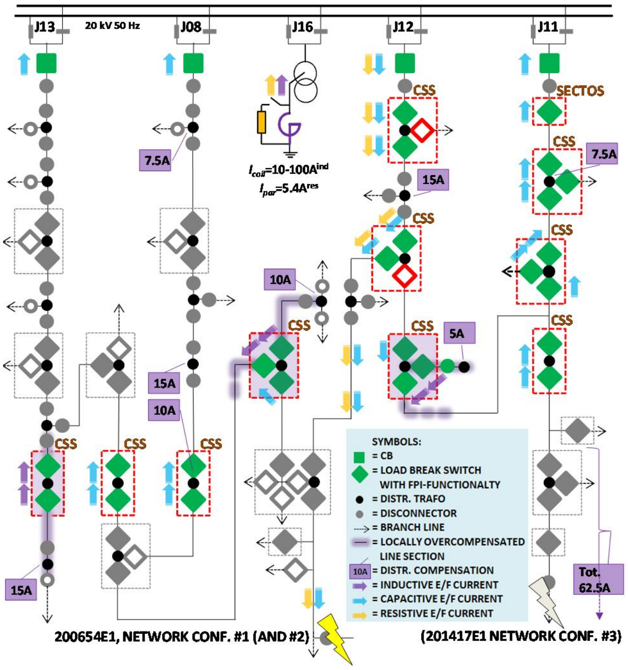


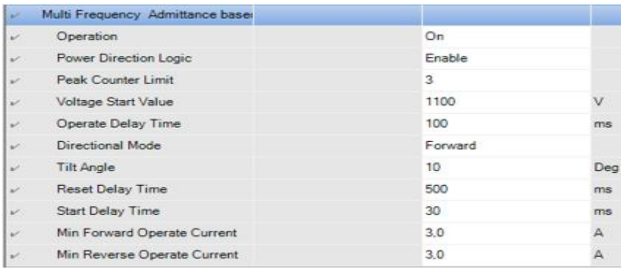
Fig. 3 *Simplified single-line diagram of the Orivesi test network with principal fault current flow in the CSSs (faulty feeder J12).*

Table 1. Network data during field test.

Network data/parameter	Value at 20kV
Uncompensated E/F current of the network	226A
Distributed compensation	138A
Central compensation	10-100A
Rated current and logic of the parallel resistor	5.4A (fixed), or 5.4-0-5.4A (logic)
Resistive losses of the system	6.3A (3%)
Compensation degree (during normal operation -5A)	-23A,-5A,+16A or unearthed
Max. healthy state Uo (parallel resistor ON)	0.7% (80V)

Referring to ***Table 1*** the parameter "*Voltage Start Value*" was set to 1100V in primary volts, which is above the maximum healthy-state residual voltage value in all practical network topologies. The parameter "*Tilt angle*" was set to 10 deg. to provide tolerance against phase displacement errors in the measurements. The parameter "*Reset Delay time*" was set to 500ms, which keeps the operate timer activated between current spikes during a restriking earth fault. And finally, the parameter "*Min Forward/Reverse Operate current*" was set to 3A based on the rated value of the parallel resistor of the ASC.

During the field tests, over 60 individual primary earth-fault tests were conducted by varying the fault type (continuous or intermittent), fault resistance (0Wto 15kW), network compensation degree (under- and overcompensated, -23A, -5A, +16A, or unearthed) and the fault spot. During compensated operation, the parallel resistor of the central ASC was fixed by default (always ON), but resistor logic (ON-OFF-ON) was also applied in some test cases to evaluate its effect on the achieved sensitivity. All tests were conducted so that there were no supply interruptions to the customers. This was achieved by setting the fault-on time shorter than the tripping time of the feeder breaker at the substation. The output signals of the FPIs were sent to the utility's SCADA system via wireless communication. The operation and performance of the FPIs was then judged based on the event lists of SCADA after each test.



Multi Frequency Admittance base		
Operation	On	
Power Direction Logic	Enable	
Peak Counter Limit	3	
Voltage Start Value	1100	V
Operate Delay Time	100	ms
Directional Mode	Forward	
Tilt Angle	10	Deg
Reset Delay Time	500	ms
Start Delay Time	30	ms
Min Forward Operate Current	3.0	A
Min Reverse Operate Current	3.0	A

Fig. 4 *Settings of MFA-function (RIO600 tool view).*

In order to demonstrate the multitude character of earth faults and its challenge to FPI in compensated networks, the recorded waveforms of one test series with a variety of fault types and fault resistances are presented in ***Fig. 5***.

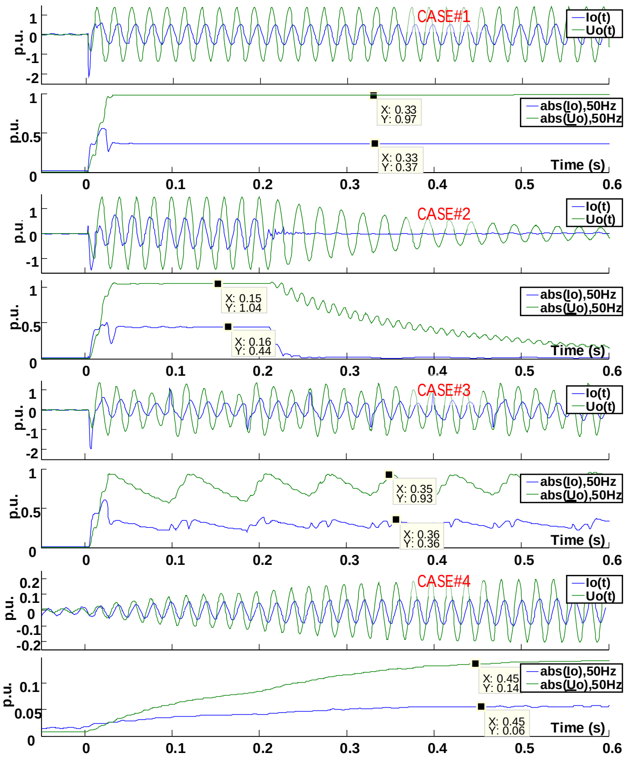


Fig. 5 *Example recordings from the field test (I_n=80A, U_n=11.547kV)*

For each fault type, first the waveforms of Io and Uo are shown, then their 50Hz magnitudes. These waveforms were captured with an additional IED installed in the outgoing cubicle of one CSS in the faulty feeder J11. Case #1 is a continuous earth fault with zero fault resistance. Case #2 is also a continuous earth fault with zero fault resistance, when the central ASC was disconnected i.e. the network was unearthed. Notice the very long duration of post-fault oscillation after the fault is disconnected. Case #3 is a restriking earth fault. Case #4 presents a high-resistive earth fault with a fault resistance of 10kW. Regardless of high level of variety of different waveforms and their amplitudes, all these trial earth faults were correctly indicated by the FPI devices of the CSSs along the main line from the substation to the fault spot.

The most important test results are summarized as follows:

CSS cubicles and SECTOS of the faulty feeder, main line:

Correct indication of fault direction was obtained in all tests i.e. FWD_IND (outgoing) and REV_IND (incoming) was obtained in all test cases in which

- $R_F \leq 10k\Omega$ (-5A detuning, only CSSs closest to the fault spot when using resistor logic)
- $R_F \leq 7.5k\Omega$ (-5A detuning, both CSSs and SECTOS with fixed resistor)
- $R_F \leq 5k\Omega$ (+16A detuning, only CSSs, SECTOS not tested)
- $R_F \leq 3k\Omega$ (-23A detuning, both CSSs and SECTOS)
- The fault was of intermittent type (both CSSs and SECTOS)
- The network was unearthed (central ASC off, only solid earth-fault tests were conducted, both CSSs and SECTOS)

CSS cubicles of the healthy feeders and branch lines:

Correct operation was primarily obtained i.e. no FWD-IND or REV-IND was given, however some false indications occurred with:

- Certain CSS cubicles located upstream from distributed ASCs (local overcompensation)
- Certain CSS cubicles of one healthy feeder due to post-fault oscillations (unearthed operation). The effects of post-fault oscillation on earth-fault detection are explained in ref. [5].

A special challenge of local overcompensation due to the distributed ASCs was recognized based on the test results. This means that some line sections located upstream from these ACSs may become inductively overcompensated from an earth-fault indication perspective. Then, in case of an outside earth fault, the FPI located at the beginning of the line section measures inductive residual current instead of capacitive current, which may cause the FPI to see the fault direction falsely. This occurs if an "extended" operation sector is applied. An example of earth-fault current calculation demonstrating the effect of local overcompensation on the operation of FPIs during an outside earth fault is shown in ***Fig. 6***.

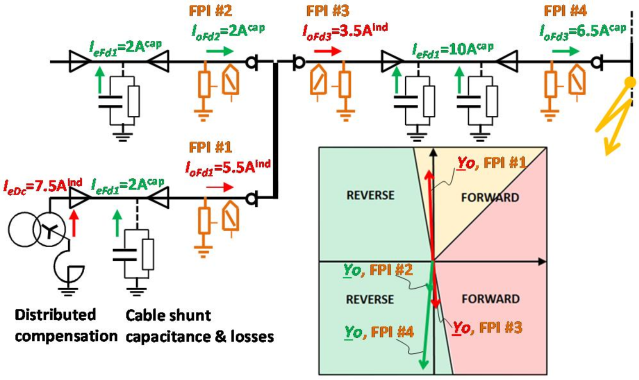


Fig. 6 *Challenge of local overcompensation for FPI.*

Fig. 6 shows that at *FPI#1* and *FPI#3* the measured residual current is inductive instead of capacitive. This is due to fact that the inductive earth-fault current produced by the distributed ASC is higher than the capacitive earth-fault current produced by the total shunt capacitance of the line downstream from the measuring point. As a result, *FPI#1* may see the fault falsely as being in a forward direction, and *FPI#3* in a reverse direction. Whereas at *FPI#2* and *FPI#4*, the measured residual current is capacitive and thus the fault directions are seen correctly. This kind of operation was seen in the field test with certain CSSs related to locally overcompensated line sections, which are indicated in ***Fig. 3***.

To overcome the challenge described above, one solution is to use the "normal" operation sector instead of the "extended" one. However, the disadvantage then is that harmonic components cannot be utilized in directional evaluation anymore with possible negative effect on the reliability. Also the FPIs become inoperable during unearthed network operation (central ASC disconnected). Thus, the preferred solution is to use the "extended" operation sector, and additionally supervise the fault indication functionality through dedicated overcurrent condition based on appropriate sequence component current. This feature will be implemented in the next version of the MFA-function.

CONCLUSIONS

This paper describes a new fault passage indicator function and device for compensated MV-networks. The operation is based on multi-frequency neutral admittance measurement (MFA), together with a cumulative phasor summing technique. This feature is an essential part of the functionality in ABB's RIO600 fault indicator device. The performance of the first large-scale practical installation including several compact secondary substations and one pole-mounted load-break switch with the RIO600-fault indicator devices was validated with a comprehensive field test in an actual 20kV network.

The results verified the highly dependable operation of the FPI-devices: all trial faults were correctly indicated by the FPIs located along the main line of the faulty feeder until the sensitivity limit in terms of fault resistance was reached. However, some false indications were obtained, the major reason for which was found to be the local overcompensation effect due to the applied distributed ASCs. This additional challenge must be taken into account when implementing and setting FPIs in networks where distributed compensation is applied. It also shows that the new FPI-device truly enables the effective location of earth faults in compensated MV-networks, and thus provides a tool for further decreasing the effects of permanent faults for customers.

References

[1] J. Altonen, A. Wahlroos, "*Novel algorithm for earth-fault location in compensated MV-networks*", CIRED, 2013

[2] J. Starck, H. Paananen, S.Vähäkuopus, J.Holmlund, M.Viholainen, "*Advanced fault detection in compensated Networks*", CIRED, 2016 Workshop

[3] A.Wahlroos, J.Altonen, "*Application of novel multi-frequency neutral admittance method into earth-fault protection in compensated MV-networks*", DPSP, 2014

[4] J. Altonen, A. Wahlroos, "*Performance of modern fault passage indicator concept in compensated MV-networks*", CIRED, 2016 Workshop

[5] S. Zubić, A. Wahlroos, J.Altonen, P.Balcerek, P.Dawidowski, "*Managing post-fault oscillations in compensated MV-networks*", DPSP, 2015