PERFORMANCE OF MODERN FAULT PASSAGE INDICATOR CONCEPT IN COMPENSATED MV-NETWORKS

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ABSTRACT

This paper introduces a novel concept for fault passage indication applicable in secondary distribution level in compensated MV-networks. A special emphasis is put to dependable and secure detection of all kind of earth faults encountered in practical networks with overhead lines and underground cables. With the proposed solution requirements for sensitivity and selectivity are fulfilled not only in continuous solid and resistive earth faults, but also during restriking faults. The operation of the fault passage indication is based on the latest evolution of the neutral admittance based detection principle utilizing the multi-frequency admittance measurement.

The performance of the proposed novel fault indication concept has been validated by a field test in a 20kV distribution network. The results show that the proposed multi-frequency admittance criterion provides very good overall performance and has thus a high potential to become a standard and widely used functionality in fault passage indication applications.

INTRODUCTION

As utilities today concentrate on continuity and reliability of their distribution networks, fault location has become an important supplementary function. One solution for this requirement is to apply computational fault distance estimation. Such functions are available in primary substation relays, and they are typically based on the calculation of impedance utilizing locally measured currents and voltages. The physical fault distance (in km) is derived by conversion from Ohms to kilometers using the entered setting values. This can be done in the relay, but more accurate and informative results are obtained when the fault reactance value is further processed in DMS (Distribution Management System) and possible fault location(s) are visualized in a map-view, ***Fig. 1***.

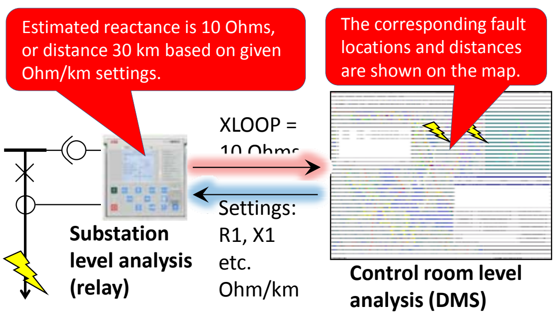

Fig.1 *Principle of the computational fault distance estimation.*

Application of computational fault distance estimation in compensated networks is currently limited to short-circuit faults. Commercial solutions for computational location of single-phase earth faults is not yet available, regardless of the research and development work done in recent years [1]. Due to lack of solutions for computational fault location of earth faults, application of Fault Passage Indicators (FPIs) is a promising alternative [2]. The purpose of FPIs is to point out whether the fault current has passed the location in question in forward or in reverse direction. Combining the directional information from FPIs in upper level systems (DMS), the faulty line section can be determined to enable effective and fast fault isolation and supply restoration, ***Fig. 2***.

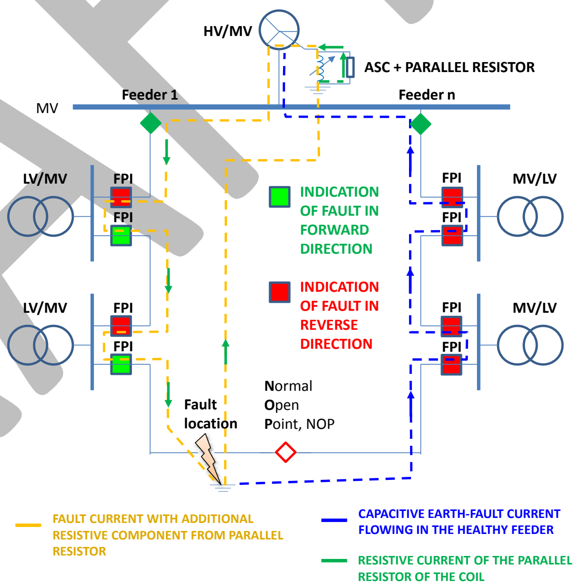

Fig.2 *The principal concept of FPIs in compensated MV-networks.*

Similarly as computational fault distance estimation, earth-fault indication in compensated networks is a very challenging task. Due to the compensation effect of the Arc Suppression Coil (ASC), the fault current magnitude itself cannot be used for indication of the faulty feeder. Furthermore, the reactive component of the residual current can have the same direction in the healthy and faulty feeders. This implies that the directional evaluation requires dedicated algorithms [3]. Attention should also be paid to intermittent earth faults, i.e. a special fault type that is often encountered in compensated cable networks.

NOVEL CONCEPT FOR FAULT INDICATION

From earth-fault indication perspective the performance target for the development of a novel fault indicator device was to productize a solution which fulfills the following requirements:

- It can detect continuous (stable) earth faults with fault resistance up to 10 kOhms
- It can detect and operate selectively during restriking/intermittent earth faults
- It can operate correctly during various compensation levels of the system, from unearthed to fully compensated operation.
- It should have as few settable parameters as possible with easy setting principles.

In order to meet the above requirements, multi-frequency admittance (MFA)-based earth-fault detection method was chosen. 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 form of harmonic admittances by adding them to the fundamental frequency neutral admittance in phasor format. The resulting sum admittance phasor is, ***Eq. 1*** [3]:

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

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

In order to secure the validity of directional estimation also during restriking earth faults, the novel concept of *Cumulative Phasor Summing (CPS)* was introduced in reference [3]. The idea of CPS calculation is to add values of the measured complex DFT-phasors together in phasor format starting at time t_{start} and ending at time t_{end}, ***Eq. 2***:

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

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 from traditional earth-fault protection functions is the shape of the operation characteristics of the MFA-function. It uses an “extended” operation sector, which makes it valid both in compensated and unearthed networks, ***Fig. 3***. This is a great practical application advantage in secondary substation applications, as connection status of the ASC is typically not available.

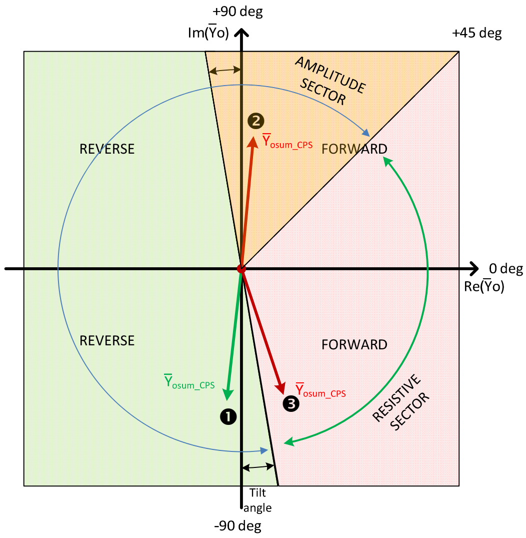

Fig. 3 *Illustration of the operation characteristics of the MFA-function.*

Current magnitude supervision element of MFA

In order to secure correct directional indication, the directional element of MFA is additionally supervised with unique current magnitude supervision element. With this element 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]:

$$\overline{Y}_{o\,stab}^1 = \frac{\overline{I}_{oCPS}^1}{-\overline{U}_{oCPS}^1}$$

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

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

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

The estimated current value given by ***Eq. 4*** matches the correct steady-state information with 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 in the 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 resistive part of the “stabilized” current phasor is used in the comparison, ***Fig. 3***. The phase angle sectors for this purpose are depicted in ***Fig. 3*** together with example accumulated sum admittance phasors. Phasor ① depicts the direction of accumulated sum admittance phasor in case of earth fault outside the protected feeder (i.e. in reverse direction). Phasor ② depicts the direction of accumulated sum admittance phasor in case of earth fault inside the protected feeder (i.e. in forward direction), when the network is unearthed. The result is also valid in compensated networks when there are harmonics present in the fault quantities. Phasor ③ depicts the direction of accumulated sum admittance phasor in case of higher-ohmic earth fault inside the protected feeder without harmonics in the fault quantities when the network is compensated. This self-adaptive feature of MFA enables operation also in unearthed network and even without the parallel resistor in compensated network in case there is plenty of harmonics present, e.g. during restriking earth faults.

Correct directional indication is further secured by directional power based supervision (DPS)-logic which is also part of the FPI's functionality, ***Fig. 4***. 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 MFA-function.

Novel indication scheme for earth faults

A simplified single-line diagram of a multiple feeder secondary substation with the novel earth-fault indication concept is shown in ***Fig. 4***.

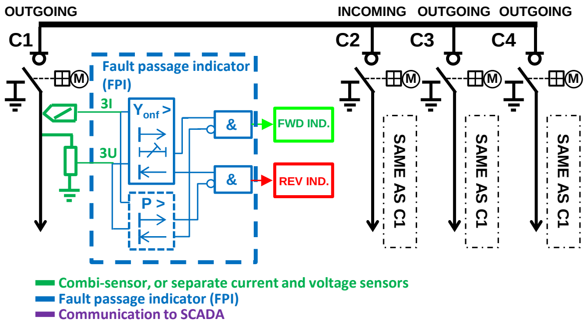

Fig. 4 *Simplified single-line diagram of a secondary substation with the novel earth-fault indication concept.*

In the proposed concept, only one stage of MFA set in forward direction is applied in each feeder, ***Fig. 4***. However, in cases where there is only one incoming and one outgoing feeder, only one FPI per secondary substation is typically sufficient. The MFA stage gives a forward indication (FWD_IND) if the fault current flows from the busbar towards the line. In case the fault current flows from line towards the busbar a reverse indication (REV_IND) is given. These directional indications are then sent to an upper level system such as DMS, e.g. via fibre-optic communication. Combining the directional fault indications from all secondary substations, the location of the faulty line section can be determined.
The phase currents (3I) and voltages (3U) are measured with combi-sensors or using separate sensors for U and I depending on the switchgear type. The residual current and voltage are calculated from the phase quantities. Regardless of the high accuracy of sensors (class 0.5 or 1) it is recommended that the errors in phase and amplitude are compensated by dedicated correction factors available in the sensor name plates for maximum measurement performance. This ensures adequate accuracy also with low residual quantities during resistive earth faults.

FIELD TESTING AND EXPERIENCE

The novel earth-fault indication concept implemented with the ABB RIO600-fault indicator devices was field tested in a practical compensated 20 kV network in Finland. The network represents a centrally compensated small rural network with overhead lines and underground cables. The test feeder configuration is shown in ***Fig. 5***. The monitored feeders of the secondary substation with the novel FPIs are denoted as *C1, C2, C3* and *C4.* The trial fault is located near the end point of the feeder. The essential network data is presented in ***Table 1***.

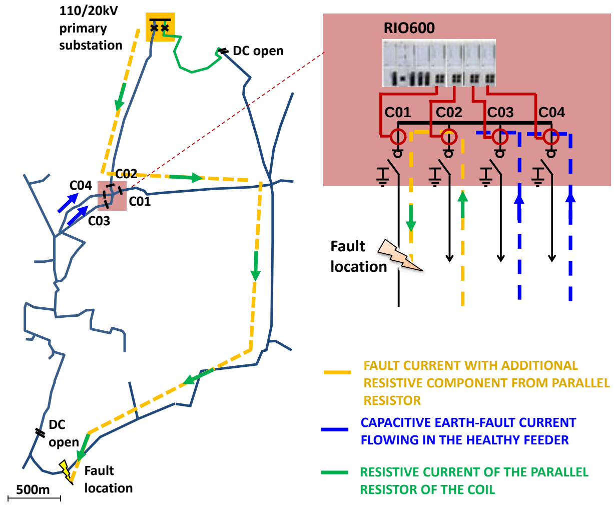

Fig.5 *Test arrangement for the field test.*

Table 1. Network data.

Network data/parameter	Value at 20kV
E/F current of the network	63A
Rated current and logic of the parallel resistor	8A-0A-8A
Resistive losses of the system	3.6A (6%)
Compensation degree	-3A or unearthed
Maximum healthy state Uo (with parallel resistor connected)	1.2% (140V)

The required settings for the MFA-function were easily determined based on the earth-fault related parameters of the network, ***Table 1***. Parameter "*Voltage Start Value*" was set to 500V (in primary volts), which exceeds the maximum healthy-state zero-sequence voltage value. Parameter "*Tilt angle*" was set to 10 deg. in order to provide tolerance against phase displacement errors in the measurements. Parameter "*Reset Delay time*" was set to 500ms, which keeps the operate timer activated between current spikes during restriking earth fault. Parameter "*Min Forward/Reverse Operate current*" was set to 4A based on the rated value of the parallel resistor. The settings are summarized in ***Fig. 6.*** It is emphasized that these settings are valid both when the network is compensated, but also when the network is unearthed.

Multi Frequency Admittance base		
Operation	On	
Peak Counter Limit	3	
Voltage Start Value	500 (4% of U_{PE})	V
Operate Delay Time	300 (*	ms
Directional Mode	Forward	
Tilt Angle	10	Deg
Reset Delay Time	500	ms
Start Delay Time	30	ms
Min Forward Operate Current	4,0	A
Min Reverse Operate Current	4,0	A

*) 150ms during unearthed operation

Fig. 6 *Settings of MFA-function (RIO600 tool view).*

During the field tests, totally nearly 60 individual primary earth-fault tests were conducted by varying the fault type (continuous or intermittent), fault resistance (0ohm to 6000ohm) and network compensation degree (undercompensated (-3A) or unearthed). In all test cases correct indication of fault direction was obtained! This included solid and resistive faults with fault resistance ≤ 6.2kOhms, transient faults (only 1-2 'current spikes' before self-extinquishment) and intermittent faults (with multiple 'current spikes'). Correct indication of fault direction was obtained regardless of network compensation degree, also the case without centralized coil connected (unearthed network). The results of one test series with variety of fault types and fault resistances are presented in ***Fig. 7***. Case #1 is a continuous earth-fault with zero fault resistance. Case #2 is a restriking earth-fault. Case #3 is resistive earth-fault with fault resistance of approx. 6000ohms. Case #4 presents a continuous earth-fault with zero fault resistance, when the ASC was disconnected at the primary substation and the network was unearthed. In all cases, the earth fault was correctly indicated as being in feeder C1 (FWD_IND). In feeder C2 reverse indication (REV_IND) was correctly obtained. In feeders C3 and C4 no indication is obtained as the fault current direction is opposite to active power flow direction (DPS-logic enabled).

CONCLUSIONS

This paper described a novel concept for earth-fault indication compensated MV-networks. This solution is based on the patented concept of Cumulative Phasor Summing, CPS, in combination with the multi-frequency neutral admittance measurement (MFA). The performance of MFA implemented in ABB RIO600-fault indicator device has been validated with field test in an actual 20 kV network. The results show that this concept provides universal earth-fault indication that detects reliably all types of earth faults, and that the multi-frequency admittance criterion has a high potential to become a standard and widely used functionality in the fault passage indication applications.

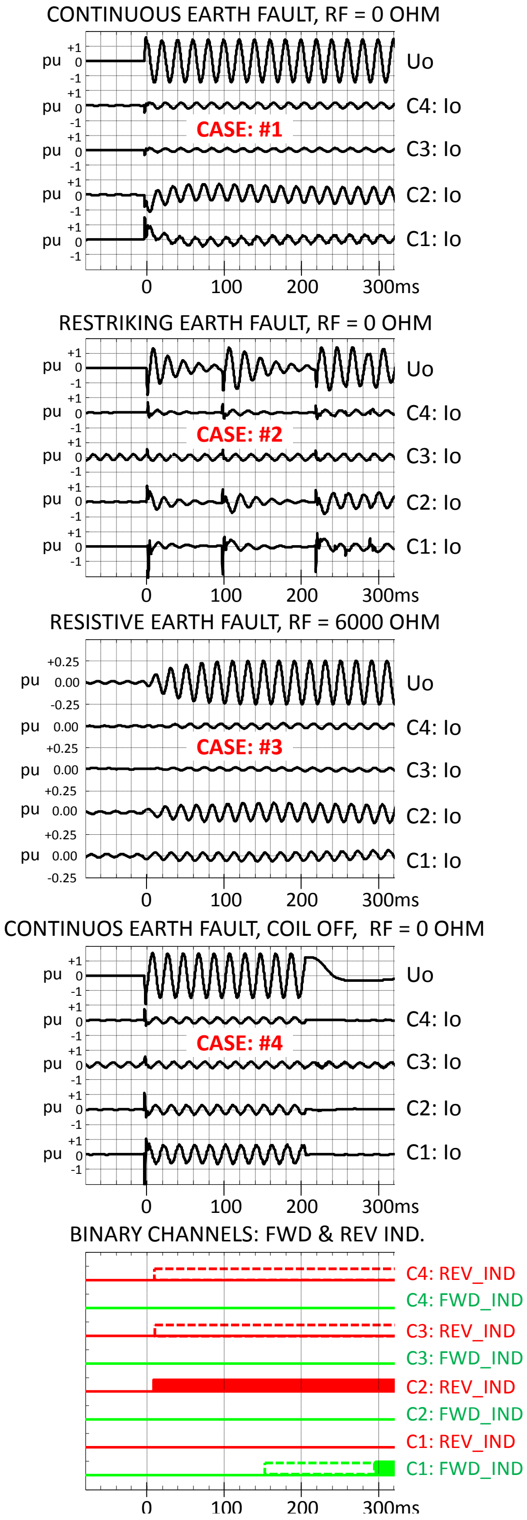

Fig. 7 *Example of field tests results, four different fault cases.*

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