APPLICATION OF NOVEL CUMULATIVE PHASOR SUM MEASUREMENT FOR EARTH-FAULT PROTECTION IN COMPENSATED MV-NETWORKS

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ABSTRACT

This paper describes a novel algorithm for feeder earth-fault protection in compensated MV-networks. The algorithm combines optimal transient and steady-state performance into one function. The operation of the algorithm is based on multi-frequency neutral admittance measurement using the cumulative phasor summing technique. The main advantage of the proposed concept is that it provides valid measurement results regardless of the fault resistance value and the fault type, whether the fault has permanent, transient or an intermittent character. It also simplifies the applied protection scheme as coordination between separate protection functions dedicated to different fault types is no longer needed.

First the paper introduces the theory of multi-frequency neutral admittance measurement. Secondly, the cumulative phasor summing technique is applied in this protection principle. Finally, the performance of the suggested protection algorithm is evaluated and compared with traditional earth-fault protection functions using data from simulations and comprehensive field tests conducted in a large 10 kV cable network with central and distributed compensation. The results show that the overall security and dependability of the protection can be significantly improved compared with the traditional earth-fault protection functions.

INTRODUCTION

The properties and problems of earth-fault protection functions applicable in compensated MV-networks are generally well known and extensively studied in numerous publications, e.g. [1]. In addition to the challenges introduced by low magnitude fault quantities, it is well known that the operation of the basic fundamental frequency phasor-based directional protection, such as *Iocosphi*, *Wattmetric* or *Admittance*-functions, is unreliable in case of transient or restriking/intermittent earth faults [2]. Therefore, the basic earth-fault protection functions are often complemented by dedicated protection functions designed especially for such fault types.

In practical MV-distribution networks today there are also completely new challenges for earth-fault protection besides intermittent earth faults. One new challenge is caused by harmonics, whose share has been gradually increasing due to continuously growing amount of non-linear, harmonics generating loads. As a consequence there is a significant portion of harmonics present in the residual quantities during an earth fault. The response of the traditional earth-fault protection to residual quantities, rich with fluctuating levels of harmonics, depends mostly on the filtering properties of the applied IED. Another new challenge is introduced when overhead-lines are replaced by cables on a large scale. In many cases this necessitates the installation of distributed compensation coils along the feeders to compensate the highly increased earth-fault current. As a consequence of long cable feeders and additional compensation the total damping of the network is increased. Especially when faults are located far away from the substation, in the end of a long cable feeder, the magnitudes and transient frequencies of the residual quantities are significantly decreased. This leads to decreased sensitivity of traditional earth-fault protection if it is based on initial fault transients.

This paper describes a novel algorithm that provides a solution to the previously described challenges. The fundamental novelty of the algorithm is that the discrete voltage and current phasors are replaced by the accumulated values of the same quantities during the fault. This cumulative phasor summation process has several advantages compared to conventional discrete measuring methods, the foremost being the inherently stable behavior in cases where the residual quantities are highly distorted and contain non-fundamental frequency and non-periodic components as in case of intermittent earth faults. This technique is therefore especially well-suited for high-impedance earthed networks where phenomena characterized by such measurement signals may frequently occur. Additionally, this technique enables practical utilization of harmonic components of the residual quantities to further enhance the security of the fault directional determination. With the novel algorithm, the problem of harmonics can be turned into a favorable situation from a protection perspective. The sensitivity of the algorithm is set with the residual over-voltage condition, $U_o>$, which allows earth faults with kilo-ohms of fault resistance to be detected in a symmetrical system. The practical maximum sensitivity limit depends on the healthy-state residual voltage value. A further advantage of this approach is also that the practical implementation of the algorithm into modern IEDs is very easy as a standard development platform and low sampling frequency can be applied. The first version of the algorithm has already been implemented into ABB *REF615* IED, a member of ABB's *Relion®* product family.

MULTI-FREQUENCY ADMITTANCE MEASUREMENT

In reference [3] a patented multi-frequency neutral admittance algorithm was described in which higher order harmonic admittances are utilized by adding them to the fundamental frequency neutral admittance in phasor format. The operate quantity can be presented as:

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

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, whose amplitude in I_o and U_o are measurable by the IED (in practice, this is around 0.5% of the nominal value).

In ***Eq. 1*** the fundamental frequency component guarantees protection sensitivity, while the harmonics are used to improve the security of the fault directional determination. Harmonics in the residual quantities during an earth fault may originate from basically three sources: harmonics generating loads, saturated magnetizing impedances (transformers and compensation coils) and the fault type. Harmonics have very advantageous properties from earth-fault protection perspective, especially in case of compensated networks. This comes from the fact that for the higher frequencies the compensation coil appears as very high impedance. This simplifies directional determination of an earth fault as it can be based solely on the sign of the imaginary part of the operate quantity phasor. For this protection function, the characteristic as shown in ***Fig. 1*** is valid. The characteristic provides universal applicability i.e. it is valid both in compensated and unearthed networks, also if the compensation coil is temporarily switched off.

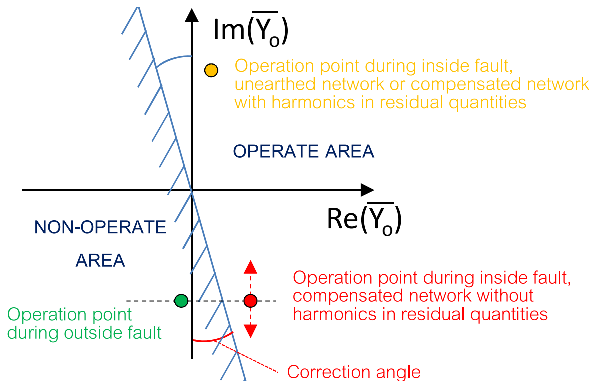

Fig. 1 *Operation characteristics of multi-frequency neutral admittance protection, which is valid both in compensated and unearthed networks.*

The practical challenge with harmonic based protection functions is that due to their origin, harmonics share and magnitudes may vary greatly in time. This is especially true, if harmonics are due to the fault type as in case of transient and intermittent earth fault. This may result in uncertainty of operation and great difficulties in calculating setting values. In addition, as higher frequency components are greatly attenuated by fault resistance, the application of purely harmonic based protection function is limited to very low-ohmic earth faults. The complete earth-fault protection scheme then always requires a separate protection function in order to fulfill the requirements for sensitivity.

In order to overcome the problems of the traditional fundamental frequency, transient and harmonic based methods in earth-fault protection, and to stabilize the operation during intermittent earth faults, a novel concept of *Cumulative Phasor Summing (CPS)* is introduced. The suggested method applies normal DFT-calculation, but is still capable in providing definite results and physical meaning of the measured quantities also when the measured signals are temporary, highly distorted, and contain non-fundamental frequency or non-periodic components.

CUMULATIVE PHASOR SUMMING

The concept of Cumulative Phasor Summing *(CPS)* is very easy to understand and straightforward to implement. Cumulative phasor sum, ***Eq. 2***, is the result of adding values of the measured complex DFT-phasors together in phasor format starting at time t_{start} and ending at time t_{end} as illustrated in ***Fig. 2***.

$$\overline{E}_{CPS} = \sum_{i=t_{start}}^{t_{end}}\overline{E}(i) = \sum_{i=t_{start}}^{t_{end}}\mathrm{Re}\left[\overline{E}(i)\right] + j\cdot\sum_{i=t_{start}}^{t_{end}}\mathrm{Im}\left[\overline{E}(i)\right] \qquad (2)$$

Where $\mathrm{Re}\left[\overline{E}(i)\right]$ = real part of phasor $\overline{E}$,

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

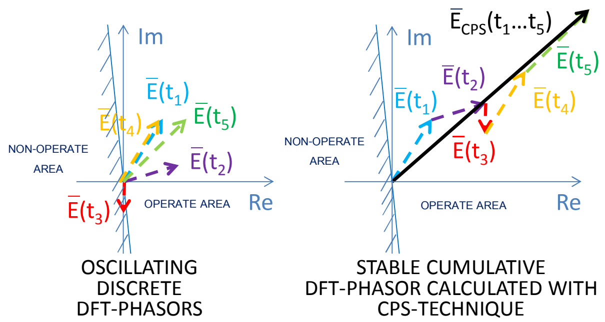

Fig. 2 *Illustration of the cumulative phasor-summing concept in case of unstable inside fault.*

Phasor $\overline{E}_{CPS}$ can be any phasor representing the fault direction e.g. current, power, impedance or admittance phasor. The start and end criteria for summing, time instances t_{start} and t_{end}, are determined based on the general fault detection criterion, which is typically the residual over-voltage condition, U_o>. The accumulation process shall be executed at sufficiently frequent intervals, e.g. at every 2.5 ms (400 Hz) in order to catch also the phasors representing the fault ignition transients as well as possible. The *CPS* provides continuous directional evaluation, which can be re-initiated during a sustained earth fault by resetting the phasor accumulation at regular intervals or by via external signal. This is advantageous, e.g. during fault location process, in cases where only alarming protection is used.

When *CPS* is applied into multi-frequency neutral admittance measurement, ***Eq. 1***, the next equation is valid:

$$\bar{Y}_{osum\_CPS} = \sum_{i=t_{start}}^{t_{end}} \mathrm{Re}\left[\bar{Y}_o^1(i)\right] + j\cdot \sum_{i=t_{start}}^{t_{end}} \mathrm{Im}\left[\bar{Y}_o^1(i) + \sum_{n=2}^{m}\bar{Y}_o^n(i)\right] \quad (3)$$

The directional phasor calculated by the *CPS* technique gives a very distinct and stable indication of the fault direction as the accumulated fault phasor points towards the direction of the highest energy flow, i.e. in the fault direction. When the harmonic components are also taken into account, the fault direction becomes even clearer as the directional phasors in the faulty and healthy feeders point into fully opposite directions as in case of an unearthed network, regardless of network's actual compensation degree. This ensures selective operation, i.e. only the faulted feeder becomes tripped. The risk for false tripping of the healthy feeder is non-existent due to the large margin between the resulting operation trajectory and the operating sector boundary lines.

Another advantageous feature of the *CPS* technique is the ability to give a meaningful amplitude estimation of the operate quantity also in case of transient or intermittent faults when the residual quantities are highly distorted and contain non-fundamental frequency and non-periodic components. The directional element of the novel algorithm based on $\bar{Y}_{osum\_CPS}$ is additionally supervised with the magnitude condition, which is achieved by calculating the quotient of two fundamental frequency *CPS* quantities in phasor format:

$$\bar{E}_{stab} = \frac{\bar{E}_{CPS1}}{\bar{E}_{CPS2}} = \mathrm{Re}\left[\bar{E}_{stab}\right] + j\cdot \mathrm{Im}\left[\bar{E}_{stab}\right] \quad (4)$$

When $\bar{E}_{CPS1}$ and $\bar{E}_{CPS2}$ are the cumulative residual current and residual voltage phasors, their quotient $\bar{E}_{stab}$ represents the "stabilized" neutral admittance, $\bar{Y}_{ostab}$, which can easily be converted into the corresponding current value [4]. The result converges to a quantity which is equivalent to the steady-state, non-cumulative value with a clear physical meaning. This is demonstrated in ***Fig. 3*** with a computer simulation, where a fault is first intermittent and then becomes permanent. In the bottom subplot, the real-parts of the operate quantity are presented using the *CPS* technique and traditional DFT-phasor calculation. It can be seen that ***Eq. 4*** provides results matching the correct steady-state information already during the fault's intermittent phase.

FIELD TESTING AND EXPERIENCE

In recent years, *ABB Oy, Distribution Automation, Finland* has undertaken intensive field testing in co-operation with some power utilities in order to test and develop new earth-fault protection functions. The proposed algorithm has been intensively tested with actual disturbance recordings representing a wide variety of network and fault conditions.

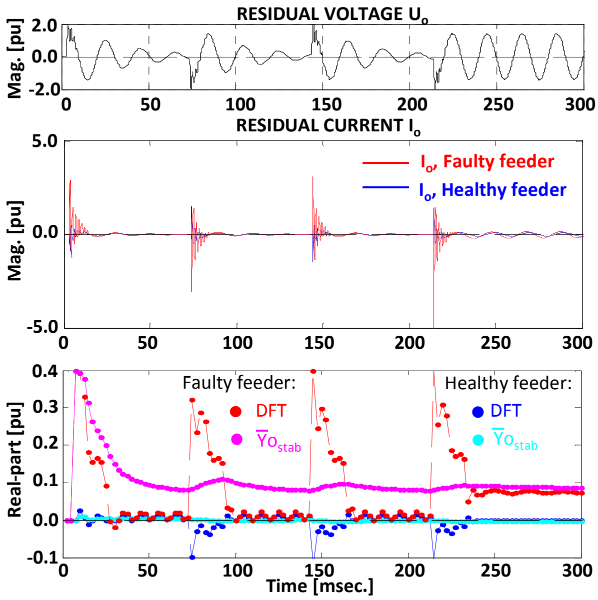

Fig. 3 *Estimation of real part of operate quantity with discrete DFT in comparison with the cumulative summing technique.*

In the following, one field test series is studied. These tests were made in a 10 kV HV/MV-substation owned by *Vattenfall* and located in Sweden. The network represents a large cable network with central and distributed compensation. ***Fig. 4*** shows the most important network parameters from the earth-fault protection perspective. The monitored feeders are denoted as *L131…L138*. The distributed compensation coils are located at the feeders *L131*, *L134* and *L135*. In the following some of the most challenging test cases are presented.

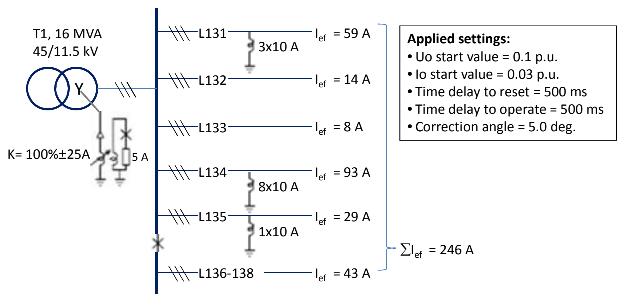

Fig. 4 *Parameters of the studied network and settings of multi-frequency neutral admittance protection.*

An intermittent earth fault in the end of the feeder *L134* at the distance of 30.1 km from the substation is presented in ***Fig. 5***. The challenge in this test case, in addition to the fault's intermittent type, is the low amplitude and low frequency of the fault transients measured at the substation due to the network parameters and considerable fault distance. This may endanger the correct operation of the traditional protection algorithms, especially if purely transient based algorithms are applied. It can be seen that the novel algorithm provides a very secure operation: both the amplitude of the operate quantity and the phase angle of the directional phasor is very stable and the oscillations are effectively filtered out.

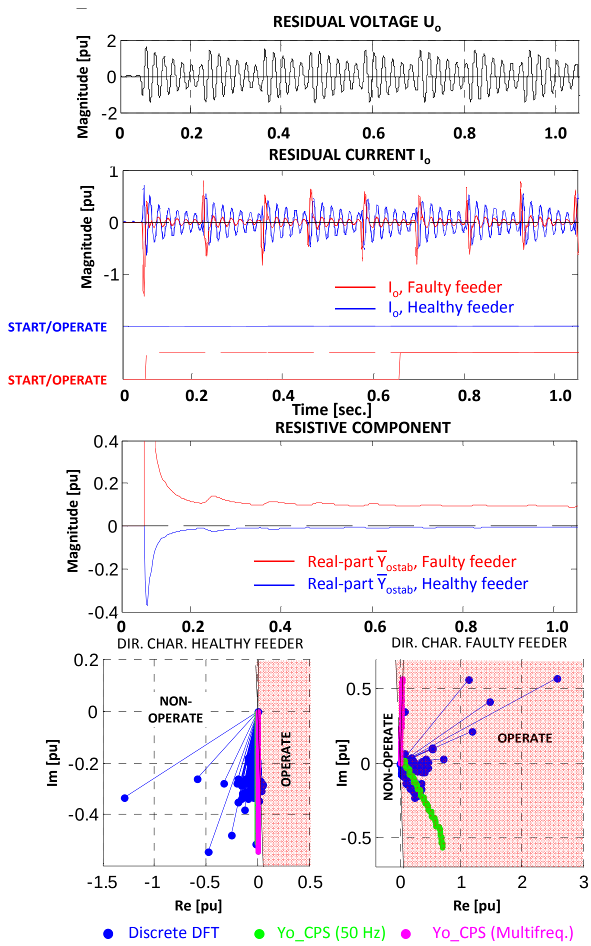

Fig. 5 Intermittent earth fault at the end of the feeder *L134*.

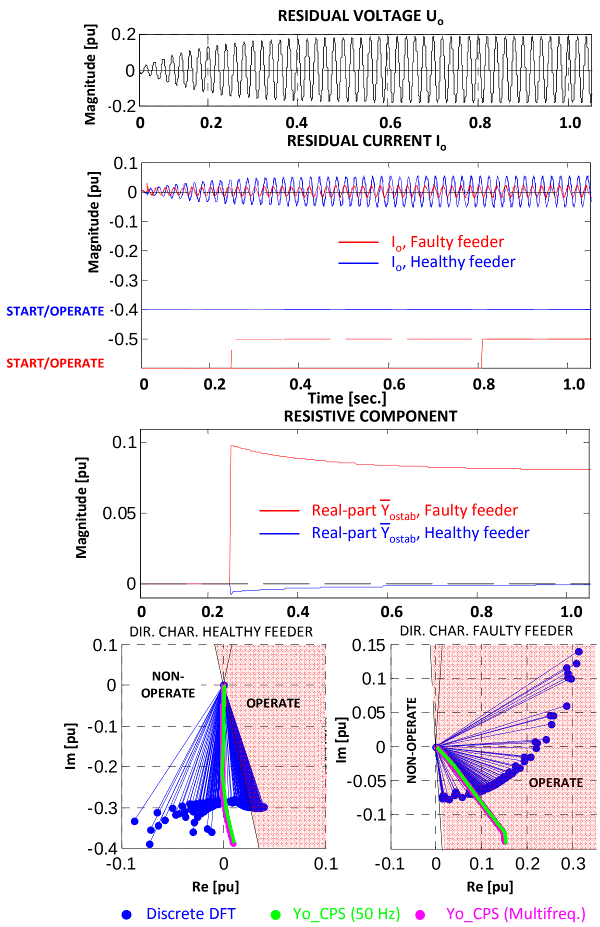

Fig. 6 Earth fault with 4 kohm fault resistance at the end of the feeder *L134*.

In ***Fig. 6*** a permanent earth fault at the end of the feeder *L134* with fault resistance of 4000 ohm is presented. The high fault resistance value results in very low measured residual quantities, which challenge the sensitivity of earth-fault protection. In this test case, the fault quantities increase very slowly to the steady-state value, which makes the traditional fundamental frequency DFT-phasor to oscillate. However, the novel algorithm provides very secure fault detection despite this phenomenon. The amplitude of the measured operate quantity, i.e. the resistive part of $\overline{Y}_{ostab}$ -phasor, is not affected by the fault resistance. After the conversion from admittance to current, it corresponds to the value of the parallel resistor of the central compensation coil (5 A) added by the losses of the network, resulting totally ~8 A of resistive current.

CONCLUSIONS

This paper described a novel and patented solution for earth-fault protection in compensated MV-networks. With a single function, a complete solution for earth-fault protection can be established. The novel function is based on the patented concept of Cumulative Phasor Summing, *CPS*, in combination with the multi-frequency neutral admittance measurement.

The performance of the novel function has been validated using actual disturbance recordings from a system, which presents "tomorrows" rural distribution network and a truly challenging environment for today's earth-fault protection functions. The results show that the proposed algorithm can greatly improve the earth-fault protection performance compared with traditional earth-fault protection solutions. The first version of the algorithm has already been implemented into ABB *REF615* IED, a member of the ABB's *Relion®* product family. In the future, authors wish to study the application of the presented novel method into other applications, such as high-impedance fault detection.

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