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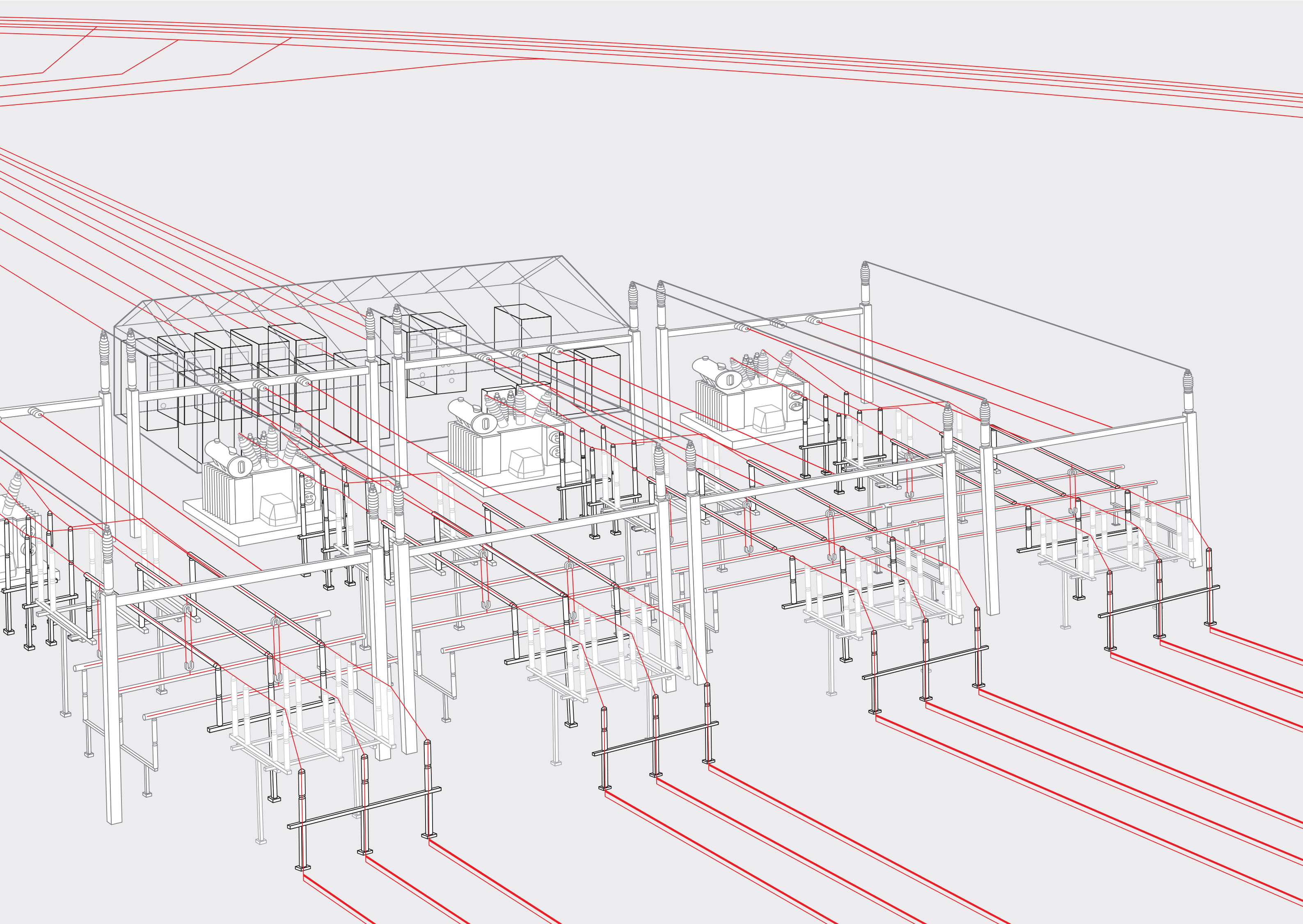
Application of Novel Multi-frequency Neutral Admittance Method into Earth-Fault Protection in Compensated MV-networks



Application of Novel Multi-frequency Neutral Admittance Method into Earth-Fault Protection in Compensated MV-networks

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Keywords: Compensated networks, earth fault, transients, intermittent/restriking earth fault, neutral admittance.

Abstract
This paper describes a novel algorithm for feeder earth-fault protection applicable in compensated and unearthed medium-voltage networks. The suggested algorithm provides good protection sensitivity and very secure discrimination between faulty and healthy feeders even in the most challenging faults with highly distorted signals such as restriking earth faults. The operation of the novel method is based on multi-frequency neutral admittance measurement in combination with cumulative phasor summing technique. In the paper, first the theory and operation of the novel algorithm is described. Secondly, the advantages and features brought by the novel method are demonstrated with variety of different fault types. The results show that the novel algorithm provides universal, all-in-one protection function that detects selectively all types of earth faults. Also the overall security and dependability of the existing protection schemes can be improved by the novel method, which can be applied either in tripping or alarming mode depending on the application.

Part 1. Introduction

The demand for the quality and reliability of supply is constantly rising as society is becoming more and more dependent on continuous electricity supply. In order to improve the quality and availability of the supply, resonant earthing has become increasingly common practice in neutral point treatment of medium-voltage networks worldwide. In such compensated networks the self-extinguishing nature of fault arcs is the main factor facilitating improved power quality. Compensation also allows continuation of network operation during a sustained earth fault, assuming the conditions for hazardous voltages set by legislation and regulations are met.

Although compensation delivers operational benefits, earth-fault protection of the network becomes more complicated. Based on experience and in-depth analysis of numerous disturbance recording, earth faults in compensated networks have very often an intermittent characteristic. This means that the fault self-extinguishes very rapidly, but then re-ignites again due to reduced dielectric withstand level of damaged insulation in the fault spot. Such faults are typically low-ohmic and must be reliably detected by the protection. On the other hand, especially in mixed networks with cable and overhead-line sections, possibility for high-ohmic earth faults exists and protection must also be sensitive enough to detect such faults.

There is a large variety of different protection methods applied in protective relays in order to detect and locate earth faults in compensated networks. Based on the operation principle, the methods can be coarsely classified as follows:

1. Fundamental frequency based methods
2. Harmonic components based methods
3. Transient components based methods

Based on their operation principle, it can be concluded that application of each method is limited to certain fault type and fault characteristics. Methods based on fundamental frequency components are generally used to fulfil the sensitivity requirements of protection set by legislation. They operate correctly in case the fault signals have a clear fundamental component and characteristic. But they may fail in case the fault has transient characteristic or the signals are rich with harmonics and non-sinusoidal content. Application of methods utilizing steady-state harmonic components is limited due to the fact that harmonic content of fault signals varies in accordance with the harmonics source(s) and may even be time-dependent. The methods utilizing transient components are typically based on measuring the charge transient of the healthy phases due to earth fault. Such transient based methods are capable in detecting steady-state low-ohmic earth faults and also restriking and intermittent earth faults manifested as adequate single or multiple transients for detection. As transients are greatly attenuated due to fault resistance the sensitivity of transient based methods in terms of fault resistance becomes very limited. Also physical fault distance may introduce a significant damping effect to transients. An example of this is illustrated in Figure 1, which shows a result from field tests conducted by the authors. A high damping of transients was observed when the fault spot was moved into the end of a long rural cable feeder (approximately 30 km from the substation). Furthermore, switching transients superimposed into fault signals may result in incorrect operation of transient based protection. Such situation may occur when closing the feeder circuit breaker onto fault during fault location process or during unsuccessful auto-reclosing sequence. Finally, in permanent low-ohmic earth faults only the initial transient due to fault inception can be detected, which makes the application of pure transient based methods obsolete during manual fault location operations in case alarming mode of protection is used.

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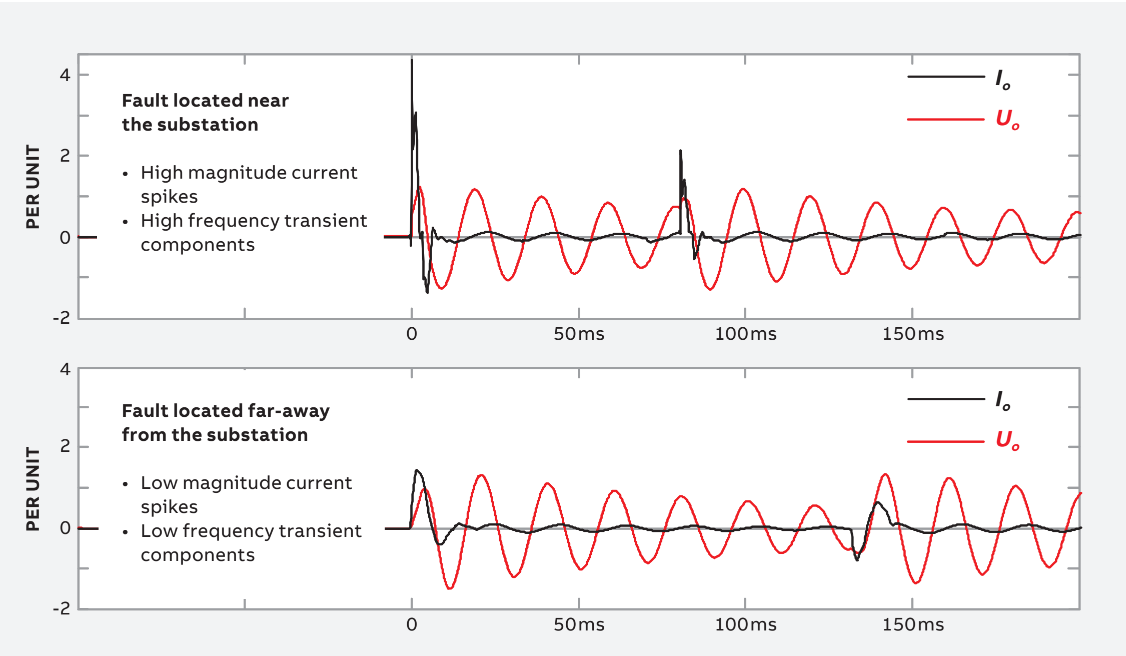
Figure 1: Damping of fault transients due to fault location.



Indeed, due to multitude of different earth-fault types that may occur in practice, earth-fault detection and directional determination in compensated distribution systems are two the most challenging and important tasks taken on by protective relays. It is clear that in order to fulfil the requirements for sensitivity, dependability and security, different protection functions must be used in parallel in order to provide a complete protection scheme. Such practice is typical today, and it necessitates careful consideration and planning, and introduces additional complexity to the protection scheme.

This paper describes a novel algorithm that provides a solution to the previously described challenges. With a single function all types of earth faults can be detected selectively.
The fundamental novelty of the algorithm is that the discrete phasors of voltages and currents 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 behaviour in cases where the residual quantities are highly distorted and contain non-fundamental frequency components. This technique is therefore especially well-suited for compensated networks where phenomena characterized by such measurement signals may frequently occur. Another novelty of the algorithm is the utilization of harmonics in fault signals in form of multi-frequency admittance measurement. With the novel algorithm, the problem of distorted signals can be turned into a favourable situation from protection perspective. The sensitivity of the algorithm is set with a simple 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, which must be considered in setting of the $U_o>$-condition. A further advantage of this approach is that the practical implementation of the algorithm into modern IEDs is easy as standard development platform and low sampling frequency can be applied.

Part 2. Multi-frequency admittance measurement

In reference [1] a multi-frequency neutral admittance based algorithm was described in which 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, applicable for directional evaluation of an earth fault, is:

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

Where $\overline{Y}_o^1 = \overline{I}_o^1 / -\overline{U}_o^1$ 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 measurable by the IED (in terms of I_o and U_o this is around 0.5% of the nominal value).

In Equation (1) the harmonics are used to improve the security of the fault directional determination, but it is also valid in case of higher ohmic earth fault as the fundamental frequency component is always utilized. 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. For the harmonic components the admittance phasors in the faulty and healthy feeders point into fully opposite directions as in case of an unearthed network, regardless of the network's actual compensation degree.

The practical challenge with state-of-art harmonic based protection functions is that due to their origin, harmonic shares 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 restriking earth fault. This may result in uncertainty and inaccuracy of operation, and great difficulties in calculating setting values. In addition, as higher frequency components are greatly attenuated by fault resistance, the application of a purely harmonic based protection function is limited to very low-ohmic earth faults. The complete earth fault protection scheme then always requires additional protection function(s) in order to fulfill the sensitivity requirements.

In order to overcome the problems of traditional fundamental frequency, harmonic and transient based methods in earth fault protection, and to stabilize the operation during intermittent/restriking earth faults, a novel concept of Cumulative Phasor Summing (CPS) was introduced by the authors in reference [2]. The suggested method applies DFT-phasor 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 components. Even transient and earth faults with current spikes of very short duration can be detected reliably thanks to the anti-aliasing filtering prior to phasor calculation, which increases their duration, making them detectable after sampling.

Part 3. Cumulative Phasor Summing (CPS)

3.1 Application of CPS to directional evaluation

The concept of Cumulative Phasor Summing (CPS) is very easy to understand and straightforward to implement. CPS 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}. This is illustrated in Figure 2, where the sum admittance phasor $\overline{Y}_{osum}$ is used in CPS-calculation and applied for directional evaluation.

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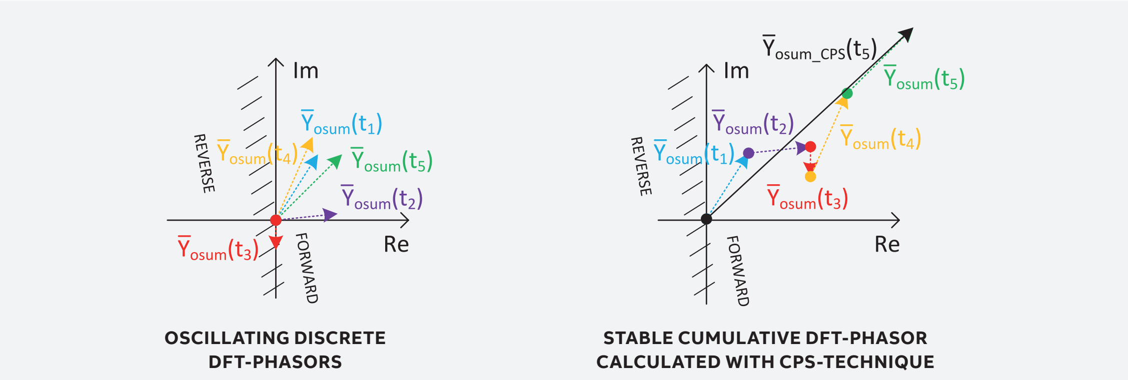
Figure 2: Illustration of the cumulative phasor summing concept (faulted feeder).



When CPS-algorithm is applied into multi-frequency neutral admittance measurement, the Equation (2) is valid:

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

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>. In order to keep the CPS activated between fault transients during a restriking fault, phasor accumulation is continued with user settable reset delay time, which should be set to a value exceeding the maximum expected time interval between the fault transients (obtained at full resonance condition). The accumulation process shall be executed at sufficiently frequent intervals, e.g. at every 2.5 ms (400 Hz) in order to catch the phasors representing the fault ignition transients as well as possible.

The directional phasor calculated by the CPS-technique, Equation (2), gives a very distinct and stable indication of the fault direction as the accumulated sum admittance phasor points always towards the direction of the highest energy flow, i.e. in the fault direction. In case the fault signals contain harmonic components, 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 advantage of the CPS-algorithm is that it provides stable directional phasor quantity despite of the fact that discrete phasors may vary greatly in magnitude and phase angle in time due to unstable fault type such as restriking/intermittent earth fault. This is also true for harmonic components, which may have a highly time-dependent character.

For this protection function, the directional characteristic as shown in Figure 3 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. The characteristic tilt angle should reflect the measurement errors of CT and VT i.e. the larger the measurement errors are, the larger the tilt angle-setting should be. In Figure 3, the following phasors are depicted:

- Phasor 1 depicts the direction of accumulated sum admittance phasor in case of earth fault outside the protected feeder (assuming that the admittance of the protected feeder is dominantly capacitive). The result is valid regardless of fault type (low ohmic, high(er) ohmic, permanent, intermittent/restriking). In case harmonic components are present in the fault quantities, they would turn the phasor to align the negative $\mathrm{Im}(\overline{Y}_o)$-axis.

- Phasor 2 depicts the direction of accumulated sum admittance phasor in case of earth fault inside the protected feeder when the network is unearthed. The result is also valid in compensated networks when there are harmonic components present in the fault quantities (typically low ohmic permanent or intermittent/restriking fault). In this case the result is valid regardless of network's actual compensation degree. Harmonics would turn the phasor to align the positive $\mathrm{Im}(\overline{Y}_o)$-axis.

- Phasors 3 and 4 depict the direction of accumulated sum admittance phasor in case of higher-ohmic earth fault in the protected feeder without harmonics in the fault quantities when the network is compensated. As there are no harmonic components present, the phase angle of the accumulated phasor is determined by the compensation degree of the network. With high degree of overcompensation, the phasor turns towards the negative $\mathrm{Im}(\overline{Y}_o)$-axis (as phasor 4).

The CPS-algorithm provides continuous directional evaluation, which can be re-initiated during a sustained earth fault by an external signal. Additionally, in parallel to the directional evaluation of the function a cyclically reset and restarted CPS is calculated during the fault. If the fault direction based on this cyclic directional evaluation is opposite to the function's direction output, the function is reset and fault direction calculation is restarted. This way the fault direction determination can be adapted to possible fault direction changes during the fault. This is advantageous in alarming mode of operation, when fault location is done by manual switching operations during a sustained earth fault.

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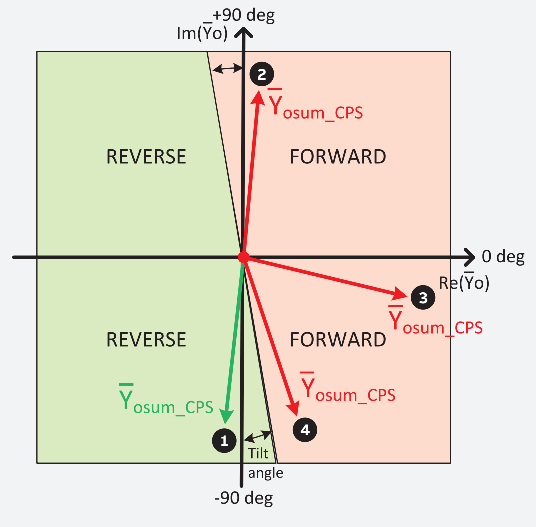
Figure 3: Behaviour of the directional phasor in relation to the operation characteristics of the novel method.



3.2 Application of CPS to current magnitude estimation

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. 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:

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

The calculation result, the stabilized neutral admittance, converges to the result, which equals the steady-state, noncumulative value with a clear physical meaning. Detailed explanations of measurement results of admittance based protection during inside and outside faults can be found from reference [1].

This stabilized admittance value can be converted into corresponding current value by multiplying it with system nominal phase-to-earth voltage value [3]:

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

The operate current value given by Equation (4) matches the correct steady-state information, and in practice 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. This is demonstrated in Figure 4, which shows results from field tests conducted by the authors. Three different fault types are compared (from left to right): permanent low ohmic fault, restriking low ohmic fault and permanent higher ohmic fault. In the bottom subplot, the real-parts of the operate current are calculated using CPS-technique in combination with fundamental frequency neutral admittance calculation, Equation (4). It can be seen that the estimated current values match each other very closely, regardless of the fault type or fault resistance value. In the algorithm, the resistive part of the stabilized current is used as the operation quantity to supervise the directional determination. Due to admittance based calculation, in case of fault inside the protected feeder, the value of $I^{1}_{oCosstab}$ is positive and the magnitude corresponds to the value of the parallel resistor of the coil added by the losses of the network. On the other hand, in case of outside fault, the value of $I^{1}_{oCosstab}$ is negative and the magnitude corresponds to the resistive shunt losses of the protected feeder. However, due to the inaccuracies in voltage and current measurement, this value may appear as positive, which should be considered in the current threshold setting.

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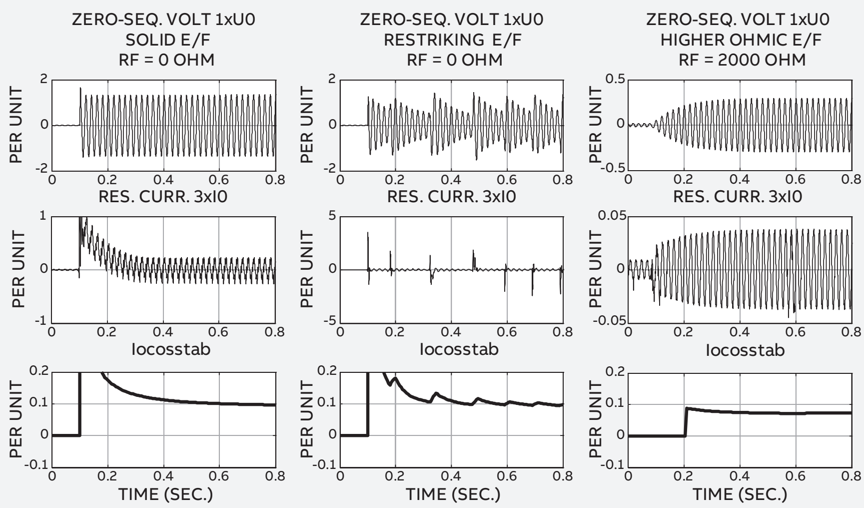
Figure 4: Estimation of real part of the operate quantity with the cumulative summing technique.



Part 4. Validation of operation

The proposed algorithm has been intensively tested with actual disturbance recordings representing a wide variety of network and fault conditions. In the following, the operation of the novel algorithm is analysed with typical fault types occurring in compensated networks in practice. In the figures, the phase angle of directional quantity $\underline{Y}_{osum\_CPS}$ is presented together with the estimated resistive part of the operate quantity $I^{1}_{oCosstab}$. The operate sector boundary lines located at -85deg. and +95deg. (tilt angle of 5 degrees) are marked into phase angle subplots. For comparison, the directional and operate quantities of a standard 50Hz DFT-phasor based protection method are also shown (denoted as IoDFT).

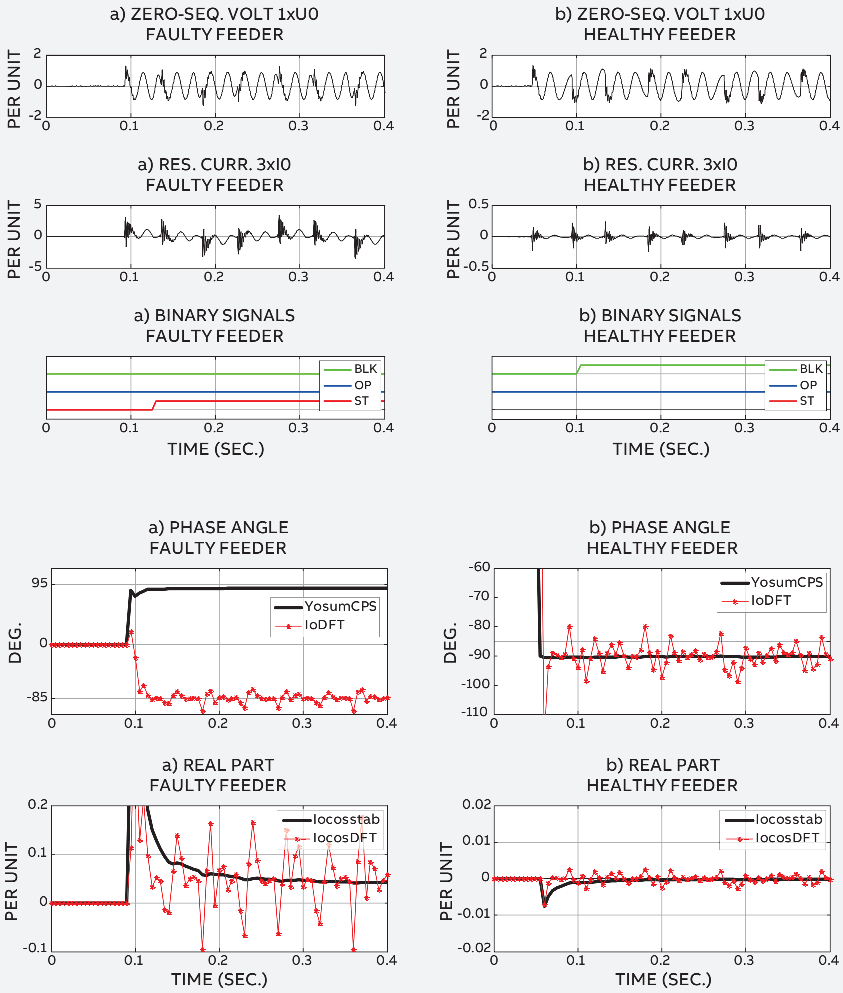
4.1 Restriking earth faults

Restriking faults are the most common type of permanent earth faults in compensated networks. These faults have generally broad frequency content and they are often low ohmic. They are formed by succession of self-extinguishing faults, where the time duration between recurring re-ignitions is typically in the order of few tens to some hundreds of milliseconds. Restriking fault creates highly non-sinusoidal and irregular voltage and current waveforms, which conventional fundamental frequency based methods are not designed for.

In Figure 5 a first type of an restriking earth fault is presented. In this case the re-ignition occurs in time interval of approximately every 50 ms. As a further challenge, each fault transient has a very high frequency content and oscillatory nature. Such waveform is known to be problematic fortransient based protection functions, especially “classical” polarity comparison based methods.

It can be seen that the novel algorithm provides very secure fault direction determination despite the highly distorted signals and it is not negatively affected by the high frequency components. On the contrary, utilization of harmonic components make the directional phasors in the faulty and healthy feeders point into fully opposite directions (+90/-90 deg.) as in case of an unearthed network, regardless of network’s actual compensation degree. Also a stable estimate for the resistive part of operate quantity can be obtained with the novel algorithm, which is used as an additional criterion to ensure selective operation of protection. In the healthy feeder, BLK-signal indicates that the fault is outside the protected feeder i.e. in reverse direction. In this case the phase angle of the standard DFT-based method oscillates around the boundaries of operate characteristic resulting in risk of unselective operation of protection.

Figure 5: Restriking earth fault with high frequency components.



In Figure 6 a second type of restriking earth fault is presented. In this case, the fault is located in the end of a long cable feeder at the distance of 30.1 km from the substation. The additional challenge in this test case is the low amplitude and frequency of the fault transients, which may endanger the correct operation of pure transient based methods. The damping is due to considerable fault distance and both the network and feeder characteristics. For standard DFT-based method both the directional and operate quantities are very unstable resulting in unreliable operation of protection. However, the novel algorithm benefits from the harmonic components and provides very secure and selective fault detection: both the directional and operate quantities are very stable and the oscillations are effectively filtered out.

4.2 Temporary earth faults

Temporary earth fault is characterized by single or few arc transient(s), which have the ability to self-heal. For temporary earth faults it is neither necessary nor desirable to trip the circuit breaker at the substation.

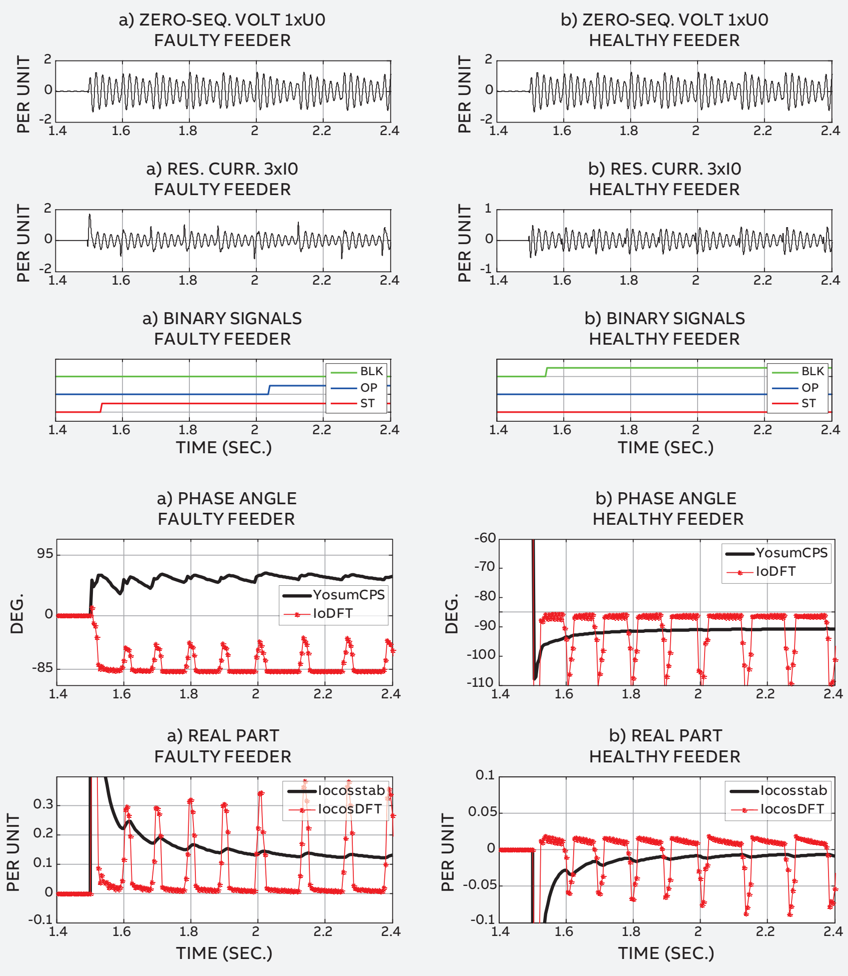


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Figure 6: Restriking earth fault with damped transients.

In Figure 7 three different types of temporary earth faults with different characteristics are presented. The two first ones (from left to right) include initial transient components with high frequency content, which would need a transient based method to be detected. The third temporary fault type has different, mainly fundamental frequency characteristic. Such fault type cannot be detected by transient methods, and would need a fundamental frequency based method to be detected. Despite the different waveforms and frequency contents of the signals, correct fault detection can be obtained with the novel algorithm. Selective detection of such faults can be used for preventive maintenance purposes and for example to give an alarm of gradually developing or latent insulation failures. This would give the possibility for the utility personnel to locate the fault before it would evolve in a more severe permanent fault resulting in customer outages.

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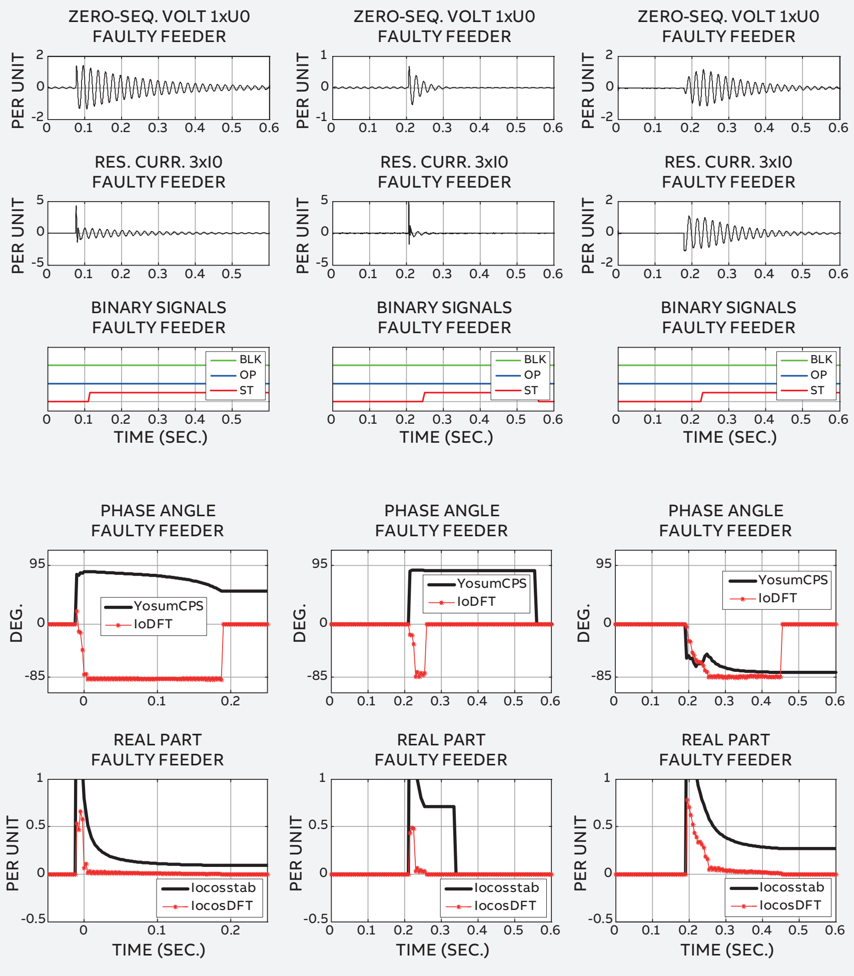
Figure 7: Three examples of temporary earth faults located in the protected feeder.



4.3 Permanent earth faults

In Figure 8 results for permanent earth faults located at the protected feeder with three different fault resistance values (0, 500 and 5500 ohm) are presented. Again, the novel algorithm provides very secure fault detection, regardless of fault resistance value.

In case of solid earth fault (R_F = 0 ohm), the utilization of harmonic components makes the directional phasor of the novel method to behave as in case of an unearthed network (angle of +90 deg.). With higher fault resistance values harmonics are dampened and thus the phase angle of the fault directional phasor given by the novel method matches the results from the fundamental frequency based method. It is important to notice, that due to admittance based operation, the resistive part of the operate quantity of the novel method is not affected by the fault resistance value. In each case it corresponds to the value of the parallel resistor of the central compensation coil added by the losses of the network.

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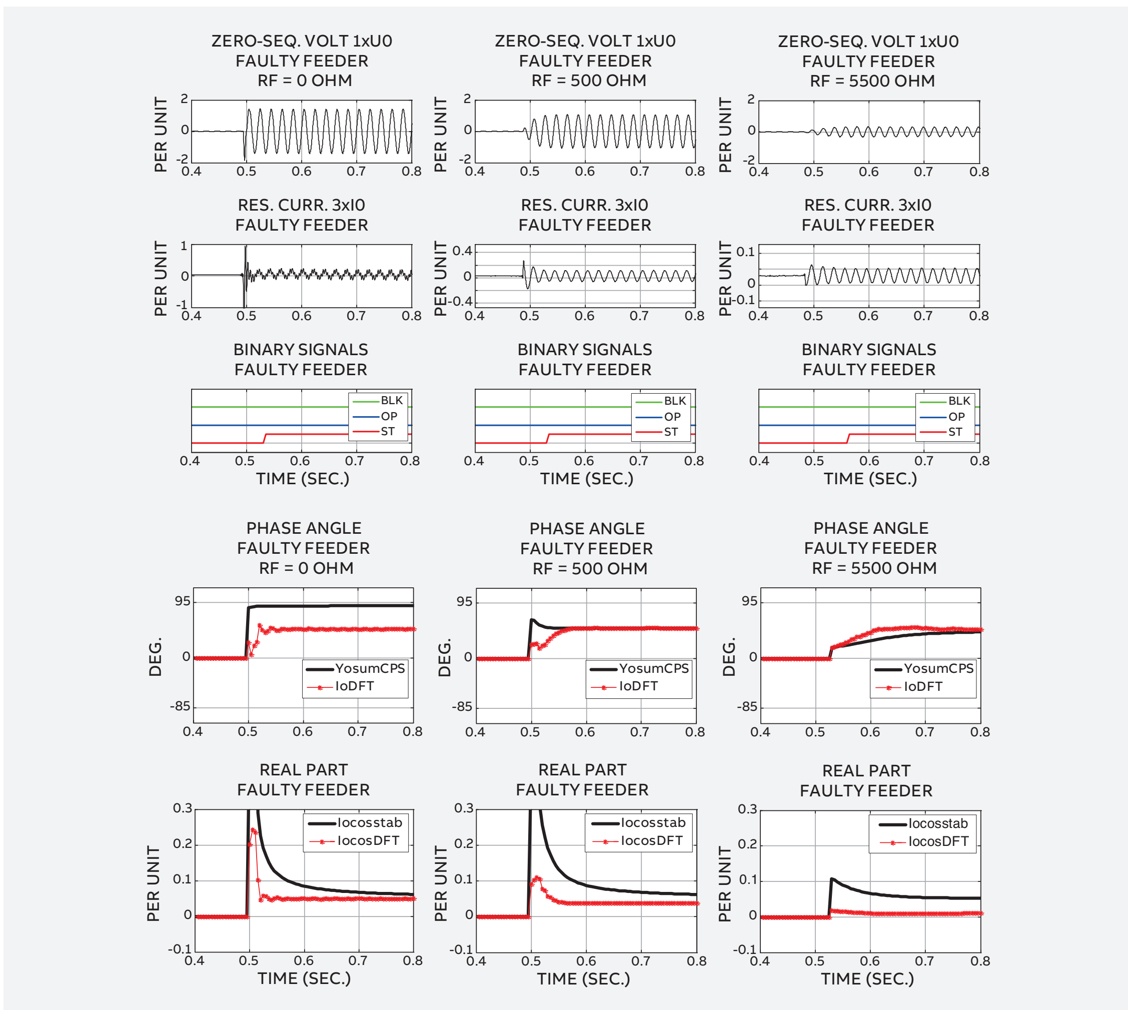
Figure 8: Permanent earth fault with fault resistance of 0, 500 and 5500 ohm.



Part 5. Conclusions

This paper described a novel and patented solution for earthfault 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 hundreds of disturbance recordings from actual compensated and unearthed networks. The results show that the novel algorithm provides universal, all-in-one protection function that detects selectively all types of earth faults, which greatly improves the overall security and dependability of the existing protection schemes. The algorithm will be implemented in the next generation of feeder terminals targeted to global power distribution and sub-transmission markets.

Acknowledgments
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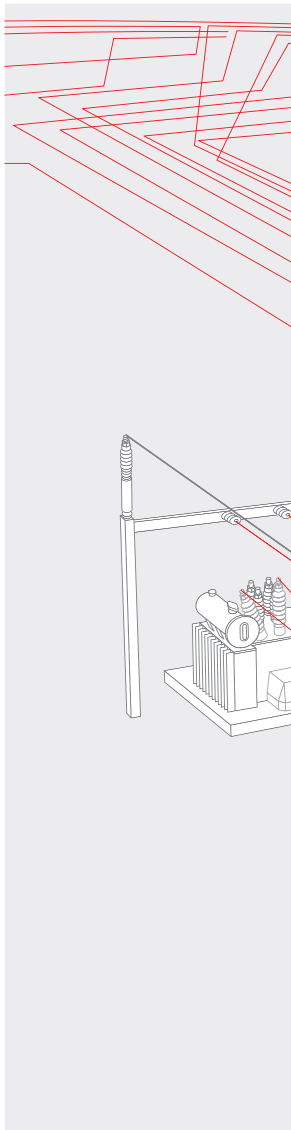

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