Can compensated networks be an alternate solution to reduce the risk of ground faults causing forest fires?

Ari Wahlroos, Janne Altonen, ABB Oy,
ABB Oy, Joe Xavier, ABB Inc, *Member, IEEE*

Abstract: **Ground faults are the most common type of fault in a distribution network. The current seen by the protection relay during a ground fault event largely depends on the impedance of the fault circuit and applied system grounding principle. Therefore, detecting a ground fault effectively and accurately becomes challenging under certain circumstances. A small percentage of ground faults have a very large impedance. They are comparable to load impedance and consequently have very little fault current. These high-impedance faults do not pose imminent danger to power system equipment. However, they are a substantial threat to human beings and properties; people can touch or get close to conductors carrying large amounts of energy. Such 'wire down' faults have resulted in causing wild forest fires in some parts of the world with large scale devastation of vegetation and property.**

There are various technologies available, which can limit the amount of energy released when a ground fault occurs and thus reduce the risk of fire ignition. This paper studies the properties of resonant grounding, also known as compensated networks, which is the prevailing technology globally to limit ground fault current magnitude. The paper also discusses a unique approach to detect ground faults based on Multifrequency admittance principle (67YN). 67YN provides selective directional ground fault protection for any high-impedance grounded networks, that is, for compensated, ungrounded and high resistance grounded systems. It can be applied for the ground fault protection of overhead lines and underground cables. The operation of 67YN is based on novel multi-frequency neutral admittance measurement utilizing Cumulative Phasor Summing (CPS) technique. This concept provides extremely secure, dependable and selective ground fault protection in compensated networks.

Key words: Arc suppression coil, compensated network, high impedance fault detection, multi-frequency admittance protection, wildfire mitigation

I. Introduction

Traditionally, distribution electrical systems in North America have been solidly or low resistance grounded. The initial advantages that utilities used to have in these electrical systems have been eclipsed by the challenges they have faced to detect high impedance ground faults.

The goal of this paper is to educate the reader considering changing the grounding of the electrical system to a compensated network to enhance ground fault detection sensitivity. Simultaneously the amount of energy released when a ground fault occurs is reduced, which should lower the risk of fire ignition during 'wire down' faults.

The paper starts by describing the fundamentals of the compensated networks, considerations for converting from a low resistance/solidly grounded system to a compensated network, special protection challenges, and finally describing a new innovative method to detect various types of practical ground faults in a compensated network.

II. Compensated networks

The power system grounding method is the way system neutral is connected to the ground. There are several grounding methods in use globally: ungrounded, solidly grounded, low resistance grounded, reactance grounded, high resistance grounded, and resonant grounded. Resonant grounded networks are also known as Petersen coil grounded networks or compensated networks. Compensated networks have been used by electrical utilities in Europe, Russia, and China for over 30 years. The primary characteristic of a resonant grounded system is that the feeding transformer neutral is grounded through a tunable inductor (Arc Suppression Coil, ASC) to almost completely cancel the capacitive current due to phase-to-ground capacitances of conductors, during a phase to ground fault. The biggest advantage of this system is that momentary ground faults are 'self-cleared' without any supply outages due to the compensation effect of ASC. Due to small fault current also electrical safety is improved. Compensated network may be operated during a sustained ground fault (when electrical safety is ensured), though it must be taken in consideration that single-phase ground fault could develop into a double ground fault (cross-county fault) where it has to be isolated immediately. The disadvantages of compensated networks include the initial cost of a tunable reactor, controller to adjust the inductance of ASC in case of reconfiguration of the system, and a protective relay system capable of detecting low magnitude phase to ground faults. In addition, all electrical components of the system such as cables, insulators, VTs, and arresters have to be rated adequately to withstand the over-voltages equal to phase-to-phase voltages that would appear on the two healthy phases during a single phase to ground fault.

III. Fundamentals of ground fault protection in compensated networks

In this section the basic theory of compensated networks and ground fault phenomenon is explained. A network model utilizing network admittances (neutral and phase-to-ground) is applied to explain the voltages and currents related to ground fault protection in compensated networks. In order to make the analysis easily understandable, all admittances are converted into equivalent current values. Such ampere values are the basic network parameters and component values enabling easy practical application of the analysis and derived equations [1].

A. The equivalent circuit

The fundamentals of ground fault protection and parameters influencing to voltages and current measured by the ground fault protection in compensated networks can be studied with a very simple three-phase equivalent circuit of a distribution network as illustrated in **Figure 1**. The equivalent scheme of the network consists of two feeders, one representing the protected feeder (Fd) and the other one the "background" network (Bg). The background network equivalent represents all the parallel feeders in the substation, which are galvanically connected. The line series impedances are neglected as their values are very small compared with the shunt admittances. Also, the loads and phase-to-phase capacitances are disregarded as they do not contribute to the zero-sequence currents.

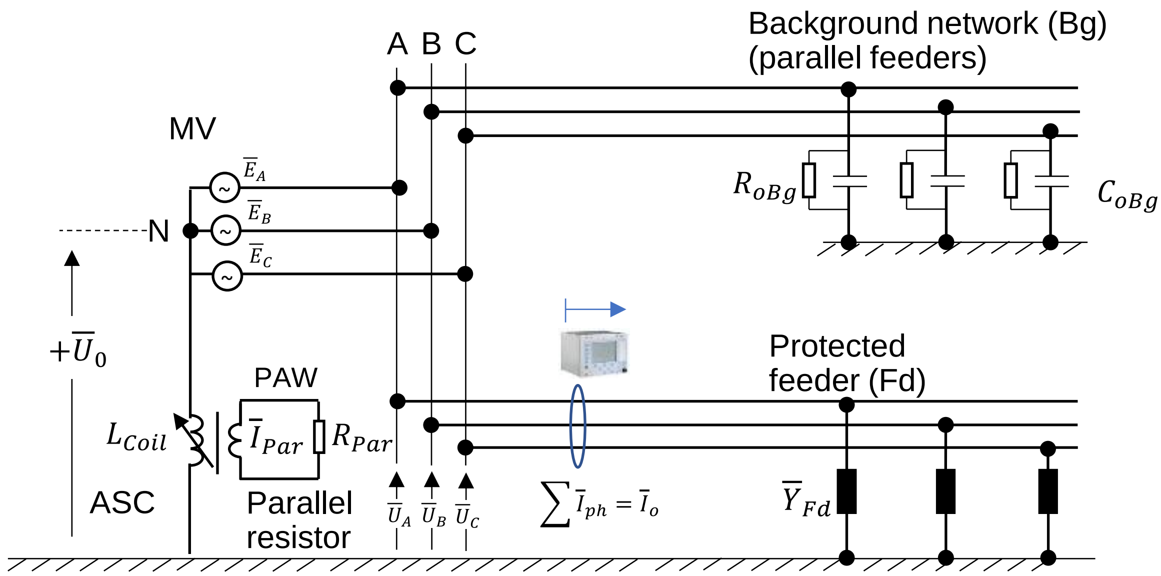

Figure 1 Three-phase equivalent circuit of a compensated distribution network.

1) Modelling of the network and feeders

The phase-to-ground admittances of the network (Net) can be written as follows: The total admittance of the network is the sum of admittances of the protected feeder and the background network:

$$\overline{Y}_{Nettot} = \overline{Y}_{Fdtot} + \overline{Y}_{Bgtot} \tag{1a}$$

The total admittance of the protected feeder (Fd) is the sum of its phase-to-ground admittances:

$$\overline{Y}_{Fdtot} = \overline{Y}_{FdA} + \overline{Y}_{FdB} + \overline{Y}_{FdC} \tag{1b}$$

where the phase-to-ground admittance can be represented as a complex phasor with real and imaginary part:

$$\overline{Y}_{Fd} = G_{Fd} + j \cdot B_{Fd} = \frac{1}{R_{oFd}} + j \cdot \omega \cdot C_{oFd} \tag{1c}$$

R_{oFd} is the phase-to-ground shunt resistance of the feeder due to shunt losses [Ω], C_{oFd} is the feeder phase-to-ground capacitance per phase [F].

Numerical value for the total admittance of the protected feeder can be obtained from basic network parameter data:

$$\overline{Y}_{Fdtot} = \frac{I_{EFFd}}{U_{PE}} \cdot (d_{Net} + j \cdot 1) \tag{1d}$$

U_{PE} is the operating phase-to-ground voltage [V], I_{EFFd} is the capacitive ground fault current produced by the feeder [A], d_{Net} is a factor [pu] to approximate the natural losses of the feeder/network, typical value is between 0.01…0.10. Note that positive imaginary part in **Equation 1d** assumes that feeder admittance is capacitive. Negative imaginary part would be possible if there would be a distributed compensation coil located in the feeder, whose inductive current would exceed the capacitive current due to the phase-to-ground capacitances.

For the background network (Bg) similar equations are valid. The total admittance of the background network is the sum of its phase-to-ground admittances:

$$\overline{Y}_{Bgtot} = \overline{Y}_{BgA} + \overline{Y}_{BgB} + \overline{Y}_{BgC} \tag{1e}$$

where the phase-to-ground admittance can be represented as a complex phasor with real and imaginary part:

$$\overline{Y}_{Bg} = G_{Bg} + j \cdot B_{Bg} = \frac{1}{R_{oBg}} + j \cdot \omega \cdot C_{oBg} \tag{1f}$$

R_{oBg} is the phase-to-ground shunt resistance of the background network due to shunt losses [Ω], C_{oBg} is the phase-to-ground capacitance per phase of the background network [F].

Note that positive imaginary part in **Equation 1f** assumes that background network admittance is capacitive. Negative imaginary part would be possible if there would be distributed compensation coils located in the parallel feeders, whose inductive current would exceed the capacitive current due to the phase-to-ground capacitances.

Numerical value for the total admittance of the background network can be obtained from the basic network parameter data, knowing that the admittance of the background network is obtained by subtracting the total admittance of the protected feeder from the total network admittance:

$$\overline{Y}_{Bgtot} = \overline{Y}_{Nettot} - \overline{Y}_{Fdtot} = \frac{(I_{EFNet} - I_{EFFd})}{U_{PE}} \cdot (d_{Net} + j \cdot 1) \qquad (1g)$$

I_{EFNet} is the capacitive ground fault current of the whole network [A].

The I_{EFFd} and I_{EFNet} value in DMS-system assumes a full symmetry of the network, meaning that phase-to-ground admittances of all phases have equal value:

$\bar{Y}_{Fd} = \bar{Y}_{FdA} = \bar{Y}_{FdB} = \bar{Y}_{FdC}$ and

$\bar{Y}_{Bg} = \bar{Y}_{BgA} = \bar{Y}_{BgB} = \bar{Y}_{BgC}$.

In practice, the network admittances are dominantly capacitive as they are due to the phase-to-ground capacitances of the electrical conductors: overhead lines and underground cables. **Table 1** compares the phase-to-ground capacitance values of MV-overhead line and underground cables (f_n=50Hz).

Table 1 Phase-to-ground capacitance comparison between a 20kV overhead line and cable.

Conductor type	C_0 [uF/km]	Ground fault current [A/km] $I_{EF} = \sqrt{3}\cdot\omega\cdot C_0\cdot 20kV$	Ratio of ground fault currents@20kV: cable vs. OH-line
Overhead line	0.0061	0.07A	1.00
Cable 3x70mm^2	0.18	1.96A	29.5
Cable 3x120mm^2	0.23	2.50A	37.7
Cable 3x185mm^2	0.26	2.83A	42.6
Cable 3x240mm^2	0.30	3.26A	49.2

From **Table 1** it can be concluded that the phase-to-ground capacitance of an underground cable is ten folds larger than that of an overhead line. Depending on the exact type of an underground cable, the phase-to-ground capacitance and thus its capacitive ground fault current contribution may be more than fifty times larger than that of an overhead line. Therefore, the capacitive ground fault current produced by an underground cable network is significantly larger than that of an overhead line network. If MV-overhead lines are replaced with underground cables by tens of kilometers, then the capacitive ground fault current of the whole network or even a single feeder may be easily increased to hundreds of amperes.

In practice, the network admittances are however not ideal capacitances, due to practical resistive shunt losses, which are always present. The total shunt losses are known as the network damping, which is due to shunt losses of conductors, losses of the ASC and losses introduced by parallel resistor (if applied). The resistive shunt losses of conductors and isolators are typically only a few percent from the capacitive component (parameter d_{Net}). Especially in underground cable networks with short cables, the natural resistive component may be very small due to the good insulation materials (low *tan*δ-value) used in modern cables. The sufficient network damping is however important as ASC together with network phase-to-ground capacitance creates a parallel resonance circuit. Especially during resonance condition sufficient amount of damping is needed to provide damping to the oscillations and transients during faults and after their disconnection. Damping is seen in measured zero-sequence currents as resistive component and it is needed to secure dependability of the ground fault protection. When the network natural losses are not sufficient, then the magnitude of resistive component may be intentionally increased. This is typically accomplished with a resistor in parallel to the ASC increasing the resistive component of measured zero-sequence current in the beginning of the faulty feeder. It should be noted that network damping due to natural shunt losses of conductors, losses of the ASC and losses introduced by parallel resistor are not compensated by the inductive ASC. Thus, the increased damping increases also the actual ground fault current at the fault location. Damping also affects ground fault detection sensitivity by decreasing the magnitude of zero-sequence currents and voltages during ground faults with fault resistance as described later in this paper.

2) *Modelling of Arc Suppression Coil (ASC)*

In compensated systems, the neutral point of main substation transformer(s) is grounded through a tunable high impedance reactor, known as the Petersen coil or Arc Suppression Coil (ASC). The inductive current of the coil limits the ground fault current magnitude by cancelling the capacitive current of the network at the fault location. Due to the fact that inductive and capacitive currents are in phase opposition, the ground fault current at fault location is greatly reduced due to the compensation effect of the coil.

The compensation coil may be installed directly to the main transformer's neutral point if technically possible, or it may be installed at the neutral point of a dedicated grounding transformer connected at the substation busbar. Furthermore, in the power auxiliary winding of the ASC, there is typically a (switchable) parallel resistor, which provides adequative resistive current to be measured at the faulty feeder during a ground fault. A typical current rating of the parallel resistor is such that it gives 5-15A of additional resistive current at the primary voltage level. This current is utilized by the ground fault protection and it is only measurable at the path of fault current flow.

Modern ASCs have typically plunger core construction, which means that the center part of the core has a movable air gap allowing the coil current to be continuously adjustable with a motor drive (**Figure 2**, left). A dedicated coil controller monitors the total phase-to-ground capacitance of the network and adjusts automatically the inductive current of the coil to match the capacitive current of the network. An example of the HMI of a coil controller is shown in **Figure 2** (right).

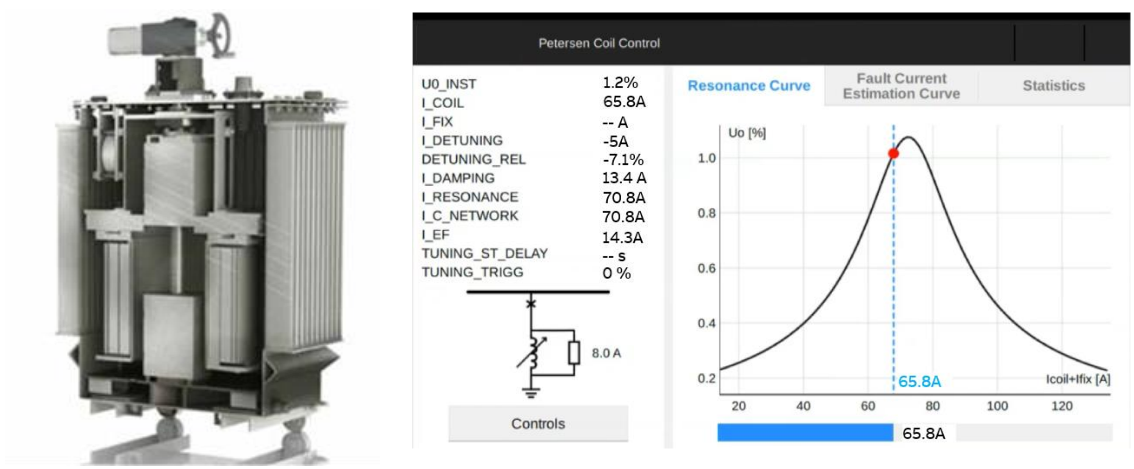

Figure 2 The key components of a compensated system (not in scale): the compensation coil (ASC) and the coil controller HMI-view. In the HMI-view network damping value I_d in amperes is noted as I_DAMPING, network resonance point as I_RESONANCE and detuning I_v as I_DETUNING.

The exact value of the ground fault current at the fault point depends on the *detuning degree* of the coil. The network is said to be under-compensated when the inductive current of the coil is smaller than the total capacitive current of the network. In this case the remaining fault current at the fault location is capacitive. On the other hand, the network is said to be *over-compensated* when the inductive current of the coil is larger than the total capacitive current of the network. In this case the remaining fault current at the fault location is inductive.

The target value for the coil current, the detuning degree, is entered for the coil controller as a setting value, which is typically slightly higher than the capacitive ground-fault current produced by the phase-to-ground capacitances of the network. This over-compensated state of the network is typically approx., +5…+15A used by the utilities in Europe. The main network parameters calculated by the coil controller are:

a) **Network resonance point [A]:** the capacitive ground fault current produced by the network phase-to-ground capacitances. In **Figure 2 (right)** resonance point equals 70.8A. This is the coil current value, which corresponds to the maximum U_o value of the "resonance curve".

b) **Network damping value I_d [A or %]:** This is the sum of the total shunt losses of the network, including the feeders shunt losses, losses of the ASC and the parallel resistor, given either in amperes or percent of the coil current at the network resonance point. In **Figure 2 (right)** network damping value equals 13.4A (19% from 70.8A with 8A parallel resistor connected).

c) **Detuning degree I_v [A or** %]: This is the detuning degree specified by the network operator given either in amperes or in percent of the coil current at the network resonance point: $I_v = I_{Coil} - I_{EFNet}$ is the detuning value in amperes, where I_{Coil} is the inductive current produced by the ASC [A] determined by the coil position and I_{EFNet} is the capacitive ground fault current of the whole network [A]. Positive value means over-compensation, negative value under-compensation. In **Figure 2 (right)** detuning degree equals -5A (-7.1% from 70.8A) meaning that the network is operating in the under-compensated state.

Traditionally the operation principle of the coil controller has been based on the fundamental electrical theory of parallel RLC-resonance circuit formed by the network admittances and the compensation coil. Resonance point of the network is found by evaluating the magnitude of neutral point voltage U_o during the healthy state by slight adjustments of the coil current. Increasing magnitude of U_o indicates that coil current is moved towards the network's resonance point, and the resonance point is found when U_o reaches its maximum value.

In modern cable networks, the increased symmetry of network admittances ($\overline{Y}_A \cong \overline{Y}_B \cong \overline{Y}_C$) decreases the healthy state U_o needed for the operation of traditional "resonance" controller. This has resulted in a development of new operation principle of modern coil controllers, which is based on injection of current in the system neutral point. The purpose of such current injection is to make sufficient variations into U_o -magnitude so that the network parameters can be calculated for ASC-tuning purposes.

The phase-to-ground admittance of the ASC with the parallel resistor can be written as follows:

$$\overline{Y}_{Coil} = (G_{Par} + G_{Coil}) - j \cdot B_{Coil}$$

$$= (\frac{1}{R_{Par}} + \frac{1}{R_{Coil}}) - j \cdot \frac{1}{\omega \cdot L_{Coil}} \tag{2a}$$

R_{Par} is the value of the parallel resistor of the ASC [Ω], R_{Coil} represents the coil losses [Ω], the value of the parallel resistor of the ASC, L_{Coil} represents the coil inductance[H].

Numerical value for the admittance of the ASC including the parallel resistor can be obtained from basic network parameter data:

$$\overline{Y}_{Coil} = \frac{(I_{Par} + I_{Coil} \cdot d_{Coil}) - j \cdot I_{Coil}}{U_{PE}} \tag{2b}$$

I_{Par} is the additional resistive current [A] at primary voltage level produced by the parallel resistor of the ASC, d_{Coil} is a factor [pu] to approximate the losses of the ASC, typical value is between 0.01…0.05.

It should be noted that the traditional ASC can only compensate the capacitive ground fault current component with systems fundamental frequency. The possible harmonic components or the resistive component present in the ground fault current are not compensated. In modern networks, the compensation effect of the coil is challenged by increasing share of harmonic components, which are not compensated by the ASC. This is demonstrated in **Figure 3**, which illustrates an actual recorded ground fault current waveform from a practical 20kV rural distribution network in Finland. The dominant harmonic components are typically either the 5th or the 7th, which originates mainly from the non-linear loads.

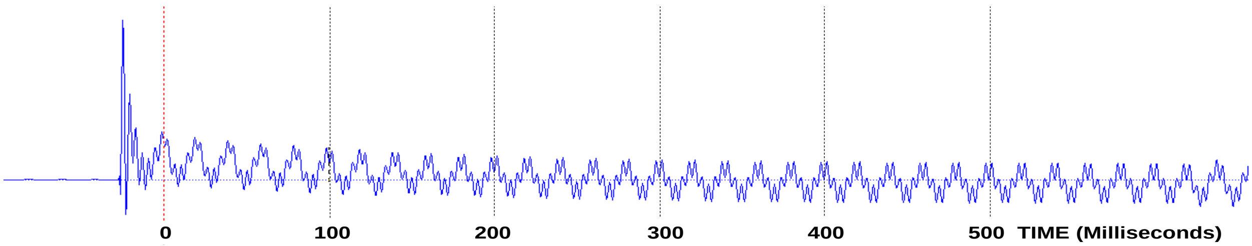

Figure 3 Recorded waveform of ground fault current during low-ohmic ground fault including a high share of harmonic components.

Another practical challenge for ground fault current compensation in cable networks occurs during a connection or disconnection of a long cable feeder with high capacitive current contribution. Such topology changes in the network leads to large and sudden variations of capacitive ground fault current of the network. After such change the coil controller must quickly re-tune the coil according to the actual resonance point of the network. If a ground fault would occur in a situation where the network detuning degree is temporarily far from the set value (due to the time required to conduct the practical tuning process), then there would be high ground fault current flowing at fault location leading to touch and hazard voltages, which may exceed limits given by legislation. Also, the operation point seen by protection may move far-away from typical, which may endanger the correct and selective operation of protection. It can be shown that the operation point of ground fault protection is very different in case of a faulty short overhead line compared to a faulty long underground cable feeder. This is also valid during a sudden excessive detuning (under-or overcompensation) state of the network.

Due to rapid increase of capacitive current due to underground cabling, it is also very likely that the existing compensation coil may have to be replaced with a larger unit or a parallel compensation coil must be installed in order to manage this increased value of ground fault current. Another option gaining popularity e.g. in Scandinavia, is to apply so called distributed compensation in the network. In this case, smaller, non-tunable compensation coils are installed along the longest cable feeders in order to limit their capacitive ground fault current contribution. Typically, the distributed compensation coils are rated to compensate about 5-15A of ground fault current as per individual distributed coil. When distributed coils are installed in the network, their ratings and locations should be carefully considered. The situation of feeder (inductive) overcompensation should be avoided, where distributed coils produce more inductive current than the feeder phase-to-ground capacitances produce capacitive current. In this case, the ground fault current produced by a feeder would be inductive, which is not typical from ground fault protection perspective and should thus be avoided. Special protection challenges in networks with distributed compensation coils are analyzed in reference [2].

IV. Directional Ground Fault Protection in Compensated Networks

A. *The measured quantities used by ground fault protection*

Ground fault protection in compensated systems is based on the measurement of zero-sequence components of current and voltage. For these, dedicated measurement devices and wirings schemes must be used. In practice the neutral point voltage (Neutral Voltage Displacement, NVD, residual voltage, zero-sequence voltage) is typically obtained from the broken-delta connected tertiary windings of three phase-to-ground connected voltage transformers, **Figure 4 (left).** Neutral point voltage may be mathematically written as (it is same as the zero-sequence voltage component $\overline{U}_0$):

$$\overline{U}_o = \overline{U}_0 = (\overline{U}_A + \overline{U}_B + \overline{U}_C)/3 \tag{3a}$$

Assuming a solid (bolted fault with zero fault resistance) ground fault in a compensated network, then the neutral point voltage raises to a value, which equals the system's nominal phase-to-ground voltage. For example, in the 20kV system, the neutral point voltage would be 11.5kV during a solid ground fault. Typically, this equals 100V in the broken-delta winding, which is measured by the ground fault protection.

The residual current (sum current), which is measured at the beginning of the protected feeder during a ground fault, has typically low value, and requires therefore dedicated current transformer to be measured accurately. Such current transformer is called as the Core Balance CT (CBCT), also known as zero-sequence current transformer, Ferranti CT, ring-core CT or cable CT, **Figure 4 (right).** Residual current measured by the CBCT may be mathematically written as (it is three times the zero-sequence current component $\overline{I}_0$):

$$\overline{I}_o = 3 \cdot \overline{I}_0 = \overline{I}_A + \overline{I}_B + \overline{I}_C \tag{3b}$$

Note that in order to measure the sum of phase current with the CBCT, the currents flowing in the cable sheaths/screen must be cancelled out. This is achieved by bringing the cable screen/sheath back through the CBCT window prior to bonding to ground, **Figure 4 (right)**.

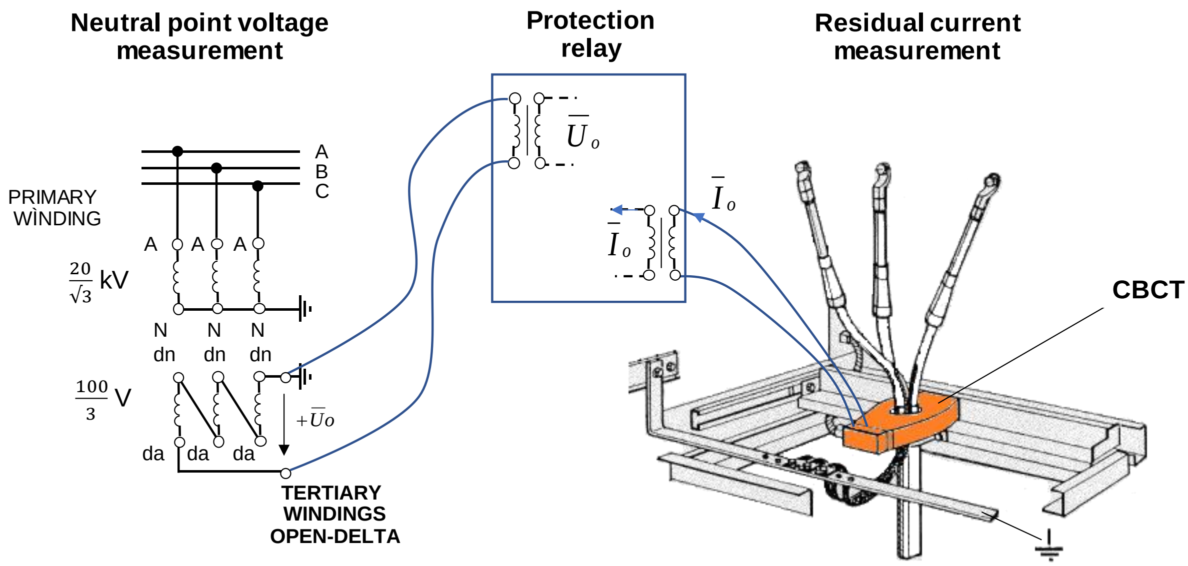

Figure 4 Measurement of zero-sequence quantities for ground fault protection purposes in compensated networks: neutral point voltage from the broken-delta winding (left), residual current with cable core CT (right).

As the ground fault current in compensated systems is typically very small, typically in the range of 1A-50A in primary and typically discrimination between faulty and healthy feeder is based on the resistive part of measured residual current, the accuracy of $\overline{I}_o$ measurement is very important for selective ground fault protection.

B. *Derivation of fault quantities for basic ground fault protection analysis*

Next, general equations for the calculation of currents and voltages during a ground fault are given. They are derived from the three-phase equivalent circuit of a compensated distribution network of **Figure 1.** Equations are valid for the fundamental frequency component, and full symmetry of the system is assumed. Equations are given in format, which allows easy hand-calculations and operation point analysis of any protection function utilizing fundamental frequency phasors of $\overline{I}_o$ and $\overline{U}_o$ for operation.

In all the following equations current terms are presented in admittance domain where inductive current is negative and capacitive positive. Conversion from admittance to 'true' current domain (where capacitive current is negative and inductive current is positive) follows **Equation 4** [3].

$$\overline{I}_o = conj(\overline{Y}_o \cdot U_{PE}) = conj(\overline{I}_o^*) \qquad (4)$$

In the equations, the following parameters at primary voltage level are used, which are the basic ground fault related parameters of the network:

- U_{PE} is the operating phase-to-ground voltage [V]
- I_{EFFd} is the capacitive ground fault current produced by the protected feeder [A]
- I_{EFNet} is the capacitive ground fault current produced by the network [A]
- d_{Net} is a factor [pu] to approximate the natural losses of the feeder/network, typical value is between 0.01…0.10 from I_{EFNet} or I_{EFFd}
- I_{Coil} is the inductive current [A] produced by the ASC determined by the set detuning degree
- d_{Coil} is a factor [pu] to approximate the losses of the ASC, typical value is between 0.01…0.05 from I_{Coil}
- I_{Par} is the additional resistive current [A] at primary voltage level produced by the parallel resistor of the Arc Suppression Coil (ASC, Petersen coil)
- $I_d = I_{Par} + I_{Coil} \cdot d_{Coil} + I_{EFNet} \cdot d_{Net}$ is the total damping of the network in amperes including the natural feeder losses, losses of the ASC and losses introduced by the parallel resistor of the coil.
- $I_v = I_{Coil} - I_{EFNet}$ is the detuning value in amperes. Positive value means over-compensation, negative value under-compensation. In case coil becomes disconnected, network becomes operated as unearthed network, then $I_v = -I_{EFNet}$.

1) Neutral point voltage $\overline{U}_o$

In protection functions applied in compensated networks, the magnitude of neutral point voltage is very often used as a general indication of a ground fault in the network and as a sensitive pick-up criterion for ground fault protection. Neutral point voltage is a favorable fault quantity since this value is practically not dependent on actual fault location: a ground fault at any location in the network results in approximately the same neutral point voltage value. However, also natural phase admittance unbalance introduces similarly neutral point voltage, which requires that compensated networks must be build as symmetrical three-phase systems. The fundamental equation describing the behavior of neutral point voltage ($\overline{U}_o$) in any high impedance earthed network (unearthed, compensated, earthed with high ohmic resistor) during the healthy state can be derived from the equivalent circuit presented in **Figure 1**:

$$\overline{U}_o^{healthy} = -U_{PE} \cdot \frac{\overline{Y}_{uNettot}}{\overline{Y}_{Nettot}+\overline{Y}_{Coil}} \quad (5a)$$

Where $\overline{Y}_{Nettot} = \overline{Y}_{ANettot} + \overline{Y}_{BNettot} + \overline{Y}_{CNettot}$ is the total network admittance of all phases. $\overline{Y}_{ANettot}, \overline{Y}_{BNettot}, \overline{Y}_{CNettot}$ are the total network phase admittances A, B and C (protected feeder and background network) [S], $\overline{Y}_{uNettot} = \overline{Y}_{ANettot} + \bar{a}^2 \cdot \overline{Y}_{BNettot} + \bar{a} \cdot \overline{Y}_{CNettot}$ represents the asymmetrical part of the total network admittance, $\bar{a}$ = cos(120°)+j·sin(120°) is the phase shift operator.

It is important to note, that the denominator of **Equation 5a** is the total system admittance including the ASC. The inductive susceptance of the ASC is used to cancel the capacitive susceptance of the network, thus decreasing the value of effective total system admittance. It should be emphasized, that ASC only decreases the imaginary part of total network admittance. The ASC cannot cancel the resistive losses, but it contributes to them by its own losses.

Admittances can be expressed in terms of currents multiplying them with operating phase-to-ground voltage U_{PE}:

$$\overline{U}_o^{healthy} = -U_{PE} \cdot \frac{\overline{Y}_{uNettot} \cdot U_{PE}}{(\overline{Y}_{Nettot}+\overline{Y}_{Coil}) \cdot U_{PE}} \quad (5b)$$

The real part of the total system admittance including the ASC is the total damping of the network and in terms of amperes it is commonly noted as I_d. The imaginary part of the total system admittance including the ASC is the detuning value of the network and in terms of amperes it is commonly noted as I_v.

Thus **Equations 5b** can be written as:

$$\overline{U}_o^{healthy} = -U_{PE} \cdot \frac{\bar{I}_{uNettot}}{I_d - j \cdot I_v} \quad (5c)$$

Where is $\bar{I}_{uNettot}$ represents the asymmetrical part of the corresponding total network admittance in terms of amperes. $I_d = I_{Par} + I_{Coil} \cdot d_{Coil} + I_{EFNet} \cdot d_{Net}$ is the total damping of the network in amperes including the natural feeder losses, losses of the ASC and losses introduced by the parallel resistor of the coil. $I_v = I_{Coil} - I_{EFNet}$ is the detuning value in amperes. Positive value means over-compensation, negative value under-compensation. In case coil becomes disconnected, network becomes operated as unearthed network, then $I_v = -I_{EFNet}$.

The maximum value of healthy-state U_o is reached at resonance, when I_v = 0:

$$\mathrm{Max}(U_o^{healthy}) = -U_{PE} \cdot \frac{\bar{I}_{uNettot}}{I_d} \quad (5d)$$

Assuming full symmetry of network admittances:

$\overline{Y}_{ANettot} = \overline{Y}_{BNettot} = \overline{Y}_{Cnettot}$

$\rightarrow \overline{Y}_{uNettot} \cdot U_{PE} = \bar{I}_{uNettot} = 0 \rightarrow U_o^{healthy} = 0$

i.e. in fully symmetrical system the asymmetrical part of the total network admittance is zero and thus also the neutral point voltage.

In practical networks phase wise network admittances are however not exactly equal, especially in case network includes overhead-line sections, especially if line sections are built with only two-phases. In compensated networks, asymmetry of phase admittances, $\overline{Y}_{ANettot} \neq \overline{Y}_{BNettot} \neq \overline{Y}_{Cnettot}$, results into 'standing' neutral point voltage, whose magnitude according to **Equations 5b-5c** depends on three parameters:

- Magnitude of phase admittance unbalance. The higher unbalance, the higher healthy state U_o.
- Magnitude of system damping. The lower damping, the higher healthy state U_o. Damping is generally related to size of network capacitances and coil currents, thus in larger networks damping increases.
- Magnitude of detuning. The lower detuning, the closer to the resonance point, the higher healthy state U_o. Maximum U_o value is achieved at resonance, when I_{Coil} equals I_{EFNet} i.e. $I_v = 0$. It should be noted that detuning is not fixed value and it may temporarily vary during e.g. network topology changes. Set detuning value to the coil controller is valid only after successful tuning procedure.

The magnitude of healthy state U_o as a function of detuning value of the ASC draws a bell-shaped curve commonly known as the resonance curve (**Figure 5**). Resonance curve has always maximum value at resonance (I_v =0) and U_o decreases with increasing value of detuning I_v.

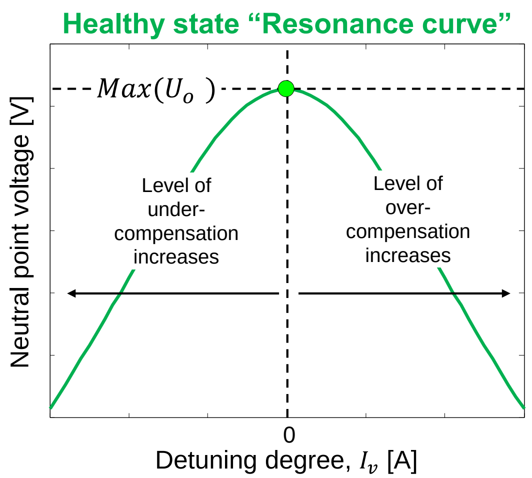

Figure 5 Resonance curve valid for compensated network.

Very often, the general detection of ground fault in compensated network is based on monitoring the neutral point voltage value. In order to obtain the best possible sensitivity, the U_o-pickup value should be set as low as possible, considering the maximum possible healthy state value defined by the peak value of the resonance curve (**Figure 5**). High peak value of the resonance curve i.e. high admittance asymmetry value limits the achievable practical ground fault detection sensitivity. Especially in overhead line networks, the non-homogeneity of individual phase-to-ground admittances $\overline{Y}_A \neq \overline{Y}_B \neq \overline{Y}_C$ may create high healthy state zero-sequence quantities, which limits the sensitivity of the protection.

On the other hand, in modern distribution networks, there is a clear trend to replace overhead lines with cables and to build new feeders with underground cables. Due to high symmetry of cable phase-to-ground capacitances, the asymmetry of network admittances decreases. In fully cabled three phase networks, the asymmetry of phase-to-ground admittances may be very low, meaning that $\overline{Y}_A \cong \overline{Y}_B \cong \overline{Y}_C$. Low value of healthy state U_o in such networks allows low U_o-pickup value to be used for general start criterion, which enhances the sensitivity of protection in terms of fault resistance.

Neutral point voltage during a single-phase ground fault can be derived also from the equivalent circuit presented in **Figure 1**. Assuming a fully symmetrical system in terms of phase to ground admittances and assuming that admittance asymmetry is only due to ground fault occurring in phase A with fault admittance Y_F, the following equation applies

$$\overline{U}_o^{faulty} = -U_{PE} \cdot \frac{Y_F}{Y_F + \overline{Y}_{Nettot} + \overline{Y}_{Coil}} \qquad (6a)$$

Again, admittances can be expressed in terms of currents multiplying them with voltage U_{PE}. Fault admittance is inverse of fault resistance i.e. $Y_F = 1/R_F$. Knowing that the real part of the total system admittance including the ASC in terms of amperes is the total damping of the network (I_d) and the imaginary part is the detuning value of the coil (I_v), **Equation 6a** can be written as:

$$\overline{U}_o^{faulty} = -\frac{U_{PE}}{\overline{a}_{RF}} = -\frac{U_{PE}^2}{R_F \cdot (I_d - j \cdot I_v) + U_{PE}} \qquad (6b)$$

where

$$\overline{a}_{RF} = \frac{R_F \cdot (I_d - j \cdot I_v) + U_{PE}}{U_{PE}} \qquad (6c)$$

is a complex attenuation factor due to fault resistance. Inverse of $\overline{a}_{RF}$ equals -$\overline{U}_o^{faulty}$ as per unit quantity:

$$\frac{1}{\overline{a}_{RF}} = \frac{U_{PE}}{R_F \cdot (I_d - j \cdot I_v) + U_{PE}} = \frac{-\overline{U}_o^{faulty}}{U_{PE}} = -\overline{U}_{o\_pu}^{faulty} \qquad (6d)$$

The interpretation of **Equations 6b** is that the neutral point voltage has a maximum value of 1pu during a solid (R_F = 0Ω) ground fault. The magnitude of $\overline{U}_o$ equals then the operating phase-to-ground voltage of the network, for example in a 20kV system, the magnitude of $\overline{U}_o$ equals 11.5kV. The effect of fault resistance R_F is to decrease the value of $\overline{U}_o$. The attenuation of neutral point voltage magnitude due to fault resistance is a function of three key parameters: fault resistance, network detuning degree, and total resistive shunt losses i.e. system damping. Attenuation is increased with increasing value of fault resistance, detuning or damping as demonstrated in **Figure 6**. At high fault resistance values (~tens of kilo-ohms), the effect of fault resistance becomes dominant.

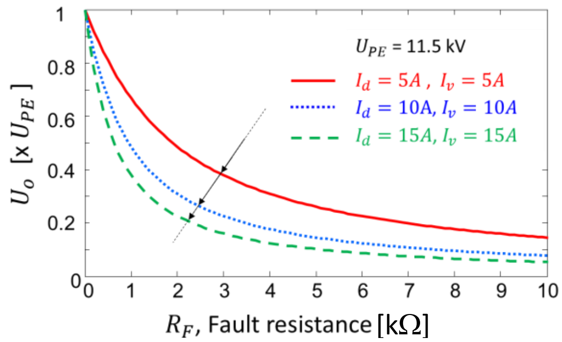

Figure 6 Neutral point voltage magnitude U_o [pu] as a function of fault resistance R_F [kΩ].

During faults with fault resistance, best sensitivity i.e. the maximum value for $\overline{U}_o$ is achieved always at resonance condition, when the inductive coil current matches the capacitive current of the network (I_{EFNet}= $I_{Coil} \rightarrow I_v = 0$).

2) Phase voltages $\overline{U}_A$, $\overline{U}_B$, $\overline{U}_C$

In compensated networks, the phase voltages are affected by the neutral point voltage. From the equivalent circuit of **Figure 1**, the following equations for phase voltages can be derived:

$$\overline{U}_A = \overline{E}_A + \overline{U}_o \tag{7a}$$

$$\overline{U}_B = \overline{E}_B + \overline{U}_o \tag{7b}$$

$$\overline{U}_C = \overline{E}_C + \overline{U}_o \tag{7c}$$

Where $\overline{E}_A = U_{PE}$, $\overline{E}_B = \overline{a} \cdot U_{PE}$, and $E_C = \overline{a}^2 \cdot U_{PE}$ are the source voltages of phases A, B and C.

General behavior of voltages during a single-phase ground fault in compensated network as a function of fault resistance is illustrated in **Figure 7**, assuming a ground fault in phase A.

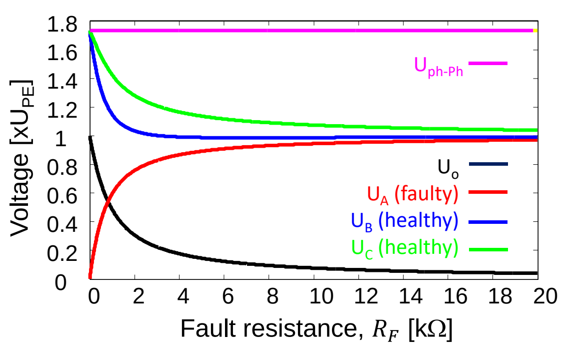

Figure 7 General behavior of voltage magnitudes as a function of fault resistance in compensated network. Ground fault occurs in phase A. $I_v = 10$A, $I_d = 10$A, $U_{PE} = 11.5$kV.

It is important to notice, that during a ground fault, the magnitude of faulted phase voltage is inverse of neutral point voltage U_o. This means that in case neutral point voltage has high value during the fault, then the magnitude of faulted phase voltage is low (and vice versa). The two healthy phase voltages are stressed by over-voltages, which means that equipment must be dimensioned to phase-to-phase voltage. However, phase-to-phase voltages during single-phase ground fault condition are not disturbed, which means that loads connected between phases are not affected by single phase ground fault.

3) Ground fault current at the fault location during a single-phase ground fault, $\overline{I}_{EF}$

The magnitude of ground fault current flowing at the fault location is due to total system admittance, which is affected by the detuning degree (I_v). It should be emphasized, that passive ASC can only decrease the imaginary part of fault current. The ASC cannot decrease the resistive part of fault current due to system damping (I_d), but it contributes to them by its own losses.

The ground fault current phasor (fundamental frequency) at the fault location can be written as:

$$\overline{I}_{EF}^{1} = (I_d - j \cdot I_v) \cdot \frac{1}{\overline{a}_{RF}} = \frac{(I_d - j \cdot I_v) \cdot U_{PE}}{R_F \cdot (I_d - j \cdot I_v) + U_{PE}} \tag{8a}$$

Equation 8a is illustrated in **Figure 8**. Magnitude of ground fault current as a function of coil detuning is known as the ‘V-curve’. Minimum fault current is always achieved, when network is operating at full resonance, $I_v = 0A$:

$$Min(I_{EF}^{1}) = \frac{I_d}{\overline{a}_{RF}} = \frac{I_d \cdot U_{PE}}{R_F \cdot I_d + U_{PE}} \tag{8b}$$

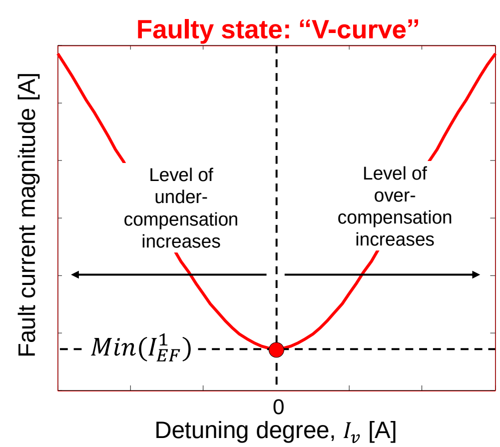

Figure 8 General behavior of fault current magnitude as a function of ASC tuning degree.

The attenuation of ground fault current magnitude due to fault resistance is a function of three key parameters: fault resistance, network detuning degree, and total resistive shunt losses i.e. system damping. Attenuation is increased with increasing value of fault resistance, detuning or damping as demonstrated in **Figure 9**. At high fault resistance values (~tens of kilo-ohms), the effect of fault resistance becomes dominant.

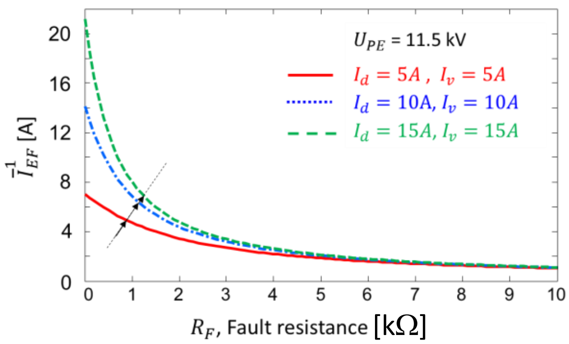

Figure 9 Ground fault current magnitude as a function of fault resistance R_F [kΩ].

The magnitude of ground fault current in compensated networks is not dependent on the fault location i.e. a fault located close to the substation busbar or far-way in the end-section of the line results practically in the same fault current magnitude. This is because longitudinal impedance is insignificant compared to shunt admittances. Fault location may have effect on the fault inception transients, but not on the steady-state fault current magnitude.

Equations 8a-8b give only the fundamental frequency component flowing at the fault location. In practical networks, and especially during low-ohmic faults, the ground fault current may have a high harmonic content, which increases the RMS-value of the fault current (refer to **Figure 3**). There is a clear tendency that in modern distribution networks the share of harmonics generating loads is increasing. As result the harmonic content of the fault current is also increasing. In case the magnitude of the harmonic components is known, then the RMS-value of ground fault current can be estimated with **Equation 8c**:

$$abs(\bar{I}_{EF}) = \sqrt{abs\left(\bar{I}^{1}_{EF}\right)^{2} + \sum_{n=2}^{m} abs\left(\bar{I}^{n}_{EF}\right)^{2}} \quad (8c)$$

It should also be emphasized, that the ground fault current flowing at the fault location does not generally equal the residual current $\bar{I}_o$ measured at the beginning of the faulty feeder, which is the operation quantity used by traditional ground fault protection. In reference [4] a novel method for ground fault protection applicable in compensated networks was introduced. In the method estimation of ground-fault current is done utilizing the change in threefold negative-sequence current measured at the beginning of the feeder due to ground fault. The harmonic components can be taken into account in real time by calculating negative-sequence current at frequency $n \cdot f_n$, where $n=1,2,\ldots,m$ and then calculating their change due to ground fault. For the ground fault current estimate utilizing the change in threefold negative-sequence current, including the harmonics, can be written:

$$I_{EF}(RMS) = \sqrt{\sum_{n=1}^{m} (3 \cdot abs(\Delta \bar{I}^{n}_{2}))^{2}} \quad (8d)$$

Where $abs(\Delta \bar{I}^{n}_{2})$ is the change in magnitude of the n^{th} harmonic negative-sequence current component due to ground fault. Adequate sensitivity and selectivity of protection can be achieved by utilizing traditional $U_o >$ condition to detect the presence of a ground fault.

The specific protection challenge in compensated networks due to small fault current magnitude and the properties of the parallel resonance circuit created by the ASC is that the ground fault current has very often intermittent and re-striking characteristics. This means that special functionality is required from protection relays. This issue is studied in the later part of this paper.

The residual current $\bar{I}_o$ measured at the substation, which is the operation quantity used by traditional ground fault protection is described in the following.

4) *Residual current $\bar{I}_o$ measured at the feeder bay during an inside and outside ground fault*

Ground fault protection in compensated systems is based on the measurements at the feeder bays of the primary substation. **Figure 10** illustrates the flow of fault current in a compensated network during a single-phase ground fault, which occurs either inside or outside the protected feeder in phase A.

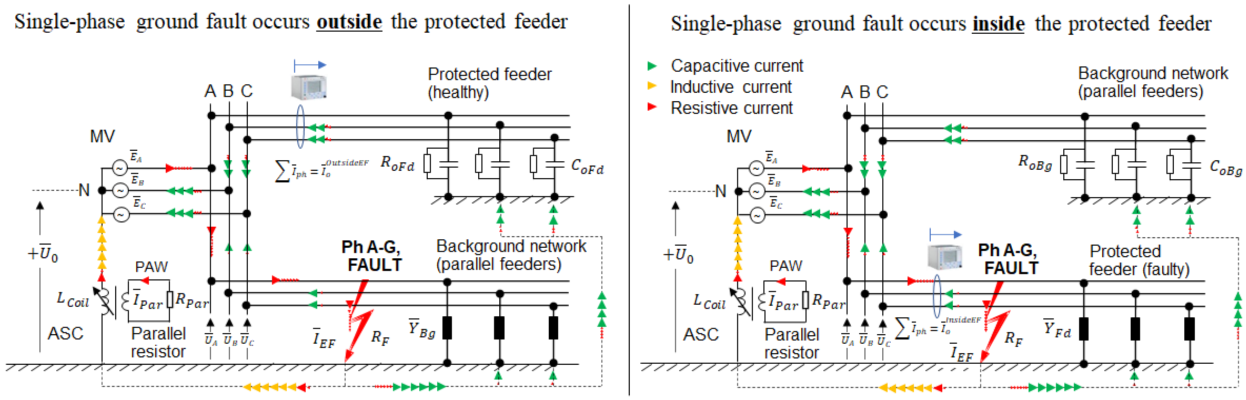

Figure 10 Three-phase equivalent circuit of a compensated distribution network, single-phase ground fault occurs: outside the protected feeder (left) or inside the protected feeder (right).

From **Figure 10 (left)** it can be seen that the residual current measured at the beginning of a healthy feeder equals the ground fault current contribution of protected feeder itself. The measured residual current phasor at the healthy feeder can be written as:

$$\overline{I}_o^{OutsideEF} = (-|I_{EFFd}| \cdot d_{Net} - j \cdot I_{EFFd}) \cdot \frac{1}{a_{RF}} \quad (9a)$$

Phase angle difference $\varphi_o^{OutsideEF}$ between reference quantity $-\overline{U}_o$ and $\overline{I}_o^{OutsideEF}$ can be calculated in radians as:

$$\varphi_o^{OutsideEF} = \pi - \text{atan}\left(\frac{I_{EFFd}}{|I_{EFFd}| \cdot d_{Net}}\right) \quad (9b)$$

Real- and imaginary parts of $\overline{I}_o^{OutsideEF}$ can be calculated as:

$$Real(\overline{I}_o^{OutsideEF}) = abs(\overline{I}_o^{OutsideEF}) \cdot \cos(\varphi_o^{OutsideEF}) \quad (9c)$$

$$Imag(\overline{I}_o^{OutsideEF}) = abs(\overline{I}_o^{OutsideEF}) \cdot \sin(\varphi_o^{OutsideEF}) \quad (9d)$$

Note that negative imaginary part in **Equation 9a** assumes that feeder admittance is capacitive. Positive imaginary-part would be possible if there would be distributed compensation coils located in the parallel feeders, whose inductive current would exceed the capacitive current due to the phase-to-ground capacitances.

From **Equation 9a** it can be seen that the imaginary part of the measured residual current in the healthy feeder is directly proportional to the ground fault current contribution of the protected feeder itself. In practice this means that in case the healthy feeder is mainly composed of overhead line sections, the measured residual current magnitude is typically very small, only a few amperes in primary. But in case the feeder has long underground cable sections, the measured residual current in the healthy feeder may become much higher, even over 100 amperes. Thus, the magnitude of residual current in such healthy feeder may be higher than that is measured in the faulty feeder. Assuming $-\overline{U}_o$ as reference, the resistive component of $\overline{I}_o$ is measured as negative. The direction of $\overline{I}_o$ current in the healthy feeder is from the line towards the substation busbar.

From **Figure 10 (right)** it can be seen that the residual current measured at the beginning of a faulty feeder is not the actual ground fault current flowing at the fault location, but the ground fault current due to the admittances of the background network (parallel feeders) and the compensation coil. It is important to notice, that the share of ground fault current produced by the admittances of the faulty feeder itself is not included in the measured residual current in the faulted feeder. The measured residual current phasor at the faulty feeder can be written as:

$$\overline{I}_o^{InsideEF} = \overline{I}_{EF}^{1} + \overline{I}_o^{OutsideEF}$$

$$= [(I_d - |I_{EFFd}| \cdot d_{Net}) - j \cdot (I_v + I_{EFFd})] \cdot \frac{1}{a_{RF}} \quad (9e)$$

Phase angle difference $\varphi_o^{InsideEF}$ between reference quantity $-\overline{U}_o$ and $\overline{I}_o^{InsideEF}$ can be calculated in radians as:

$$\varphi_o^{InsideEF} = \text{atan}\left(\frac{I_v + I_{EFFd}}{I_d - |I_{EFFd}| \cdot d_{Net}}\right) \quad (9f)$$

Real- and imaginary parts of $\bar{I}_o^{InsideEF}$ can be calculated as:

$$Real(\bar{I}_o^{InsideEF}) = abs(\bar{I}_o^{InsideEF}) \cdot \cos(\varphi_o^{InsideEF}) \quad (9g)$$

$$Imag(\bar{I}_o^{InsideEF}) = abs(\bar{I}_o^{InsideEF}) \cdot \sin(\varphi_o^{InsideEF}) \quad (9h)$$

From **Equations 9a-9h** it can be seen that the sign of the measured resistive current component of residual current is opposite in the faulty and healthy feeders, regardless of coil position. It is therefore traditionally used as the criterion of fault direction determination in compensated systems:

- In the faulty feeder the measured resistive current component of residual current is positive (assuming $-\bar{U}_o$ as reference) and it is due to the resistive losses of the background network, the losses of ASC and the current of the parallel resistor of the coil, i.e. it is the total system damping subtracted by the losses of the protected feeder itself. As the natural resistive losses of the network are typically not high enough for reliable fault detection, the resistive component may be intentionally increased. This is typically done with help of a parallel resistor of the coil. In practice this parallel resistor is typically connected to the power auxiliary winding (PAW) of the coil at low voltage side, 500V. A typical value of this parallel resistor (I_{Par}) used in the Nordic countries is in the range of 5-15A at primary voltage level.

- In the healthy feeder the measured resistive current component of residual current is negative (assuming $-\bar{U}_o$ as reference). Value is typically very small as it is only due to the resistive shunt losses of the feeder itself. It is thus subjected to measurement inaccuracies. The high requirement for measurement accuracy applies especially during higher-ohmic ground faults, where the fault resistance strongly decreases the magnitude of the resistive component.

Similarly, as in case of neutral point voltage, fault resistance decreases the value of the measured residual current. The attenuation due to fault resistance is defined by the complex factor $\bar{a}_{RF}$, which has a value of 1 during a solid ground fault, **Equation 6c**.

C. Performance comparison of traditionally applied directional ground fault protection principles

In compensated networks, the traditionally applied directional ground fault protection is based on the fundamental frequency resistive component of selected operation quantity. This operation quantity may be based on one of the following:

- resistive component of residual current (*Iocos*): $Io\ cos = abs(\bar{I}_o) \cdot cos(\varphi)$
- resistive component of residual power (P_o): $P_o = abs(\bar{I}_o) \cdot abs(\bar{U}_o) \cdot cos(\varphi)$
- resistive component of residual admittance (G_o): $G_o = Real(\bar{I}_o/-\bar{U}_o)$

where phase angle difference φ is calculated as $-\bar{U}_o$ being the reference phasor: $\varphi = \angle -\bar{U}_o - \angle \bar{I}_o$.

By applying previously derived equations, we can see that in residual current based protection, the operate quantity (*Iocos*) is directly dependent on the magnitude of measured residual current, which can be calculated with **Equations 9a-9h**. During ohmic faults, the magnitude of residual current is affected by the complex attenuation factor $\bar{a}_{RF}$, **Equation 6c**. It should be noted that neutral point voltage, **Equation 6b,** is similarly affected, so they behavior in terms of per unit value magnitude is the same.

In residual power based protection (P_o) operate quantity is the product of magnitudes of measured residual current and neutral point voltage. As both quantities attenuate due to fault resistance as determined by the complex attenuation factor $\bar{a}_{RF}$, their product, residual power, is attenuated more than in case of residual current based protection.

In admittance based protection, the operate quantity is admittance, which is calculated as ratio of residual current and neutral voltage phasors, $\bar{Y}_o = \bar{I}_o/-\bar{U}_o$. Due to the fact that the magnitudes of $\bar{U}_o$ and $\bar{I}_o$ decrease similarly with increasing value of R_F as determined by the attenuation factor $\bar{a}_{RF}$, their ratio, i.e. the admittance phasor, $\bar{Y}_o = \bar{I}_o/-\bar{U}_o$, remains constant. This means that the measured conductance G_o is not affected by the value of fault resistance.

Comparison of different operation quantities is visualized in **Figure 11**. The parameters used in this numerical example are primary voltage level:

$U_{PE} = 22000\text{V}/\sqrt{3} = 12702\text{V}$, $I_{EFNet} = 50\text{A}$, $I_{Coil} = 51\text{A}$, $I_v = +1\text{A}$, $I_{Par} = 0\text{A}$, $I_{EFFd} = 5\text{A}$, $d_{Net} = 0.05\text{pu}$, $d_{Coil} = 0.02\text{pu}$, $I_d = 3.52\text{A}$. All values are presented in per unit format enabling comparison of results. In this case 1pu in U_o equals 12.7kV, and 1pu in ground fault operation quantity equals value that is measured in case of a solid ground fault inside the protected feeder ($Iocos$=3.27A, P_o = 3.27A*12.702kV = 41.536kW, G_o = 3.27A/12.702kV = 0.257mS).

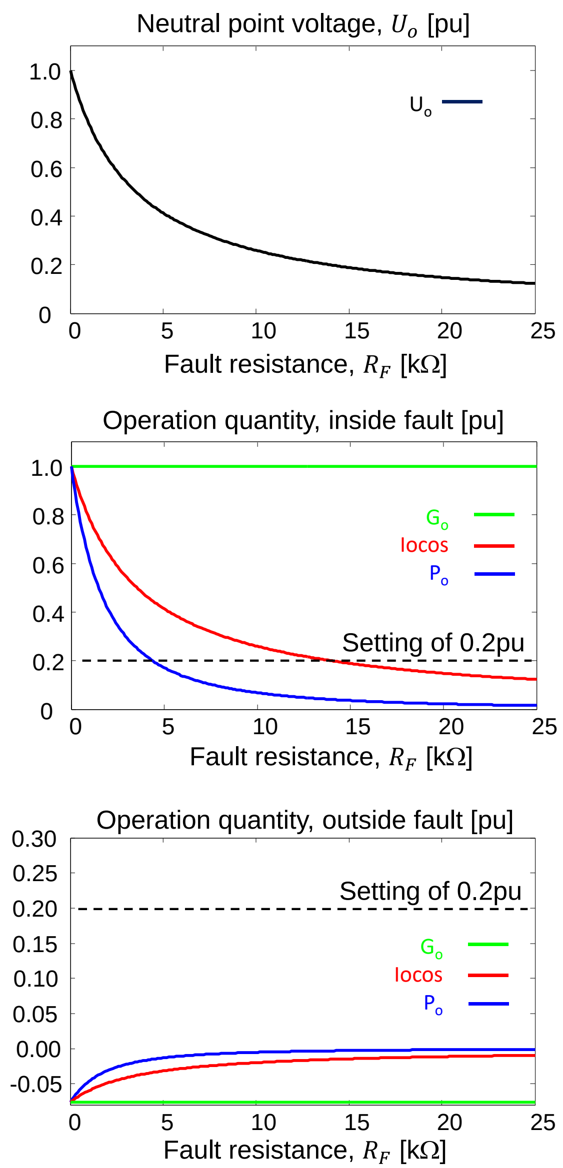

Figure 11 Comparison of ground fault protection quantities (*Iocos*, P_o and G_o) as a function of fault resistance. Protection pick-up value is assumed as 0.2pu.

From protection performance perspective, **Figure 11**, it can be concluded that the best sensitivity and largest margin between operation quantities in the faulty and healthy feeder is obtained with admittance protection. Poorest sensitivity and smallest margin between operation quantities in the faulty and healthy feeder is achieved with residual power based method i.e. with wattmetric criterion (P_o). This is due to the fact that as the fault resistance increases, both residual current and zero-sequence voltage decreases. Their product $abs(\bar{I}_o) \cdot abs(\bar{U}_o)$ results thus into the smallest operation value and lowest selectivity margin.

V. Considerations to Convert from a Low Resistance or Solidly Grounded Network to a Compensated Network

Transition from a low impedance grounded network into a high impedance grounded network is a paradigm change in how the network is designed, operated and maintained. Entire distribution network components need to be examined in order to validate that they comply with resonant grounding [5].

In this section we will cover at a high level the requirements for the rating of equipment, the asymmetry of the network, what types of loads can be connected to a compensated network, the protection philosophy, backup protection, and the capacitive current levels of the system.

A. Rating of the Equipment

The fundamental principle of resonant grounding is that in the event of a phase-to-ground fault, the tuned ASC creates a resonant circuit between the network and ASC, resulting in voltage displacement across the neutral. Assuming a galvanic fault, this leads to the faulted phase voltage becoming virtually zero, with the phase to ground voltages of the healthy phases increasing to phase-to-phase voltages. Consequently, the elevated phase to ground voltage on the healthy phases requires that all equipment must be rated to withstand the overvoltage by a factor of 1.73. Such over-voltages are experienced regularly and repeatedly during operation of compensated network. **Figure 12** illustrates time domain behavior of voltages and currents during a galvanic phase B-to-ground fault.

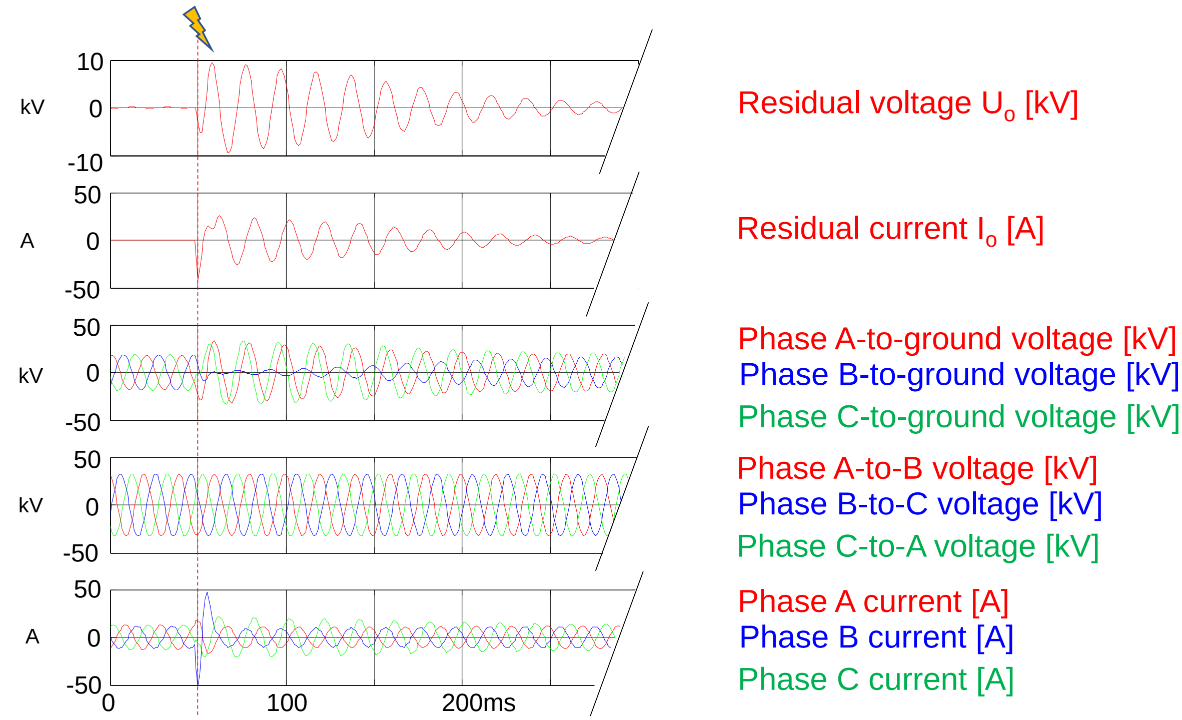

Figure 12 Time domain behaviour of voltages and currents during a galvanic phase B-to-ground fault occurring at time t=50ms.

The voltage stress on network equipment connected to unfaulted phases can lead to a ground fault evolving into a 'cross country fault', where a second simultaneous ground fault occurs at other location in another phase than the initial fault. Outcome of such fault would be over-currents in the magnitude of two-phase short-circuit currents flowing through ground as the ASC cannot provide fault current compensation when a cross-country fault occurs in the network. In order to limit the risk of cross-country faults, primary equipment inside the substation and out on the feeders such as surge arrestors, capacitor banks, cables, joints, terminations and VTs must be 'up-rated'. Such 'hardening' work increases the ability of the equipment to withstand over-voltage events, and it is vital part of ASC installation program.

B. Asymmetry of the network

The tuned ASC creates a resonant circuit between the network and ASC resulting in amplification on zero-sequence voltage and current values during network healthy-state due to network asymmetry towards ground. Effective operation of a compensated network is highly sensitive especially to capacitive imbalances ($\bar{C}_{0A} \neq \bar{C}_{0B} \neq \bar{C}_{0C}$). High degree of capacitive asymmetry results in the build-up of healthy-state (standing) residual voltage and current quantities. During a ground fault the fault quantities measured by protection relay are the healthy-state residual quantities superimposed into the actual fault generated values. Thus, asymmetry of network influences the residual current and neutral point voltage values measured during the fault.

The equations for the neutral point voltage and residual current of the protected feeder during the healthy state including the effect of admittance asymmetry can be derived from the three-phase equivalent circuit of a compensated distribution network of **Figure 1**:

$$\overline{U}_o^{healthy} = -U_{PE} \cdot \left(\frac{\overline{Y}_{uFd}+\overline{Y}_{uBg}}{\overline{Y}_{Coil}+\overline{Y}_{Fdtot}+\overline{Y}_{Bgtot}}\right) \qquad (10a)$$

$$\overline{I}_o^{healthy} = \overline{U}_0^{healthy} \cdot \overline{Y}_{Fdtot} + U_{PE} \cdot \overline{Y}_{uFd} \qquad (10b)$$

Admittances $\overline{Y}_{uFd} = \overline{Y}_{FdA} + \bar{a}^2 \cdot \overline{Y}_{FdB} + \bar{a} \cdot \overline{Y}_{FdC}$ and $\overline{Y}_{uBg} = \overline{Y}_{BgA} + \bar{a}^2 \cdot \overline{Y}_{BgB} + \bar{a} \cdot \overline{Y}_{BgC}$ represent the asymmetrical part of the corresponding total network admittance, $\overline{Y}_{Fdtot}$ and $\overline{Y}_{Bgtot}$. In an ideally symmetrical network, $\overline{Y}_{uFd}$ and $\overline{Y}_{uBg}$ equal zero.

High capacitive unbalance results into protection performance and sensitivity deterioration as fault detection is no longer single valued but depends on the faulted phase and the degree of asymmetry.

In order to achieve selective protection performance and high ground fault detection sensitivity it is thus required that network is balanced so the capacitance on each phase to ground is equalized to close tolerances. Networks which have single or two-phase line sections must be equipped with dedicated 'admittance balancing units', which are used to provide supplementary capacitance to cater for imbalances on particular feeders. Admittance balancing can be accomplished e.g. with single phase and/or three phase balancing units, as well as by re-phasing overhead lines.

It should also be noted that all switching devices including fuses must de-energize all phases on the faulted line section during two phase short-circuit faults in order to avoid capacitance imbalance, which would otherwise result. From ***Equations 5a-5d, 7a-7c*** and ***10a*** one can conclude that large capacitance imbalance due to e.g. open phase condition may result in severe over-voltages, especially in case of resonance condition where over-voltages are only limited by the system damping.

Open delta regulators (or two tank regulators) are not compatible with the compensated networks as they displace the system neutral voltage by regulating line-line voltages on two phases as opposed to three. Any existing installations must thus be converted to a full three-phase set. All single-phase controllers will need to be replaced with a three-phase controller so that voltages across all phases remain consistent to avoid asymmetrical voltages [5].

C. VTs and CTs

As described in the earlier analysis of ground fault protection, the selectivity of ground fault protection in compensated networks is inherently very challenging, as faulted feeder discrimination must be based on the very small measured residual current, and in most cases based on the resistive component of it. This measurement is subject to measurement inaccuracies of the whole measurement chain including Uo-measurement, Io-measurement and accuracy of the relay. Especially phase displacement error should be minimized to avoid apparent resistive component measured by ground fault protection. This may lead to unwanted, unselective operation of the protection, particularly when sensitive operation settings are used. It is therefore important to recognize the measurement errors and understand their effect. In real-world networks, in order to achieve compliance, accurate VTs and CTs are required. Especially for current measurement of residual current, Core balance CTs (CBCT) are required to detect and measure the residual current magnitude and angle accurately.

D. Loads being connected

Perhaps one of the greatest challenges when looking at moving from a low resistance grounded and solidly grounded system to a compensated network is to look at all the different loads connected to the electrical system and ensure that any single-phase loads connected between phase and ground are removed. All loads must be connected between phases and loads should be balanced between phases.

E. Primary and backup protection and control schemes

In the case of compensated networks, the ground fault protection must always be set directional. Due to multitude nature of ground faults, protection configuration includes typically sensitive ground fault protection functionality based on fundamental frequency measurements. This is complemented with special protection functionality for intermittent and re-striking faults. Dedicated protection against high current cross-country fault is recommended to be accomplished with non-directional ground fault protection (50N/51N), which measures residual current with sum connected phase CTs. This avoids saturation, which could delay tripping in case low ratio CBCT would be used.

Protection is typically set the same way for all feeders. Ground fault protection of substation busbar is based on residual overvoltage protection (59N) which acts also as back-up protection for feeders. In case ground fault is detected by busbar 59N protection, but none of the feeders detect the fault, the main (incomer) breaker is tripped. This tripping must be time-coordinated (delayed) with feeder protection. Most electrical utilities in Europe follow European standard EN50522: "Earthing of power installations exceeding 1kV a.c." to define trip delay time in case of a ground fault. Typical trip times are in order of seconds, which allow self-extinguishment of temporary transient faults.

Also, it should be noted that ground fault protection functionality in Automatic Circuit Reclosers (ACRs) may need to be updated to avoid miss operation due to the transition to a compensated network. This is due to the fact that protection functions valid for low resistance or solidly grounded network applied in ACRs, such as nondirectional ground fault or sensitive ground fault protection functions, can trip unselectively when ASC is connected. Protection configuration should also consider the case when Arc Suppression Coil is switched off, e.g. for maintenance. In such case, system may continue operation as ungrounded or grounding can be changed to low or solidly grounded system. Protection must be adapted according to prevailing grounding practice.

F. Capacitive current levels and sizing of ASC

Network capacitive current and damping increases with network size, i.e. depending on the total route length of powerlines and cables supplied by the primary substation. When determining sizing of ASC, the capacitive charging current of all the feeders in the electrical system should be known and considered. Also, the anticipated growth of network capacitance should be considered. Especially in case network development involves a significant amount of underground cable, it should be considered that the network's total capacitance may dramatically increase.

Under-sizing of coils does not bring the wanted reduction of ground fault current magnitude. On the other hand, over-sizing of coils is economically not feasible, and it may also decrease fault detection sensitivity by increasing total damping.

VI. CAN COMPENSATED NETWORKS BE AN ALTERNATE SOLUTION TO REDUCE THE RISK OF GROUND FAULTS CAUSING FOREST FIRES?

In reference [6, 7] the results of 22kV powerline vegetation conduction ignition tests concluded that:

- "…if powerline earth-fault protection systems were to detect and respond to 0.5 Amp faults within two seconds, fire risk in 'branch touching wire' faults in worst case conditions would be reduced tenfold compared to current levels."
- "…if powerline protection systems can detect and respond to a 0.5 amps earth fault, fire risk from 'wire into bush' faults might be cut by about 80%."
- "…Fault detection and response within about five seconds might achieve substantial reductions in 'branch across wires' fire risk."

Based on the findings and test results, performance standard [8] was defined for Rapid Earth Fault Current Limiter (REFCL) technology by the Victorian Government in Australia. The recommendations are summarized as follows for high fire risk areas:

For a high-impedance fault (defined as a resistance equal in ohms to twice the nominal phase-to-earth voltage in volts, e.g. 25.4kohms in a 22kV network):

- *Fault must be detected within 1.5 seconds of its occurrence*
- *Within two seconds of fault occurrence, the voltage on the faulted conductor must be limited to less than 250 volts except during diagnostic tests*
- *During diagnostic tests to confirm if the fault is sustained or not or to identify which powerline it is on, the:*
    - *Fault current must be limited to less than 0.5 amps*
    - *the I^2t must be limited to less than 0.1 A^2 i.e. the thermal energy on the electric line to a maximum value of $0.1A^2s$. This means that fault current of 0.5A magnitude must be cleared within 400ms.*

For a low impedance fault (defined as a resistance equal in ohms to the nominal phase-to-earth voltage in volts divided by 31.75, e.g. 400 Ohms in a 22kV network):

- *Within 85 milliseconds of fault occurrence the voltage on the faulted conductor must be limited to less than 1,900 volts*
- *Within 500ms of fault occurrence the voltage on the faulted conductor must be limited to less than 750 volts*
- *Within two seconds of fault occurrence the voltage on the faulted conductor must be limited to less than 250 volts except during diagnostic tests.*

In order to study the performance of compensated network with passive ASC in respect to the requirements of the REFCL performance standard, the following numerical example is used. **Equations 11a and 11b** are applied to illustrate how fault resistance

(R_F), network damping (I_d) and coil detuning (I_v) affect to the faulted phase voltage and ground fault current magnitude - the most important parameters from fire risk perspective based on the findings and test results from vegetation conduction ignition tests [6, 7].

Condition for faulted phase voltage in the following numerical example is that it should not exceed 0.1pu, i.e. 1.27kV in the studied 22kV network. As neutral point voltage U_o is inverse to the faulted phase voltage, faulted phase voltage of 0.1pu equals U_o = 0.9pu. In order to study the faulted phase voltage condition, fault resistance R_F is solved from **Equation 6b**:

$$R_F[ohm] < \frac{U_{PE}\cdot\left(\sqrt{I_d^2+I_v^2-I_v^2\cdot U_{o\_pu}^2}-I_d\cdot U_{o\_pu}\right)}{(I_d^2+I_v^2)\cdot U_{o\_pu}} \qquad (11a)$$

Condition for ground fault current magnitude is that it must not exceed 0.5A in primary. In order to study the ground fault current magnitude condition, fault resistance R_F is solved from **Equation 8a**:

$$R_F[ohm] > \frac{U_{PE}\cdot\left(\sqrt{I_d^4+2I_d^2\cdot I_v^2-I_{EF}^2\cdot I_v^2+I_v^4}-I_d\cdot I_{EF}\right)}{(I_d^2+I_v^2)\cdot I_{EF}} \qquad (11b)$$

where U_{PE} is the system phase-to-ground voltage [V], 12702V in 22kV network, I_d is the total system damping [A] varied as 0A, 0.25A, 0.50A and 2.0A, I_v is the detuning [A] varied from 0A to 2A. U_{o_pu} is zero-sequence voltage threshold = 0.9pu (equals faulted phase voltage of 0.1pu = U_{FPE}), I_{EF} is ground fault current magnitude threshold = 0.5A.

Results of this numerical example are presented in **Figure 13.**

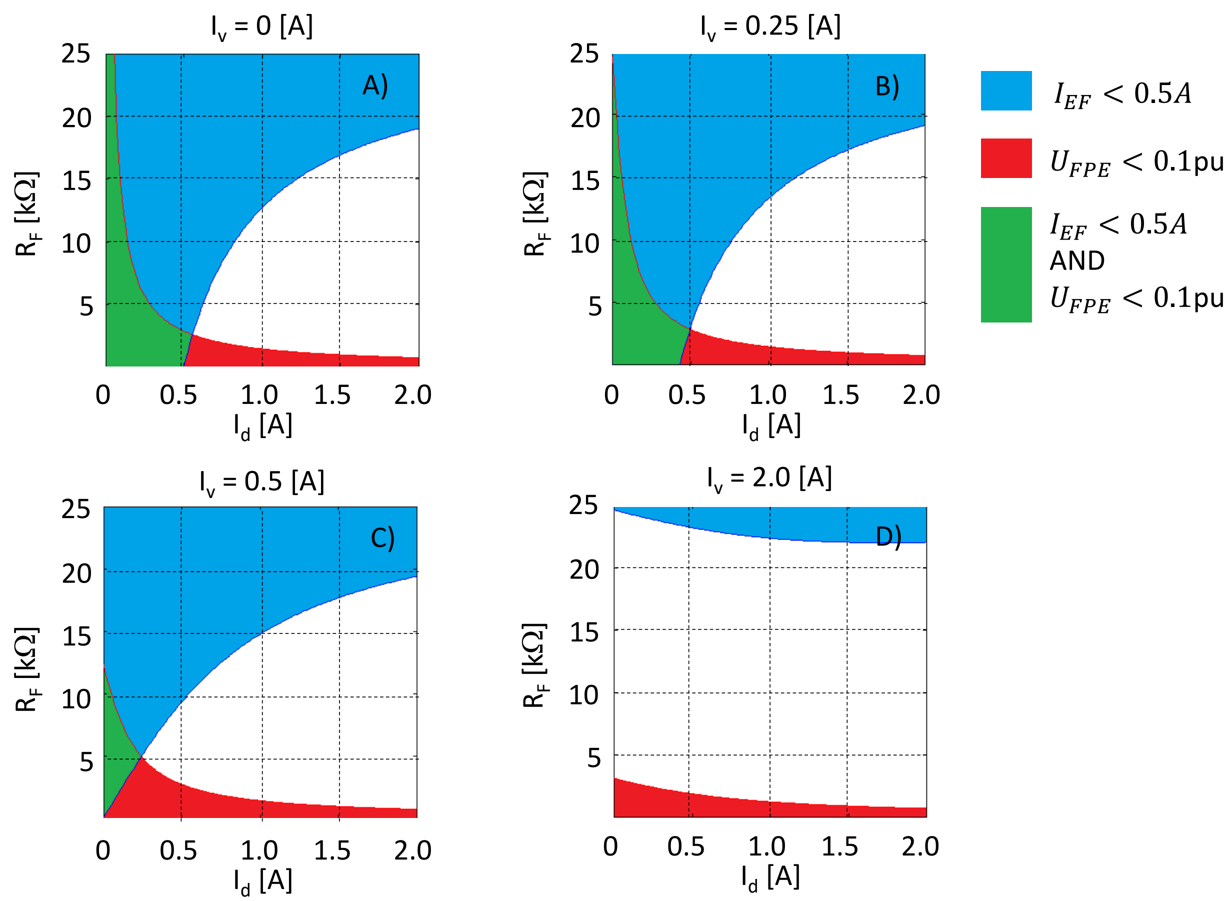

Figure 13 **Illustration on how fault resistance (R_F), network damping (I_d) and detuning (I_v) affect to the faulted phase voltage (U_{FPE}) and ground fault current magnitude (I_{EF}) in compensated 22kV network with passive ASC. In the figure, the shaded areas represent fulfillment of conditions: I_{EF} < 0.5A (blue), U_{FPE} < 0.1pu (red). Fulfilment of both conditions is presented with shaded green color.**

Starting from **Figure 13D** one can see that with detuning value of $I_v = (\pm)2A$, set conditions cannot be fulfilled simultaneously. Voltage condition is fulfilled only with low fault resistance values and ground fault current condition only with high fault resistance values. When detuning is reduced in **Figures 13C-13A** simultaneous fulfilment of both conditions becomes theoretically possible. But fulfilment of both conditions at high fault resistance values is only possible when both network damping and detuning are extremely small, close to zero amperes. Same result would be obtained in case of small unearthed network, where the capacitive current has similar low magnitude.

In typical compensated systems, where phase-to-ground capacitance values equal to tens to hundreds of amperes and where rated value of ASC have approximately same magnitude, such low values of damping and detuning cannot be achieved. This is due to the fact, that in practical system conductor and coil losses are typically already few per cent and the practical inaccuracy of coil tuning may be few amperes.

From **Figure 13** it can be concluded that to maximize sensitivity of ground fault detection, detuning and damping should be minimized. The exact value of network damping cannot be known before an ASC is installed. But after ASC is commissioned, the modern coil tuner provides numerical value for this important network parameter as illustrated in **Figure 14**.

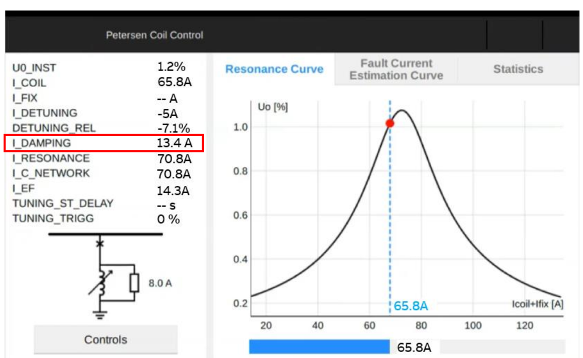

Figure 14 Example of interpretation of network damping value, I_d = I_DAMPING, calculated by the coil controller.

In order to construct a compensated network with passive ASC with extremely low damping and detuning value, large network can be splitted into smaller networks by e.g. opening bus-tie circuit breakers at the primary substation and by installing ASC for each transformer neutral point supplying such smaller networks. Another possibility is to apply an isolation transformer as suggested in reference [9] and illustrated in **Figure 15.**

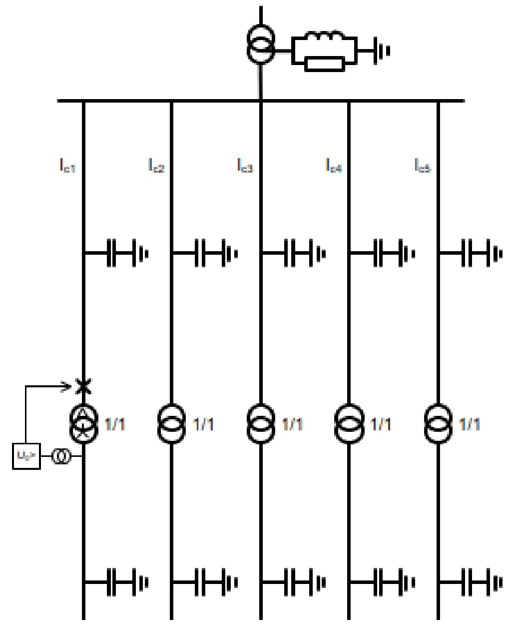

Figure 15 Example of applying isolations transformers to split a large network into smaller fault isolated networks [9].

In this solution, network section is isolated using 1:1 ratio isolation transformer (ITR), with neutral point treatment that prevents the flow of earth-fault current through the transformer. It should be noted that with the ITR, also through-fault short-circuit currents are considerably reduced. Therefore, the electrical parameters of the ITR must ensure dependable protection operation in case of short-circuit faults occurring behind the ITR, considering also faults in the LV-side. The advantage of the proposed concept is its technical simplicity, which greatly improves ground fault detection sensitivity compared to large network. Even reliable detection of high-ohmic and open-phase faults is possible. Further reduction of ground fault current magnitude can be achieved by installing an ACS into the load side neutral point of the ITR as suggested in reference [10]. One of the challenges of such small compensated network with very small value of damping and detuning is its inherent sensitivity to admittance unbalance. Large capacitance imbalance due to e.g. open phase condition may result in severe over-voltages, especially in case of resonance condition where over-voltages are only limited by the system damping, **Equation 5b-5c**. Similarly, the time constant of DCcomponent of ground fault current, oscillations, and transients during faults and after their disconnection may have long value. Voltage measurement should be made with sensor technology in order to avoid problems with ferro-resonance. Network should be preferable be operated in over-compensated mode, so that after tripping of the faulted feeder, resonance condition in the remaining network is not exhibited. In order to obtain selective detection of high ohmic faults, fault isolated compensated network must be well balanced in terms of phase admittances so that healthy state U_o remains at low value.

VII. SPECIAL PROTECTION CHALLENGES IN COMPENSATED NETWORKS

The principle solutions for ground fault protection in compensated networks have been known for decades. Based on the practical experience from real faults, it has been recognized that not all practical ground fault types can be selectively detected by fundamental frequency-based methods. They may fail in case there is no clear fundamental frequency component present in the measured voltages and currents. This may occur when the fault has transient or intermittent characteristic or when the waveforms generated by faults are rich with harmonics and non-sinusoidal content. Therefore, it is highly recommended that the fundamental frequency-based methods are complemented with protection methods utilizing:

1. Harmonic components
2. Transient components

Based on their operation principle, it can be concluded that application of such method is limited to certain fault type and fault characteristics.

Application of methods utilizing steady-state harmonic components (typically based on the 5th harmonic component) is limited due to the fact that harmonic content of fault signals varies in accordance with the harmonics source(s) and is thus time-dependent. Harmonics are also dependent on fault location and greatly attenuated due to fault resistance [11]. Setting values for such protection functions are thus rather difficult to be determined as the estimation of harmonic magnitudes during a ground fault must be done based on the harmonic levels measured in the phase-to-ground voltages during the healthy state [12].

The methods utilizing transient components are typically based on measuring the charge transient of the residual current at time of fault ignition. This transient component is due to the charging of the phase-to-ground capacitances of the healthy phases due to the fault. Equations for the charge transient frequency and initial amplitude can be found e.g. from reference [13]. Based on real measurements recorded in distribution networks, the typical frequency value of charge transient is rather low, in the range of 100 - 1000 Hz.

The classical transient based method, called as the *Wischer-method*, evaluates the fault current direction based on the polarities of residual current and neutral point voltage waveforms at time of fault ignition. Such time-domain methods are challenged in case switching transients or other non-fault related transients are superimposed into fault signals. Such situation may occur when closing the feeder circuit breaker onto fault during fault location process or during unsuccessful auto-reclosing sequence. This challenge and the basic operation principle of a classical Wischer-method is illustrated in **Figure 16**.

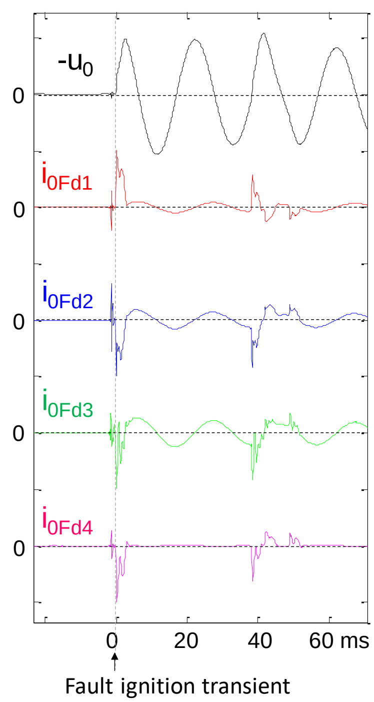

Figure 16 The basic operation principle of a classical Wischer-method: polarity comparison of neutral point voltage and residual current. Residual currents of four feeders Fd1-Fd4 are shown. Feeder Fd1 is the faulty one with superimposed switching transient.

Such transient based methods are capable in detecting steady-state low-ohmic ground faults and also re-striking and intermittent ground faults manifested by 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 17**, which shows a result from field tests conducted in Sweden. A high damping of transients, both amplitude and frequency, was observed when the fault spot was moved into the end of a long rural cable feeder (approximately 30 km from the substation).

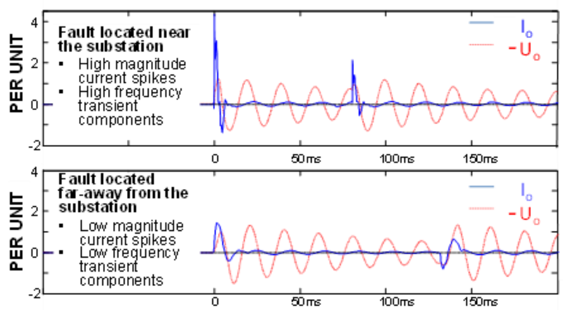

Figure 17 Effect of fault distance on ground fault transients during a re-striking ground fault.

In permanent low-ohmic ground 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.

Next, a few special, but typical, fault types encountered in practical compensated systems are studied in more details.

A. Transient ground faults

Transient or temporary ground fault is characterized by single or few arc transient(s), which have the ability to self-extinguish due to the compensation effect of the ASC. For temporary ground faults it is neither necessary nor desirable to trip the circuit breaker at the substation. In **Figure 18** three different types of temporary ground faults recorded in a real network 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.

Selective detection of transient faults can be used for example on preventive maintenance purposes or to give an alarm of gradually developing or latent insulation failures. Early detection of incipient faults 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.

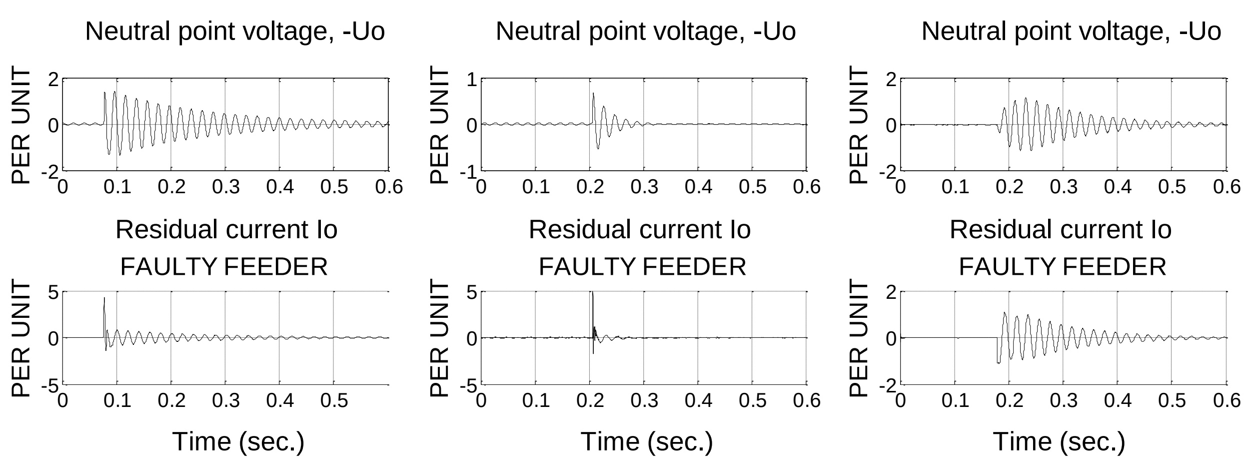

Figure 18 Transient ground faults with different time domain waveforms.

B. Restriking or intermittent ground fault

Re-striking ground fault is known to be the one of the most common fault type of permanent ground faults in compensated networks [14].

Re-striking ground faults have been in the focus of research of protection relay manufacturers during recent years, in order to develop selective, reliable and sensitive methods for this particular fault type. Several totally different methods and protection algorithms have been developed and implemented into protection relays in the past by different manufacturers. Re-striking ground fault has also been one of the most important single factors affecting the design of latest protection functions for compensated networks.

Re-striking ground fault is typically a result of insulation failure in cable sheaths, in cable joints or in cable terminations. Re-striking ground fault is characterized by repetitive and recurrent ground fault arcs with very short duration. This results in highly irregular and intermittent waveforms of residual quantities, which challenges the operation of conventional ground fault protection functions.

Figure 19-20 shows a few examples of recorded waveforms of residual current and neutral point voltage during a re-striking ground fault in a practical network.

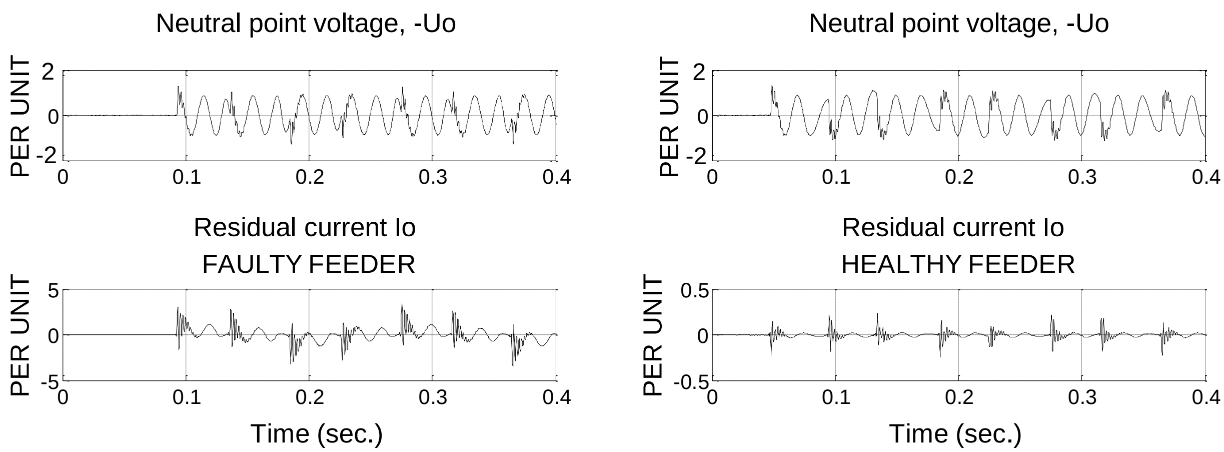

Figure 19 Restriking ground fault with high frequency components in the waveforms of Uo and Io

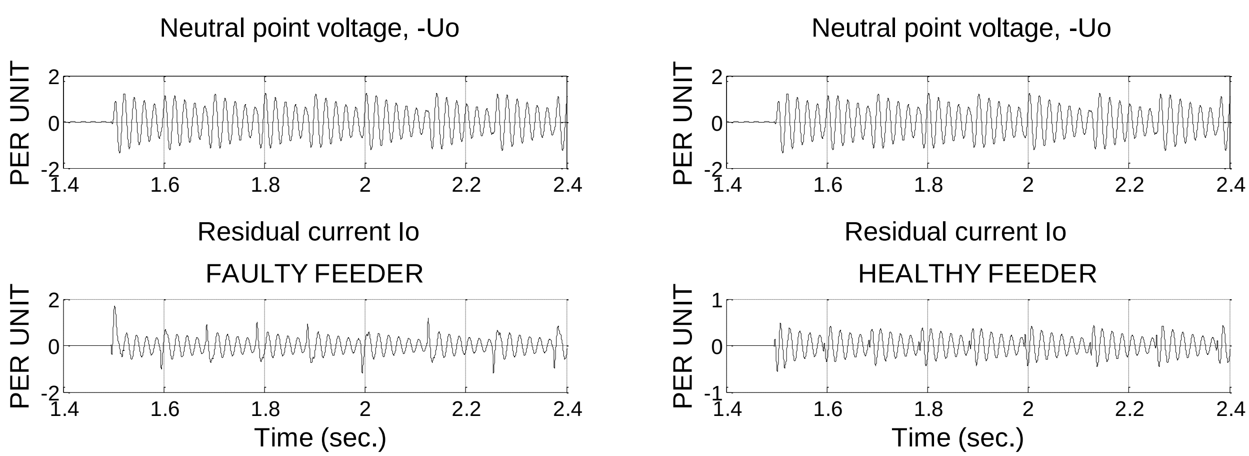

Figure 20 Restriking ground fault with damped transients in the waveforms of U_o and I_o.

During a re-striking ground fault, when the voltage exceeds the reduced voltage withstand level of damaged insulation, an insulation breakdown with very short duration occurs from phase conductor to grounded cable sheath. This is seen as a current spike with very short duration and high amplitude in the measured residual current. Simultaneously the measured neutral point voltage increases to its maximum value. The fault current is then extinguished by the compensation effect of the ASC after which the network returns back to healthy-state through the post-fault oscillations. The frequency and time constant of these oscillations is determined by the network parameters. Typically, the duration between the current spikes is between 100-500ms.

In overhead line network the fault condition would be over after the first fault arc extinguishment as the insulation, the air, can recover from the arcing fault. The fault would be in this case classified as a "transient" ground fault. In underground cables, however, the damage in insulation material is permanent that is, it is not able to self-heal. Therefore, in compensated cable networks the fault condition is not over, but it starts to repeat itself as a function of time.

Typically, after a maximum of few hundreds of milliseconds, the recovering voltage of the faulted phase exceeds again the reduced voltage withstand level of damaged insulation and a new short duration of arcing occurs. The re-striking fault mechanism is triggered, and it will continue until the fault is disconnected.

It is important to note that during a re-striking ground fault the actual fault duration is very short, typically only a few milliseconds at maximum. The main duration of re-striking ground fault consists of "post-fault oscillations" between successive fault current spikes, during which the network is healthy, and it is recovering from the fault.

Exact mathematical analysis of a re-striking ground fault is very difficult as the fault type is affected by several network and fault parameters. Based on the experience from analysis of hundreds of disturbance recordings, the waveforms of residual quantities during a re-striking ground fault are never similar, but each time different and therefore each fault is unique.

The great variation of waveforms of residual quantities during re-striking ground faults has hindered the finding of general solution for the appropriate protection function and algorithm. A novel solution for protection against this fault type will be introduced later in this paper.

1) *Why the basic ground fault protection is then not capable in operating correctly during a re-striking ground fault?*

The main purpose of "basic" ground fault protection functions applied in compensated system, such as *Iocos* or *conductance* criterion, is to provide sufficient sensitivity of protection. As high frequency components (transient, harmonics) are greatly damped due to fault resistance, these methods are based on the resistive fundamental frequency component of residual quantities.

When the fundamental frequency component is extracted from waveforms with non-sinusoidal, intermittent and decaying characteristic, high oscillations of protection operation quantities results. See **Figure 21** for illustration of oscillations in fundamental frequency phasor magnitude, phase angle and the extracted resistive component (*Iocos*).

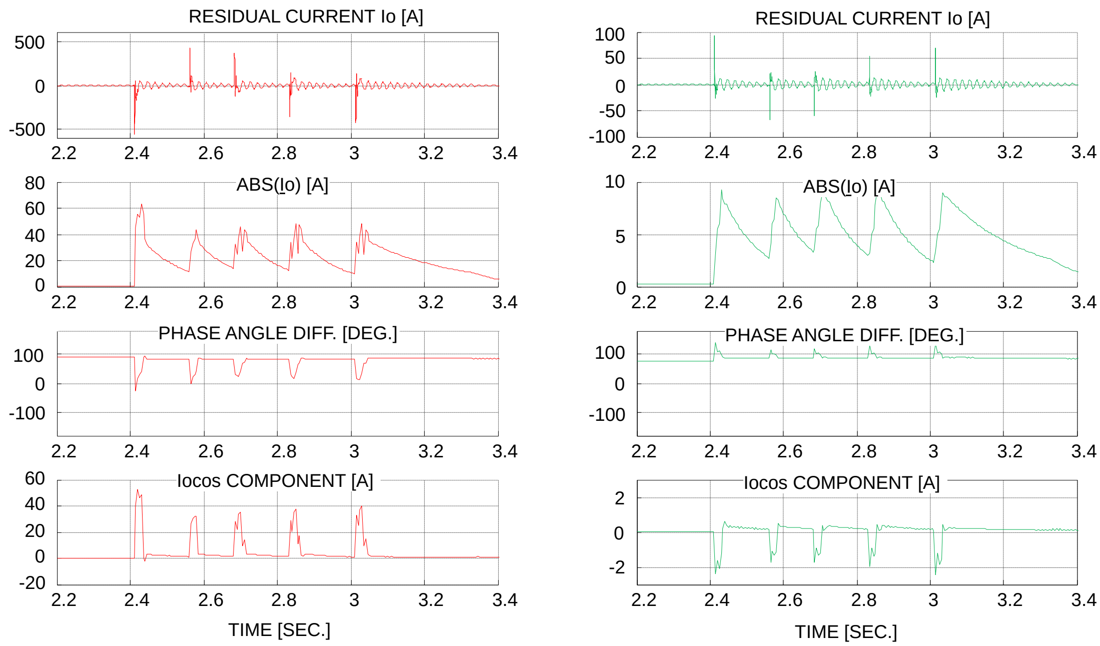

Figure 21 Oscillation of fundamental frequency phasor magnitude and phase angle. Measurement from the faulty feeder (left) and from the healthy feeder (right).

Oscillations in fundamental frequency phasor magnitude and phase angle leads to many risks that jeopardize the correct operation of fundamental frequency based protection functions during re-striking ground faults:

- The protection at the healthy feeders, which should not operate, may produce unselective pickups, or even unselective tripping due to the fact that operation phasor is falsely seen in the operate sector of protection.

- The trip of faulty feeder may be delayed or even totally hindered. The dependability of the protection scheme is therefore jeopardized.

- Due to delayed or hindered operation of protection in the faulty feeder, the substation back-up protection may become activated before the fault is disconnected. This may lead to tripping of the incoming breaker resulting in unwanted and unnecessary outages for all the customers fed by this substation.

Such protection maloperations have been reported from practical compensated networks, where dedicated re-striking ground fault protection has not been applied. It is therefore highly recommended to always use a dedicated protection function for re-striking ground fault in protection configurations in compensated cable networks.

Based on the experience, ground faults in compensated cabled networks are very often initially started as re-striking ground faults. It should be noted that during a single phase ground fault, there is a 173% voltage stress in the healthy phases. If protection is not capable to detect and disconnect these types of faults, there is a risk that such single phase fault may evolve in to more serious fault type, typically into two-phase cross-country fault or into two or three phase short-circuit fault with more serious consequences.

VIII. MULTI-FREQUENCY ADMITTANCE BASED GROUND FAULT PROTECTION

Next, the novel ground fault protection function available in the latest versions of ABB's protection relays for compensated MV-networks is presented. With the novel algorithm, the protection challenges of modern compensated networks can be faced. Multi-frequency admittance protection provides reliable protection against all types of ground faults in a single function, including intermittent and transient ground faults, and also ground faults with higher fault resistance value.

A. *Background and motivations for the new functionality*

Based on practical experience of studying the ground fault protection challenges in practical compensated distribution networks, the residual quantities measured by ground fault protection are very seldom pure sinusoidal, but they are characterized by ever increasing share of harmonics. Also, faults have very often intermittent characteristics, and so the exact waveforms of residual quantities cannot be predicted beforehand [1].

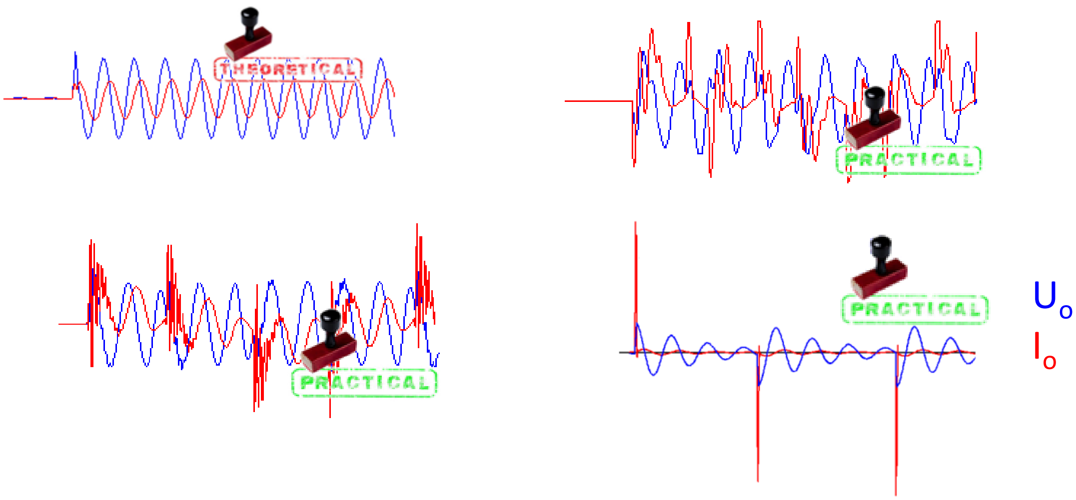

Figure 22 Recorded waveforms of U_o and I_o during a real ground faults in compensated networks.

The goal for this new protection algorithm was to design a single protection function, which could protect against all ground fault types encountered in practical compensated networks. The setting principles should be easy and based on the basic network parameter data. Protection reliability should be independent of network's actual compensation degree.

In order to achieve these goals, the novel protection function includes several totally new and innovative ideas in the field of ground fault protection in high-impedance grounded networks.

Firstly, the sufficient sensitivity of protection is achieved with admittance based phasor calculation, which includes always the fundamental frequency component. The admittance calculation makes the estimated operation quantity independent of fault resistance. This enhances sensitivity and makes setting principles very easy.

Secondly, the non-sinusoidal, distorted and intermittent waveforms of residual current and neutral point voltage, which are encountered especially during re-striking ground faults, are actually utilized in the algorithm. Traditionally, these higher frequency components have been considered as disturbances that need to be filtered out. However, in the multi-frequency admittance protection function, these higher order harmonic components improve the discrimination between faulty and healthy feeder. This is achieved by calculating admittances at harmonic frequencies and adding them in complex phasor format into the fundamental frequency admittance phasor. The resulting *sum admittance phasor* $\overline{Y}_o^{sum}$ applied in directional estimation of fault is given by **Equation 12** [15]:

$$\overline{Y}_o^{sum} =$$

$$Re\left[\overline{Y}_o^1\right] + j \cdot Im\left[\overline{Y}_o^1 + \sum_{n=2}^{m} \overline{Y}_o^n\right] \qquad (12)$$

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.

Harmonic admittance components are included in the sum admittance phasor, if the specific harmonic component is measurable by the protection relay.

Utilization of harmonic components in residual quantities is beneficial as this eliminates the influence of the compensation coil's inductive current from residual quantities measured at the faulty feeder. This is based on the fact that the inductive reactance of ASC is directly proportional to frequency

($X_{ASC} = \omega \cdot L_{ASC}$). At higher than nominal frequencies, the impedance of ASC is high, and its compensation effect is thus very low. For the harmonic components the admittance phasors in the faulty and healthy feeders point into opposite directions as in case of an ungrounded network, regardless of the network's actual compensation degree. This makes the directional evaluation at harmonic frequencies independent from networks actual compensation degree resulting in more distinct discrimination between faulty and healthy feeder.

Thirdly, multi-frequency admittance protection introduces a completely new method of determining fault direction with phasor calculation. With traditional phasor calculation methods there are great problems with selectivity of protection due to the fact that during re-striking ground faults, high magnitude of oscillation is introduced to such discrete phasors. This is however not the case with the multi-frequency admittance protection, which utilizes a novel phasor calculation method called as *Cumulative Phasor Summing* (CPS).

In CPS-calculation, values of the complex *sum admittance* phasors are added together in phasor format starting at time t_{start} (fault start) and ending at time t_{end} (fault end), **Equation 13**:

$$\overline{Y}_{osum_{CPS}} = \sum_{i=t_{start}}^{t_{end}} Re[\overline{Y}_{osum}(i)] + j \cdot \sum_{i=t_{start}}^{t_{end}} Im[\overline{Y}_{osum}(i)] \quad (13)$$

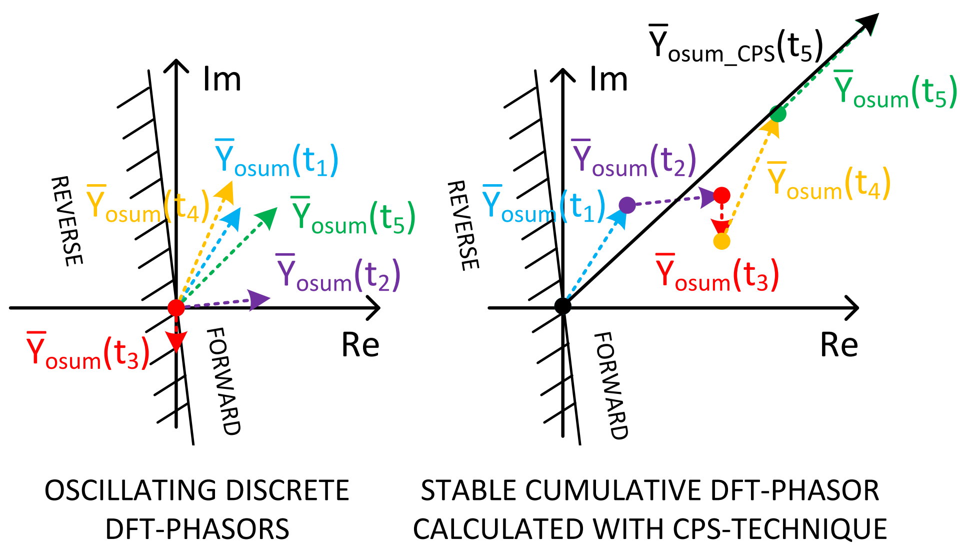

Figure 23 Illustration of the Cumulative Phasor Summing (CPS) concept (faulted feeder).

The start criterion for the CPS-calculation is obtained from internal residual over-voltage condition (Uo>), which defines the basic sensitivity of the multi-frequency admittance protection. The benefit of CPS-calculation is the unique filtering effect to the oscillating discrete DFT-phasors. It enables very dependable and secure fault direction evaluation with DFT-phasors, regardless of the fault type – even the direction of re-striking ground faults can be indicated reliably.

Fourthly, the previously described novel directional element is additionally supervised by a unique current magnitude supervision element. With this element, the correct fundamental frequency current magnitude can be obtained regardless of fault type or fault resistance value, **Equation 14** [15]:

$$\overline{Y}^{1}_{o\,stab} = \frac{\overline{I}^{1}_{oCPS}}{-\overline{U}^{1}_{oCPS}} = Re\left[\overline{Y}^{1}_{o\,stab}\right] + j \cdot Im\left[\overline{Y}^{1}_{o\,stab}\right] = G_{ostab} + j \cdot B_{ostab} \quad (14)$$

This "stabilized" admittance value can be converted into the corresponding current value by multiplying it with the system nominal phase-to-ground voltage value (U_{PE}), **Equation 15**:

$$\bar{I}^{1}_{o\,stab} = (G_{ostab} + j \cdot B_{ostab}) \cdot U_{PE}$$
$$= I^{1}_{oCosstab} + j \cdot I^{1}_{oSinstab} \quad (15)$$

The operate current value given by **Equation 15** matches the correct steady-state information, and in practice it does not depend on the fault type or fault resistance value. This means that 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 24**, which shows results from field tests conducted in Finland. Three different fault types are compared (from left to right): permanent low-ohmic fault, re-striking fault and permanent higher-ohmic fault. The bottom row shows the real-parts of stabilized admittance calculation converted into corresponding current value according to **Equation 15**.

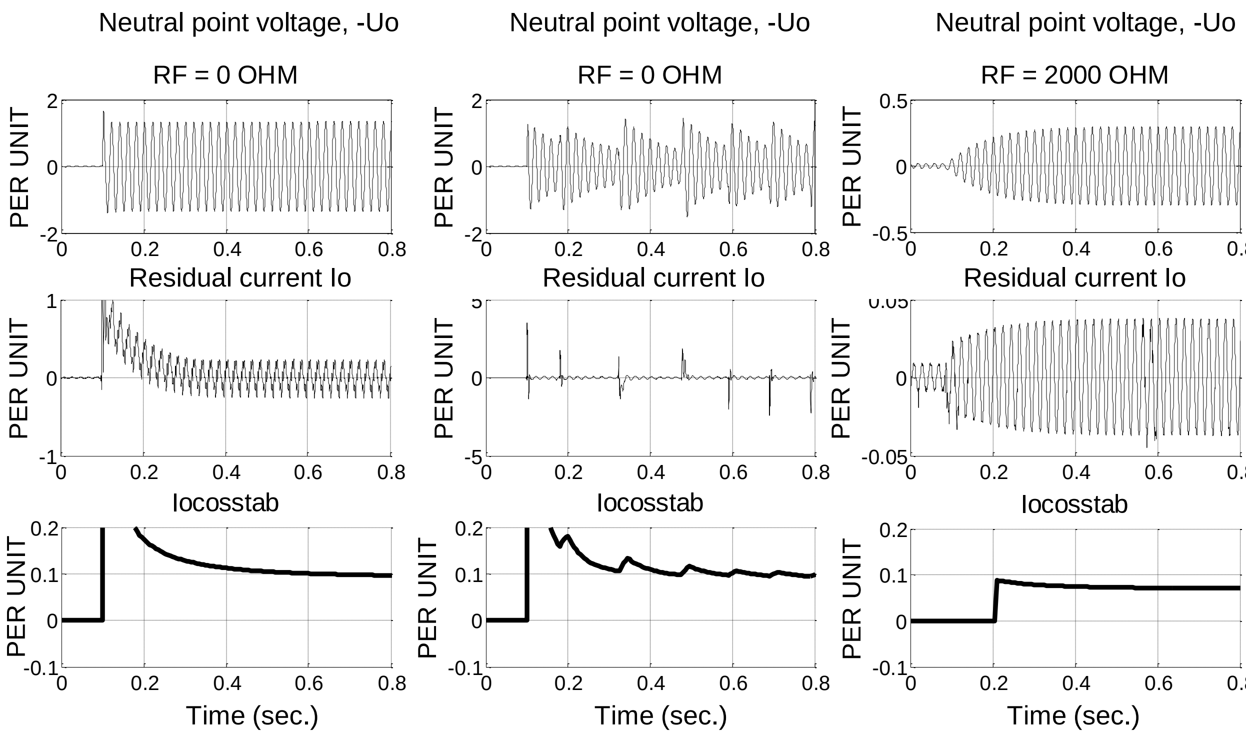

Figure 24 Estimation of real part of the operate quantity with the cumulative summing technique in the faulty feeder.

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 background 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.

Fifth unique feature of the multi-frequency admittance protection is the automatic adaptation of operation current 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 current magnitude supervision element. The phase angle sectors for this purpose are depicted in **Figure 25** together with the examples of accumulated sum admittance phasors.

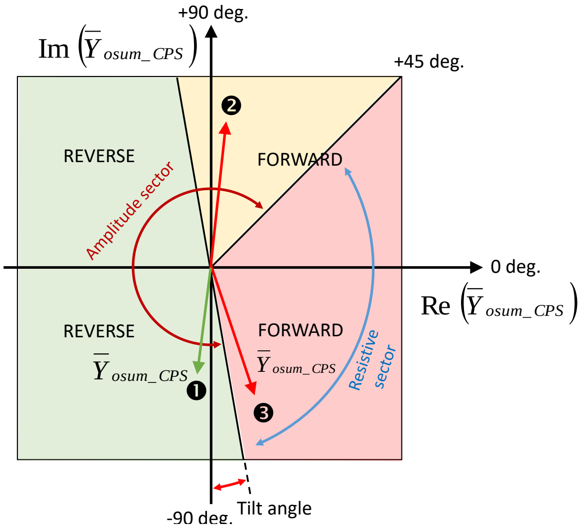

Figure 25 Illustration of the directional characteristics of the multi-frequency admittance function.

- Phasor ① depicts the direction of the accumulated sum admittance phasor if a ground fault occurs outside the protected feeder (i.e. in reverse direction).
- Phasor ② depicts the direction of the accumulated sum admittance phasor if a ground fault occurs inside the protected feeder (i.e. in a forward direction) regardless of the fault type, when the network is ungrounded. The result is also valid in compensated networks when there are harmonics present in the fault quantities.
- Phasor ③ depicts the direction of the accumulated sum admittance phasor if a resistive ground fault occurs inside the protected feeder without harmonics in the fault quantities, when the network is compensated.

This self-adaptive feature of multi-frequency admittance enables operation in ungrounded networks as well. Operation is possible even without the parallel resistor in compensated networks if there are plenty of harmonics present, e.g. during restriking ground faults.

B. Validation of performance with real network test

This novel method for selective ground fault detection and protection for compensated networks is the result of intensive research and development work of many years. One crucial factor enabling the development of this new functionality is the numerous practical field tests conducted in live MV-networks. The correct operation of this novel function is validated with tens of practical field tests and with thousands of individual test shots.

Next the novel features of multi-frequency admittance protection are demonstrated with examples from a practical field test from a 20kV distribution network (f_n=50Hz). Also, the calculation principle of the key setting parameters is explained.

1) Description of network topology and selected settings

The network is a 20kV compensated network with 61.5A of capacitive ground fault current. Network consist of mixture of over-headlines and underground cables; the share of cabling is increasing continuously. The network is operated normally with -2A under-compensation (coil current is 61.5-2 = 59.5A) with 8A parallel resistor (@20kV). The parallel resistor has ON-OFF-ON logic i.e. it is continuously connected during the healthy state, but after the ground fault is detected with residual overvoltage condition, the resistor is disconnected for 500ms and then connected back. The purpose of the logic is to decrease the ground fault current during the fault and alleviate conditions for self-extinguishment of fault arc. The shunt losses of the coil and the feeders are determined by the coil controller to be 3.6A.

There are four feeders connected to the substation and their capacitive ground fault currents vary between 2-31A. The basic network parameters required for ground fault calculations are then at primary voltage level:

U_{PE} = 20000V/√3 = 11547V, I_{EFNet} = 61.5A, I_{Coil} = (I_{EFNet} -2A) = 59.5A, I_{Par} = 8A, I_{EFFd} = 2-31A, d_{Net} = 0.03pu, d_{Coil} = 0.03pu

The key setting values for multi-frequency admittance protection are derived from basic network values as follows:

- **Voltage start value**: The setting *Voltage start value* defines the basic sensitivity of the multi-frequency admittance protection. To avoid unselective start or operation, *Voltage start value* must always be set to a value which exceeds the maximum healthy-state zero-sequence voltage value, taking into consideration of possible network topology changes, compensation coil and parallel resistor switching status and compensation degree variations.

- From the resonance curve of the coil controller, maximum value of neutral point voltage during the healthy state is determined. It is approximately 2% when parallel resistor is connected. It will not exceed 3% at any conditions.

⇒*Voltage start value* is set to 5%.

Utilizing **Equation 11a**, the theoretical sensitivity of protection corresponding the *Voltage start value* can be calculated - it is approximately 18kΩ.

- **Min operate current**: The setting *Min operate current* is the set threshold level for the current magnitude supervision element, **Equation 15**. The value is selected based on the total resistive (wattmetric) leakage loss current of the network [A], which is calculated by the coil regulator. In order to secure operation with the current of the parallel resistor, the value must be set to value that is lower than the value of parallel resistor of the coil (with margin). In this case parallel resistor gives 8A@20kV

  ⇒*Min operate current is set to 4.2A (0.06*In, In = 70/1A)*

  - From the basic network parameters calculated by the coil controller, the total resistive leakage loss current of the network is 11.6A (=total damping value). With the knowledge that the parallel resistor gives 8A, the natural losses of the network and the coil are 11.6-8 = 3.6A. There is large margin used in *Min operate current* setting (11.6A-4.2A = 7A), which enables dependable operation in the protected feeder.

  - This setting 4.2A@11.547kV provides also a good security for protection operation as it allows a phase displacement for the CBCT used for residual current measurement.

- **Tilt angle**: The setting *Tilt angle* should be selected based on the measurement errors of the applied residual current and voltage measurement transformers.

  - In this case the inaccuracy of CBCT is considered to be the most dominant. CBCT is a protection class CBCT: 10P10, 1VA. Accuracy of CBCTs with low current values was evaluated prior to the tests and the setting *Tilt angle* is set accordingly.

  ⇒ *Tilt angle* is set to 10 degrees.

- **Reset delay time**: Setting *Reset delay time* is used to keep the operate timer activated between current spikes during intermittent or re-striking ground fault. This avoids repetitive activation and reset of the function in case of intermittent faults. Setting *Reset delay time* should be set to a value exceeding the maximum expected time interval between the current spikes, which is typically obtained at full resonance condition of the network. The recommended value is at least 300 ms.

  ⇒ *Reset delay time* is set to 500 ms.

2) Performance comparison

In the following, the operation of the novel algorithm is analyzed with typical fault types occurring in compensated networks in practice. For comparison, the directional and operate quantities of a standard residual current based protection method utilizing fundamental frequency phasors are also shown (denoted as DFT).

In the figures, measurement results from the faulty feeder (on the left) and from one of the healthy feeders (on the right) are shown. The meaning of the subplots are as follows:

- first row: measured neutral point voltage [kV]
- second row: measured residual current [A]
- third row: estimated magnitude of residual current (50Hz): DFT and CPS-method.
  - The estimate of CPS-method is according to **Equation 15**: abs($I^1_{oCosstab} + j \cdot I^1_{oSinstab}$)
- fourth row: estimated resistive component of residual current (50Hz): DFT and CPS-method.
  - The estimate of CPS-method is according to **Equation 14**: $I^1_{oCosstab}$
- fifth row: phase angle difference is calculated as $-\overline{U}_o$ being the reference phasor
  - The phase angle difference of CPS-method is according to: $\varphi = \angle -\overline{U}_o$ - $\angle \overline{Y}_{osum\_CPS}$
- sixth row: binary signal, ST = Start, OP = Operate, BLK_EF = Indication of outside fault

a) Permanent, stable, resistive ground faults

In **Figures 26-28** results are presented for permanent, stable ground faults with three different fault resistance (R_F) values 0, 5000 and 10000 Ω.

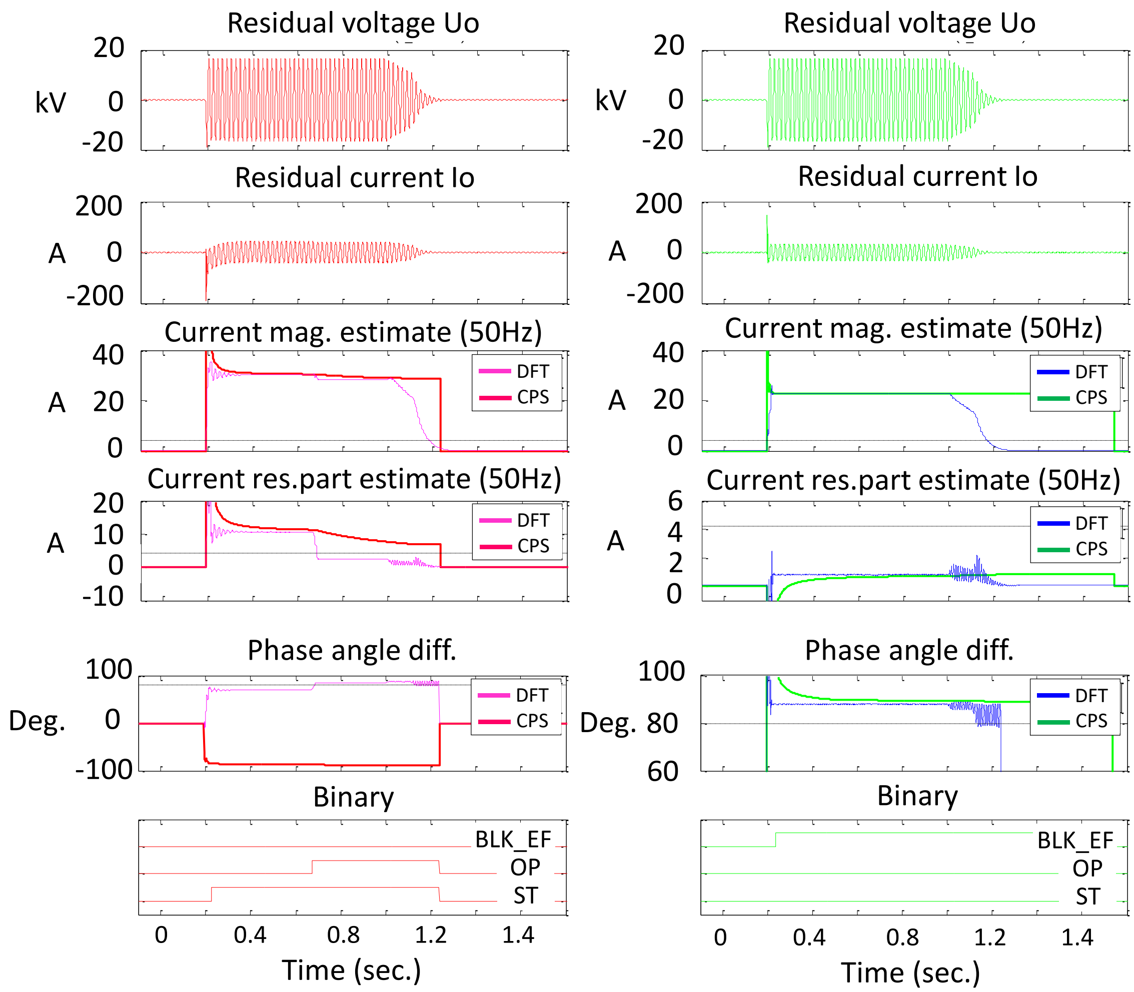

Figure 26 Permanent, stable ground fault, R_F = 0Ω; faulty feeder (left), healthy feeder (right).

From **Figure 26** it can be concluded that in this test case with solid ground fault (R_F = 0Ω), there is a lot of harmonics included in the residual quantities. The utilization of harmonic components makes the directional phasor of the novel method in the faulty feeder to behave as in case of an ungrounded network (angle difference is close to -90 deg.). This makes the directional evaluation at harmonic frequencies independent from networks actual compensation degree resulting in more distinct discrimination between faulty and healthy feeder.

It can be seen that the estimated resistive component in the faulty feeder corresponds to the value of the parallel resistor of the coil (plus the resistive losses of the background network). In the healthy feeder, due to the measurement inaccuracies, the estimated resistive component has the same polarity as in the faulted feeder. However, this apparent resistive component is considered by proper selection of settings *Tilt angle* and *Min operate current*.

The combination of the novel directional phasor evaluation method with the novel method of estimating the resistive component, provides us an extremely selective and secure fault directional determination.

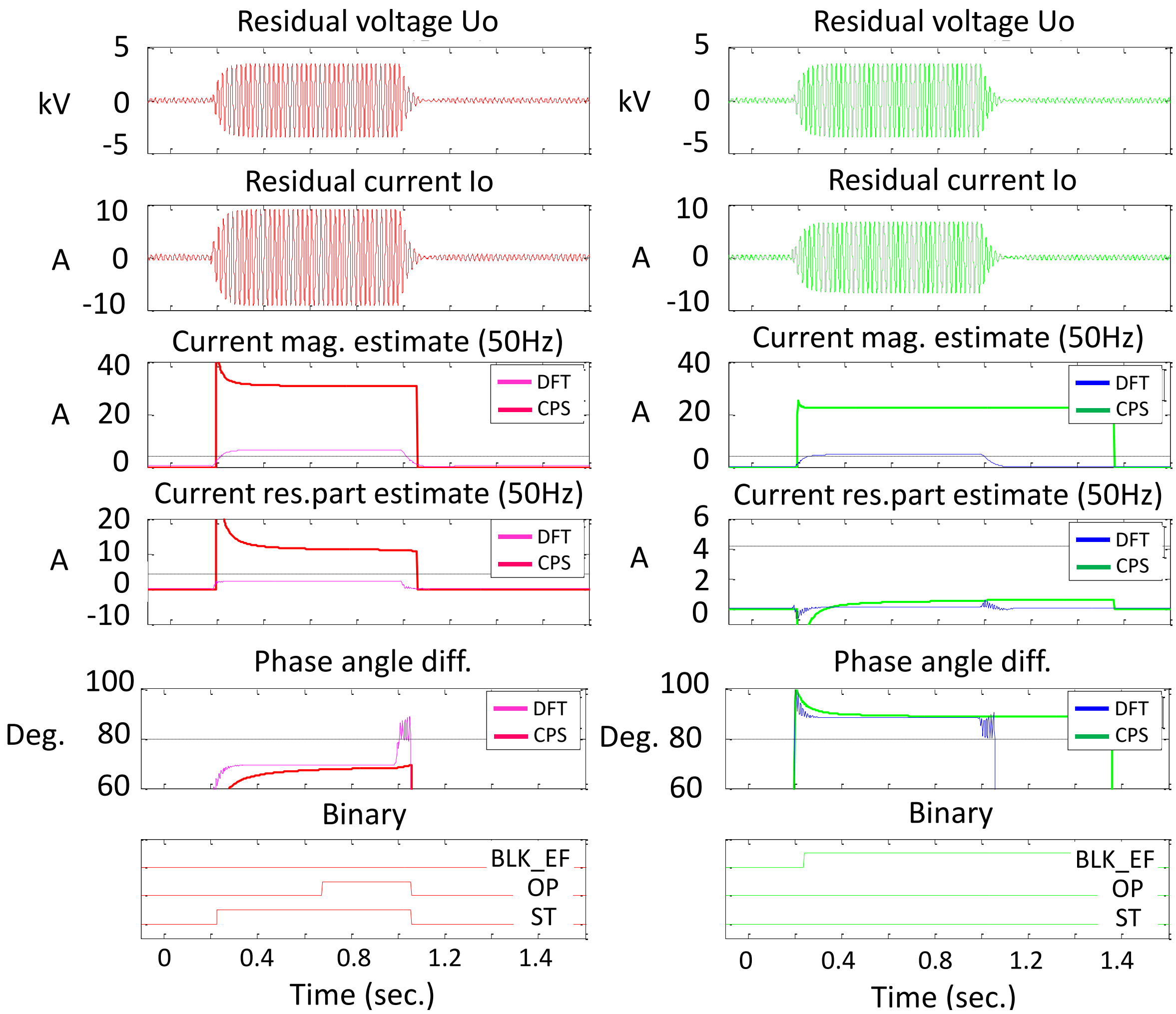

Figure 27 Permanent, stable ground fault, R_F = 5000Ω; faulty feeder (left), healthy feeder (right).

From **Figures 27-28** it can be concluded that when the fault resistance value increases, the magnitudes of neutral point voltage and residual currents are greatly reduced and there is also a long time constant introduced into the build-up of fault quantities. However, the high fault resistance does not affect the resistive component estimate of the novel algorithm. The estimated resistive component in the faulty feeder corresponds to the same value obtained with a solid ground fault. This is achieved with the admittance calculation in combination with the cumulative phasor summing technique.

Due to the fact that higher order harmonics are fully damped by the fault resistance, the directional evaluation in the novel algorithm operates in this case based on the accumulated fundamental frequency phasor.

Again, the combination of the novel directional phasor evaluation method with the novel method of estimating the resistive component, provides us an extremely selective and secure fault directional determination also during resistive faults. In this particular case even ground faults with 10000Ω of fault resistance can be selectively detected.

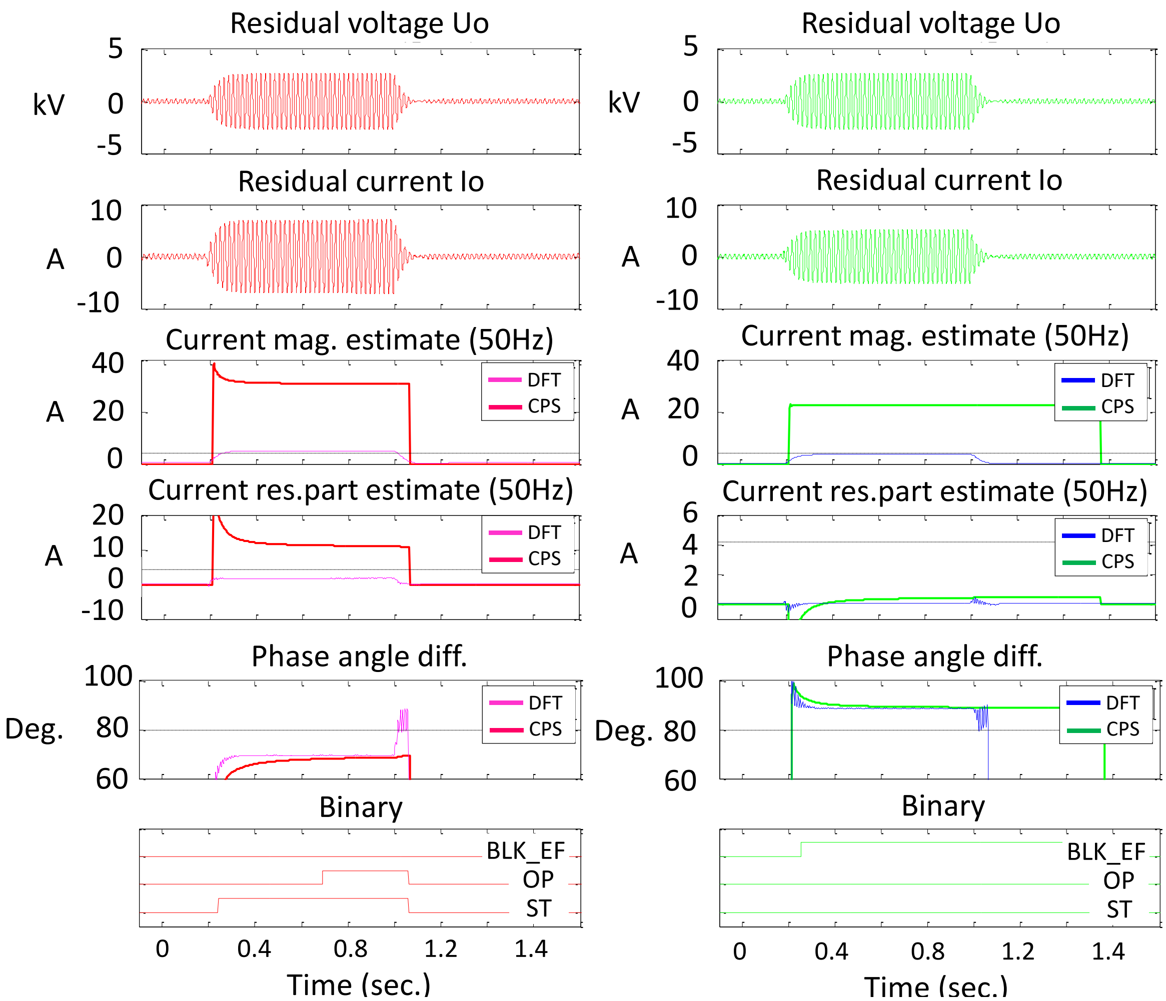

Figure 28 Permanent, stable ground fault, R_F = 10000Ω; faulty feeder (left), healthy feeder (right).

b) Restriking ground faults

In **Figure 29** the results from a re-striking ground fault test are presented.

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 makes the directional phasors in the faulty and healthy feeders point into fully opposite directions (angle difference φ is +90/-90 deg.) as in case of an ungrounded 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_ST-signal indicates that the fault is outside the protected feeder i.e. in reverse direction.

For the standard DFT-based method both the directional and operate quantities are very unstable resulting in unreliable operation of protection. The traditional phasor calculation does not produce stable resistive component estimate during an intermittent ground fault. There is a risk for unselective tripping of the healthy feeder and non-operation or delayed operation of the faulty feeder.

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.

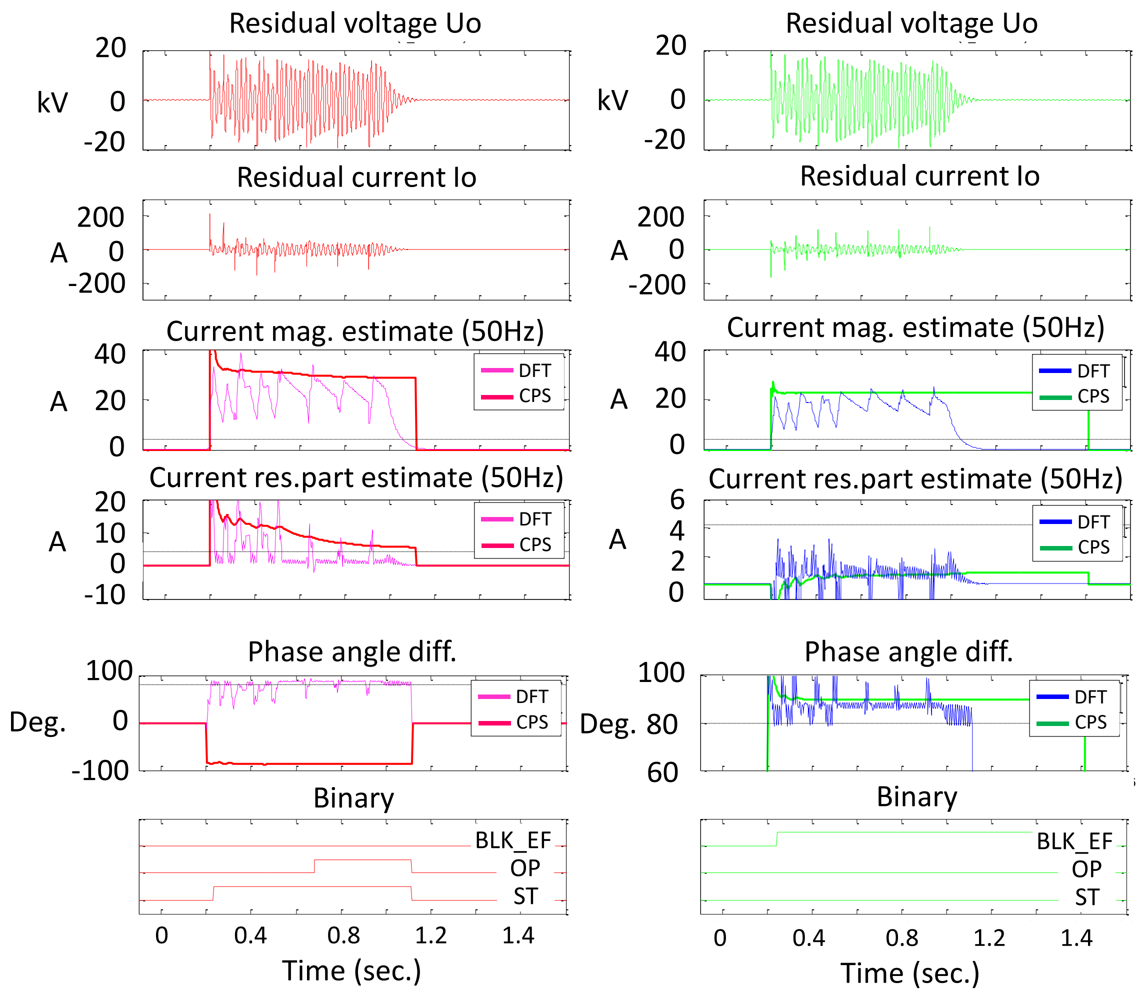

Figure 29 Re-striking ground fault; faulty feeder (left), healthy feeder (right).

From **Figure 29** the great stabilization effect introduced by the cumulative phasor summing technique is seen, which is utilized in the novel algorithm. In the novel algorithm, the resistive component produced by the parallel resistor of the coil can be estimated regardless of the fault type or fault resistance value. This unique feature is achieved by combining admittance calculation with the accumulative phasor calculation. It can be seen that the estimated resistive component in the faulty feeder corresponds to the value of the parallel resistor of the coil (plus the resistive losses of the background network) as it should be.

By combining the novel directional phasor evaluation method with the novel method of estimating the resistive component, gives us an extremely selective and secure fault directional determination during an intermittent ground fault.

VIII. Conclusion

As discussed in this paper, compensated networks could be a solution to the challenges faced today by North American utilities to detect high impedance faults in electrical grids. Reliably detecting ground faults is even more critical when the power lines run close to areas where people, animals are around, and forest fires can spread very swiftly if started. Compensated networks offer the greatly lower energy levels in case of a ground fault compared with solidly grounded networks, and therefore the likelihood of initiating a fire is reduced dramatically. Furthermore, with the Multi-frequency admittance-based ground fault protection introduced here, the specific protection challenges of compensated networks can be solved, the setting of the protective element can be simplified and the need to have different protective elements to detect ground faults in compensated networks with high harmonic content, transient, or re-striking/intermittent behavior is eliminated.

IX. References

[1] A. Wahlroos and J. Altonen, "Compensated neutral networks and multi-frequency admittance protection," Cigre, Australia, 2017.

[2] S. Zubic, A. Wahlroos and J. Altonen, "Managing post-fault oscillation phenomenon in compensated MV-networks," DPSP-conference, 2016.

[3] A. Wahlroos, J. Altonen and et.al., "Practical application and performance of novel admittance based earth-fault protection in compensated MV-networks," CIRED, 2011.

[4] A. Wahlroos, J. Altonen and et.al., "Improving personal safety in MV-networks through novel earth-fault current based feeder protection," CIRED, 2019.

[5] A. Services, "Rapid Earth Fault Current Limiter (REFCL) Program. Equipment Buiding Blocks Functional Descriptions.," 2017.

[6] m. consulting, "REFCL Trial: Ignition Tests," Beaumaris, 2014.

[7] Powerline bushfire safety program, REFCL technologies final report, 4 December, 2015.

[8] Electricity Safety (Bushfire Mitigation) Regulations 2013, version 005 in force, https://www.legislation.vic.gov.au/in-force/statutory-rules/electricity-safety-bushfire-mitigation-regulations-2013/005

[9] Jordfelsdetektering i mellanspänningsnät, raport 2015:128, 2015, (in Swedish)

[10] Wildfire Mitigation: SCE's Approach to Isolating Ground Faults, Andrew Swisher, Jesse Rorabaugh, August 04, 2020, https://www.tdworld.com/

[11] K. Frowein and et.al., "Model for the Calculation of the Fundamentals and Harmonic Component of the Residual Earth Fault Current in Medium Voltage Networks," STE-conference, 2017 (in German).

[12] E. Hufnagl and et.al., "Efficient calculation of earth fault currents in compensated networks," in 24th expert meeting "Komunalna energetika/Power engineering", 2015.

[13] M. R. Adzman, "Earth Fault Distance Computation Methods Based on Transients in Power Distribution Systems," in Doctoral dissertation, Aalto University, 2014.

[14] J. Bergeal, et.al., "Single-phase faults on compensated neutral medium voltage networks," CIRED, 1993.

[15] A. Wahlroos, J. Altonen and et.al., "Application of novel cumulative phasor sum measurement for earth-fault protection in compensated MV-networks," CIRED, 2013.

Biographies

Ari Wahlroos is working as a senior principal engineer at the ABB Distribution Solutions located in Vaasa, Finland. His recent work has focused on research and development of earth fault detection and localization algorithms. He has a M.Sc. degree in electrical engineering from the Technical University of Tampere, Finland.

Janne Altonen is working as a senior application specialist at the Distribution Solutions located in Vaasa, Finland. His recent work has focused on research and development of earth fault detection and localization algorithms. He has a M.Sc. degree in electrical engineering from the Technical University of Tampere, Finland.

Joe Xavier received his bachelor's degree in Electrical & Electronics Engineering from Mahatma Gandhi University, India with a Distinction. In 1993, he started his career as a protection engineer. He joined ABB India in 1996 and served over 13 years before moving to ABB in the United States. During these years Joe has been involved with Application & Marketing of Protection, Automation, MV, HV products and systems of ABB. Currently Joe is the West Region Technical Manager for ABB Distribution Protection & Automation division based out of Camas WA. He is involved with Application, Marketing, Training & Solution building for customers in Utility, Industry, Transportation & Infrastructure segments. Joe has co-authored and presented several technical papers on Protection & Automation applications and is an active member of IEEE – PSRC