PHASOR-BASED
TRANSIENT EARTH-FAULT PROTECTION

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Abstract

The main problem for any transient earth-fault (i.e. ground-fault) protection in high-impedance grounded system is to extract the useful signal components from the measured residual current I_0. Many used solutions are based on either complete fundamental frequency and/or complete higher harmonic phasors. However, for the fundamental frequency current phasor of the I_0 current, only the $I_{01}*\cos(\phi_1)$ component has useful physical meaning during the ground fault transient, while the $I_{01}*\sin(\phi_1)$ component is just a disturbing part which can only cause the wrong operation of the protection. At the same time, for all higher harmonic phasors of the I_0 current the situation is exactly the opposite. The $I_{0h}*\sin(\phi_h)$ is the useful component with a clear physical meaning while the $I_{0h}*\cos(\phi_h)$ component is a disturbing part which can only upset the ground-fault measurement. In the proposed solution, only the two useful phasor components are used. They are first integrated over short period of time deriving values proportional to the energy content of the two original signals. Only the positive or negative sign of these integrated values is then used in the design to determine the direction of the ground fault. Before being used for directionality check, the integrated value must also exceed the pre-set minimum threshold level, for security reasons. Another important property of these two quantities is that they will be approximately equal to zero during all operating conditions of the protected network except during the transient period of the ground-fault and consequently they can be then easily detected.

1. Introduction

Most of publications regarding transient ground-fault protection (67NT) are mainly concerned about problems and challenges posed by radial distribution networks which are high-impedance grounded [1,2,3,4,5]. However, we shall be aware that large, meshed, HV sub-transmission networks exist which also have resonant grounding (i.e. arc suppression coil or Petersen coil grounding). For example, 132kV network in Norway, 110kV network in Germany and Finland, 70kV network in Sweden, 50kV and 60kV networks in Denmark, etc. Such networks can be compensated by several, for example nine, geographically spread-out Petersen coils. The total capacitive Ground-Fault (GF) current in such networks can be in order of several hundred or even more than thousand amperes. All, or some of the used Petersen coils are automatically regulated in order to provide adequate resonant compensation. Such networks raise the complexity for the transient ground-fault protection to a new level. Some of the possible issues are:

1. Compensation coils are geographically distributed. The flow of reactive power in the zero-sequence system will be different for the same GF location depending on any line outage in the interconnected system or maintenance periods of the individual compensation coils, at the actual time of the fault.
2. Certain parts of the network can be either heavily over- or under-compensated. Such network states shall not affect the ground-fault protection performance.
3. Breaker switching in the network during a ground-fault will change the compensation degree and consequently distribution of the reactive power flow. Such switching shall not affect the ground-fault protection performance.
4. Steady state GF current in a healthy feeder does not necessarily correspond to its own capacitance to ground
5. In meshed networks, overhead power line (OHL) asymmetries can cause false flow of the zero-sequence currents. Such circulating currents should have minimum impact on the ground-fault protection performance.
6. The possibility of a cross-country fault is much bigger due to much higher voltage levels. Such high-level cross-country faults shall not affect the ground-fault protection performance.

2. Grounding of Power System Neutrals via High-Impedance

For all high impedance grounded system, a common thing that will happen in case of a ground fault are:

1. Steady state current in the faulty phase will be relatively small
2. Voltage of the faulty phase will be zero (for a ground fault without any fault resistance)
3. Voltages on the two healthy phases will rise from phase-to-ground level before the fault to the phase-to-phase voltage level
4. The neutral point voltage will be raised from zero (before the fault) to the rated phase-to-ground voltage level. This neutral point voltage at the same time represent the zero-sequence voltage U_0.

The voltage raise of the healthy phases is shown in Figure 1.

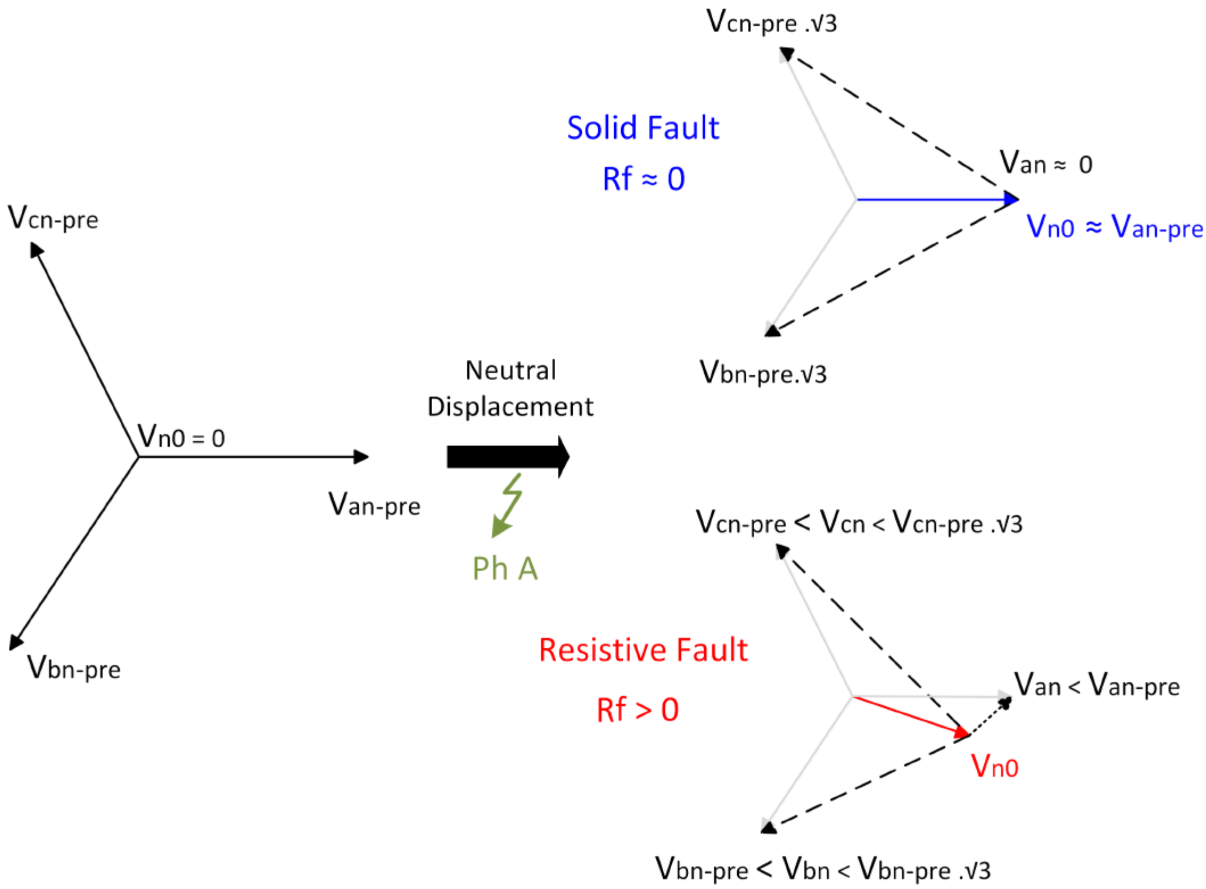


Figure 1: Neutral Displacement for a Phase A to Ground fault in high impedance grounded system

There are several ways to ground an electrical power supply system via an impedance. The most typically used solution throughout the world are briefly described in the following sections.

2.1. Ungrounded systems

All started here. Namely first commercial HV three-phase power systems were ungrounded. In such system all neutral points are intentionally left unconnected to ground (i.e. floating). This was the initial approach with the basic idea that in case of a ground fault the fault current will be zero at the fault point. However, it was quickly learned that the distributed capacitances to ground of the individual phase conductors will actually determine the ground-fault current at the fault point in such system. Today in many European countries, due to personal safety reasons (i.e. step and touch voltages in the surroundings of the fault point), it is per law not allowed to run an isolated power network if the total capacitive GF current exceeds certain value, for example 35A primary. It is also well-known fact that in such isolated systems directional GF relays operating on $\mathbf{I_0}*\sin(\phi)$ principle shall be used. Such relays effectively measure the flow of reactive (i.e. capacitive) current component in the zero-sequence circuit [2,5,6].

2.2. *Resistance-grounded systems*

In such system at least one neutral point is connected to ground via a resistor. Such resistor is typically sized to limit the maximum GF current to specific primary current level. Typical values are between 100A and 2500A. In the present power system practice the influence of the distributed capacitances to the fault current is typically ignored for such systems. However, one shall be careful with such assumptions in case of a large cable network as described in [12,13,17,18].

Seldom more than one neutral point resistor is used. However, if there are several neutral resistors connected at the same time the total GF current at the fault point will be the sum of all current contributions from each individual resistor. It is well known that in such system I_0*cos(ϕ) ground fault protection principle shall be used. Such relays effectively measure the active current component in the zero-sequence circuit (i.e. also sometimes called watt-metric GF relays).

2.3. *Reactance-grounded systems*

In such system at least one neutral point is connected to ground via a reactor. Such reactor is typically sized to limit the maximum GF current to specific primary current level. Typical values used around the world typically lays between 100A and 2500A. In such systems the influence of the distributed capacitances to ground shall not be ignored because the parallel L-C oscillating circuit in the zero-sequence system (see Figure 2), with quite low active resistance available for damping, can cause a lot of trouble for the GF protection. This is especially true for the networks having intensive use of power cables (i.e. large capacitance to ground). Ground fault protection for such systems shall be carefully designed.

Note also that the post-fault voltage transients are typically present in such network. Residual and phase-to-ground voltage oscillations might have almost arbitrary frequency after the fault clearing because the coil is typically not tuned at all to the system capacitance. As well such oscillations will be also present during (i.e. in-between) restriking ground faults.

2.4. *Resonant-grounded systems*

In such system at least one neutral point is also connected to ground via a reactor, which is often called Petersen coil. However, inductance of such reactor is then tuned to match the equivalent impedance of all distributed capacitances throughout the system (i.e. ωL=1/(ωC) at rated frequency). Practically the zero-sequence circuit then operates at or very close to the resonance point giving the name for such network grounding. Theoretically, such approach shall suppress the total GF current to zero at the fault point. This then shall ensure self-extinction for majority of the GFs in such network. Even in case of a permanent GF in many countries, due to very low GF current, such systems are allowed to operate for several hours before the faulty feeder must be disconnected from the network. This offers extremely good continuity of supply for the end users.

However, note that the residual currents will still flow through the individual feeders in such network during a GF. This is especially true for a large network which is grounded via multiple coils. It can be shown that it is impossible to use the steady state residual currents in such system in order to determine the direction of a ground fault, because the residual current especially in the faulty feeder might have an arbitrary direction. Consequently, a relatively large resistance might be used in parallel with the coil(s). That will enable use of sensitive watt-metric GF relays to detect and clear ground faults [5,6]. Note that even Petersen coil losses can also be represented as one parallel resistance to an ideal coil. Alternatively, transient based ground fault protection relays shall be used in such systems [7]. The transient GF relay determines the direction of the ground fault during the initial fault transient and store this determined direction to be used latter if the fault becomes persistent.

The post-fault residual voltage transients are also well-known phenomena in resonant grounded networks. Such transients may cause problems for protection relays [16] if they are not carefully designed and set.

In practice several variants of resonant grounding are used. The following list summarizes the most commonly used ones:

1. **Single Petersen coil** (i.e. centralised compensation). Here only one large, single Petersen coil is used to compensate capacitance of the entire network. This was the original solution. Typically used for smaller distribution networks.
2. **Multiple Petersen coils**. Here several large Petersen coils are used. Some of the coils might be fixed and some of the coils can be with automatic regulation. This is a typical solution used in more complex sub-transmission systems.
3. **Distributed compensation**. Here typically only one large Petersen coil is used for regulation. However, at the same time many small fixed neutral coils are distributed along the (long) feeders to partly compensate the feeder capacitance. Different strategies may be used for sizing of the small coils. For example, every small coil can compensate for just 5km of the line/cable length. This is quite a modern approach to resonant grounding and is typically used in distribution networks having long feeders or extensive cable feeders. However, this is also a relatively expensive solution because many additional physical items are required which shall also be installed and maintained.

The following three operating modes can be used for resonant grounded networks:

1. **Resonance:** If the size of the Petersen coil is selected so that the magnitude of the inductive current exactly compensates that of the capacitive current, the resulting earth fault current at the fault point will only consist of a resistive part. Systems which are exactly compensated (i.e. operating exactly at the resonance point) are seldom used in practice due to excessive neutral point voltage during normal operation of the system.

2. **Under-compensated:** If the Petersen coils are dimensioned to generate an inductive current that is slightly smaller than the total capacitive current, the resulting fault current will also consist of a small capacitive component and then the system is said to be under-compensated.
3. **Over-compensated:** If the Petersen coils are dimensioned to generate an inductive current that is slightly bigger than the total capacitive current, the resulting fault current will also consist of a small inductive component. In many parts of Europe such over compensated systems are actually used in practice. Vector diagram for such over-compensated system is shown in Figure 2b.

2.5. Effectively (solidly) grounded systems

In such systems the transformer neutral point is intentionally connected to ground via a copper conductor (i.e. without any impedance). This effectively fixes the neutral point potential at the ground level (i.e. zero) and causes a high level of the GF current at the fault point. In such systems the GF currents are typically in the same order of magnitude as the short-circuit currents. This type of system is not further discussed in this paper.

2.6. Simplified Equivalent Circuit

In many published books and papers a simplified zero-sequence circuit, as shown in Figure 2a, is used for an high-impedance resonant grounded system. It is a simple parallel RLC circuit. The ground fault instant is determined when the switch in this circuit is closed. The fault is cleared when this switch opens. The post-fault oscillation starts after the switch opening due to trapped energy in the distributed capacitances.
It is very important to understand under which assumptions this circuit is derived, because this will give a hint when such circuit can or cannot be used. The most important assumptions and shortcomings of this circuit are listed below:

1) This circuit can be used to calculate the I_0 current at the fault point. Unfortunately, this fault point current is not measured by any of the ground fault relays installed in the network. Or in simple words this circuit does not help us to understand which residual currents will be measured by individual ground fault relays installed throughout the protected network.
2) All feeders are represented only by their distributed, but lumped, capacitance to ground. All series parameters (i.e. R and L) of the lines are simply ignored. This is done under assumption that impedance of the distributed capacitances is much bigger than the equivalent series impedances. This is typically true for overhead lines. However, for longer cables (e.g. 40km-50km long power cable [13]) such assumption may already lead to wrong results.
3) Positive and negative sequence impedances (i.e. Z1 and Z2) of all feeders are ignored. The reasoning is similar as already given in point 2) above.
4) Grounding impedance is represented as parallel connection of an ideal reactor and one resistor. Their values shall be calculated appropriately. For example, in a centralised grounded resonance system Ln is equal to three times the Petersen coil inductance, while Rn is equal to three times the value of the parallel resistor.
5) C_{0eq} is equivalent zero-sequence capacitance. It is equal to lumped phase to ground capacitance of one phase of all feeders in the network at the moment of the fault.
6) R_f is the fault resistance
7) U_{ph} is a phase to ground voltage in the faulty phase, but it shall be rotated by 180 degrees. Note that U_{ph} and U_0 voltages actually have opposite reference directions as shown in Figure 2.
8) Note also that I_0 and U_0 are values which are used for this equivalent circuit. In a real installation the IED will measure $3I_0$ and $3U_0$ (i.e. residual quantities), but the difference between them is just a fixed factor of three. In further text only I_0 and U_0 notation will be used, but whatever is written there it is also applicable to $3I_0$ and $3U_0$ quantities.

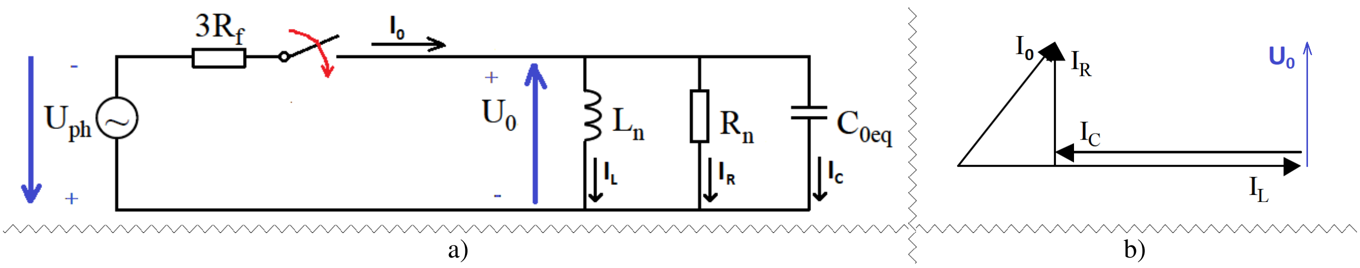


Figure 2: Simplified equivalent zero-sequence circuit, which is drawn from the fault point and corresponding phasor diagram for over-compensated system

3. Proposed Ground-Fault Methodology

Use of I_0*cos(ϕ) method for GF protection in resistively grounded or resonant grounded systems and use of I_0*sin(ϕ) method for GF protection in isolated systems are well known in protective relaying practice [2,5,6], but neither of them is universally applicable in complex network configurations (different grounding principles, meshed networks, distributed compensation). Also, there are several other methods [7-11,14,16] proposed to cope with I_0 signal complex waveforms in compensated networks, but most of them rely on either raw samples or the use of compete phasors, which are inherently polluted and pose a risk for incorrect relay operation. In this paper a new method that relies only on healthy I_0 phasor components is proposed for transient ground fault protection. Basic operating conditions for the new directional transient ground fault protection will be explained here for a substation, having a single incoming transformer feeding a MV busbar having three outgoing feeders, as shown in Figure 3. However, the proposed solution is also applicable for more complex network conditions. The network grounding impedance is connected to the transformer MV winding neutral point as shown in Figure 3.

Figure 4 shows a simplified zero-sequence equivalent circuit during a ground fault in Feeder 1. The associated transient directional GF protections for every feeder are also shown. Such an equivalent circuit can be used to facilitate the understanding of the basic physics-processes which occur in a high-impedance grounded power system when a ground-fault happens. Note that the zero-sequence circuit is typically dominantly reactive in nature (i.e. L and C dominate over R values) except for the resistively grounded systems.

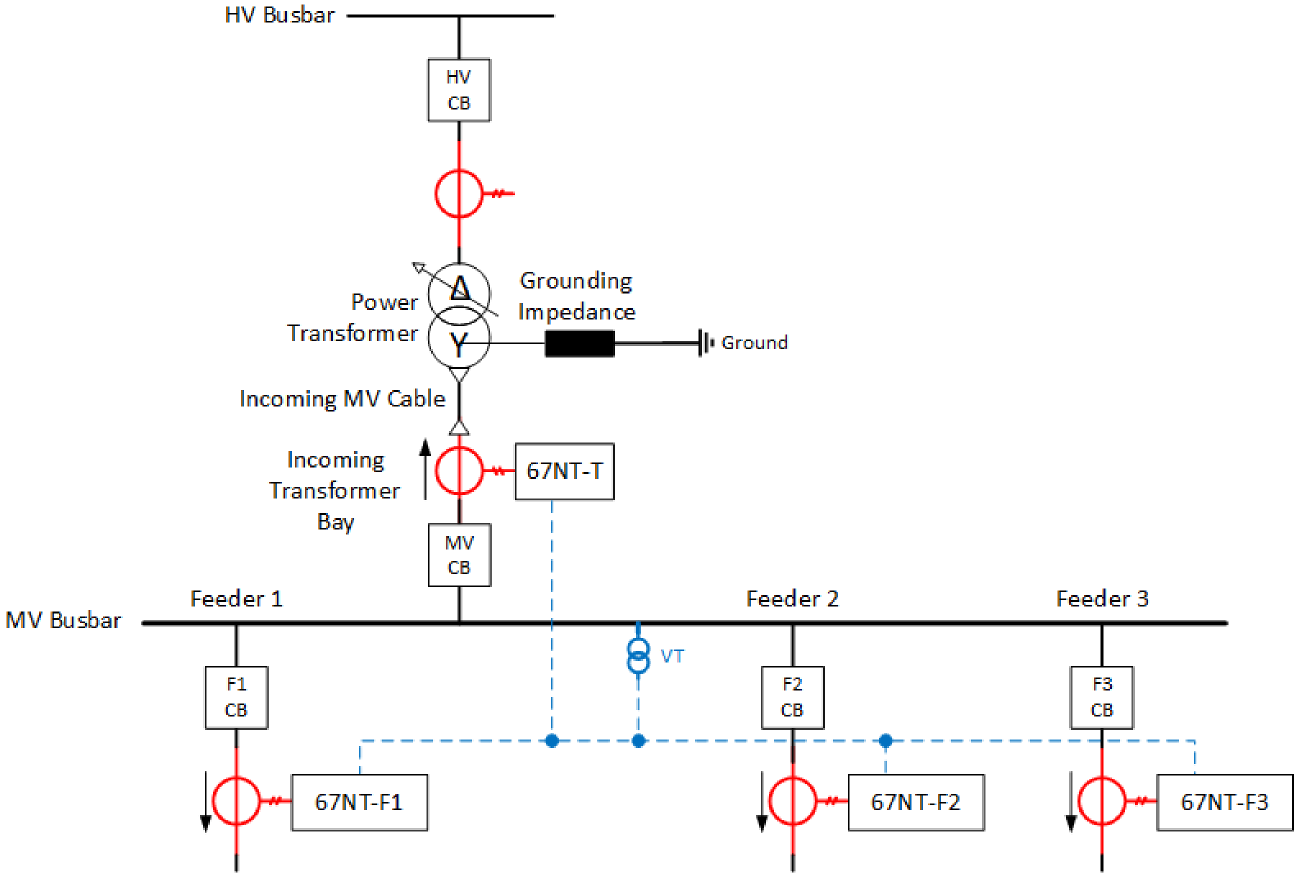


Figure 3: Example substation layout

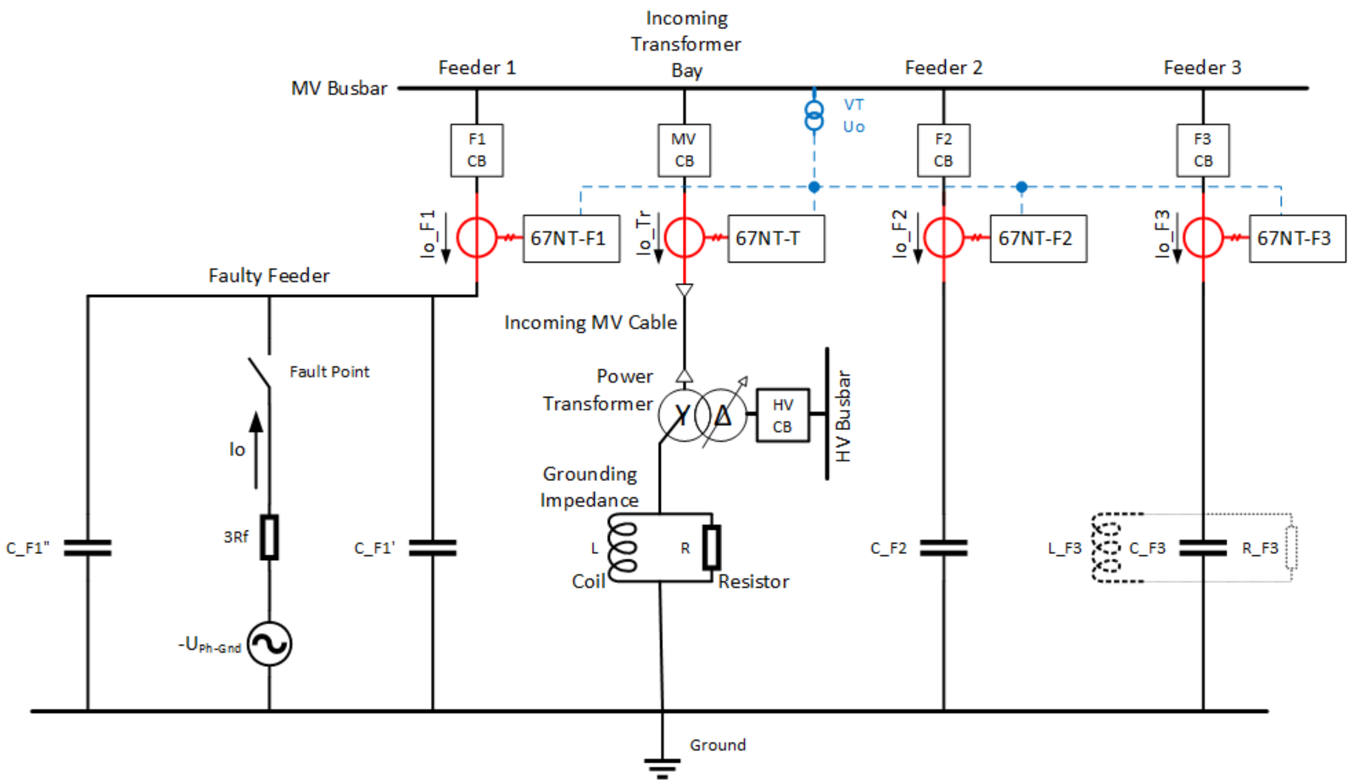


Figure 4: Used zero-sequence equivalent circuit to understand ground fault process

Note the following in respect to this equivalent circuit shown in Figure 4:

1. All feeders are represented with a capacitance to ground. All series parameters of any feeder are ignored because their impedance is much lower than this capacitive impedance to ground.
2. The ground-fault location is in Feeder 1. Consequently, its distributed capacitance is split into two parts, one in-between the MV busbar and the fault point (C_F1') and the second one behind the fault point (C_F1").
3. The grounding impedance at the transformer MV winding neutral point is represented as a parallel connection of an inductor (L) and a resistor (R). This is the most practical representation because it can then represent all the most commonly used grounding principles (for isolated system L= R=∞).
4. The location of all CTs and VTs are also given because these are used to determine the measurement points for I_0 and respectively U_0 signals in each feeder.
5. Note that I_0 and U_0 are correct values for this equivalent circuit. In a real installation the IED will measure 3Io and 3Uo (i.e. residual quantities), but the difference between them is just a fixed factor of 3. In further text only I_0 and U_0 notation will be used, but whatever is written is also applicable to 3Io and 3Uo.
6. The reference direction for current measurement (towards the protected feeder) is also given with associated transient GF protection (67NT-F1 for Feeder 1) in each outgoing feeder.
7. A resistance to ground (R_F3) is shown with dashed lines for Feeder 3. In practice these resistances are extremely large and typically can be ignored. Consequently, these are not shown for other feeders.
8. An inductance to ground (L_F3) is also shown with dashed lines for Feeder 3. This, in practice may represent either distributed coils along that feeder or in a power system using multiple Petersen coils, a remote coil located in the other substation at the remote end of Feeder 3. The above-mentioned resistance to ground (R_F3) may also represent the coil losses.
9. As per superposition theorem a single source in the zero-sequence system is located at the fault point. Its magnitude is equal to the phase-to-ground voltage in the faulty phase, but its phase angle shall be turned-around by 180 degrees. When the fault resistance (Rf) has approximately a value of zero, a bolted fault, then the U_0 voltage will be equal to this source voltage. The U_0 voltage is roughly the same throughout the protected system. Therefore, only the measurement of the I_0 currents in the individual feeders is actually important to distinguish between the faulty and the healthy feeders.
10. The I_0 current through the fault point is the same as the I_0 current shown in Figure 2a. However, the circuit presented in Figure 4 will help to understand the residual current distribution throughout the protected systems and associated ground fault relays.

3.1. Fundamental frequency phasors behavior during an GF in a high-impedance grounded system

When GF happens (i.e. when switch at the fault point closes in Figure 4), the source located at the fault point will energize distributed capacitances in all feeders connected to the MV busbar. Note that these distributed capacitances are not energized (all are without any stored energy) before the GF. Thus, they are first charged to an energy level corresponding to the $\mathbf{U_0}$ voltage magnitude (using the well-known formula 0.5*Uo^2/C) before starting to exchange reactive power with either the source located at the fault point or with the Petersen coils located at transformer neutral points.

This charging process will cause a short active power surge from the source located at the fault point towards all distributed capacitance. If this active power surge can be measured by the transient GF protections, then this can be used to detect the faulty feeder in a radial system or the relevant GF position in meshed system. Note that the flow of the active transient power will be in the opposite directions through the CTs in the faulty feeder and in the healthy feeders for a radial system. In simple words this active power will be negative in the faulty feeder and positive in a healthy feeder. For a meshed system this power sign will be negative on both ends of the faulted line only, while for all other healthy feeders it will have opposite signs on the two-line ends.

It is quite a common protection practice to use -U_0 voltage phasor (rotated by 180 degrees) for all GF protection functions instead of +U_0 phasor. This will only swap all power directions previously explained. For example, in an actual implementation the measured power will be essentially positive for the faulty feeder and negative for the healthy feeders in a radial system. This $\mathbf{U_0}$ rotation can be simply understood as a sign convention which is often used in relay protection practice.

For a radial system transient GF protection installed in a healthy feeder will measure the transient charging power of its own distributed capacitance, while the one installed in the faulty feeder will measure the active transient charging power of all healthy feeders lumped together. Consequently, transient charging power signal magnitude will be the largest for the faulty feeder and the smallest for the shortest healthy feeder. Note that the existence of any shunt resistance in the system (R or R_F3 in Figure 4) will only increase the active power flow in the faulty feeder and consequently make it easier to determine the GF position. The same is true if the fault resistance R_f is present in the circuit. At the same time the existence of any inductor in the circuit (L or L_F3) will not influence this initial active power flow during transient period in any way, because the practical power systems are always based on voltage sources and not on current sources.

<u>In an actual power system, the active power can only be supplied by the fundamental frequency signals</u>, which means that it must be produced by one or more generating plants connected to the network. Consequently, only the fundamental frequency phasors of the I_0 and U_0 signals shall be used to measure this active transient power flow in every feeder. To calculate active and reactive power based on fundamental frequency phasors the well-known formulas given below are used.

$$\boldsymbol{P_{01}} = \boldsymbol{U_{01}} * \boldsymbol{I_{01}} * \mathbf{cos}(\phi_1) \sim \boldsymbol{I_{01}} * \mathbf{cos}(\phi_1) = \boldsymbol{IP1} \quad \textbf{(1)} \qquad \boldsymbol{Q_{01}} = \boldsymbol{U_{01}} * \boldsymbol{I_{01}} * \mathbf{sin}(\phi_1) \sim \boldsymbol{I_{01}} * \mathbf{sin}(\phi_1) = \boldsymbol{IQ1} \quad \textbf{(2)}$$

Where ϕ_1 is angle between I_{01} and -U_{01} phasors. The index one in the above equations indicates that only the fundamental frequency phasors are used. As mentioned previously U_{01} magnitude is a constant for all transient GF protections in the protected system, and consequently only the active fundamental frequency current component IP1=I_{01}*cos(ϕ_1), (see equation 1), shall be used to derive an operating signal which is proportional to the active transient power flow towards the distributed capacitances. How I_0*cos(ϕ) and I_0*sin(ϕ) components are derived is shown in Figure 5.

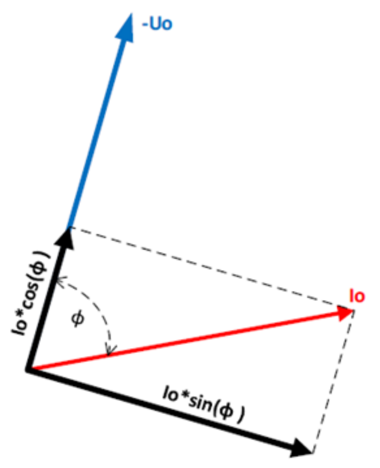


*Figure 5: Deriving I_0*cos(ϕ) and I_0*sin(ϕ) quantities from I_0 and -U_0 phasors*

Because the instantaneous value of IP1 (and IQ1 as well) may vary quite a lot during the transient period of the GF, the integrated value over certain time (e.g. one-and-a-half cycles) is used in the new design. The simplest way to do numerical integration is to calculate averaged value of the IP1 signal over the used integration time. This averaged signal, called EIP1, will actually correspond to the total active energy value stored in the distributed capacitances during the ground fault transient. For a radial system, the EIP1 value will always be positive in a faulty feeder, while in all healthy feeders it will always be negative during the transient period of the GF. Thus, by setting two simple current threshold levels (one positive and the second one negative) the direction of the GF can be determined. For a more complex meshed sub-transmission systems a permissive directional comparison scheme shall be used between two line ends in order to identify the faulty line.

In the similar way EIQ1 signal can be derived. However, the EIQ1 signal is not used at all by the new method. The calculated EIP1 and EIQ1 values are given as service values from the new function to make it easier to understand the behavior of the protected system during a GF and the behavior of the new method. They will also facilitate secondary injection testing.

The advantages of this transient active power method to detect the GF direction in high-impedance grounded system are:

1. Simplicity, because only the active part of the I_{01} current phasor (i.e. component which is in phase with $-U_{01}$ phasor, as shown in Figure 5) is used and marked as IP1 quantity in this paper.
2. Use of widely recognized ground-fault protection method based on $I_0*\cos(\phi)$.
3. Not influenced by the compensation degree, number of coils used and their physical location in the protected network (coils will not consume any active power during the transient part of an GF).
4. No need to start and/or stop the calculation of the EIP1 quantity. It is calculated continuously using moving average principle.
5. EIP1 value will be approximately equal to zero during all operating conditions of the protected network except during the transient period of the GF.
6. Low sampling rate of the protection is sufficient because only the fundamental frequency phasors of U_0 and I_0 are used as input signals. For example, a sampling rate of twenty samples per fundamental power system cycle is adequate for proper operation of this method.
7. Raw samples of residual voltage and current are not directly used in the transient GF protection algorithm which simplifies the overall design.
8. No angle-based operating criterion is used; thus, there are not any angular accuracy issues because typically value of IP1 will be bigger or at least equal to IQ1 value during the transient period.
9. This method requires relatively low CPU resources.
10. Separate operate levels for forward and reverse directions can be used.

3.2. Higher harmonic phasors behavior during an GF in a high-impedance grounded system

It is well known fact that the energization of a shunt capacitor in a power system is followed by relatively large current and voltage transients, which typically contain a lot of harmonics. When a ground fault happens, the same transient will appear in the zero-sequence circuit due to distributed capacitances. The frequency of that oscillation is determined by network zero-sequence parameters L, R and C, as shown in Figure 2a, and is almost never an exact multiple of the fundamental frequency. The frequency of the oscillating signal may vary from 100Hz up to 5kHz. In modern numerical IEDs typically a full-cycle digital Fourier filters are used to extract both the fundamental frequency phasor and the higher order harmonic phasors. This one fundamental frequency cycle filtering time is quite short, and the high-frequency oscillations present in the residual signals during an GF inception will pass-through this filter making them visible in some higher harmonic phasors of the I_0 current.

For resonant grounded systems the total inductance of all coils is tuned to the distributed capacitance of the protected power system only at the rated frequency. For all higher harmonic signals the coils have a h^2 times higher impedance than the corresponding capacitive reactance, where "h" is the harmonic number. Therefore, all coils can be simply omitted from the zero-sequence equivalent circuit shown in Figure 4 for all higher harmonic components. Consequently, all higher harmonic signals in any high-impedance grounded systems behave as the fundamental frequency signals in an isolated power system. Thus, the $I_{01}*\sin(\phi_1)$ principle which is typically used in an isolated power system for fundamental frequency phasors can now be applied to all higher order harmonic phasors irrespective of the actual type of grounding impedance used in the protected network. Since the higher harmonics will primarily be present only during the transient part of the GF, these harmonic components will behave in a similar transient way as previously explained for the IP1 and IQ1 quantities. Consequently, the same integration/averaging principle can be used to measure a new signal which is proportional to the transient harmonic reactive power exchange between the distributed capacitances and the source located at the fault point. To simplify the overall calculations, the following sum is first formed, where all reactive residual current components for all used higher frequencies are lumped together:

$$\boldsymbol{IQh} = \sum_{n=2}^{Nmax} \mathbf{I_{0n}} * \mathbf{sin}(\phi_n) \qquad (3)$$

where "Nmax" is the maximum order of harmonic which can be measured by the relay. Since this lumped harmonic value IQh may vary quite a lot during a transient period of the ground fault, the averaged (i.e. integrated) value called EIQh is used instead, in the new algorithm. It can be shown that in a radial system the EIQh value will always be positive for the feeder where the ground fault is located, while all other healthy feeders will see the ground fault in reverse direction (i.e. EIQh value will be negative). Consequently, the two current threshold levels (one positive and the second one negative) can also be used to determine the direction of the ground fault.

The EIQh value can also be provided as a service value from the 67-NT function to simplify testing and understanding of GF protection operation in the field. Advantages of this harmonic based transient reactive power method to detect the GF direction in high-impedance grounded system are:

1. Simplicity, because only the reactive part of the higher harmonic phasors of I_0 current is used (i.e. component which is perpendicular to $-U_0$ phasor as shown in Figure 5).
2. Use of the widely recognized $I_0*\sin(\phi)$ method.
3. Not influenced by the compensation degree, number of coils used and their physical location in the protected network (all coils are disregarded for harmonic calculations).
4. No need to start/stop the calculation of the EIQh quantity. It is performed continuously using moving average principle.
5. EIQh quantity will be approximately equal to zero during all operating conditions of the protected network except during the transient period of the GF. As an additional security measure, it can be verified that its increase coincides with the jump of the fundamental frequency U_0 voltage magnitude.
6. Low sampling rate is sufficient, because typically only up to and including the 5th harmonic component is required to be included in the calculation.
7. Raw samples of residual current and voltage are not at all directly used in the algorithm, which simplifies the overall design.
8. Separate operate levels for forward and reverse direction are possible.

4. Built-in Features in the New Transient Ground Fault Protection

In order to cope with different types of ground faults which can be encountered in such networks the new transient protection has the following built-in features:

1. Adaptive residual voltage measurement in order to ensure proper reset in case of residual voltage post-fault oscillation transients, which might have frequency different from the rated frequency of the protected network.
2. Separate pickup levels and separate START outputs for ground faults in forward and reverse direction.
3. TRIP output in case of a forward fault. Note that TRIP signal can be inhibited via parameter setting for applications where network operation is allowed for several hours during a ground fault.
4. Both START and TRIP outputs can be intentionally delayed in order to allow the Petersen coil to extinguish the ground fault without any action of the protection relays.
5. Forward START output in combination with a permissive communication scheme shall be used in meshed networks in order to determine and trip the faulty line when that is required.
6. WARNING signal to indicate presence of a forward transient ground fault (especially useful in cable networks)
7. Intermittent start logic which allows this protection to detect and operate during intermittent/restriking faults.
8. Detection and blocking during cross-country fault (i.e. The term cross-country fault is used to designate two single phase-to-ground faults that occur simultaneously at two different locations on the system. It can also be understood as phase-to-phase fault via ground from the source point of view).
9. Detection and automatic pickup level adjustment for residual circulating currents caused by meshed line asymmetries in the protected network

5. Testing of the Proposed Methodology

Several hundreds of actual field recordings from many different installations around the world were initially used to verify the new transient ground fault protection methodology. After that, several trial installations have been arranged in order to verify performance of the proposed method when implemented in the target hardware. Several interesting recordings will be presented in the paper to present method performance. Most of these records are captured in various installation by the target hardware but some of them are also captured by different devices. In the following figures all current waveform, EIP1 and EIQh quantities are given in secondary amperes, while 3Uo voltage is given in secondary volts if not stated otherwise. Note that all ground faults were always detected in the correct direction by the proposed methods.

5.1. *Single phase to ground fault in 13.8kV, 60Hz, three-phase system having resistive grounding*

This recording was captured on a 13.8kV line having VT ratio VTR=13.8/0.12 and CT ratio CTR=1000/1. This line is a part of a resistively grounded distribution system. Phase L3 conductor (i.e. Phase C) broke off on the far end of the line, swinging in the air and temporarily touching a metallic object due to a strong wind which was blowing at the moment of the fault. In Figure 6, a ten-second-long recording of the three-phase current set of the line is shown, while in Figure 7 one second long zoomed-in view of this record is given. Note how the phase L3 current (i.e. the green trace) is spiky with a short burst of currents which repeats at irregular intervals. Traditional time delayed ground fault protections could not detect such ground fault due to its intermittent nature and applied settings and only operated once the fault became permanent.

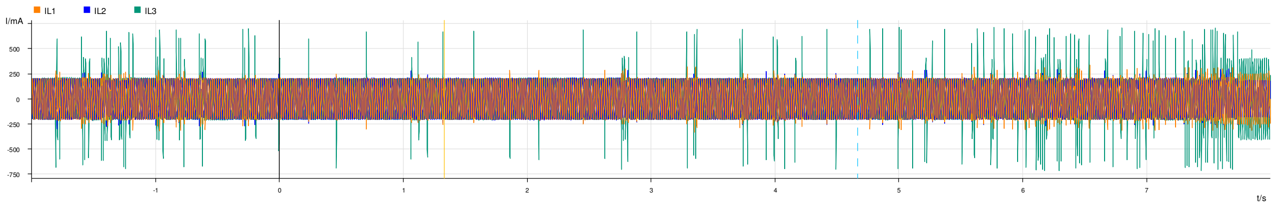


Figure 6: Intermittent GF in phase L3 on a 13.8kV distribution line (10s long record)

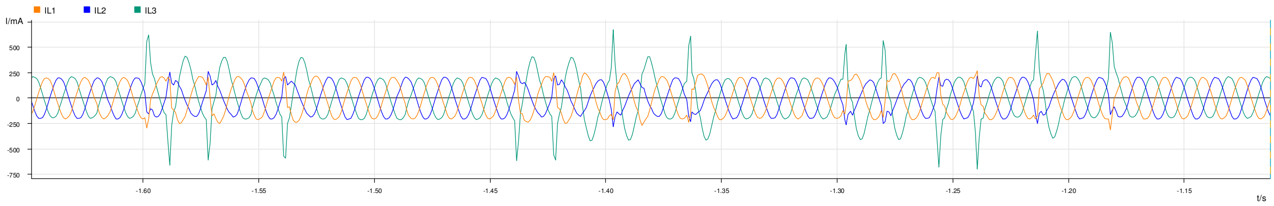


Figure 7: A zoomed-in view into one second long part of the GF given in Figure 6

The proposed transient ground fault protection easily detects the bursts of the active power in the zero-sequence circuit caused by the fault, and reliably operates due to its built-in intermittent feature. If the minimum pickup level for EIP1 and EIQh magnitudes is set to 5% (i.e. 50mA secondary) even a single 3Io current pulse will be detected by the transient ground fault protection. Due to presence of the neutral point resistor 3Io and 3Uo signals are exactly in contra-phase during entire fault clearly indicating that the grounding impedance is a resistor. Note also that the higher order reactive harmonic residual current components are practically not existing (i.e. damped by the resistor).

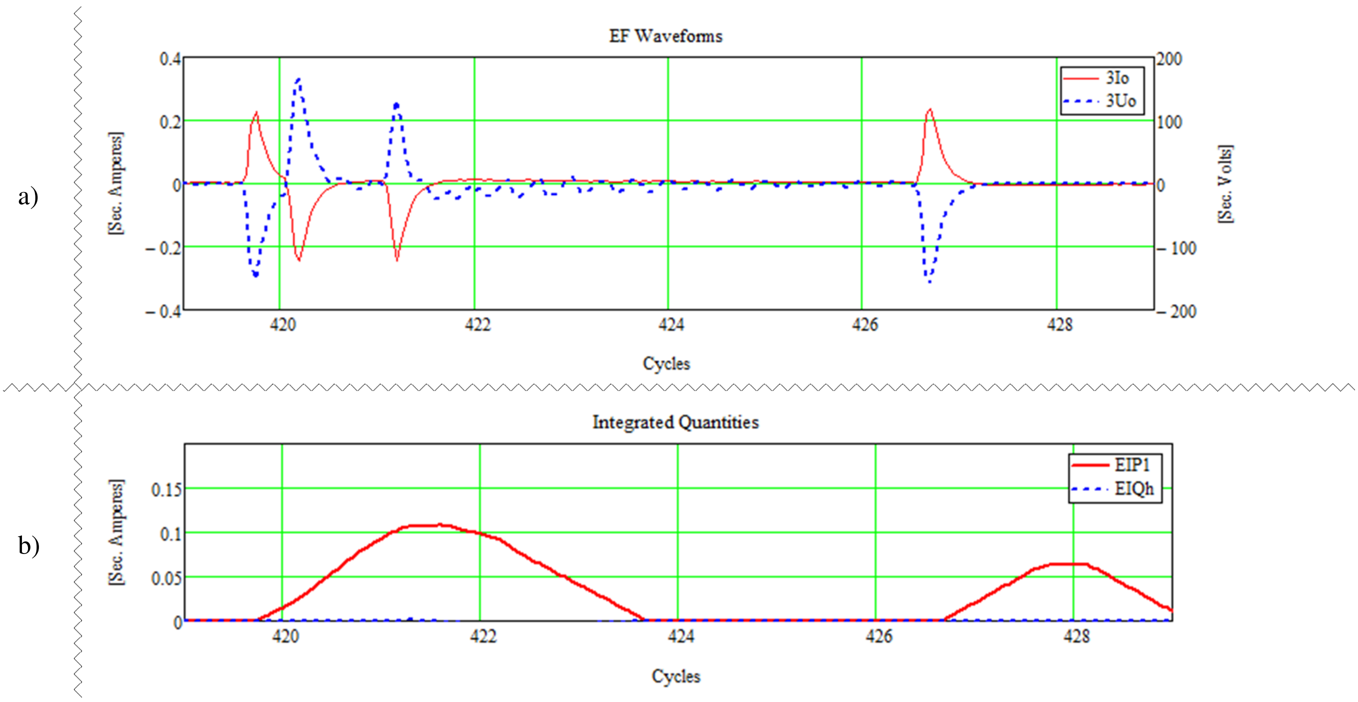


Figure 8: Behavior of Transient GF protection during the fault shown in Figure 6 and Figure 7

5.2. *Single phase to ground fault in an offshore wind farm having resistive grounding*

This DR was captured in an offshore wind farm installation. The 34kV, 50Hz system is grounded via a neutral grounding transformer (NGT) and a neutral grounding resistor (NGR) as shown in Figure 9. The total GF current on 34kV side is limited to 600A primary and is mainly resistive in nature due to NGR and NGT sizing. The complete wind farm is then connected via a power transformer (PT) and long HV, under-water sea cable to onshore HV transmission grid. The instrument transformers used for this recording have ratio of VTR=34/0.1 and CTR= 1000/1.

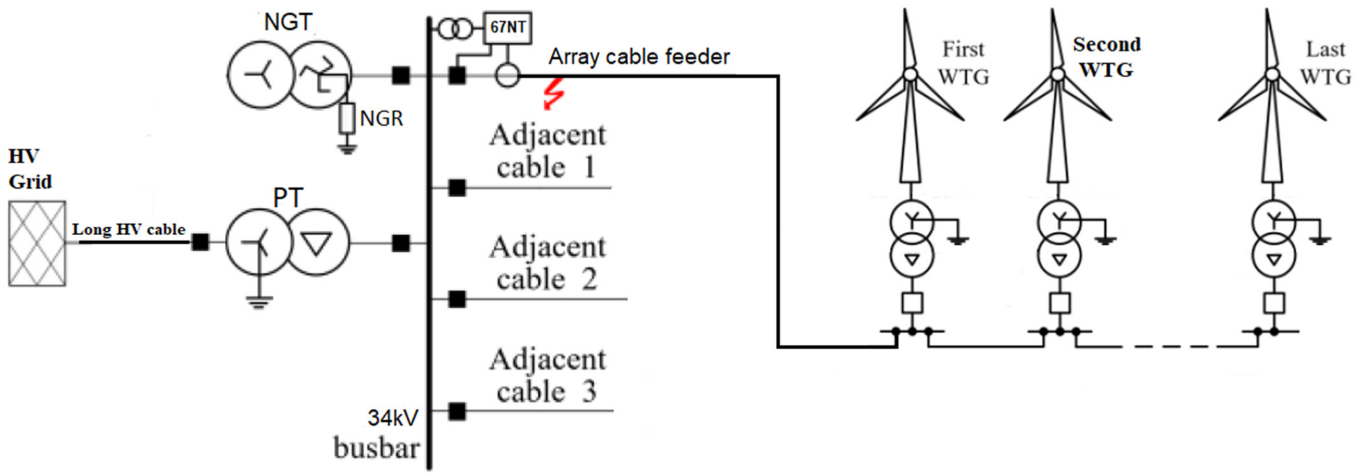


Figure 9: Simplified SLD of the offshore wind farm and GF location in Array Cable Feeder

The actual GF has happened in one array cable feeder which connects several wind turbine generators (i.e. WTG) to the 34kV bus, as shown in Figure 9. Up to six such array feeders can be connected to the same 34kV bus. Because the entire 34kV network is made of cables, quite large capacitive GF current contribution from parallel cable feeders which are in operation on the same bus, at the moment when the ground fault happened, are also present. They can be clearly seen as a transient at the beginning of the ground fault (i.e. especially during the first fault strike), as shown in Figure 10a. However, such transients are quickly damped by the neutral point resistor. Note also that during the steady state part of the fault 3Io and 3Uo signals are exactly in contra-phase indicating the dominance of the neutral point resistor in the zero-sequence circuit.

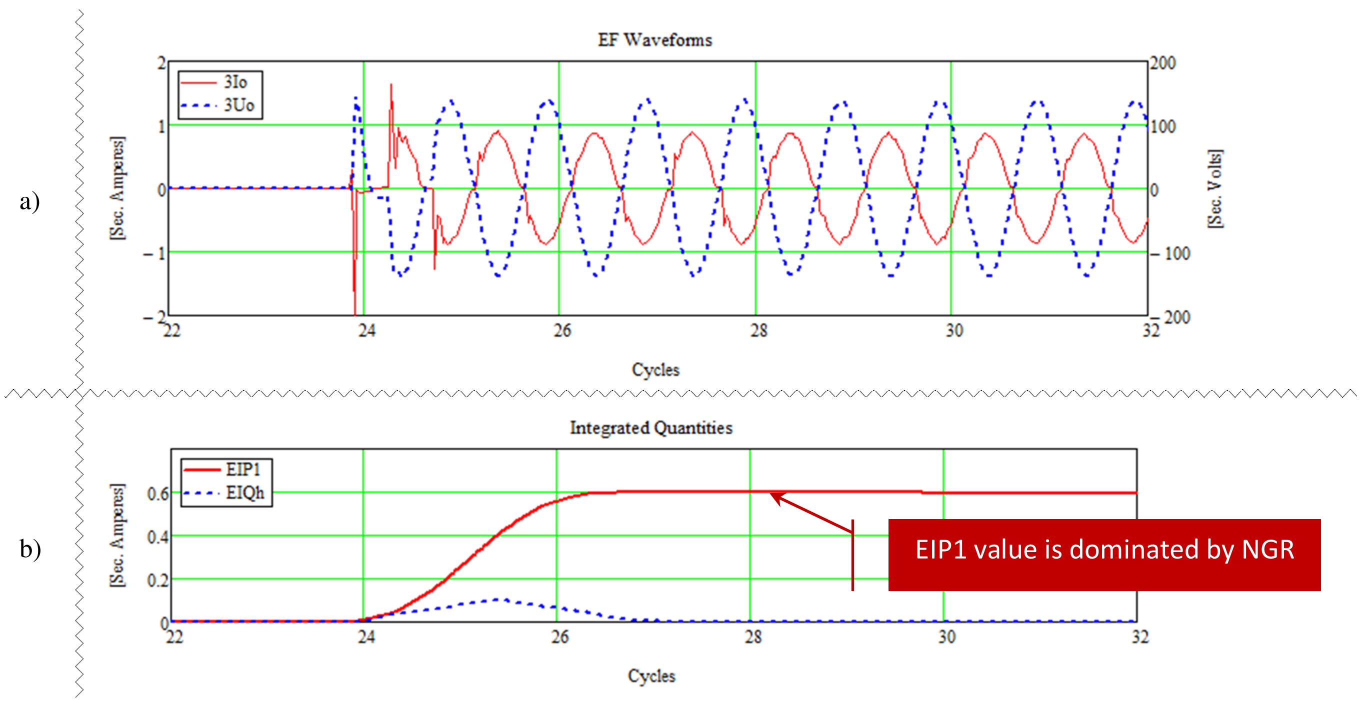


Figure 10: Behavior of Transient GF protection for a fault in Array Cable Feeder, given in secondary Amps and Volts

Another important property of such network grounded via a "strong resistor" is that EIP1 value is completely dominated by it. As well after breaker opening in the faulty feeder there were not any post-fault voltage transients because the neutral grounding resistor (NGR) effectively damps all such oscillations. Due to limited space this is not explicitly shown in this paper.

5.3. Single phase to ground fault in an onshore wind farm having reactive grounding

This recording was captured in an onshore 35kV, 50Hz wind farm installation. The SLD shown in Figure 9 is still applicable here for the MV network, but in this installation the neutral grounding resistor (NGR) was not used at all and the 35kV system is grounded via a neutral grounding transformer (NGT) only. The total GF current was limited to 300A primary and is mainly inductive in nature. The used instrument transformers have ratio of VTR=38/0.1 and CTR= 400/5.

Such grounding arrangement makes GF detection much more complicated than in the previous example. Namely here the zero-sequence circuit becomes completely reactive (i.e. having very little active resistance). This causes that the ground fault initial transients are much bigger as shown in Figure 11a. Note that now the post-fault residual voltage oscillations are also present, and that they have different frequency than rated, because the reactor was not tuned at all to system capacitance. However, both proposed measurement methods operated as expected indicating forward direction by detecting positive EIP1 and EIQh values, as shown in Figure 11b. Note also that these two values are the largest during the initial transient period of the ground fault.

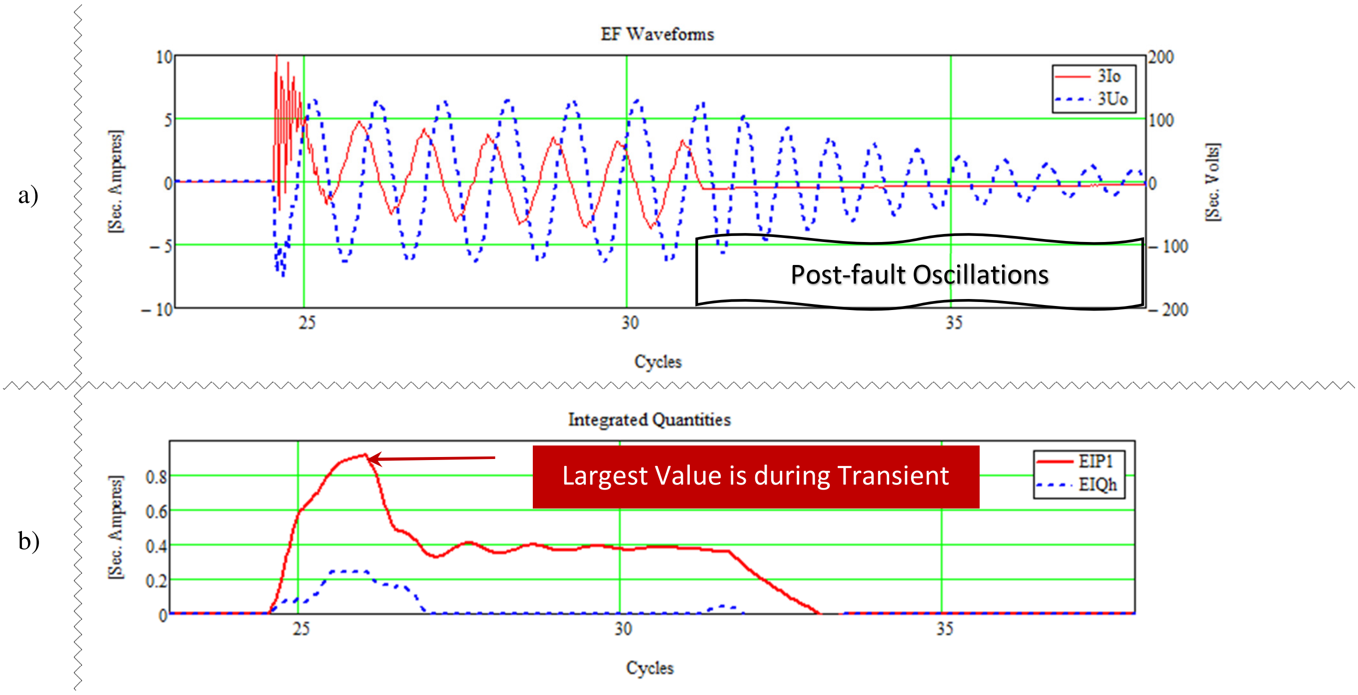


Figure 11: Behavior of Transient GF protection in faulty feeder during the GF in onshore windfarm

Even a disturbance record from a parallel, healthy array feeder was available for this fault, and it is shown in Figure 12a. However, both proposed measurement methods operated as expected indicating reverse direction by detecting relatively large negative EIP1 and EIQh values at the beginning of the fault, as shown in Figure 12b. It shall be also pointed out that after breaker opening in the faulty feeder (i.e. when 3Io signal disappears in Figure 11a) there are extensive post-fault residual voltage transients , as shown in Figure 11a and Figure 12a, caused by the stored energy in the distributed cable capacitances at the point of CB opening in the faulty feeder. This energy shall vanish on the quite small active resistive value in the zero-sequence circuit (i.e. due to missing NGR). Note that the frequency of this oscillation is different from the rated frequency due to not exact tuning of the coil to the network capacitance. This frequency is determined only by the L and C values in the simplified equivalent zero-sequence circuit which is shown in Figure 2a.

Used ground fault protection relays shall be able to cope with such input signals without causing any unwanted signaling and/or operation. This is especially true for the healthy feeders because in them both residual voltage and residual current are present during this post-fault period, as shown in Figure 12a. This is well known fact and is described in reference [16]. However, the newly proposed transient ground fault relay methodology can cope with that by setting appropriate minimum pickup level (e.g. 50mA secondary) for EIP1 and EIQh magnitudes before the transient ground fault relay is allowed to declare the fault direction. Nevertheless, there is also the built-in internal logic which shall help to avoid any such problems during the post-fault transients.

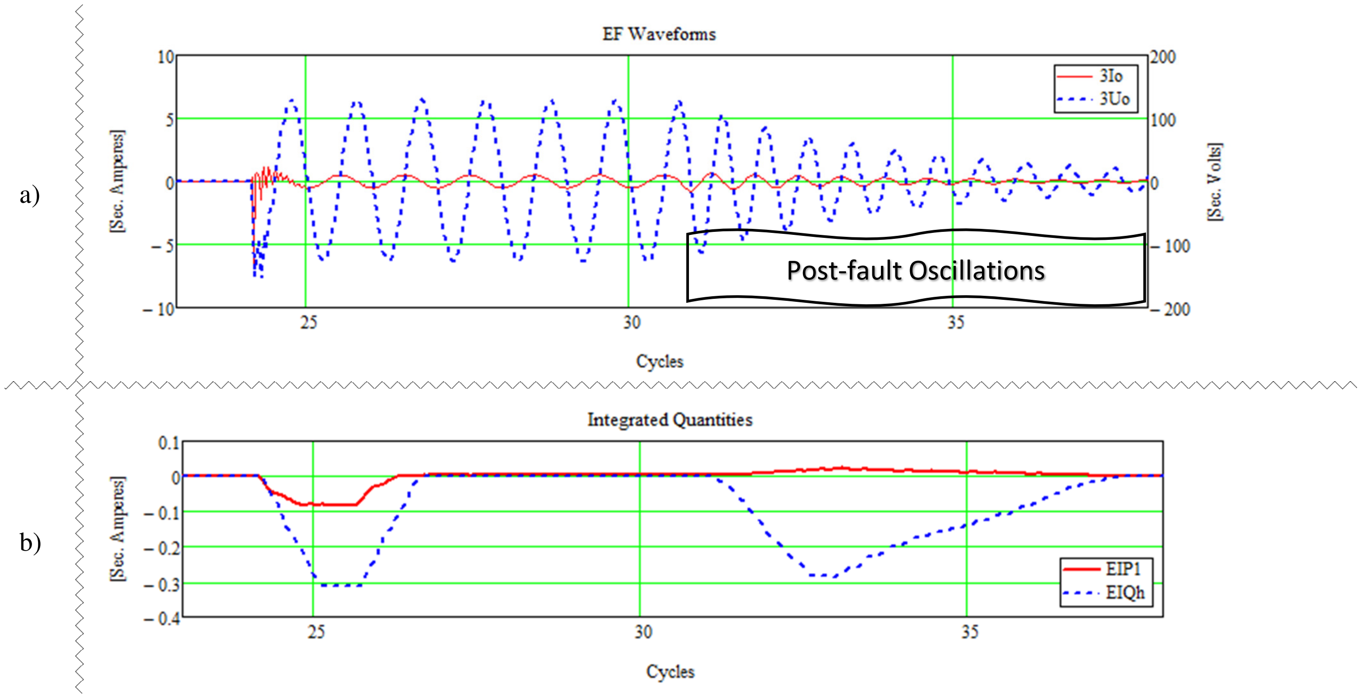


Figure 12: Behavior of Transient GF protection in a healthy feeder during the GF in onshore windfarm

Note also that for both feeders $3I_0$ and $3U_0$ signals are phase shifted by 90 degrees during the steady state part of the fault indicating missing active resistance in the zero-sequence circuit. The phase displacement between 3Io and 3Uo signals is the same in the healthy and in the faulty feeder (i.e. 3Io signal leads by approximately 90 degrees the 3Uo signal). This also confirms that in such networks is not advisable to use directional ground fault relays which make their decision during the steady-state part of the fault.

5.4. Single phase to ground fault in the MV cable of the incoming transformer feeder

This record was captured in a 35kV, 50Hz distribution network, which supplies a large town. The 35kV network is supplied via an incoming transformer having rating of 40MVA; 110kV/36.75kV; 50Hz. The entire 35kV MV network has only one grounding point via a resistor located in the transformer secondary winding neutral point. This resistor limits the EF current to 300A primary. A ground fault happens in the 35kV incoming transformer cable (see Figure 3 and Figure 4) connecting the power transformer MV side to the 35kV bus. The relay 67NT-T (see Figure 3 and Figure 4 for this relay location) shall operate for such fault. This fault was actually cleared by the 35kV winding low-impedance REF protection with little bit of luck as described in reference [17]. However, we still can check how the new transient ground fault protection would operate for such fault. The instrument transformers used for this recording have ratio of VTR=35/0.1 and CTR= 800/1.
This fault location is actually quite special for transient ground fault protection, and many relay manufacturers do not declare behavior of their protection for such fault. Namely, the fault location separates the neutral grounding resistor from the incoming feeder CT where transient ground fault relay is connected, and consequently the ground fault relay only sees the capacitive zero sequence current of the entire 35kV network during this fault.
It can be seen in Figure 13a that 3Io and 3Uo signals are phase shifted by 90 degrees indicating missing active resistance in the zero-sequence circuit despite the fact that the network is grounded via resistor! However, both proposed measurement methods operated as expected indicating forward direction, as shown in Figure 13b. It is also possible to see that during fault clearing EIP1 value becomes very small but negative. The proposed transient ground fault relay methodology can cope with it either by setting appropriate minimum pickup magnitude level for EIP1 signal and also by built-in logic.

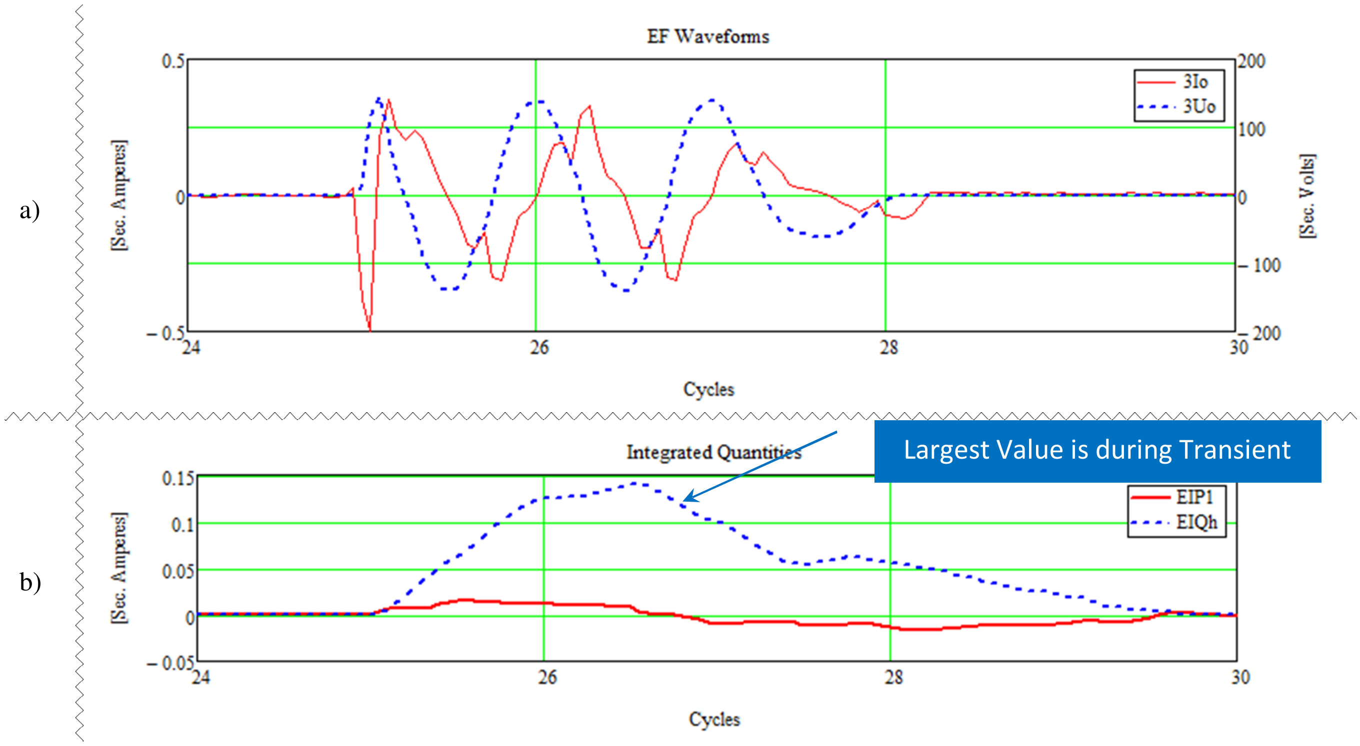


Figure 13: Behavior of Transient GF protection for a fault in the incoming transformer cable, given in secondary Amps and Volts

5.5. *Ground faults in 10kV, 50Hz, three-phase cable network with variable type of grounding*

Problems encountered in high impedance grounded MV networks consisting mainly of cables feeders (e.g. typically used in a large city) is quite well known and documented [12,13]. Due to such reason a series of primary tests were performed in a such 10kV distribution network having total capacitive ground fault current of approximately 90A primary. Not exactly tuned, 60A, single coil and a 15A single resistor connected in parallel was used as grounding impedance in the feeding substation. The used instrument transformers during this testing have ratio of VTR=10/0.11 and CTR= 90/1. Original recordings were captured using 6.3kHz sampling rate. They have been re-played into the target IED using a modern secondary injection test set.
Two records when both reactor and resistor were connected in the neutral point are presented here. The first presented ground fault is of a transient nature (on a cable !!!) and disappears after a single residual current pulse as shown in the first trace of Figure 14. Note the post-fault residual voltage oscillations which are clearly visible in this figure. Note that the frequency of this oscillation is different from the rated frequency due to not exact tuning of the coil to the network capacitance. However, both proposed measurement methods operated as expected indicating forward direction by detecting positive EIP1 and EIQh values, as shown in Figure 14. Note also that the new 67NT function is also capable to give "forward warning" binary signal even for such a short transient ground fault on a cable as presented in the bottom of Figure 14.

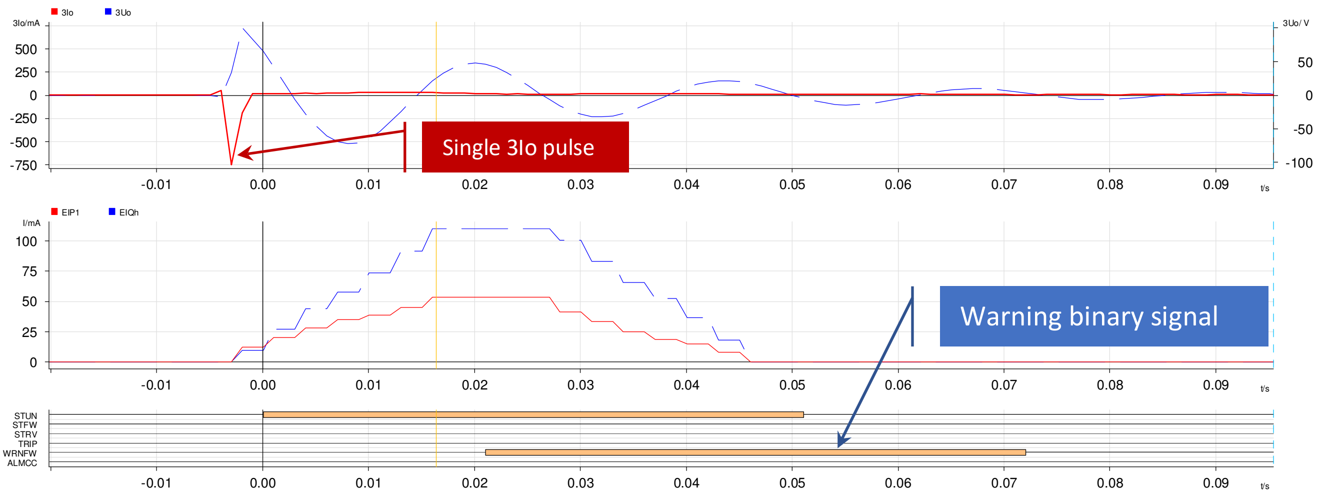


Figure 14: Operation of the algorithm for forward GF on a 10kV cable, shown in secondary quantities

The second presented ground fault is a restriking (i.e. intermittent) ground fault in a cable. Residual current pulses are of irregular nature and do not repeat after every half cycle or every zero-crossing of the residual voltage waveform, as shown in Figure 15. Sometimes even several consecutive residual current pulses have the same polarity which may influence the ground fault relay if not properly designed. Such ground fault behavior is already described in Reference [12]. Even for such fault both proposed measurement methods operated as expected indicating forward direction by detecting positive EIP1 and EIQh values, as shown in Figure 15. Binary outputs from the new GF relay are also shown in this figure as well. Due to long duration of the fault both START and TRIP signals are now given by the relay.

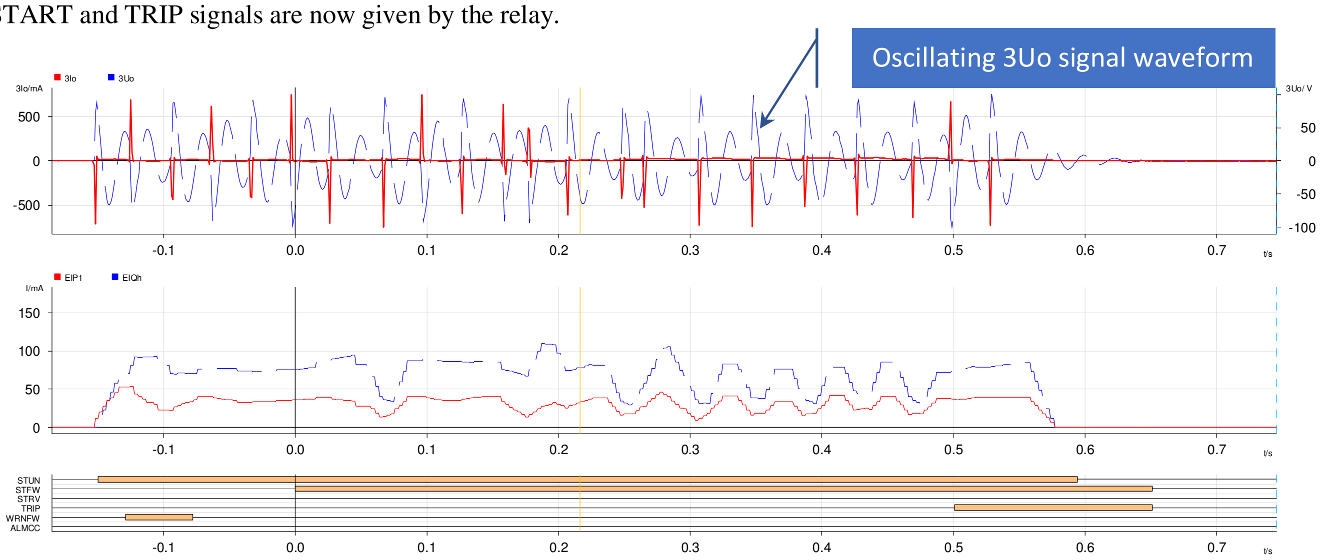


Figure 15: Restriking GF on 10kV cable, resonant grounding, shown in secondary quantities

During the second part of this primary testing, the coil in the neutral point was switched off and then network became grounded only via the 15A resistor. Restriking, forward ground fault as shown previously in Figure 15 was then repeated at exactly the same location for the resistively grounded network and it is presented here in Figure 16. Note now "squared" 3Uo voltage waveform during this fault which is quite different from the oscillating 3Uo voltage waveform having multiple zero-crossings when coil was connected (i.e. compare Figure 16 with Figure 15). Also note that without the neutral point reactor re-striking 3Io current pulses appear regularly every half cycle and have opposite directions every time. These peaks now actually correspond to every 3Uo waveform zero crossing. Note also that the post-fault voltage oscillations are almost not present at all now due to absence of reactance from the neutral point. Instead trapped voltage (i.e. energy) in the distributed capacitances just discharges through the neutral point resistor.

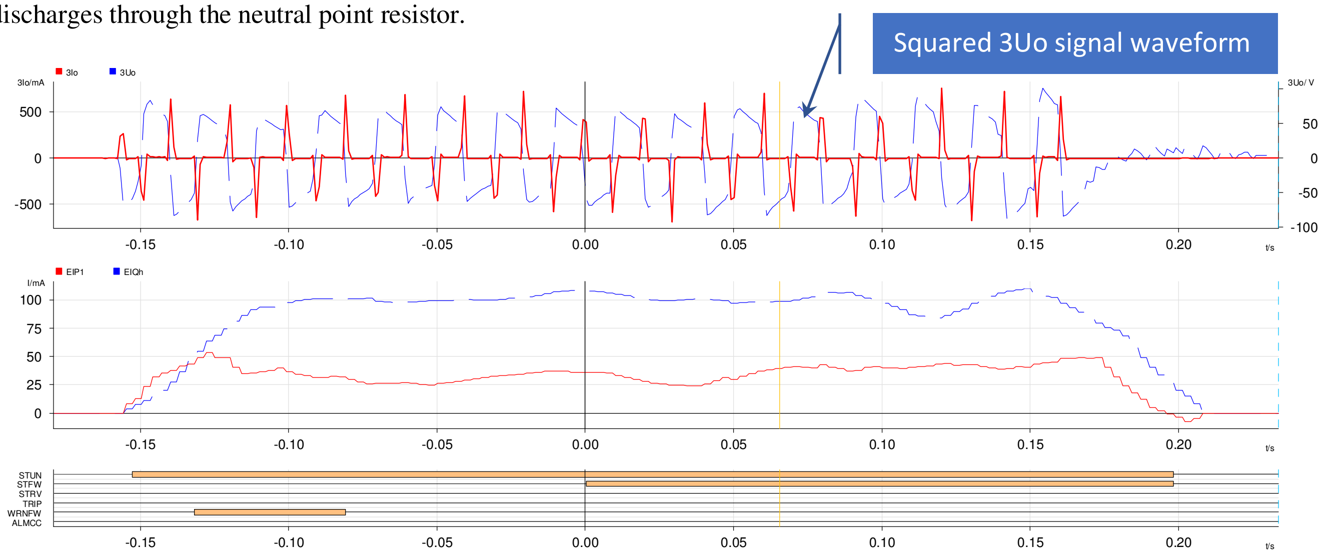


Figure 16: Restriking GF on 10kV cable, resistive grounding, shown in secondary quantities

Even for this fault the newly proposed transient methods operated as expected indicating forward direction by detecting positive EIP1 and EIQh values, as shown in Figure 16. Due to duration of the fault only START signal is now given by the transient GF protection.

5.6. High Impedance ground fault in 22kV, 50Hz, three-phase system having resonant grounding

A series of primary tests were done in a 22kV distribution network. Exactly tuned single Petersen coil was used as grounding impedance during tests. The used instrument transformers have ratio of VTR=22/0.1 and CTR= 100/1. Original DRs were captured using 1.6kHz sampling rate. They have been re-played into the target IED using a modern secondary injection test set having comtrade play-back feature. Only one record of a ground fault having high fault resistance at the fault point is presented in Figure 17. The new relay operated correctly.

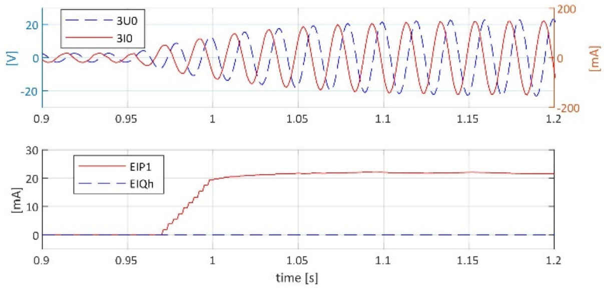
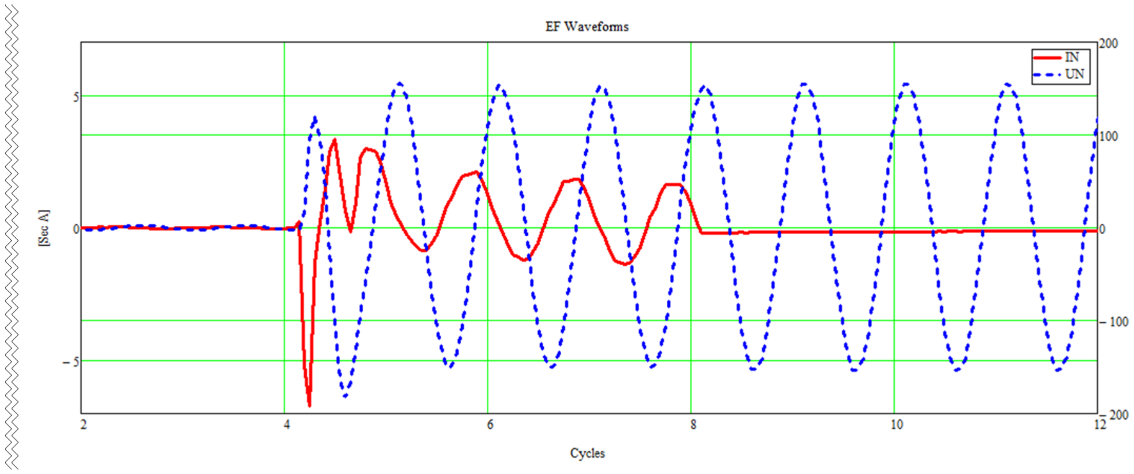


Figure 17: High-resistive GF on 22kV cable, resonant grounding, shown in secondary quantities

5.7. Single phase to ground fault in 60kV, 50Hz, three-phase system having resonant grounding via single coil

This recording was captured on a 60kV OHL having instrument transformers with the following ratios: VTR=60/0.11 and CTR=400/5. The line is a part of a meshed power system where resonant grounded via a single coil is used. This system is installed on an island, having a single connection to the mainland. The neutral coil is located on the mainland. Therefore, if the connection to the mainland is lost this system becomes an isolated system. Consequently, the ground fault protection shall be able to work for both types of grounding. Figure 18a shows a forward fault captured in such system. Note also that during steady state part of the fault 3Io and 3Uo signals are phase shifted by 90 degrees indicating that the reactor was used as the grounding impedance. Both proposed methods operated as expected indicating forward direction by detecting positive EIP1 and EIQh values as shown in Figure 18b. Note that the largest integrated values are obtained during the transient period of the fault.

a)



b)

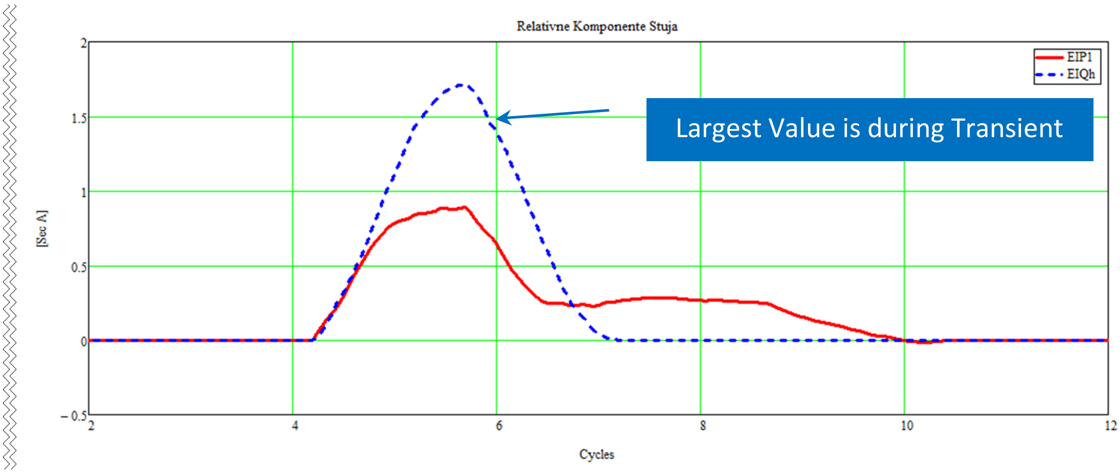


Figure 18: GF protection operation for a 60kV; 50Hz OHL

5.8. Single phase to ground fault in 66kV, 50Hz, three-phase system having resonant grounding via multiple coils

This recording shown in Figure 19 was captured on a 66kV OHL having instrument transformers with VTR=66/0.11 and CTR=600/5. This line is connected to the bus where an 200A Petersen coil is installed. During this forward ground fault, the measured residual current on this line is heavily influenced by the coil current. Such heavy dc-current component is caused by the reactor and typically only flows in the faulty feeder which is located in the vicinity of the neutral coil. Such relatively large residual current (i.e. 200A primary) with quite heavy DC component might influence many protection functions depending on their design and settings.

This DR also confirms that relatively large residual currents may flow in resonant grounded networks despite the fact that the current at the fault point is relatively small (typically less than 50A primary). Note also that during steady state part of the fault 3Io and 3Uo signals are phase shifted by 90 degrees indicating that the reactor is used as the grounding impedance. Both proposed methods operated as expected indicating forward direction by detecting positive EIP1 and EIQh values as shown in Figure 19b. Note that the largest values are again obtained during the transient period of the fault.

a)

b)

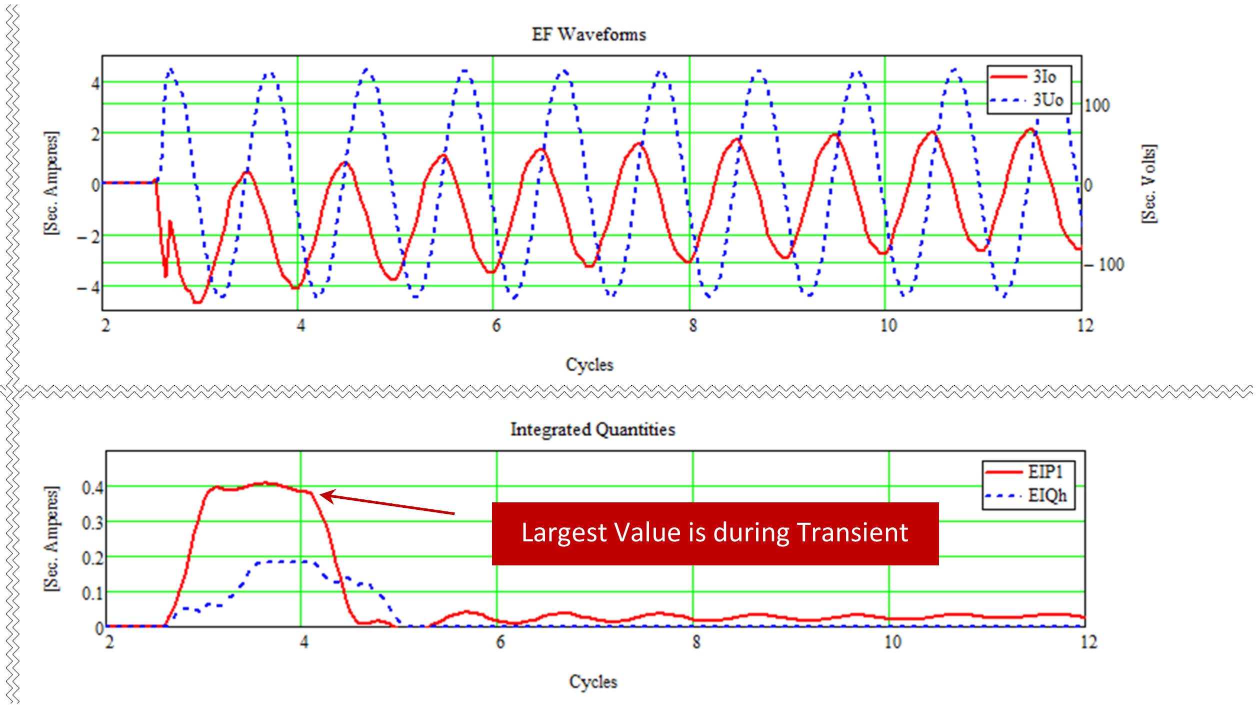


Figure 19: GF protection operation for a 66kV; 50Hz OHL

5.9. *Ground fault in 110kV, 16.7Hz, two-phase supply network for a railway system*

Due to historical reasons 16.7Hz railway supply system is used in five European countries. In some of these countries even a dedicated 110kV, 16.7Hz, two-phase transmission system has been developed in order to provide power supply to the extensive railway network. This 110kV system has resonant grounding via multiple coils. The capacitive earth fault current can be bigger than 1000A primary. Up to sixteen large neutral coils are used to compensate this system.
Another practical problem is that 16.7Hz, two-phase OHLs often share right-of-way corridor with other three-phase, 400kV, 50Hz OHLs. Sometimes they are even suspended on the same power towers. As a result, there is a possibility for induction of a 50Hz signal into the 16.7Hz OHLs during a ground fault. Note also that the 50Hz is exactly the third harmonic component for the 16.7Hz system. Due to that fact the harmonic part of the proposed methodology, as described in Section 3.2, has been deliberately modified for the new transient ground fault protection when used in 16.7Hz railway power systems. This protection by design excludes the third harmonic current from the EIQh value calculation.
Series of primary tests have been performed in this two-phase, 16.7Hz system and one ground fault will be presented here for the faulty and two healthy feeders. The used instrument transformers have ratio of VTR=110/0.1 and CTR= 600/1 for all bays.

The captured recordings from three 16.7Hz feeders are shown in Figure 20, Figure 21 and Figure 22 respectively. As shown in these three figures the proposed ground fault relay methodology would operate correctly for all three 16.7Hz feeders. In the faulty feeder positive EIP1 and EIQh values are measured indicating forward direction while in the healthy feeders smaller but negative values are measured. Note also that quite large third harmonic residual current component is present after the initial fault transients in all three feeders. It has varying magnitude among these feeders. However, this third harmonic residual current component is by design excluded from the EIQh calculations for 16.7HZ systems only. By doing that proper behavior of the proposed ground fault methodology is assured irrespective of the influence from the nearby three-phase, 400kV, 50Hz OHL(s).

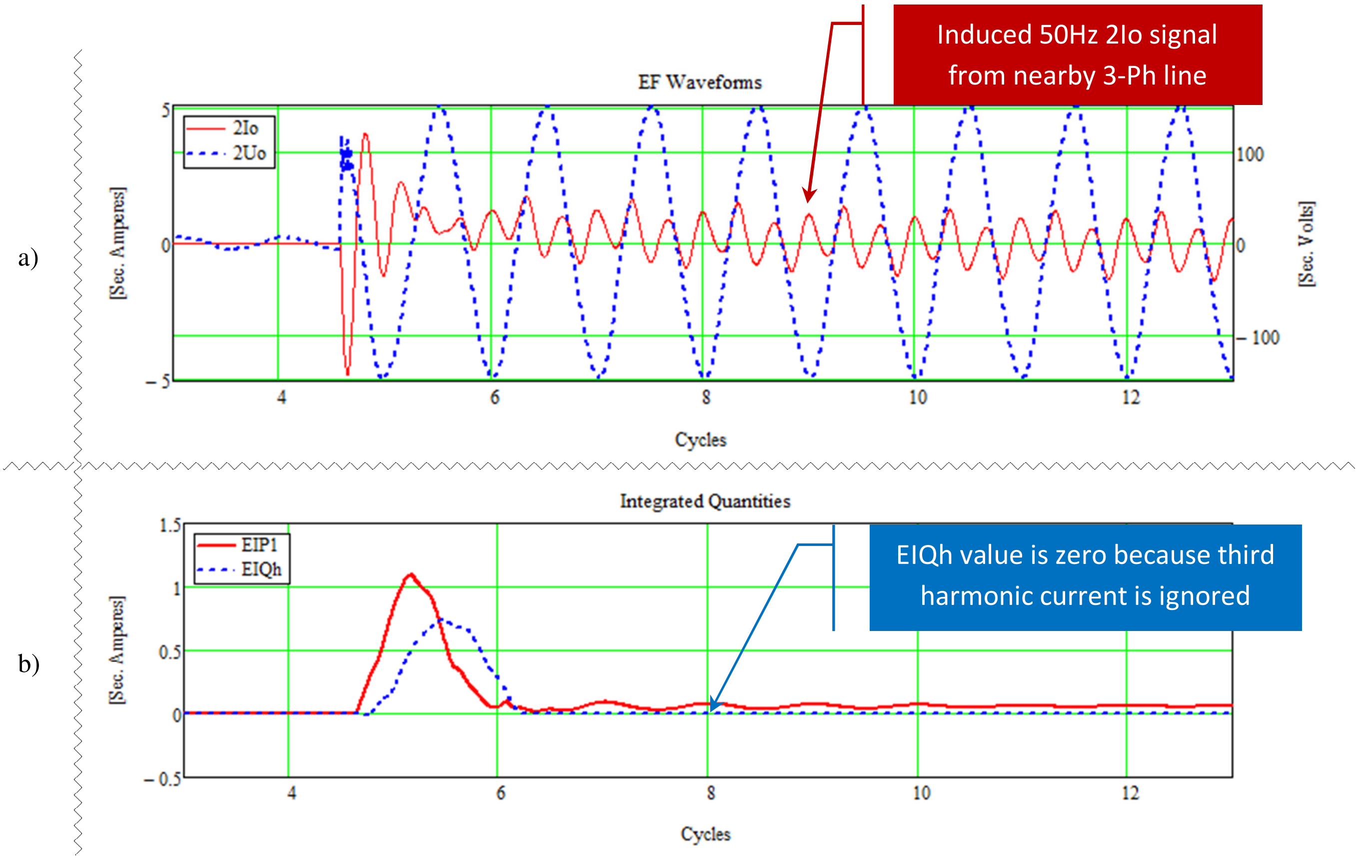


Figure 20: Behavior of Transient GF protection in 110kV; 16.7Hz; 2-Ph system in the faulty feeder

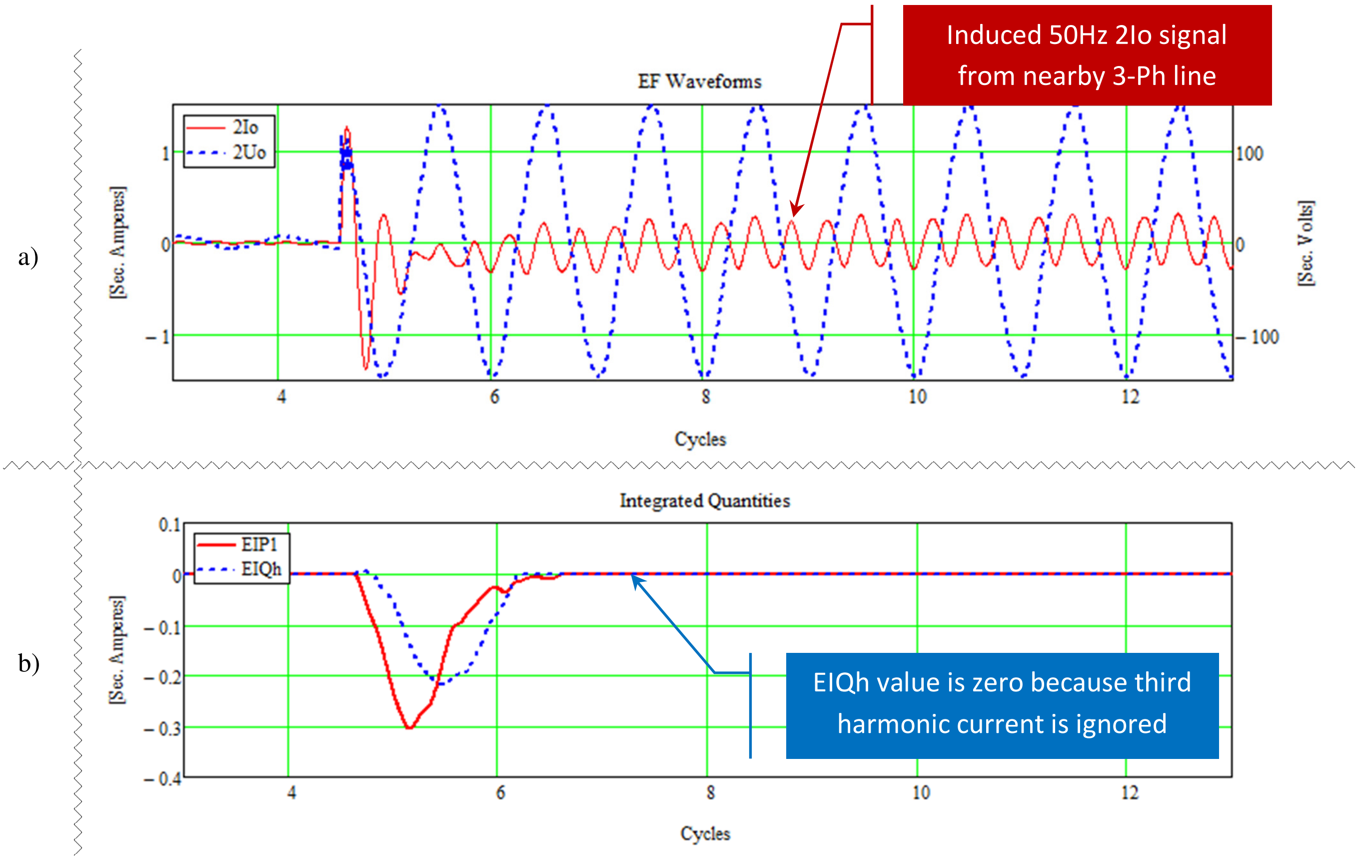


Figure 21: Behavior of Transient GF protection in 110kV; 16.7Hz; 2-Ph system in the first healthy feeder

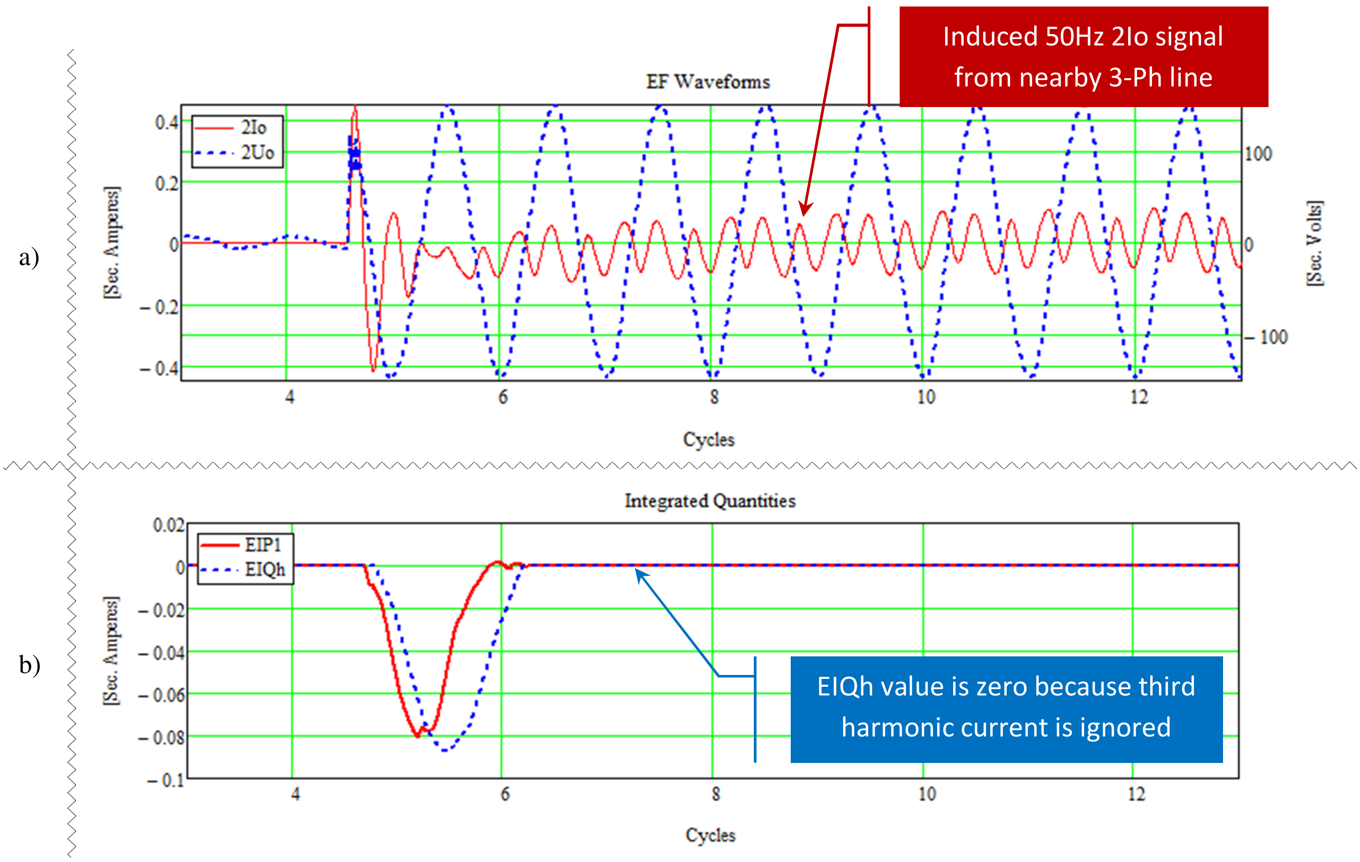


Figure 22: Behavior of Transient GF protection in 110kV; 16.7Hz; 2-Ph system in the second healthy feeder

Note that the largest values for EIP1 and EIQh are again obtained during the transient period of the fault for all three feeders and that proposed methodology operates equally well in two-phase and three-phase electrical power networks.

5.10. Restriking ground fault in 132kV, 50Hz, three-phase system having resonant grounding via multiple coils

The recording was captured on a 132kV OHL having CTR=800/5 and VTR=132/0.11. This line is connected in a resonant grounded system having multiple neutral coils. Figure 23 shows how the target hardware reacted for this forward GF when a tree was touching a phase conductor. Three residual current strikes are clearly visible on this record. Proposed method detects a forward fault for every strike by measuring positive values for EIP1 and EIQh quantities. The largest integrated values are always obtained immediately after each residual 3Io current strike. Note also the post-fault residual voltage oscillations which are clearly visible during this fault (i.e. in-between two residual current strikes). This oscillation has almost rated frequency because the coils are tuned quite well with the overall system capacitance.

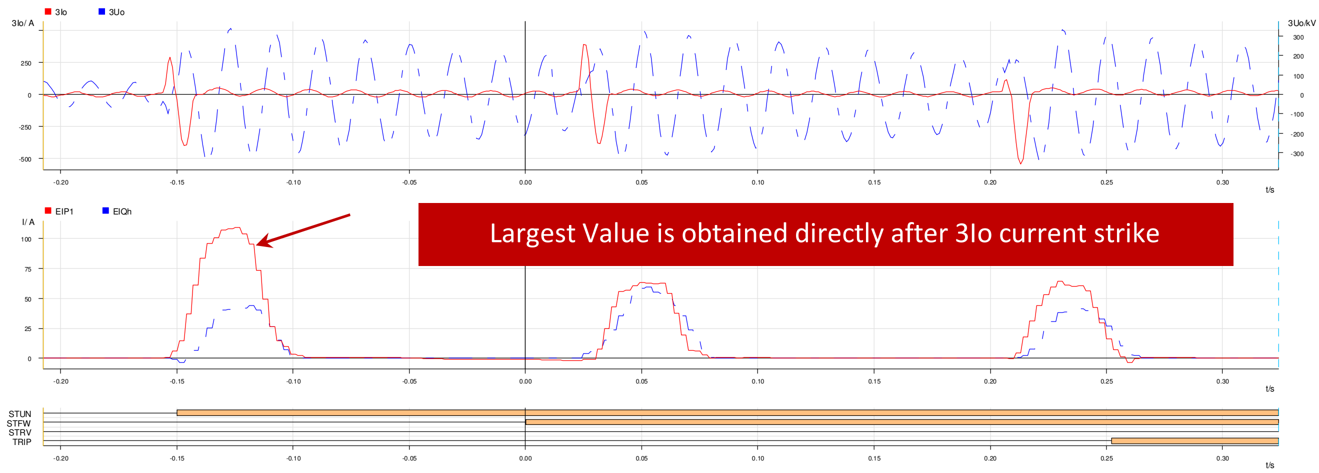


Figure 23: Forward ground fault on a 132kV OHL

5.11. Pilot installation in a 132kV, 50Hz, three-phase system having resonant grounding via multiple coils

A prototype of the new algorithm was installed in a 132kV substation. Six instances of the new algorithm have been used within a single target IED hardware [15] to protect six different feeders at the same time. This gives a possibility to compare algorithm response for the faulty and healthy feeders during the same ground fault.
The protected system has a total capacitive ground fault current of roughly 600A primary and resonant grounding is used. This is achieved by using several large Petersen coils. Several ground faults captured in this pilot installation confirmed that direction of the reactive power flow based on the fundamental frequency residual phasors can have opposite directions in two healthy feeders during a ground-fault in such complex network. How one particular ground fault was seen on four different feeders is shown in figures below.
The proposed method correctly detected the ground fault direction with both measuring principles for all feeders.

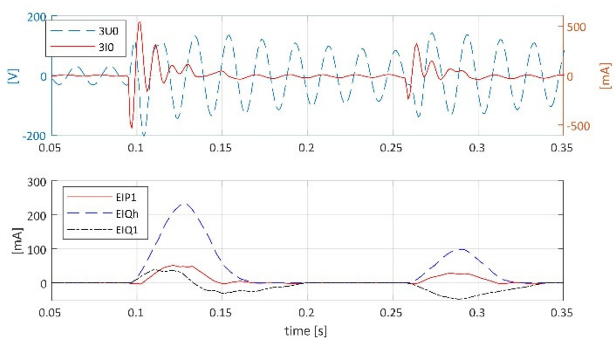


Figure 24: Recording from the faulty feeder

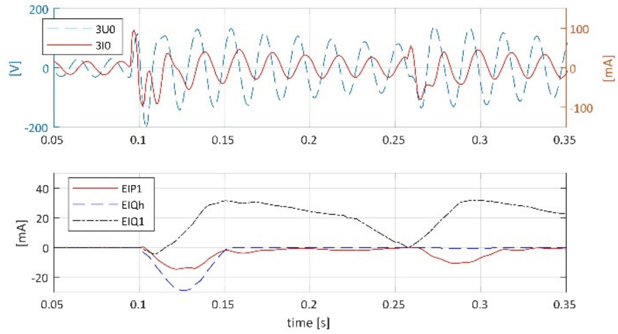


Figure 25: Recording from a healthy feeder No 1

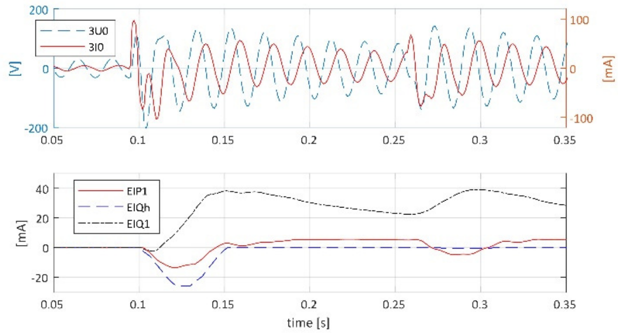


Figure 26: Recording from a healthy feeder No 2

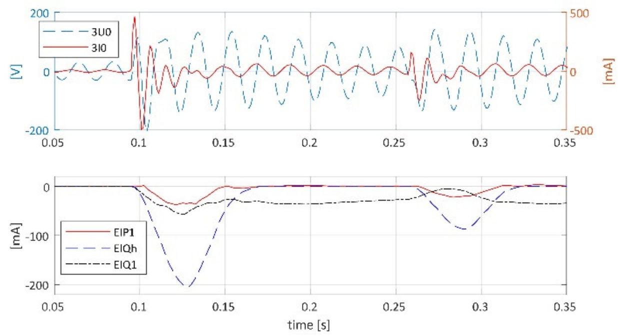


Figure 27: Recording from a healthy feeder No 3

Note the contradictory flow direction of the fundamental frequency reactive power (i.e. quantity EIQ1 which is added in the previous four figures). The EIQ1 quantity can have arbitrary directions in healthy feeders and even in the faulty feeder. Consequently, all transient ground-fault protections which use either complete I_0 current phasors or IQ1 or EIQ1 quantities in their algorithm may have problems to correctly determine the direction of the ground-fault in meshed sub-transmission networks.

6. Understanding Sampling Rate Issues for Transient Ground Fault Protection

Recordings from primary testing described in Section 5.5 are used to verify if a protection algorithm using 20 samples per power system cycle is capable to be used as transient ground fault protection. The original field records have high sampling rate of 6,3kHz (i.e. 128 samples per power system cycle). These recordings are then injected into the target hardware by a secondary injection test set. One such ground fault is presented here. Both the original 3Io and 3Uo waveforms and the one captured by the target hardware are shown in Figure 28a and Figure 28b respectively. Note that shown curves are drawn by using each individual step (i.e. each sample value) in order to emphasizes the differences/similarities between the two records.

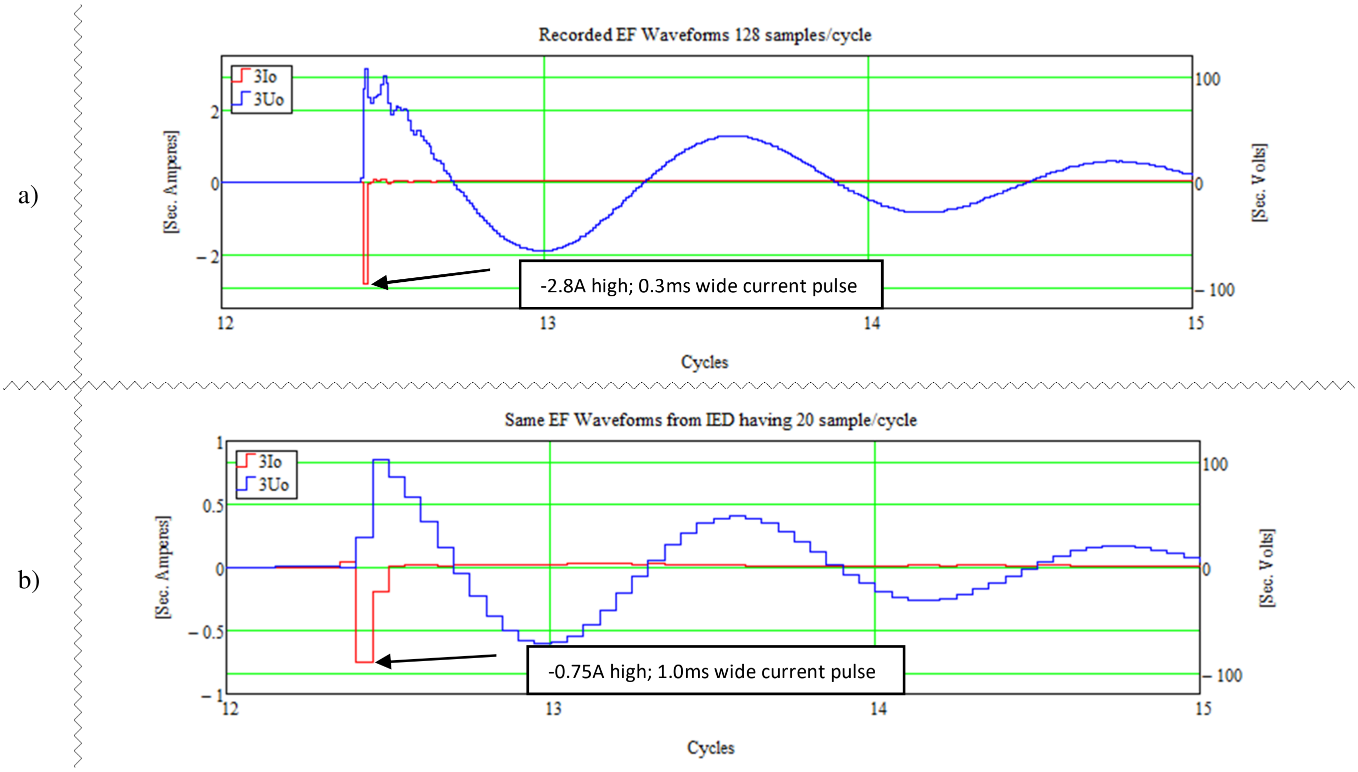


Figure 28: Recording from a faulty cable feeder in 10kV network, shown in secondary quantities
a) Original ground fault record having 128 samples per cycle
b) The same fault captured by the target hardware showing only 20 samples per cycle

From Figure 28a it can be seen that the original residual current pulse is very thin, about 0.3ms wide, but have quite high magnitude of -2.8A secondary. This actually agrees quite well with material presented in Reference [12]. Can this be seen at all by the protection relay using 20 samples per cycle in their algorithms (i.e. using one sample every millisecond)? It appears that the relay might easily miss such slim current spike.

When this record is re-played into the target hardware this pulse is still clearly visible, but it is now 1.0ms wide (i.e. one sample period) and its magnitude is only -0.75A secondary, as shown in Figure 28b. Note that for the sake of simplicity the next consecutive sample with magnitude -0.17A is simply ignored in this discussions. It shall be also noted that the actual signal energy content (i.e. area below the current pulse) is quite well preserved because the two mathematical products (i.e. "0.3ms×2.8A=0.84A•ms" and "1.0ms×0.75A=0.75A•ms") have approximately the same value. This enables the algorithm (which is actually based on the energy content of the current signal) in the target hardware to consistently operate properly for such ground fault. One can play-back the original recording hundred times in succession with the same correct behavior of the relay. Similar observations regarding hardware properties have been reported by other relay manufacturers as well [14].

Another way to check target hardware performance is to calculate EIP1 and EIQh values two times. The first time by using original record having 128 samples per cycle and the second time by the transient ground fault protection algorithm running in the target hardware. Results of such calculations are presented in Figure 29.

a)

b)

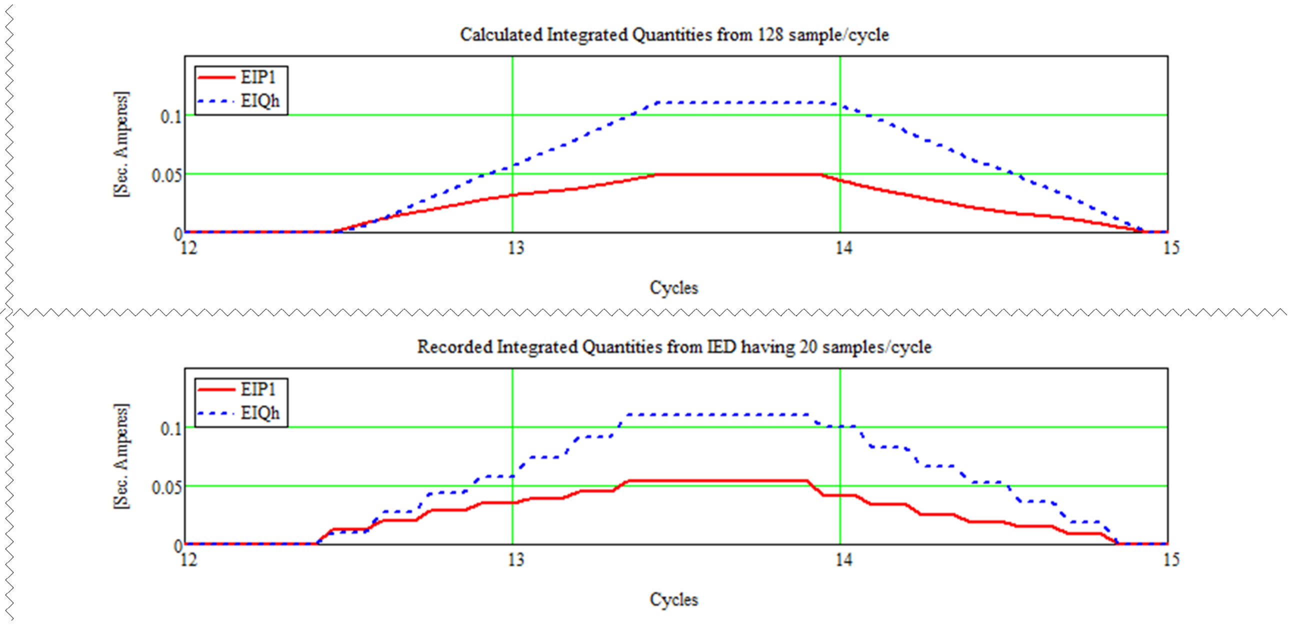


Figure 29: EIP1 and EIQh quantities for this ground fault when
a) calculated by using all 128 samples per cycle (see Figure 28a for waveforms)
b) calculated by the algorithm running in the target hardware using 20 samples per cycle (see Figure 28b for waveforms)

Figure 29 verifies that the calculations done within the transient ground fault protection algorithm using 20 samples per cycle gives practically identical result for EIP1 and EIQh values as if full 128 samples per cycle were used. How this is possible?

The secret lies in the design of the analogue acquisition chain of the target hardware [15]. Although such relays do use 20 samples per power system cycle for the protection algorithms, the actual sampling rate in the hardware platform is higher (i.e. it can be approximated as 10kHz). The captured samples on the hardware are first passed through several stages of digital low-pass filtering before the 20 samples per cycle are derived for the protection algorithms. We can simply envisage this as if one used sample in the protection algorithm is approximately calculated as average value of ten samples taken on the actual hardware. By doing this the energy content of the measured voltage and current signals are properly preserved. In simple words one can say that 20 high quality samples per cycle are actually used by the protection algorithms, indicating that these 20 samples are not the actual hardware sampling rate of the device.

One can conclude that the used sampling rate by the protection algorithm might not be a limiting factor for the design of transient ground fault protection. It is actually the design of the complete analogue acquisition chain of the target hardware and the measuring principle which determines such limitations in reality. Of course, one also needs to realize that a disturbance record having 20 samples per cycle does not accurately represent the magnitudes and durations of the thin residual current spikes which have occurred in the primary system during a ground fault.

Note also that the three integrated values (i.e. EIP1, EIQh and even EIQ1 which is not used in the algorithm) are provided by the new transient ground fault protection as a service value. They can be read online and also can be recorded by the built-in disturbance recorder as already shown in some of the Figures in this paper. This facilitates commissioning, testing and field operation of such protection IED. Practically operation of such transient ground fault protection is quite transparent for the end users and in simple words this 67NT protection does not behave as a Black Box!

7. Correlation with other Methods used for Transient GF protection

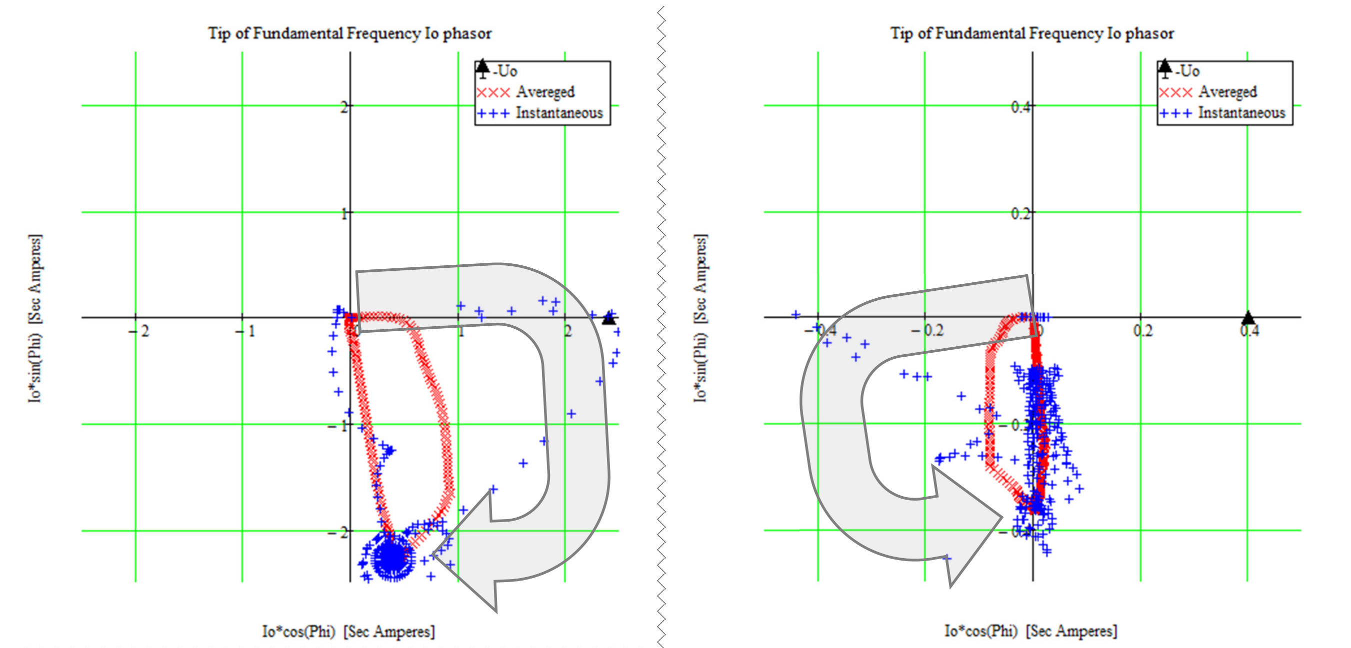
The proposed methodology does not mix residual current and voltage measurement because such solution will pose practical problems how to correctly set appropriate pickup level for such function. Namely the residual current measurement is the main source of all practical problem for this type of protection. Why then mix it with a residual voltage?

However, many manufacturers of the transient ground fault protection do use an admittance operating plane or measurement of instantaneous active residual power as input signals for their relays. Note that such solution means that voltage and current measurements are mixed together. Anyhow some correlations between such principles and the proposed methodology in this paper can be drawn and is given below.

The operation of the new transient ground fault protection can be also visualized by using the voltage-current plane (i.e. similar principle as sometimes used for generator protection) where fundamental frequency residual voltage phasor (i.e. $-U_{01}$) is always positioned along the real part of the x-axis and the tip of the residual current phasor (i.e. I_{01}) is plotted on the plane. Effectively this plots two residual current components $I_{01}*\cos(\phi)$ on x-axis and $I_{01}*\sin(\phi)$ on y-axis of such U_{01}-I_{01} plane. In principle such a residual current plot does correspond to the admittance plot for the fundamental frequency admittance component which is used by some manufacturers.

This voltage-current plane will be presented in Figure 30 for the two ground faults presented in Section 5.3. Both instantaneous (blue marks) and integrated (red marks) trajectories are shown in the U_{01}-I_{01} plane. The gray U-turn-arrows in Figure 30 indicate trajectory of the tip of the instantaneous Io phasor during transient part of the ground fault (i.e. at the beginning of the fault). Practically this arrow shows the ground fault behavior in the U_{01}-I_{01} plane during transient. Note that this transient trajectory for the forward fault takes its path only through the first and fourth quadrant in the plain (i.e. in the right-hand side of the U_{01}-I_{01} plane only) as shown in Figure 30a. At the same time for the reverse fault it takes its path through the second and third quadrant (i.e. in the left-hand side of the U_{01}-I_{01} plane only) as shown in Figure 30b. This confirms that only the sign of the EIP1 value (i.e. either positive or negative) during the transient period shall be used to determine the direction of the ground fault.

Note that the steady state operating points for both forward and reverse fault end-up in close proximity of the negative part of the y-axis in this plane. This just confirms that the measurements taken during the steady state conditions cannot be really used to determine the actual direction of the ground fault. Note also that the tip of the instantaneous residual current phasor (i.e. blue marks in Figure 30) is much more stochastic then the corresponding averaged value (i.e. red marks). The blue trace actually passes through all four quadrants for both healthy and faulty feeder. Thus, it seems to be difficult to get a stable directional indication by using such operating plane.



a) Faulty Feeder (forward GF) b) Healthy Feeder (reverse GF)

Figure 30: U_{01}-I_{01} Operating plane for faulty and healthy feeders for GF presented in Section 5.3

8. Conclusion

The new transient GF protection is based on the following two fundamental principles of physics:

1. Distribution of the active power and associated energy for fundamental frequency phasors of the residual quantities at the moment of a ground fault inception in a high-impedance grounded network.

2. Distribution of the reactive power and associated energy for higher harmonic frequency phasors of the residual quantities at the moment of a ground fault inception in a high-impedance grounded network.

These two basic principles will follow the same rules in any type of high-impedance grounded power system including isolated, resonant grounded and resistive grounded networks. By using them in combination with advanced analogue measurement chain which is built-into the hardware platform, all types of ground-faults including low-ohmic, high-ohmic, intermittent and restriking ground-faults will be properly detected in such networks. By using two independent measurement principles, which extremely well complement each other, the best practical results in respect to dependability and security for the transient ground-fault protection is ensured. This methodology can be used without any modification even for power systems where the type of high-impedance grounding changes during operation. The reason is that these two principles are applicable to all types of high-impedance grounded systems.

Another advantage of the proposed method is that the residual voltage signal (i.e. -3Uo) is only used as a polarizing quantity. Its magnitude will not have any influence on the operation of the proposed transient ground-fault protection. Consequently, it shall be easier to set an operating level for the transient GF protection because it is not voltage dependent.

The main advantage for the end user is the method universality. It has been also validated on different types of:

1. power systems (60Hz, 50Hz and 16.7Hz; two- and three-phase; sub-transmission, distribution, railway)

2. network grounding (isolated, resistive, reactive, resonant being either undercompensated or overcompensated)

3. network configurations (both overhead lines and/or cable feeders; and centralized and/or distributed Petersen coils)

The presented methodology can be easily integrated within a multi-functional distance protection IED [15], eliminating any need for a separate transient ground-fault relay in high-impedance grounded sub-transmission or distribution networks.

9. References

[1] Wilhelm, R., Waters, M.: 'Neutral grounding in high voltage transmission', Elsevier, New-York, 1956

[2] Lehtonen, M., Hakola, T.: 'Neutral Earthing and Power System Protection', Kirjapaino, ISBN 952-90-7913-3, 19

[3] Electrical Transmission and Distribution Reference Book, Westinghouse Electric Corporation, 1964, Chapter 19 “Grounding of Power System Neutrals”, pp.643 –665.

[4] ' Erdschlussrelais', https://de.wikipedia.org/wiki/Erdschlussrelais, (in German Language), accessed 11 August 2020

[5] ABB Relays: 'Räleskydd för distributionsnät', Document ID: 1MDA07-SV, 1991 (in Swedish Language), Available at: https://library.e.abb.com/public/3137ea3e24d59789c125754d00499c09/1MDA07017-SV_sv_Relaskydd_for_distributionsnat.pdf, accessed 11 August 2020

[6] ABB Relays: 'RXPF 4 Directional ground-fault relay', Document ID: B03-3014, 1987

[7] ABB Relays: 'RXPG 4 Transient earth-fault relay', Document ID: UG03-3110E, 1988

[8] Werben, S., Hubl, I., Bohme, K.: 'New digital method for the directional detection of transient ground faults', International Conference on Electricity Distribution, Lyon-France, 2015

[9] Pitot, F., Vassilevsky, N., Venkataraman, K., Teoh, C.-P.: 'Wattmetric Earth Fault Protection – Innovation for Compensated Distribution Networks', CIRED 23rd International Conference on Electricity Distribution, Lyon-France, 2015

[10] Altonen, J., Wahlroos, A., Vähäkuopus, S.: 'Application of Multi-Frequency Admittance-Based Fault Passage Indication in Practical Compensated MV-Network', CIRED 24th International Conference on Electricity Distribution, Glasgow-UK, 2017

[11] Loos, M.: 'Single Phase to Ground Fault Detection and Location in Compensated Network'. PhD thesis, Université Libre de Bruxells, 2014

[12] Colding, S.: 'A study of transients of earth faults in cable networks, choice of earth fault relays', Paper 301, CIGRE Session 1960, Paris, France

[13] Guldbrand, A.: 'Earth Faults in Extensive Cable Networks'. Licentiate thesis, Lund University, 2009
[14] VAMP: 'Intermittent Transient Earth Fault Protection', Document ID: AN200-EN003, 2018
[15] ABB: 'REL670 Technical Manual', Document ID: 1MRK 506 370-UEN, 2020
[16] Zubić, S., Wahlroos, A., Altonen, J., Balcerek, P., Dawidowski, P.: 'Managing Post-fault Oscillation Phenomenon in Compensated MV-networks', IET Developments in Power System Protection Conference, March 2016, Edinburgh, UK
[17] Gajić, Z.: 'Challenges for Earth-Fault Protections due to Extensive Use of Cables in the Grid', IET Developments in Power System Protection Conference, March 2020, Liverpool, UK
[18] Tsylin, A., Kruse-Nielsen, R., Yang, G., Sedaghat, B.: 'Influence of Collection Network Parameters on Performance of Distance Protection Directional Elements in Offshore Wind Farms', IET Developments in Power System Protection Conference, March 2020, Liverpool, UK

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