Restricted Earth-Fault (REF) Protection Challenges due to Extensive Use of Cables: A Case Study

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Keywords: Capacitive earth-fault currents, Resistive grounding, Resonant grounding

Abstract

Capacitive zero-sequence currents do exist in any power system during an earth-fault regardless network grounding principle. However, existence of these currents is typically ignored in traditional protection practice. In many countries some type of high-impedance grounding is used which limits the earth-fault current to a certain level. Increased use of cables in medium voltage distribution grids and high voltage sub-transmission grids can also significantly raise the capacitive earth fault currents, which in combination with the used grounding principle in the power network can pose a problem for proper operation of some relays.

1. Introduction

Many distribution networks around the world have limited earth-fault current (i.e. ground-fault current) by a resistor (i.e. R1 in Fig. 1) located in the medium voltage (i.e. MV) winding star point of for example a 132/X kV infeed transformer [1]. The MV system voltage level (i.e. X kV) depends on utility and country practice and can have different values. Some typical values are 6.3kV, 13.8kV, 20kV and 33kV. Simplified single-line diagram of such distribution network and the relevant fault points for the MV winding low-impedance restricted earth-fault protection (i.e. REF) are shown in Fig. 1.

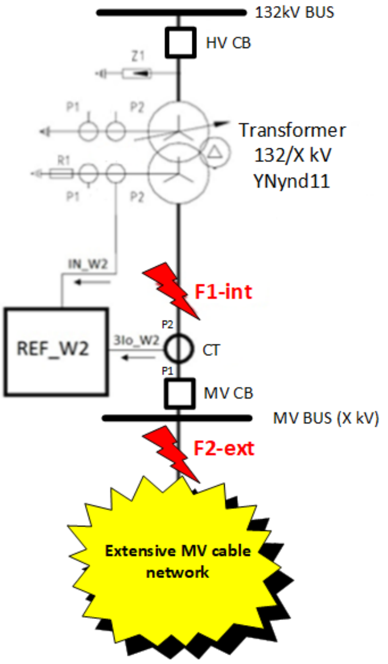

Fig. 1 Simplified SLD of the Transformer

Note that internal earth-fault location (i.e. F1-int) and external earth-fault location (i.e. F2-ext) are also marked in Fig. 1.

For such installation special attention regarding application of the MV winding low-impedance restricted earth-fault protection shall be taken. The REF protection is a zero-sequence current based differential protection for one transformer winding. It measures two zero sequence currents. A neutral current from the MV winding star point (i.e. IN_W2) and a residual current (i.e. 3Io_W2) from a three-phase CT set located at the MV CB as indicated in Fig. 1. The differential current is then calculated as a sum of these two current measurements. For security reason the direction (i.e. the phase angle relationship) between these two zero-sequence current components is also checked for REF protection [4]. Use of REF for the MV winding shall be carefully checked when only a single grounding resistor located in the protected winding neutral point is used for the entire MV network, and at the same time the MV network consist mainly of cable feeders. The capacitive zero-sequence current of such cable network can be quite large [2, 3], even of the similar order of magnitude as the resistor EF current, and this may cause difficult operating condition for MV REF protection for an internal ground-fault.

2. Field recordings

Two actual disturbance recordings captured in the field will be used here to emphasize the problem.

2.1. Recording from a 33kV Industrial Network

This recoding was taken in a 50Hz industrial network having rated voltage of 33kV. The entire 33kV network has only one grounding point via resistor located in the 33kV transformer winding star point. This grounding resistor limits the EF current to 1000A primary. The 33kV network has relatively large capacitance to ground.

An internal earth-fault happens at location F1-int on the transformer 33kV side, as shown in Fig. 1. However, the associated MV side low-impedance REF protection did not operate at all. Fault was cleared by the transformer differential protection 300ms latter (not shown in the figures given in this document) only when the fault involved into a multi-phase fault. Fig. 2 and Fig. 3 shows the relevant currents captured by the built-in disturbance recorder.

The following can be noted regarding this earth-fault:

1) IN_W2 current through the R1 resistor had magnitude of 858A primary during the entire single-phase-to-ground fault.

2) 3Io_W2 residual current from the 33kV grid side had magnitude of 233A during the steady-state part of the EF. Transiently 3Io_W2 magnitude went up to 384A primary.

3) From captured DR it is obvious that a lot of transients were present in the recorded 3Io_W2 current waveform.

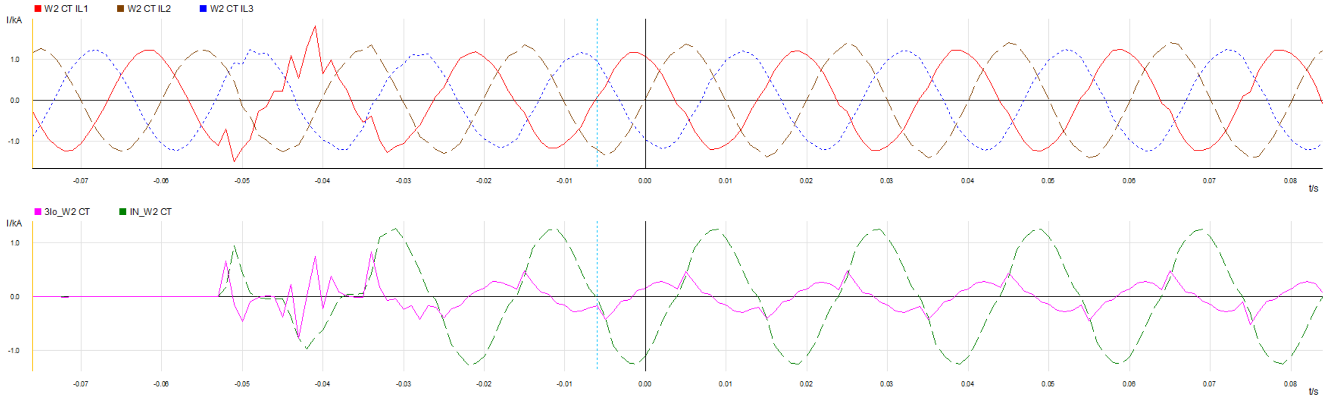

Fig. 2: Current waveforms during the 33kV EF

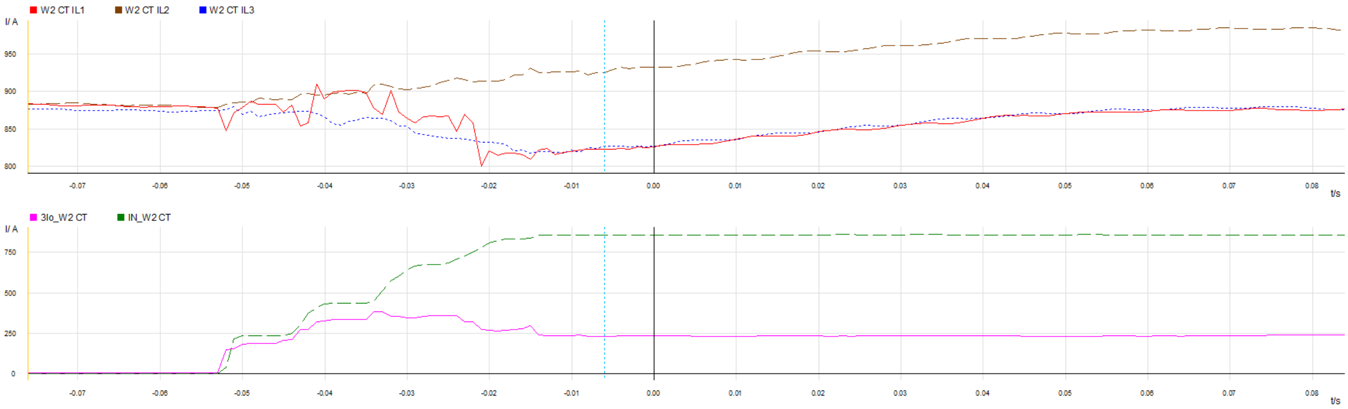

Fig. 3: Current magnitudes during the 33kV EF

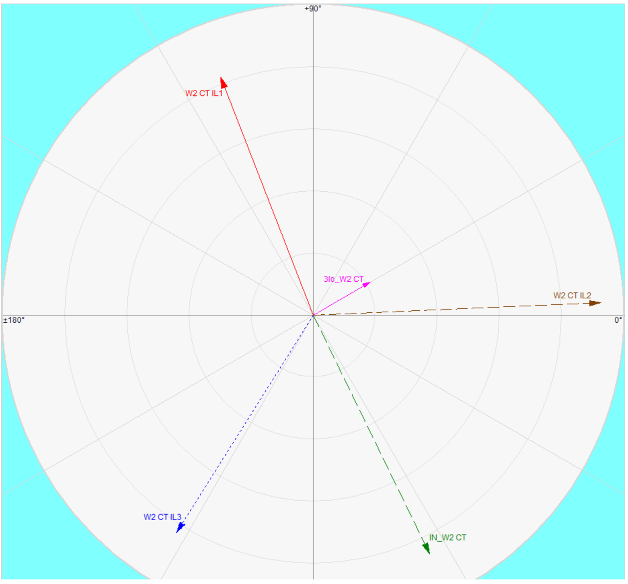

Fig. 4: Phasor Diagram during the 33kV internal EF

4) The phase angle between IN_W2 and 3Io_W2 phasors was slightly bigger than 90° (see Fig. 4). By using more precise calculation it was concluded that value of this angle was around 95° as seen by the MV side REF protection for this EF.
5) The REF protection [4] has built-in directional criterion for security reasons. Its operating area was set to 60°. However, the actual angle measured during this EF was around 90°. Consequently, it was outside of the set directional operate area or the REF protection. This was actually the main reason for missing operation of the 33kV REF protection.

2.2. *Recording from a 35kV Distribution Network*

This record was captured in a 35kV, 50Hz distribution network, which supplies a large city. The entire 35kV network has only one grounding point via resistor located in the MV transformer winding star point. This grounding resistor limits the EF current to 300A primary.
An internal EF happens at location F1-int on the transformer 35kV side, as shown in Fig. 1. However, the associated MV side low-impedance REF protection gives only extremely short trip pulse. Such short trip pulse first confused the operating personnel, and they assumed that this was a maloperation of the REF protection. However, by site inspection it was confirmed that this was genuine internal EF.

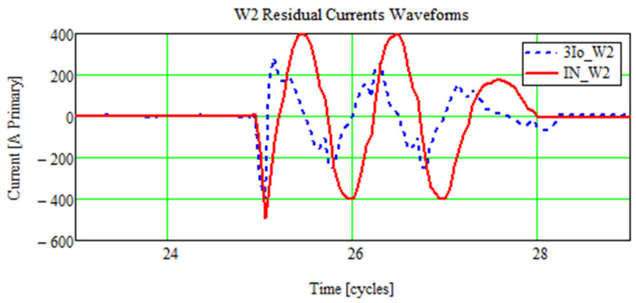

Fig. 5: Residual current waveforms during the 35kV EF

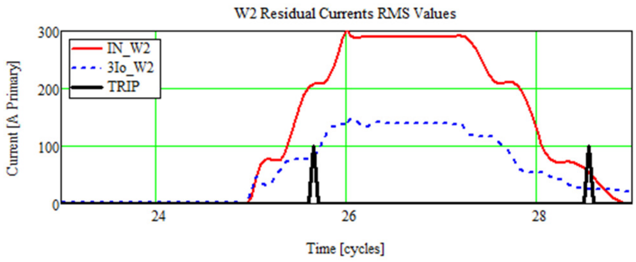

Fig. 6: Residual current magnitudes during the 35kV internal EF and TRIP signal from the REF protection

The following can be noted regarding this internal earth-fault:
1) IN_W2 current through the R1 resistor had magnitude of 290A primary during this EF, as shown in Fig. 6.
2) 3Io_W2 residual current from the 35kV grid side had magnitude of 140A during this EF, as shown in Fig. 6.
3) The phase angle between IN_W2 and 3Io_W2 phasors was also around 90°, as it can be seen from waveforms in Fig. 5.
4) This strange phase angle value was again the main reason for extremely short trip pulse from the REF protection.

Now the following questions can be raised:
1) Why for both these cases the angle between IN_W2 phasor and 3Io_W2 phasor is around 90° when in theory shall be close to 0° for an internal fault?
2) What will happen for external earth-fault? Would then this angle still be 180° or something else (e.g. maybe -90°)?

3. Understanding the Basic EF Theory

The low-impedance REF protection is measuring separately the two zero-sequence currents from the two sides of the protected MV transformer winding as shown in Fig. 1. Namely, IN_W2 in the star point and 3Io_W2 at the winding terminal side.

The two zero-sequence current components present in the MV distribution network during any EF can be calculated by using an equivalent zero-sequence circuit. A simplified zero-sequence equivalent circuit during an internal EF is shown in Fig. 7 and during an external EF in Fig. 8.

The following symbols are used in Fig. 7 and Fig. 8:

1) IN/3 is zero-sequence current component which flows through the transformer MV winding neutral point and associated grounding resistor during an earth-fault. Note that this is only one third of total IN current which will be measured through the neutral point resistor during an earth-fault.

2) Io_Net is zero-sequence current component which flows through the distributed cable capacitance of the MV network during an earth-fault.

3) Uo is zero-sequence voltage source at the fault point. Practically its magnitude can be taken as MV side phase-to-ground voltage magnitude in the faulted phase just before the earth-fault. However, its phase angle shall be turned 180°. This voltage source will then drive the two above mentioned zero-sequence current components through the two branches of the equivalent circuit.

4) R_1 is the grounding resistor in the MV winding star point. Note that its value must be multiplied by three because Io currents and Uo voltages are used in this equivalent circuit.

5) L_T is the per-phase leakage inductance of the power transformer.

6) R_E and L_E are the equivalent resistance and reactance in one phase of the MV cable network. Note that both of them typically have very low value and usually can be disregarded.

7) C_E is the equivalent capacitance to ground of one phase in the MV cable network. Its equivalent impedance at rated frequency has relatively large value.

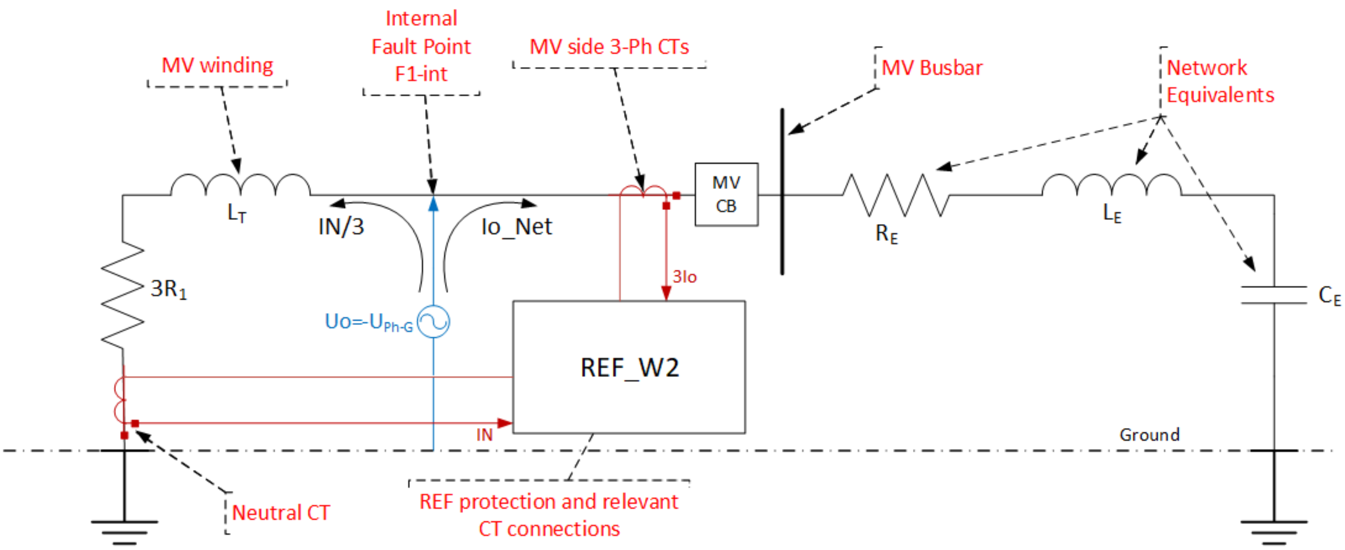

Fig. 7: Simplified equivalent circuit for the zero-sequence system during internal earth-fault

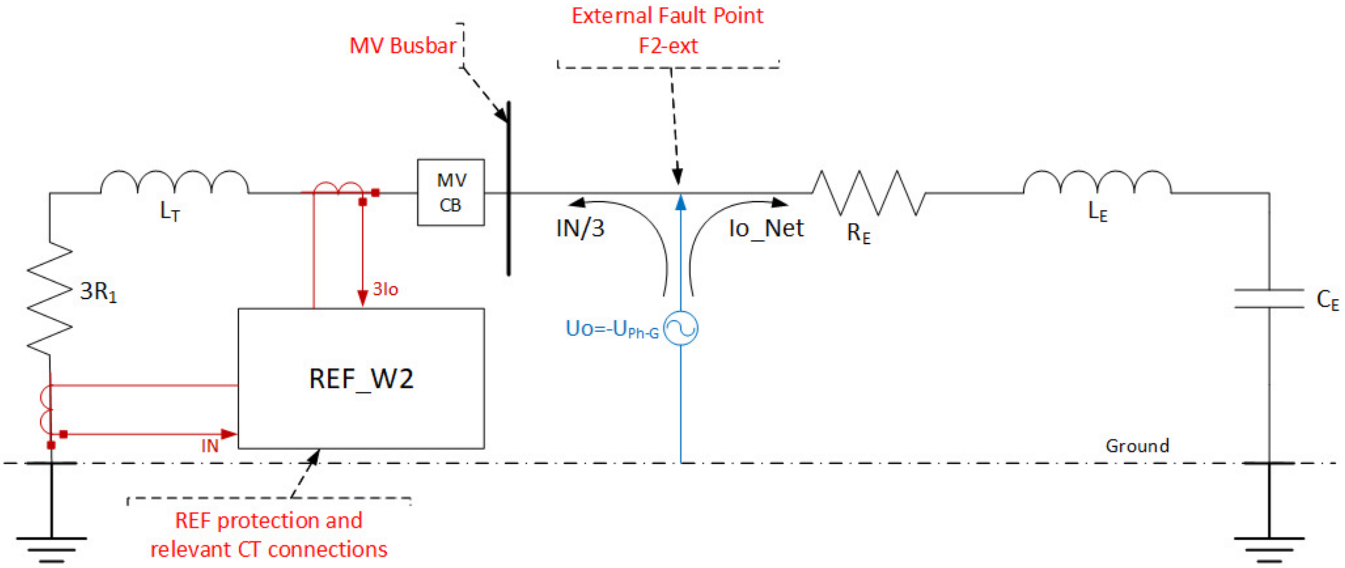

Fig. 8: Simplified equivalent circuit for the zero-sequence system during external earth-fault

Note that in Fig. 7 and Fig. 8 only two circuit branches are present. One on the left-hand side and another one on the right-hand side of the voltage source which is located at the fault point. By looking into the two equivalent circuits the following can be concluded:

1) Left-hand-side IN/3 current component will be always dominantly resistive in nature due to dominant resistance (i.e. R_l) in that branch (i.e. IN/3 will lag behind the Uo voltage for just several degrees)
2) Right-hand-side Io_Net current component will be always dominantly capacitive in nature due to dominant capacitance (i.e. C_E) in that circuit branch (i.e. Io_Net will lead the Uo voltage for almost 90°).
3) During an internal earth-fault (see Fig. 7), the REF function will measure the resistive current component IN/3 in the neutral point and the capacitive current component Io_Net at the winding terminal side.
4) During an external earth-fault (see Fig. 8), the REF function will measure only the resistive current component IN/3 on both sides of the protected MV winding.

Therefore, during an internal EF the phase angle between these two zero-sequence current components measured by the REF protection will be approximately 90° or even somewhat bigger. For example, see Fig. 4 for the angle value recorded in practice. This can cause problems if the low-impedance REF protection utilizes directional criterion for its operation.

For such installations, this directional criterion shall be either switched off or it shall be set to operate for such large phase angle shifts. Consequently, it is recommended to set the operating angle of the low-impedance REF directional criterion at least to 90° but preferably to 115° if it is used [4]. Only with such setting value, stable and reliable operation of the low-impedance REF protection will be achieved.

It shall be also understood that before mention 0° theoretical phase shift for internal EF can only be expected in installations where the zero sequence impedances of the two branches in the equivalent circuit are of the same kind (i.e. both resistive or both inductive or both capacitive). If that is not the case the actual phase angle shift will be different from this 0° value.

However, note that at the same time for all external earth-faults the 180° phase angle shift will still be valid for the REF protection, even in such installations. The reason is that IN current component (i.e. the component flowing through the neutral point resistor at the star point) will be measured on the both sides of the protected MV transformer winding during external fault, as shown in Fig. 8. Because the same current component is measured on the two sides of the protected winding the phase angle of 180° will be seen by the REF protection due to used CT connections, as shown in Fig. 8. When these two measured currents are then summed the resultant differential current will be zero as expected during any external earth-fault.

Finally, it shall be noted that very often in such system time delayed, non-directional EF protection function is used as EF protection for outgoing MV feeders. However even such simple protection can be tricked by a relatively high capacitive EF current magnitude (i.e. the Io_Net current component magnitude). Consequently, directional EF protection based on I*cos(ϕ) principle is the best practical choice for EF protection of individual outgoing MV feeders in such networks. The simple reason is that the EF protection based on I*cos(ϕ) principle will not operate at all for capacitive earth-fault current contribution from the MV cables (i.e. for the capacitive earth-fault current contribution the following will be valid: $\phi \approx 90°$ and $\cos(\phi) \approx 0$). Note also that negative-sequence-based EF protections will not operate properly in such networks.

4. Resonant grounded systems

In the previous sections power system grounded via a resistor was investigated. What will happen in a resonant grounded system for internal respectively external earth-fault? That can be easily estimated by replacing the resistor R1 in the equivalent circuits, which are given in Fig. 7 and Fig. 8, with a reactor tuned to overall system capacitance.

For an external earth-fault the situation will be exactly the same as for the resistively grounded system. The REF protection will measure 180° phase shift.

However, what is very interesting is that even during an internal earth-fault the REF protection will again measure 180° phase shift between two zero-sequence current components. The reason is that the left-hand side branch impedance in the equivalent circuit will be inductive while the right-hand side branch will be capacitive. As a result, internal earth-fault will not be detected at all! This also agrees well with the theory of resonant grounded system where the earth-fault current at the fault point is theoretically forced to zero! Consequently, it can be concluded that low-impedance REF protection having directional criterion, or even any other type of REF protection based on other measuring principles, shall not be applied at all in such resonant grounded networks.

What then can be used to protect the MV winding and associated connections against earth-faults in such networks? Some types of directional transient earth-fault protection having suitable measurement principles, as for example the one described in reference [5], can be used to protect the transformer MV side. Also, for all earth-faults within the transformer tank, the alarm or the trip signal from a Buchholz relay shall operate as well, but only after a quite long-time delay.

5. Possible Issue for Distance Protection

Recently, potential problems for ground distance directional element was reported from an offshore wind farm installation [6]. Typical single line diagram of an offshore wind farm is presented in Fig. 9. The MV system is grounded via a neutral grounding transformer (NGT) and a neutral grounding resistor (NGR). The total GF current on MV 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 grid transformer (GT) and long HV, under-water sea cable to onshore HV transmission grid.

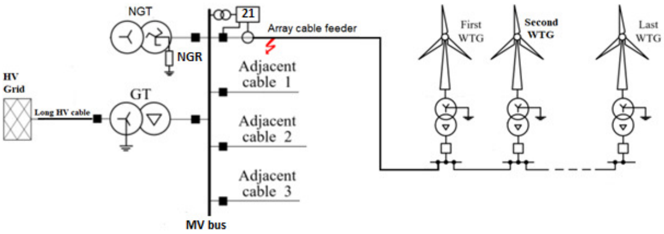

Figure 9: Simplified SLD for a wind farm

The earth fault has happened in one array cable feeder which connects several wind turbine generators (i.e. WTG) to the MV bus, as shown in Fig. 9. Several array feeders can be connected to the same MV bus. Each array feeder can be several tens of kilometers long. Because the entire wind farm MV network is made of cables, quite large capacitive ground fault current contribution from parallel connected healthy cable feeders is present during the ground fault in the faulty phase current. The vectorial sum of this capacitive ground fault current component, neutral point resistor current component with active power export from the WGTs during the ground fault might cause trouble for the traditional ground distance element [6]. The reason is that the faulty phase current under such conditions may start to lead (i.e. not lag as expected) the faulty phase voltage. Consequently, the measured impedance in the faulty phase will actually reside in the fourth quadrant. This might cause problem for the directional element and for such installations additional measures shall be taken to ensure proper behavior of ground distance directional element.

6. Conclusion

Increased use of cables in medium voltage distribution grids and high voltage sub-transmission grids can significantly raise the level of capacitive earth fault currents, which in combination with the used grounding principle in the network can pose a problem for proper operation of protection functions intended to detect ground faults. Especially low-impedance REF protection having directional criterion or ground distance directional elements can be affected. However, even plain feeder ground-fault protection relays may experience problems in extreme cases.

Protection engineers shall be aware of such problematic applications. Hopefully this paper will help them to:

1. Understand the nature and behavior of various residual current components in such networks
2. Choose appropriate operating principles for earth-fault protections
3. Apply adequate settings for already installed earth-fault protections in such networks

7. References

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Zoran likes playing chess and when time allows, he participates in chess tournaments and Swedish chess league competition.

Mike Kockott joined Hitachi ABB Power Grids (formerly ABB Inc.) in Raleigh, North Carolina as a Senior Applications / Product Specialist in November 2011. Prior to relocating to North America, Mike worked as a Senior Applications Specialist / Senior Regional Technical Manager for 12 years at the SA Product factory in Vasteras, Sweden. Before joining ABB AB in Sweden in January 2000, Mike was Senior Consultant, Protection (Transmission) at Eskom (national power utility, South Africa). Mike joined Eskom as an engineer-in-training in 1983 and rose to Protection Design Manager (Line Protection), before switching to Senior Consultant. Mike graduated from the University of Cape Town with a BSc (electrical engineering) degree (with honors) in 1980.