Evaluation of the limitations of a Permissive Overreach protection scheme in a Distribution Loop in case of cross country faults and proposal of alternative solutions

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Abstract

This paper evaluates the performance of a Permissive Overreach protection scheme proposed to ensure rapid fault clearance, in a real example of an MV distribution loop by one of the largest European Distribution System Operators (DSO). The MV loop and the protection devices including the proposed signal comparison schemes have been modelled in detail in the power system analysis software DIgSILENT PowerFactory. The evaluation has been performed using steady state short circuit calculations and electromagnetic transient (EMT) simulations. This analysis reveals limitations in the Permissive Overreach scheme based on the zero sequence phase comparison directional logic in the case of Cross Country faults (CCFs). Alternative solutions, such as phase, zero sequence and negative sequence magnitude differential protection schemes, have been assessed. A Permissive Overreach protection scheme based on the negative sequence phase comparison directional algorithm has also been considered.

1 Introduction

As part of the POI-P4 Operating Interregional Plan project, financed by the European Commission, which studies MV networks operated in loop configuration (both loop line ends connected to the same MV substation), a loop permissive overreach blocking logic protection scheme based on directional overcurrent protection relays has been proposed: MV/LV substations along the loop are equipped with circuit breakers supervised by digital protection relays (the so-called RGDM) which are interconnected by a fiberoptic network; the fault direction detection is based on the Zero Sequence polarisation method [5]. The largest Italian Distribution System Operator, e-distribuzione, is currently testing five MV loops configured with this protection scheme. The behaviour of the protection system of the Taurianova substation MV loop has been studied in [5] and [3]. In [5] it was observed that the position of Cross Country Faults (CCF) were being incorrectly determined. This finding was confirmed by [3] which additionally found that the problem can arise for multiple fault combinations in the case of high impedance (>10 Ω) faults. [3] also reported that, in case of a CCF, the problem seems to depend on the order in which the faults occur. This paper aims to provide an explanation for this observation. Moreover a negative sequence polarising method as well as a negative sequence impedance directional detection have both been considered in [3] as independent alternative solutions. This paper evaluates other solutions based on line magnitude differential protection algorithms.

2 System Model

The MV power system described in [5] has been modelled in the power system analysis software DIgSILENT PowerFactory version 2017. No additional information has been received by e-distribuzione. The model is illustrated in Figure 1. The host network operates at 20 kV and supplies the 20 kV system from a single 150kV/20kV transformer. The 20kV system consists of 5 feeders, 5 main bus bars and 12 additional nodes at which loads are connected. The system is earthed at the 20kV transformer winding through a Petersen coil.

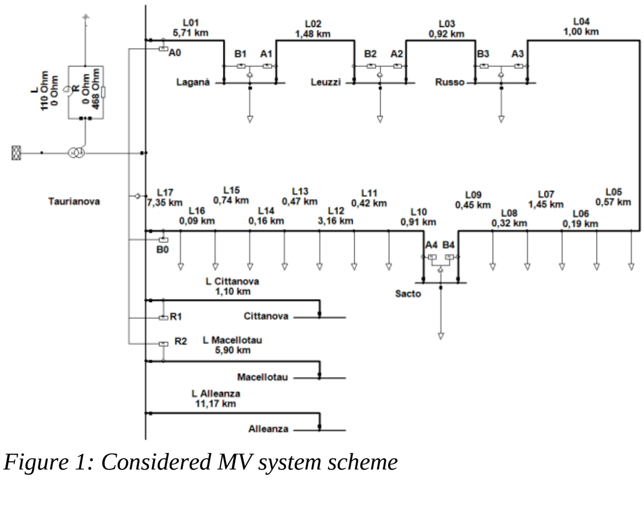

Figure 1: Considered MV system scheme

3 The problem

It has been reported in [5] that in the case of a 15 Ω high impedance CCF involving consecutive poles of the line section 5 (between the stations Sacto and Russo), the relay A4 located at Sacto in the feeder to Taurianova (see Figure 7), detects the fault as a forward fault instead of reverse as it should be. Due to the permissive overreach blocking logic all other "A" ground overcurrent relays are inhibited. The protection system fails; the fault is removed by the breaker controlled by the A4 relay and then, after the blocking signal reset, by the A3 relay breaker, but at the cost of a longer removal time. Moreover the Sacto substation power supply is lost.

Additionally, it has been demonstrated in [3] that the incorrect direction recognition is present for a large number of CCF positions, for any fault resistance greater than about 10 Ω. [3] also concludes that a zero sequence polarising directional method is not a reliable solution for identifying the direction of a CCF.

3.1 A "hands-on" explanation

In order to explain the described problem two different configurations of CCF between the connection point of Load 6-5 (Terminal 6-5, located between the stations Sacto and Russo) and the station Laganà is considered. The CCF configurations are shown in Figure 2.

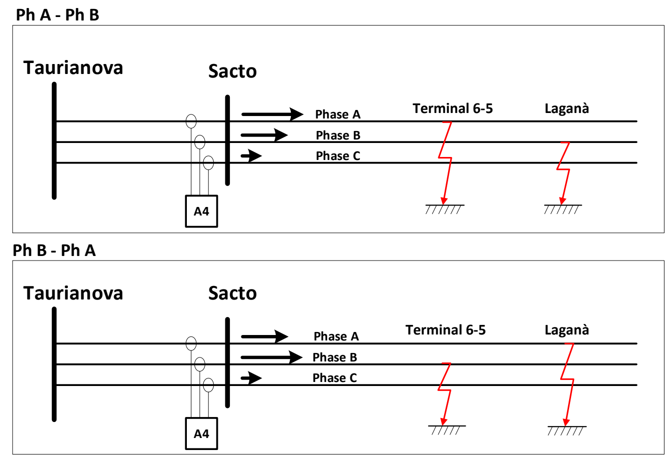

Figure 2 . CCF configuration and position of relay A4

Fixing one fault position at Laganà and letting the second fault position sweep along the whole loop the values for the polarisation angle in relay A4 can be plotted as presented in Figure 3 (anticlockwise short circuit sweep) [3]. The green continuous line shows the polarisation angle fixing the fault on phase A (bottom scheme of Figure 2) and the pink dashed line displays the polarisation angle fixing the fault on phase B (top scheme of Figure 2).

It can be observed that the fault position is wrongly recognised by the relay A4 in the forward direction for the considered CCF configuration with the fault at Laganà fixed on phase A. This behaviour depends upon the unbalanced distribution of the phase currents during the fault. It strongly affects the calculation of the angle of I_0. The V_0 phasor depends mainly on the Petersen's coil impedance and remains constant while the relative position of the faulted phases of the CCF are varied.

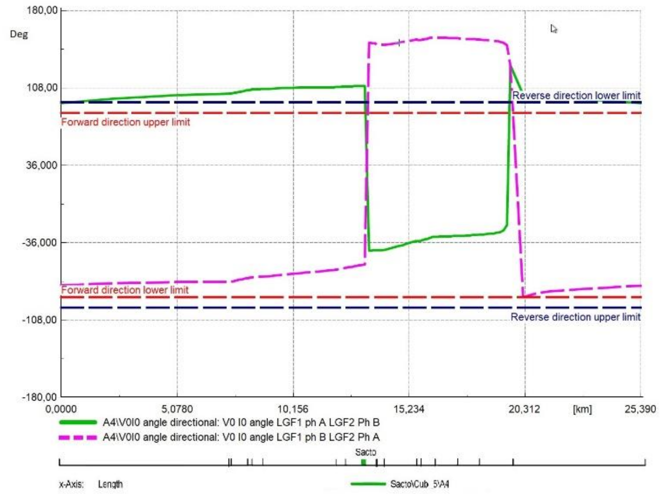

Figure 3: I0V0 angle at A4, CCF with LGF1 at Laganà, Rf=15 Ω

Figure 4 and Figure 5 show the phasor representation of the phase voltages and currents measured by the relay A4 for the fault configurations described in Figure 2. It can be noticed that the voltage of the unfaulty phase C is much higher than the voltages of phase A and phase B which, moreover, have a phase displacement between them of approximately 180º degrees. Therefore, the zero sequence voltage strongly depends upon the phase C voltage.

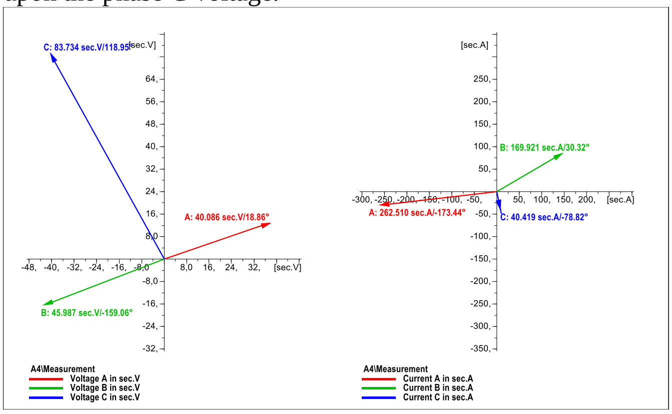

Figure 4: Fault PhA-PhB – Voltages and Currents

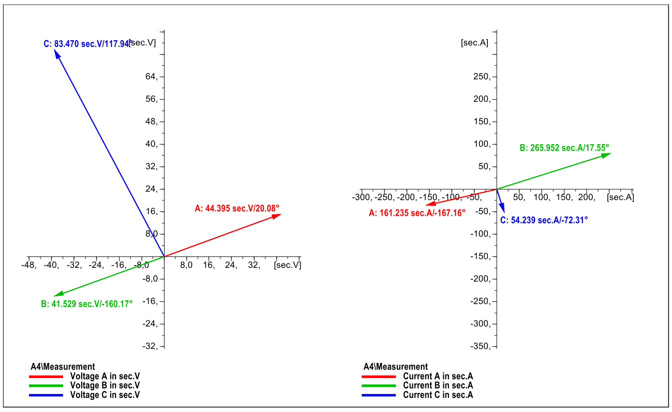

Figure 5: Fault PhB-PhA – Voltages and Currents

The difference between the phase currents in Figure 4 and Figure 5 have a big influence on the value of the angle of the zero sequence current. The zero sequence polarising voltage and operating current are shown in Figure 6. The angular difference between the operating current for the CCF configurations A-B and B-A is close to 180º so it is clear that correct fault direction detection is not possible for both cases even by changing the maximum torque angle (MTA) or the amplitude of the forward direction detection sector.

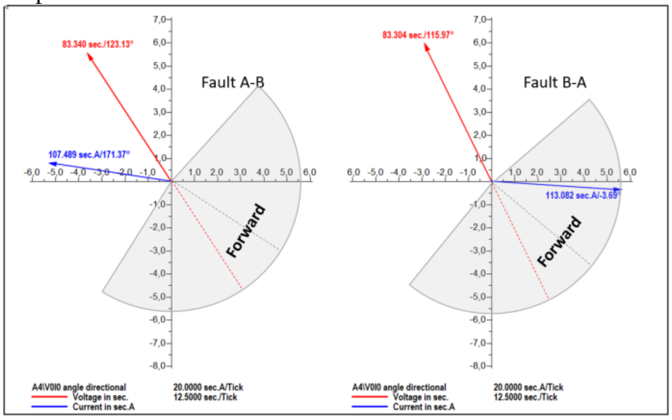

Figure 6: Vo and Io at Relay A4

The same calculations have been carried out for the same CCF with Rf=0 Ohms and it has been observed that this phenomenon is further amplified. In any case, CCF faults with a fault resistance smaller than about 10 Ω produce a phase fault current greater than 400 A and can therefore be recognized by the phase overcurrent elements.

4 Alternative solutions

According to the results of [3], the negative sequence impedance directional logic provides acceptable behaviour for all studied fault positions. However, this logic uses a patented algorithm available only with the relays of a unique manufacturer. The negative sequence algorithm is generally suitable for the identification of the fault direction but it fails to properly detect the direction for faults close to the power supply substation (Taurianova). For this reason the permissive overreach negative sequence phase comparison directional combined with a magnitude differential logic is considered in this paper.

The differential relays should protect the lines Taurianova-Laganà and Taurianova-Sacto where the negative sequence directional method could fail for high impedance CCFs. Negative sequence, zero sequence as well as more conventional phase magnitude differential relaying method have been considered to protect those loop sections. The sequence differential relay logics are supposed to provide many advantages over the phase differential in terms of sensitivity and operation speed [1] [2].

The studied protection scheme is shown in Figure 7. All the relay models utilise an interblocking scheme. The differential relays are faster than the overcurrent relays and would remove any fault along section L1 (Taurianova-Laganà) and section L10-L17 (Taurianova-Sacto).

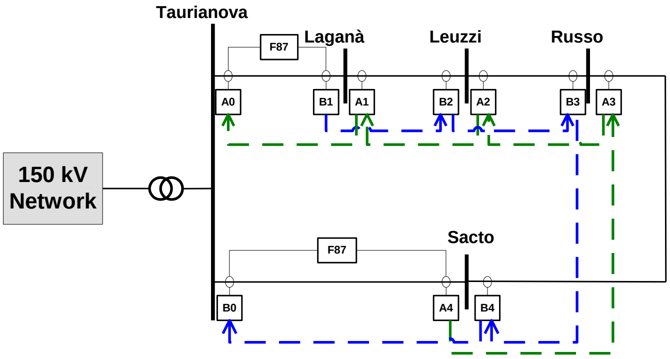

Figure 7. Improved protection scheme

The RGDM devices, used to protect the MV loop, contain three current sensors measuring signals derived by means of Rogowski coils with an accuracy class of 0.2% [4], and the authors declare through the signal conditioning an even higher overall accuracy. In any case, the presence of such coils guarantees superior performances over a protection system based on the differential principle. Moreover the IEC 61850 SV (sampled values) messaging system over Ethernet for peer-to-peer communication could be used to implement the differential logic.

The Rogowski coils don't saturate and guarantee an overall accuracy compatible with the very low thresholds required by the e-distribuzione policies [6].

4.1 Relay models

To simulate the behaviour of such differential relays three models have been implemented in DIgSILENT Power Factory version PF2017 (see Figure 8 for the modelling of the negative sequence differential relay).

The models consist of:

- Acquisition (with error simulation)
- Filtering & Measuring.
- Differential Logic
- Interblocking logic with other relays

The model differential element implements a differential threshold with double percentage current biased restraint characteristic, unrestrained differential threshold and 2nd harmonic blocking (not used in this study).

The relay model calculates the operating quantities, sampling (for EMT simulation) the current and voltage values at 20 samples/cycle. After that, a low pass filter cut off frequency of 650 Hz has been applied to the values returned by the Rogowski coils.

A DFT (Discrete Fourier Transformation) filter is then applied to groups of 20 samples to calculate the current and voltage vectors (real and imaginary part).

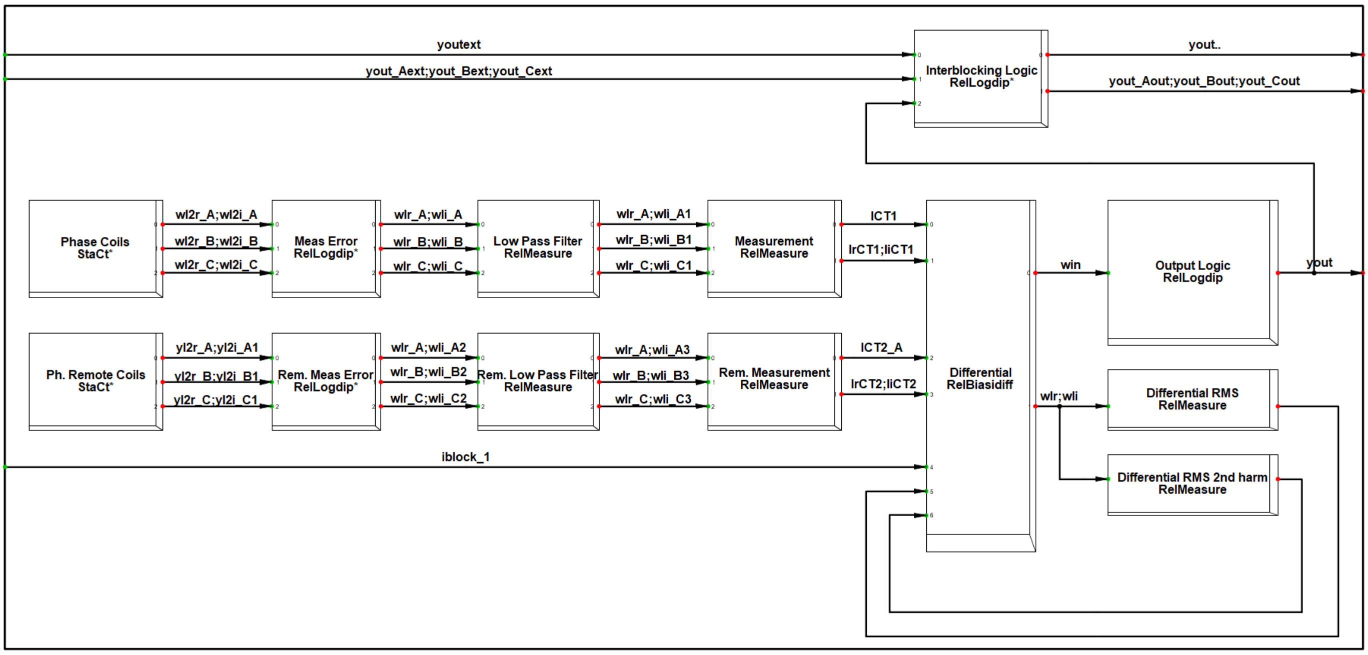

Figure 8. Improved RGDM relay model connection scheme

The “Meas Error” and the “Remote Meas Error” blocks are used to simulate the Rogowski coil error (possibly amplified by external magnetic fields or by the incorrect position of the conductor inside the coil [6]), with separate values calculated for each phase, as well as the RGDM calibration errors and the errors introduced by the definite number of points of the RGDM analog/digital converter. A very conservative ±2% total error has been considered in the simulations. The errors used during the simulation are listed in Table I

Table I: Phase magnitude and angle error local and remote coil

Phase	Magnitude error [%]	Angle Error [deg]
Phase A local	2.0	1.0
Phase B local	1.0	0.5
Phase C local	1.5	0.0
Phase A remote	-1.0	-0.5
Phase B remote	2.0	-1.0
Phase C remote	-1.5	0.5

Moreover, due to the SV messaging delay (5 ms) and the internal RGDM firmware execution time, a 15 ms conservative operation time of the differential logic has been considered.

The MV loop energisation transient has been estimated using EMT-Simulations to evaluate the line capacitance charging current effect. The Taurianova –Sacto breaker is left open and the MV loop is energised closing the Taurianova-Laganà breaker. Accordingly, the MV loop supplies about 5.5 MW of load. The results are shown in Figure 9.

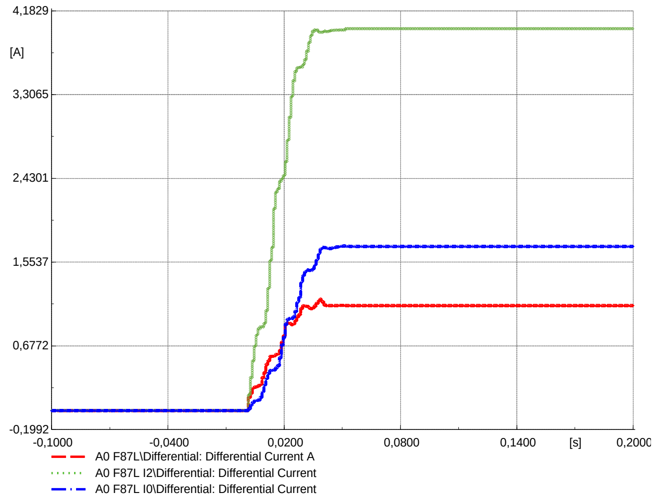

Figure 9: Differential currents during MV loop energization

Considering these results, the differential threshold can be set equal to a very low value e.g. 5 A but it has been decided to use a conservative value, so for all methods 75 A has been set as the differential current threshold and the slope of the first restrain zone has been set equal to 30%. The Rogowski coils are not affected by saturation, so the 2nd restrain zone has been disabled. The unrestrained threshold has been set at 1000A so it operates only for multiphase faults.

The differential characteristic as modelled in the power systems analysis software DIgSILENT PowerFactory is shown in Figure 10. The values for the stabilising and differential currents for all phases for a defined fault are displayed.

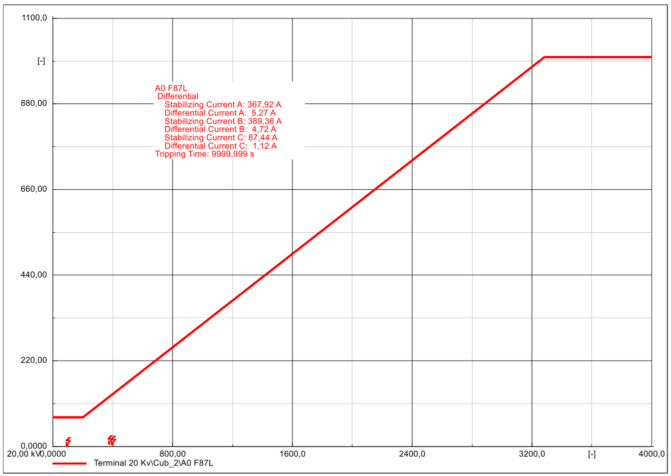

Figure 10: Stabilisation Curve

4.2 Differential logic evaluation

The performance of each differential method (negative sequence, zero sequence and phase magnitude) have been evaluated for the following faults:

- Single phase to ground fault for all possible positions along the MV loop.
- CCF with one Line to Ground Fault (LGF2) moving around the MV loop anticlockwise, starting from Taurianova, relative to a fixed fault position (LGF1) at the following busbars:
  - Terminal 17-16
  - Sacto
  - Laganà

A Python script has been developed in order to simulate any possible configuration of a CCF, with both faults located in the MV loop using the calculation features of the network calculation software. The script defines the position of one Phase-Ground fault with a fault resistance. It runs CCF calculations varying the position of the 2nd Phase-Ground fault along all busbars and lines of the MV loop. For each position of the moving fault, the values of the differential current and of the differential threshold as measured and calculated by the differential relay are recorded.

Both differential relay location have been evaluated and similar results have been obtained. Hereby the results for the differential relay protecting the line between Taurianova and Laganà are presented.

4.3 Phase A-Ground

In Figure 11 the differential currents measured and the threshold calculated by the three different types of differential protection for a Ph-Grnd fault (R_f = 15 Ω) with fault position moving along the loop are shown. The simulated values of the differential currents are similar for any differential method and smaller than the differential threshold so the fault will not be detected by the differential elements. This is acceptable if the purpose of the differential element is only to complement the negative sequence polarising directional method applied in the detection of CCFs close to the Taurianova substation. In order to detect a single phase fault, a differential threshold smaller than 40 A can be set.

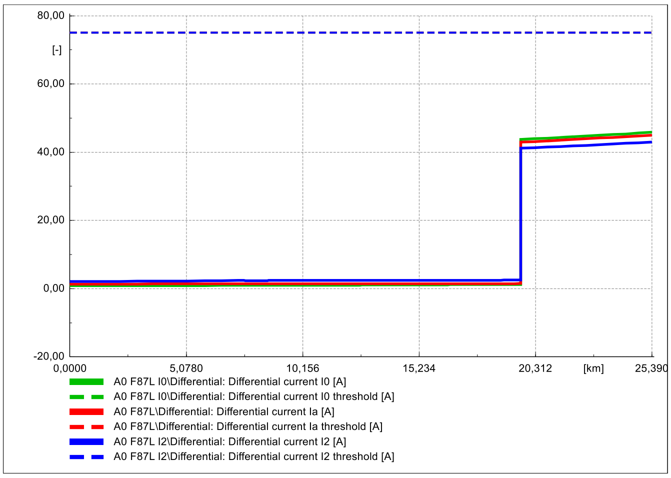

Figure 11: Ph A-Grnd Rf=15 Differential current

4.4 Cross Country Fault (CCF)

The behaviour of each differential method (Phase, Negative Sequence or Zero Sequence) in relation to the measured differential currents and the calculated current thresholds is shown in Figure 12, Figure 13 and Figure 14. Two curves are shown for each considered CCF-sweep with the fixed position of LGF_1 as stated in the legend. The CCF-sweep is run anticlockwise starting from Taurianova

Figure 12 shows the zero sequence differential results. It can be observed that a differential current method based on the zero sequence current can work only if a very low current threshold is set.

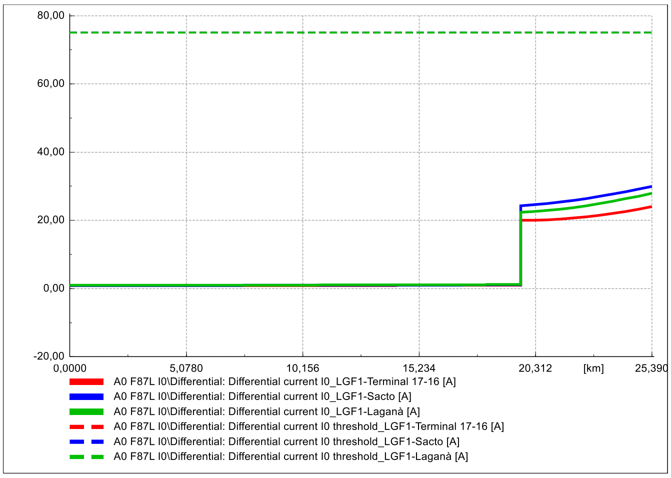

Figure 12: CCF_I0-Differential (Rf = 15Ω)

Figure 13 and Figure 14 show respectively the measured and calculated values for the negative sequence differential and phase differential methods. Special attention should be paid to the continuous variation of the current threshold which depends on the value of the stabilising current as defined in Figure 10. Both methods can effectively complement the negative sequence polarising directional method.

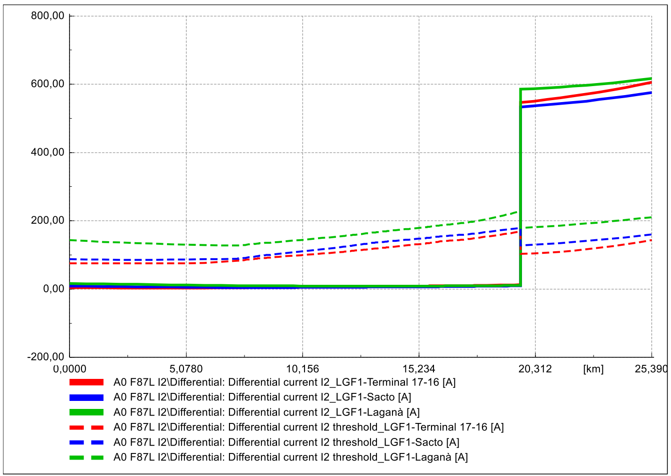

Figure 13: CCF_I2-Differential (Rf = 15Ω)

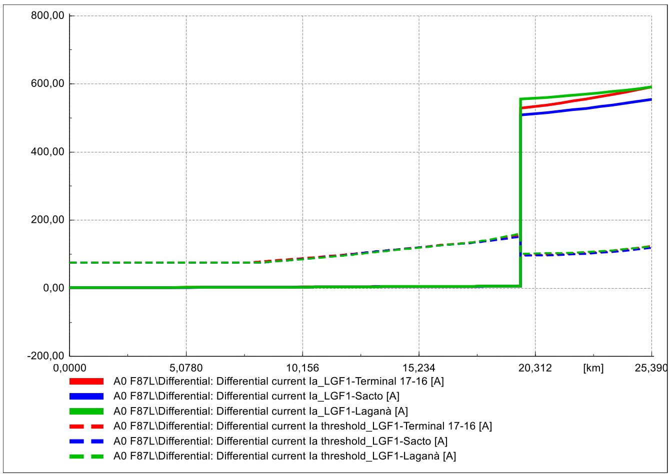

Figure 14: CCF_Phase-Differential (Rf = 15 Ω)

4.5 Evaluation results

For the examined high impedance CCF's (R_f = 15 Ω) the differential current measured by the zero sequence differential method is much smaller (about 30 A instead of 500A) than the current measured by the other differential methods. This is due to the relatively high value of zero sequence impedance of the system. As a result, the zero sequence differential method is less sensitive to high impedance CCF's.

The phase differential and the negative sequence differential methods have similar performances to each other; however, running the EMT simulation for the MV loop energization, it has been found that, for the listed set of coil and measurement errors, the negative sequence differential method is more sensitive to the cumulative error than the phase differential method. Therefore, a higher sensitivity could be obtained using the phase differential by decreasing the differential threshold.

The main disadvantage of the negative sequence and of the phase differential logic is the low security for faults in the LV network; by setting low differential threshold, asymmetrical faults at the LV side of the MV/LV transformers of the Taurianova-Sacto loop section will be detected be the MV differential. A zero sequence release threshold (i.e. 2 A) is required to operate only for the faults along the MV loop.

5 Conclusions

A hypothesis has been provided in this paper regarding the reason why the zero sequence polarising directional method fails for some configurations of Cross Country Faults (CCF). This has been validated using software modelling.

The behaviour of different differential methods applied in a network model of an experimental MV loop with a compensated star point, for cases of high impedance CCFs occurring along the loop have been investigated.

Composite protection systems, consisting of overcurrent negative sequence polarising directional relays and two differential relays based on either phase differential, negative sequence differential or zero sequence differential methods have been evaluated.

The phase differential method, integrated with a minimum zero sequence release threshold, is the most suitable solution.

The importance of carrying out detailed modelling of the current differential algorithms with simulation software that allows the automatic and comprehensive calculation of short circuit sweeps throughout the network area has been demonstrated. Furthermore, the importance of evaluating the behaviour of protection devices in the time domain in order to identify limits and weaknesses of the applied protection schemes has also been demonstrated.

6 References

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