Comparison of the performance of different directional polarizing methods in cross country fault protection of a MV Loop

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***Abstract*—The correct position detection of cross country faults (CCFs) occurring in MV network loops with Petersen coil compensated neutral or not grounded star point can sometimes be critical. This paper examines the performance of overcurrent directional relays protecting a MV distribution loop in an existing power system. The MV network has been modelled in the calculation software DIgSILENT PowerFactory. Different polarizing methods, based on data from the manuals of commercially available protective devices, have been implemented in the relay models. The performance of the zero sequence directional polarizing algorithm has been compared with the performance of the negative sequence phasor directional polarizing method and of the negative sequence impedance directional algorithm. The comparison has been performed using steady state short circuit calculations and electromagnetic transient (EMT) simulations. The results make clear the limitations of the zero sequence directional polarizing method and clearly show the importance of the detailed modelling of protective devices in network protection studies.**

***Index Terms*—Cross Country faults, Petersen Coil grounding, Ground fault directional protection, Negative Sequence directional protection.**

I. INTRODUCTION

High penetration of distributed generation (DG) requires significant changes in the network configuration and in the protection philosophy. In this context, as part of the project Operating Interregional Plan (named POI-P4), which is financed by the European Commission, ENEL Distribuzione (ENEL-D) has experimented with MV networks with lines operated in loop configuration and overcurrent multipurpose directional relays based on a Zero Sequence directional polarizing method and supervised by a permissive overreach signal comparison scheme. The detection of Cross Country Faults (CCFs) an MV distribution network, including one or more line loops, has been studied in [1]. One of the outcomes of that study was that the protection system could fail for some CCF positions involving a ground resistances greater than 10-15 Ω. This study aims to reproduce such results modelling the power system with the network calculation software DIgSILENT PowerFactory version 2017 with the purpose of comparing/evaluating the performance of zero sequence directional polarizing method with/and the negative sequence impedance directional algorithm in order to propose alternative protection solutions.

II. CROSS-COUNTRY-FAULT SIMULATIONS

The MV power system described in [1] has been modelled in the network calculation software using the data available in the paper. No additional information has been received by ENEL-D. The effort has been concentrated in the simulation of the MV loops, where the protection system showed a possible problem. Accordingly with the available data a 20 kV system consisting of one HV/MV transformer, 5 feeders, 5 main bus bars and 12 additional load nodes, with grounding through a Petersen coil has been modelled. The MV system layout is shown in Figure 1.

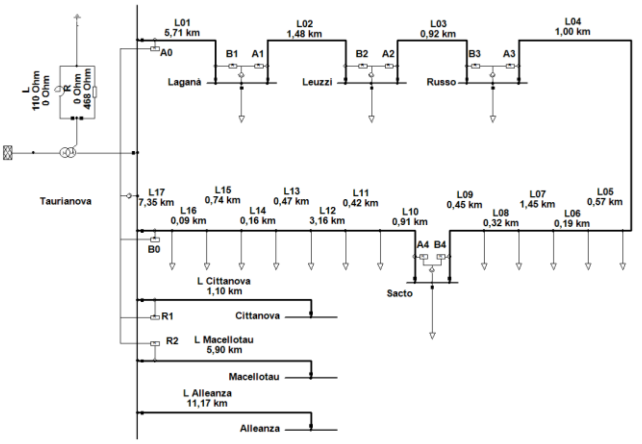


Figure 1: Considered MV system scheme

The available data in [1] has been summarized in Table I. Table II shows the assumed values for the lines in the neighbourhood of the loop. That information is the basis for the creation of the network model.

With that information, the calculated capacitive earth fault current is about 80 A. The equivalent network capacitance is $C_{1N}=C_{0N}= 7.5\mu F$. The Petersen coil ($R_n= 468\Omega$, $X_n = 110.4\Omega$) is connected at the star point of the incoming transformer at Taurianova substation ($P_n= 40$ MVA, $V_{n1}/V_{n2}=150/20$ kV, $u_k= 15.5\%$, $P_{cu} = 0.315\%$).

Table I: Electrical values of the Laganà-Cirello MV loop

Line Nº	Length (km)	r1+jx1 (Ω/km)	c1 (nF/km)	r0+j x0 (Ω/km)	c0 (nF/km)
1	5.71	0.52+j0.33	38.1	0.90+j1.35	33.0
2	1.48	0.73+j0.14	185.1	3.54+j0.12	273.0
3	0.92	0.73+j0.14	185.1	2.39+j0.08	185.1
4	1.00	0.44+j0.08	111.1	1.44+j0.05	111.1
5	0.57	0.72+j0.32	67.0	1.38+j1.11	64.0
6	0.19	0.74+j0.15	184.9	2.40+j0.09	184.9
7	1.45	0.57+j0.25	146.9	1.22+j1.20	145.0
8	0.32	0.73+j0.14	185.1	2.39+j0.09	185.1
9	0.45	0.59+j0.13	226.3	2.11+j0.28	226.3
10	0.91	0.73+j0.14	186.5	2.38+j0.09	186.5
11	0.42	0.73+j0.14	185.0	2.39+j0.09	185.0
12	3.16	0.64+j0.01	207.4	1.82+j0.67	207.3
13	0.47	0.60+j0.14	211.9	1.68+j0.84	211.8
14	0.16	0.88+j0.15	170.2	2.58+j0.07	170.2
15	0.74	0.86+j0.14	169.9	2.58+j0.09	169.9
16	0.09	0.58+j0.13	218.5	1.56+j0.93	218.5
17	7.35	0.15+j0.43	9.8	1.06+j1.29	6.8

Table II: Electrical values of the other MM lines (assumption)

Line Nº	Length (km)	r1+jx1 (Ω/km)	c1 (nF/km)	r0+j x0 (Ω/km)	c0 (nF/km)
18(Cittanova)	1.1	0.7+j0.14	185.1	0.75+j0.6	273.0
19(Macellotau)	5.9	0.7+j0.14	185.1	0.75+j0.6	273.0
20(Alleanza)	11.17	0.7+j0.14	185.1	0.75+j0.6	273.0

A. Protection system

The system is protected by a set of directional relays which implement an angular comparison between a polarizing voltage rotated by the Maximum Torque Angle (MTA) and an operating current. Both phase and ground directional characteristics are available and they are shown in Figure 2. A value of 25° can be calculated for the parameter MTA applied on the Earth Directional Characteristic.

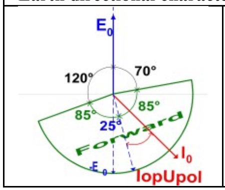
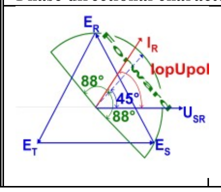
Earth directional characteristic (67N)		Phase directional characteristic (67)	
	Voltage threshold E_0 = 690V Current Threshold I_0=2A		Current Threshold I=400A

Figure 2. Line protection settings

The protective relays are interconnected and the functions are supervised by a permissive overreach blocking logic. The behaviour of the protection system has been simulated by inserting the protective relay models in all cubicles where the digital relays (named RGDM) are present. In Figure 3 a simplified view of the protection system is shown.

Multiple interlinks between the relay models implement the permissive overreach blocking logic of the protective philosophy used by ENEL-D to protect the MV loop, as indicated in Figure 1 and Figure 3 by the blue and green dotted connections.

The RGDM fault detectors have been modelled creating a relay model type which has been implemented in the software PowerFactory using the standard protective blocks available. Such blocks are connected together and allow, in principle, the simulation of any kind of protective relay; in this case a directional overcurrent relay with a zero sequence directional logic based on the comparison between the phase angle of the zero sequence current and voltage has been used.

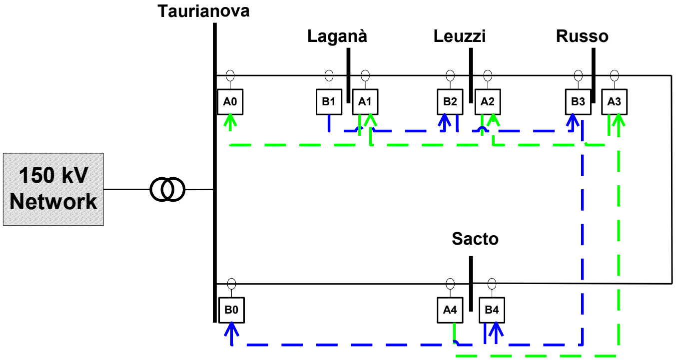


Figure 3. Protection system with permissive overreach blocking logic.

The scheme of the implemented RGDM relay model, simulating the new ENEL-specified multipurpose directional overcurrent digital relays is shown in Figure 4.

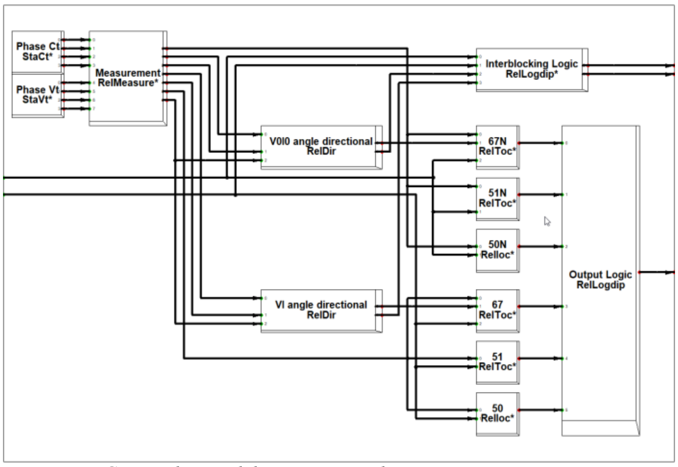


Figure 4. RGDM relay model connection scheme

B. System validation

The validation of the network model is done by intending to reproduce the results provided in Table V of [1]. The first problem faced was that in [1] the results are for a CCF in two different poles of the overhead line between the stations Sacto and Russo with a fault resistance of 15 Ω, but the exact location of the faults has not been specified. There are many CCF combinations where the short circuit currents are similar to the presented in [1]. For the purpose of this study the CCF where the currents and angles at A3 and B4 are similar to the presented in [1] has been selected. Table III summarizes the fault currents and angles for a CCF between phase A of Line L05 at 35% of the length seen from Russo side and phase B at the connection point of Load 6-5. The loads in the loop have been neglected.

Table III: Phase and Current as measured at the relays locations for a CCF between Phase A at 35% of L05 and 0% of L06.

Station	Relay	E_0 (kV∠°)	I_0 (A∠°)	RGDM (°)	$\lvert I_A\rvert$ (A)	$\lvert IB\rvert$ (A)	$\lvert I_C\rvert$ (A)
Taurianova	B_0	5.71∠120	12∠-142	-262	231	237	6
	A_0	5.71∠120	5∠-18	-138	318	306	8
Laganà	B_1	5.71∠120	6∠169	49	318	306	7
	A_1	5.71∠120	6∠-11	-131	318	306	7
Leuzzi	B_2	5.71∠120	8∠180	60	318	306	5
	A_2	5.71∠120	8∠0	-120	323	306	5
Russo	B_3	5.71∠120	9∠177	57	318	306	5
	A_3	5.71∠120	9∠-3	-123	318	306	5
Sacto	B_4	5.77∠119	6∠-133	-254	231	237	1
	A_4	5.71∠120	6∠47	-72	231	237	6

C. The problem

It has been reported in [1] that in case of a 15 Ω high impedance CCF involving consecutive poles of the line stretch 5, the relay located in A4 detects the fault as a forward fault instead of as a reverse fault. 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.

D. Problem confirmation

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 makes it possible to define the position of one Phase-Ground fault with a fault resistance. It runs CCFs calculations varying the position of the 2nd Phase-Ground fault along all busbars and lines of the MV loop. For each position of the second fault the value of the angle between the polarization voltage and the operation current of a selected relay is recorded. In this case the recorded relay is A4.

The results are displayed in a two dimensional diagram showing along the x-axis the position of the 2nd Phase-Ground fault (Taurianova is at 0 km and the loop is in counter-clock direction according to Figure 3) and along the y-axis the angle between the operating current and the polarizing voltage inverted and rotated by the value of MTA (Max Torque Angle). In this case and in the graphical representation the forward detection sector is between -88° and +88° (red band) and the reverse detection sector is between +92° and +268° (blue band). A proper forward direction recognition of the relay A4 is considered when both phases of the CCF are between the stations Taurianova and Sacto, if both faulty phases of the CCF are after Sacto the relay should recognise the fault in reverse direction.

The simulation shows that indeed, the protection system can fail in the case of a 15 Ω impedance CCF. If the fault impedance is smaller than about 10 Ω, the phase fault currents are greater than 400 A and the fault is removed by the phase overcurrent elements. Moreover it has been found that the problem is present for a very large set of different positions of the CCF.

Figure 5 shows the zero sequence directional angle for a 15 Ω CCF with Phase B-Ground fault position fixed at 2,41 km from Sacto to Russo (Load 6-5) and Phase A-Ground fault position moving all around the MV loop. The angle is wrong in the forward band for any position of the second ground fault after the station Russo.

A change in the setting of the parameter MTA does not improve the wrong operation of the directional polarization method. Additionally, it can be observed, that the method works differently if the faulty phases at both locations of a CCF are interchanged.

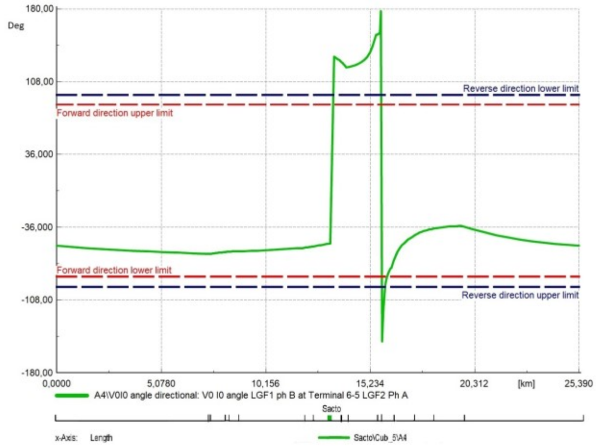


Figure 5: I0V0 angle at A4, CCF with LGF_1 at Load 5-6, Phase B, Rf=15 Ω

A CCF-sweep has been simulated with the fixed position of the 1st fault between Taurianova and Sacto (at 7,35 km from Taurianova, at the position of the first load in the loop which is called "Terminal 16-17"). Ideally such fault should be detected by the A4 protection as a fault in forward direction only for every position of LGF_2 fault between Taurianova and Sacto (counter clock wise along the loop). The continuous green line represents the results with the 1st fault on phase A and the dotted pink line represents the results with the 1st fault on phase B. Figure 6 shows that the algorithm fails in both cases of the fixed LGF_1, in one case for the 2nd fault location between Taurianova and LGF_1 (phase B) and in the other case between LGF_1 (phase A) and Sacto.

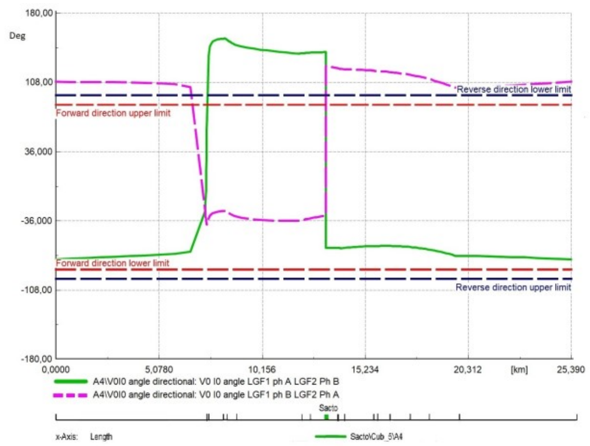


Figure 6: I0V0 angle at A4, CCF with LGF_1 at Terminal 17-16 between Taurianova and Sacto, Rf=15 Ω

Figure 7 shows the results for a 15 Ω CCF-sweep with the 1st fault location fixed at station Sacto. With phase B-Ground fault position fixed the direction of the fault is wrongly forward recognized for any position of LGF_2 between Sacto and Taurianova (counter-clock wise along the loop) leading to a complete failure of the protection system. On the other hand, if the fixed fault is on phase A the protection scheme works perfectly.

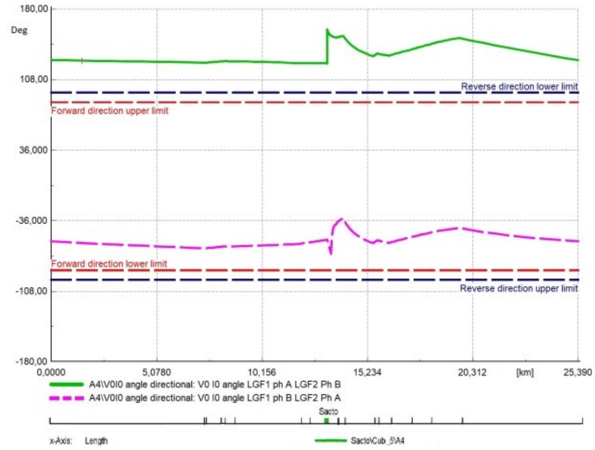


Figure 7: I0V0 angle at A4, CCF with LGF_1 at Sacto, Rf=15 Ω

In Figure 8 the recorded values for the polarization angle at A4 are shown for CCFs with Phase A-Ground (continous line) or Phase B-Ground (dotted line) fault position fixed at Laganà station. Again it can be observed that the fault position is wrongly recognized in forward direction after Laganà (LGF_1 Ph B-Grnd) or between Sacto and Laganà (LGF_1 Ph A-Grnd).

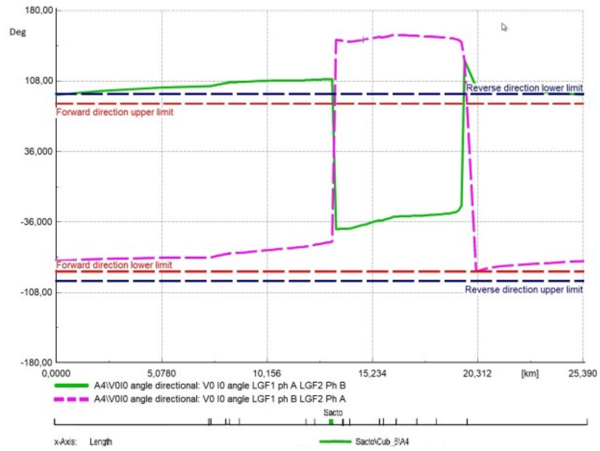


Figure 8: I0V0 angle at A4, CCF with LGF_1 at Laganà, Rf=15 Ω

III. Alternative Directional Algorithm Performances

Considering the large set of cases where the zero sequence directional logic fails to detect the correct direction of the fault, alternative polarizing methods have been evaluated. The possibility of using a negative sequence polarizing directional method or negative sequence impedance directional method has been examined.

A. Negative sequence polarizing directional method

This "traditional" logic compares the angle between the negative sequence *polarizing* voltage rotated by the selected value of MTA and the negative sequence *operating* current. The function can be described by the following equation [2]:

$$T = |V_2|\,|I_2|\cos(\angle \boldsymbol{V_2} + \boldsymbol{MTA} - \angle \boldsymbol{I_2})$$

Where T is the torque produced by the directional logic and a positive value indicates a fault in the forward direction. This logic is provided in many commercially available relays, however, in case of high resistance faults, the level of negative sequence current can represent a minimum sensitivity limit for this logic. A protective block which simulates a negative sequence directional logic with MTA = 25° and a forward detection sector between +77° and -77° (red band), and a reverse detection sector between +90° and +270° (blue band), has been implemented.

As first step a CCF-sweep is simulated with the fixed position of the 1st fault between Taurianova substation and Sacto station (at 7,35 km from Taurianova, at the position of the first load in the loop). Ideally such fault should be detected by the A4 protection as a fault in forward direction only for every position of LGF_2 fault between Taurianova and Sacto (counter clock wise along the loop). Figure 9 shows clearly that the fault is detected in the forward direction for LGF_2 located between Taurianova and Sacto independent of the defined faulty 1st phase. When the LGF_2 is after Sacto and LGF_1 is set as Ph-B Ground fault (dotted pink line) this method fails and the fault is detected in forward direction.

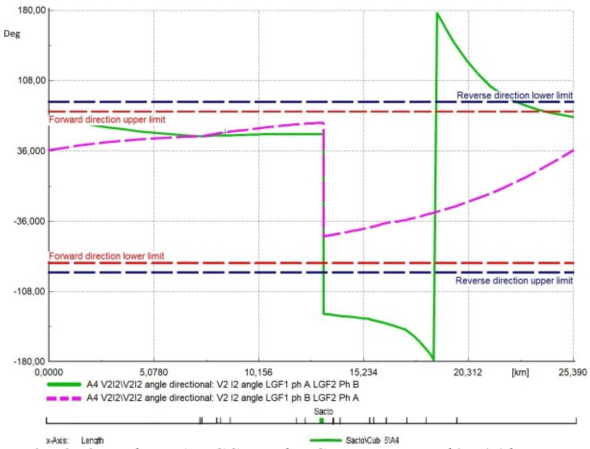


Figure 9: I2V2 angle at A4, CCF with LGF_1 at Terminal17-16 between Taurianova and Sacto, Rf=15 Ω

However, by using a fixed fault location of LGF1 at Sacto and moving the second fault along the loop, the direction of the CCF is correctly recognized for every position of the 2nd fault between Sacto and Laganà correctly (see Figure 10).

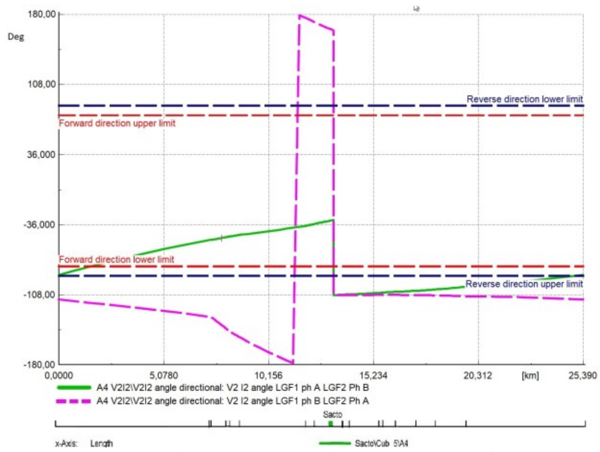


Figure 10: I2V2 angle at A4, CCF with LGF_1 at Sacto, Rf=15 Ω

Figure 11 shows the same behaviour of the polarizing angle for a CFF-sweep with LGF1 fixed at Laganà. When both poles of the CCF are after Sacto the direction recognition of the fault is also correctly detected in the reverse direction for both configurations of LGF_1.

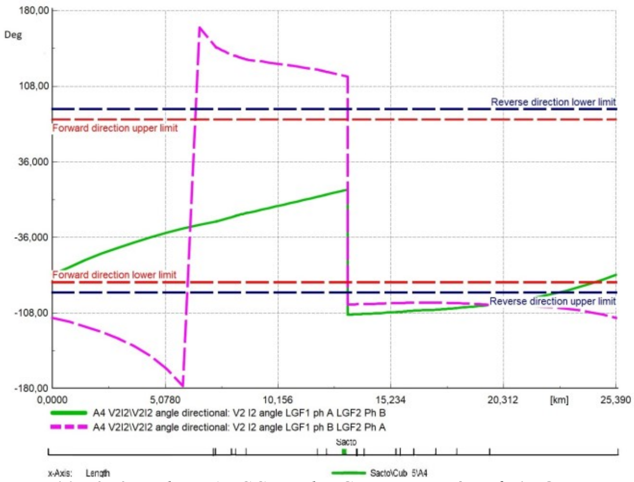


Figure 11: I2V2 angle at A4 CCF with LGF_1 at Laganà,, Rf=15 Ω

It can be observed that the behaviour of the algorithm for LGF_2 very close to Taurianova at the end of the loop can be critical and the calculation of the forward/reverse threshold angles difficult.

B. Negative sequence impedance directional method

This logic has been conceived to overcome the sensitivity limitations of the *negative sequence polarizing directional* logic. The ratio of negative-sequence voltage to negative-sequence current gives a resulting negative-sequence impedance accordingly to the following equation [3]:

$$Z2 = Re[\bar{V}_2 * (\bar{I}_2 * 1\angle Z1L)]/|\bar{I}_2|$$

Where Z1L is the line positive sequence angle. It can be demonstrated [4] that the negative-sequence voltage is always negative, and that the negative-sequence current is positive for a forward fault and negative for a reverse fault. Therefore for a forward fault, the negative-sequence impedance is always negative (and for a reverse fault the negative-sequence impedance is always positive).

The logic is available in some overcurrent relays present in the market [5] and has been modelled in the network calculation software using a dedicated directional block. The block contains the following settings:

- forward and reverse negative-sequence impedance threshold (*Z2F* and *Z2R*)
- a forward and reverse negative-sequence current threshold (*50QF* and *50QR*)
- a positive-sequence current restraint factor (*a2*)

The impedance directional characteristic implemented by the block is shown in Figure 12:

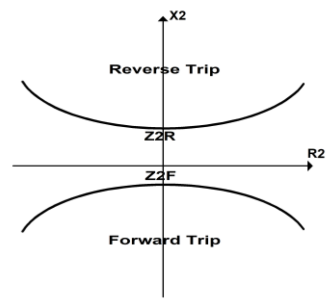


Figure 12: Z_2 directional characteristic

As first step a Python script is executed in order to identify the Z_2 values calculated by the relay for a phase A-ground fault all along the MV loop. The results are shown in Figure 13.

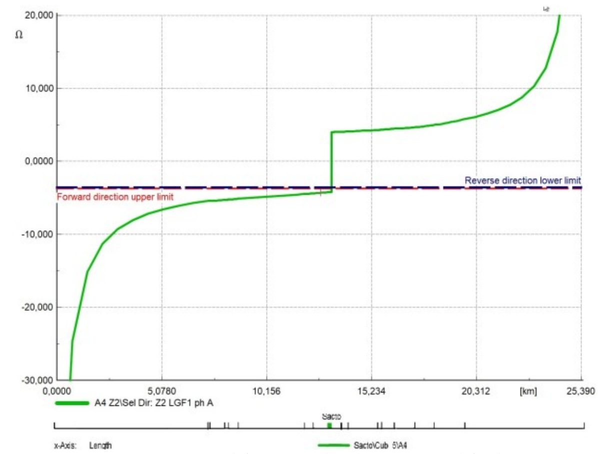


Figure 13: Z2 at A4 measured for a single phase-ground fault moving along the MV loop (phase A)

Using the calculated Z_2 values, *Z2R* and *Z2F* are set at *-3.4* **Ω** and =*-3.5* **Ω** respectively. As done for the evaluation of the behaviour of the negative sequence polarizing method, a CCF-sweep is simulated under the same conditions of Figure 9. Ideally such fault should be detected by the A4 relay as a forward fault for every position of LGF_2 fault between Taurianova and Sacto (counter clock wise along the loop). The results are shown in Figure 14. The algorithm shows a suboptimal behaviour when the fixed fault position (LGF_1) is on the phase B and the moving fault is on phase A (LGF_2), indeed the CCF is recognised in forward direction for 2^{nd} faults after Leuzzi.

As it can be seen in Figure 15, with LGF_1 set at Sacto, the fault is always correctly detected in reverse direction for any kind of LGF_1 involved phase. That is exactly the same case when LGF_1 is set at Laganà substation, here a CCF with LGF_2 after Sacto is always detected correctly by A4 in reverse direction but when the 2^{nd} fault is on phase B between km 6.5 from Taurianova and Sacto a forward direction is declared (s. Figure 16); this is a suboptimal behaviour.

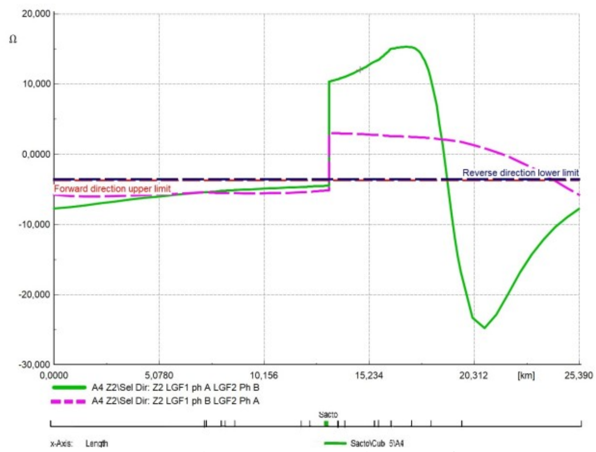


Figure 14: Z2, CCF with LGF_1 at Terminal 17-16, Rf=15 Ω, LGF_2 moving along the MV loop, Rf=15 Ω

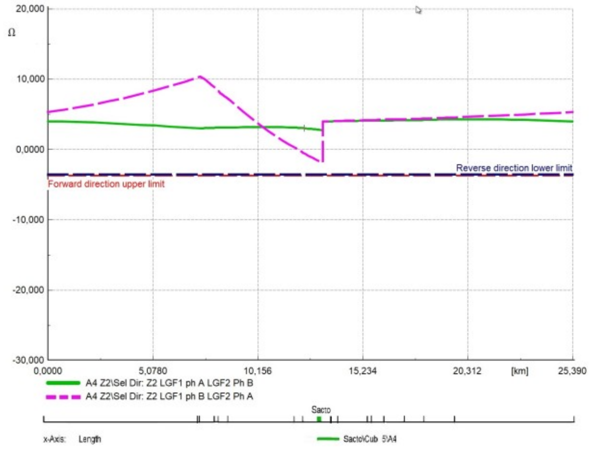


Figure 15: Z2, CCF with LGF_1 at Sacto busbar, Rf=15 Ω, LGF_2 moving along the MV loop, Rf=15 Ω

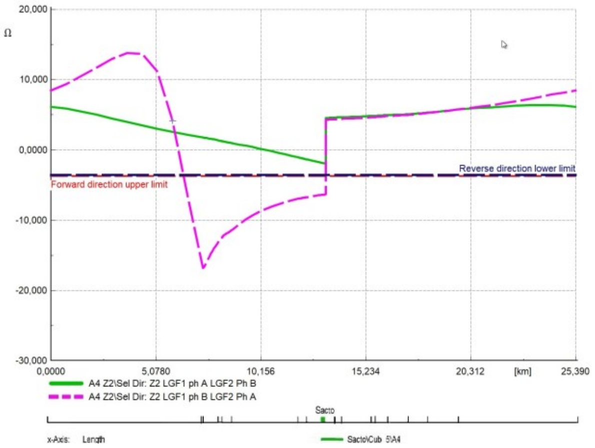


Figure 16: Z2, CCF with LGF_1 at Laganà busbar, Rf=15 Ω, LGF_2 moving along the MV loop Rf=15 Ω

C. Comparison of the evaluated directional polarization methods

The behaviour of the different directional algorithms for relay A4 has been evaluated by running the script for 3 different fixed position of LGF_1: at Terminal 17-16, at Sacto and at Laganà. The expected behaviour should be:

- Reverse fault detection for any CCF with both faults between Sacto and Taurianova (counter clock wise along the loop)
- Forward fault detection for any CCF with both faults between Taurianova and Sacto.

It would be also expected, as optimal behaviour that a CCF with only a fault between Sacto and Taurianova would be detected as a reverse fault.
The ideal behaviour of the A4 relay is summarized in Table IV.

Table IV: Ideal behaviour of the A4 relay.

LGF_1 position	LGF_2 position	Ideal behavior
Terminal 17-16	Before Sacto	Always forward
	After Sacto	Not relevant
Sacto	Before Sacto	Not relevant
	After Sacto	Always reverse
Laganà	Before Sacto	Not relevant.
	After Sacto	Always reverse

The results based on the expected behaviour are summarized in Table V (in red incorrect behaviour).

Table V: Behaviour of the A4 relay with different algorithm and LGF_1 positions.

LGF_1 Position		Terminal 17-16		Sacto		Laganà	
Fixed fault		A	B	A	B	A	B
Algorithm	V_0I_0	Reverse between LGF_1 and Sacto	Reverse between Taurianova and LGF_1	OK	Always Forward	Forward between Sacto and LGF_1	Forward between LGF_1 and Taurianova
	V_2I_2	OK*	OK	OK*	OK	OK*	OK
	Z_2	OK	OK	OK	OK	OK	OK

* Marginal problems detected at the extremes of the loop regarding the proper directional recognition

It's clear that the zero sequence directional algorithm fails for many fault configurations and is greatly affected by the fault resistance. Both the negative sequence polarizing directional and negative sequence impedance directional work under all CCF configurations as expected in the relevant locations; moreover they are not affected by the fault resistance.

The calculation of the threshold angles of the negative sequence polarizing directional is more critical than the calculation of the impedance limits of the negative sequence impedance directional. Moreover the two suboptimal behaviours of the negative sequence impedance directional have been detected for CCFs with the faults located at the opposite ends of the loop which require in any case a complete loop disconnection. For these reasons the negative sequence impedance directional method provides better performances than the negative sequence polarizing directional method.

D. Time domain simulation

The MV loop behaviour during CCFs has been studied in the time domain. The relay models implemented in the network calculation software DIgSILENT PowerFactory calculate the operating quantities, sampling the current and voltage values at 20 samples/cycle. A DFT (Discrete Fourier Transformation) filter is applied to groups of 20 samples to calculate the current and voltage vectors (real and imaginary part).

Some EMT (Electro Magnetic Transient) simulations have been run and have substantially confirmed the results obtained running short circuit calculations. It has been found that the directional element must operate at least with a delay of 30 ms to remain stable during the fault transients. As an example the results obtained running an EMT simulation with phase-ground faults at Terminal 9-8 (phase B) and Terminal 5-4 (phase A) with a time difference of 10 ms and a fault resistance of 15 Ω are shown.

Figure 17 shows the phase voltages at Terminal 5-4 during this CCF. In Figure 18 the real and imaginary parts of the zero sequence voltages and currents as well as the angle between the polarization voltage and operational current as measured by the relay A4 are shown.

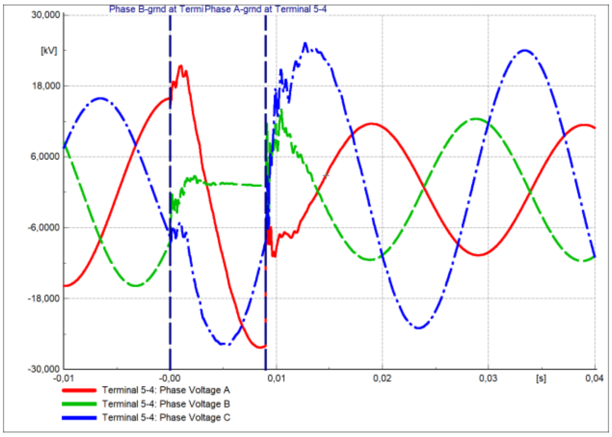


Figure 17: Phase voltages at Terminal 5-4.

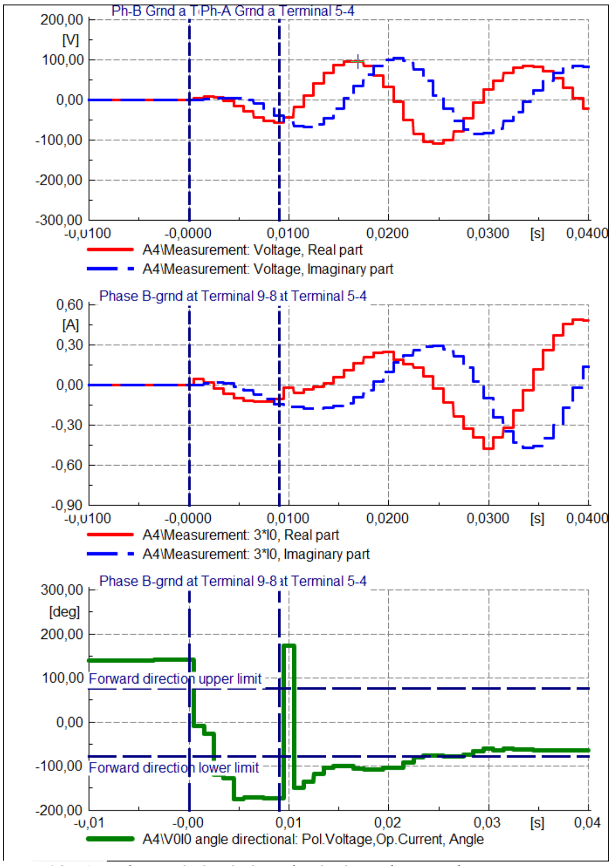


Figure 18: A4 relay, U0x3, I0x3 and U0V0 angle signals.

It can be seen that in extreme situations the accuracy of the developed relay models is enough to evaluate the real behaviour of the protection devices during short circuit faults.

IV. CONCLUSIONS

This paper deals with the behaviour of the directional polarization methods applied in an experimental MV loop belonging to the ENEL-D networks with a compensated star point, for cases of high impedance CCFs occurring along the loop.

As well as confirming that a protection system based on the zero sequence directional polarizing method and an overreach blocking logic can fail in case of a high impedance CCF, this paper demonstrates that the incorrect behaviour is present in the studied case for a large number of CCFs positions for any fault resistance greater than about 10 Ω. It has also been demonstrated that a zero sequence polarizing directional method is not a reliable solution for identifying the direction of a CCF.

The negative sequence polarizing and the negative sequence impedance directional algorithms have been evaluated and can be considered as viable solutions to guarantee a faster and selective CCF detection and removal.

The negative sequence impedance algorithm is the most suitable solution.

The importance of the detailed modelling of the directional polarization algorithms with a simulation software that allows the automatic calculation of short circuit sweeps or even the evaluation of the behaviour of the protection devices in the time domain in order to identify the limits and weak points of applied protection schemes has been demonstrated.

V. REFERENCES

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