Protection Scheme for Single-Phase Fault along a Half Wavelength Transmission Trunk Using Conventional Relay

Elson C. Gomes, Maria C. Tavares, Carlos A. Floriano

Abstract — **This paper presents a proposal for single-phase fault protection of Half Wavelength (HWL) transmission lines using conventional relays. The behavior of the voltages and currents caused by single-phase faults does not allow the use of the conventional philosophy to identify and locate faults. The study was performed for an energization test of an isolated HWL transmission line. This work describes the digital relay functions necessary to properly trip the line. The simulations were performed with RTDS real-time simulator.**

Keywords: **Protection, half wavelength transmission, AC-Link, RTDS, digital relays, single line faults.**

I. Introduction

Countries with continental extensions such as Brazil, China and Russia are faced with the need to transport large blocks of energy over distances above 2,000 km. An alternative to this extremely long trunk in Alternate Current (AC) is to use transmission lines with electrical length a little greater than a half wavelength. For a frequency of 60 Hz, the adequate length of the transmission trunk will be approximately 2,600 km. The half wavelength lines exhibit very similar behavior to short lines in steady state and are more robust during transients [1, 2]. This is an alternative to the HVDC line, due to lower implementation cost and no need of Power Electronic Technology [3, 4].

In 2008, the Brazilian Electrical Regulatory Agency (ANEEL) proposed an energization test in a set of existing 500 kV lines in the Brazilian system. The transmission lines can form a HWL trunk of 2,600 km when connected in series and can be energized at one shot directly, from one of its terminals. This trunk is also called an AC-Link as it is an AC point-to-point transmission system. For the test, the circuit-breakers (CB) in intermediate substations will be locked in the closed position, the remote end circuit-breaker will be locked in the opened position, the series compensation will be short-circuited and the parallel compensation will be bypassed. Only the surge arresters, current transformers (CTs) and voltage transformers (VTs) present in the intermediate substations will be kept in service. After the test this AC alternative may be considered for forthcoming expansion transmission systems in Brazil.

Among the studies needed for the test, there is the protection of the system against single-phase faults. This type of defect is the most common in transmission systems [5]. The protection equipment existent in the switchgear substation is a conventional distance relay (SEL 321-1). The relay shall be adjusted to protect the link when subjected to single-phase faults anywhere along its entire length, i.e. the 2,600 km of lines. In the following sections the main results of the proposed protection scheme are presented.

II. Characteristics of the System

The AC-Link will be formed by similar 500 kV transmission lines that when put together will totalize 2,600 km. These lines are the interconnections North-South I (NS-1) and North-South II (NS-2) and part of the interconnection NorthEast-SouthEast (NE-SE), as seen in Fig. 1 [6, 7].

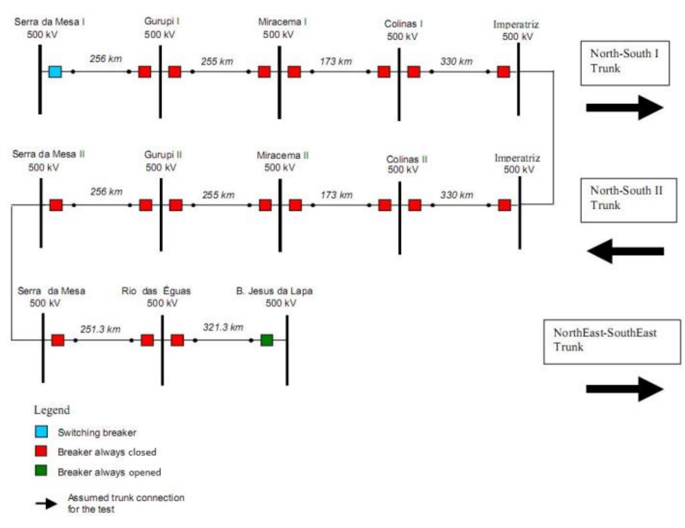

Fig. 1. Single-phase diagram of AC-Link - 500 kV.

The AC-Link will be energized at once through the Serra da Mesa I CB, where the digital relay is located.

Despite being lines of the same voltage level, the silhouettes of towers are different. Tables I to III show the line longitudinal and transversal parameters per unit length in

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sequence components, calculated assuming ideally transposed lines for 60 Hz.

TABLE I
LONGITUDINAL AND TRANSVERSAL PARAMETERS CALCULATED AT 60 HZ - NORTH-SOUTH I

Sequence	***Unitary Resistance [Ω/km]***	***Unitary Inductance [mH/km]***	***Unitary Capacitance [μF/km]***
Zero	0.3714	4.1166	0.00725
Positive/Negative	0.0159	0.7070	0.01612

TABLE II
LONGITUDINAL AND TRANSVERSAL PARAMETERS CALCULATED AT 60 HZ - NORTH-SOUTH II

Sequence	***Unitary Resistance [Ω/km]***	***Unitary Inductance [mH/km]***	***Unitary Capacitance [μF/km]***
Zero	0.3482	3.7445	0.00946
Positive/Negative	0.0160	0.7109	0.01634

TABLE III
LONGITUDINAL AND TRANSVERSAL PARAMETERS CALCULATED AT 60 HZ - NORTH EAST-SOUTH EAST

Sequence	***Unitary Resistance [Ω/km]***	***Unitary Inductance [mH/km]***	***Unitary Capacitance [μF/km]***
Zero	0.3482	3.7577	0.00934
Positive/Negative	0.0160	0.7240	0.01603

The soil resistivity was considered constant with frequency [8] over the entire length of the AC-Link trunk with the value of 4,000 Ω.m due to the high soil resistivity in these regions.

The system was modeled using RTDS real time simulator where the system response for single-phase faults along the AC-Link was obtained. Afterwards the SEL 321-1 relay was tested with RTDS in order to trip the line when single-phase faults occurred along the transmission line during the energization maneuver.

The lines were represented with Bergeron model and the CT saturation was not included.

III. CHARACTERISTICS OF SINGLE-PHASE FAULTS

Conventional AC transmission systems composed by short lines have a well-known behavior under single-phase faults. In a radial system, the highest current at CBs happens for terminal faults, and it decreases as the fault moves towards the remote end. Regarding the voltage at CB, it is minimum for terminal fault and it increases as the fault moves towards the opened terminal. These data sets are used to determine the type of fault and its location in the system. However, this behavior is not observed in the AC-Link, making it inappropriate to use conventional distance protections schemes.

The characteristics of phase current and voltage were observed at the sending end considering the application of single-phase faults every 20 km along the AC-Link. Both the transient peak results (Vp and Ip) and the rms fault values (Vs and Is) were measured. The maximum transient phase-to-ground voltage and CB current are presented in Fig. 2.

For certain fault locations, as when the fault occurs in the line central region, similar or even lower voltage values than the steady state ones can be observed. This situation does not allow a proper distinction of a single-phase fault from a non-load case. Moreover, the behavior of voltages and currents are not monotonic, which increase the problem of fault location identification.

In order to properly identify the fault the current and voltage curves in sequence components were also obtained, as presented in Figs. 3-8.

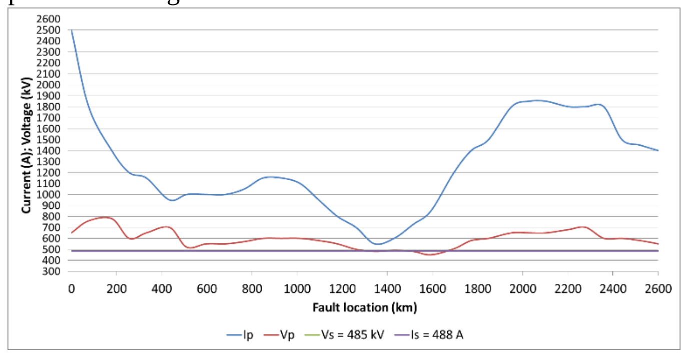

Fig. 2. Maximum transient values of current and voltages in phase components at the sending end for faults applied along the AC-Link.

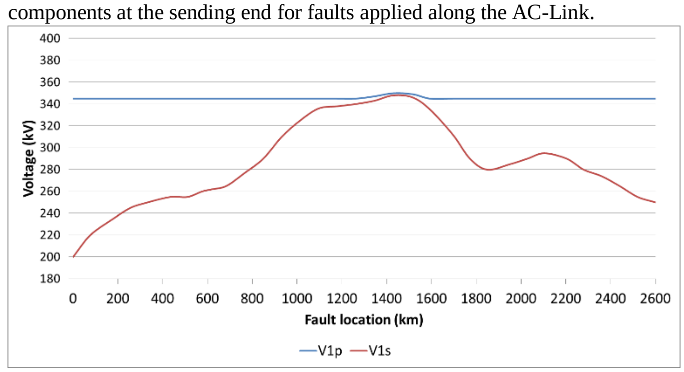

Fig. 3. Phase to ground positive sequence voltage component at Serra Mesa I - peak (V1P) and rms (V1S) values for single-phase faults along the AC-Link.

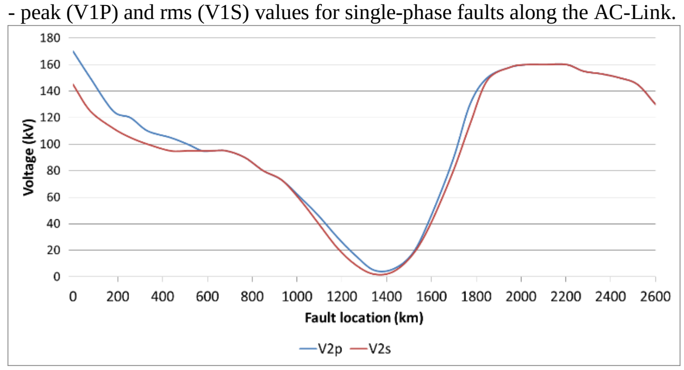

Fig. 4. Phase to ground voltage of negative sequence component at Serra Mesa I - peak (V2P) and rms (V2S) values for single-phase faults along the AC-Link.

Analyzing these curves and considering the case for a non-load maneuver, limits have been established for the protection setting. These values are summarized in Table IV.

To set the parameters on Serra da Mesa I relay the following parameters are used for the equipment at the substation: the ratio for the CT: 3000:1, and the ratio for the VT 517,500 / √3:115 / √3.

IV. ADJUSTMENTS OF THE DIGITAL RELAY

Due to the current and voltage profile of the AC-Link under single-phase fault, the conventional distance protection scheme is not adequate. Other relay functions have to be set to provide an efficient protection and a fast line tripping after a single-phase fault occurrence. Table V presents some information regarding the relay settings. In Fig. 9 each function with its respective tripping area is shown. The protected areas were obtained simulating the system in RTDS with the relay.

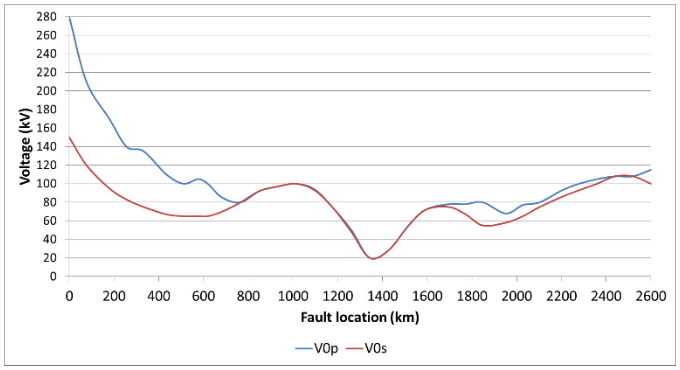

Fig. 5. Phase to ground voltage of zero sequence component at Serra Mesa I - peak (V0P) and rms (V0S) values for single-phase faults along the AC-Link.

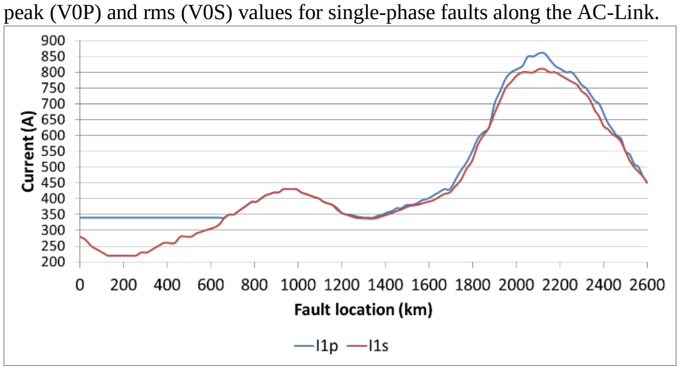

Fig. 6. Phase to ground current of positive sequence component at Serra Mesa I - peak (I1P) and rms (I1S) values for single-phase faults along the AC-Link.

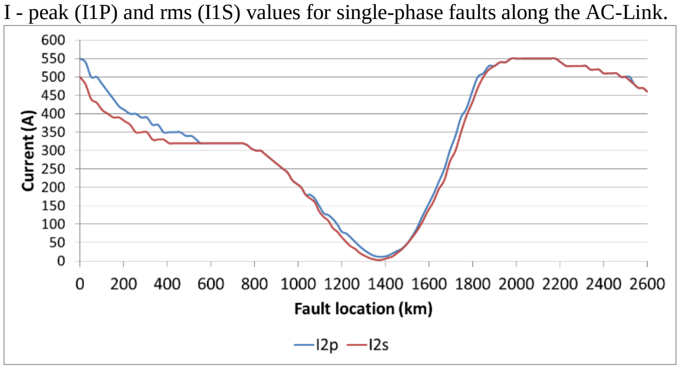

Fig. 7. Phase to ground current of negative sequence component at Serra Mesa I - peak (I2P) and rms (I2S) values for single-phase faults along the AC-Link.

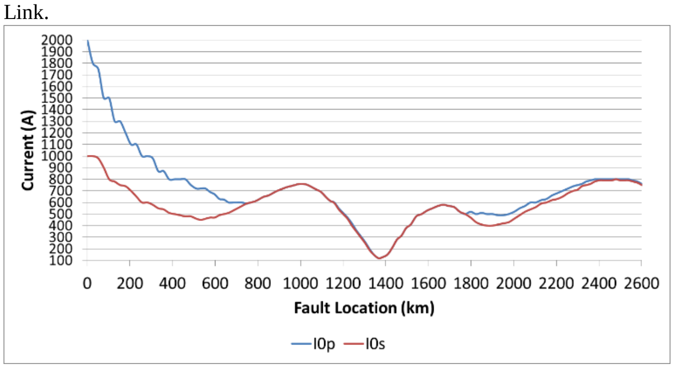

Fig. 8. Phase to ground current of zero sequence component at Serra Mesa I - peak (I0P) and rms (I0S) values for single-phase faults along the AC-Link.

TABLE IV

RMS VALUES FOR PROTECTION SETTING IN THE CASE OF A NON-LOAD SWITCHING MANEUVER OF THE AC LINK

	Instantaneous	Timed	Relay Set (Instantaneous)	Relay Set (Timed)
Vph	> 495 kV	> 345 kV	> 110 V	>76,67 V
V1	> 480 kV	> 345 kV	> 106.67 V	> 76,67 V
V2	> 28 kV	> 0 kV	> 6.22 V	> 0 V
V0	> 10 kV	> 0 kV	> 2.22 V	> 0 V
Iph	> 1130 A	> 343 A	> 0.377 A	>0.114 A
I1	> 875 A	> 343 A	> 0.292 A	> 0.114 A
I2	> 120 A	> 0 A	> 0.04 A	> 0 A
I0	> 12 A	> 0 A	> 0.004 A	> 0 A

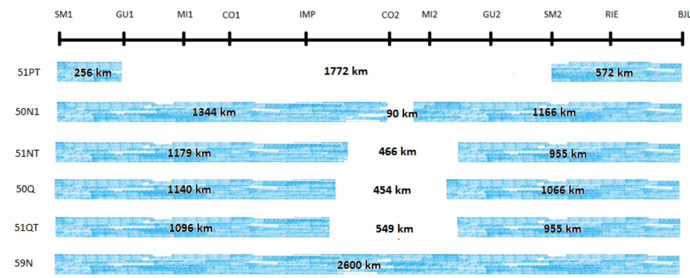

Fig. 9. AC-Link regions protected by each relay function.

Another difficulty in the fault identification for the AC-Link is the lower negative and zero sequence components values for voltage and current. Most of these values are below the relay setting limits due to the high VT and CT transformation ratio values. Faults in the central region of the line behave as high impedance ones, producing little variation in the voltages and currents at the line sending end (either as phases or sequence components), as shown in Fig. 10.

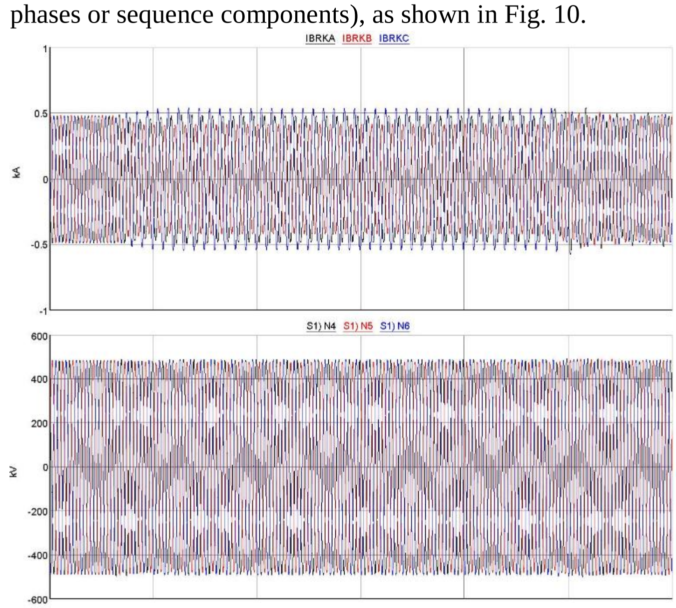

Fig. 10. Phase-to-ground current and voltages in Serra da Mesa I during a single-phase fault in Colinas II substation (km 1344).

The only function that properly identified the fault in this region was the 59N (zero sequence overvoltage). The other three current functions listed below were maintained in order to increase security on faults identification in other regions:

- 50N1: Instantaneous zero sequence overcurrent;
- 51QT: Timed negative sequence overcurrent;

TABLE V
RELAY ADJUSTMENTS

Setting	Range	Value	Description
50QF	1A: 0.05-1 amp sec, 3I (2)	0.12	50QF Forward Directional Current Threshold
E51P	Y,N	Y	E51P Phase Time Overcurrent Element: Enable
51PP	1A: 0.1-3.2 amp sec	0.20	51PP Phase Time Overcurrent Element: Pickup
51PC	U1,U2,U3,U4,C1,C2,C3,C4	U1	51PC Phase Time Overcurrent Element: Curve Family
51PTD	US 0.5-15, IEC 0.05-1	0.50	51PTD Phase Time Overcurrent Element: Time Dial
E51N	Y,N,S	Y	E51N Residual Time Overcurrent Element: Enable
51NP	1A: 0.1-3.2 amp sec	0.10	51NP Residual Time Overcurrent Element: Pickup
51NC	U1,U2,U3,U4,C1,C2,C3,C4	U1	51NC Residual Time Overcurrent Element: Curve Family
51NTD	US 0.5-15, IEC 0.05-1	0.50	51NTD Residual Time Overcurrent Element: Time Dial
E50N	N,1,2,3,4	1	E50N Enable Number of Residual Instantaneous Overcurrent Levels
50N1	1A: 0.05-16 amp sec, 3I (0)	0.05	50N1 Residual Instantaneous Overcurrent Pickup: Level 1
E51Q	Y,N,S	Y	E51Q Negative Sequence Time Overcurrent: Enable
51QP	1A: 0.1-3.2 amp sec, 3I (2)	0.10	51QP Negative Sequence Time Overcurrent Pickup
51QC	U1,U2,U3,U4,C1,C2,C3,C4	U1	51QC Negative Sequence Time Overcurrent Curve Family
51QTD	US 0.5-15, IEC 0.05-1	0.50	51QTD Negative Sequence Time Overcurrent Time Dial
E50Q	N,1,2,3,4	1	E50Q Enable Number of Negative Sequence Instantaneous Overcurrent Levels
50Q1	1A: 0.05-16 amp sec, 3I (2)	0.12	50Q1 Negative Sequence Definite-Time Overcurrent Pickup: Level 1
EVOLT	Y,N	Y	EVOLT Enable Voltage Elements
59N	0-150 V sec., 3V0	10.0	59N Zero Sequence Over-Voltage
27L	0-100 V sec.	57.7	27L Bus Phase Under-Voltage
59L	0-100 V sec.	100.0	59L Bus Phase Over-Voltage
59PB	0-150 V sec., V1	89.0	59PB Positive Sequence Bus Over-Voltage
MTU	0,1,NA, Relay Word Elements (+,*,!,())	50N1 + 59N + 51QT + 51NT	MTU Mask for Unconditional Trip Variable
MTO	0,1,NA, Relay Word Elements (+,*,!,())	NA	MTO Mask for Trip-Breaker Open Variable
MER	0,1,NA, Relay Word Elements (+,*,!,())	50N1 + 59N + 51QT + 51NT	MER Mask to Trigger Event Report Variable

– 51NT: Timed zero sequence overcurrent.

Some simulation results are presented in Fig. 11 to 13, specifically the waveforms of the phase-to-ground voltages and currents in Serra da Mesa I substation with single-phase faults occurrence at three different AC-Link locations. Formerly the fault near the sending end, then the fault in the middle of the AC-Link and finally the fault near the remote end. In all the cases the relay rapidly responded and sent the line tripping signal. The same happened when the fault occurred in other locations. Thus, the overvoltages to which the equipment are submitted at the sending end substation are not severe, even in case of a fault in the most severe location, near Serra da Mesa II [9].

For faults occurring within 65 to 85 % of the AC-Link (distance measured from the sending end) the overvoltages at sending end substation are high and the energy absorbed by surge arresters can become extreme. The RTDS simulations showed that the relay promptly identified the fault, tripping the line in a short time, assuring that the surge arrester energy consumption was within its thermal limit of 8.4 MJ (Figs. 14 and 15). This is an important result to assure that no equipments will be damaged during the energization experiment and that the assets used in the test will be restored to the national grid immediately after the test.

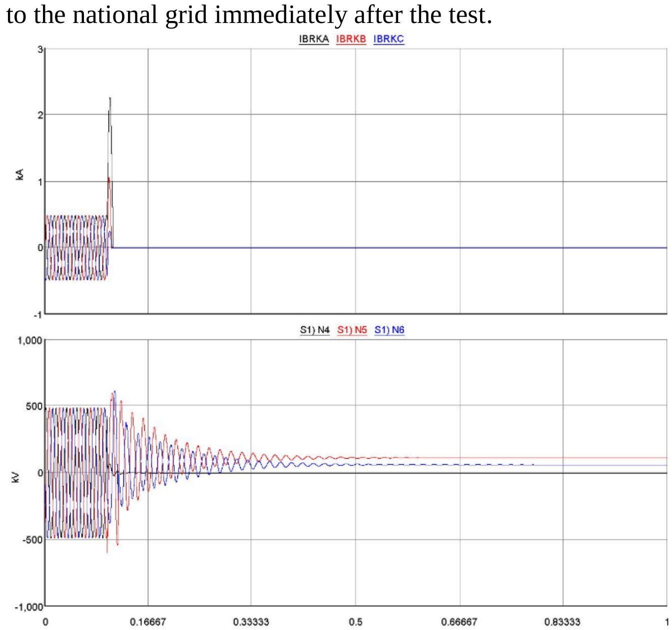

Fig. 11. Phase-to-ground voltages in Serra da Mesa I and CB currents during a single-phase fault in Serra da Mesa I substation (km 0) and relay operation.

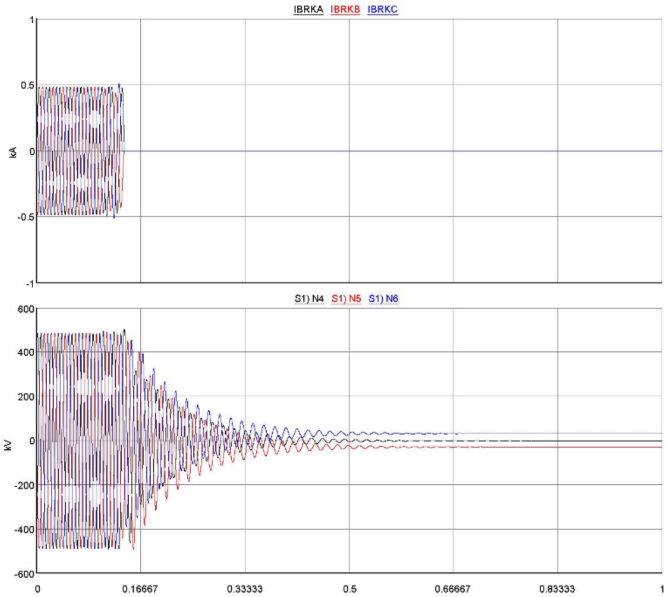

Fig. 12. Phase-to-ground voltages in Serra da Mesa I and CB currents during a single-phase fault in Colinas II substation (km 1344) and relay operation.

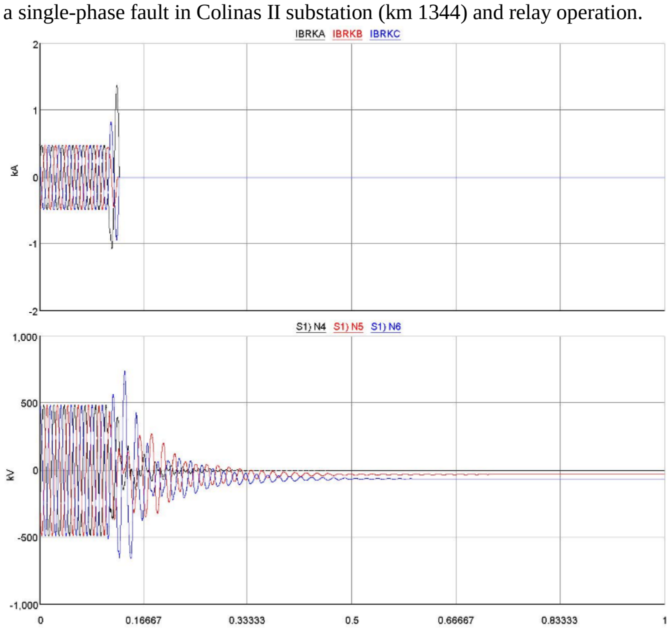

Fig. 13. Phase-to-ground voltages in Serra da Mesa I and CB currents during a single-phase fault in Serra da Mesa II substation (km 2028) and relay operation.

V. Conclusions

This study presented the necessary adjustments for a conventional distance relay to quickly identify the occurrence of single-phase faults anywhere in the AC-Link, a transmission line with length slightly greater than a half wavelength.

The basic approach was that a single conventional relay located at sending end substation should protect the whole AC-Link. As the relay used was designed for conventional protection of few hundreds of kilometers long highly compensated transmission lines, a new setting adjustment was necessary. Specifically the main protection used was based on instantaneous zero sequence voltage (59N), which does not locate the fault but quickly protects the system. Three other adjustments were implemented, specifically the instantaneous zero sequence overcurrent (50N1), the timed negative sequence overcurrent (51QT) and the timed zero sequence overcurrent (51QT).

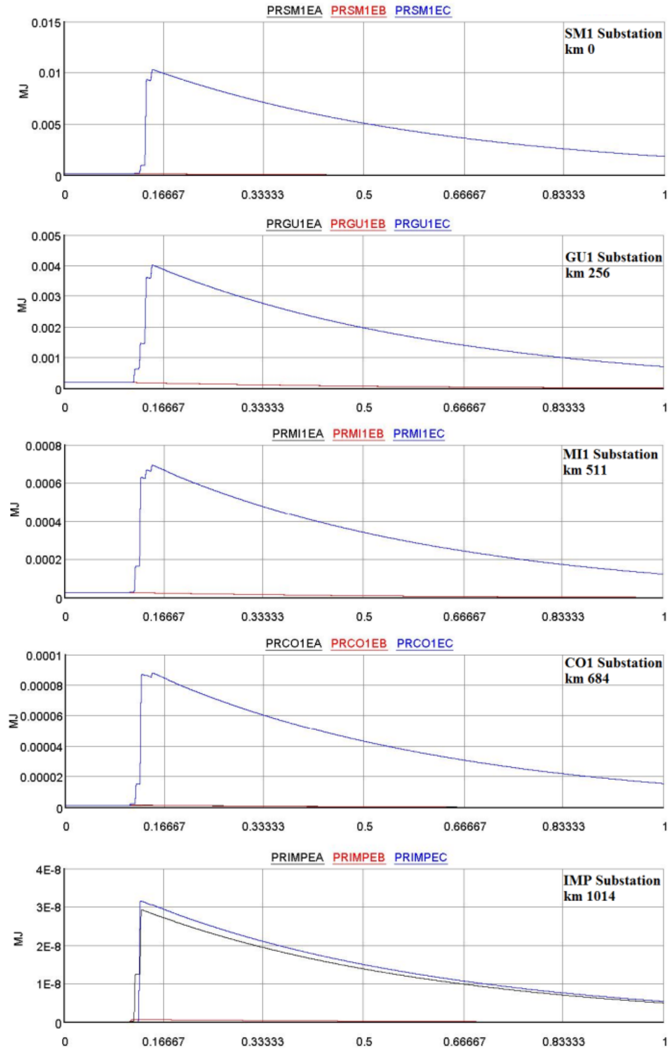

Fig. 14. Energy absorbed by surge arresters along the North-South 1 trunk during the worst single-phase fault case, in km 2028 (Serra da Mesa II substation)

The proposed protection scheme was developed and tested for the AC-Link energization maneuver, where the AC-Link is isolated, just connected to the generation unit substation.

The protection scheme promptly identified the fault, sending the order to trip the AC-Link. The existent equipment, namely the generation unit, the step-up transformer, the CB and the surge arresters located along the AC-Link were not damaged or suffered any severe stress that would result in life-time reduction. This is an important and necessary result as the assets will have to return to Brazilian electrical grid immediately after the experiment.

The proposed protection approach may be adapted for an AC-Link operating within an electrical power system. New results regarding the operation of AC-Link under different load profiles are being developed and will be presented in forthcoming papers.

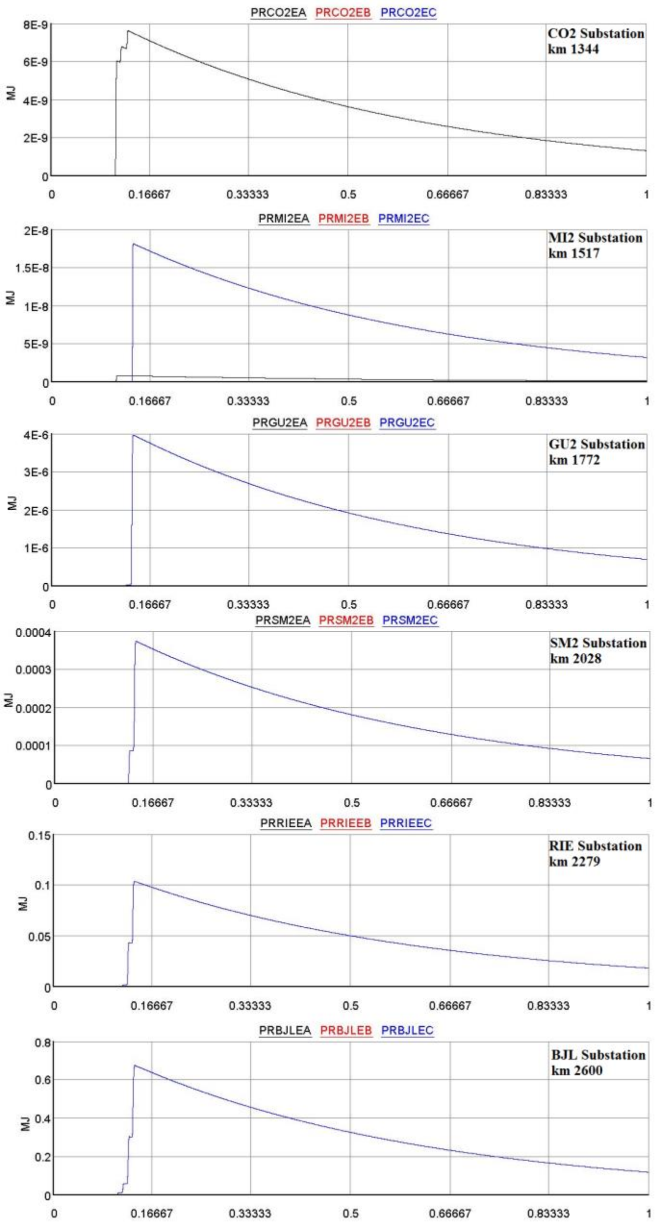

Fig. 15. Energy absorbed by surge arresters along the North-South 2 and NorthEast-SouthEast trunks during the worst single-phase fault case, in km 2028 (Serra da Mesa II substation)

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