Using of Conventional Relays for Protecting Half-Wavelength Transmission Line from Three-Phase Faults

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***Abstract*—In the present paper the main results on Half-Wavelength Transmission Line (HWL) protection scheme for three-phase faults are presented. The analyzed system consisted of an experimental trunk of 2600 km formed with actual 500 kV lines existent in Brazilian electrical power system. This AC transmission alternative is a point-to-point transmission that does not need neither shunt nor series compensation, resulting in a lower implementation cost when compared to HVDC solution, with the additional advantage of not being based on Power Electronic technology. The HWL protection scheme for three-phase faults was implemented in RTDS real time simulator with the relay that will be used with the experimental trunk. It was possible to properly protect the 2600 km long line with conventional relay, only using the functions available in the equipment.**

***Keywords*—Half-wavelength transmission, Line energization, RTDS simulation, Protection, Three-phase faults, Reduced Insulation Distance (RID).**

I. Introduction

Due to the increasing electricity demand around the world, the expansion of the transmission system is necessary. Often, regions with still available high energy potential are very distant from power consumption centers: cities, industrial centers, etc. To harness the energy that would be produced, it is necessary to establish point to point links between these regions with potential energy and the load centers.

Currently, these connections are made by high-voltage direct current transmission lines (HVDC), but an alternating current (AC) alternative with some particular characteristics might be the most economical one, having much less dependence on the Power Electronics technology. In the 1960s, the first studies were done showing that the AC line has an interesting behavior in terms of voltage, current and stability of the system when it has electrical length a little greater than half the length of the electromagnetic wave [1]-[2]. Nowadays new reasearches have been studing this alternative, as [3]-[4].

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Brazil is a country with continental dimensions that need this type of connections between the south-east and north-west regions, between the south-east and north regions and potentially with some neighboring countries. For 60 Hz operation systems these links would have distances of approximately 2600 km [5].

As there is not a system of half-wavelength transmission in the world, it was proposed to carry out an energization test connecting in series sections of existing lines in the Brazilian interconnected system [6], [7], [8], [9]. This test will allow the examination of the behavior of the AC-Link and the comparison with the studies made so far.

The energization test needs a protection system, and it is necessary to analyze whether the current existing schemes could protect it against possible faults along the line. Otherwise, a more efficient protection scheme that is sensitive to faults should be proposed.

The results of the study on the protection for three-phase faults using the relays available in substations are presented. Initially, the distance protection was analyzed, but the protection scheme that uses only the distance device is not capable of protecting the entire the AC-Link during the energization test. Some additional features are analyzed to properly protect the system.

The studies were performed using the RTDS real-time simulator together with the same relays available on-site. The analysis of the variables to identify the relays settings are presented in the following sections, as well as the results of the protection system proposed and the main conclusions.

II. Analysis of protection system

In the study of protection for the energization maneuver of the AC-Link it was initially observed the behavior of the variables: voltage, current and impedance for three-phase faults along the transmission line. Initially, it was studied the existent distance protection and later other additional functions of the relay SEL 321-1. It was studied specifically the three-phase-to-earth faults assuming an impedance at the site of defect of 20 Ω.

The system simulated in the RTDS is shown in Fig. 1: all transmission lines have been represented using the Bergeron line model. This model does not represent the line longitudinal parameter frequency dependence, but it was used to promptly implement transmission line sliding fault device in RTDS. There were monitored the voltages in the buses and the

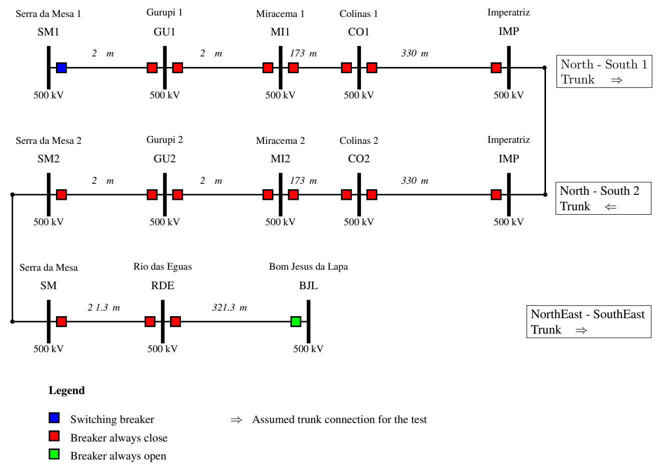

Fig. 1. Single line diagram of the primary circuit of the AC-Link to be tested.

currents in the circuit-breakers (CB), as well as the magnitudes measured by instruments transformers (CT and PT), where the CTs ratio is 3000:1 and the PTs ratio is 4500:1. The CT saturation was not represented. At this stage of the analysis, only the relay from the substation Serra da Mesa 1, SEL-321-1, was used.

A. *Using conventional distance protection*

In this section the distance protection is analyzed to verify if it would properly identify fault in any AC-Link location. A component was developed for RTDS to represent the impedance seen by the relay. The voltage and current signal at the sending end were acquired and filtered with a low-pass filter (cutting frequency of 480 Hz). Afterwards the phasors were calculated using FFT with 8 samples per cycle. With the voltage and current phasor the impedance seen from the CB bar was calculated. This component was programmed in standard C language using CBuilder tool of RSCAD [10].

In certain locations of the line, faults reach quasi resonance conditions, either of positive or zero sequence, rising the voltages and currents along the AC-Link. In the case of grounded or isolated three-phase faults, for faults occurring in the region between 65% and 90% of the AC-Link measured from the sending terminal, the resonance condition becomes critical, with rapid voltage increase at the terminals of the breaker and high currents, therefore not allowing a safe opening maneuver without a mitigation procedure. In [11] it was proposed the use of a reduced isolation distance (RID) positioned at approximately 40% of the total length of the line from the sending end to quickly remove the AC-Link Test from the quasi resonance condition.

This RID mitigation method consists in adjusting the number of insulators in order to provoke the flashover for overvoltages higher than 1.6 p.u. In that location the overvoltages will not be higher than 1.2 p.u. during energization transient and therefore RID will not operate during the experiment. However, if a severe condition appears RID will actuate immediately, removing the Link from the quasi resonance condition.

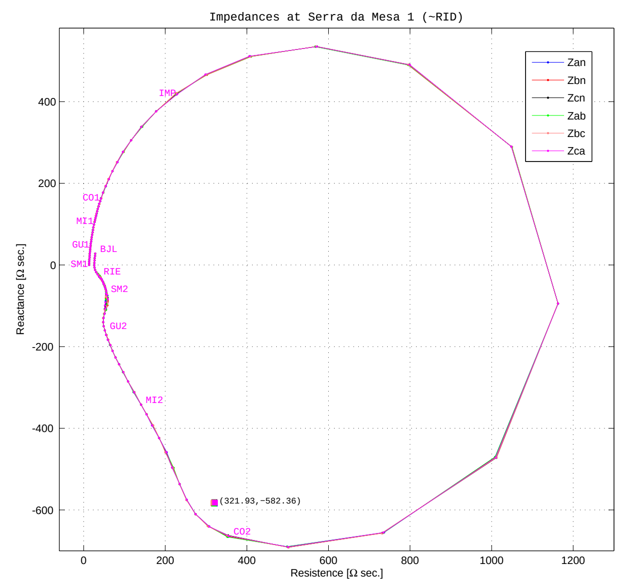

Fig. 2. Impedances seen at Serra da Mesa 1, without RID in Imperatriz.

Figure 2 shows the impedances (steady state) calculated from the voltages and currents of the PTs and CTs from Serra da Mesa 1, for faults applied along the line, and the faults were applied at intervals of 10% of the length of each line section. Each point on the graph indicates the place of fault applied. In this graph, it was supposed that the insulator string of the Imperatriz substation had a normal length, i.e. it was not reduced. The squares represents the impedances at the energization steady state of the AC-Link without the occurrence of fault.

As the maximum impedance that the relay SEL 321-1 can identify is 320 Ω, it can be verified that the relay could only protect the section of Serra da Mesa 1 (SM1 - km 0) up to the area near the Imperatriz (IMP - km 1040) substation. However, the reverse protection zones can be used to protect the section from Bom Jesus da Lapa (BJL - km 2601) up to the area near Miracema 2 (MI2 - km 1517). The no fault steady state impedances should be dealt properly (squares), as these points are close to the impedances for faults that occur near Colinas 2. From the above information, it can be seen that the distance protection cannot cover the section between Imperatriz and Colinas 2 and that it is necessary to block the trip of the distance protection for faults near Colinas 2.

Figure 3 shows the impedances (steady state) calculated from the voltages and currents of the PTs and CTs of Serra da Mesa 1 considering the operation of RID in a tower near the Imperatriz substation. It can be seen that the RID will not significantly modify the distance protection performance, i.e., if the fault occurs on the section between Imperatriz and Colinas 2 the protection will not operate as the AC-Link normal operation results in steady state impedances without fault close to the faulty-impedance in this region. The protection, therefore, cannot distinguish between the normal condition and the faulty-condition in this area.

RID starts working for faults that affect the Link from the

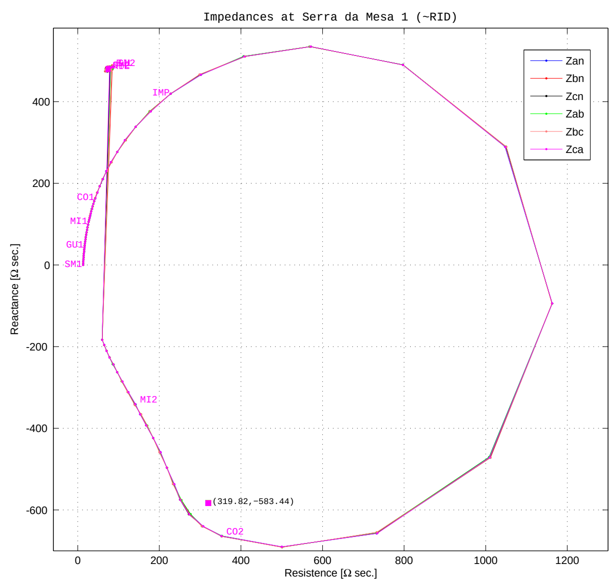

Fig. 3. Impedances seen at Serra da Mesa 1, with RID in Imperatriz.

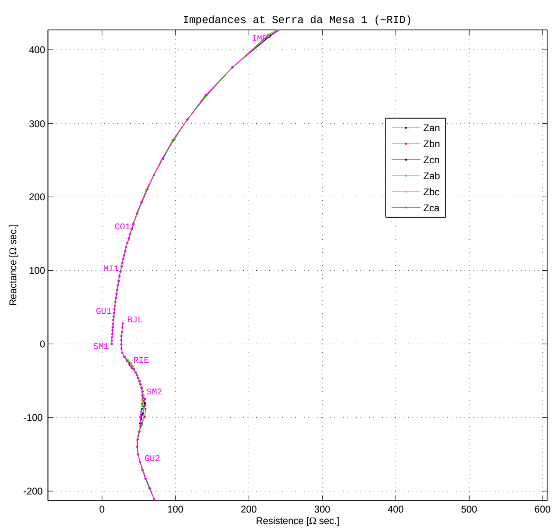

Fig. 4. Details of the impedances seen at Serra da Mesa 1, without RID in Imperatriz.

Gurupi 2 (GU2 - km 1772) substation toward the remote terminal, as highlighted in Fig. 4 and Fig. 5, which show the details of the impedances seen by the relay. It can be seen that the impedance changes drastically for fault between Colinas 2 and Gurupi 2, specifically the upstream and downstream of the first location where the RID acts.

B. *Additional functions of protection*

From the above, the existing distance protection can protect the line in its initial and final sections through the forward and reverse zone. It can indeed be used two forward zones and two reverse zones, with Zone 1 forward with instant action, Zone 2 forward with delayed action, Zone 3 reverse with instant action and Zone 4 reverse with delayed action. This makes it possible to identify the fault site, as the indication of Zone 1,

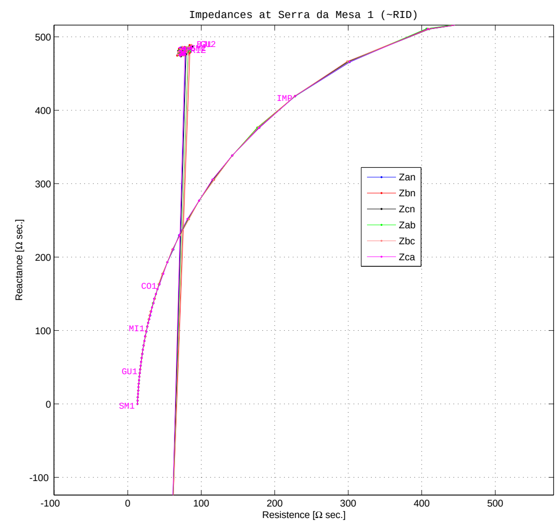

Fig. 5. Details of the impedances seen at Serra da Mesa 1, with RID in Imperatriz.

2, 3, or 4 would indicate the section of the line where the fault occurred. However, it can be seen that the distance protection of the relay SEL 321-1 would not be capable of protecting the entire line during the energization test in the event of three-phase faults in the central region of the line.

Alternatives should be searched to obtain a more efficient protection scheme. Therefore, it is necessary to analyze the voltages and currents for faults along the line. As the faults are three-phase faults, the components of zero and negative sequence will only appear during fault transient and they are of low magnitude compared with the energization.

In Fig. 6 the voltages and currents in the primary and secondary sides of the PTs and CTs are presented for the occurrence of three-phase to ground fault along the entire line.

Figure 6.a) shows the phase voltage at the primary side of the PT at Serra da Mesa 1 (SM1). It can be observed that the voltage at operation without fault is 286.76 kVrms. The blue and green curves correspond to the rms values of phase voltages held for faults along line, without RID and with RID, respectively. The red and cyan curves are peak voltages arising in the faults along the line, again without RID and with RID, respectively. It can be observed that for faults in SM 1 voltage is reduced to close to zero, then, as the fault moves away from the generator terminal, voltage at SM1 increases, which is the expected behavior for a conventional line. However, for faults near the middle of the line, the voltage at SM1 exceeds the voltage of the steady state without fault, which is the characteristic behavior of the AC-Link. As the fault location moves toward the open terminal, the voltages at SM1 reach maximum for faults near Serra da Mesa 2 (SM2) and then decrease as the fault moves to Bom Jesus da Lapa (BJL). The color legend is maintained for the other graphics.

Figure 6.b) shows the rms voltage at the secondary side of the PT at SM1. This voltage is similar to that shown in Fig. 6.a, but it should be noted that there is no record of peaks of the transient faults, as the PT filters voltages. It is understood that it is desirable to analyze the voltages at the secondary of the

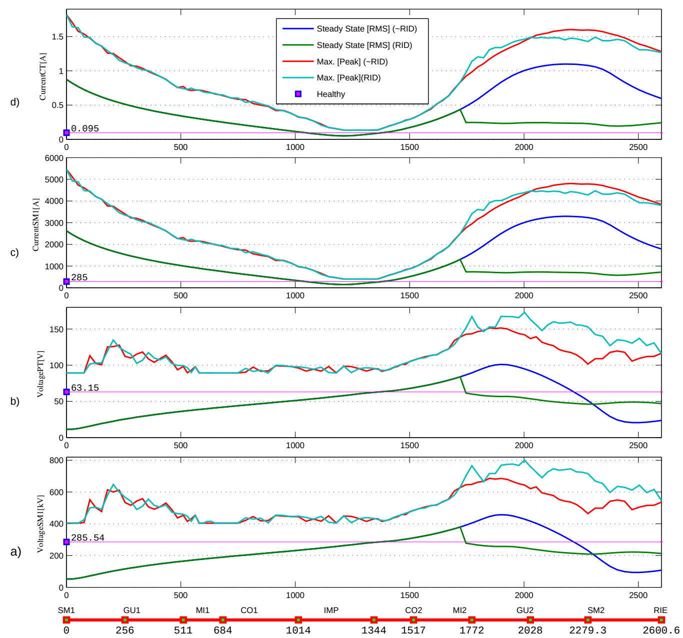

Fig. 6. Voltages and currents at sending end for faults along the line. a) Voltage in primary side of PT. b) Voltage in secondary side of PT. c) Current in primary side of CT. d) Current in secondary side of CT.

PTs because these are the voltages that the relay will use.

Figure 6.c) presents the current on the primary side of the CT, which has a current of 285 Arms in the operation without fault. It can be verified that for faults near SM1, the current measured is quite high when compared to the current value without fault. As the fault moves toward the open terminal the current decreases, but is still higher than the current from the operation without fault. This would be an expected behavior in conventional lines; however, for faults located near the middle of the line, the current in SM1 becomes lower than the current from the operation without fault. This is a characteristic of the AC-Link. After reaching its lowest value, the current begins to increase as the fault moves to the remote terminal, peaking near SM2 and finally decreasing as the fault continues to move to BJL. The high currents measured for faults near Serra da Mesa 2 are similar to those obtained for terminal faults, a characteristic behavior of the AC-Link that is different from a line with conventional length.

In Fig. 6.d) it is shown the current in the secondary side of the CT, and there is a similarity between these curves and those shown in Fig. 6.c). Analyzing the voltages and currents, it can be observed situations characteristics of a AC-Link, mainly in the region corresponding to faults near the middle of the line. It can be seen that it is possible to use Undervoltage, Overvoltage and Overcurrent devices to identify three-phase faults along the AC-Link, but there are still problems of selectivity for faults that occur near the middle of the line.

It is convenient to analyze the voltages and currents in the other buses for faults that occur near the middle of the line to verify how the system is affected by these faults.

Figure 7 shows the voltages in all buses for three-phase fault at Colinas 2 with fault impedance of 20 Ω. Figure 8 shows the currents in all breakers for the same fault.

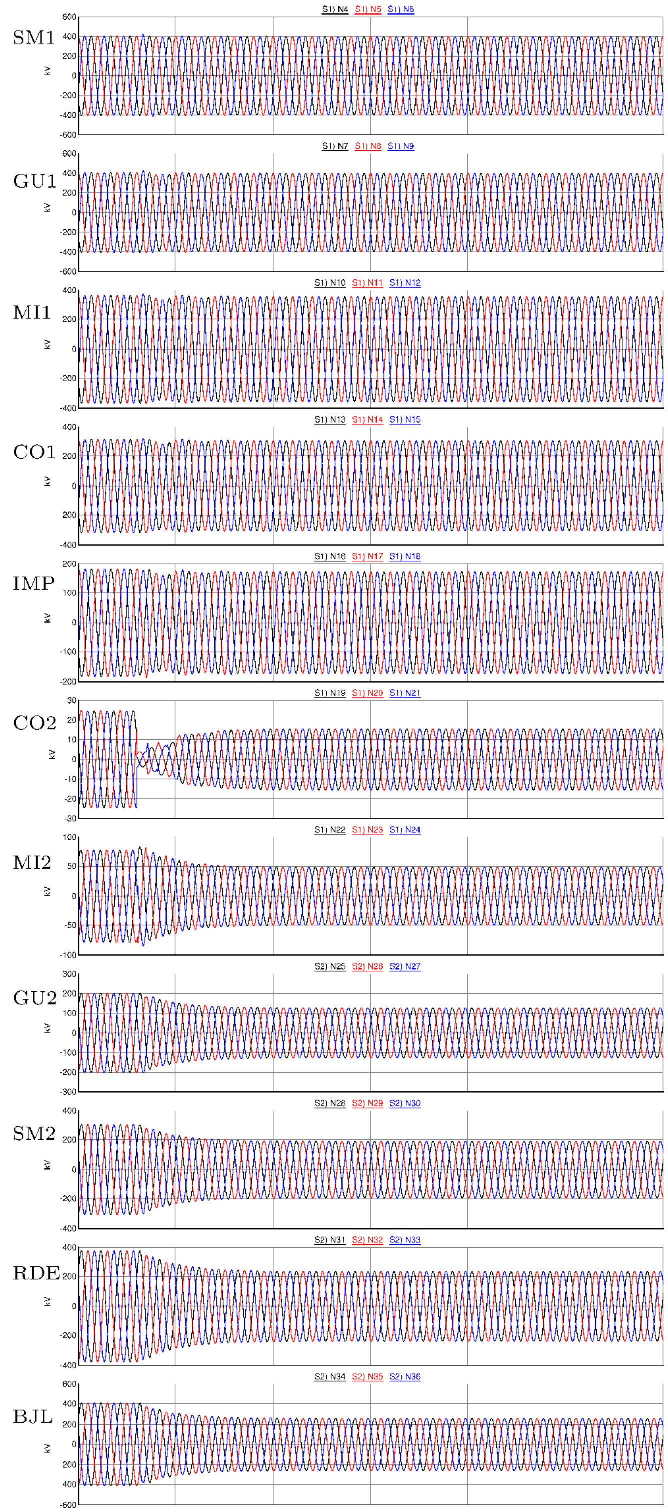

Fig. 7. Voltages in all buses for fault at Colinas 2.

In Fig. 7 it can be verified that voltages hardly suffer variation in the substations at the upstream of the fault location, as well as the currents (Fig. 8). It can still be observed that the currents at the fault location do not suffer variation. This explains the difficulty in identifying these faults.

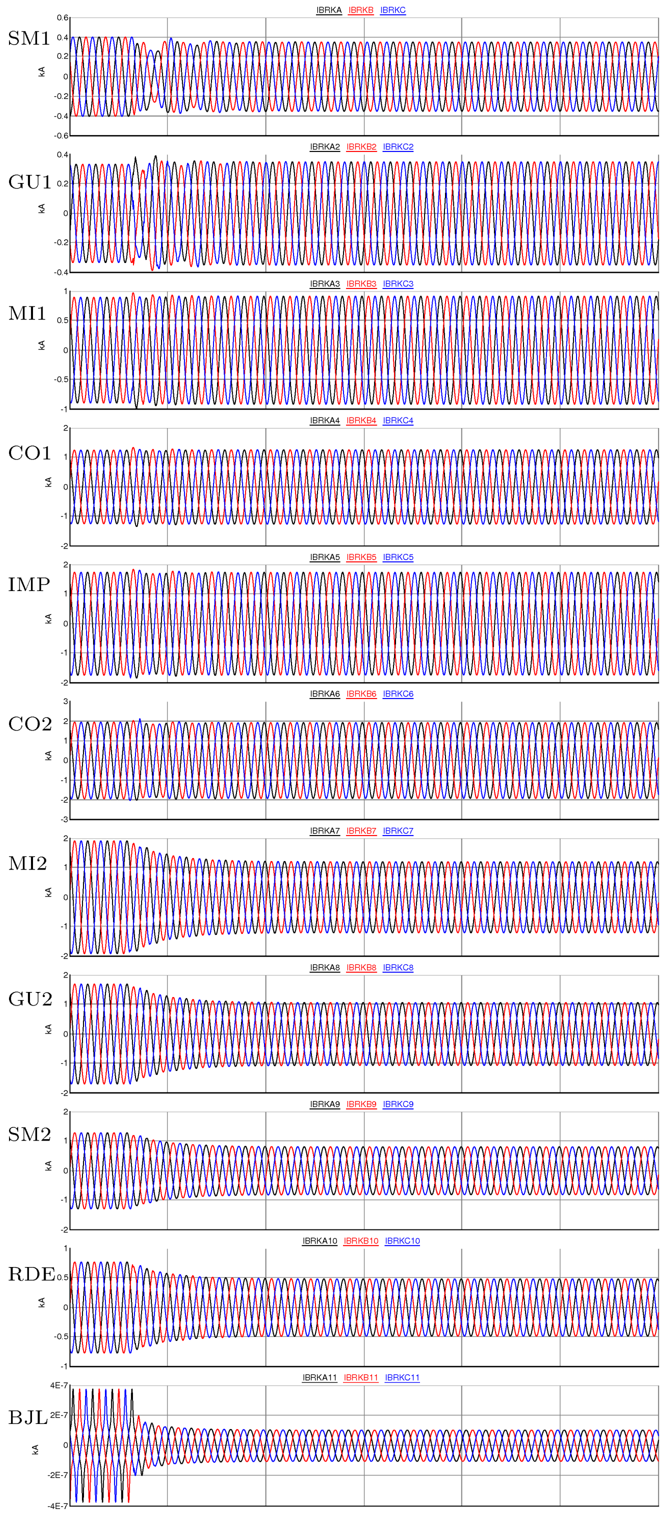

Fig. 8. Currents in all breakers for fault at Colinas 2.

C. *Additional settings for the relay SEL 321-1*

With the above considerations, it was analyzed the possibility of additional settings in order to complement the distance protection trying to protect the entire line against three-phase faults.

Initially, it was used the distance protection (21) of the relay as it is more selective, since it uses two variables, namely voltage and current, for its identification. The distance protection used will have 4 zones: Zones 1 and 2 forward, Zones 3 and 4 reverse. Zone 1 must cover the initial section of line, being adjusted in 160 Ω; Zone 2 must be adjusted to the maximum range of the relay, i.e., 320 Ω. Zone 3 was set at 160 Ω in reverse and Zone 4 was set at 320 Ω in reverse. Zones 1 and 3 will have instant action, and Zones 2 and 4 will have a delayed action.

TABLE I
SUMMARY OF RELAY SEL 321-1 SETTINGS

Distance (21)				
Zone	Reach MHO Phase-Phase	Reach Quadrilateral Ground		Delay
	Impedance [Ohm sec.]	Resistance [Ohm sec.]	Reactance Ohm [sec.]	Cycles
1 [Fwd.]	160	160	120	No Delay
2 [Fwd.]	320	320	250	5
3 [Bwd.]	160	160	120	No Delay
4 [Bwd.]	320	320	250	5
Overcurrent (51P)				
Pickup [A]		Curve type		Time dial
0.5		U3		2
Undervoltage (27L)				
<= [p.u.]		Relay Setting [V]		Delay [Cycles]
0.84		53.6		5
Overvoltage (27L)				
>= [p.u.]		Relay Setting [V]		Delay [Cycles]
1.2		76		12

From Fig. 2 and Fig. 3 it can be seen that Zone 1 will identify the faults that occur at the beginning or end of the line; Zone 2 will protect up to near the Imperatriz substation; Zone 3 will identify the faults at the end of the line; and Zone 4 will identify the faults in the section at the upstream of the end of the line.

The relay signals which zone was under fault allowing its use to identify in which portion of the line the fault has occurred. As can be seen in Fig. 2 and Fig. 3, the impedances of operation without fault should be considered. For this, the operation of the distance protection should be blocked for these conditions using the Load Encroachment.

Some additional devices were used, as described below, considering the voltages and currents of energization:

- Undervoltage Device (27L): was set at 0.84 p.u., timed in 5 cycles. The 27L device was adjusted with the loss of potential device (LOP), and the final logical was: 27L*!LOP. The performance of the relay would improve significantly if it was used the state of the breaker together with the 27L device, in place of the LOP device;
- Overvoltage Device (59N): was set at 1.2 p.u., timed in 12 cycles.
- Overcurrent Device (51P): pick-up value of 0.5; family of curve: U3; and time dial: 2.

III. TESTS PERFORMED AND RESULTS

To verify the protection performance in the electrical system, the simulations were performed with RTDS, generating signals of voltages and currents that were amplified and finally injected into the relay SEL 321-1. The relay trip was injected back into RTDS.

The three-phase-to-ground faults have been applied along the entire line, initially every 20% of the length of each

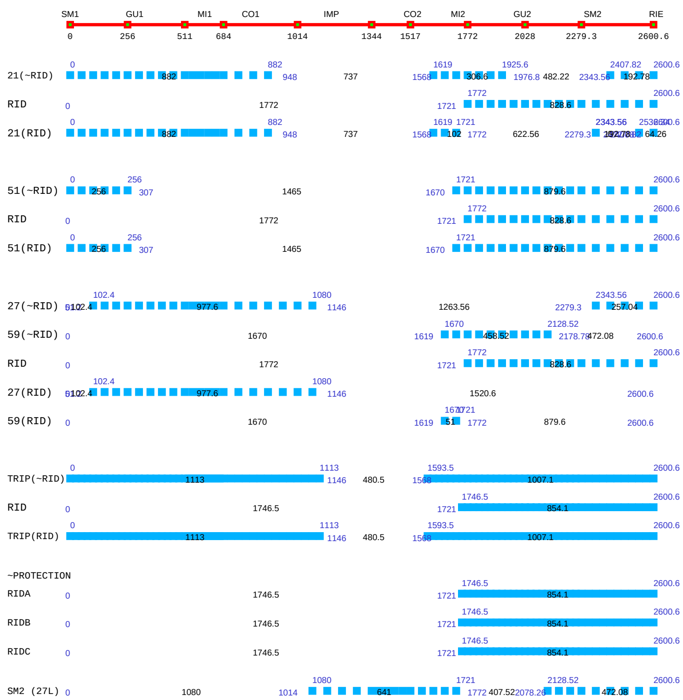

Fig. 9. Results of testing relay SEL 321-1.

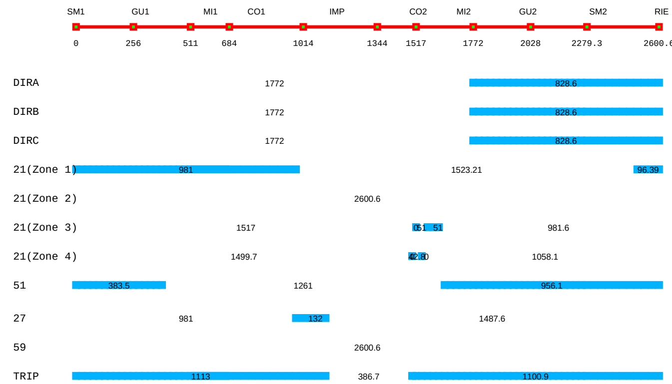

Fig. 10. Results of testing relay SEL 321-1 (CT ratio = 750:1).

section, to allow observing the performance of each protective device. Finally all the devices were tested simultaneously for faults every 10% of the length of each section. Table I summarizes the relay settings.

Figure 9 shows the results obtained. For clarity, the AC-Link is displayed at the top of the figure, with the distance of the substations measured from the switching terminal. For each fault location where the relay acted, a blue square was placed, which represents the logical 1 (one); and where there was no performance of the relay, it was left blank, representing the logical 0 (zero). The length of the sequence of *ones* ("1") was set as the distance that goes from the first *one* to the last *one* and the sequence length of *zeros* ("0") as the distance that goes from the first *zero* until the first *one* of the following sequence.

At the end of the sequence of operation of the relay ("1") it is given the length of the section protected; likewise, at the end of the sequence of no operation of the relay ("0") it is given the length of the section unprotected. The lengths are shown as black numbers.

Initially, the performance of distance protection (21) without the RID is presented (the trip logic was placed only with the distance function on). It can be seen that the distance protection operates for faults that occur in the first 948 km and in the last 828.8 km of AC-Link. Then it was tested the distance protection with RID. In the next line, it can be observed when the RID operates, and in the third line it is shown the relay response. It can be seen that the RID starts to operate from kilometer 1772, which corresponds to the Gurupi 2 substation. The distance relay operates at 1721 km from Serra da Mesa 1, and after that the distance protection does not operate for a 308 km section due to the operation of RID, returning to operate in the last 572.6 km from the AC-Link.

Below it is shown the results of the Overcurrent (51P), Undervoltage (27L) and Overvoltage (59L) devices, which show the consistent performance of the relay with the variables studied in Fig. 6.

After the isolated tests, in Fig. 9 there are presented the results of tests performed using all the devices together in the Trip logic, without RID and with RID. It can be verified that the result did not change with the actuation of RID and that the central section of 480.5 km is not protected. Then, there are presented the performances of RID for each phase, without considering the role of protection. It can be seen that RID always acts from the kilometer 1746.5 up to the end of the AC-Link. In order to verify the influence of the fault impedance value in the results, the tests were repeated considering a fault resistance of 0.01 Ω. The region that was not protected reduced in 25 km.

The last line of Fig. 9 corresponds to the performance of a relay located in Serra da Mesa 2, as, according to the voltage results along the Link for fault in Colinas 2 shown in Fig. 7, the relays existing upstream of Colinas 2 cannot identify the faults that occur in the central region. For this relay, the Undervoltage device (27L) is used. It can be observed that it suitably covers the central region and it does not operate for faults at the beginning of the AC-link because the Undervoltage device (27L) was adjusted to act together with the negative (!) of the loss of potential device (LOP), and the Trip logic is: 27L*!LOP. For faults at the beginning of the AC-Link, the voltage in Serra da Mesa 2 is so low that the LOP device is activated, blocking the action of the 27L device.

The relay performance can be improved using the state of the breaker instead of the LOP device in the trip logic for Undervoltage. The protection previously shown was adjusted considering the PT and CT ratios existing in field.

Additionally, it was checked the impact of variation of the CT ratio in the performance of the protection. Specifically, the simulations were performed again considering the ratio of the current transformers of 750:1. At this stage, the faults were located every 10% of the length of each section and all devices were activated together. Figure 10 shows the results for these tests.

The main conclusion of this sensitivity analysis is that with the new CT ratio a greater section of the line is covered by the relay, but there is still an area without protection when only the relay located in the Serra da Mesa 1 substation is used. It can be observed that the same initial section is covered and that there is an improvement in the coverage of the final section, leaving the central part of 386.7 km not covered. There was an improvement of approximately 100 km compared with earlier tests where we used the transformation ratio of current transformers of 3000:1.

IV. Conclusions

In this paper, there were presented the necessary settings so that the existent conventional relay (SEL 321-1) at Serra da Mesa 1 (SM1) can quickly identify the occurrence of three-phase faults along the AC-Link Test during an energization experiment. This protection is specific to the AC-Link energization maneuver test, i.e., to the condition of no load energization of an isolated AC-Link, assuming the occurrence of a three-phase fault during the experiment. It was found that it is not possible to protect the entire AC-Link with only the one relay available in Serra da Mesa 1. It is necessary to use a second relay SEL 321-1 available at another substation (Gurupi 2, 1772 km).

As the available relay is a regular one for conventional protection of a transmission line that is short and highly compensated, the adjustment of settings was needed and implemented in RTDS with successful performance.

The main conclusions are as follows:

- The conventional philosophy of transmission line protection is not the most efficient way to protect the AC-Link in the energization test. It is necessary to adapt the conventional protection based only in distance protection, including the under and overvoltage protection, and also the overcurrent protection, supposing that only the relay from Serra da Mesa 1 may be used for the test;
- The entire AC-Link could not be properly protected for three-phase faults with only the relay from SM1, leaving a central section of 480.5 km without protection;
- If the CT ratio of Serra da Mesa 1 were changed to 750:1, it would be possible to enlarge the coverage area in approximately 100 km; however, it would still not protect the entire Link;
- If the relay from Gurupi 2, or another one located in a substation between Gurupi 2 and the remote terminal of the Link were used, it would be possible to protect the entire Link during the test with conventional relays.

A remarkable conclusion is that the 2600 km long Link was protected for three-phase faults with the use of two conventional relays located at the beginning of the Link and at a substation located after the middle of the Link, namely at 70 % of the Link.

It is worth noting that the occurrence of faults in the central region does not damage or reduce life-time of assets located in the generation terminal, and these faults are seen by the relay from SM1 as AC-Link normal operating condition, what prevents the relay from operating. The second relay located around 70 % of the Link will be able to see the defect, protecting promptly the remainder of the trunk.

Again, it should be noted that the adjustments were made for the no load energization test of the AC-Link. More comprehensive studies are needed for the protection of a line with a little more than half-wavelength under operation.

The AC-Link is a reliable and technically robust solution for very long transmission trunks and due its constant terminal voltage for all load profile it should also be carefully analyzed for intermittent power transfer as the ones produced by green energy sources, as large solar and wind power plants.

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