Energization of the Half-Wavelength Transmission Trunk Considering the Occurrence of Single Phase Fault

M. A. Paz, M. C. Tavares

***Abstract*-- The natural resources still available in several countries, including Brazil, are located far from the main load centers. Among the alternatives considered for long distances transmission is the transmission in a little more than half wavelength (HWL+), here called AC-Link. Aiming to contribute to the viability of this alternative, this paper presents the main results related to the energization of the AC-Link, with special considerations to the occurrence of single-phase fault along the trunk.**

The study considered the series connection of an actual 500 kV line sections from the Brazilian system, forming a 2600-km long AC-Link. To evaluate the AC-Link behavior, simulations were performed by energizing the no-load trunk with and without the presence of defect.

The simulations were performed with ATP.

***Keywords*: Half-wavelength transmission, AC-Link, electromagnetic transient, single-phase faults.**

I. Introduction

THE increase in energy consumption in recent years led to the challenge of aggregating large blocks of energy to electrical systems to supply the growing demand. In such situations that available resources are located far away from the major consumption centers the need arises to carry this energy through long transmission systems.

When considering the best alternative to transmit these huge blocks of energy, an AC ultra-high voltage transmission trunk with electrical length of a little more than half wavelength (HWL+) [1] was considered. Its cost is moderate and competitive when compared to HVDC transmission. This Link (UHVAC-Link) does not need reactive compensation (either shunt or series) along the trunk and is basically a point-to-point transmission, with only conventional AC terminals substations. The theoretical and functional aspects of this type of transmission are described in [2]-[5].

This transmission trunk, here called AC-Link, is being researched by several groups from countries whose electrical systems present similar characteristics [6]-[7]. One of these countries is Brazil, with large water resources located in remote regions, at 2000 to 3000 km from the main load centers [8].

In order to properly evaluate this alternative, a real test is being planned in Brazil [9], specifically the energization of an AC-Link test. This AC-Link is formed by 500 kV lines with similar characteristics, which when connected in series will form a 2600 km long trunk, suitable for half wavelength transmission in a 60 Hz system.

This paper aims to contribute to studies on half wavelength transmission [9]-[13], presenting the analysis of the AC-Link behavior during the energizing maneuver under single-phase fault. This trunk presents voltage and current profile along its length that are different from the conventional short line, such as a few hundred of kilometers long line.

For analysis purposes the simulations consisted initially in energizing the test system without considering any defect. Subsequently, the line was energized considering the occurrence of single phase faults. With this procedure it was possible to obtain the voltage and current profiles along the AC-Link. Subsequently it was possible to identify the most critical regions for this type of defect and to verify if it was necessary to develop any special mitigation procedure. The simulations were performed with ATP.

II. Description of the AC-Link Test

The transmission system is formed by the 500 kV interconnections North-South I (NS-1), North-South II (NS-2), and Northeast-Southeast (NE-SE), forming a trunk with approximately 2600 km, as shown in Figure 1. The AC-Link consists of these three line trunks that have different characteristics, as shown in Table 1. The test system consists of a 497 MVA generator unit connected to Serra da Mesa substation and a step-up transformer that connects the generator unit to the trunk.

The lines were supposed to be ideally transposed (balanced lines) and were modeled with distributed parameter model. The soil resistivity was considered equal to 4000 Ω.m for the entire length of the Link test.

The AC-Link does not have shunt compensation, therefore the only neutral element that existed was at the step-up transformer which had the following connection: delta in low voltage side; solidly grounded wye in high voltage side.

III. Description of the Simulations Performed

The line energization is carried out with the circuit breaker

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(CB) closing at Serra Mesa. In each simulated maneuver the CB poles were all closed at the same instant, in 15.4 ms, corresponding to the maximum phase to ground voltage in phase A. The use of existing 400-Ω pre-insertion resistor was taken under consideration. The resistors were kept for 10 ms, which is not adequate to mitigate the transient overvoltages of an AC-Link. This trunk, due to its length, requires a resistor kept in service for 20 ms so the travelling waves can reach the remote end and return to the sending end at least once. To avoid using the existent resistor in a condition different from its specification, it was kept in service just the regular time. This procedure transformed the resistor in an ineffective mitigation method, on the other hand it will not be damaged or have its life time reduced.

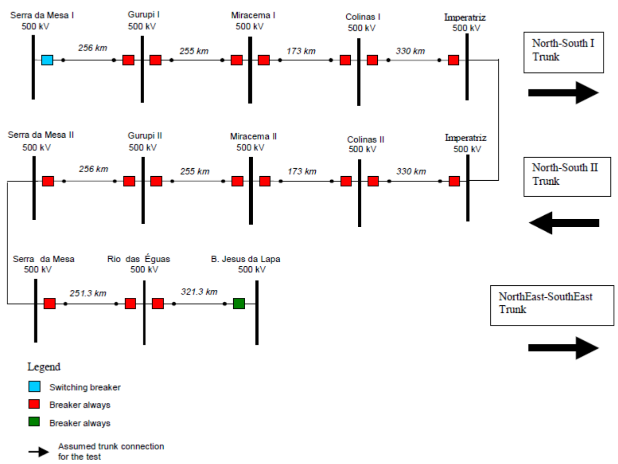


Fig. 1. Single-phase diagram of AC-Link Test – 500 kV.

TABLE I

LONGITUDINAL AND TRANSVERSAL PARAMETERS PER UNIT LENGTH OF THE TRUNK LINES (NS-1, NS-2, NE-SE), FOR 60 Hz

Trunk	Mode	Resistance [Ω/km]	Inductance [mH/km]	Capacitance [μF/km]
NS-1	Homopolar	0.4696	4.1849	0.00726
	Non-Homopolar	0.0159	0.7081	0.01613
NS-2	Homopolar	0.4352	3.8257	0.00936
	Non-Homopolar	0.0161	0.7253	0.01603
NE-SE	Homopolar	0.4352	3.8257	0.00935
	Non-Homopolar	0.0161	0.7252	0.01604

In order to reduce the setup time, the existing surge arresters were kept in service in all substations. It was verified that by keeping them the AC-Link operation was not mischaracterized, once the surge arresters would not be necessary during the energization of the line without defect.

Subsequently, the energization maneuvers of the 500 kV AC-Link were carried out considering the phase-ground fault applied along the trunk (phase A, with the fault resistance of 20 ohms). The fault was applied at various points along the Link to identify the possible critical regions for this type of defect.

It is noteworthy that the possibility of a fault occurring during the short-time experiment is very low, but as the assets involved should be restored to the system immediately after the experiment without any damage or reduction of its life expectancy, special care should be taken.

The results here obtained can be used in future AC-Link studies for the proper design of protection system and surge arresters. However, the present system is an isolated one, while an AC-Link should have terminal networks and the interconnected system should be properly represented and analyzed.

In transient studies the equipment must withstand disturbances for a minimum time of 100 ms. It was assumed that the protection would act after this period, that means after this time the circuit breaker would be opened. The simulations performed consisted of phase to ground fault applied and the circuit breaker tripping 100 ms after the fault occurrence.

The total simulation time was of 500 ms, with a fixed time step of 50 μs. Table II shows the measurement locations.

TABLE II

MEASURING LOCATION

Substation	km
Serra da Mesa	0
Gurupi I	256
Miracema I	511
Colinas I	684
Imperatriz	1014
Colinas II	1344
Miracema II	1517
Gurupi II	1772
Serra da Mesa II	2028
Rio das Éguas	2279.3
Bom Jesus da Lapa	2601.6

IV. RESULTS OBTAINED FROM THE SIMULATION OF THE LINE ENERGIZATION WITHOUT DEFECT

Initially the energization was performed without defect. Figure 2 shows some results for the Link energization simulation. It shows the voltage at the line terminals and in the middle of the Link.

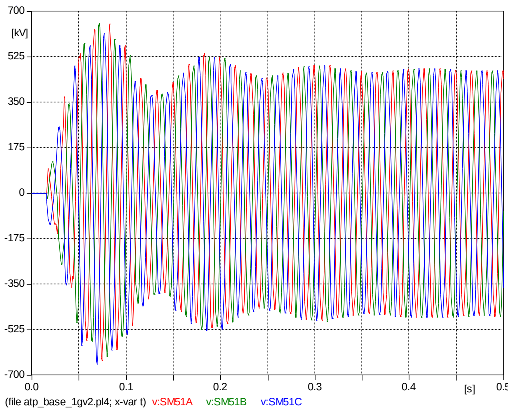
The transient phenomenon is extinguished in nearly 300 ms and the overvoltages are not too severe. It can be noted that the transient overvoltages and the steady state voltage in the substation in the middle of the line are low.

Table III and Figure 3 show the maximum transient voltages obtained during the AC-Link energization without defect. Table IV and Figure 4 show, respectively, the voltage levels and the voltage profile in steady state for the AC-Link.

The Colinas II (1344 km) and Miracema II (1517 km) substations had steady state voltage values below 0.5 pu, with the Colinas II substation presenting the smallest voltages values (around 0.08 pu).

The current levels in both circuit breaker and the transformer neutral point are shown in Figure 5. The maximum current level during Link energization without defect was 1.59 kA. In the steady state CB current value was 490 A. For the current on the neutral point at the transformer, the maximum value during energization was 56 A. This value drops to approximately 2 A when the system reaches the steady state.

Figure 6 shows the levels of absorbed energy by the surge arresters during the energizing maneuver. These values are far beyond their thermal capacity, being the highest measured at the remote end arrester with 111.67 kJ.



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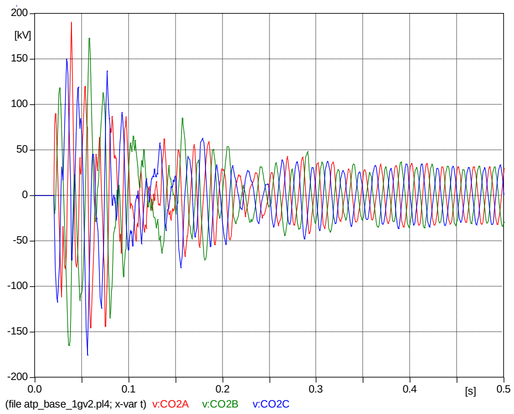

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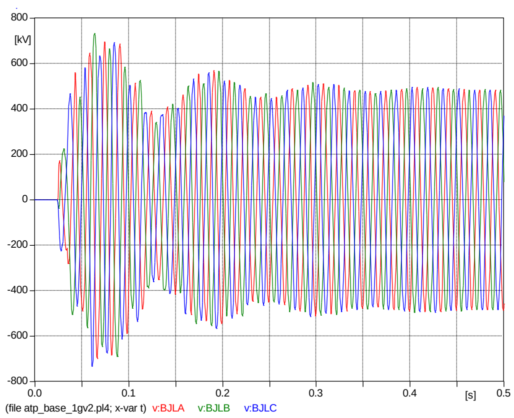


(c)

Fig. 2. Phase-to-ground voltage : (a) Serra da Mesa I – km 0, (b) Colinas II – km 1344, (c) Bom Jesus da Lapa - km 2600 - Energization without defect.

TABLE III

MAXIMUM TRANSIENT OVERVOLTAGES ALONG THE LINE – ENERGIZATION WITHOUT FAULT

Substation	km	Voltage [pu]	Phase
Serra da Mesa I	0.0	1.618	C
Gurupi I	256.0	1.706	C
Miracema I	511.0	1.627	C
Colinas I	684.0	1.499	A
Imperatriz	1014.0	0.999	A
Colinas II	1344.0	0.467	A
Miracema II	1517.0	0.484	B
Gurupi II	1772.0	0.917	B
Serra da Mesa II	2028.0	1.384	B
Rio das Éguas	2279.3	1.709	B
Bom Jesus da Lapa	2600.6	1.795	B

V. SIMULATION RESULTS OBTAINED FROM LINE ENERGIZATION UNDER SINGLE-PHASE FAULT (PHASE A-G)

The single-phase fault was applied at several points along the AC-Link, to monitor the occurrence of overvoltages, fault currents, currents in the Serra da Mesa CB, current in the neutral transformer, and energy absorbed in the surge arresters located along the AC-Link.

Tables 5-7 summarize the transient overvoltages behavior for the single-phase fault applied respectively at the beginning, middle and end of the AC-Link. The maximum overvoltages results for such events can be visualized in Figures 7-9.

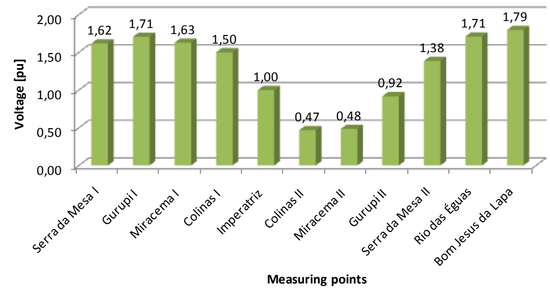


Fig. 3. Maximum transient overvoltages along the line.

TABLE IV

STEADY STATE VOLTAGE ALONG THE LINE AFTER ENERGIZATION WITHOUT FAULT

Substation	km	Voltage [pu]
Serra da Mesa I	0.0	1.156
Gurupi I	256.0	1.166
Miracema I	511.0	1.056
Colinas I	684.0	0.916
Imperatriz	1014.0	0.539
Colinas II	1344.0	0.078
Miracema II	1517.0	0.216
Gurupi II	1772.0	0.573
Serra da Mesa II	2028.0	0.877
Rio das Éguas	2279.3	1.085
Bom Jesus da Lapa	2600.6	1.183

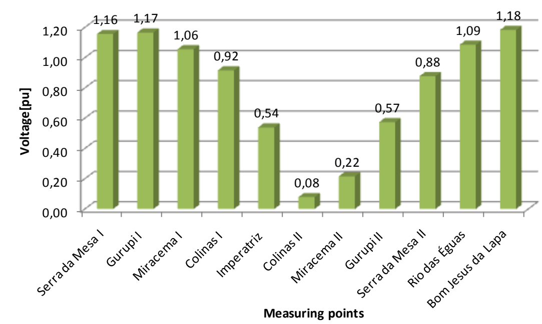
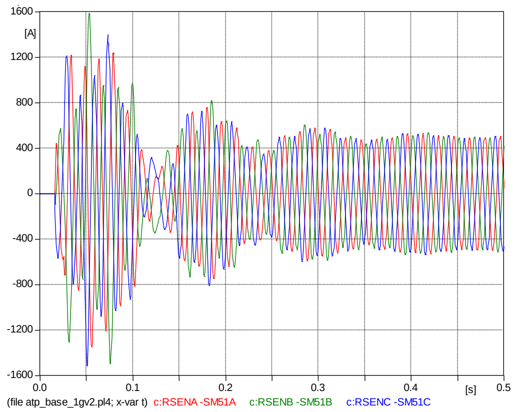


Fig. 4. Steady state voltage profile along the line after energization without fault.

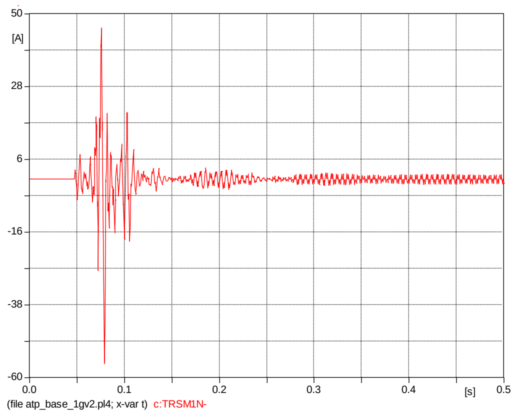
It is important to remember that the arresters are represented at each substation, which limits the overvoltages. The energy consumption of the arresters will indicate the transient severity.

The dominant factor for single-phase fault is the zero sequence component response seen from the sending end terminal. Due to its low propagation velocity, the zero-mode wavelength sequence for 60 Hz is almost equal to the AC-Link length. Therefore, when a fault occurs in some specific locations high overvoltages may arise.

These results were derived for an isolated system and the network zero sequence response will influence the results for the AC-Link analysis within an electrical system.



(a)



(b)

Fig. 5. Current of the AC Link energization without defect: (a) in the circuit breaker at Serra da Mesa, (b) in transformer neutral.

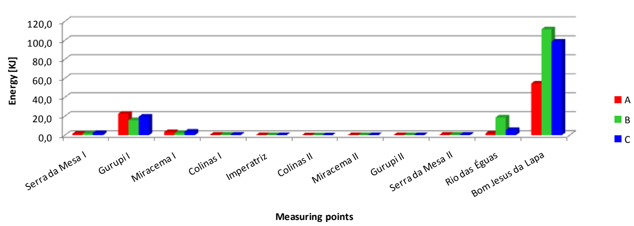


Fig. 6. Energy [J] absorbed by the surge arresters.

TABLE V
MAXIMUM TRANSIENT OVERVOLTAGE. A-G FAULT AT THE SENDING END

Measuring points		Voltage [pu]		
Substation	km	A	B	C
Serra da Mesa I	0.0	0.13	1.39	1.41
Gurupi I	256.0	0.17	1.44	1.54
Miracema I	511.0	0.16	1.32	1.49
Colinas I	684.0	0.19	1.17	1.37
Imperatriz	1014.0	0.22	0.74	0.94
Colinas II	1344.0	0.20	0.33	0.46
Miracema II	1517.0	0.17	0.40	0.47
Gurupi II	1772.0	0.12	0.79	0.84
Serra da Mesa II	2028.0	0.19	1.14	1.22
Rio das Éguas	2279.3	0.30	1.39	1.54
Bom Jesus da Lapa	2600.6	0.36	1.52	1.68

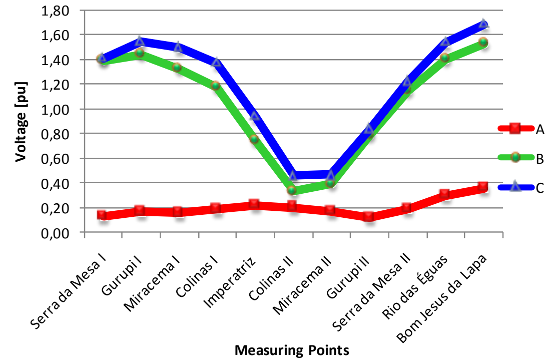


Fig. 7. Maximum transient overvoltage due to A-G Fault at the sending end

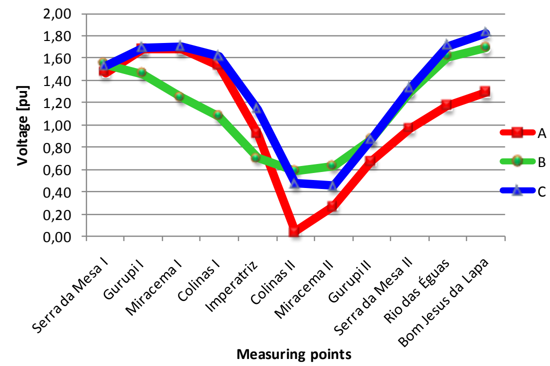


Fig. 8. Maximum transient overvoltage due to A-G Fault in Colinas II.

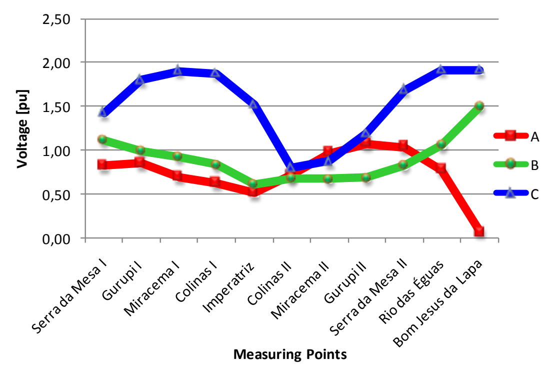


Fig. 9. Maximum transient overvoltage due to A-G Fault at the receiving end

TABLE VI
MAXIMUM TRANSIENT OVERVOLTAGE. A-G FAULT IN COLINAS II

Measuring points		Voltage [pu]		
Substation	km	A	B	C
Serra da Mesa I	0.0	1.47	1.54	1.53
Gurupi I	256.0	1.68	1.46	1.69
Miracema I	511.0	1.68	1.24	1.70
Colinas I	684.0	1.53	1.07	1.61
Imperatriz	1014.0	0.92	0.70	1.14
Colinas II	1344.0	0.04	0.59	0.47
Miracema II	1517.0	0.27	0.63	0.46
Gurupi II	1772.0	0.67	0.87	0.87
Serra da Mesa II	2028.0	0.97	1.29	1.33
Rio das Éguas	2279.3	1.17	1.61	1.70
Bom Jesus da Lapa	2600.6	1.29	1.69	1.82

TABLE VII

MAXIMUM TRANSIENT OVERVOLTAGE. A-G FAULT AT THE RECEIVING END

Measuring points		Voltage [pu]		
Substation	km	A	B	C
Serra da Mesa I	0.0	0.82	1.12	1.43
Gurupi I	256.0	0.85	0.99	1.80
Miracema I	511.0	0.70	0.92	1.90
Colinas I	684.0	0.63	0.84	1.87
Imperatriz	1014.0	0.51	0.61	1.52
Colinas II	1344.0	0.71	0.68	0.80
Miracema II	1517.0	0.97	0.67	0.88
Gurupi II	1772.0	1.07	0.69	1.19
Serra da Mesa II	2028.0	1.03	0.82	1.68
Rio das Éguas	2279.3	0.77	1.05	1.91
Bom Jesus da Lapa	2600.6	0.08	1.50	1.91

The substations with the highest overvoltages values were: Gurupi I, Miracema I, and Colinas I located before ¼ of the length of the line, and substations Serra da Mesa II, Rio das Eguas, and Bom Jesus da Lapa, located after ¾ of the length of the line. The most severe faults occurred in the final line section, from Serra da Mesa II towards the remote end, producing higher voltages both at the receiving and the sending ends of the line.

The 31 fault points along the AC-Link were simulated. The maximum current in the circuit breaker was caused by the fault located at the sending end, Serra da Mesa, with 2.6 kA in the faulted phase, as presented in Figure 10.

The fault current presents high values at the beginning of the line, as shown in Figure 11. This value decreases as the fault moves towards the remote end until reaching Colinas II where it starts to rise. The maximum fault current occurs between Gurupi II and Serra da Mesa II substations, reaching 2.9 kA.

The current in the transformer neutral was also monitored, with its maximum at 2.68 kA (Figure 12). Insofar as the point of the fault moves towards the remote end, the maximum current tends to decrease.

The performance of the surge arresters on energization of AC-Link under phase-to-ground defect was also monitored. Figures 13-16 show the behavior of the surge arresters.

The surge arresters with important energy consumptions were located at Miracema I, Colinas I, Rio das Éguas, and Bom Jesus da Lapa. The energy absorption capacity of these surge arresters is 13 kJ/kV. Thus, for a nominal voltage of 420 kV, the surge arrester can absorb the maximum energy of 5.46 MJ.

Faults located between Gurupi II and Bom Jesus da Lapa resulted in high energy consumption by the arresters (above their thermal capacity) in Rio das Eguas and Bom Jesus da Lapa. This is not an issue for the Rio das Eguas arrester, since in that substation two arresters are available, for both incoming and outgoing lines. However, at the remote end the energy is around twice the thermal capacity and only one arrester is available. Another arrester will be installed for the experiment.

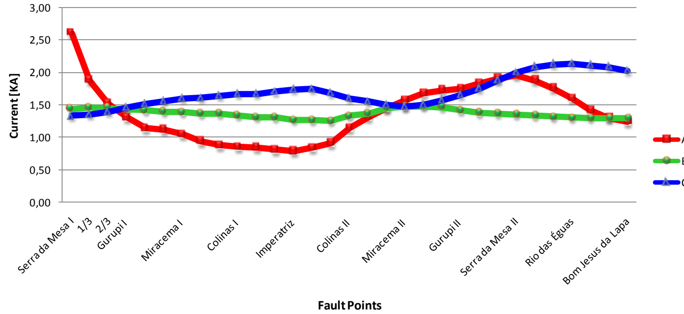


Fig. 10. Maximum currents in the circuit breaker due to A-G Fault along the line.

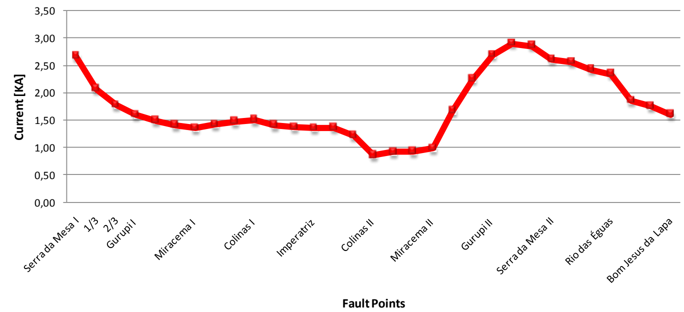


Fig. 11. Maximum fault currents along the AC-Link.

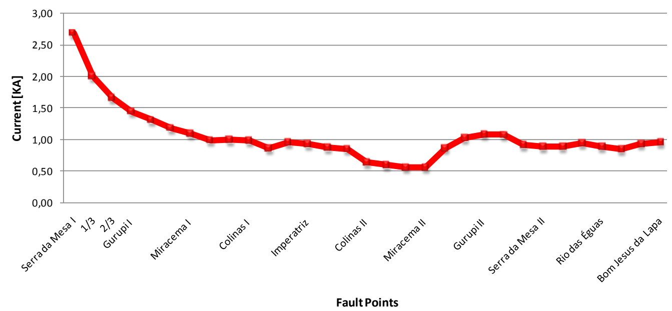


Fig. 12. Maximum currents in the transformer neutral for faults along the line.

VI. CONCLUSIONS

This paper shows the main results of an AC-Link energization maneuver, were the energization was considered without defect and with the occurrence of single-phase defect along the trunk.

It was verified that the transient condition is eliminated after 300 ms. Due to the length of the Link, the attenuation of the transients is quite fast.

For the energization maneuver without defect the overvoltages were not severe, and a maximum value of 1.96 pu was monitored at the remote end of the Link. This result was obtained without any method of mitigation.

The single-phase faults were applied along the entire line to identify potential critical locations. The most critical region was located between $^{1}/_{8}\,\lambda$ and the remote end of the line. Single phase faults located in this region produced high overvoltages at specific points of the line and high fault current.

The CB current values are greater for faults occurring near the sending terminal, and decrease as the defect moves towards the remote end; however, in the critical fault region this current rises, but not enough to overcome the value obtained for the fault on the sending terminal.

Since the simulations were performed with the surge arresters present in every substation, the monitored overvoltages were not high. It is important to observe the energy dissipated in these devices in order to evaluate the severity of the maneuver.

The surge arresters are not necessary, except for faults in well-defined locations, and for the critical region the energy dissipated was important, exceeding the absorption capacity of the existing surge arresters in a possible occurrence of single phase defect during the energization test of the AC-Link.

One must consider that the defect was maintained for 100 ms and the protection actuation was not properly represented. Results of simulations in RTDS [13] demonstrate that the existing relay acts faster and that the surge arresters' energy is lower than its thermal limit.

The occurrence of defect along an AC-Link produces different results than those found in much shorter lines, specifically the occurrence of critical locations far away from the sending end. However there are mitigating solutions that can be used, such as a fast protection or the use of surge arresters with high absorption capacity.

It is very important to emphasize that this alternative has a transmission cost very competitive when compared with HVDC transmission and requires no power electronic technology. This is an important feature for the majority of the countries.

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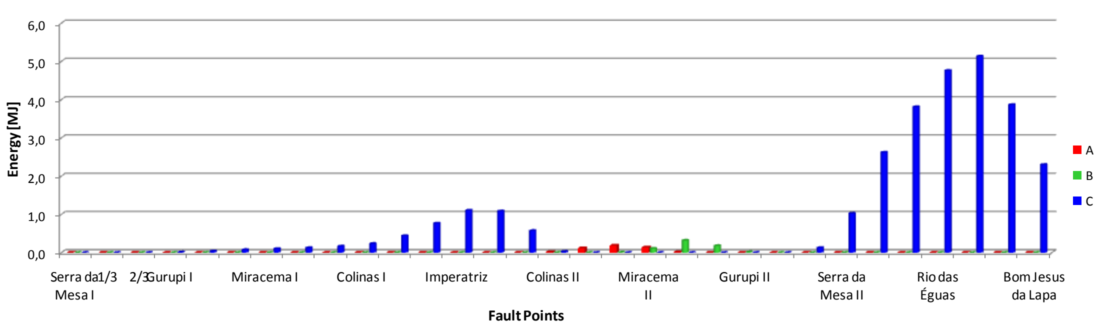

Fig. 13. Energy absorption [MJ] of the surge arresters in Miracema I considering faults along the line.

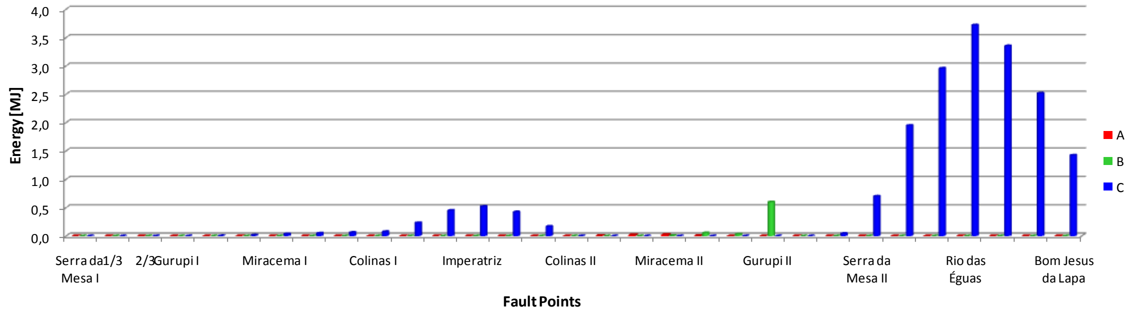

Fig. 14. Energy absorption [MJ] of the surge arresters in Colinas I considering faults along the line.

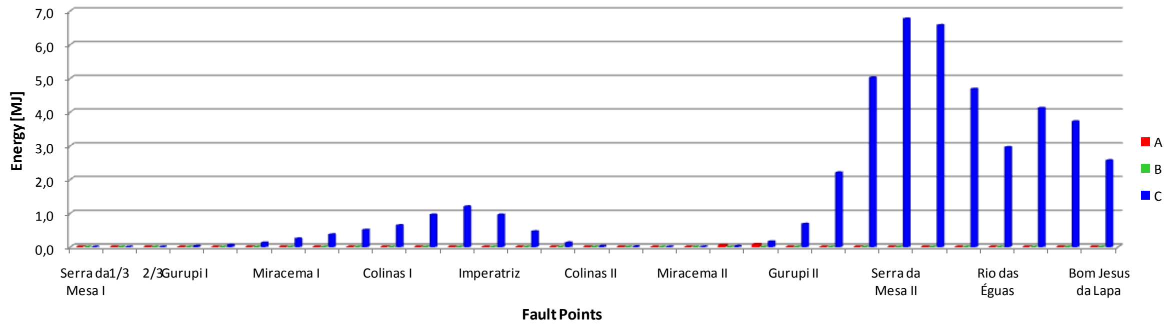

Fig. 15. Energy absorption [MJ] of the surge arresters in Rio das Eguas considering faults along the line.

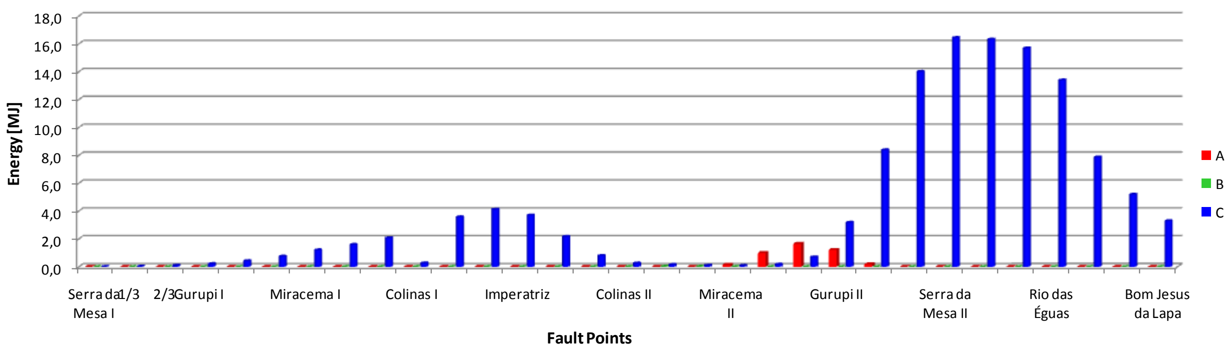

Fig. 16. Energy absorption [MJ] of the surge arresters in Bom Jesus da Lapa considering faults along the line.