Electromagnetic Transients Studies Related to Energization of a Half-Wavelength Transmission Line

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***Abstract*—In the present paper the main results of the pre-operational studies related to the energization maneuver of an AC-Link are presented. The simulations were performed in PSCAD with actual Brazilian system data.**

Specifically the following studies were performed: electromagnetic transient studies of energization maneuver considering no fault and the occurrence of fault along the trunk; dynamic analysis of generator units that will energize the AC-Link; TRV on the circuit-breaker that will energize the trunk.

The main conclusion is that the AC-Link energization experiment can be implemented without jeopardizing or causing time-life reduction of the equipment involved in the experiment, which comprises the generator unit that will energize the trunk, the step-up transformer, the arresters that will be kept during the experiments, as well as the circuit-breaker that will energize and then trip the AC-Link.

Keywords: **Electromagnetic transients, Half-wavelength transmission, AC-Link, energization test, dynamic analysis, TRV, faults.**

I. INTRODUCTION

In 2008 the Brazilian Electrical Energy Regulatory Agency (ANEEL) proposed a so called Strategic R&D project to be supported by utilities and coordinated by universities named: “*Half-Wavelength transmission line experiment*". According to the call: "it is considered of great relevance to the Brazilian Electrical System the execution of field tests to confront with theoretical and computational results, especially the ones related to overvoltages derived from line energization and the voltage profile along the line without reactive compensation, for the half-wavelength transmission system." [1-4]. And even more: "This effort has the main objective of evaluating the possibility of including the line with a little more than half-wavelength in the studies of future integration of the forthcoming hydro plants to the Brazilian Integrated Electrical System" [5].

In 2011 the research project began, technically and financially supported by the Brazilian Utilities: ELETROBRAS/ELETRONORTE, ELETROBRAS/CHESF and ENTE, being executed by the following universities: UNICAMP, UEFS and UFBA.

Specifically the project main objective is the implementation of the energization maneuver in a set of Brazilian system composed of 500 kV transmission lines that when connected in series will form a 2600-km long trunk [6]. That corresponds to a little more than half-wavelength to 60 Hz.

The proposed circuit will use the interconnections North-South 1, North-South 2 and part of Northeast-Southeast, totaling 2600 km [7].

The test trunk, here called AC-Link for being an AC point-to-point transmission, has economical advantages when compared with AC conventional interconnection that are heavily compensated, as this alternative needs neither intermediate substations nor reactive compensation (series or shunt). The AC-Link is also a competitive alternative when compared with HVDC Link as its terminal substations only have ordinary AC transformers and no harmonic filters are needed. That is an important feature as there is no Power Electronic Technology involved [8].

For the experiment the heavily compensated line sections will have the series compensation by-passed and the shunt compensations removed. The circuit breakers (CB) of the intermediate substations will be locked in closed position and the one at the remote end substation will be locked at opened position. Only the CB at the sending end will be in use. With this a 2600-km long 500-kV trunk is obtained. The energization maneuver will be implemented through the 500 kV CB at the sending end. All the protection schemes at intermediate substations should be out-of-service so that no CB changes position during the test.

The main electromagnetic transient results are presented in the following sections.

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II. ANALYZED SYSTEM DESCRIPTION

The transmission system used in the study is formed by three 500 kV interconnection trunks that have similar characteristics and will be connected to form the AC-Link [6, 7]. The characteristics of the transmission lines are summarized in Tables 1 to 3 where the sequence components of longitudinal and transversal parameters per unit length were calculated assuming ideally transposed lines, for 60 Hz.

These trunks have same terminal substations which allows connecting them in series. During the test the Brazilian electrical system will become practically disconnected, for the North and Northeast systems will remain connected to the Southeast, South and Central systems by only a single 500 kV interconnection trunk instead of the three normally in service.

It is a major concern that the test has the shortest duration possible. In order to reduce the setup time for the test and afterwards, to recompose the system, all surge arresters at lines terminals will be kept in service. As the transient overvoltages are expected to be very low, the arresters will not operate during the test and their presence will not impact the validity of the test. The single-phase diagram with the substations and lines involved is depicted in Fig. 1.

The energization will be performed from Serra da Mesa substation (sending end – SE) in one shot, what means that the entire trunk will be energized at a single shot using a pre-insertion resistor circuit-breaker (CB). This was identified as the most adequate procedure for AC-Link, as the controlled switching is not effective [6].

The Brazilian ISO (ONS) will identify when the lines that will form the AC-Link can be disconnected without jeopardizing the Brazilian electrical system. The period when these interconnections have low power flow will be chosen to perform the test. The test is planned to be as short as possible and it should not last more than 2 to 3 hours, comprising the experiment setup, the sequence of energization and finally the system restoration.

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	0.37138	4.11662	0.00725
Positive/Negative	0.01589	0.70700	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	0.34822	3.74452	0.00946
Positive/Negative	0.01602	0.71089	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	0.34821	3.75767	0.00934
Positive/Negative	0.01602	0.72403	0.01603

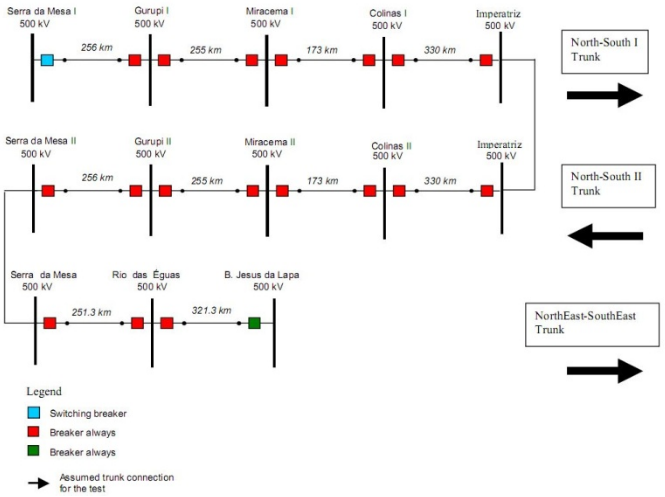


Fig. 1. Single-phase diagram of AC-Link Test - 500 kV.

Traditional soil representation was applied during the tests, specifically the soil resistivity was considered constant with frequency over the entire length of the AC-Link trunk with value of 4000 Ω.m due to high soil resistivity in these regions [9].

III. ELECTROMAGNETIC TRANSIENT STUDIES

For the implementation of the energization maneuver the regular transient studies were performed in PSCAD, as described in the following sections.

Due to the line length the overvoltages are expected to be much lower than the ones observed in regular transmission lines of few hundreds of kilometers long. This occurs because the traveling waves are attenuated as they travel along the line, mainly the zero sequence one.

The lines were modeled in PSCAD with the phase domain model which properly represents the line longitudinal parameters frequency dependence.

A. *Line energization without faults*

The insulation level of the 500 kV lines and the equipment connected in the test system were not surpassed during the energization tests.

The surge arresters that were kept connected during the simulations did not compromise the AC-Link behavior as the results were similar when they were considered just in the AC-Link terminals or in all line sections' terminals.

The overvoltage levels observed and the surge arresters energy consumption during the energization were very low, far below the equipment limits. In Fig. 2 the line-to-ground voltage at AC-Link terminal is presented.

Compared to an equivalent short line (133 km long line), the AC-Link had lower overvoltages and reached steady state faster. This short line length corresponds to the length of the AC-Link that is greater than the exact half wavelength.

When the number of generator units was varied for the line energization the lower overvoltage levels were obtained when

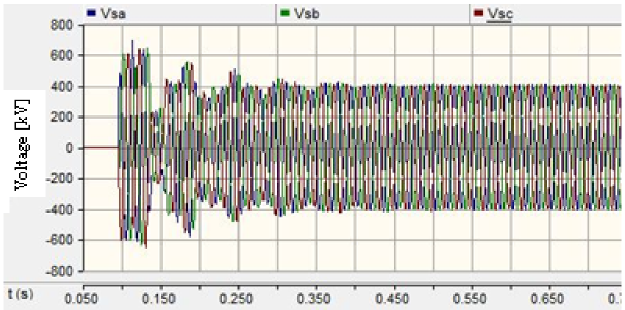


Fig. 2 – Voltage at receiving end during AC-Link energization - Pre-switching terminal voltage of 0.9 pu and no pre-insertion resistor.

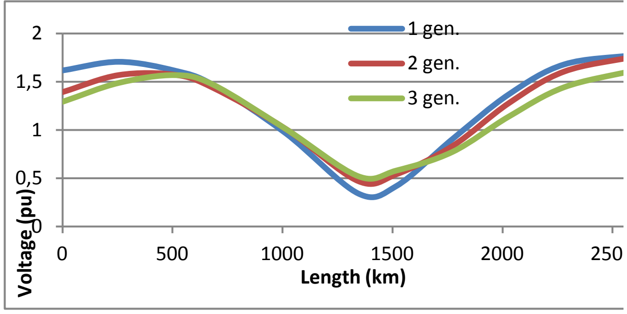


Fig. 3 - Maximum overvoltage along the Link during AC-Link energization with pre-insertion resistor (400 Ω – 8 ms), surge arresters at Link terminals, with pre-switching terminal voltage of 0.9 pu.

more units were used. However it was possible to energize the link with any number of units available at the SE substation. The simulation results showed that the overvoltage levels and the sustained voltage were within the system capability. In fig. 3 the maximum overvoltage along the Link regarding the number of generation units presented is shown.

It was also verified that it is possible to perform the maneuver with or without the pre-insertion resistor. The resistor is designed to remain in service for 8-10 ms and that is not adequate to mitigate the AC-Link overvoltages [6]. For an AC-Link the resistor should be kept for 20 ms so the traveling waves could reach the opposite terminal and return at least once. As this would entail important device modification the other alternative would be the resistor bypass. However that would affect the test setup time. As the overvoltages with the resistor kept for 10 ms and without the resistor were not important the test shall be implemented with the resistor operating as originally designed.

B. *Line energization with fault*

Some simulations were performed supposing occurrence or existence of single line to ground faults and three-phase faults, involving or not the ground, during the AC-Link energization test.

Although the experiment will be performed with fine weather in the majority of the AC-Link, due to its length there is a possibility of rain in part of the Link. However, due to the short duration of the experiment the probability of occurring a fault during the test is very low. Nevertheless, the equipment involved in the test, namely the generator unit, the step-up transformer, the circuit-breaker and the line sections with their arresters should not be damaged and should be put back into service in the following hours.

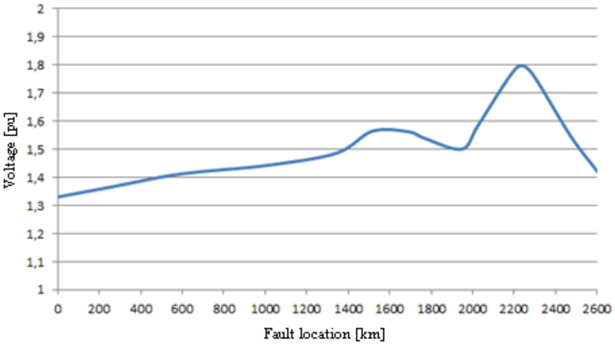


Fig. 4 – Maximum transient overvoltages measurured at Sending End terminal for single-phase fault.

The faults were represented along the Link, at each line section terminal and in the middle of each section. When the fault caused important overvoltage the interval was reduced. The fault was represented by a 20-Ω resistor.

The simulations consisted of energizing the line with fault and removing the fault after 100 ms.

The voltage at SE terminal for single phase fault (SLF) is presented in Fig. 4.

The measured overvoltages due to SLF were limited to 2.0 pu along the line as the surge arresters were represented. In order to observe the transient severity the arrester energy was analyzed. The energy was not important except for faults occurring between 85 and 90 % of the AC-Link length measured from the SE. If a fault occurs in this region the arrester located at the remote end absorbs high amount of energy. An additional arrester could be installed for the test at that location. However the probability of occurring a fault in that specific region during the short duration of the experiment is extremely low. The existent relay was used in RTDS study and the protection operation time avoided this severe energy consumption [9].

The maximum overcurrent observed in the CB occurred for terminal fault and was of 2.6 kA. The highest fault current was produced for a fault at 70 % of the Link length reaching 2.9 kA. The transformer neutral current reached a maximum value of 2.9 kA.

The results for isolated and grounded three-phase faults (3LF) were similar. The overvoltages and overcurrents vary with the fault location, being more severe if the fault occurs between 65% and 95 % of the AC-Link length.

The critical regions for both SLF and 3LF are related to the sequence impedances seen by the SE. For instance, the SLF critical region occurs at multiples of quarter wavelength of zero sequence seen from the terminal. The network at this terminal will also influence the quasi-resonance region, but in this experiment the major effect will be the AC-Link itself as the terminal is just formed by the generation unit and the transformer (this is an isolated system).

For the 3LF the critical regions corresponds to multiple of quarter wavelength positive sequence seen from the SE. At these regions sustained overvoltage may be produced and shall be mitigated promptly.

For 3LF the overvoltage increases in an accentuated rate as the positive sequence attenuation for 60 Hz is very small. This is a common mistaken analysis seen in a large number of researches that deal with AC-Link. As the overvoltage that arises is very high, far beyond line flashover level, the simulations cannot measure the voltages along the line supposing flashovers will not happen. There is no meaning in measuring a 4.0 pu overvoltage as before that a flashover will occur. When the flashover occurs the Link will immediately be removed from the quasi-resonance condition and the voltages that will arise will depend on the new fault location.

In order to mitigate the stresses produced by 3LF at critical locations it was proposed to use a mitigation method called Reduced Insulation Distance (RID) [10]. This method, proposed for the no-load test, consists in reducing the insulator string length in a selected tower in order to provoke the flashover in that specific location. The RID was installed in a tower near Imperatriz substation (40% distant from the SE).

The RID was prepared to disrupt at 1.6 pu (line to ground), for:

- This voltage is much higher than the transient overvoltage at this location during energization without any faults (maximum transient value of 1.2 pu);
- During no-load steady state the sustained voltage is very low at this location (0.54 pu);
- 3LF produces no severe overvoltages or overcurrents along the AC-Link when it occurs this location.

With this method the severe overvoltages/overcurrents are not established and the severe condition is immediately eliminated. Using RID the overvoltages due to 3LF are below withstand levels and regular thermal capability arresters can be used. The maximum current levels obtained in CB, transformer neutral and RID are, respectively, 3.11 kA, 2.41 kA and 8.32 kA. The RID current value is lower than the electric discharge current that can reach more than 30 kA and, therefore, it will not damage the insulator string.

In Fig. 5 the maximum voltages measured at SE during grounded 3LF are presented. In Fig 6 the maximum currents measured at CB are during grounded 3LF are shown. In Fig. 7 RID current is presented for grounded 3LF.

This RID will not act for SLF as the voltage at this location will not reach 1.6 pu, as presented in Fig. 8. It will only operate for 3LF at the severe region. If the RID operates for a lower voltage for SLF this will not be a severe condition, as can be observed in Fig. 4.

C. *Generator unit performance during energization without fault*

The AC-Link can be energized from 1, 2 or 3 power units. The requirements of the generators are greater if only one machine is used. However the measured values do not compromise the equipment integrity or reduces its life-time.

In Figs. 9 and 10 the active and reactive power are presented for energization without pre-insertion resistor.

D. *Generator unit performance during energization with faults*

Simulations were performed considering the occurrence of faults along the AC-Link during the energization Test.

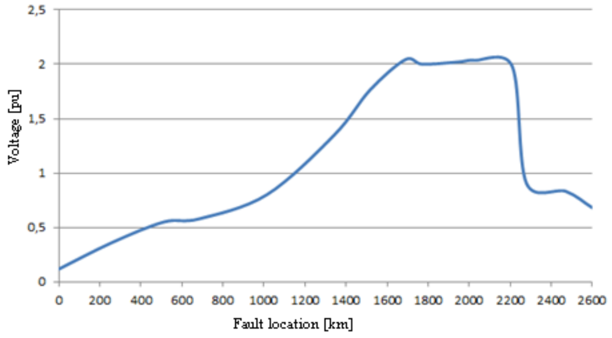


Fig. 5. - Maximum transient overvoltages at sending terminal for grounded 3LF along the Link with RID.

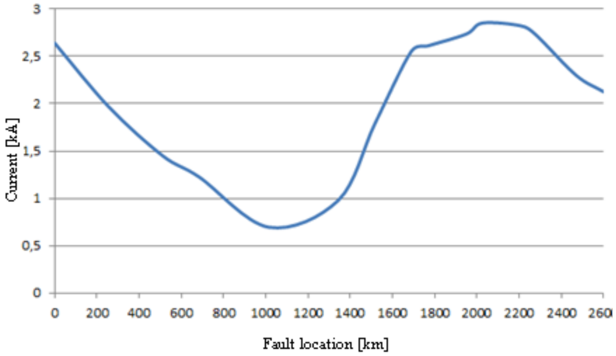


Fig. 6. - Maximum transient current at circuit-breaker for grounded 3LF along the Link with RID.

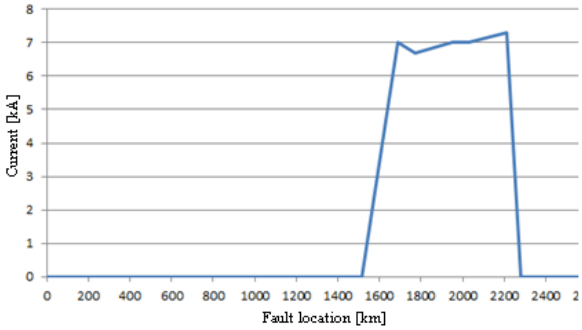


Fig. 7. – RID maximum transient current for grounded 3LF along the Link.

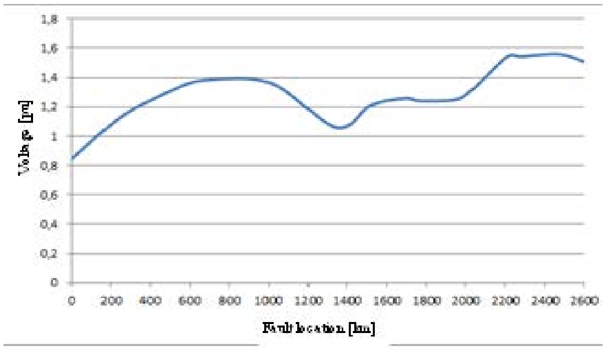


Fig. 8. – Maximum transient overvoltages measured at RID location during single-phase faults along the Link.

If a single-phase fault occurs the stress will not damage the generator unit. Specifically, if a fault occurs in the critical region for SLF the generator will send 1.5 pu of active power and 0.5 pu of reactive power. These values do not affect its unit due to the short duration of this event.

In case of three-phase fault, grounded or isolated, the stress again will not damage the generator. Specifically, if a fault occurs in the critical region RID will operate immediately,

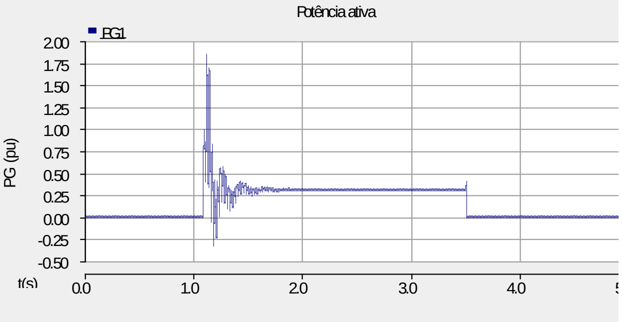


Fig. 9 – Active power injected by 1 generator unit during energization without fault – Pre switching voltage: 0.9 pu – Without pre-insertion resistor

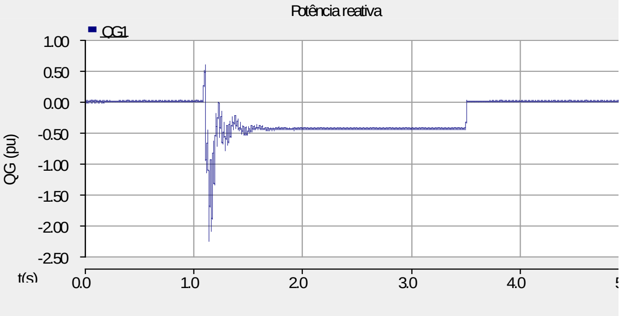


Fig. 10 – Reative power consumed by 1 generator unit during energization without fault – Pre switching voltage: 0.9 pu – Without pre-insertion resistor.

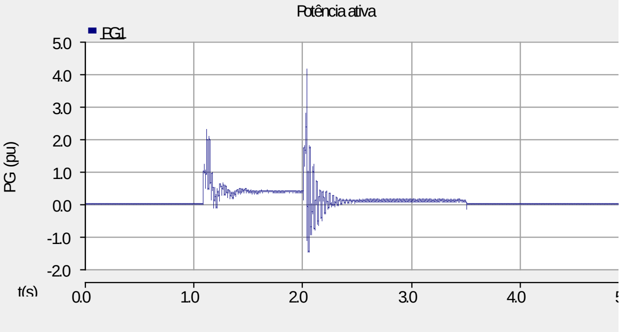


Fig. 11 – Active power injected by 1 generator unit during energization with three-phase fault at worst location – Pre switching voltage: 0.9 pu – Without pre-insertion resistor.

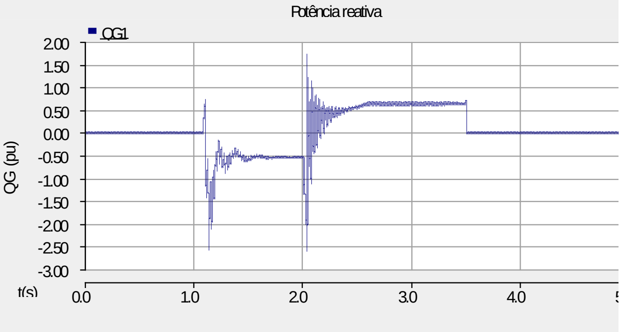


Fig. 12 – Reative power injected by 1 generator unit during energization with three-phase fault at worst location – Pre switching voltage: 0.9 pu – Without pre-insertion resistor.

protecting the generator. During the transient the current in the generator will reach 3.0 pu, reducing promptly to 0.7 pu. After the transient the machine injects 0.1 pu active power and 0.60 pu reactive power, as presented in Figs 11 and 12.

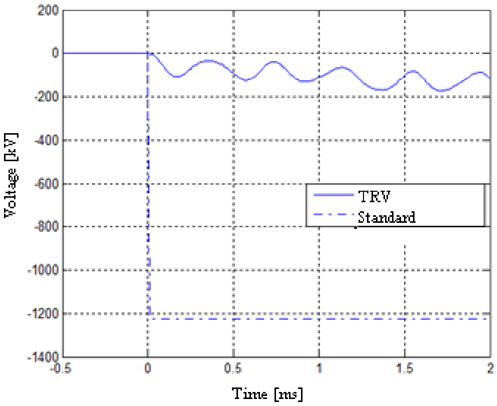


Fig. 13 – TRV of pole A during AC-Link no-load tripping after energization without fault.

E. Line tripping without faults

The opening of no-load AC-Link results in very low capacitive current and the voltage between the breaker poles is not severe and attenuates very fast, as presented in Fig. 13. The results showed that it is possible to open the AC-Link using the existing CB at Serra da Mesa substation (SE). The capacitive current through CB poles and the voltage across its terminals are much lower than its capability.

F. Line tripping with faults

The simulations consisted of energization and subsequent tripping considering terminal fault, short-line fault and remote fault. The faults analyzed were SLF and 3LF. For remote faults the fault location was varied in order to verify the behavior in critical regions. As there is no standard for such a long trunk tripping, simulations were performed comparing the AC-Link with the line for which the CB was designed for terminal and short-line faults. The actual line is 256 km long with shunt compensation in both terminals.

It was observed that:

- The terminal fault current is similar to the one observed for shorter lines even when shunt compensated, as presented in Fig. 14;
- The short-line-fault for AC-Link is less severe than for similar lines of hundreds of kilometers, as in the latter the inductance of the shunt compensation will produce higher TRV (Fig. 15);
- The highest current to be interrupted is not defined by terminal fault, but rather by three-phase fault in specific location which varies with the short circuit power (Ssc) of the terminal network. These locations can be from 60 to 85 % of the line length for low and high Ssc, respectively, measured from the circuit breaker;
- The voltages at the circuit breaker contacts for remote 3LF faults are not severe when RID mitigation procedure is applied, as presented in Fig 16;
- The TRV produced by remote SLF are not severe.

IV. CONCLUSIONS

In the present paper electromagnetic results concerning an energization of an AC-Link trunk formed by existing 500 kV

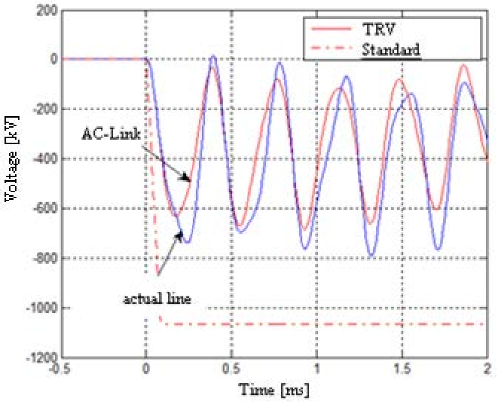


Fig. 14 – TRV across pole A during AC-Link tripping after energization under SLF terminal fault.

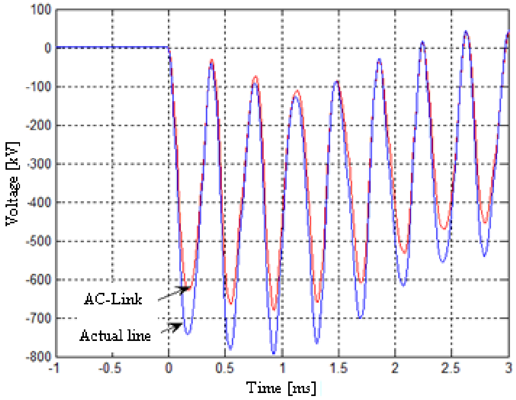
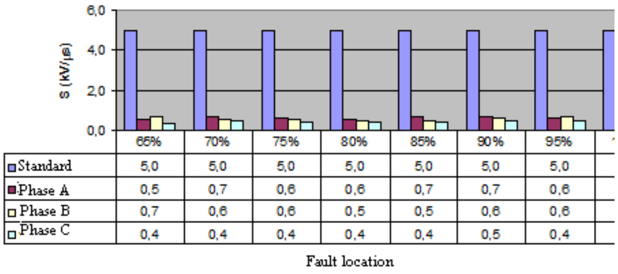


Fig. 15 – TRV across pole A during AC-Link tripping after energization under 2-km SLF at phase A (last pole to open).



	65%	70%	75%	80%	85%	90%	95%
Standard	5,0	5,0	5,0	5,0	5,0	5,0	5,0
Phase A	0,5	0,7	0,6	0,6	0,7	0,7	0,6
Phase B	0,7	0,6	0,6	0,5	0,5	0,6	0,6
Phase C	0,4	0,4	0,4	0,4	0,4	0,5	0,4

Fig. 16 – TRV rate of rise for critical region for remote 3LF.

lines are presented.

The results showed that it is possible to perform the experiment keeping the surge arresters at each line section terminal without affecting the AC-Link behavior. These arresters will not operate during the energization test. That measure will reduce drastically the experiment setup time and the system restoration time to Brazilian system.

The use of pre-insertion resistor to mitigate overvoltages would be useful if the insertion time were changed to 20 ms. However, as this is not possible, the resistor will be connected for 8 ms, what will not damage the device, but will not benefit the AC-Link.

The use of Reduced Insulation Distance (RID) at a tower near Imperatriz substation (1306 km) will mitigate the overvoltages that are produced when a three-phase fault occurs in a specific region (65 to 95 % of Link length measured from SE). This method is adequate for the energization maneuver but is not a straightforward solution to be used during normal operation.

With RID the 3LF is not a sever condition for the AC-Link energization. The SLF does not produce high overvoltages, but the energy absorbed by the arresters at the remote end can become excessive if protection does not operate as designed [9]. In that case an additional arrester or a higher thermal capacity arrester may be needed.

Regarding the generator units, the requirements for normal operation and operation under faults did not result in special requirements, and the actual machine can cope with the experiment without damaging or reducing its life-time.

The actual circuit-breaker designed for a highly shunt compensated 256-km long line was capable of opening the no-load AC-Link and also tripping the AC-Link under SLF and 3LF (terminal, short-line and remote). Even for the critical region for SLF and 3LF the CB suffered no special stress.

It can be stated that the AC-Link energization test can be implemented in the analyzed system without impacting the equipment involved (specifically generator unit, transformer, circuit-breaker, line surge arresters and line structure). There will be no damage to the devices involved and their life-time will not be reduced due to the stresses imposed by the experiment.

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

In [10, 12] some results regarding line protection are presented. Ongoing research on Single-Phase Auto Reclosing will be presented in a near future. As the AC Link cost is attractive for very long transmission, proper technical solution can be developed if necessary to solve specific needs.

V. ACKNOWLEDGMENT

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VI. REFERENCES

[1] Hubert, F. J.; Gent, M. R.; , "Half-Wavelength Power Transmission Lines," *Power Apparatus and Systems, IEEE Transactions on* , vol.84, no.10, pp.965-974, Oct. 1965.

[2] PrabhakAra, F.S.; Parthasarathy, K.; Rao, H.N.R.; , "Analysis of Natural Half-Wave-Length Power Transmission Lines," *Power Apparatus and Systems, IEEE Transactions on* , vol. PAS-88, no.12, pp.1787-1794, Dec. 1969.

[3] Gatta, F.M.; Iliceto, F.; , "Analysis of some operation problems of half-wave length power transmission lines," *AFRICON '92 Proceedings., 3rd AFRICON Conference* , vol., no., pp.59-64, 22-24 Sep 1992.

[4] Portela, C. - Some Aspects of Very Long Lines Switching - CIGRE SC 13 Colloquium 1995, 12 p., Florianópolis, Brazil, 1995.

[5] J. L. Alqueres and J. C. Praca, "The Brazilian power system and the challenge of the Amazon transmission," in *Proc. 1991 IEEE Power Engineering Society Transmission and Distribution Conf.*, pp. 315-320.

[6] Tavares, M.C.; Portela, C.M.; “Proposition of a Half-Wave Length Energization Case Test”; *International Conference on Power Systems Transients (IPST’09)* Kyoto, Japan, 2009.

[7] Gomes, E.C.; Tavares, M.C.; "Analysis of the Energization Test of a Half-Wavelength AC-Link Composed of Similar Transmission Lines" *Power and Energy Engineering Conference (APPEEC), 2011 Asia-Pacific* , vol., no., pp.1-5, 25-28 March 2011.

[8] C. Portela, J. Silva, M. Alvim, “Non-Conventional AC Solutions Adequate for Very Long Distance Transmission - An Alternative for the Amazon Transmission System”, *Proc. 2007 IEC/CIGRE UHV Symposium Beijing*, article 2-2-5, 29 p., Beijing, China, 2007.

[9] Portela, C. M., Tavares, M. C., Pissolato Filho, J., Gertrudes, J. B., “Earth Conductivity and Permittivity Data Measurements - Influence in Transmission Line Transient Performance”, *Electric Power Systems Research*. Vol 76, No 11, p 907-915, Jul. 2006.

[10] Gomes, E.C.; Tavares, M.C.; Floriano, C. "Using conventional protection for line-to-ground fault at AC-Link”, *International Conference on Power Systems Transients, 2013 IPST*.

[11] Gertrudes, J. B., Gomes, E. C., Tavares, M. C., “Circuit breaker TRV on AC-Link trunk with a little more than half-wavelength”, *IPST 2013*.

[12] Fabián, R.; Tavares, M.C., “Using of Conventional Relays for Protecting AC-Link from Three-Phase Faults”, *IPST 2013*.