Circuit Breaker TRV on a No-load AC Half-Wavelength Transmission Line

J. B. Gertrudes, E. C. Gomes, M. C. Tavares

***Abstract* -- In the present paper results regarding circuit-breaker Transient Recovery Voltage (TRV) for a no-load transmission line with a little more than half wavelength (HWL^+) tripping are presented. The results obtained with PSCAD simulations based on actual system data proposed for an energization test are discussed. The maneuvers analyzed are: line opening without faults; line opening with terminal faults; short-line faults (former 5 kilometers) and opening remote faults. It is shown that the no-load tripping of the HWL^+ line can be implemented with the conventional circuit-breaker without jeopardizing or causing reduction of life-time for the actual equipment.**

***Keywords*: TRV, Half wavelength Transmission, AC-Link, Very long transmission, Electromagnetic transients.**

I. INTRODUCTION

With the lack of resouces near large centers and growing energy demand, new technologies are needed for optimized transmission of large blocks of energy over long distances. Brazil is one of the countries with a major hydroelectric generation potential in the world. Currently, (2009 data) this form of energy represents 71.7% of the energy matrix, and the remainder is distributed between thermal (12.8%), renewable (7.4 %) and nuclear (1.9 %) power plants. Most of the hydraulic potential (66 %) is concentrated in the Northern region, far from large centers of higher energy consumption. The distances involved are in the range of 2500 to 3000 km [1]. New ultra high voltage (UHV) lines and high transmission capacity must be built, increasing even further the existing interconnected system [2].

One of the promising alternatives being studied is the AC transmission lines with a little more than half wavelength (HWL^+), here called AC-Link for being a point-to-point transmission. This type of solution, extensively studied in the 60s and 90s, has some interesting properties in terms of cost (for the absence of intermediate substations and reactive compensation, both series and shunt) and operational behavior [3 - 5]. It should be clarified that the choice of a trunk with exactly half wavelength is not a convenient choice [6, 7].

Recent studies have shown that the AC-Link cost is comparable or even lower than the HVDC transmission, mainly due to the cost of converter stations with filters banks compared to no intermediate substations and no reactive compensation scheme for AC-Link [8, 9]. The differences observed in favor of the AC-Link motivated recent research and optimization of this transmission trunk aiming at its use in forthcoming transmission systems [8], [10]. It is also important to attend small demand of energy in the vicinity of these huge trunks as a way to promote socioeconomic development and social inclusion. In this context, technologies that enable low power drainage for small loads services [11], such as the AC-Link, take advantage over strictly point-to-point transmission technology [12].

As there is not an AC-Link in operation in the world, Brazilian Electrical Energy Agency (ANEEL) has proposed the R&D strategic project call 004/2008 "*Energization test of a transmission line with a little more than half-wavelength*" [13]. This project consists of energizing an AC-Link test trunk composed of three Brazilian 500 kV interconnection trunks of lines with similar electrical characteristics, that when put together form a link of 2600 km, what corresponds to a little more than half wavelength at 60 Hz.

The system that will form the AC-Link test will be composed of trunks North-South I (NS-1), North-South II (NS-2) and part of the interconnection Northeast-Southeast (NE-SE). The single line diagram of the AC-Link is presented in Figure 1. The measurements results made during the test will be compared with simulations obtained with PSCAD and ATP, and will serve as a type of AC-Link prototype. With these results the AC-Link will be studied as one of the possible alternative for the forthcoming huge transmission trunks.

The present test authorization has been postponed and is still being evaluated by Brazilian ISO as during the experiment the National grid will operate almost disconnected (North-Northeast grid almost separated from the remainder of Brazilian grid).

In the present paper the transient recovery voltage requirements imposed on the circuit breaker (CB) of Serra da Mesa (sending end substation - SE) during the AC-Link energization maneuver are presented. This CB is current in operation and was designed for a 256-km highly compensated transmission line. As the AC-Link test requirements will be different from the equipment specification it was necessary to study the energization test conditions considering the CB tripping the no-load 2600-km trunk considering "no fault" and the fault ocurrence conditions during the test. The main results are presented in the following sections.

Financial support from the agencies: FAPESP, CNPq and CAPES.

J. B. Gertrudes is with State University of Feira de Santana, Department of Technology, Av. Transnordestina S/N, M3, Feira de Santana City, BA, Brazil (corresponding author: jbosco@ecomp.uefs.br)

M.C. Tavares and E.C. Gomes are with the University of Campinas, Brazil (cristina@dsce.fee.unicamp.br, elson.gomes86@gmail.com).

Paper submitted to the International Conference on Power Systems Transients (IPST2013) in Vancouver, Canada, July 18-20, 2013.

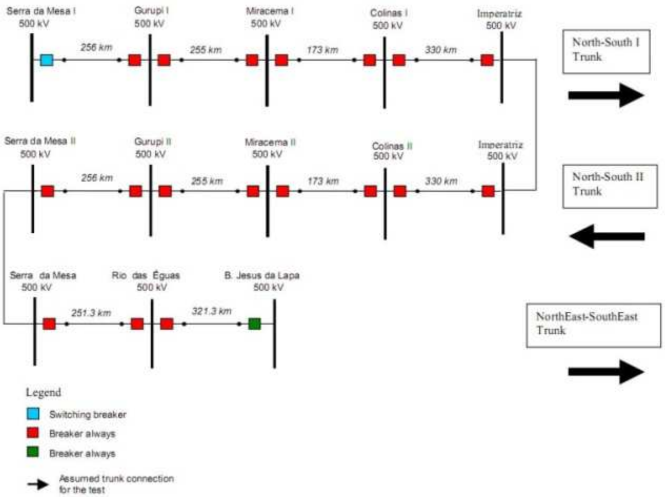

Figure 1 - Single line diagram of AC-Link Test circuit

II. METHODOLOGY

The results presented in this paper were obtained from the actual data of the link components presented at [13, 14], for the following specific test conditions:

- Pre-operation voltage of 1.1 p.u (550 kV) on the transformer busbar in SE;
- Stray capacitance of the transformer bushing in SE, the circuit breaker upstream, 6 nF;
- Stray capacitance of the capacitive divider, downstream of the circuit breaker, of 8 nF;
- AC-Link Test energizing with one generator unit of 492 MVA.

A TRV study involves high frequency oscillation and consequently requires more details in the modeling system [15]. The results are obtained considering the CB without the arc modeling. The TRV peaks with the arc presence should be lower and the results presented here should be considered conservative [16, 17].

The CB characteristics of Serra da Mesa (SM) substation are presented in Table I. In order to establish TRV parameters it was considered the standard NBR IEC 7118/1994 to which the CB is bounded [18]. The CB specifications are compared with TRV obtained in the simulations [19]. An additional routine was developed to trace the TRV envelope as well as the identification of TRV parameters obtained in PSCAD simulations.

For terminal faults analyzis there were considered single-phase faults (SLG), three-phase grounded fault (3LG) and isolated three-phase fault (3LI).

In simulations of short-line faults there were considered SLG faults applied on the former 5 kilometers of the line. The opening sequence of the CB poles was coordinated so that the last pole interrupted the fault current - a situation that generates the highest rizing rates.

In the simulations of short-line fault and terminal faults the time step used was 1 µs. In order to proper evaluate the CB performance the results obtained for the AC-Link trip maneuver were compared with the ones for the actual transmission line between Serra da Mesa and Gurupi (SM-GU), represented in no-load condition with all its compensation on service. As the CB is designed to meet the latter operation, the results were used as a guide. It was assumed that if the AC-Link requiments were less severe than those obtained considering the SM-GU line then the circuit breaker would be capable to trip the AC-Link without damage or reduction life-time.

In simulations of remote fault there were considered single-phase and three-phase faults (grounded and isolated). The fault was represented at increments of 10% of the total length of the Link (from SE) in order to search for highest stresses. The time step used for remote faults was 10 µs.

In all simulations it was considered that the fault was established prior energization. There were monitored the CB pre-operation conditions, the TRV parameters established on CB terminals (E_1- first reference voltage; U_c - peak value of the TRV; S - rising rate) and the voltage along the AC-Link.

TABLE I
CHARACTERISTICS OF SERRA DA MESA CIRCUIT BREAKER [16]

1. Nominal voltage (kV, rms)	550
2. System characteristics	
Nominal voltage (kV, rms)	500
Maximal operating voltage (kV, rms)	550
3.Nominal frequency (Hz)	60
4. Rated current (A, rms)	3150
5. Nominal interruption capacity in short-circuit	
Periodic component value (kA, rms)	40
Percentage of the non-periodic component (1.5) of the failure beginning and X/R = 50	83 (1.5)
6. Nominal interruption period (from 0% to 100% of the Nominal interruption in short-circuit capacity) in cycles	2
7. Ability to establish nominal in short-circuit (kA, peak)	110
8. Nominal duration of short-circuit current (s)	1
9. Short-duration nominal withstand current (kA rms)	40
10. Peak value rated withstand current (kA peak)	110
11. Nominal characteristics of isolation	
11.1 Nominal characteristics of isolation	
Closed circuit breaker (kV, peak)	1675
Opened circuit breaker (kV, peak)	1675
Opened circuit breaker, 60 Hz voltage applied to the opposite terminal (kV, peak)	315
11.2 Nominal impulse withstand voltage of switchgear	
Closed circuit breaker (kV, rms)	1300
Opened circuit breaker (kV, peak)	1100
11.3 Nominal frequency withstand to industrial voltage, for 1 minute	
Closed circuit breaker (kV, rms)	740
Opened circuit breaker (kV, peak)	830
11.4 Minimum distance of flowage (mm) (20 mm/kV)	**11000**
11.5 Closing or pre-insertion resistor (*)	
Resistor value (Ω)	400
Insertion period (s)	6
12. Technical standard	NBR 7118/(1994)

III. TRV AT SERRA DA MESA CIRCUIT BREAKER

A. *No-load AC-Link tripping without fault*

The maximum capacitive current interrupted by the CB during no-load AC-Link tripping without faults was 350.3 A_{rms} (495.4 A_{peak}), below the 710 A_{rms} standard of voltage class of 550 kV CB. The time step used was 10 µs.

The maximum overvoltage established at CB terminals is 487.1 kVp. The waveform obtained is shown in Figure 2.

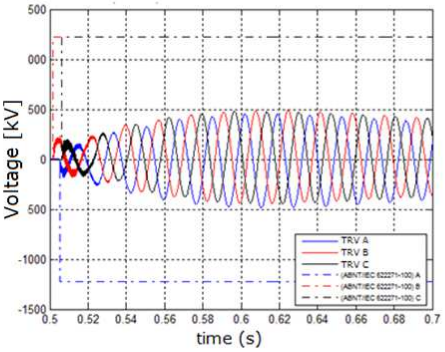

Figure 2 – Voltage at CB poles for no-load AC-Link tripping

The NBR/IEC 7118 standard does not establish limits for maximum TRV for line tripping. For comparison it was considered the value established by the current standard (ABNT/IEC 622271-100) of 1226 kV_p [19].

The results show that the existent conventional circuit breaker in Serra da Mesa is capable of tripping the no-load AC-Link without damaging or reducing its life-time. The TRV waveform is shown in Figure 3.

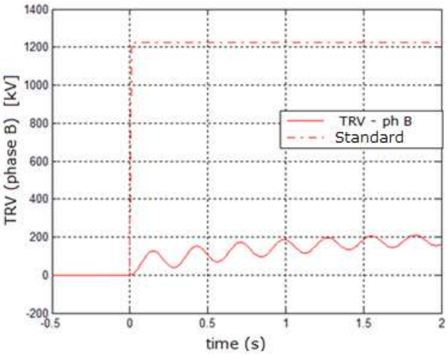

Figure 3 - TRV established at the terminals of the circuit breaker (No-load AC-Link tripping without fault).

B. *AC-Link opening with terminal faults*

The energization test can be performed in a few minutes. However, all system components connected at the AC-link will be subjected to the new transient conditions. Hence, fault conditions were analyzed namely terminal faults, short-line faults and remote faults along the trunk for the purpose of finding the most severe conditions for the CB.

The TRV results were compared with the requirements for the actual operation condition, when the existent CB had to trip the no-load highly compensated SM-GU line (136 MVAr at SM and 200 MVAr at GU). If the results for the AC-Link were lower than for SM-GU the CB would be capable of tripping the no-load AC-Link.

Namely for terminal faults the maximum value of interrupted current (AC-Link) is 1.51 kA_{rms} (Table II), which corresponds to 5.3 % of nominal capacity of CB interruption on short-circuit.

TABLE II
CURRENT INTERRUPTED (KA_{RMS}) FOR TERMINAL FAULTS

Type of fault	AC-Link	Actual line (SM-GU)
SLG	1.51	1.80
3LG	1.46	1.69
3LI	1.17	1.35

In Figures 4 to 6 the most severe cases for terminal faults are presented.

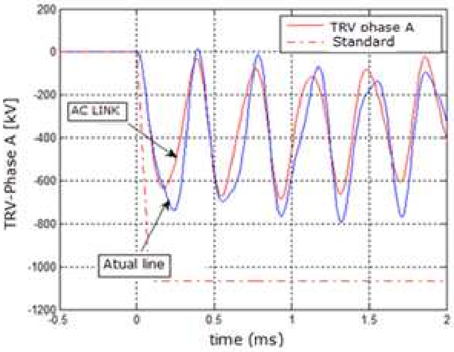

Figure 4 - TRV for a single-phase terminal fault.

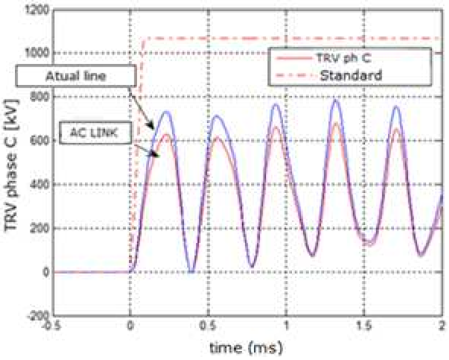

Figure 5 - TRV for three-phase grounded terminal fault.

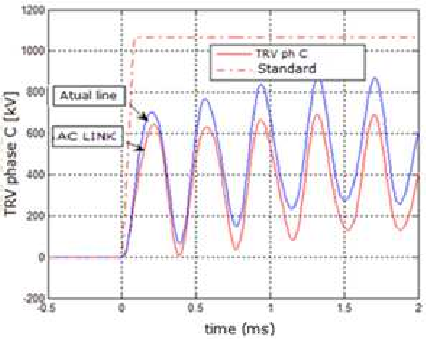

Figure 6 - TRV for three-phase isolated terminal fault.

Table III presents a summary of TRV requirements for terminal faults. From the results it can be seen that the CB can trip the no-load AC-Link with terminal faults.

TABLE III
TRV SUMMARY FOR TERMINAL FAULTS.

Type of fault	E1(kV)		Uc (kV)		S (kV/µs)	
	AC-Link	Atual line	AC-Link	Atual line	AC-Link	Atual line
SLG	633.63	739.12	66.03	793.14	3.73	3.08
3LG	664.34	771.25	678.90	787.30	4.15	5.14
3LI	643.40	703.68	693.70	874.54	2.92	3.52

C. AC-Link tripping with short-line faults

In this case, single-phase faults were applied in the first five kilometers of the AC-Link Test, always with the last pole to open the fault current. The maximum CB current values and TRV requirements are shown in Table IV and V, respectively.

TABLE IV
INTERRUPTED CURRENT (KA_{RMS}) FOR SHORT-LINE FAULTS

Fault location	AC-Link	SM-GU
2 km	1.50	1.73
3 km	1.48	1.73
4 km	1.48	1.72
5 km	1.47	1.71

TABLE V
TRV REQUIREMENTS FOR SHORT-LINE FAULTS

Fault location	E1(kV)		Uc(kV)		S (kV/µs)	
	AC-Link	SMGU	AC-Link	SMGU	AC-Link	SMGU
2 km	628.55	743.11	680.18	793.16	3.49	4.13
3 km	624.08	735.07	676.76	790.61	3.47	4.08
4 km	619.96	739.31	673.03	789.51	3.44	4.11
5 km	612.49	733.38	671.02	787.46	3.22	4.08

It can be observed that the TRV requirements for no-load AC-Link under short-line faults are lower than for SM-GU. It can be said that the existent CB is capable of tripping the no-load AC-Link for this kind of fault.

In figures 7 to 10 the TRV waveforms for short-line faults are presented.

D. AC-Link tripping with remote faults

For analysis of remote faults three types of faults were considered : SLG, 3LG and 3LI. The fault location was varied in steps of 10 % of the AC-Link length.

In Figures 11 to 13 are presented the CB current profiles considering the fault location. The maximum value (6.6 kA_p) was obtained for the three-phase isolated fault (Figure 13) corresponding to 17 % of the CB nominal interruption capacity. The CB standard curve used was the one immediately above this value, namely the 30 %.

It can be observed that the CB current decreases as the fault moves towards remote end, having its lowest value near the middle of the line. Afterwards the CB current starts to increase, being the critical region diferent for SLG and three-phase faults. For SLG the critical region is between 75 and 95 % on the AC-Link length while for three-phase faults the critical region is between 65 and 85 %.

This is a characteristic of the isolated AC-Link, where these regions corresponds to multiples of 1/4 wavelength of zero sequence component and positive sequence component, respectively for SLG fault and three-phase faults. When the fault occurs in these regions a quasi-ressonance condition is established and both current or voltage can reach high values.

It is important to note that these high CB current values are close to the terminal fault for SLG, but are much higher than the terminal fault current for three-phase faults. The current for SLG attenuates more due to the high zero sequence resistive value while the attenuation is rather small for positive sequence.

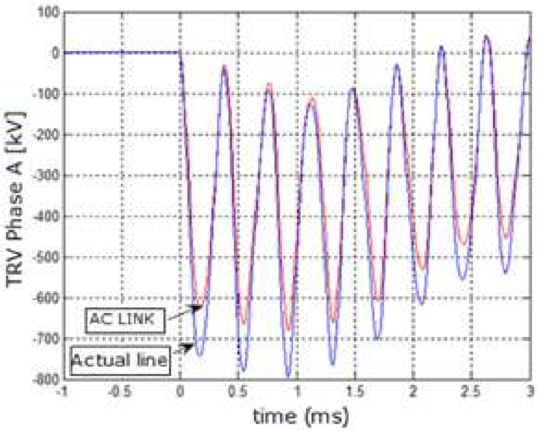

Figure 7 - TRV for 2 kilometer fault (SLG) - last pole opens the fault.

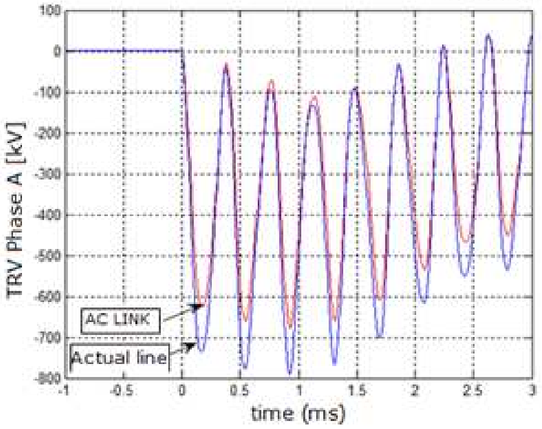

Figure 8 - TRV for 3 kilometer fault (SLG) - last pole opens the fault.

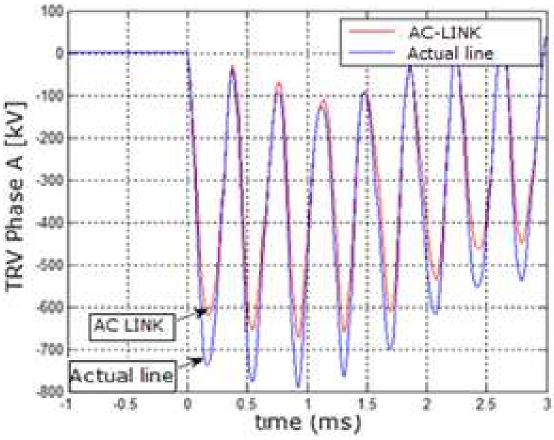

Figure 9 - TRV for 4 kilometer fault (SLG) - last pole opens the fault.

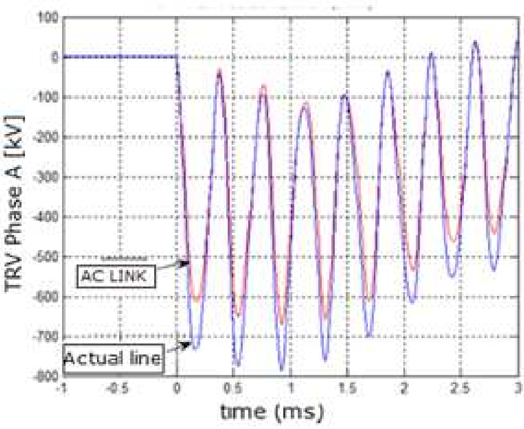

Figure 10 - TRV for 5 kilometer fault (SLG) - last pole opens the fault.

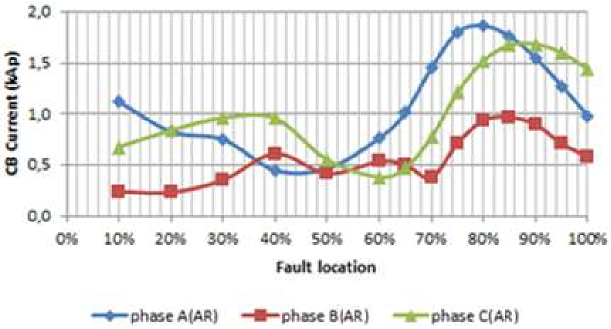

Figure 11 - CB current profile for SLG remote fault.

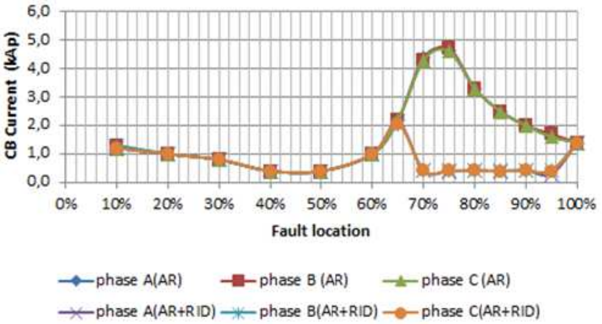

Figure 12 - CB current profile for 3LG remote fault.

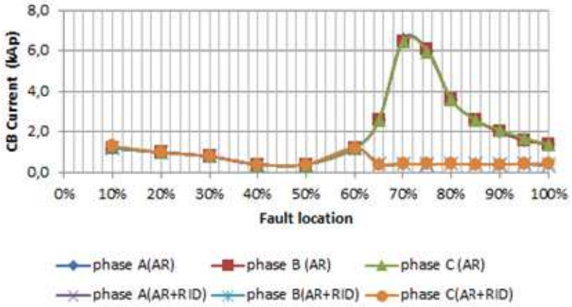

Figure 13 - CB current profile for 3LI fault.

Profiles of the main TRV parameters for the SLG remote faults are shown in Figures 14 to 16. It can be seen that the existent CB is capable of opening the no-load AC-Link under SLG remote faults.

The energy to be dissipated by surge arresters located at remote end substation is high when the SLG fault occurs in the critical region. The surge arrester is a class 420 kV with thermal capacity of 5.46 MJ. A protection study was made in RTDS [20] with the existent relay and the line was tripped in a very short time, resulting in low energy comsumption at this arrester. A high thermal capacity arrester could be also used during the energization test.

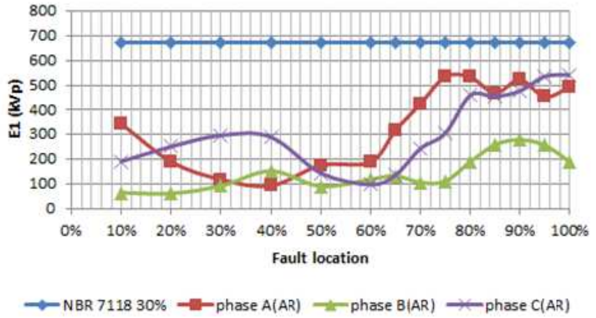

Figure 14 - Profile of the first reference voltage to SLG remote fault.

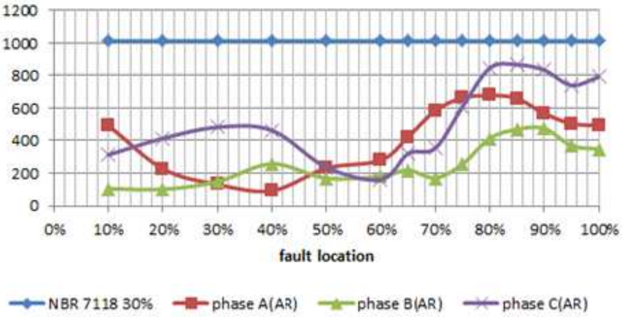

Figure 15 - Profile of the TRV peak value to SLG remote fault.

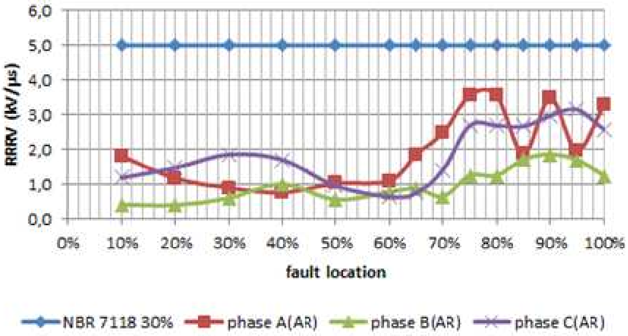

Figure 16 - Profile of the TRV growth rate peak to SLG remote fault.

It was found that when the three-phase faults occur in the critical region there are higher overvoltage along the AC-Link on the busbars before the fault. These overvoltage can be very high, and it is a common error the assumption that such high voltage will be established along the line. When the voltage rises to very high values (above 3.0 pu) flashovers will be produced along the line, removing the line from this quasi-ressonance condition.

A mitigation method to protect the line during three-phase faults in this critical condition is to provoke the flashover in a defined location. One way to suppress these overvoltages effectively, with low cost and fast actuation, is by weakening the insulation distance on a pre-identified location. Thus, when overvoltages start to increase a flashover will occur in the selected location for a defined voltage range, mitigating the overvoltages.

This mitigation method proposed was named RID (Reduced Insulation Distance) and consists of removing some insulators from the insulator string at a tower near 40 % of the

AC-Link (measuring from sending end), specifically this corresponds to Imperatriz substation (IPZ). At this location a flashover will occur for voltages above 1.60 pu (phase to ground).

When a three-phase fault occurs in the critical region the voltages along the AC-Link will increase and at IPZ the RID will suffer flashover when the voltage reaches 1.60 pu, or better, a 3LG fault. When a three-phase fault occurs at this location it does not cause significant overvoltage along the AC-Link and the CB currents are not severe.

It has been observed that the maximum overvoltage during energization maneuver without fault at IPZ is lower than 1.20 pu (Figure 17). This result was obtained through statistical simulation case with 500 shots. This means that the insulator string at IPZ can be reduced, if necessary, during the AC-Link Test energization operation, without compromising the test.

With the weakening of the insulation distance in a tower near to IPZ the three-phase faults in the critical region will produce the occurrence of 3LG fault at RID (IPZ). The RID was modeled as an ideal circuit breaker controlled by voltage closing for values greater than 1.6 pu. It promptly removes the AC-Link from the quasi-ressonance condition. This result can be seen by analyzing the graphics of TRV requirements for 3LI fault (the worst fault condition) in Figs 18 to 20.

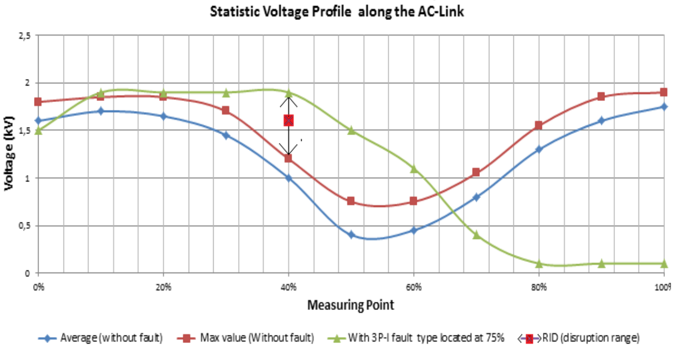

Figure 17 - Overvoltage profiles along the AC-Link energization without defect and under 3LI fault at 75 % with RID at IPZ substation

The RID actually shifts the fault site for IPZ substation where the three-phase fault is not severe.

In Figs. 12 and 13 CB current for three-phase remote faults in the AC-Link are presented for both considering or not the use of RID. It can be seen that RID wil reduce drastically the CB current for the occurrence of fault in the critical region. Even more, RID only operates for three-phase faults at this region.

When RID is implemented the CB is capable of dealing properly with three-phase faults, as can be seen in Figs 18 to 20.

IV. CONCLUSION

In this paper the main results of TRV study for tripping the no-load AC-Link are presented.

From the results obtained it can be concluded that the circuit breaker existent at Serra da Mesa substation, that is a conventional CB designed for a regular compensated 256-km long line, is capable of tripping the no-load AC-Link.

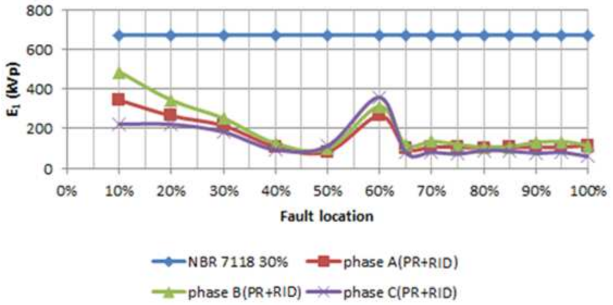

Figure 18 - Profile of the first reference voltage for 3LI fault.

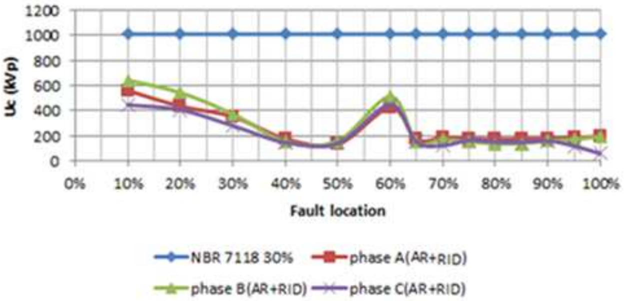

Figure 19 - Profile of the peak value of TRV for 3LI fault.

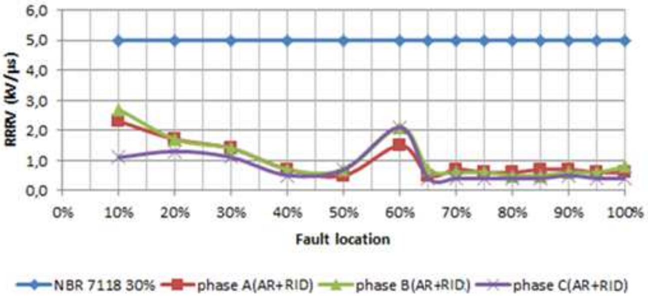

Figure 20 - Profile of the TRV growth rate for 3LI fault.

The studies were performed considering the line without fault or the occurrence of SLG, 3LG and 3LI, eventhough the energization experiment will have a short duration. The faults considered were: terminal, short-line and remote.

For terminal and short-line faults it was observed that the CB requirements are smaller than those occurring during the actual CB operation, for which the CB was designed. It is concluded then that the CB can trip the no-load AC-Link under terminal and short-line faults.

The behavior of the isolated AC-Link for remote faults is different from the few hundreds of kilometers long line, as quasi-ressonance conditions occurs when the fault is located in multiples of ¼ wavelength of positive and zero sequence component. In these regions, specifically between 75 and 95 % for SLG and 65 to 85 % for three-phase faults high CB currents and overvoltages along the AC-Link will arise.

The existent CB is capable of tripping the no-load AC-Link with SLG fault in any location. However, for the SLG faults occurring in the critical region a fast protection response is necessary to prevent high energy consumption at the receiving end arrester. Tests performed with actual relay in RTDS [20] showed that the existent relay operates fast enough in order to prevent any damage to the arresters.

In order to reduce the high overvoltage produced by three-phase faults in the critical region a mitigation procedure was proposed. It consists of reducing the insulation distance (RID) of a tower located at 40 % length of the AC-Link (at IPZ substation). A flashover at RID will be occur when the phase to ground voltage reaches 1.60 pu, what **only** occurs when a three-phase fault is located in the critical region.

RID does not operate during energization without fault or when tripping the no-load AC-Link without fault or with SLG faults. It will only operate when 3LG or 3LI occurs at the critical region.

With RID the existent CB is capable of tripping the AC-Link under 3LG or 3LI.

It can, therefore, be stated that the existent conventional circuit breaker is capable of tripping the no-load AC-Link during the enrgization test. There will not be damage to the circuit breaker or reduction of its useful life, even if there is any fault during the test at any site of the AC-Link Test.

The RID mitigation procedure is adequate for the energization test, but extensive on-going studies are being performed in order to verify if this method is also applicable to reduce overvoltages for three-phase faults during AC-Link normal operation.

V. ACKNOWLEDGEMENT

The authors would like to thank the engineers C. Machado Jr. (ELETRONORTE), E. Carvalho Jr. (ENTE) and M. Maia (CHESF) that have given important contributions to the study.

The results presented in this paper are partial results from the project supported by ELETROBRAS/ELETRONORTE, ELETROBRAS/CHESF and ENTE as part of ANEEL (Brazilian Electrical Energy Regulatory Agency) strategic project 2008 (proc. 4500072477) "*Energization Test of Transmission Line with a Little More Than a Wavelength*". The project was coordinated by UNICAMP with the participation of UFBA and UEFS.

VI. REFERENCES

[1] Brazilian Electrical Agency (ANEEL), "Atlas of Electrical Energy in Brazil", 3th. Edition, 2010, available on [www.aneel.gov.br].

[2] Brazilian Electrical Planning Agency, "Ten year Expansion Planning 2009-2019", Published in 2011, pg. 21, available on [www.epe.gov.br].

[3] F. J. Hubert, M. R. Gent, "Half wavelength Power Transmission Lines". *IEEE Transac. on PAS*, vol 84, no. 10, pp. 966-973, Oct 1965.

[4] F.S. Prabhakara, K. Parthasarathy, H. N. Ramachandra Rao, "Analysis of Natural Half waveLength Power Transmission Lines". *Trans. On PAS*, vol. 88, no. 12, pp. 1787-1794, Dec 1969.

[5] F. M. Gatta, F. Iliceto, "Analysis of some operation problems of half wave length power transmission lines". *IEEE AFRICON'92* Proc.Conference, Sept. 1992.

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

[7] C. Portela, M. Aredes, "Very Long Distances Transmission", Proceedings 2003 International Conference on AC Power Delivery on at long and Very Long Distances, Russia, Sept. 2003.

[8] C. Portela, J. Silva, M. Alvim, "Non-Conventional AC Solutions Adequate for Very Long AC Transmission- An Alternative for Amazon Transmission" - IEC-CIGRE UHV Symposium, China, Jul. 2007.

[9] Y. Song; B. Fan; Y. Bai; X. Qin; Z. Zhang, "Reliability and economic analysis of UHV Half-Wave-length AC Transmission", *IEEE International Conference on Power System Technology (POWERCON), 2012*, pp.1,6, Oct. 30-Nov. 2 2012, doi: 10.1109/PowerCon.2012.6401413, 2012.

[10] R. Dias, A. C. S. de Lima, C. Portela, "Extra Long-Distance Bulk Power Transmission", *IEEE Transactions on Power Delivery*, Vol. 26, No. 3, July 2011.

[11] M. Aredes, R. Dias, "FACTS for Tapping and Power Flow Control in Half wavelength Transmission Lines", *IEEE Trans. on Industrial Electronics*, Vol. 59, No. 10, Oct. 2012.

[12] M. C. Tavares, R. T. Borges, "Attending Small Loads along a Half-Wavelength Transmission Line", *IEEE Electrical Power and Energy Conference (EPEC)*, Winnipeg, Canada, Oct. 2011.

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

[14] E. C. Gomes, M. C. Tavares, "Analysis of the Energization test of the 2600-km long AC-Link composed of similar transmissions lines", *EPEC*, Winnipeg, Canada, 2011.

[15] IEEE Fast Front Transients Task Force, "Modeling Guidelines for Fast Front Transients", *IEEE 1995 Winter Power Meeting*, Paper No. 95WM278-2 PWRD, 1995.

[16] A. D'Juz et al., "Electrical Power Systems Transients and Insulation Coordination", Book, FURNAS/UFF, 1987 (in Portuguese)

[17] L. C. Zanetta Jr. "Electromagnetic Transients in Power Systems", Book, 2003 (in Portuguese).

[18] J. Amon Filho et al., "Requirements TRV coming from the opening maneuver of the 500 kV Circuits Breakers in the trunk of the North-South interconnection", *SNPTEE Technical Article*, 1999 (in Portuguese).

[19] Brazilian Technical Standard "ABNT NBR IEC 62271-100" "High voltage equipment - Part 100: High Voltage Circuit Breakers Alternating Current", 2006.

[20] E. C. Gomes, M. C. Tavares, C. Floriano, "Using conventional protection for line-to-ground fault at AC-Link", *IPST 13*, Vancouver, Canada, July, 2013.