Proposition of a Half-Wave Length Energization Case Test

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***Abstract* -- In Brazil big blocks of energy will be transported through distances between 2500 and 3000 km to strong network nodes. Among the AC transmission systems alternatives being analyzed the half-wave length transmission seems to be the natural solution as the lengths involved are around a half-wave length of a 60 Hz frequency system, as the Brazilian one. As there is no half-wave transmission system in operation in the world, there is a major sense of caution in order to be the first to construct and use this new AC-link. In order to give some support a field test with a set of existing similar 500 kV lines that could be connected in series was proposed to simulate the AC-link behavior under some controlled switching. The main results of the proposed AC-link test simulated in PSCAD/EMTDC and ATP are presented.**

***Keywords*: Very long transmission systems, Half-wave length, electromagnetic transients, life-test.**

I. Introduction

In recent years several countries are experiencing the necessity of enlarging their systems aggregating large blocks of energy. When the new resources are located far away from load centers requiring very long distance transmission, the use of non-conventional alternatives may be more adequate.

In Brazil, 66 % of still not used hydroelectric resources are located in Amazon region, summing about 120 GW. The blocks of energy will be transported through distances between 2500 and 3000 km to strong network nodes in main consumption regions. Several transmission systems alternatives are being analyzed, from UHV AC to HVDC. Among the AC alternatives, the half-wave length plus (HWL+) transmission trunks with a little more than HWL (e.g.190 º) seems to be the natural solution, as the lengths involved are around a HWL of a 60 Hz frequency system, as the Brazilian one. This type of solution presents some interesting properties in what concerns cost and functional behavior, as had been extensively studied in 60's and 90's [1]-[3]. It must be clarified that a trunk with "exactly" HWL is not a convenient choice [4]-[6].

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A comparative cost analysis was performed between the HWL+ (AC-link) and two other alternatives, which are being analyzed by planning engineering. These alternatives are a DC-link formed by two bipoles and a hybrid system composed of a bipole and one conventional AC line heavily shunt and series compensated, with several intermediate substations. The AC-link has a cost 24 % lower than the DC-link and 37 % lower than the hybrid alternative. As the DC-link cost was estimated in official reports in the range of USD 3.5 billions, the cost difference between the alternatives fully justifies a serious study of the AC-link performance.

As there is no HWL transmission system in operation in the world, there is a major sense of caution in regard to be the first to construct and use this new AC-link solution. In order to give some support, a field test was proposed using elements of the existing power system to simulate an AC-link with a little more than HWL. It was identified a set of existing similar 500 kV lines that could be connected is series, forming a 2600 km long line, without series or shunt compensation and switched from one extremity, using only one circuit breaker from a power station. As the existing lines are series and shunt compensated, for the test, all shunt compensation must be disconnected, all series compensation must be short-circuited, all the line arresters must be removed except the ones at the trunk extremities and all circuit breakers connecting in series the presently used lines must be blocked in closed position.

The test condition to be executed consists of the energization of a 2600 km line, with no reactive compensation, using only one circuit breaker.

The proposed 2600 km test line was carefully simulated, in order to:

− Evaluate its behavior in permanent operation and in switching conditions.

− Have adequate information of the line behavior, in test conditions, before the test, for comparison with test results.

− Evaluate the "test line" behavior for several types of faults and several fault locations, and to define a very simple protection system that allows disconnecting the line with the only circuit breaker used in the test, for an eventual fault during the test.

Most of basic studies were done using programs developed for line studies, covering aspects that are not dealt with by most used programs. The proposed 2600 km test was also simulated in PSCAD/EMTDC and ATP.

The simulation results of the proposed 2600 km line test are presented in the following sections.

II. Brazilian Hydro Resource

A. Brazilian hydroelectric potential

Brazilian hydroelectric potential is 260 GW, of which only 28 % is being used (in 2003) to produce energy in large and medium size power plants. Eight large hydro basins compose the Brazilian hydraulic map. The North region (Amazonas River and Tocantins River basins) has a potential for hydro generation of 131.6 GW, 50.9 % of Brazilian potential, of which 120.6 GW are not yet used (63.6 % of not yet used hydroelectric resources), as shown in Table 1 and Fig. 1.

TABLE 1
BRAZILIAN HYDRO POTENTIAL AND INSTALLED POTENTIAL

Hydrographic basin	Existing Power (PE) (GW)	(%)	Installed Power (PI) (GW)	(%)	PI / PE [%]
Amazonas River	105.0	40.6	0.6	0.87	0.6
Tocantins River	26.6	10.3	10.4	15.07	39.1
Atlantic North/Northeast	3.1	1.2	0.3	0.43	9.7
São Francisco River	26.2	10.1	10.5	15.22	40.1
Atlantic East	14.6	5.6	2.6	3.77	17.8
Paraná River	60.9	23.5	39.2	56.81	64.4
Uruguai River	12.8	4.9	2.9	4.20	22.7
SouthEast Atlantic	9.4	3.6	2.5	3.62	26.6
Brazil	258.6	100.0	69.0	100.00	26.7

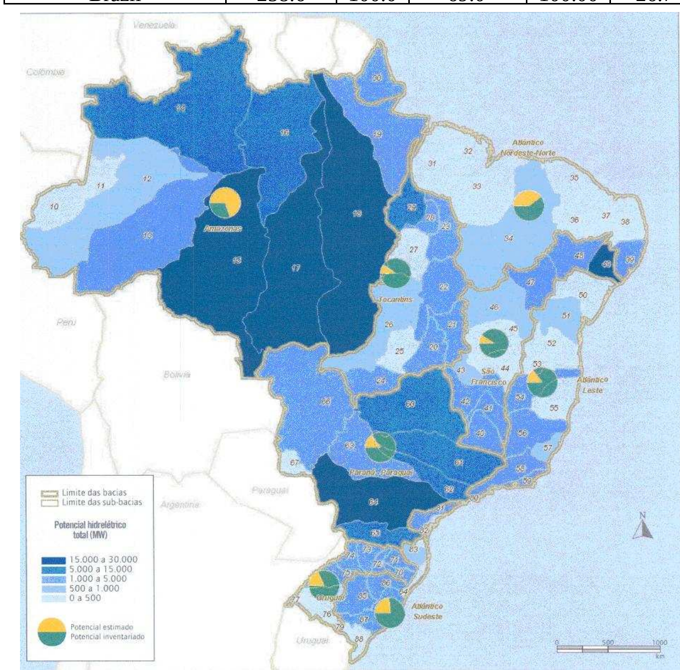

Fig. 1. Brazilian hydroelectric potential by hydrographic basin – green : evaluated; yellow : estimated.

B. Used Brazilian hydro resources

In Table 1 the installed potential and the estimated potential are presented. The ratio between these two potentials shows that Brazil has a great amount of non-explored resources, mainly in Amazon River Basin.

Amazon basin generating potential has not been used mainly because it is located very far from the main load centers. However, the country is growing towards the interior and beside that the resources near the loads are being exhausted, what will lead in the near future to the use of hydro resources in remote areas not much economically developed.

C. Hydro power plants in Brazil

Brazil has 96 GW installed and in the fore coming years new 27 GW will be installed. The majority of the installed hydro power plants are composed of large plants, being 23 hydro plants with capacity greater than 1 GW. This corresponds to 71.4 % of the installed capacity in Brazil, as presented in Fig. 2.

III. New Transmission System

Although there are others energetic resources in the energy matrix, the hydropower is still the most important in the expansion of Brazilian electric system. In Table 2 the largest fore coming hydro plants are summarized.

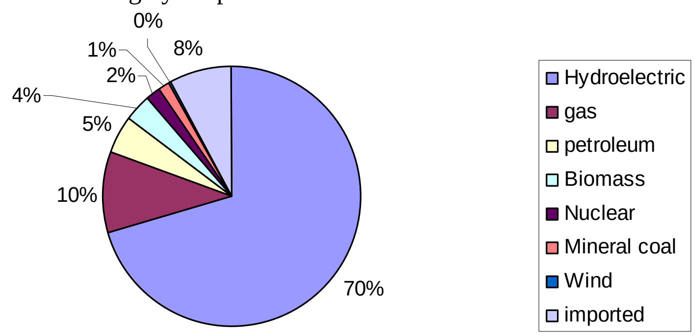

Fig. 2. Electric Brazilian matrix

TABLE 2
FORE COMING LARGEST HYDROELECTRIC PLANTS

Hydro Plant	River	Capacity [MW]	Date
Estreito	**Tocantins**	**1087**	**Sept-10**
Foz do Chapecó	**Uruguai**	**855**	**Sept-10**
Santo Antônio	**Madeira**	**3150**	**Jun-12**
Jirau	**Madeira**	**3300**	**Jan-13**
São Manuel	**Teles Pires**	**746**	**Jan-15**
Belo Monte	**Xingu**	**11.000**	**Oct-15**
Marabá	**Tocantins**	**1755**	**Jan-16**
Teles Pires	**Teles Pires**	**1820**	**Jan-16**
São Luiz Tapajós	**Tapajós**	**8381**	**Jan-16**
Serra Quebrada	**Tocantins**	**1328**	**Jan-17**

In order to quantify the distances involved in the electric system expansion from the Amazon Region, in Fig. 3 mean distances from the new plants in Amazon basin to the load centers in Southeast region and Northeast region are presented. These distances are much higher than the actual transmission lines in Brazil, even the interconnection trunks of 1000 km long. The new transmission trunks will interconnect generation centers to load centers, which are 2500 to 3000 km far from each other. These new trunks must be studied under a new perspective in order to take full profit of very long transmission and huge blocks of energy transmission.

In previous studies [1] - [3] the use of HWL transmission lines were thought for trunks with lower length, and in those cases the lines would be tuned for 190 º. These Brazilian lines will have half-wave length without the need of any additional device [7]. There will be few opportunities like the Brazilian one in the world to make use of this technology in such an economical advantage and therefore a big effort is being put up by engineers to overcome conservative policies of some planning sectors that insist in less or even non adequate solutions. It can be said that this is a unique opportunity that should be properly analyzed. Environmental impact should be minimized when analyzing the amount of energy produced.

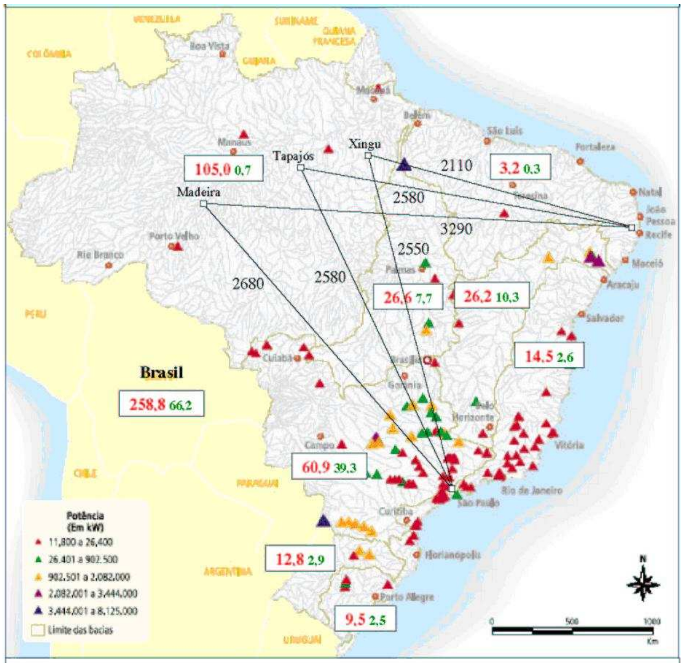

Fig. 3. Basic transmission distances from new Amazon plants and load centers – Distances in km; installed power and power capacity in GW

IV. Test Transmission System

In order to give some support to planning engineers a real test was proposed. It was identified a set of existing similar 500 kV lines that could be connected is series, forming a 2600 km long line, without series or shunt compensation and switched from one extremity, using only one circuit breaker, from a power station. The test line is composed of North-South (NS) interconnection trunk and part of North East-South East (NE-SE) interconnection trunk. The N-S interconnection is composed of 2 lines of 1014 km long, which together with part of NE-SE interconnection can sum up to 2601 km long. These are all 500 kV lines, but with slightly different towers. N-S interconnection is heavily shunt and series compensated and NE-SE trunk is also heavily shunt compensated. For the test, all shunt compensation must be disconnected, all series compensation must be short-circuited, all line arresters should be removed except those at the test line extremities, and all circuit breakers connecting in series the presently used lines must be blocked in closed position. So, the test condition applies to energization of a 2600 km line, with no reactive compensation, using only one circuit breaker.

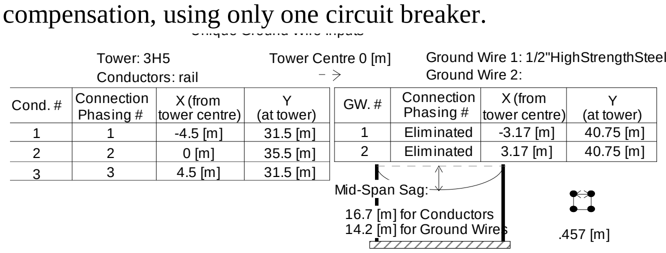

Fig. 4. N-S I towers data – phase conductor : rail

In fact, if this were a regular new transmission system no planning engineer would ask for a site-test, all the studies would be performed with the usual simulation tools. But in order to be on the safe side with regulatory agencies a real-life test was suggested.

The 500 kV lines characteristics that form the line test are summarized in Fig. 4 to Fig. 6. The soil resistivity was supposed to be 4000 Ω.m as these lines regions have very high soil resistivity.

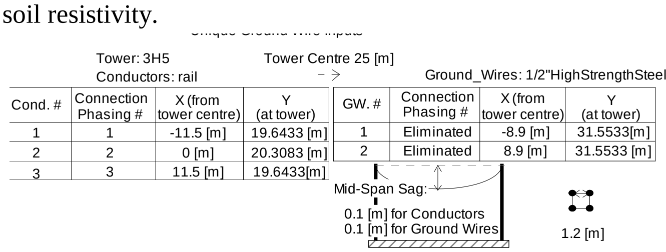

Fig. 5. N-S II towers data – phase conductor : rail

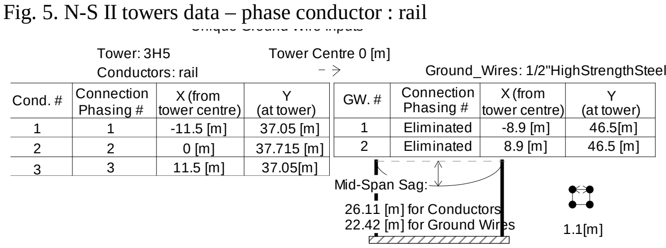

Fig. 6. NE-SE towers data – phase conductor : rail

The conductors' data are summarized in Table 3 to Table 4. In Table 5 to Table 7 the zero and positive sequence series impedance and shunt admittance per unit of length calculated at 60 Hz for each interconnection line are presented. These data were used in ATP statistical simulations as the lines were represented with distributed parameter model.

TABLE 3
CONDUCTOR DATA OF NS-I LINES

Conductor	Per unit. resistance [Ω/km]	External radius [m]	Internal radius [m]	μr
RAIL	0,0614	0,014795	0,0037	1
GW - EHS	3,51	0,00457	-	70
OPGW	0,405	0,00695	-	70

TABLE 4
CONDUCTOR DATA OF NS-II AND NE-SE LINES

Conductor	Per unit. Resistance [Ω/km]	External radius [m]	Internal radius [m]	μr
RAIL	0,0614	0,014795	0,0037	1
GW - EHS	3,51	0,00457	-	70

TABLE 5
PER UNIT SERIES AND SHUNT PARAMETERS CALCULATED AT 60 HZ – NS-I

Sequence	Per unit resistance [Ω/km]	Per unit inductive Reactance [Ω/km]	Per unit Susceptance [μS/km]
Zero	0,324303927	1,37639888	2,74171359
Positive	0,0198327539	0,266903723	6,08082036

TABLE 6
PER UNIT SERIES AND SHUNT PARAMETERS CALCULATED AT 60 HZ – NS-II

Sequence	Per unit resistance [Ω/km]	Per unit inductive Reactance [Ω/km]	Per unit Susceptance [μS/km]
Zero	0,355735418	1,42521984	3,58461397
Positive	0,0199493468	0,268508460	6,16648040

TABLE 7
PER UNIT SERIES AND SHUNT PARAMETERS CALCULATED AT 60 HZ – NE-SE

Sequence	Per unit resistance [Ω/km]	Per unit inductive Reactance [Ω/km]	Per unit Susceptance [μS/km]
Zero	0,357640199	1,42834687	3,52370352
Positive	0,0199706270	0,273449634	6,04576819

In Fig. 7 the single line diagram of the simulated circuit is presented. The locations for measurement are summarized in Table 8 in order to observe the voltage profile along the AC link.

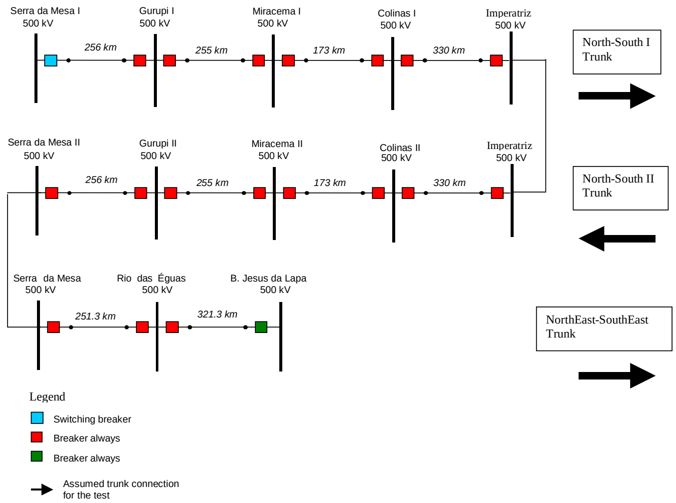

Fig. 7. AC-link 500 kV "test line" single phase diagram

TABLE 8
MEASURING LOCATION

Interconnection	Substation	km
NS I	Serra da Mesa	0
	Gurupi I	256
	Miracema I	511
	Colinas I	684
NS I – NS II	Imperatriz	1014
NS II	Colinas II	1344
	Miracema II	1517
	Gurupi II	1772
NS II – NE/SE	Serra da Mesa II	2028
NE/SE	Rio das Éguas	2279
	Bom Jesus da Lapa	2601

V. SIMULATION RESULTS

The proposed 2600 km test line was simulated with PSCAD/EMTDC and ATP. The AC link was energized from a weak network, specifically a generation unit (Serra da Mesa) with 3 generators of 472 MVA each.

As the NS interconnection trunks (NS I and NS II) are separated by 40 m, this distance among the trunks were represented and shall have some influence in the results. This would not be the case of the AC Link, but it was represented to reproduce the test line. The lines were supposed ideally transposed, but the transposition direction is also important as the coupling in the line test can be cancelled or enlarged.

The energization was simulated in PSCAD representing the frequency dependence of the longitudinal parameters (single shot); and with ATP to represent a statistical energization (500 shots), representing the line with distributed parameter model.

The results obtained with both simulators are coherent; the overvoltages obtained with PSCAD are slightly lower than those obtained with ATP, as in the latter the line was modeled with frequency independent longitudinal parameter model. Some cases were simulated with no mitigation method to reduce the overvoltage, except the surge-arrester located at the line extremities (km 0 and km 2600) and also with pre-insertion resistor. The energy absorbed by the arrester at the line end in all cases was much lower than its limit.

A. *Single shot results*

Formerly the switch breaker poles were all closed at the same instant, at the maximum of one phase voltage without any mitigation procedure, such as pre-insertion resistor. Additional simulations were performed using the 400-ohms pre-insertion resistor existent in the switching-breaker, but with a by-passing time greater than one cycle (20.8 ms) instead of the regular 8 ms and another simulation with a 140-ohms pre-insertion resistor (20.8 ms by-pass time), which is much lower than the line surge impedance (around 200 ohms). The by-pass time must be increased in order to wait for the first traveling wave to reach the beginning of the line and to interact with the weak generation system. Only after that perturbation has moved towards the line opened end the resistor is by-passed, imposing full voltage to the line. It can be observed that the transients along the line are strongly attenuated due to the line length.

In Fig. 8 to Fig. 10 the complete simulation is presented and in Fig. 11 to Fig. 13 the former 150 ms after the shot are presented for the energization without mitigation procedures.

In Table 9 the maximum overvoltages along the line are summarized for all the simulations.

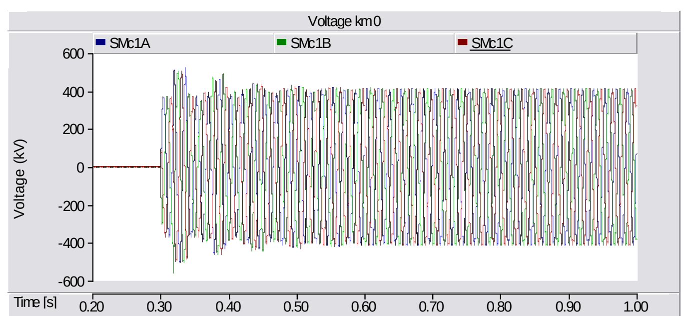

Fig. 8. Voltage at Serra da Mesa – km 0 – Complete simulation – Without pre-insertion resistor

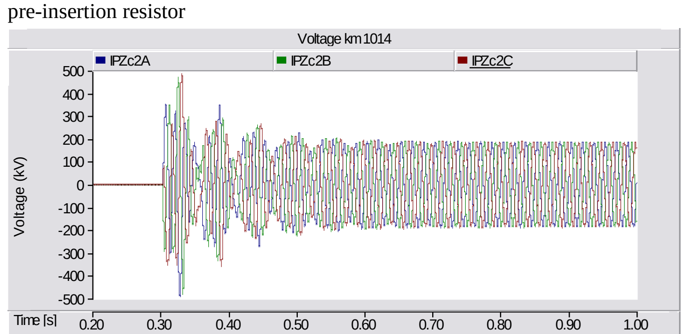

Fig. 9.Voltage at Imperatriz – km 1014 – Complete simulation – Without pre-insertion resistor

In Figs. 14 to 17 the former 140 ms after the shot are presented for the two others simulations with the 400 Ω and the 140 Ω pre-insertion resistor. Analyzing the voltages at the line end it is possible to observe the traveling wave resultant from the interaction between the sending end network and the line arriving at the reception end and only afterwards the waves due to the resistor by-pass arrive. With the higher by-pass time it was possible to avoid the superposition of these waves, reducing the overvoltage from 1.72 pu to 1.28 pu at the receiving end.

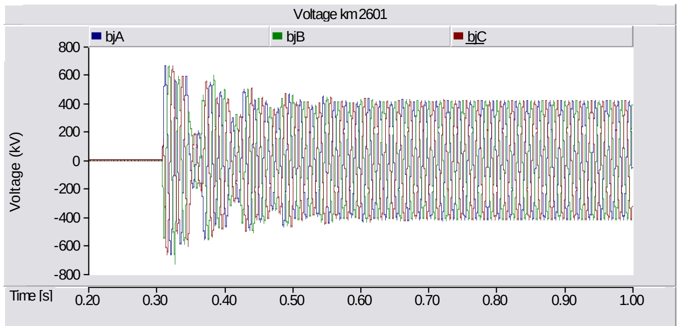

Fig. 10.Voltage at Bom Jesus da Lapa – km 2601 – Complete simulation – Without pre-insertion resistor

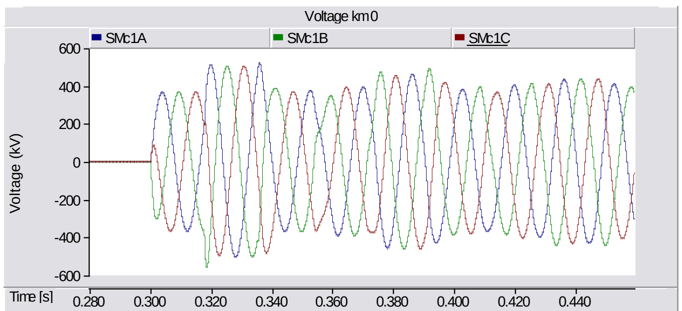

Fig. 11.Voltage at Serra da Mesa – km 0 – Simulation detail – Without pre-insertion resistor

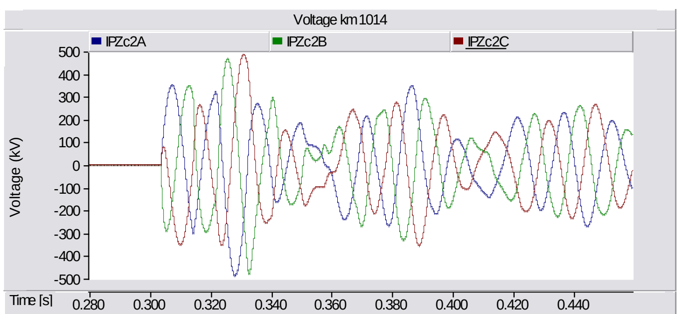

Fig. 12.Voltage at Imperatriz – km 1014 – Simulation detail – Without pre-insertion resistor

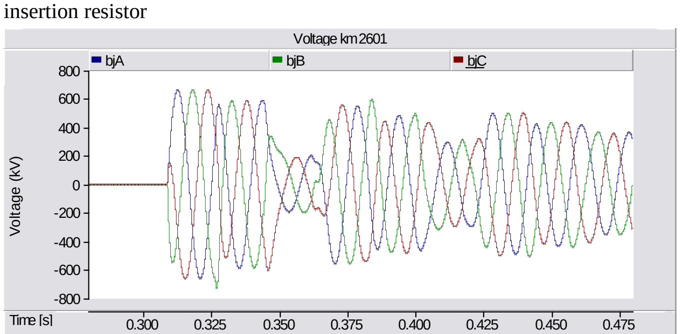

Fig. 13.Voltage at Bom Jesus da Lapa – km 2601 – Simulation detail – Without pre-insertion resistor

Another important factor that helps to reduce the overvoltage is the attenuation, as the transient waves have to travel through 2600 km back and forth, what will filter the higher frequencies.

It can be observed that the overvoltages measured at the line end are much lower than the normally obtained for a few hundreds km long transmission lines.

TABLE 9

MAXIMUM OVERVOLTAGE ALONG THE LINE [PU]

Measuring location [km]	Without mitigation procedure	Using 400-ohms pre-insertion resistor	Using 140-ohms pre-insertion resistor
0	1.341	1.201	1.128
1014	1.144	0.774	0.738
2028	1.184	1.008	0.947
2279	1.529	1.226	1.165
2601	1.742	1.358	1.280

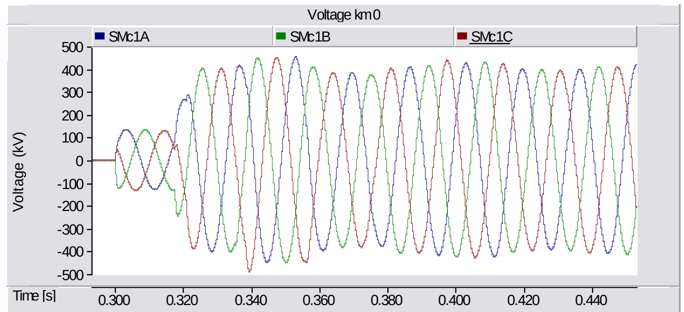

Fig. 14.Voltage at Serra da Mesa – km 0 – Simulation detail – 400 Ω pre-insertion resistor

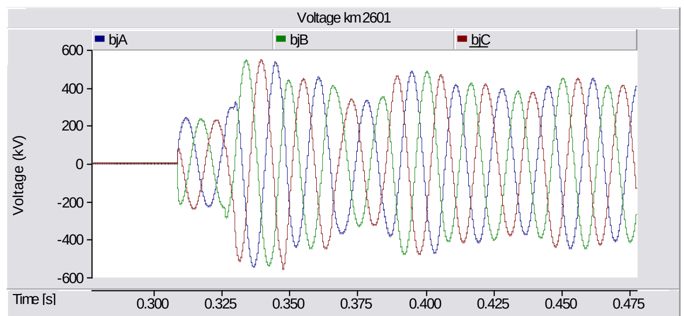

Fig. 15.Voltage at Bom Jesus da Lapa – km 2601 – Simulation detail – 400 Ω pre-insertion resistor

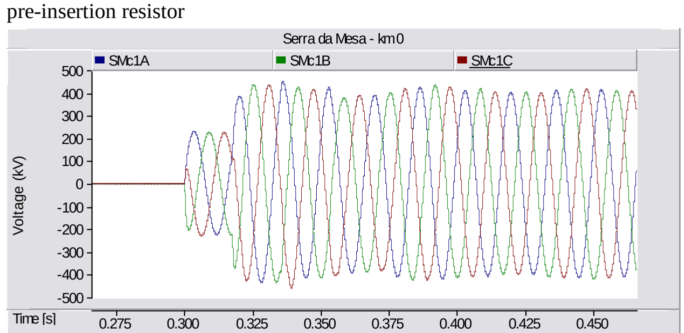

Fig. 16.Voltage at Serra da Mesa – km 0 – Simulation detail – 140 Ω pre-insertion resistor

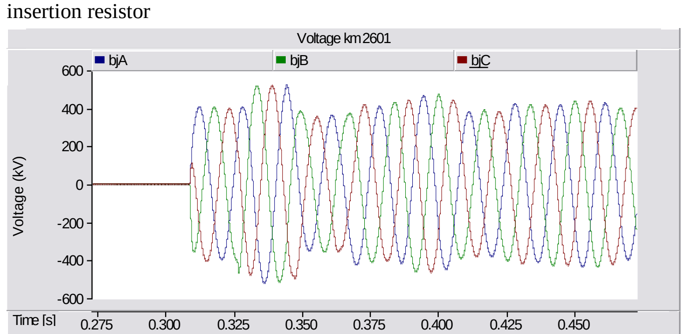

Fig. 17.Voltage at Bom Jesus da Lapa – km 2601 – Simulation detail – 140 Ω pre-insertion resistor

B. Statistical results

The statistical energization was performed with 500 shots supposing that the pre-insertion resistor mean closing instant is near the maximum voltage time at one phase. The pole spread of the pre-insertion resistor breaker was represented with a standard deviation (σ) of 2 ms for the master breaker pole and 3 ms for the slave breakers poles. The by-pass breaker was represented with slaves' switches in relation to each phase with a 20 ms delay and the standard deviation of 2.0 ms. The Gaussian distribution tail was truncated at 2.5 σ. The pre-energization voltage was 0.96 pu, but no voltage control was implemented to reduce the steady-state voltage after the energization.

In Table 10 the steady-state (SS) voltage profile after the energization is presented. The sustained voltages at some substations (Imperatriz, Colinas II, Miracema II e Gurupi II) are lower than 0.5 pu and near the middle of the line is around 0.073 pu. It is important to block the undervoltage protection so it will not trip during the experiment. The reduced voltage near the middle of the test line should change when the coupling between the interconnection trunks N-S-I and N-S-II are properly represented. No important change in the overvoltage level is expected.

In Table 10 the maximum overvoltage ranges are presented. The overvoltage at the end of the line will not be higher than 1.65 pu, which is much less than what is observed when switching smaller lines, around a few hundreds of kilometers. The energy absorbed by the surge arrester at the line end is much lower than its limit.

TABLE 10
STEADY-STATE VOLTAGE PROFILE AFTER ENERGIZATION; MAXIMUM OVERVOLTAGE OF STATISTICAL SWITCHING

Substation	location [km]	SS Voltage [pu]	Statistical energization Voltage [pu]
Serra da Mesa	0	1.031	1.40-1.45
Gurupi I	256	1.036	1.45-1.50
Miracema I	511	0.935	1.35-1.40
Colinas I	684	0.809	1.30-1.35
Imperatriz	1014	0.468	0.95-1.00
Colinas II	1344	0.073	0.65-0.70
Miracema II	1517	0.198	0.65-0.70
Gurupi II	1772	0.511	0.85-0.90
Serra da Mesa II	2028	0.775	1.15-1.20
Rio das Éguas	2279	0.956	1.40-1.45
Bom Jesus da Lapa	2601	1.046	1.60-1.65

VI. CONCLUSIONS

Some simulations results of natural HWL+ transmission trunk energization transients performed both for selected point-of-wave switching and statistical switching were presented. It was possible to observe that no extreme overvoltage occurred along the line, as the overvoltages obtained were lower than the ones of medium size lines.

The HWL+ line overvoltage energization without any mitigation procedure (no pre-insertion resistor) produced low overvoltage, which could be further reduced if pre-insertion resistor were applied, optimizing both the pre-insertion resistor value and the by-pass time. The optimization of the by-pass time aims to avoid unfavorable superposition of first switching traveling wave with short-circuiting the pre-insertion resistor traveling wave.

Some additional results analyzing the occurrence of fault during the experiment were also performed. The regular protection properly adjusted can trip the link without jeopardizing the existent lines.

The test was proposed for governmental planning engineers to give more confidence to the AC Link alternative, as there is no such transmission in operation in the world. It should be understood, however, that the great inovation in this transmission system will be the line length, whichever is the final transmission option. For all of them new possible transients may occur and should be carefully studied. The new transmission system should be properly optimized, and not just extrapolated from other existent systems in operation. With this test it is expected that the rest of the HWL+ studies could be performed as any regular transmission system expansion studies are normally done, and as were done with the other alternatives being studied, based on simulation performed with reliable tools.

Due to the possible cost saving, it is urged that the HWL+ alternative is properly studied, and if the proposed field-test helps, the energization test should be realized promptly.

VII. REFERENCES

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

[2] Prabhakara, F.S., Parthasarathy, K, Ramachandra Rao , H.N., "Analysis of Natural Half-Wave-Length Power Transmission Lines". Transac. on PAS, vol 88, no. 12, pp. 1787-1794, Dec 1969, SP, Brazil, 38p, 2002.

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

[4] Portela, C. , Tavares, M. C., "Modeling, simulation and optimization of transmission lines. Applicability and limitations of some used procedures". IEEE T&D Latin America 2002, Brazil, 38p, 2002.

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

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

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