Energization Simulations of a Half-Wavelength Transmission Line when Subject to Three-Phase Faults

E. A. Silva, F. A. Moreira, M. C. Tavares

***Abstract* – The purpose of this paper is to supply technical data for the proposal of field energization of 500 kV transmission lines present in the Brazilian interconnected system, forming a line, here called AC-Link, slightly over a half-wavelength in 60 Hz. The purpose of the test is the investigation about the overvoltages and currents that result from the energization of the AC-Link. This paper shows the results of simulations performed in ATP when considering the occurrence of three-phase faults along the AC-Link during energization. The results obtained show that in certain situations, the overvoltages and energies in the arresters may reach very high values and some specific mitigation procedure should be implemented.**

***Keywords* – Half-wavelength, three-phase fault, overvoltage, surge arrester, line energization.**

I. Introduction

With a national territory over 8.5 million square kilometers and a population that exceeds 220 million people, Brazil faces the challenge of increasing its electrical energy generation capacity in an integrated, profitable, and sustainable form. Great part of the remaining hydraulic potential in Brazil is located in the Amazon region at a distance of about 2,000 km to 3,000 km from the main load centers in Brazil, which are located in the Southeast and Northeast regions of the country, as illustrated in Fig. 1. In the search for adequate solutions for bulk power transmission over such long distances, non-conventional transmission lines [1] may be adopted and one such non conventional line is the transmission in alternate current in a line with a length slightly over the half wavelength, which is approximately 2,500 km at 60 Hz, the frequency in use in Brazil.

Although there are studies about half-wavelength transmission since the 1960´s [2-3], there is no such line in operation in the world. This leads to a great deal of precaution and reservation among the engineers responsible for the expansion of the Brazilian electrical system in allowing this alternative even to be taken into further consideration.

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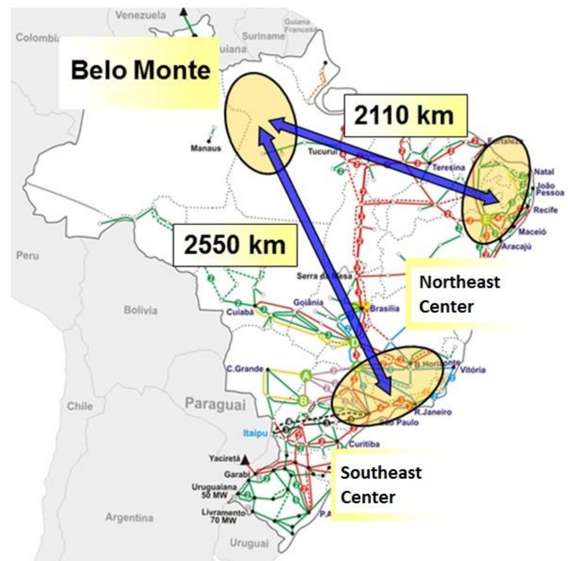

Fig. 1. Distances from the generation in the Amazon region to the main load centers in the Southeast and Northeast.

For this reason, in response to a Strategic Research and Development Project proposed by the National Electric Energy Agency – ANEEL, an energization switching under well defined conditions was proposed to be performed in a transmission line that would resemble an AC-Link. This transmission line results from the series connection of the North-South I and II interconnections and part of the Northeast-Southeast interconnection [4]. Together, these 500 kV lines form a link of 2,600 km in length, slightly over the half wavelength in 60 Hz. The purpose of the test is the investigation on the overvoltages and currents that result from the energization of the AC-Link, as well as the voltage profile along the line. All series compensation should be short-circuited and all shunt compensation should be removed. However, the surge arresters in the intermediate substations cannot be disconnected from the network since this procedure would demand an excessive amount of time for the energization test setup.

Therefore, after confirming that their presence would not compromise the test, it was necessary to verify if the overvoltages would occur during the energization test and the resulting energy absorbed by the surge arresters would not damage them. An important study is the energization under different fault conditions, which may result in very high overvoltages along the line. In this paper, the possibility of energization under three-phase faults is considered and the main results are presented.

II. Basic Characteristics of the Half-Wave Length Transmission Line

The half-wavelength transmission line does not need any type of reactive compensation, or, at most, it needs a minimum compensation. This characteristic makes the cost of the transmission very attractive when compared to other alternatives, such as the traditional AC transmission, heavily dependent on series and shunt reactive compensation, and the DC transmission, with the high costs associated to the converter substations and the filters.

When the AC-Link operates with its receiving end terminal opened, it is noticed that the Ferranti effect is close to unit, i.e., the voltages measured at the receiving end terminal is very close to the voltage values at the sending end terminal. For this reason, it is not necessary to install any shunt reactive compensation to reduce the receiving end terminal voltage when the line is operating under very light load or no-load.

The distances involved in the half-wavelength transmission lines should produce a phase shift of slightly over 180 degrees between the sending and receiving end terminals. In the case of the AC-Link under consideration (2,600 km) the phase shift is approximately 191 electrical degrees. The behavior of this line is equivalent to that of a line that produces a phase shift of 11 electrical degrees. This margin allows safety in the operation of the line against the risk of loss of stability due to the variation of the fundamental frequency and possible operation of the line in the second quadrant, between 90 and 180 electrical degrees that would make the operation of the line unstable. This characteristic makes the installation of series reactive compensation unnecessary.

For transmission lines slightly shorter than a half-wavelength, it is possible to consider the alternative of installing some reactive compensation in order to modify its electrical length to the usually allowed margin of 30 electrical degrees, that is, the electrical length would vary between 180 and 210 electrical degrees and the line would then operate in the third quadrant, making its operation stable [5].

These lines, during steady-state operation, present a characteristic of interdependency between the voltage and current values in the middle of the line and those in the receiving end of the line.

Equations (1) and (2) present the observed results for the positive sequence component of the AC-Link in steady-state.

$$|V_{ml}| = |Z_C \cdot I_r| \quad (1)$$

$$|I_{ml}| = \left|\frac{1}{Z_C} \cdot V_r\right| \quad (2)$$

where V_{ml} and I_{ml} are the voltage and current in the middle of the line, respectively; V_r and I_r are the voltage and current at the receiving end terminal, respectively, and Z_C is the characteristic impedance of the line.

In (1) it is verified that the voltage in the middle of the line depends on the current at the receiving end terminal. Since the voltage at this terminal is kept close to 1.0 pu, the current becomes directly proportional to the transmitted power. This way, the voltage in the middle of the line will also be directly proportional to the transmitted power. This characteristic implies that for the AC-Link the operation condition corresponds to the transmission up to the characteristic power to avoid steady state high voltage levels in the middle of the line.

The 1.0 pu voltage in the receiving end also indicates that the current in the middle of the line is kept close to 1.0 pu for any loading condition in the transmission line as presented in (2). The nominal current would then be associated to the characteristic power of the line.

III. Description of the System Analyzed

The transmission system under consideration is based on the lines that compose the AC-Link. The North-South I and II interconnections are parallel with a distance around 60 m between their towers. The intermediate substations are close, although not electrically connected. Part of the Northeast-Southeast link may also be connected in series from the receiving end of the North-South II link, as shown in Fig. 2. The system operates in 500 kV.

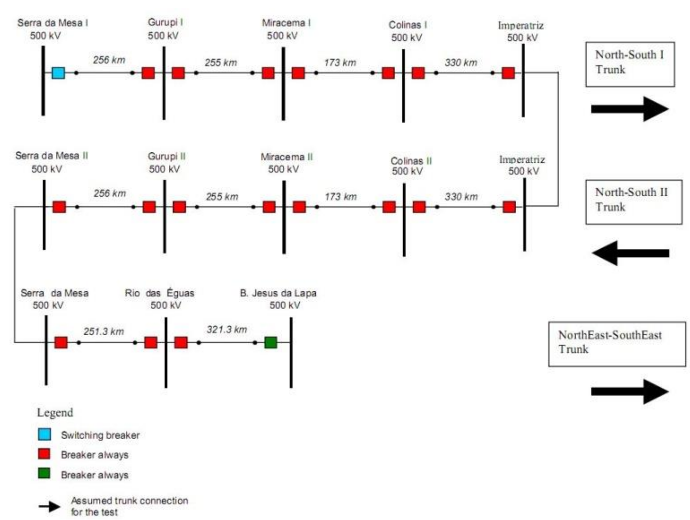

Fig. 2. One line diagram of the AC-Link simulated.

The simulations were performed with the energization switching occurring in Serra da Mesa I. The effect of the coupling between the North-South I and II links has not been represented at this point. The software used was the ATP, and the lines were represented with the distributed parameter model, first using the constant parameters (cp) line model and subsequently the JMarti model, in order to compare the results obtained with both models. The distances between the substations are presented in Table I.

The fault conditions analyzed consist of three-phase faults applied along the line, considering a fault resistance of 20 Ω. The fault was applied at every substation and for every fault condition the voltages at every substation are measured, as well as the currents at the sending end and the energies dissipated by the surge arresters located at every substation.

With this procedure the most critical regions for the occurrence of faults was clearly defined. As previously mentioned, the surge arresters in the intermediate substations are not removed from the system due to time constraints whenever the real test shall be performed. The pre-insertion resistors were maintained in the network, although the time they are connected to the network is not enough for the travelling waves to return to the sending end terminal, since modifying this parameter is not an option for the real test. The three poles of the circuit breaker are closed at the maximum voltage in phase A.

TABLE I
DISTANCES BETWEEN THE SUBSTATIONS AND FROM THE SENDING END OF THE AC-LINK

Substations	Distance from Serra da Mesa 1 (km)	Distance from substations (km)
Serra da Mesa 1 (SM1)	0.0	-
Gurupi 1 (GU1)	256.0	256.0
Miracema 1 (MI1)	511.0	255.0
Colinas 1 (CO1)	684.0	173.0
Imperatriz (IMP)	1014.0	330.0
Colinas 2 (CO2)	1344.0	330.0
Miracema 2 (MI2)	1517.0	173.0
Gurupi 2 (GU2)	1772.0	255.0
Serra da Mesa 2 (SM2)	2028.0	256.0
Rio das Éguas (RIE)	2279.3	251.3
Bom Jesus da Lapa (BJL)	2600.6	321.3

The simulated system presents the following characteristics:

- The AC-Link is energized from the substation of Serra da Mesa 1, with one generator in operation;
- A step-up transformer is connected to the generator in Serra da Mesa 1;
- Surge arresters are connected at the sending and receiving ends of the line and also at the intermediate substations;
- The path of connection is Serra da Mesa 1 – Imperatriz through the North-South I line, Imperatriz – Serra da Mesa 2 through the North-South II line, and Serra da Mesa 2 – Bom Jesus da Lapa through the Northeast-Southeast line;
- The line energization is performed through the switching of the circuit breaker in Serra da Mesa 1. The pre-insertion resistors are kept in the circuit for 10 ms.
- The total simulation time is 300 ms and the time step adopted is 50 µs.
- The faults are applied at the start of the simulation and are cleared after 100 ms.
- The generator voltage was adjusted so that the pre-switching voltage in the transformer is 0.95 pu.

Although the lines operate at the same voltage levels, the tower outlines are different. Tables II to IV present the series and shunt parameters of the lines per unit length in sequence components, calculated assuming the lines ideally transposed and for a frequency of 60 Hz. A previous work has shown that using similar transmission lines provides very similar results when compared to those obtained when a single line is used for the representation of the AC-Link [6]. Also, the consideration of ideally transposed lines instead of representing the real transposition does not present any significant influence in the results [5].

TABLE II
SERIES AND SHUNT PARAMETERS OF THE NORTH-SOUTH I TRANSMISSION LINE CALCULATED AT 60 Hz

Sequence	Resistance $[\Omega/km]$	Inductance $[\mathrm{mH}/km]$	Capacitance $[\mu\mathrm{F}/km]$
Zero	0.37138	4.11662	0.00725
Positive/Negative	0.01589	0.70700	0.01612

TABLE III
SERIES AND SHUNT PARAMETERS OF THE NORTH-SOUTH II TRANSMISSION LINE CALCULATED AT 60 Hz

Sequence	Resistance $[\Omega/km]$	Inductance $[\mathrm{mH}/km]$	Capacitance $[\mu\mathrm{F}/km]$
Zero	0.34822	3.74452	0.00946
Positive/Negative	0.01602	0.71089	0.01634

TABLE IV
SERIES AND SHUNT PARAMETERS OF THE NORTHEAST-SOUTHEAST TRANSMISSION LINE CALCULATED AT 60 HZ

Sequence	Resistance $[\Omega/km]$	Inductance $[\mathrm{mH}/km]$	Capacitance $[\mu\mathrm{F}/km]$
Zero	0.34821	3.75767	0.00934
Positive/Negative	0.01602	0.724032	0.01603

The characteristic curve of the surge arresters is presented in Fig. 3 and their energy absorption capacity is shown in Table V

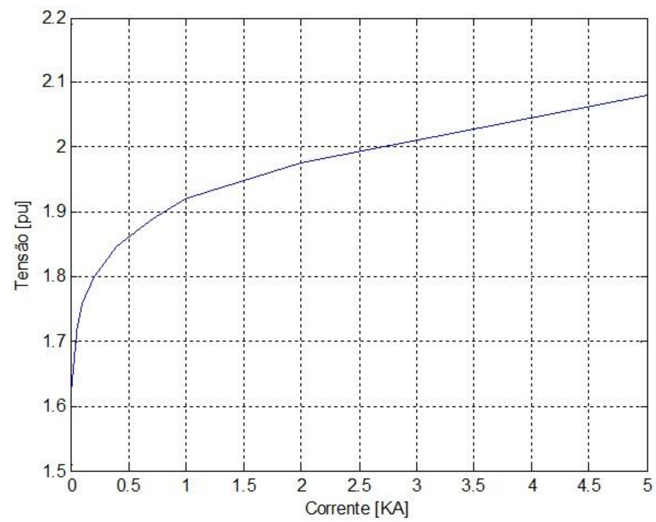

Fig. 3. Characteristic curve of the surge arresters.

TABLE V
ENERGY ABSORPTION CAPACITY OF THE SURGE ARRESTERS

Value for a single impulse (MJ)	Thermal capacity according to the IEC 994/91 Standard (MJ)	Thermal capacity according to the manufacturer (MJ)
4.83	7.56	8.40

The soil resistivity was considered constant with frequency with a value of 4,000 Ω.m for all the AC-Link due to the rocky soil in the region.

IV. Simulation Results Under Three Phase Faults

Initially, faults at every substation were considered, and for each fault condition, the voltages at every substation were measured. Table VI presents the peak voltage magnitude in pu measured during the period of simulation. The table shows the peak voltage magnitude independently of the phase. The transmission lines that form the AC-Link were modeled with the cp-line model. Table VII shows the same results, however when the transmission lines are modeled with the JMarti line model. The steady-state frequency considered was 60 Hz.

TABLE VI
VOLTAGES IN (pu) MEASURED ALONG THE AC-LINK CONSIDERING THE LINES MODELED WITH THE CP-LINE MODEL

		Location of the three-phase faults										
		SM1	GU1	MI1	CO1	IMP	CO2	MI2	GU2	SM2	RIE	BJL
Location of the voltage measurements	SM1	0.123	0.670	0.637	0.659	0.801	1.396	1.795	1.900	1.935	1.313	1.012
	GU1	0.125	0.097	0.472	0.543	0.694	1.450	1.879	1.976	1.820	1.234	1.068
	MI1	0.125	0.095	0.089	0.315	0.511	1.345	1.864	1.918	1.907	1.405	0.929
	CO1	0.119	0.082	0.088	0.084	0.379	1.203	1.807	1.893	1.896	1.540	0.967
	IMP	0.097	0.064	0.071	0.067	0.077	0.742	1.297	1.861	1.883	1.632	1.157
	CO2	0.098	0.082	0.079	0.090	0.064	0.104	0.493	1.159	1.883	1.506	1.193
	MI1	0.120	0.100	0.087	0.107	0.080	0.172	0.142	1.159	1.345	1.339	1.139
	GU2	0.157	0.133	0.128	0.128	0.125	0.383	0.445	0.221	0.761	0.977	0.974
	SM2	0.188	0.157	0.147	0.140	0.175	0.563	0.728	0.306	0.198	0.563	0.745
	RIE	0.210	0.170	0.151	0.168	0.199	0.687	0.918	0.389	0.268	0.155	0.461
	BJL	0.225	0.173	0.166	0.188	0.223	0.750	1.023	0.433	0.330	0.190	0.113

TABLE VII
VOLTAGES IN (pu) MEASURED ALONG THE AC-LINK CONSIDERING THE LINES MODELED WITH THE JMARTI MODEL

		Location of the three-phase faults										
		SM1	GU1	MI1	CO1	IMP	CO2	MI2	GU2	SM2	RIE	BJL
Location of the voltage measurements	SM1	0.123	0.576	0.636	0.654	0.805	1.398	1.791	1.897	1.925	1.263	0.922
	GU1	0.126	0.096	0.405	0.539	0.700	1.456	1.878	1.967	1.775	1.188	0.967
	MI1	0.127	0.094	0.089	0.303	0.511	1.349	1.864	1.933	1.879	1.345	0.856
	CO1	0.120	0.082	0.087	0.084	0.379	1.200	1.775	1.904	1.887	1.484	0.913
	IMP	0.100	0.065	0.067	0.065	0.077	0.729	1.276	1.833	1.879	1.586	1.111
	CO2	0.097	0.081	0.075	0.087	0.062	0.104	0.524	1.203	1.652	1.462	1.158
	MI1	0.119	0.099	0.087	0.105	0.080	0.172	0.141	0.831	1.318	1.301	1.110
	GU2	0.156	0.131	0.126	0.125	0.123	0.385	0.451	0.221	0.784	0.955	0.950
	SM2	0.187	0.156	0.145	0.139	0.173	0.561	0.735	0.310	0.196	0.527	0.732
	RIE	0.209	0.168	0.151	0.167	0.199	0.687	0.928	0.397	0.267	0.153	0.453
	BJL	0.224	0.171	0.166	0.184	0.223	0.749	1.039	0.441	0.324	0.180	0.112

From the observation of Tables VI and VII, it is possible to conclude that the differences between the representation of the lines with the cp-line or the JMarti models are very small. When the three-phase faults occur until the substation of Imperatriz, the voltages obtained at every substation are below the nominal voltage of the line. The highest overvoltage (1.976 pu) is obtained in the substation of Gurupi 1 for a three-phase fault occurring at the substation of Gurupi 2. In order to be more specific in the location of the worst case scenario, simulations were also performed for faults occurring inside the lines of Miracema 2 – Gurupi 2 and Gurupi 2 – Serra da Mesa 2. Distances of 1/3 and 2/3 of the total lengths of these lines were considered as the location of the faults. Fig. 4 presents the peak voltage profile along the AC-Link considering the occurrence of a three-phase short circuit in Miracema 2, and the transmission lines modeled with the cp-line model and the JMarti model.

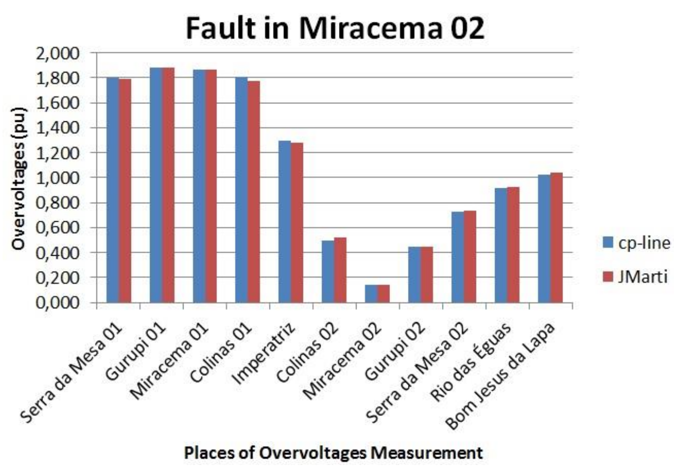

Fig. 4. Peak voltage profile along the AC-Link considering a three-phase fault in Miracema 2.

Figs. 5 and 6 show the peak voltage profile along the AC-Link now considering the three-phase fault at 1/3 and 2/3 of the length of the line Miracema 2 – Gurupi 2, respectively.

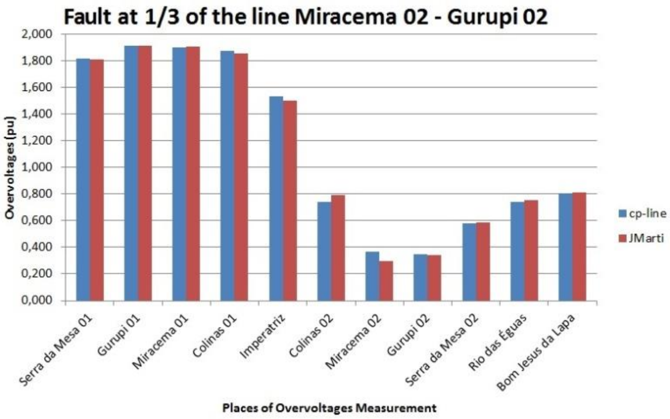

Fig. 5. Peak voltage profile along the AC-Link considering a three-phase fault at 1/3 of the length of the line Miracema 2 – Gurupi 2.

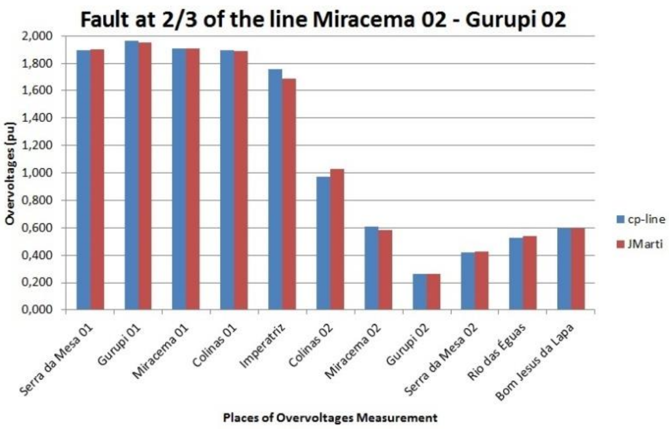

Fig. 6. Peak voltage profile along the AC-Link considering a three-phase fault at 2/3 of the length of the line Miracema 2 – Gurupi 2.

Fig. 7 shows the maximum voltage profile along the AC-Link when the three-phase fault occurs at the substation of Gurupi 2.

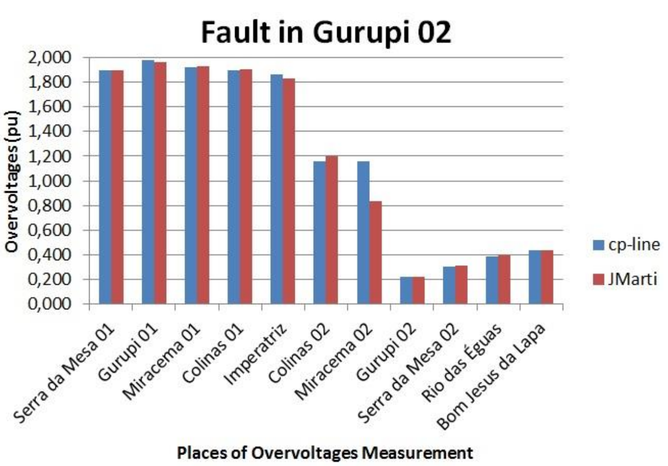

Fig. 7. Peak voltage profile along the AC-Link considering a three-phase fault in Gurupi 2.

Figs. 8 and 9 present the peak voltage profile along the AC-Link now considering the three-phase fault at 1/3 and 2/3 of the length of the line Gurupi 2 – Serra da Mesa 2, respectively.

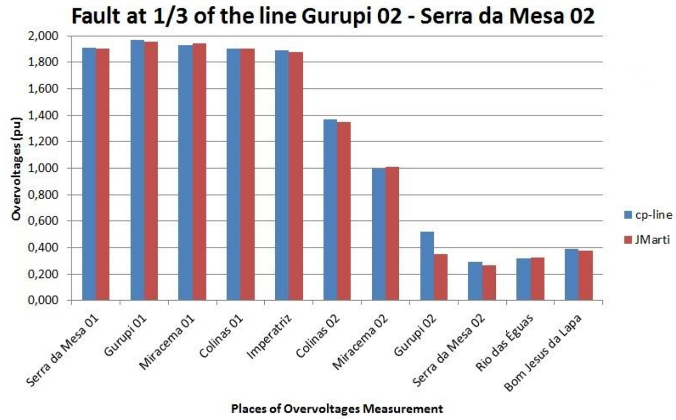

Fig. 8. Peak voltage profile along the AC-Link considering a three-phase fault at 1/3 of the length of the line Gurupi 2 – Serra da Mesa 2.

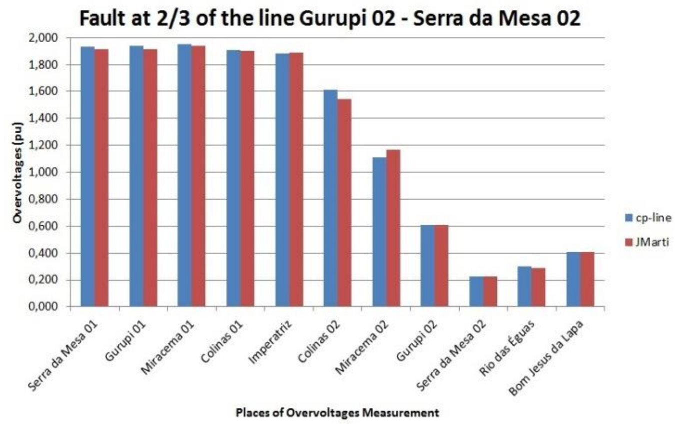

Fig. 9. Peak voltage profile along the AC-Link considering a three-phase fault at 2/3 of the length of the line Gurupi 2 – Serra da Mesa 2.

Fig. 10 shows the maximum voltage profile along the AC-Link when considering the three-phase fault occurring at the substation of Serra da Mesa 2.

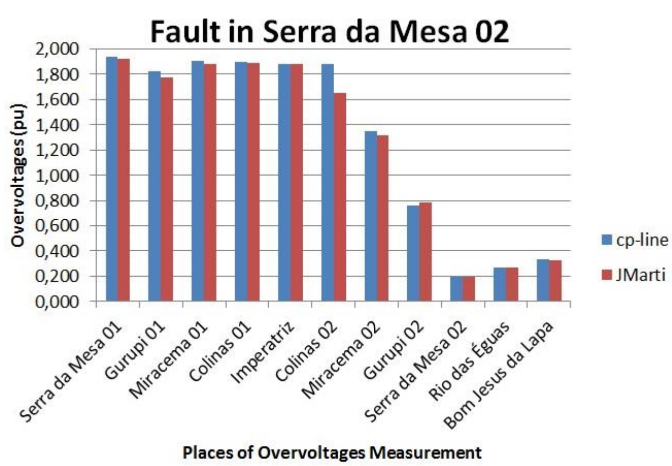

Fig. 10. Peak voltage profile along the AC-Link considering a three-phase fault in Serra da Mesa 2.

From the analysis of Figs. 4 to 10, it is possible to verify that three-phase faults around the substation of Gurupi 2 produce the highest overvoltages in the AC-Link, specifically in the substation of Gurupi I. The surge arresters in this substation and in neighboring substations may therefore be subjected to high levels of energy stresses.

TABLE VIII
CURRENTS MEASURED AT THE SENDING END OF THE AC-LINK (KA) UNDER THE OCCURRENCE OF THREE-PHASE FAULTS

	Location of the three-phase faults										
	SM1	GU1	MI1	CO1	IMP	CO2	MI2	GU2	SM2	RIE	BJL
cp-line	2.740	2.023	1.499	1.339	0.692	0.994	1.907	2.954	3.377	2.933	2.285
JMarti	2.739	2.023	1.494	1.335	0.687	1.002	1.916	3.028	3.424	2.860	2.237

Table VIII shows the maximum currents measured at the sending end of the AC-Link considering the occurrence of three-phase faults along the link. The lines forming the AC-link have been modeled with the cp-line model and also with the JMarti model.

The highest fault currents measured at the sending end of the AC-Link are obtained for three-phase faults that occur at the substation of Serra da Mesa 2, with a peak value of 3.424 kA when the lines are modeled with the JMarti model and 3.377 kA when the lines are modeled with the cp-line model.

The energies absorbed by the surge arresters at the substations that form the AC-Link should be determined in order to verify the possibility of damage to these equipments. Table IX shows the maximum energies absorbed by the surge arresters at each substation, considering a three-phase fault in the region from Miracema 2 to Serra da Mesa 2, since this is the most critical region for the occurrence of three-phase faults regarding the maximum overvoltages that appear in the AC-Link. The results in Table IX are obtained with the transmission lines modeled with the cp-line model. Table X presents the same results shown in Table IX, but with the lines modeled with the JMarti line model.

From Tables IX and X it is possible to conclude that three-phase faults around the substation of Gurupi 2 may result in very high energy stresses (higher than 7 MJ) in the surge arresters located in the substations of Gurupi 1 and Miracema 1, that may exceed the thermal limits of these equipments and possibly result in their failure. This indicates that the voltage along the line sections will be very high, as the surge arresters only reduces the voltage at their locations. Therefore, some specific mitigation procedure need to be implemented in order to protect the surge arresters in case of energization under three-phase faults in critical location and also control the overvoltage along the line sections. One possible alternative is the method called Reduced Insulation Distance (RID), which is described in detail in [7, 8], and consists in reducing the insulator string length in a selected tower in order to provoke the flashover in that specific location. The RID should be placed near the center of the AC-Link (IMP substation in Tables VI and VII) where a three-phase fault would produce no overvoltage.

It is interesting to note that although there are no significant differences in the voltage profile along the AC-Link due to surge arresters operation, whether the transmission lines are modeled with the cp-line or the JMarti line models, the energies absorbed by the surge arresters have significant differences. This is probably due to the line model used that will produce important variations in voltages and currents.

It is also important to consider that as the line models presently available do not consider the corona effect, it is not correct to consider that those extremely high voltages would actually occur. The corona effect would damp these voltages and it is necessary to identify the degree of attenuation it would produce. More results will be presented in near future.

The extremely high overvoltage observed is a result of the simplified line model used, but it indicates that a resonant or quasi-resonant phenomenon has occurred and that mitigation procedures should be considered to remove the system from that condition. Although the overvoltage value can vary depending on the line modeling, a critical condition was identified and will actually occur in the field.

TABLE IX
MAXIMUM ENERGIES ABSORBED BY THE SURGE ARRESTERS (MJ) CONSIDERING THE LINES MODELED WITH THE CP-LINE MODEL

		Location of the three-phase faults						
		MI2	1/3 MI2 – GU2	2/3 MI2 – GU2	GU2	1/3 GU2 – SM2	2/3 GU2 – SM 2	SM2
Location of the energy measurements	SM1	0.124	0.299	0.791	0.787	0.781	0.028	1.139
	GU1	0.831	3.084	7.237	7.130	4.804	2.383	0.278
	MI1	0.619	2.341	4.636	7.009	7.062	5.484	2.502
	CO1	0.156	1.187	3.874	5.299	5.977	4.732	3.149
	IMP	< 1 kJ	< 1 kJ	0.179	1.507	2.936	3.339	2.474
	CO2	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ	0.007	0.085
	MI1	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ
	GU2	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ
	SM2	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ
	RIE	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ
	BJL	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ

TABLE X

MAXIMUM ENERGIES ABSORBED BY THE SURGE ARRESTERS (MJ) CONSIDERING THE LINES MODELED WITH THE JMARTI LINE MODEL.

		Location of the three-phase faults						
		MI2	1/3 MI2 – GU2	2/3 MI2 – GU2	GU2	1/3 GU2 – SM2	2/3 GU2 – SM 2	SM2
Location of the energy measurements	SM1	0.132	0.297	0.720	0.713	0.776	0.897	0.954
	GU1	0.895	2.769	5.589	5.534	3.522	1.364	0.109
	MI1	0.628	2.742	5.699	7.954	7.447	5.106	1.911
	CO1	0.099	0.885	3.899	6.204	6.973	5.759	3.249
	IMP	< 1 kJ	< 1 kJ	0.025	0.849	1.99	2.595	2.117
	CO2	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ	0.005
	MI1	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ
	GU2	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ
	SM2	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ
	RIE	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ
	BJL	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ	< 1 kJ

V. CONCLUSIONS

This paper presents some of the simulation results that have been required by the Brazilian electrical agencies in order to allow the real energization test that should be performed in the series connection of transmission lines that form an AC-Link of 2,600 km, slightly over than the half wavelength at 60 Hz. The purpose of the paper is to give subsidy on the overvoltages and energy stresses on the surge arresters in the intermediate substations that may result from energizations performed under three-phase faults. These energy stresses must be determined because the surge arresters will not be disconnected from the system during the test due to time constraints.

The transmission lines have been modeled with the cp-line model and also with the JMarti line model. The results indicate that there are no significant differences between the results obtained for the voltages along the line and for the current at the sending end of the line. Regarding the energy stresses, the differences between the two models are more significant. This is probably due to the line model used that will produce important variations in voltages and currents near the piecewise linear resistance model used for the surge arresters in the ATP program.

There is a particular region of the AC-Link around the substation of Gurupi 2 and its neighboring substations (Miracema 2 and Serra da Mesa 2) that are particularly critical for the occurrence of three-phase faults, with a possible failure of surge arresters in the substations of Gurupi 1 and Miracema 1.

Some specific mitigation procedure have to be implemented in the AC-Link in order to protect the surge arresters in case of energization under three-phase faults, as the Reduced Insulation Distance (RID), which consists in reducing the insulator string length in a selected tower in order to provoke the flashover in that specific location.

The extremely high overvoltage observed is a result of the line models used, as they do not represent corona effect that would damp these extremely high overvoltages. It is necessary to identify the degree of attenuation corona effect would actually produce.

However the study indicates that a resonant or quasi-resonant phenomenon has occurred and that mitigation procedures should be considered to remove the system from that condition. Although the overvoltage value can vary depending on the line modeling, a critical condition was identified and will actually occur in the field.

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