Electromagnetic Transient Study of a Transmission Line Tuned for Half Wavelength

J.A. Santiago, M.C. Tavares

***Abstract* — In this paper an electromagnetic study of a 1500 km long transmission line tuned to have the properties of a line with a little more than half wavelength (HWL) is presented. The tuning is based on inductive and capacitive components, which turn the line into a 190 electrical degrees transmission system. The line under study is a non-conventional 500 kV line, which has special bundle geometry to achieve a nominal power of 1920 MW. Typical switching maneuvers study considering line energization, three-phase reclosing and load rejection were performed. Typical transient switching overvoltage mitigation procedures were applied. The line was represented with frequency-dependent phase model and additional studies regarding the influence of transposition representation were implemented. Statistical analysis was implemented and typical waveforms are presented. Simulations were performed with PSCAD.**

***Keywords*: Transient overvoltages, Tuned transmission line, Half wavelength, Energization, Statistical analysis, Controlled switching, PSCAD.**

I. INTRODUCTION

There is a constant demand for efficient and low cost transmission systems to carry power from high power generation to large load centers through very long distances. Such is the case of renewable energy sources like hydropower and wind farms and solar plants, which can be located at great distances from the end-use areas. The industrial progress and the population growth of recent years have generated an increasing demand for electricity, especially in large cities, leading to the need of expanding energy supply and building transmission networks with bulk transmission systems based on very long line lengths [1], [2].

At the present, there are power transmission projects around the world, which use UHVAC (Ultra High Voltage AC) or HVDC technology. Although conventional UHVAC can be considered feasible in principle [2], there are currently no transmission system with distances greater than 640 km in operation. Due to the great technological evolution in power electronics area, the transmissions over very long distances are made mainly through HVDC lines, which are seen as a natural solution to the problem due to its good performance [2]. There are HVDC lines in operation in the world up to 2375 km.

An interesting alternative for very long distance transmission is made with AC line with a little more than half wavelength (HWL). For 60 Hz systems, this corresponds to a line of approximately 2600 km in length. Preliminary studies show that the cost per unit length of HWL line is much smaller than the conventional AC transmission lines and even than HVDC lines with similar SIL (Surge Impedance Level) with cost reduction of about 25% with reference to HVDC lines [3].

The HWL is a point to point transmission without the need for intermediate substations. The main advantage is terminals´ voltage level close to the nominal value for no-load or light-load operation conditions, moderate load current and strong dynamic stability [4 - 7].

The need of 2600 km HWL line can occur in some few practical cases, mainly in very large countries, such as Brazil, China and Russia. However, there may be interesting opportunities for lines with transmission distance between 1000 km to 2000 km, for which an artificial increase of the line length can be performed to take advantage of HWL properties. These lines could connect intermittent solar plants and wind farms as the HWL lines have nominal voltage at their terminals regardless of the load level. The artificial lengthening of these lines to HWL can be achieved by proper selection of tuned compensation composed of inductors and capacitors [1], [8].

In the present paper, a study of the tuned HWL behavior for switching maneuver is presented. Additionally, results of 2600 km line and a regular compensated 400 km line are presented and analyzed. The main switching maneuvers were simulated as well as the regular mitigation techniques.

II. TEST SYSTEM

Three lines were considered in the present study: the tuned one with 1500 km, the HWL with 2600 km and a conventional 400 km line. Fig. 1 shows the 1500 km system under analysis. The system under analysis comprises a generator, a step-up transformer, the transmission system and the load.

A. Generation System

To represent the generation system actual data from a Brazilian power plant were used. It consists of five units of 15 kV totaling 2125 MW. The resistance and inductive reactance of each unit are, respectively, $Rg = 0.00377\ \Omega$ and $X''g = 0.12952\ \Omega$. There are five power transformers of 490 MVA, 15/500 kV Delta-Wye connection with 0.125 p.u. impedance.

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J.A. Santiago and M.C. Tavares are with the School of Electrical and Computer Engineering, University of Campinas (UNICAMP), Av. Albert Einstein, 400, 13083-250, Campinas, SP, Brazil (e-mail: javiersa, cristina@dsce.fee.unicamp.br).

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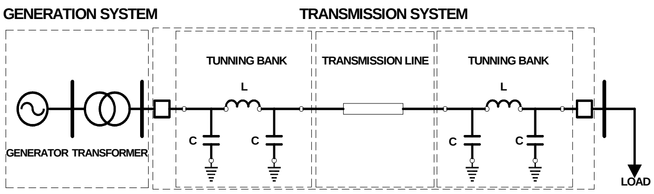

Fig. 1. One line transmission system diagram

B. Transmission Line

A non-conventional line was used in the present study with high power capacity (1920 MW). Although the objective is to study a 1500 km line, this should be a bulk transmission with low loss level.

The line has six conductors per phase (Rail) and two ground wires (EHS 3/8"). The geometric configuration of the line tower is shown in Fig. 2, which indicates the mean conductor's height (considering the sag). The bundle was designed bearing in mind constraints such as corona effect. The soil resistivity is constant in frequency and equal to 2000 ohm.m. Table 1 shows the balanced line electrical parameters calculated for 60 Hz.

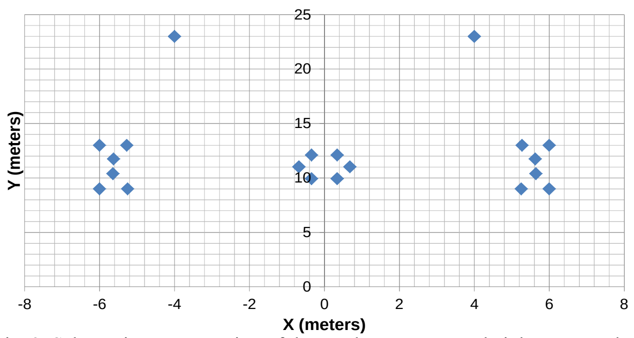

Fig. 2. Schematic representation of the conductors – Mean height presented

TABLE I
BASIC LINE UNITARY PARAMETERS – 60 HZ

Sequence	Resistance [Ω/km]	Reactance [Ω/km]	Susceptance [μS/km]
Zero	0.3845	1.3481	4.1924
Positive / Negative	0.0106	0.1694	10.0243

The influence of properly representing the line transposition section was considered. The line was represented as a balanced one and also with its actual transposition section. For the balanced line, the ideal transposition was considered for the whole frequency range. The actual transposed line was represented using non-transposed line section with the transposition tower. This analysis is important to properly observe the higher frequencies transient response and its influence in the overvoltage attenuation [12].

A transposition cycle consists normally of three phase rotations, which seek to balance the phase parameters for fundamental frequency. To achieve this, the length of each transposition cycle should be much less than a quarter of half wavelength for network frequency (60 Hz), which means a much smaller length than 1200 km. For the 1500 km line, this results in splitting the line into four transposition cycles of 375 km each one. The cycle is divided into 4 sections of 62.5 km, 125 km, 125 km and 62.5 km.

The line was represented with PSCAD frequency dependent phase model.

C. Tuning Banks

The bank options that were analyzed are shown in Fig. 3. “Pi”, “T” and “L” banks were respectively connected symmetrically in the line terminals. Additionally the Pi and T banks were connected in the middle of the line.

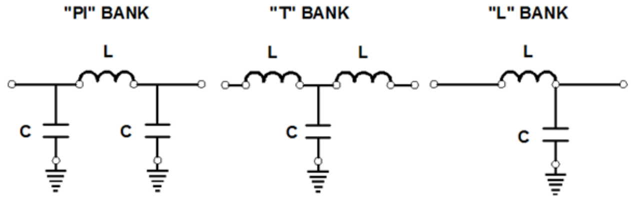

Fig. 3. Tuning bank options

The tuning banks are formed by inductive and capacitive elements that were designed to reproduce a 190 degrees electrical angle line in normal operating conditions (for positive sequence). The study of tuning banks was performed with two-port elements connected in series, representing the tuning banks and the transmission line, as in (1).

$$M_{bank} \times M_{line} \times M_{bank} = M_{system} = M_{HWL} \quad (1)$$

In order to obtain the bank parameters, the equivalent two-port system (M_{system}) should be equivalent to the 2600 km HWL two-port element.

Table II presents the inductance and capacitance values determined for tuning bank. It is important to observe that the shunt capacitors' sizes are moderate and they are regular shunt elements, as the nominal voltage is 500 kV. Regarding the series inductor, they should be located on an isolated platform, just like series capacitor. They should not be isolated for nominal 500 kV.

TABLE II
TUNING BANK PARAMETERS

Tuning Bank	Reactance - X		Susceptance - B	
	(Ohm)	X/R	(µS)	Total MVar
Pi – Ends	81.807	400.0	2720.3	1360.2
T – Ends	46.030	400.0	4837.1	1209.3
L – Ends	82.938	400.0	4595.5	1148.9
Pi – Middle	127.046	400.0	6216.2	3108.1
T – Middle	105.180	400.0	7526.2	1881.5

The Pi banks located at line ends were selected in the present study, as they best reproduced the HWL behavior. In Fig. 4 the voltage profile along the tuned trunk and the HWL are presented for several load levels. It can be verified that the voltage at line ends, sending (S) and receiving (R), are close to nominal voltage and the voltage profiles are similar in the middle of the line. The constant terminal voltage is a very important requirement for intermittent green power plants.

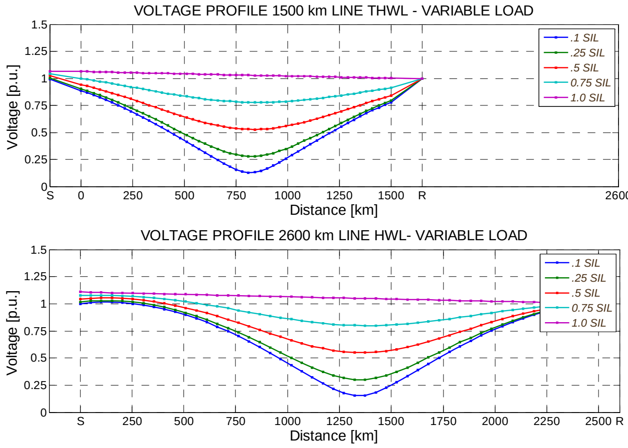

Fig. 4. Voltage profile for different load levels under normal operation conditions. Comparison between 1500-km Pi tuned line and HWL.

D. HWL Line and Conventional system

The 2600 km HWL line and 400 km conventional line have the same tower configuration of the 1500 km line. The 400 km line was compensated with a 667 Mvar shunt reactors at both terminal (65 % compensation level). The phase reactor had a quality factor of 400 and the neutral reactor was of 250 Ω, with quality factor of 40.

III. CASES ANALYZED DESCRIPTION

The following switching maneuvers were analyzed: energization, three-phase reclosing and load rejection. It was made a comparison of overvoltage level response of 1500 km tuned line, 2600 km HWL line and 400 km line.

Because of the random nature of the breaker poles closing time, a statistical study was performed considering 100 cases with normal distribution. For non-controlled switching cases standard deviation (SD) of 2 ms was applied and for controlled closing the SD was set to 0.5 ms. The closing time was obtained using an uniform random distribution over a full cycle, equal for all phases, to simulate that the mean closing time can occur at any point of the voltage wave [12].

The worst statistical case was reproduced in a deterministic simulation in order to observe the waveforms and the voltage profile along the lines. In each case the overvoltage profile was obtained along the line, the sending busbar (S) and receiving busbar (R). It was also analyzed in each case the voltage waveforms at the receiving busbar.

A. Energization

These tests consisted in energizing the lines considering the regular mitigation methods, specifically: no mitigation, pre-insertion resistors, surge arresters at line ends and controlled switching. The value of pre-insertion resistor was set to 130 Ω, that is equal to the line characteristic impedance and the by-pass period was of 20 ms for tuned and HWL line and 10 ms for 400 km line. This value was defined to ensure transient attenuation considering the travel time for the tuned line and the HWL line, respectively 5 ms and 8.3 ms. This time must be larger than at least two travelling waves reflections.

In the controlled switching, the circuit breaker making should be close to the zero crossing of the voltage at circuit breaker poles [13].

B. Three-phase Reclosing

For these simulations, it was considered the line opening without internal fault. Three-phase tripping is produced at a mean time of 800 ms and reclosing after a dead-time of 500 ms.

It is also considered a temporary single-phase fault in the reception busbar, applied at t = 550 ms with a duration of 500 ms. In this case the protection trips the circuit breaker in a mean time of 250 ms after the fault occurrence and reclosure occurs after a fixed dead-time of 500 ms.

C. Load rejection

For these cases the system was in normal operation attending the full load that was modeled by a RL element. Circuit-breaker tripping is made at 800 ms at reception busbar.

IV. TEST RESULTS

A. Energization

Previously the influence of transposition representation was analyzed. In Fig. 5 the maximum transient overvoltage profiles produced for direct energization are presented considering the actual line transposition cycles or not (balanced line). It is observed that there are no critical differences between two transposition representations for these very long lines. The maximum overvoltages in the 1500 km tuned line are similar to those obtained in the 2600 km HWL and they occur at the receiving end.

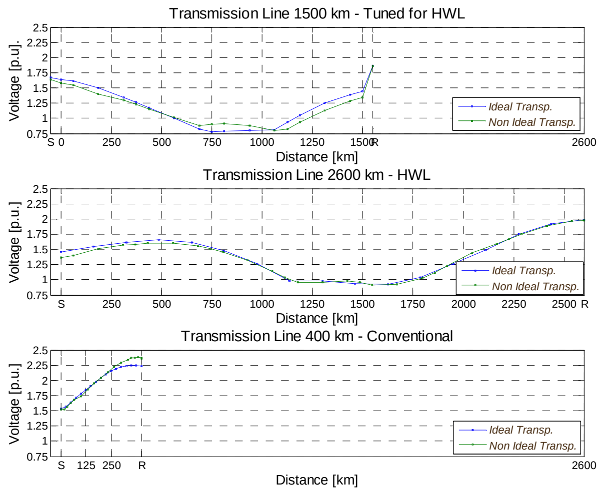

Fig. 5. Maximum transient overvoltage profile along line for direct energization. Statistical worst case at receiving end. Results for tuned line, 2600 km and 400 km.

The overvoltage statistical summary for 100 energization cases simulated is shown in Table III, indicating the average value, standard deviation (SD) and the statistical highest overvoltage with 2% of probability to be exceeded. The overvoltages are statistically higher for the 400 km line (2.303 p.u.) and lower for the HWL line (1.829) and tuned line (1.842 pu).

TABLE III
STATISTICAL MAXIMUM TRANSIENT OVERVOLTAGE FOR ENERGIZATION - DIRECT ENERGIZATION (PU VALUES)

Transposition	Value	1500 km	2600 km	400 km
Ideal	Average	1.719	1.707	1.988
	SD	0.068	0.068	0.144
	98% level	1.860	1.847	2.284
Real	Average	1.687	1.660	2.006
	SD	0.075	0.083	0.145
	98% level	1.842	1.829	2.303

The voltage waveform at the receiving busbar is shown in Fig. 6. The transient response for 1500 km line is attenuated in approximately 350 ms, and this is much longer than the observed for the 2600 km line, which attenuates in 250 ms. However, both waveforms are similar with low content of high frequency components, what is not verified for the 400 km line. This waveform is much noisier and the transient phenomenon lasts much longer, as it can still be observed up to 450 ms.

For these very long lines the high harmonics contents attenuate along the lines, leaving roughly the fundamental frequency response at line terminals. This does not happen for the short line, which presents a much noisier response. The actual representation of line transposition is relevant for the short line, but does not influence the very long line waveform at its terminal.

The slower transient attenuation in 1500 km line occurs because the tuned line is shorter than the HWL line, reducing the total line resistance. The tuning bank only enlarges the reactive parameter, what will not attenuate the transients as in the 2600 km line. This occurs for positive/negative sequence as well as for zero sequence resistance.

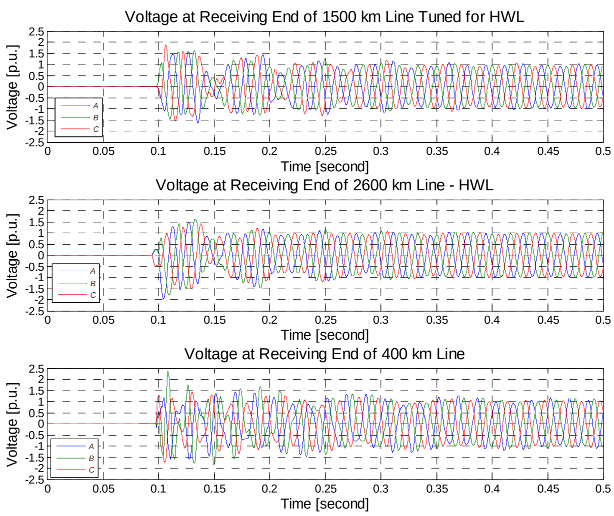

Fig. 6. Direct energization voltage waveform at receiving end. Statistical worst case at receiving end. Comparison between transmission lines: tuned 1500 km, 2600 km – HWL and 400 km. Lines with actual transposition.

In Fig. 7, the results of the maximum overvoltage profiles are presented for different mitigation methods. For tuned 1500 km line, pre-insertion resistor technique reduces more effectively the transient overvoltages up to 1.394 p.u. for 98% statistical level and controlled switching can limit the overvoltages up to 1.651 p.u. for 98% statistical level. The pre-insertion resistor should be used for tuned and HWL lines, with 20 ms resistor insertion time.

This maneuver does not produce severe overvoltages and with pre-insertion resistor the higher overvoltages are similar to those obtained with 400-km line.

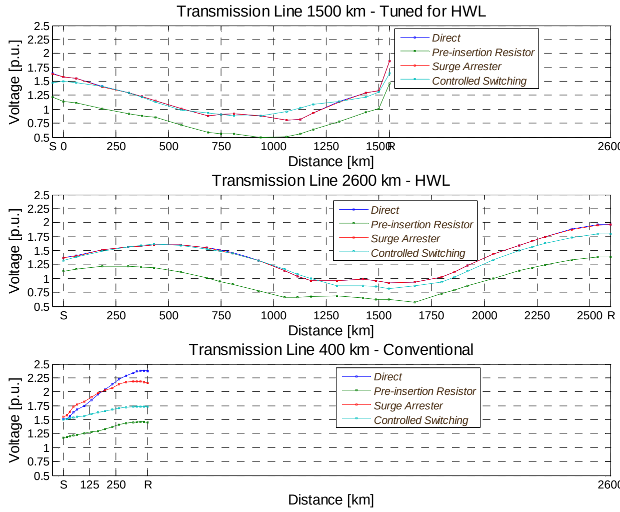

Fig. 7. Maximum transient overvoltage profile along line for different energization overvoltages control techniques. Statistical worst case at receiving end of 1500 km transmission line tuned for HWL. Line considered with actual transposition.

B. *Three-phase reclosing*

Three-phase reclosing was analyzed considering the line transposition representation. Fig. 8 shows that overvoltages for 1500 km tuned line and 2600 km HWL line are similar for both ideal and real transposition. Similar response is not observed for short line.

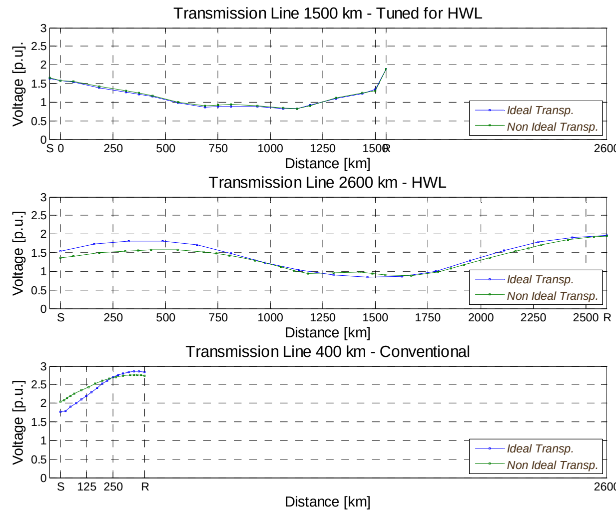

Fig. 8. Three phase reclosure overvoltage profile. Statistical worst case at receiving end. Comparison between transmission lines: tuned 1500 km, 2600 km – HWL and 400 km conventional.

The overvoltage statistical summary for 100 three-phase reclosing cases simulated is shown in Table IV, indicating the average value, standard deviation (SD) and the statistical highest overvoltage with 2% of probability to be exceeded.

The overvoltages are statistically higher for the 400 km line (2.651 p.u.) and lower for the HWL line (1.855 p.u.) and tuned line (1.856 p.u.). This maneuver is a very severe one for short lines, but is not important for very long lines.

TABLE IV
STATISTICAL MAXIMUM TRANSIENT OVERVOLTAGE FOR THREE-PHASE RECLOSING (PU VALUES)

Transposition	Value	1500 km	2600 km	400 km
Ideal	Médio	1.688	1.827	2.472
	S.D.	0.082	0.040	0.177
	98% Level	1.856	1.910	2.836
Real	Médio	1.697	1.671	2.177
	S.D.	0.077	0.090	0.231
	98% Level	1.856	1.855	2.651

Overvoltage profiles for 1500 km tuned line and 2600 km HWL line are similar to those obtained for energization, as shown in Fig. 5 and Fig. 8. For 400 km line, overvoltage due to three-phase reclosing is much greater than those obtained in its energization case. This occurs because the trapped charge is null when the line is reclosed for 1500 km and 2600 km lines, while it is still high for the short line after 500 ms dead-time, as can be observed in Fig. 9.

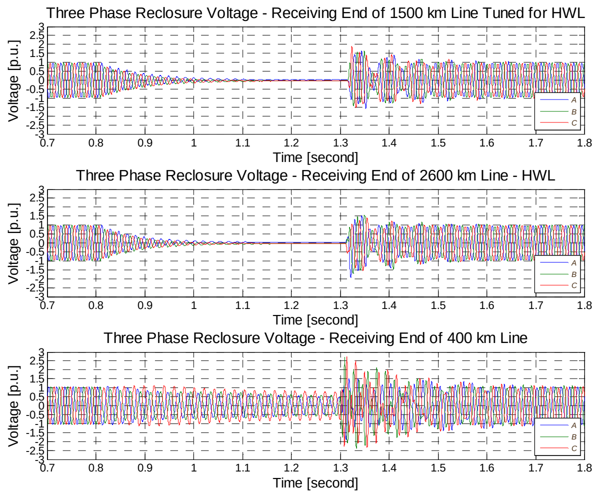

Fig. 9. Three phase reclosure voltage waveform at receiving end. Statistical worst case receiving end. Comparison between transmission lines: tuned 1500 km, 2600 km – HWL and 400 km conventional.

The results of the worst overvoltages profiles case with typical mitigation methods are presented in Fig 10. In the case of 1500 km tuned line, pre-insertion resistor technique reduces more effectively the overvoltages up to 1.397 p.u. for 98% statistical level.

For controlled switching technique, reclosing action usually takes into account the voltage across contacts of circuit breaker. Fig. 11 shows this voltage for lines under study. Reclosing must be applied near to voltage zero crossing for tuned and HWL lines, as there is no trapped charge in these lines. It is observed that the 400 km line presents a beat shape that permits the reclosing at an optimal region that was made at second lower voltage interval for this study [13]. In the 1500 km tuned line and the 2600 km HWL line, reclosing was applied near the voltage zero crossing between circuit breaker poles, like controlled switching for energization case using typical angles delay of 0-60°-120° with a dead-time of 200 ms.

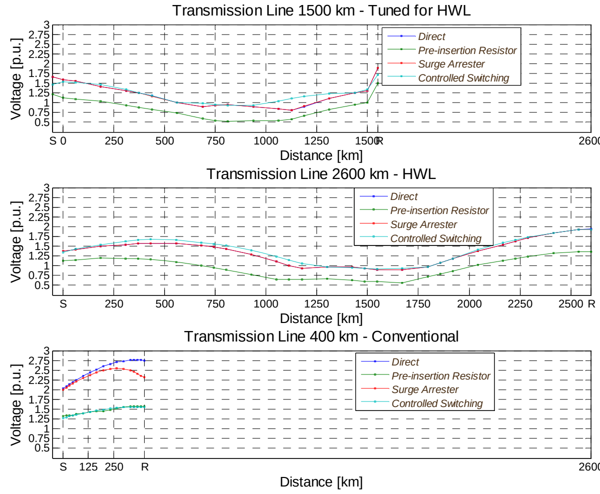

Fig. 10. Three phase reclosing transient overvoltage profile for different transient overvoltages control techniques. Statistical worst case at receiving end. Comparison between transmission lines: Tuned 1500 km, 2600 km – HWL and 400 km conventional.

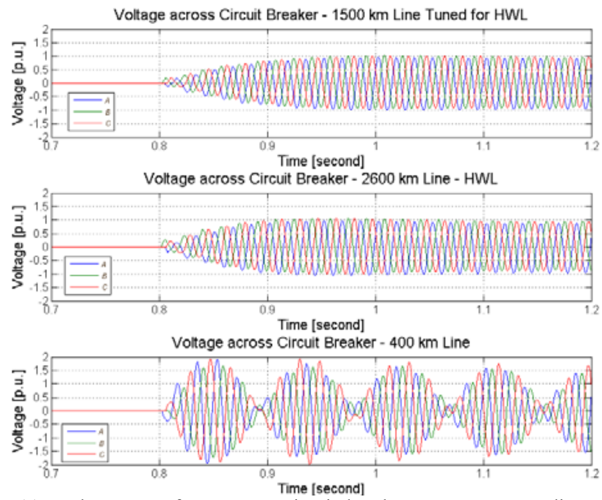

Fig. 11. Voltage waveform across circuit breaker contacts at sending end. Comparison between transmission lines for opening breaker maneuver.

C. Three-phase reclosing due temporary fault

In this section a temporary single phase to ground fault was applied at receiving busbar represented by a 10 ohm resistance. The influence of the representation of ideal and actual transposition can be observed in Fig. 12. There are differences at line terminal overvoltages for tuned line (2.394 p.u.) and HWL line (1.879 p.u.).

The overvoltage statistical summary for 100 three-phase reclosing with transient fault cases simulated is shown in Table V, indicating the average value, standard deviation (SD) and the statistical highest overvoltage with 2% of probability to be exceeded. The overvoltages are statistically higher for the 400 km line (2.847 p.u.) and lower for the HWL line (1.879 p.u.) and tuned line (2.394 p.u.).

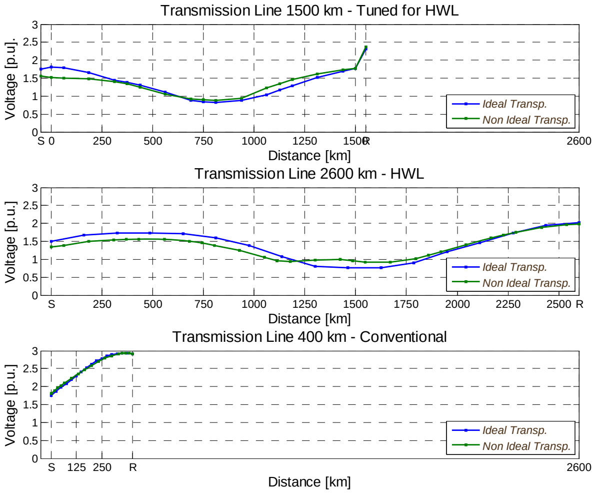

Fig. 12. Overvoltage profile for three phase reclosure due temporary fault. Statistical worst case receiving end. Comparison between transmission lines.

TABLE V
MAXIMUM OVERVOLTAGE FOR RECLOSING WITH TRANSIENT FAULT
(PU VALUES)

Transposition	Value	1500 km	2600 km	400 km
Ideal	Médio	2.035	1.898	2.337
	S.D.	0.131	0.041	0.252
	98% Level	2.304	1.982	2.855
Real	Médio	2.121	1.718	2.312
	S.D.	0.133	0.078	0.261
	98% Level	2.394	1.879	2.847

The voltage waveform at receiving busbar for the worst case is shown in Fig. 13. It can be observed that the trapped charge has disappeared at reclosing time for HWL line. However, for the tuned line the trapped charge did not disappeared, resulting in higher overvoltages for this line when reclosing is applied, as seen in Table V. For short line the overvoltage are even higher.

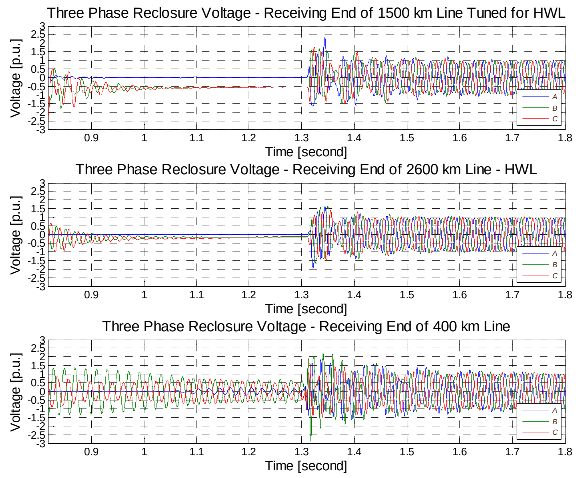

Fig. 13. Voltage waveform at receiving end for three phase reclosing due to temporary single phase to ground fault. Statistical worst case receiving end. Comparison between lines: 1500 km, 2600 km HWL and 400 km.

The overvoltages profiles for different mitigation methods are presented in Fig. 14. For 1500 km tuned line, similar to the case of reclosing without fault, pre-insertion resistor technique reduces more effectively the overvoltages, up to 1.429 p.u. for 98% statistical level. This regular mitigation procedure can be applied successfully to the tuned line, controlling the higher overvoltages at levels similar to those obtained in 400-km regular line (1.512 p.u.) with same mitigation technique.

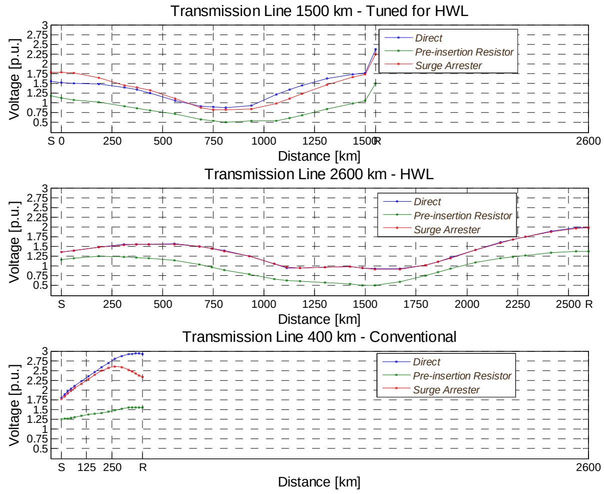

Fig. 14. Transient overvoltage profile for three phase reclosing due to temporary single-line fault using different mitigation techniques. Statistical worst case at receiving end. Comparison for different lines.

D. *Load Rejection*

Fig. 15 shows the transient overvoltage profile produced by the circuit breaker tripping at receiving busbar, assuming a complete load trip equal to nominal load (SIL). The maximum overvoltages occur at the receiving busbar and are similar for the three lines analyzed: 2.33 p.u. for 1500 km line, 2.37 p.u. for 2600 km line and 2.46 p.u. for 400 km line.

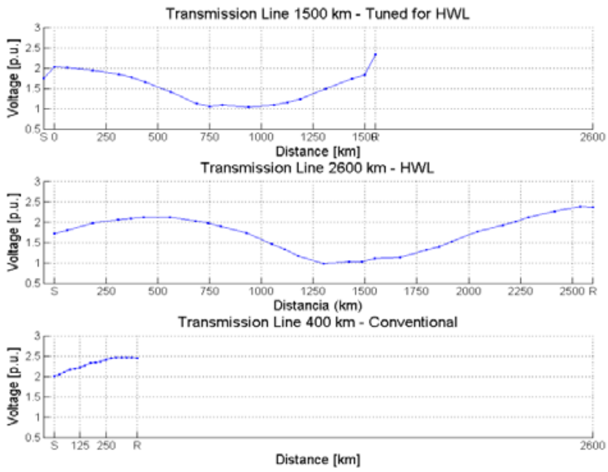

Fig. 15. Transient overvoltage profile along line for full load trip. Comparison for different lines.

Fig. 16 presents the voltage waveform at the receiving end measured before the circuit breaker. Voltages in the 1500 km line and 400 km line reach steady state in approximately 600 ms and 2600 km line takes 400 ms. In the first 5 cycles the transient responses of the 1500 km line and 2600 km line have lower frequency components than 400 km line. Another important result is that the sustained overvoltage after load trip is 1.2 p.u. for the long lines while for the 400-km line it is 1.5 p.u.

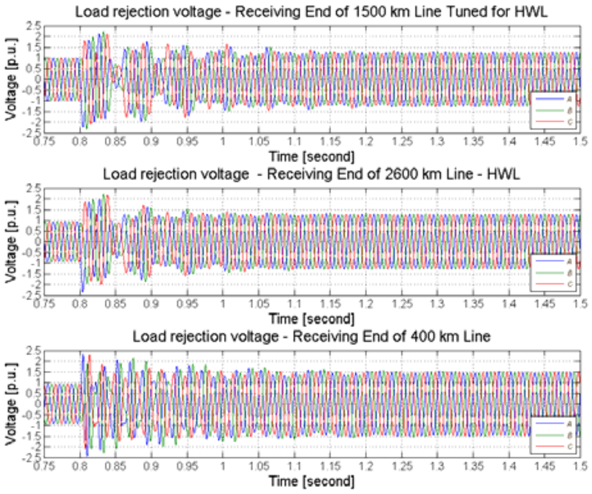

Fig. 16. Full load rejection voltage waveform at receiving end. Comparison for different lines.

V. CONCLUSIONS

This paper presents the main results for typical switching maneuvers for 1500 km long transmission line tuned for a HWL. It was also analyzed a 2600 km HWL line and a conventional 400 km shunt compensated line. The objective of analyzing all these lines was to properly compare the transient response.

After a careful analysis the tuning equipment used consisted of two shunt capacitors connected with a series reactor making a Pi circuit, placed at each line terminal. This tuning compensation has proved to best reproduce the half wavelength behavior under normal operating conditions. However, it is important to remark that the compensation is made only for positive sequence, leaving the original zero sequence of the 1500 km long line. This explains the differences observed during transient response, also related to a much smaller positive/negative and zero sequence attenuation. Besides, due to the reduced line length, the positive sequence travel time is much smaller.

For typical maneuvers such as energization, three phase reclosing and load rejection the transient response of the 1500 km line produces overvoltage levels similar to those obtained with 2600 km line, and they are also much smaller than those on conventional 400 km line. Also for line energization and three-phase reclosing, pre-insertion resistor mitigation control method produces similar overvoltage reduction for all three lines. For 1500 km tuned line and 2600 km HWL line, the fact that the switching overvoltages is basically made of fundamental frequency makes the controlled switching a non-efficient mitigation method.

For these very long lines, the actual transposition cycle representation is not important as the high harmonic orders attenuate along the lines. The overvoltages are basically generated by fundamental frequency transient response, which is similar for ideal or non-ideal transposed line representation, both for natural or tuned HWL lines.

Based on the studies the use of HWL can include transmission trunks with lengths above 1500 km, taking advantages of the half wavelength transmission properties, such as constant nominal voltage at line terminals, regardless of the load level. This can be an important feature for intermittent power plant transmission trunks.

The obtained overvoltages for the studied maneuvers are smaller than those of conventional transmission lines, what will result in low insulation level of system assets and enlarge their lifetime.

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