2019 International Symposium on Lightning Protection (XV SIPDA), São Paulo, Brazil, 30th September – 4th October 2019.

Overvoltage Suppression in Half-Wavelength Transmission Systems using Line Surge Arresters

Felipe Proença, Ronaldo F. R. Pereira, Eduardo C. M. Costa
Dept. Energy and Automation Engineering
Polytechnic School – University of S. Paulo (EP-USP)
São Paulo, Brazil
felipe.proenca.albuquerque@usp.br

Luisa Helena B. Liboni
IFSP – Federal Institute of Education, Science and Technology of S. Paulo
Sertãozinho, SP, Brazil
luisa.liboni@ifsp.edu.br

Abstract**—**The principal electric characteristics of half-wavelength transmission lines are discussed taken into account possible voltage transients resulted from asymmetric faults. Although this non-conventional technology has some attractive advances for electric power transmission through long distances, if compared to well-established HVDC and HVAC systems, important issues should be investigated concerning overvoltage levels along the transmission line due to temporary asymmetric operation conditions, e.g. phase-to-ground faults. Depending of the type of fault and location along the half-wavelength transmission line, overvoltage levels at some points through the line exceed 1.8 p.u. Thus, since some critical fault occurrences and overvoltage location are known, an alternative method for overvoltage suppression is proposed by using ZnO surge arresters directly at the phases in parallel with the tower insulators**.**

Keywords—half-wavelength transmission lines; ZnO surge arresters; electromagnetic transients; overvoltage suppression.

I. INTRODUCTION

Electric power transmission has been a great challenge in countries with continental territorial dimensions, environmental issues, rugged areas and various other geographic barriers. Transmission lines without corridors supported by tall steel towers, with more than 150 meter height, have been proposed to overcome natural barriers, such as: tropical forests, large rivers, flooded areas and ecological reserves [1, 2]. A recent example of this emerging technology is the Tucuruí-Macapá-Manaus interconnection across the Brazilian Amazon region that is composed of tall line sections with more than 200 meters height over the tropical forest and flooded areas [1].

A well-established technology for power transmission through long distances is the High-Voltage Direct Current – HVDC systems with bipolar and monopole topologies. Bipolar HVDC transmission systems using Line Commuted Converters (LCC-HVDC) is a mature technology for point-to-point power transmission through very long distances. The LCC-HVDC systems present several advantages if compared to conventional AC transmission systems: less power losses during transmission, point-to-point power control using the LCCs and no intermediary substations along the HVDC link. The Itaipu HVDC bipolar system is an emblematic example of this technology, which links the hydroelectric power plant of Itaipu (Foz do Iguaçu, Brazil), with installed power capacity of 12.000 MW, to Ibiuna converter substation (São Paulo, Brazil). Another example is the LCC-HVDC link from the Madeira hydroelectric complex to the São Paulo state, connecting the Northern Brazil to the Southeast region by a point-to-point transmission line with approximately 2.400 km length, which represents almost half wavelength of the fundamental voltage signal at 60 Hz. A half-wavelength line was suggested as an economic and technical attractive solution for the North-Southeast power transmission issue, however, the well-known HVDC technology was chosen as a more reliable and mature alternative [3, 4]. Although the theory provides various economic and technical advantages of the half-wavelength line compared to point-to-point HVDC systems, there are no practical reports on the reliability and effective performance to encourage substantial financial supports for project and construction of an AC half-wavelength transmission line. However, the half-wavelength technique is still a viable alternative for further transmission lines in Brazil, from unexplored hydroelectric potential in the North to the industrial centers in the South and Southeast, as well as other countries with continental territorial dimensions.

Another emerging HVDC technology that has been widely diffused in the Europe is the voltage source converters in modular multilevel converter topology for high-voltage direct (VSC-MMC-HVDC). This technology differs from the LCC-HVDC systems because the converters architecture is based on Insulated Gate Bipolar Transistors (IGBTs) and commuted by Pulse Width Modulation (PWM), which means that the commutation of the IGBTs is controlled varying the PWM, differently of the LCCs that are commuted from the AC signal frequency using thyristors. The VSC-HVDC technologies are a reliable solution for multi-terminal transmission systems with distributed generation, even for power transmission along very short distances [5, 6].

Some non-conventional methods were also proposed in order to improve the reliability and power transmission stability through medium and long distances. Such methods are only based on the line geometrical characteristics (distance between phases, bundle configuration, tower structure, cable characteristics etc) and electrical parameters. The technical literature proposes a four-phase transmission line in which the three-phase to four-phase conversion is carried out by a simple double Scott or Le Blanc arrangements using two power transformer at each line terminal. A four-phase line can continue operating as a three-phase line after a phase-to-ground fault with 100% and 85% of the nominal power under short-term and long-duration post-emergency conditions, respectively, improving the reliability of the system [7, 8]. Another example of alternative technology, to increase the power transmission through long distances, is the High Surge Impedance Loading Line (HSIL) that is characterized by asymmetrical configuration of the phase bundled conductors, varying the electric field distribution in the bundle and increasing the load profile of the transmission system by up to 25% more than a conventional transmission line [9, 10].

In the case of power transmission through very long distance, there is a constant search for more efficient and less costly alternative solutions. The half-wavelength technology for point-to-point power transmission is technically and economically viable for power transmission through long distances. For AC transmission lines longer than 1.500 km, the half-wavelength line would require less capital investment than an AC conventional transmission line with capacitive and inductive reactive compensation. Furthermore, half-wavelength systems have no problems with the Ferranti effect and excessive line loading current [11].

The recent literature has proved that half-wavelength transmission lines are technically and economically reliable considering transposed AC transmission lines under steady state operation [3]. However, some issues should be concerned during electromagnetic transients, overload operation and asymmetric faults (e.g. phase-to-ground fault). Although a few recent references have approached half-wavelength transmission systems under such specific operation conditions, more details and information are required for a more complete and reliable analysis on this emerging transmission technology [4, 12]. In this context, this research proposes a brief review on half-wavelength line theory followed by an in depth analysis on possible overvoltages resulted from unbalanced operation and fault conditions. In addition, some critical overvoltage levels are located along the line length during fault occurrences in some specific points of the line. From this procedure, an alternative technique for overvoltage suppression is proposed by using line ZnO surge arresters at specific locations along the half-wavelength transmission line. Simulations are carried out using the *Alternative Transient Program* – ATP and metal-oxide surge arresters are modeled using the IEEE standard circuit representation.

II. HALF-WAVELENGHT TRANSMISSION LINE

Initially, some theoretical issues are introduced in order to provide a background about half-wavelength power transmission systems. First, the voltage and current profiles as a function of the line length can be obtained from the two-port representation by distributed parameters, as expressed in (1) [11].

$$\begin{bmatrix} \hat{V}(x) \\ \hat{I}(x) \end{bmatrix} = \begin{bmatrix} cosh(\gamma x) & -Z_c\, sinh(\gamma x) \\ -\dfrac{1}{Z_c} sinh(\gamma x) & cosh(\gamma x) \end{bmatrix} \begin{bmatrix} \hat{V}_s \\ \hat{I}_s \end{bmatrix} \quad (1)$$

The voltage and current phasors $\hat{V}(x)$ and $\hat{I}(x)$, respectively, are expressed as functions of the line length in which the index x is the distance from the receiving end along the transmission line. Terms $\hat{V}_s$ and $\hat{I}_s$ are voltage and current phasors at the sending end of the line, respectively. The line constants Zc and γ are the characteristic impedance and propagation constant, respectively, which are dependent on the line series impedance *Z* and admittance *Y*. These are expressed as follows [13]:

$$\gamma = \sqrt{ZY} = \sqrt{(R + j\omega L)(G + j\omega C)} \quad (2)$$

$$Z_c = \sqrt{\frac{Z}{Y}} = \sqrt{\frac{(R+j\omega L)}{(G+j\omega C)}} \quad (3)$$

The series impedance is composed of resistance *R* and series inductance *L*, as expressed in (2) and (3). The admittance *Y* is composed of conductance G and a reactance as a function of the shunt capacitance *C*. The propagation constant is $\gamma = \alpha + j\beta$, where the real part is attenuation and the imaginary term is the phase delay or also know as phase constant. Usually, high voltage alternating current lines are characterized by low losses, i.e., the series resistance is neglected compared to the inductive reactance ($R \ll \omega L$). In these terms, the propagation constant is ideally expressed only by the phase delay $\gamma = j\beta$, without attenuation term α [13, 14].

Equation (1) can be expressed as a function of the voltages and currents at the sending and receiving ends, as follows in (4).

$$\begin{bmatrix} \hat{V}_s \\ \hat{I}_s \end{bmatrix} = \begin{bmatrix} cosh(\gamma l) & Z_c\, sinh(\gamma l) \\ \dfrac{1}{Z_c} sinh(\gamma l) & cosh(\gamma l) \end{bmatrix} \begin{bmatrix} \hat{V}_r \\ \hat{I}_r \end{bmatrix} \quad (4)$$

Since $R \ll \omega L$ and then $\alpha = 0$, the line wave length is expressed as:

$$\lambda = \frac{2\pi}{\beta} = \frac{2\pi}{\omega\sqrt{LC}} = \frac{1}{f\sqrt{LC}} \quad (5)$$

Considering a transmission line with f = 60 Hz, the half wave length is approximately 2.500 km [3]. In these terms, equation (4) can be analytically developed for a half-wavelength transmission line as follows in (6).

$$\hat{V}_e = \hat{V}_r cosh(j\beta l) + \hat{I}_r Z_c\, sinh(j\beta l)$$

$$\hat{V}_e = \cos\left(\frac{2\pi}{\lambda}\frac{\lambda}{2}\right)\hat{V}_r \rightarrow \hat{V}_e = -\hat{V}_r \quad (6)$$

The development in (6) shows that the voltages at the receiving and sending ends are similar and independent of the load. Thus, the half-wavelength line does not require reactive power compensation at the sending and receiving terminals. The relationship between currents at the sending and receiving ends is analogous to the voltage relationship in (6), i.e.:

$$\hat{I}_e = -\hat{I}_r \quad (7)$$

The voltage and current values can be also calculated at each point along the line considering a load impedance Z_L connected to the receiving end ($x = 0$), such as expressed in (8) and (9).

$$\hat{V}(x) = cosh(j\beta x)\ \hat{V}_r - Z_c\, sinh(j\beta x)\left(\frac{\hat{V}_r}{Z_T}\right) \quad (8)$$

$$\hat{I}(x) = -\frac{1}{Z_c} sinh(j\beta x)\, \hat{V}_r + cosh(j\beta x)\left(\frac{\hat{V}_r}{Z_T}\right) \quad (9)$$

The voltage and current magnitude profiles can be demonstrated along the line length x and varying the line load in figures 1 and 2, respectively.

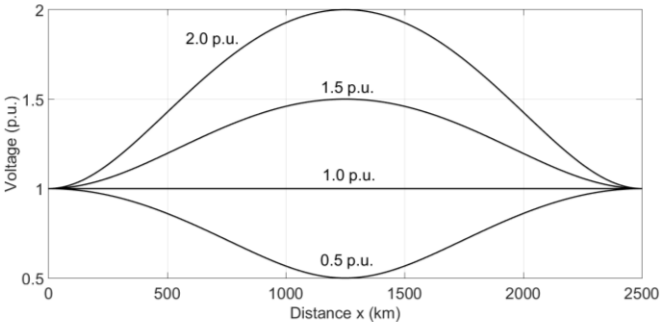

Fig. 1. Voltage along the half-wavelength line varying the loading.

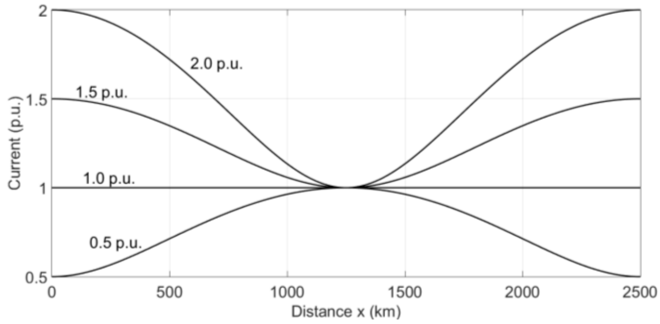

Fig. 2. Current along the half-wavelength line varying the loading.

Figure 1 shows that the voltage level at the terminals and line loading must to be both rigorously controlled in order to avoid overvoltages in middle sections of the transmission line. Thus, although half-wavelength transmission systems do not require substations and reactive compensation along the line length, both voltage and current (figure 2) at the terminals as well as line loading have to be constantly monitored and controlled.

The current at the sending and receiving ends are intrinsically related to the line loading, which is established in the technical literature as Surge Impedance Loading – SIL [13]. The half-wavelength line should operate with power demand close to the SIL in order to maintain the current at the terminals in nominal operation conditions, i.e. 1 p.u. This way, the power delivery has to be controlled in order to maintain the acceptable current levels at the line terminals.

III. Half-Wavelenght Transmission System and Line Surge Arrester Modeling

The analytic formulation presented previously shows the eventual overvoltage and current levels in which half-wavelength transmission systems are subject varying the power demand above the line surge impedance load. In this section, the half-wavelength system is modeled in the time domain using the Alternative Transient Program – ATP in order to analyze the voltage transients during fault occurrence. The line is modeled by a cascade with 100 π circuits.

The half-wavelength system and the line surge arresters are described in this section as follows.

A. Half-wavelength transmission system

The half-wavelength system parameters, electromagnetic constants and Thevenin impedances at the line terminals are described in tables I, II and III, respectively [3].

TABLE I. Impedance and Admittance Parameters

Zero Sequence			Positive Sequence		
R_0 (Ω/km)	X_0 (Ω/km)	B_0 (μS/km)	R_1 (Ω/km)	X_1 (Ω/km)	B_1 (μS/km)
0.3487	1.259	3.335	0.01276	0.2121	7.7642

TABLE II. Electromagnetic Constants

α	$3.3515\ 10^{-4}$ dB/km
β	$3.8585\ 10^{-5}$ Np/km
Z_c	$165.44e^{-j1.72°}$ Ω
P_c	6042 MW
v	293623 km/s
λ	4894 km
λ/2	2447 km

TABLE III. Thevenin Impedance

Terminal	Zero Seq.	Positive Seq.
Sending (S)	$0.206 + j14.434$ Ω	$0.206 + j14.434$ Ω
Receiving (R)	$1.444 + j28.868$ Ω	$1.444 + j28.868$ Ω

The sequence impedance and admittance parameters are presented in table I. Table II shows the electromagnetic and propagation constants of the line: attenuation, phase constant, characteristic impedance, surge impedance load P_c, propagation velocity and wave length of the line at 60 Hz. The Thevenin impedance at the sending and receiving ends of the line are given in table III.

A single-circuit three-phase transmission line is modeled in the ATP with 2500 km of length, nominal voltage 1.0 MV and following the electrical and electromagnetic characteristics in tables I, II and III [3]. The modeled transmission line is a few kilometers longer than half wavelength (53 km), such as indicated in table II (λ/2 = 2447 km).

B. Metal-oxide surge arrester modeling

Surge arresters are basically defined from the previous knowing of the Continuous Operating Voltage (nominal voltage of the system) and the Maximum Continuous Operating Voltage – MCOV, which is the maximum designed rms value of power frequency voltage that may be applied continuously between the terminals of the arrester. From these technical specifications, other technical characteristics of the surge arrester can be defined, such as the nominal voltage and power classification. However, the surge arrester selection is not a trivial task; other technical specification should be taken into account, e.g. the Temporary Overvoltage Curve – TOV, which comprehend to a graph that shows the power frequency withstand voltage as a function of the time for arrester from 10 ms to 100 s [15].

A relationship between the MCOV U_C and the nominal voltage of the system U_S is expressed as follows [15]:

$$U_C \geq 1.05 \frac{U_S\sqrt{2}}{\sqrt{3}} \quad (10)$$

The nominal voltage of the surge arrester can be determined as a function of U_C and an empiric constant in (11).

$$U_r \geq 1.25\, U_C \quad (11)$$

The half-wavelength transmission system has a nominal operating voltage of 1.0 MV. Thus, the MCOV obtained from (10) is UC ≥ 857.32 kV. However, half-wavelength lines present abrupt voltage surges due to variations in the line loading. This way, a higher MCOV of 923 kV and nominal voltage of 1.154 MV are determined for the line surge arresters of the half-wavelength system. These values are also calculated based on the nominal discharge current, which varies from 1.5 kA up to 20 kA, and discharge class that is associated with the arrester capacity to dissipate energy during switching and lightning surges [15, 16]. The nominal voltage and MCOV are defined in the first region of the TOV curve that is characterized by a low leakage current with capacitive nature.

Since the electrical parameters of the surge arresters are calculated based on available information in the manufacturer's datasheet and the transmission system, the line surge arresters can be modeled by means of the equivalent electric circuit in figure 3 [17].

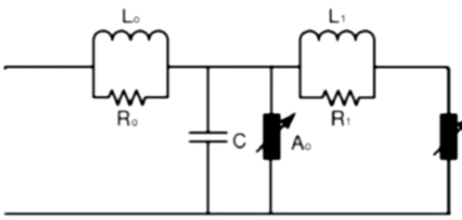

Fig. 3. Equivalent electric circuit of metal-oxide surge arresters.

The nonlinear behavior of the leakage current as a function of the residual voltage on the metal-oxide arrester is represented by the variable resistances A_0 and A_1. These two nonlinear resistances are connected with two RL filters composed of R_0, R_1, L_0 and L_1.

The nonlinear elements are calculated based on the circuit response from a current signal 8/20 µs and peak of 10 or 20 kA, depending of the energy class of the surge arrester. The resistances and inductances are calculated using analytic formulation based on constructive characteristics of the surge arresters, e.g.: height and quantity of varistor columns [18].

The capacitance C is also calculated from an analytic formulation and represents the capacitive leakage current when the surge arrester is operating in region 1, i.e., in steady state and nominal voltage levels of the transmission system [17].

Thus, the line surge arresters are modeled based on the transmission system specifications, MCOV and nominal voltage, as established in the technical literature [17, 18]. The equivalent circuit modeled in the ATP is described in figure 4.

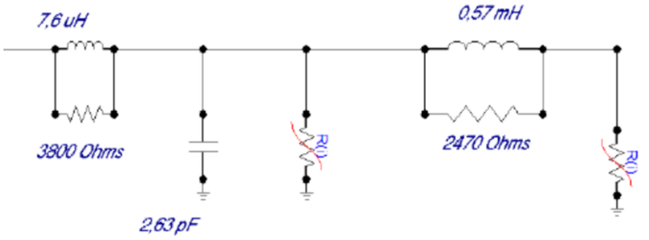

Fig. 4. Equivalent electric circuit of the line surge arresters in the ATP.

The modeled arrester in figure 4 is firstly validated using the Heidler function to apply an atmospheric impulse of 10 kA 8/20 µs. The residual voltage should not exceed 1.82 p.u., such as described in the technical literature. In this context, the residual voltage on the modeled arrester is no more than 0.4% of suggested voltage value, which validate the surge arrester modeling for the 1000-kV transmission line protection.

Figure 5 shows the leakage current through the line arrester modeled based on the circuit in figure 4, which was simulated using the software ATP. The phase voltage on the line surge arrester is 800 kV.

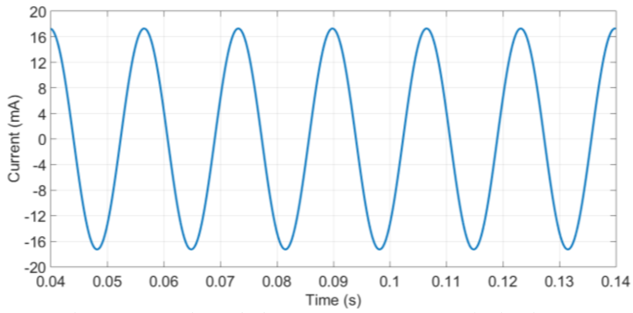

Fig. 5. Leakage current through the surge arrester on nominal voltage.

The peak leakage current is approximately 17 mA in nominal operation condition in steady state, which is in accordance with conventional values for transmission systems with more than 500 kV.

The same surge arrester in figure 4 is applied to content temporary overvoltages during phase-to-ground faults in half-wavelength transmission lines, which are also modeled in the ATP by a cascade with 100 π circuits.

IV. TEMPORARY OVERVOLTAGE ANALYSIS AND SUPPRESION

The three-phase transmission system was modeled in the ATP following the characteristics presented previously in tables I, II and III by means of a cascade with 100 π circuits and constant lumped parameters, i.e. R, X and B (table I).

An iterative procedure was carried out for simulation of phase-to-ground faults along the line length. This type of fault corresponds more than 70% of the faults in distribution and transmission systems. Thus, the phase-to-ground, also known in the technical literature as single-phase fault, was considered during this research. More than 250 simulations were carried out in different points along the line length and the maximum overvoltage and respective location were registered. This way, the highest overvoltage points are located as a function of the fault occurrence along the line length. According with the technical literature, temporary overvoltage levels in UHV transmission systems should be from 1.8 up to 1.9 p.u. [19].

Since the most critical overvoltage are predicted, ZnO surge arresters can be included in such points of the line in order to suppress the eventual temporary overvoltages simulated using the ATP. All cases were simulated considering the voltage at the line terminals and SIL fixed at 1 p.u., which is in fact a premise for stable operation of half-wavelength transmission systems, as demonstrated in section II.

The most critical situation was observed in phase-to-ground fault occurred around 1770 km from the sending end of the line. Overvoltage levels with more than 2.2 p.u. were observed during simulations at 625, 730 and 830 km from the sending end on the same faulty phase. To content these excessive voltage levels, line surge arresters were included in these critical points of the line in order to maintain the temporary overvoltage under 1.9 p.u. The voltage profile, with and without line arresters, and leakage current are described in figures 6, 7 and 8.

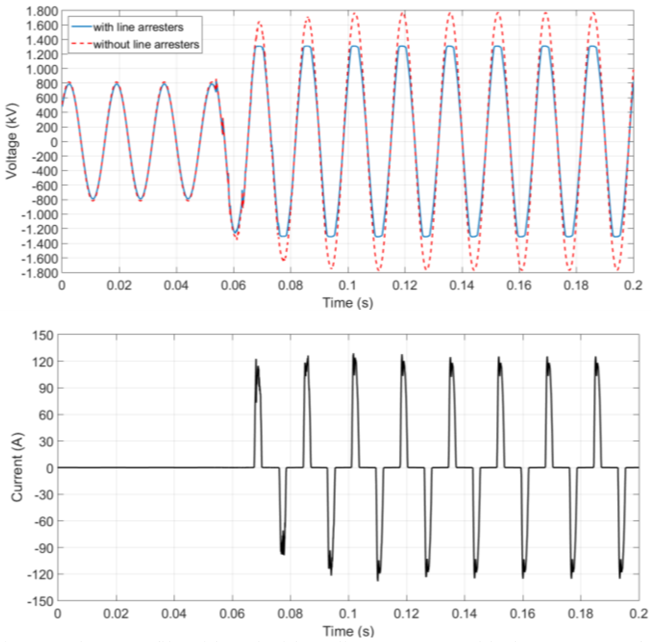

Fig. 6. Voltage profile with and without line arresters and leakage current of the surge arresters at 625 km from the sending end of the line.

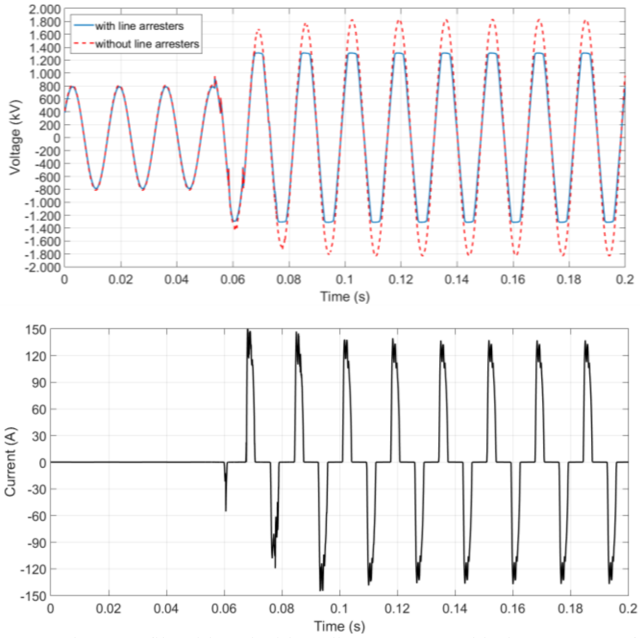

Fig. 7. Voltage profile with and without line arresters and leakage current of the surge arresters at 730 km from the sending end of the line.

Figures 6 and 7 show that the line surge arrester suppresses the overvoltage at 625 and 730 km from the sending end of the line. The overvoltage levels without surge arresters lead to more than 2.2 p.u. whereas the presence of line arresters at these critical line sections, the voltage remains approximately 1.6 p.u., which is in agreement with the insulation coordination standards for UHV transmission systems [19].

Figure 8 describes the voltage profile with and without line arresters at 830 km from the line sending end, and the leakage current profile of the line surge arrester during the overvoltage suppression.

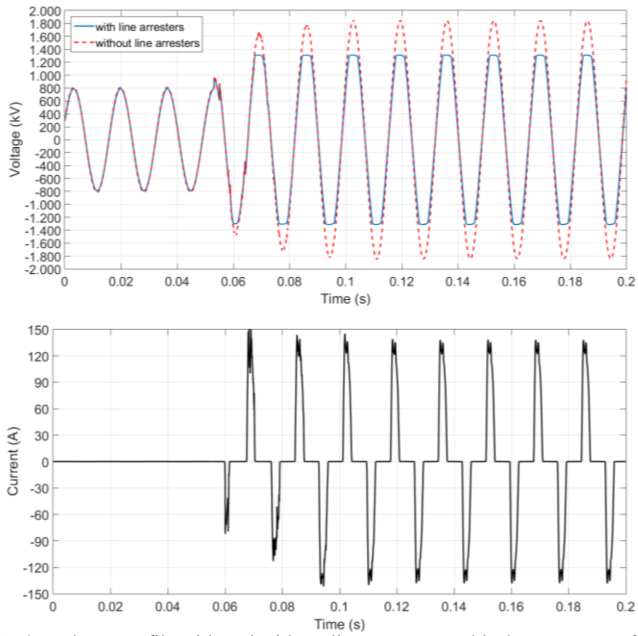

Fig. 8. Voltage profile with and without line arresters and leakage current of the surge arresters at 830 km from the sending end of the line.

V. Conclusion

Half-wavelength transmission systems prove to be a reliable technology for electric power transmission through long distances, therefore representing an alternative to the well-established point-to-point HVDC transmission systems composed of line commuted converters – LCC. However, as discussed in section II, half-wavelength transmission systems require some additional attention in voltage and power/load control at the sending and receiving ends of the line.

Another important issue about this non-conventional transmission technology is the possible overvoltages along the line that are resulted of asymmetrical operation conditions and fault occurrences. The observed overvoltage levels during some fault conditions are more than 2.2 p.u. at some points of the line, such as demonstrated in this paper. In this context, the inclusion of line surge arresters in possible overvoltage points shows to be an efficient method to maintain acceptable voltage level at some critical line sections, no more than 1.6 p.u.

However, a more meticulous analysis is required to identify other possible overvoltage points along the line during occurrence of phase-to-ground fault as well as other types of fault (double-phase, double-phase-to-ground and three-phase faults). Furthermore, since the most critical fault conditions are known and possible overvoltage locations are mapped in the system, the line surge arresters can be strategically installed at the most critical line sections in order to suppress overvoltages resulted from different types of fault. In addition, another important issue for further researches is the analysis on the quantity and location of arresters installed along the line in order to determine an optimized financial cost and benefit relationship.

VI. Acknoledgement

Fundação de Amparo à Pesquisa do Estado de São Paulo – FAPESP (Proc. 16/16078-7).

Conselho Nacional de Desenvolvimento Científico e Tecnológico – CNPq (Proc. 306142/2015-5).

Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – CAPES.

VII. References

[1] A. J. G. Pinto, E. C. M. Costa, S. Kurokawa, J. Pissolato, “Analysis of the electrical characteristics of an alternative solution for the Brazilian-Amazon transmission system”, Electric Power Components and Systems, vol. 39, 2011, pp. 1424-1436.

[2] S. Kurokawa, E. C. M. Costa, A. J. G. Pinto, J. Pissolato, “Analysis of electric characteristics of high-elevation stretches of the Tucuruí-Macapá-Manaus connection”, Journal of Control, Automation and Electrical Systems, vol. 24, 2013, pp.714-724.

[3] M. L. Santos, J. A. Jardini, R. P. Casolari, R. L. V. Arnez, G. Y. Saiki, T. Sousa, G. L. C. Nicola, “Power transmission over long distances: economic comparison between HVDC and half-wavelength line”, IEEE Trans. Power Delivery, vol. 29, 2014, pp. 502-509.

[4] R. G. Fabian, M. C. Tavares, “Faulted phase selection for half-wavelength power transmission lines”, IEEE Trans. Power Delivery, vol. 33, 2017, pp. 992-1001.

[5] R. Itiki, S. G. Di Santo, E. C. M. Costa, R. M. Monaro, “Methodology for mapping operational zones of VSC-HVDC transmission system on offshore ports”, International Journal of Electrical Power & Energy Systems, vol. 93, 2017, pp. 266-275.

[6] V. A. L. Freitas, D. V. Coury, R. M. Monaro, “LCL filter design for VSC-HVDC systems supplying passive grids”, Electric Power Systems Research, vol. 152, 2017, pp.160-167.

[7] G. Mazzanti, S. Quaia, “Four-phase AC connections: an alternative possibility for the expansion of transmission grids”, IEEE Trans. Power Delivery, vol. 25, n. 2, 2010, pp.1010-1018.

[8] S. Kurokawa, E. C. M. Costa, I. S. Brandt, J. Pissolato, “New approach to four-phase transmission systems: analysis of the transient response and the possible voltage surges”, IET Gener. Trans. Distri., vol. 6, 2012, pp. 387-394.

[9] A. S. Farag, J. M. Bakhashwain, A. Al-Shehri, Y. Gao, “Bundled conductor configuration optimization for compact transmission lines incorporating electromagnetic fields management”, Electric Power Systems Research, vol. 39, n. 10, 1998, pp. 1053-1071.

[10] J. S. Acosta, M. C. Tavares, “Methodology for optimizing the capacity and costs of overhead transmission lines by modifying their bundle geometry”, Electric Power Systems Research, vol. 1, pp. 1-10 [online].

[11] F. J. Hubert, M. R. Gent, “Half-wavelength power transmission lines”, IEEE Trans. Power App. Syst., vol. PAS-84, n. 10, 1965.

[12] E. A. Silva, F. A. Moreira, M. C. Tavares, “Energization simulations of a half-wavelength transmission line when subject to three-phase faults – application to a field test situation”, Electric Power System Research, vol. 138, 2016, pp. 58-65.

[13] P. Kundur, Power system stability and control, 3rd ed., vol. 7. New York: McGraw-Hill, 1994.

[14] W. D. Stevenson Jr. Elements of power system analysis. McGraw-Hill, 1962.

[15] IEC 60099-4, Surge arresters – part 4: metal-oxide surge arresters without gaps for a.c. systems, 2nd ed., 2004-2005.

[16] IEC 60060-1, High-voltage test techniques – part 1: general definitions and test requirements, 2nd ed., 2009-2010.

[17] F. P. Albuquerque, L. F. N. Lourenço, E. C. M. Costa, S. Kurokawa. “Surge arrester modeling for electromagnetic transient analysis in power systems”. In International Symposium on Lightining Protection – XIV SIPDA, Natal, RN, Brazil, 2017.

[18] IEEE Working Group on Surge Arrester Modeling, “Modeling of metal oxide surge arresters”. IEEE Trans. Power Delivery, vol. 7, n. 1, 1992, pp. 302-309.

[19] F. M. Gatta, F. Iliceto. “Analysis of some operations problems of half-wave length power transmission lines”, 3rd AFRICON Conference, IEEE, 1992.