A Real Time Reduction of Spurious Oscillations Inherent of Lumped Parameters Line Model

A. R. J. Araujo, S. Kurokawa, A. Shinoda, E. C. M. Costa

***Abstract*-- This paper proposes a simple and efficient procedure to reduce spurious oscillations, characterized by high-frequency and erroneous magnitude peaks, in electromagnetic transient simulations from Lumped Parameter Model (LPM). This method consists to include adequate analog filters into the classic LPM and the proposed model (consisting of LPM plus analog filters) is developed directly in time domain and can be directly inserted in Transients Programs such as EMTP and ATP. A single and three-phase transmission line were used to simulate the energization procedure and the results demonstrate these high inherent peaks from the LPM were meaningly mitigated and the proposed model can be used for simulation in electromagnetic transients on power systems.**

***Index Terms*-- Electromagnetic transients, Frequency Domain, Lumped parameters, Time domain, Spurious oscillations, Transmission line model.**

I. Nomenclature

LPM-Lumped Parameter Model.
ULM-Universal Line Model.

II. Introduction

It has been knowing that an efficient representation of transmission lines must take into account the fact that longitudinal and transversal parameters are distributed along the line length [1,2]. Due to this consideration, the currents and voltages along the line are described by differential equations (telegrapher's equations) whose solutions directly in time domain are not easily solved. Since 1960 decade several researchers have been dedicating efforts to develop and to improve computational transmission line models for simulating electromagnetic transients in electric power systems.

For simulations of the electromagnetic transients resulting from sudden changes in the network configuration, such as, switching, faults and opening/closing breakers in power systems, LPM can be used as an efficient model to represent single-phase and multiphase lines [3, 4, 5].

Lumped parameters representation of a single-phase transmission line considers that a line segment can be represented by lumped resistors, capacitors and inductors association constituting a π circuit and, consequently, a long transmission line is approximated by π-circuits cascade [6]. For representing multiphase lines, modal decomposition theory is used and an *n* phase transmission line can be represented in modal domain as being *n* uncoupled single-phase lines [4, 5,7-10]. This line model is an efficient representation for transmission lines in electromagnetic transient simulations and it is also developed directly in time domain, being fully compatible with Electromagnetic Transient Programs such as EMTP and ATP. The LPM also has the advantage of considering the nonlinear components inserted in the line, the loss for corona effect and fault arcs [11].

However, simulation evaluated with LPM is characterized by intrinsic high-frequency components associated by spurious oscillations that produce a general distortion of the wave shapes and exaggerated magnitude peaks. This phenomenon is not present if distributed parameter transmission line models are used for the line representation. These models are obtained directly from solutions of the differential equations written in frequency domain and, consequently, but cannot be inserted in in EMTP or ATP programs because they are developed directly in frequency domain [12, 13]. The mitigation of the spurious oscillations in the simulations from LPM was proposed by [14] which a digital filter reduced the intrinsic high-frequency components. As an alternative to improve the reduction procedure last described, this paper proposes to substitute the digital filter by analog filters. The advantage of this substitution is that analog filters can be directly inserted in the LPM and proposed model in an efficient and friendly tool to represent transmission lines for electromagnetic transient simulations.

The performance of the proposed model, some energization procedures of single and three-phase untransposed transmission line are carried out. In the simulations, the transmission line was represented by the proposed model, by traditional LPM and by a classic distributed parameter line model developed in frequency domain (being a standard model called *Universal Line Model* or ULM) [12]. The results obtained showed improved LPM is as efficient as ULM but the first one has the advantage of being developed directly in time domain, while the ULM requires numeric inverse Laplace

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Transform [12,13].

III. Lumped Parameters Transmission Line Model

A line segment can be represented, considering an adequate frequency range, as being a π-circuit cascade constituted by lumped circuit elements [6]. Consequently a single phase transmission line can be represented as shown in Fig. 1.

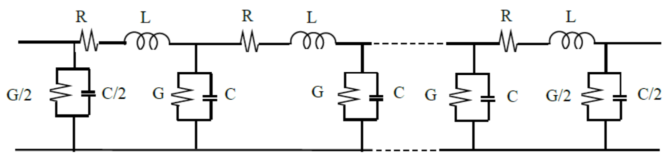

Fig. 1. Single phase line represented by a cascade of π circuits.

In Fig. 1 *R* and *L* are the longitudinal resistance and inductance and the elements *C* and *G* are the transversal capacitance and conductance of the line segment respectively, being written as:

$$R = R'\frac{d}{n} \quad L = L'\frac{d}{n} \quad C = C'\frac{d}{n} \quad G = G'\frac{d}{n} \qquad (1)$$

In (1), the R' and L' are the per unit length longitudinal parameters and C' and G' are the per unit length transversal parameters. In the representation of a single phase line by a π-circuit cascade there is an important relation that should be considered in the analyses: is the rate between the number of π circuits (*n*) and the length line (*d*). In this paper will be denominated *k*, given by:

$$k = \frac{n}{d} \qquad (2)$$

For the circuit shown in Fig. 1 it is possible to write the longitudinal current and transversal voltage as a state equation form and easily solved, directly in time domain, by any numerical integration method. This fact makes the LPM useful to represent transmission lines in transient simulations considering nonlinear components such as corona effects and fault arcs [11]. However, LPM has as negative aspect which introduces high frequency components and exaggerated magnitude peaks in the simulations, as it will be shown in following.

IV. Characteristics of the LPM and ULM

The characteristics of the LPM and ULM will be compared in the electromagnetic transient simulations with these models. A 100 km single-phase transmission line, submitted to energization procedure by a 1 p.u., 60 Hz, cosine voltage source as it is shown in Fig.2. The transmission line was represented by LPM (by 100 π-circuits cascade) and by ULM.

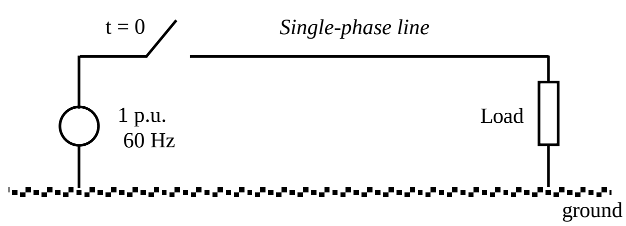

Fig. 2. Energization procedure of a single-phase transmission line.

The per unit length parameters of the line were calculated by using classic formulations [15] resulting in R' = 0.05 Ω/km, L' = 1.7 mH/km, G' = 0.556 μS/km and C' = 6.58 ηF/km and a resistive load equal to 2000Ω. All the simulations were performed in MatLab®.Voltages at the receiving end are shown in Fig. 3.

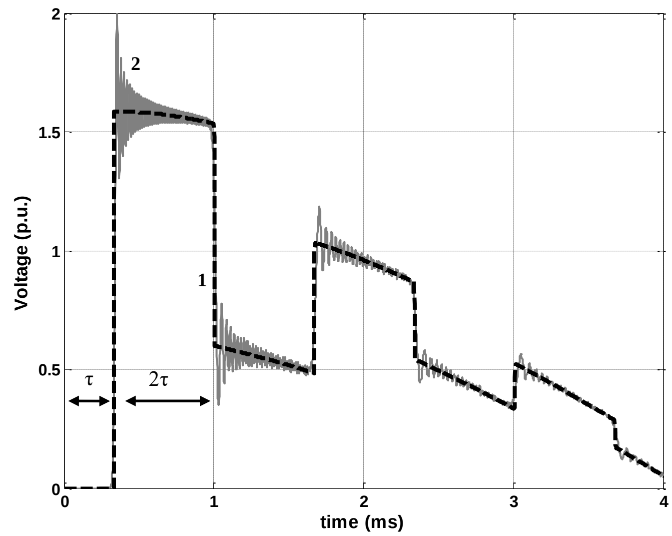

Fig. 3. Receiving end voltage: Universal Line Model (1) and Lumped Parameters Model (2).

This is a typical transient response for receiving end with a resistive load in transmission line. In Fig. 3 one can observe that ULM transient response can be described as a dumped periodic function and the LPM response is composed by the superposition of the ULM response with the high frequency oscillations (spurious oscillations). The frequency of the spurious oscillations considering the π-circuits used in line representation (parameter *k*) and the length line was evaluated from 100 to 500-km lines, taking into account several values for *k* as depicted in Fig. 4.

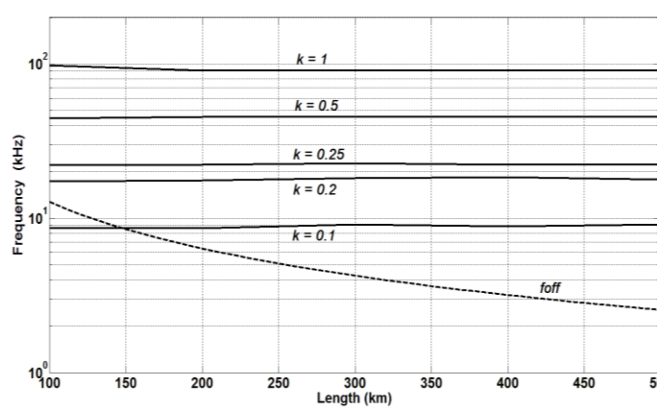

Fig. 4. Frequency of the spurious oscillations for several values of the *k* and length line

Fig. 4 shows spurious oscillations frequency practically does not vary in function of line length, being just dependent of parameter *k*. So this parameter is very important during the project of the analog low pass filter to reduce the spurious oscillations.

V. Frequency Spectrum of the ULM

The frequency spectrum of the ULM responses can be analyzed using the energization procedure shown in Fig. 2. In Fig. 3, τ is the time interval required for the voltage wave to go from sending to the receiving end. Considering that voltage wave travels with speed of the light, the time interval τ is given by:

$$\tau = \frac{d}{c} \tag{3}$$

In (4) c is the speed of the light and d is the line length. The voltage at the receiving end in Fig. 3 during transient conditions is a dumped periodic function written as:

$$v_r(t) = \left(\cos(2\pi f(t-\tau)) + x(t-\tau)e^{-a(t-\tau)}\right)u(t-\tau) \tag{4}$$

In (5) f is the frequency of the voltage at the sending end of the line, $x(t)$ is a symmetric rectangular wave with amplitude ± 0.5 p.u. and $u(t)$ is a unit step function with period 4τ. The function $x(t)$ is written as being:

$$x(t) = \frac{2}{\pi}\sum_{n=0}^{\infty}\frac{(-1)^n}{2n+1}\cos(2\pi(2n+1)f_0 t) \tag{5}$$

In (5) f_0 is the fundamental frequency of the $x(t)$. From Fig. 3 it is possible to obtain the frequency f_0 given by:

$$f_0 = \frac{1}{4\tau} = \frac{c}{4d} \tag{6}$$

This equation shows that frequency f_0 is inversely proportional to the length line. Observing Fig. 3 the LPM is composed by the response of the ULM superposed with high frequency oscillations. The f_0 is represented by the dashed-curve in Fig.4 (f_{off}). The project of the filter must take into account that the filter will mitigate the high frequency oscillations but cannot affect the response of the ULM. Because the frequencies of the spurious oscillations are higher than the frequency of the response of the ULM, it is necessary to use a passive low pass filter to improve the performance of the LPM. Several passive low filters were tested and it was verified that the best performance was achieved with an adapted π-filter, whose circuit is shown in Fig. 5.

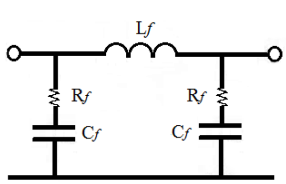

Fig. 5 Passive low p ıs oscillations.

From the circuit of the filter shown in Fig. 9 it is possible to calculate its cut off frequency whose expression is written as:

$$f_c = \frac{1}{2\pi}\left[\frac{\beta + \sqrt{\beta^2 + 4L_f^2 C_f^2}}{2L_f^2 C_f^2}\right]^{\frac{1}{2}} \tag{7}$$

Where

$$\beta = R_f^2 C_f^2 - 2L_f^2 C_f^2 \tag{8}$$

The filter cannot reject frequencies less than the frequency f_0, defined in (6). Using eq. (5), it was established that 8th harmonic frequency of $x(t)$, whose frequency is 17 times the fundamental frequency of $x(t)$, is the maximum frequency for the low pass filter. Thereby, in this article will be considered that components of $x(t)$ can be disregarded after the maximum frequency:

$$f_{max} = 17\, f_0 = \frac{17c}{4d} \tag{9}$$

In (9) that frequency f_{max} is function of the length line. The proposed filter must mitigate the spurious oscillations inherent of the LPM and the cut off frequency of the filter (f_c) must be less than spurious oscillations (f_s) but the filter should not filter the f_{max} for not distort the transient response.

$$f_{max} < f_c < f_s \tag{10}$$

According to Fig. 4 the maximum cut-off frequency (black) depends on the line length and it also show how the maximum frequency of spurious oscillations behaves. The f_s increases for when k also increases, that suggests that the number of oscillations in the simulation will enlarge during transient. For 150 km line length and k = 1/10 is not possible to design a low pass-filter using this methodology. Once the low pass filter is established, it will be included in the LPM. It was observed that better results are obtained when one filter is inserted at each end of the line represented by a LPM as shown in Fig. 6.

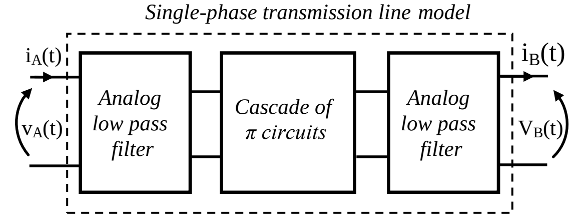

Fig. 6. LPM with two low pass filters (proposed model).

VI. Applications in Single Phase Lines

The same single-phase line represented by n-circuits cascade in Fig. 2 was used to evaluate the transient response for the proposed and classical model. In the simulations from Fig.7-9, it will used the value of k=1. Considering the cut off frequency equal to 60 kHz and by using (7) and (8) the low pass filter was defined with components L_f = 0.5 mH, C_f = 10.0 ηF and R_f = 800 Ω. In Figs. 7 to 9 are presented the voltage at the receiving end of the line. Curves 1 and 2 show results obtained with classical and proposed model, respectively.

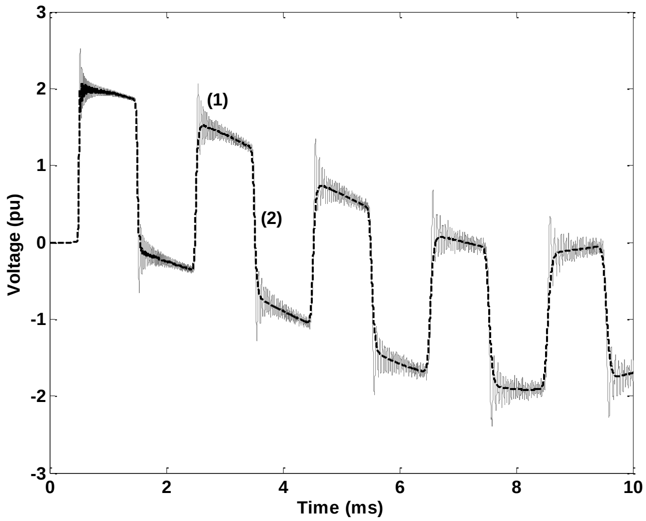

Fig. 7. Receiving end voltage for 150 km single-phase line: Classical (curve 1 - grey line) and proposed model (curve 2 - dotted line).

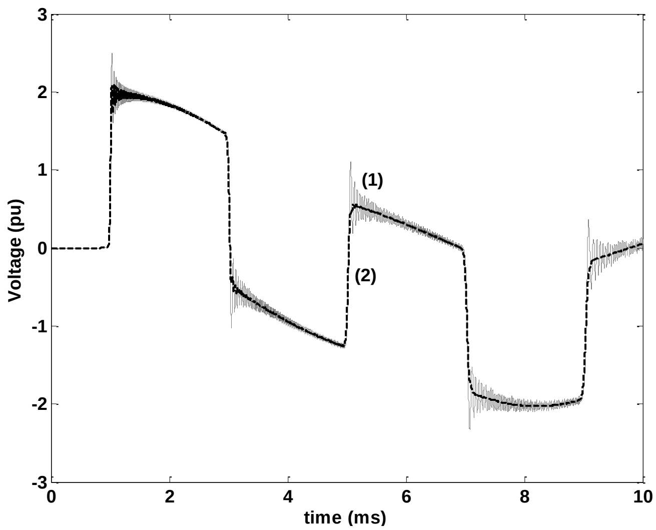

Fig. 8. Receiving end voltage for 300 km single-phase line: Classical (curve 1 - grey line) and proposed model (curve 2 - dotted line).

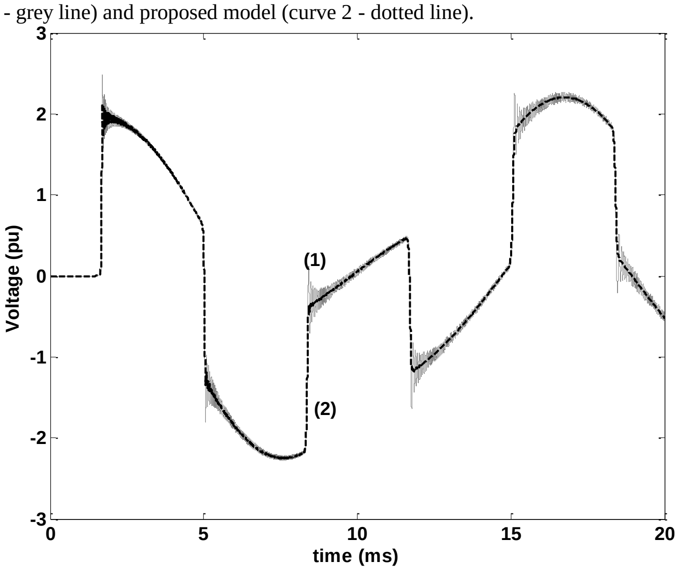

Fig. 9. Receiving end voltage for 500 km single-phase line: Classical (curve 1 - grey line) and proposed model (curve 2 - dotted line).

Figs 7 to 9 showed that the proposed filter specified for diverse line lengths presents a good performance reducing the spurious oscillations. The dotted-line presents more accurate results when compared by classical model and the proposed model can be used for studying the transient in transmission lines.

VII. Applications in Three Phase Lines

The single phase LPM is used to represent three phase lines if modal decoupling theory is applied. A coupled three-phase line is represented in modal domain as being three single-phase lines, named *propagation modes*. Then, the currents and voltages are calculated in modal domain and, after that, the phase currents and voltages are obtained by using a modal transformation matrix [7-10].

In Fig. 10, phase-mode transformation matrix decouples the three-phase line into its uncoupled propagation modes. Then, each propagation mode is represented in modal domain as being a single-phase line and currents and voltages in modal domain are calculated. After that, by using a mode-phase transformation matrix, currents and voltages are calculated in phase domain.

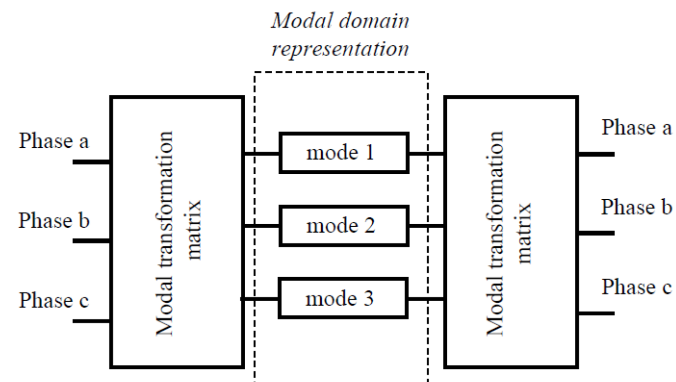

Fig. 10. Three-phase line represented in modal domain

The transient analyses are performed on 100 km 440-kV untransposed three-phase transmission line shown in Fig. 10.

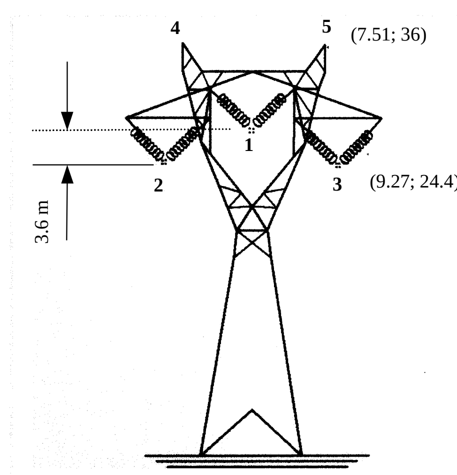

Fig. 11. 440-kV three-phase line structure.

In Fig. 11, each one of the phases is constituted by 4 Grosbeak conductors. The 4 and 5 are EHSW-3/8" ground wire and soil resistivity is 1000 Ω.m.

The line was energized by a synchronous three-phase generator at t=0 and, after 16.85 ms, a 2 p.u. DC voltage source was applied at the sending end of the phase 1 during 0.3 ms as shown in Fig. 12. This voltage degree was used to simulate a disturbance during the operation of the line in steady state.

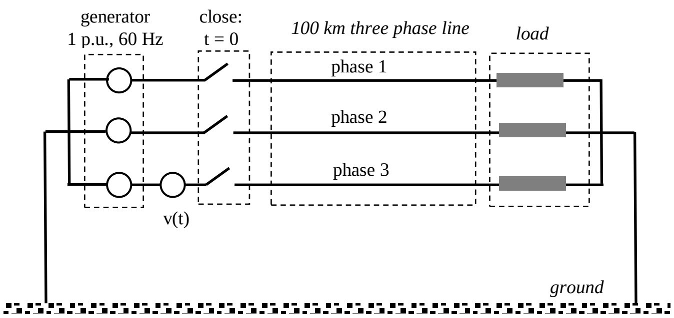

Fig. 12. Energization of the 440 kV line followed by an impulsive surge.

In Fig. 12 $v(t)$ is an impulsive voltage. This voltage source represents an impulsive voltage applied at the sending end of the line during its stead state operation and it is written as being:

$$v(t) = \begin{cases} 0\,;\ t \le 16.85\ \text{ms} \\ 2\ \text{p.u.};16.85 \le t \le 17.15\ \text{ms} \\ 0;\, t > 17.15\ \text{ms} \end{cases} \quad (11)$$

The simulations were evaluated considering that each propagation mode shown in figure 7 was represented by using the ULM and the classic and proposed LPM Results obtained with these models are shown in Figs. 13-15.

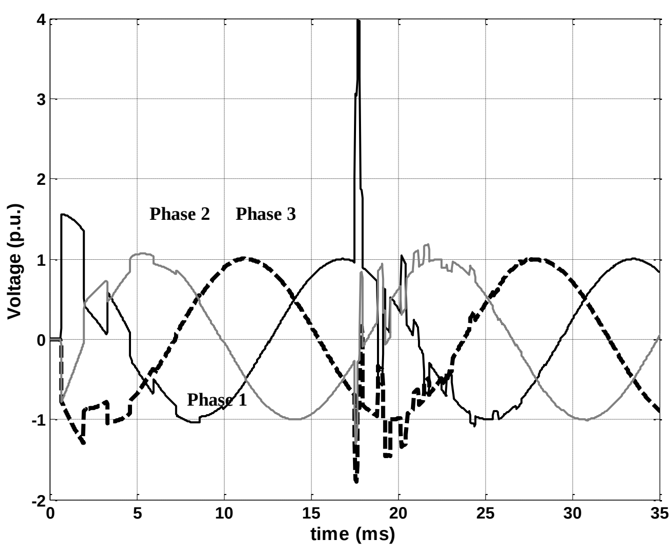

Fig. 13. Simulated voltages at the receiving end of the line (using ULM).

Simulation results obtained with ULM, showed in Fig. 13, will be considered as reference results. Fig.14 contains higher frequency spectrum and exaggerated magnitude peaks during transient operation of the line as expected.

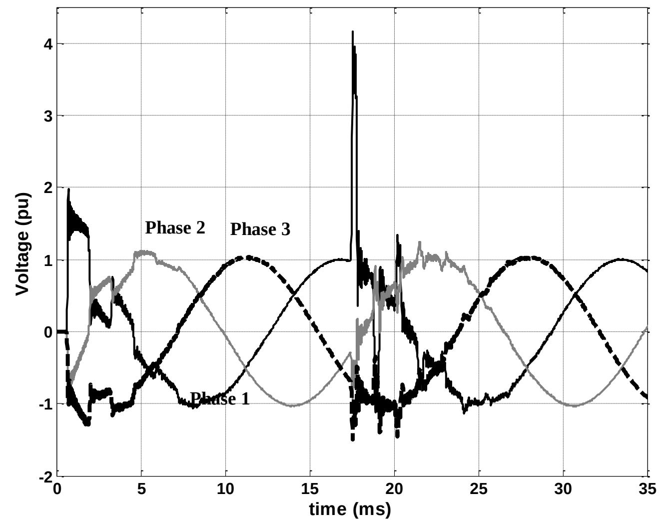

Fig. 14. Simulated voltages at the receiving end of the line (using lumped parameters line model).

The magnitude of the higher frequency spectrum resulting from LPM is observed during all transient time and the peaks can be observed at the initial instants after energization of the line (taking into account results obtained with LPM, overvoltage in phase 1 is 2 p.u., but results obtained with ULM show that the value of this overvoltage is approximately equal to 1.5 p.u).

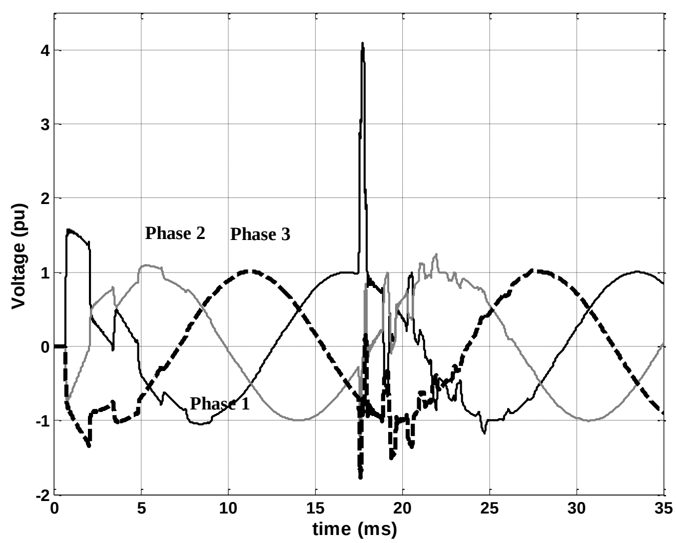

Fig. 15. Simulated voltages at the receiving end of the line (using proposed line model).

When results obtained with ULM are compared with proposed model, which are shown in Fig. 15, one observes that proposed model practically eliminates higher frequency spectrum. The overvoltage peaks resulting from simulations evaluated with ULM is equal to value obtained with proposed model. This way, taking into account results obtained, the inclusion of two analog filters in the LPM improve the performance of this line model. One observes that the excessive peaks of the transient are caused by the spurious oscillations, but even for the filtered responses, their format is the same, reducing just the peaks.

VIII. Conclusions

This work has presented the improvement of the lumped parameters transmission line model also used to study the electromagnetic transient in power system. The improvement consist to include analog low pass filters at the sending and receiving ends of the single phase line represented by π-circuits cascade. This procedure did the results obtained with proposed model more realistic when compared with classical lumped parameters line model. Using the proposed model, the high frequency spectrum was mitigated and the peaks were reducing to values obtained with Universal Line Model. The proposed filtering process is done simultaneously with the evolution of the simulations, because the low pass filters are inserted in the transmission line model, differently when it is used the digital filters for filtering in transient analysis. Then the proposed line model is an efficient and friendly tool to represent transmission lines during simulations of the electromagnetic transients. If were considered the frequency dependence on the distributed parameters, the simulations will not have the spurious oscillations, because that characteristic on the line parameters acts as a natural filter. The proposed model is a time domain model; it can be easily inserted in electromagnetic transient programs such as ATP and EMTP.

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