A Proposal to Represent in Tree-Phase Transmission Lines Directly in Time Domain

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***Abstract*— In this paper is being proposed a lumped parameters model to represent multiphase transmission lines directly in phase domain. The proposed model is based on the idea that a small multiphase line segment can be represented by lumped parameters and the resulting circuit takes into account the mutual phase coupling of this small line segment. After that, a cascade of the resulting circuit before mentioned is used to represent a long multiphase transmission line directly in phase domain. To validate the proposed model, it was considered an ideally transposed three-phase line submitted to open and short circuited tests. The main advantage of the proposed model is that it is developed directly in phase domain without to use modal decomposition theory and, therefore, it can be used to model symmetrical and unsymmetrical lines.**

***Index Terms*-- Transmission line model, phase domain, time domain, lumped parameters, unsymmetrical line.**

I. Introduction

It is known that an important characteristic of the transmission lines is the fact that its longitudinal and transversal parameters are distributed along the length and this characteristic needs to be taken account during electromagnetic transient simulations [1].

However there are situations where lumped parameter transmission line models can be used, like as analysis of transient current and voltages on transmission lines with nonlinear components [2], [3]. In these situations distributed parameter line is discretized by many segments and each segment is represented by lumped parameter circuits [4]. Lumped parameters transmission line models can be used in situations where frequency independent parameters constitute a reasonable simplification. Such situations occur in simulations where low and median frequencies are involved.

Lumped parameters models are developed directly in time domain and they are easily implemented in Electromagnetic Transient Programs such as EMTP [5].

For representing a transmission line using lumped parameters model, it is taken into account that a small line segment can be represented by a π circuit and, consequently, a long transmission line can be represented by larger quantity of π circuits connected in cascade [4]. In this case the currents and voltages along the line are written as state equations and its solutions are obtained by using numerical integration methods [1-5].

To represent a multiphase transmission line, first it is separated in its propagation modes [6] and, after that, each mode can be considered a single phase line that can be represented by lumped model [4]. This way, a transmission line with n phases is represented in modal domain by its n propagation modes and these modes behave like as n uncoupled single phase lines. Then, the currents and voltages are calculated in modal domain and, after that, are converted to phase domain [1].

The phase-mode-phase transformation before mentioned is done by using a modal transformation matrix and, if this matrix is a real and frequency independent matrix, the representation of propagation modes by using lumped parameter models permits to evaluate simulations directly in time domain [7]. This representation will be denominated in this paper as classical model.

However, in general way, modal transformation matrices are complex and frequency dependents [6] and only in same particular cases they are real and frequency independents. As example of transmission line that modal transformation matrix is real and frequency independent, is possible to mention ideally transposed lines and two phase lines with a vertical symmetry plane. For non-transposed three-phase lines with a vertical symmetry plane it is usual to consider, taking into account that a small error is accepted, that modal transformation matrix is real and frequency independent matrix too [7]. For other lines configuration the classical model cannot be used.

This way, the objective of this paper is to extend the possibility of using lumped parameter models to represent any line configuration, with or without nonlinear components. To achieve this objective it is being proposed to develop a lumped transmission line model directly in phase domain, where it is not necessary to use a modal transformation matrix.

To obtain a lumped multiphase line model directly in time domain it is assumed that a small multiphase line segment can be represented by lumped parameters and the resulting circuit takes into account the mutual phase coupling of this small line segment. After that, a cascade of the resulting circuit before mentioned is used to represent a long multiphase transmission line directly in phase domain.

II. Using Lumped Parameters Model to Represent Three-Phase Lines in Time Domain Without Modal Decomposition Theory

A. *Generic considerations about the proposed model*

Because only few line configurations can be separated in its propagation modes by using a real and frequency independent transformation matrix, the representation of multiphase lines by lumped models together with modal decomposition theory is not an adequate model for representing multiphase lines without a vertical symmetry. However, lumped models can be used if the line is represented directly in phase domain.

To obtain a lumped parameters model for a three-phase line it was considered that a small three-phase line segment can be represented by the circuit showed in Fig. 1.

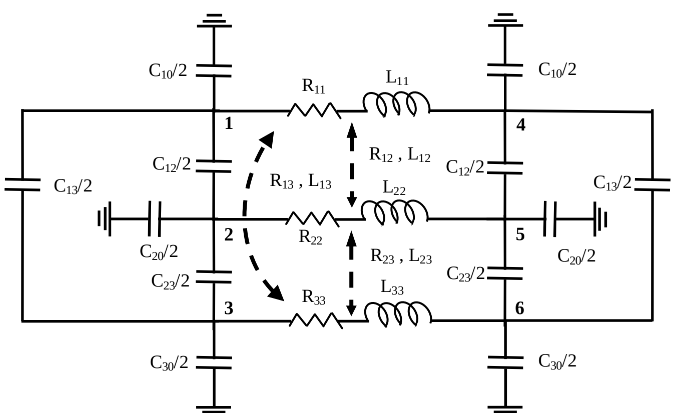

Fig. 1. Small three phase line segment represented by lumped elements.

In Fig. 1, numbers 1, 2 and 3 indicate sending end and numbers 4, 5 and 6 indicate the receiving end of the small three-phase line segment. An element R_{ii} corresponds to the self-resistance of the phase *i* and R_{ik} is the mutual resistance between phases *i* and *k* [8]. Self longitudinal inductance of the phase *i* is represented by element L_{ii} and element L_{ik} is the mutual longitudinal inductance between phases *i* and *k*. The partial capacitance between phase *i* and the ground is C_{i0} and partial capacitance between phases *i* and *k* are represented by element C_{ik}. Due to the fact that in overhead lines conductances are disregarded, these parameters were not included in Fig. 1.

For representing a long transmission line, it was used a large quantity of lumped parameter circuits (described in Fig. 1) connected in cascade as shows Fig. 2.

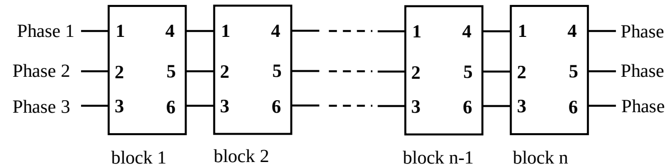

Fig. 2. Three-phase line represented by a cascade of three-phase π circuits.

It is possible to write the currents and voltages equations, along the cascade shown in Fig. 2, using state space techniques and the numerical integration of these equations provides phase currents and voltages along the line directly in time domain. The proposed model can be applied to represent three-phase lines independently of the geometrical configurations.

B. *Representing the coupling of the line*

As it is shown in Fig. 1, phases of a multiphase transmission line are coupled due to external impedance and ground effect. The coupling due to external impedance is a inductive coupling and the ground effect results in self and mutual resistances and inductances [8].

To take into account the inductive coupling in each small three-phase line segment, shown in Fig. 1, it was used the Faraday's Law that ensures that current in a generic phase of the Fig. 1 induces a drop voltage at the others phases [9].

To include the resistive coupling, due to ground effect, it was used the concepts shown by Schulze [10]. Then, let us to consider two conductors *j* and *k* coupled by mutual resistances and inductances as it is shown in Fig. 3.

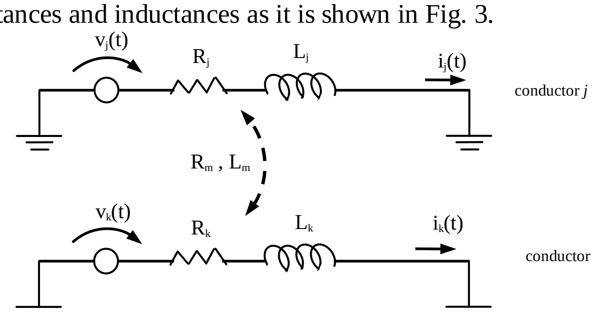

Fig. 3. Conductors *j* and *k* coupled by mutual inductance and resistance.

In Fig. 3 are shown two conductors with self-longitudinal resistances (R_j and R_k, respectively) and inductances (L_j and L_k, respectively). These conductors are coupled by mutual resistance and inductance R_m and L_m, respectively. In the conductors *j* and *k* currents $i_j(t)$ and $i_k(t)$ are resulting from voltage sources $v_j(t)$ and $v_k(t)$, respectively.

In agreement with [10], due to mutual resistance R_m, current $i_k(t)$ induces a voltage drop $E_j(t)$ in the conductor *j* written as being:

$$E_j(t) = R_m \ i_k(t) \tag{1}$$

Similarly, current $i_j(t)$ induces a voltage drop $E_k(t)$ in the conductor *k* that may be expressed as [9]:

$$E_k(t) = R_m \ i_j(t) \tag{2}$$

Then, taking into account resistive and inductive coupling between conductors in Fig. 3, the following ordinary differential equations are obtained:

$$v_j(t) - R_j i_j(t) - L_j \frac{di_j(t)}{dt} - L_m \frac{di_k(t)}{dt} - E_j(t) = 0 \qquad (3)$$

$$v_k(t) - R_k i_k(t) - L_k \frac{di_k(t)}{dt} - L_m \frac{di_j(t)}{dt} - E_k(t) = 0 \qquad (4)$$

In (3) and (4) $E_j(t)$ and $E_k(t)$ are voltage drops in conductors *j* and *k*, respectively, due to resistive coupling between conductors.

Then, using the representation of the drop voltage due to resistive coupling proposed in [10], it is possible to obtain the space-state equations for an small segment of a three-phase line (as shown in Fig. 1) and for a long three-phase line represented by lumped parameters (as shown in Fig. 2).

C. State space equation for a three-phase transmission line

As before mentioned, it was supposed that a three-phase line may be represented by a larger quantity of small three-phase line segments connected in cascade as shown in Fig. 2.

In this case, considering that are used *n* small three-phase line segments to represent the three-phase line, matrices of the state space representation will be written as followed:

Vector [x(t)]: Vector [x(t)] is written as being:

$$[x(t)] = \left[[i_1] \quad [v_1] \quad [i_2] \quad [v_2] \quad [i_3] \quad [v_3]\right]^T \qquad (5)$$

Where $[i_1]$, $[i_2]$ and $[i_3]$ are currents at the phases 1, 2 and 3 of the line whereas $[v_1]$, $[v_2]$ and $[v_3]$ are phase voltages of the line.

For j = 1, 2 and 3, generic vectors $[i_j]$ e $[v_j]$, in (5), are written as being:

$$[i_j] = [i_{j1}(t) \quad i_{j2}(t) \quad \cdots \quad i_{jn}(t)] \qquad (6)$$

$$[v_j] = [v_{j1}(t) \quad V_{j2}(t) \quad \cdots \quad v_{jn}(t)] \qquad (7)$$

Considering elements $i_{jk}(t)$ and $v_{jk}(t)$, in (6) and (7), *j* and *k* indicate, respectively, the *j*th phase of the line and the *k*th three-phase π circuit of the cascade. If three-phase line is represented by *n* three-phase π circuits, [x(t)] is a column vector with *6n* rows.

Vector [u(t)]: Vector [u(t)] contains input voltages at the sending end of the line and is written as follows:

$$[u(t)] = \left[v_1(t) \quad v_2(t) \quad v_3(t)\right]^T \qquad (8)$$

In (8) $v_1(t)$, $v_2(t)$ and $v_3(t)$ are respectively the phase voltages applied at the sending end of the line.

Matrices [A] and [B]: Matrices [A] and [B] are written as:

$$[A] = \begin{bmatrix} [A_{11}] & [A_{12}] & [A_{13}] & [A_{14}] & [A_{15}] & [A_{16}] \\ [A_{21}] & [A_{22}] & [A_{23}] & [A_{24}] & [A_{25}] & [A_{26}] \\ [A_{31}] & [A_{32}] & [A_{33}] & [A_{34}] & [A_{35}] & [A_{36}] \\ [A_{41}] & [A_{42}] & [A_{43}] & [A_{44}] & [A_{45}] & [A_{46}] \\ [A_{51}] & [A_{52}] & [A_{53}] & [A_{54}] & [A_{55}] & [A_{56}] \\ [A_{61}] & [A_{62}] & [A_{63}] & [A_{64}] & [A_{65}] & [A_{66}] \end{bmatrix} \qquad (9)$$

$$[B] = \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ 0 & 0 & 0 \\ \vdots & \vdots & \vdots \\ 0 & 0 & 0 \\ b_{(2n+1)1} & b_{(2n+1)2} & b_{(2n+1)3} \\ 0 & 0 & 0 \\ \vdots & \vdots & \vdots \\ 0 & 0 & 0 \\ b_{(4n+1)1} & b_{(4n+1)2} & b_{(4n+1)3} \\ 0 & 0 & 0 \\ \vdots & \vdots & \vdots \\ 0 & 0 & 0 \end{bmatrix} \qquad (10)$$

In (9) [A] is a matrix with dimension *6n* x *6n* and elements of [A] are matrices with dimension *n* x *n* ,where *n* is the quantity of three-phase π circuits used to represent the line.

Generic elements $[A_{pp}]$ are written as:

$$[A_{pp}] = \begin{cases} \begin{bmatrix} a_{pp} & & & & \\ & a_{pp} & & & \\ & & \ddots & & \\ & & & a_{pp} & \\ & & & & a_{pp} \end{bmatrix} & \text{for } p = 1, 3, 5 \\ \begin{bmatrix} 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & \cdots & 0 & 0 \end{bmatrix} & \text{for } p = 2, 4, 6 \end{cases} \qquad (11)$$

Generic elements $[A_{pq}]$ and $[A_{qp}]$, considering p=2j-1 and q=2j+1, for j =1, 2, are diagonal matrices written as being:

$$[A_{pq}] = \begin{bmatrix} a_{pq} & & & & \\ & a_{pq} & & & \\ & & \ddots & & \\ & & & a_{pq} & \\ & & & & a_{pq} \end{bmatrix} \qquad (12)$$

$$[A_{qp}] = \begin{bmatrix} a_{qp} & & & & \\ & a_{qp} & & & \\ & & \ddots & & \\ & & & a_{qp} & \\ & & & & a_{qp} \end{bmatrix} \qquad (13)$$

For elements $[A_{15}]$ and $[A_{51}]$ are used the following formation rules:

$$[A_{15}] = \begin{bmatrix} a_{15} & & & & \\ & a_{15} & & & \\ & & \ddots & & \\ & & & a_{15} & \\ & & & & a_{15} \end{bmatrix} \qquad (14)$$

$$[A_{51}]=\begin{bmatrix} a_{51} & & & & \\ & a_{51} & & & \\ & & \ddots & & \\ & & & a_{51} & \\ & & & & a_{51} \end{bmatrix} \quad (15)$$

The generic elements $[A_{p2}]$, $[A_{p4}]$ and $[A_{p6}]$, considering p=1, 3, 5, are matrices written as being:

$$[A_{p2}]=\begin{bmatrix} a_{p2} & & & & \\ -a_{p2} & a_{p2} & & & \\ & -a_{p2} & \ddots & & \\ & & \ddots & a_{p2} & \\ & & & -a_{p2} & a_{p2} \end{bmatrix} \quad (16)$$

$$[A_{p4}]=\begin{bmatrix} a_{p4} & & & & \\ -a_{p4} & a_{p4} & & & \\ & -a_{p4} & \ddots & & \\ & & \ddots & a_{p4} & \\ & & & -a_{p4} & a_{p4} \end{bmatrix} \quad (17)$$

$$[A_{p6}]=\begin{bmatrix} a_{p6} & & & & \\ -a_{p6} & a_{p6} & & & \\ & -a_{p6} & \ddots & & \\ & & \ddots & a_{p6} & \\ & & & -a_{p6} & a_{p6} \end{bmatrix} \quad (18)$$

Elements $[A_{p1}]$, $[A_{p3}]$ and $[A_{p5}]$, for p = 2, 4, 6, are written as:

$$[A_{p1}]=\frac{1}{2}\begin{bmatrix} a_{p1} & -a_{p1} & & & \\ & a_{p1} & -a_{p1} & & \\ & & \ddots & \ddots & \\ & & & a_{p1} & -a_{p1} \\ & & & & 2a_{p1} \end{bmatrix} \quad (19)$$

$$[A_{p3}]=\frac{1}{2}\begin{bmatrix} a_{p3} & -a_{p3} & & & \\ & a_{p3} & -a_{p3} & & \\ & & \ddots & \ddots & \\ & & & a_{p3} & -a_{p3} \\ & & & & 2a_{p3} \end{bmatrix} \quad (20)$$

$$[A_{p5}]=\frac{1}{2}\begin{bmatrix} a_{p5} & -a_{p5} & & & \\ & a_{p5} & -a_{p5} & & \\ & & \ddots & \ddots & \\ & & & a_{p5} & -a_{p5} \\ & & & & 2a_{p5} \end{bmatrix} \quad (21)$$

Elements $[A_{22}]$, $[A_{24}]$, $[A_{26}]$, $[A_{42}]$, $[A_{44}]$, $[A_{46}]$, $[A_{62}]$, $[A_{64}]$ and $[A_{66}]$ in (9) are null matrices.

Matrix [B] in (10) has dimension *6n* x *3*, where *n* is the quantity of the three-phase π circuits used to represent the line, and its non-null elements are written as:

$$b_{11} = -a_{12} \ ; \ b_{12} = -a_{14} \ ; \ b_{13} = -a_{14} \quad (22)$$

$$b_{(2n+1)1} = -a_{32}; b_{(2n+1)2} = -a_{34}; b_{(2n+1)3} = -a_{36} \quad (23)$$

$$b_{(4n+1)1} = -a_{52}; b_{(4n+1)2} = -a_{54}; b_{(4n+1)3} = -a_{56} \quad (24)$$

Equations (11)-(21) show that elements of the matrices [A] and [B] are written as functions of the transmission line parameters.

III. RESULTS OBTAINED

To validate the proposed model, it was considered an ideally transposed three-phase 440 kV three-phase line submitted to open and short circuited tests. The phase conductors consist of four Grosbeak subconductors and the soil resistivity is 1000 ohm.m. It was considered longitudinal parameters as being calculated in 60 Hz. This line was chosen because it can be easily represented in modal domain by using a real and frequency independent modal transformation matrix. This way, it was possible to compare results obtained with proposed model and with *classical model* where currents and voltages are calculated firstly in modal domain.

After the validation of the proposed model, it was used to model a 440 kV non-transposed line with a vertical symmetry plane and a 230 kV unsymmetrical line. Simulations of electromagnetic transients due to load and capacitor bank switching were evaluated.

Comparisons of the results obtained with proposed model and *classical model* showed the error when classical representation is used to represent a non-ideally transposed line.

A. *Validation of the proposed model*

Fig. 4 shows a 100 km 440 kV three-phase line.

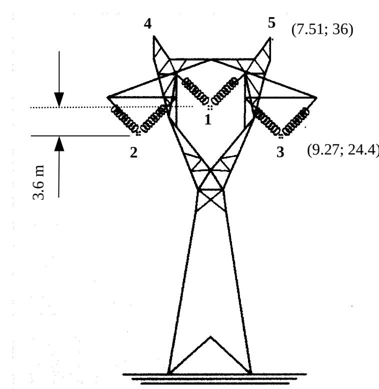

Fig. 4 - 440 kV three-phase transmission line.

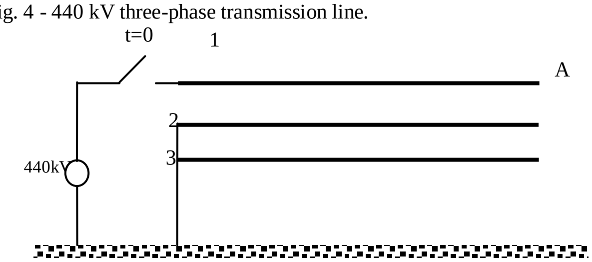

Fig. 5 - Open circuit energization.

To verify the performance of the proposed model, it was considered that the line showed in Fig. 4 is ideally transposed. Then, the line was modeled by proposed model and by *classical model*. After that these models were used to simulate the open and short circuit energization of the line.

In the simulations a 440 kV step voltage was applied at the sending end of the line as shown in Fig. 5. In these figures, a correction procedure based on digital signal processing theory is used to smooth the numeric oscillations [11].

Fig. 6 show open circuit voltages at the receiving end of the conductor 1 of the ideally transposed line. The Fig. 7 show short circuit voltages when the terminal A is connect with ground. Curves 1 and 2 show results obtained with proposed model and with classical model, respectively.

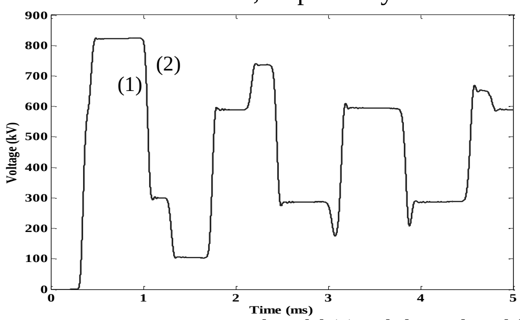

Fig. 6 - Open circuit responses: Proposed model (1) and classical model (2).

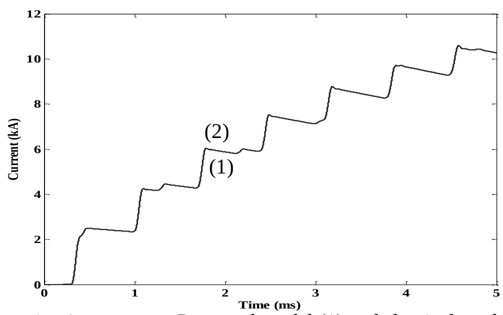

Fig. 7 - Short circuit responses: Proposed model (1) and classical model (2).

It is seen in Figs. 6 and 7 that response obtained with proposed model matches the response obtained with classical model. Taking into account that response obtained with classical model is a reference response, it is possible to conclude that proposed model has been correctly implemented.

B. *Time domain results for non-transposed line with a vertical symmetry plane*

Let us to consider now that transmission line shown in Fig. 4 is a non-transposed line. This line was represented by proposed and classical models during open and short circuit tests, as shown in Fig. 5.

Figs. 8 and 9 show open and short circuit voltages, respectively, at the receiving end of the conductor 1 of the non-transposed line shown in Fig. 4. In these figures, a correction procedure based on digital signal processing theory is used to smooth the numeric oscillations [11]. Curves 1 and 2 show results obtained with proposed model and with classical model, respectively.

Figs. 8 and 9 show that results obtained with proposed and *classical* models present some differences. These differences are present because the transmission line was not considered ideally transposed. However, because the line has a vertical symmetry plane, the errors is small and can be neglected.

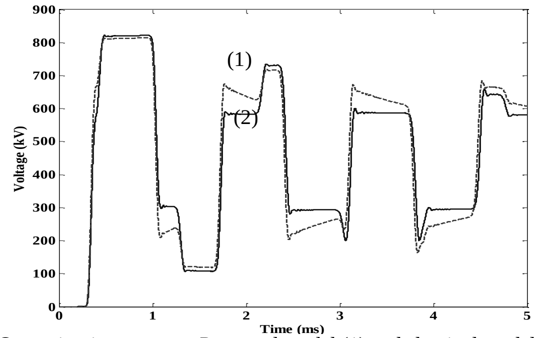

Fig. 8 - Open circuit responses: Proposed model (1) and classical model (2).

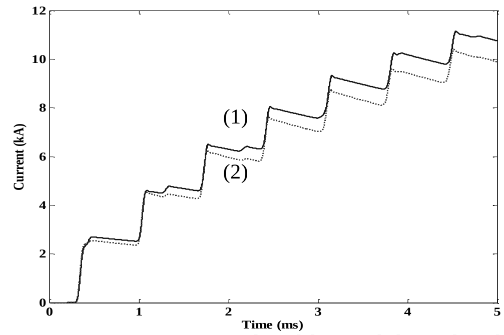

Fig. 9 - Short circuit responses: Proposed model (1) and classical model (2).

C. *Time domain results for non-transposed line without a vertical symmetry plane*

Simulations directly in time domain taking into account non transposed line without a vertical symmetry plane is not possible with *classical model* because this model cannot be decoupled into propagation modes by using a real and frequency independent modal transformation matrix. In this case, simulations in time domain must be evaluated with models developed directly in phase domain. Therefore, the proposed model is extremely useful to represent non transposed line without a vertical symmetry plane.

In Fig. 10 is shown a typical 230 kV, 100 km length, non-transposed three-phase line without a vertical symmetry plane.

The proposed model was used to simulate the energization of the line shown in Fig. 10, considering a load of 15.85 MVA, with a power factor of 0.98, connected at its receiving end as shown in Fig. 11. At time t = 20 ms there was a switching load and the load change abruptly to 100 MVA.

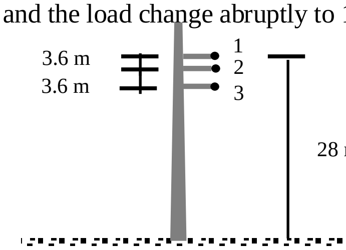

Fig. 10 - A non-transposed three-phase line without a vertical symmetry plane.

Fig. 12 shows the resulting voltages at the receiving end for the line, considering the switching load. Curves 1, 2 and 3 show the voltages at the phases 1, 2 and 3, respectively.

In Fig. 13 it is possible to observe the energization at time t= 0 and the switching load at time t= 20 ms. After the switching load there was same oscillations at the voltages as it was expected.

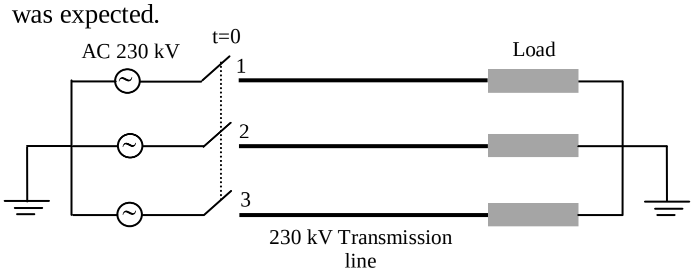

Fig. 11 - Load switching at the n of an unsymmetrical transmission line.

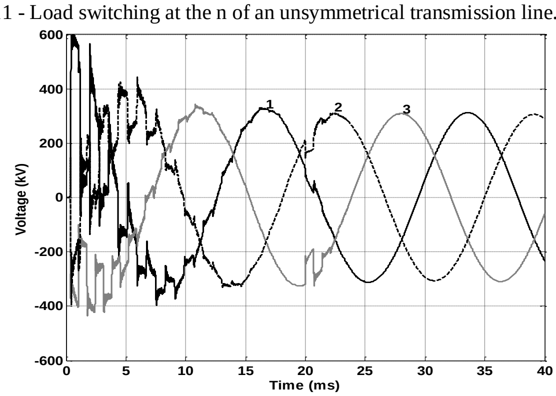

Fig. 12 - Receiving end voltages for a switching load.

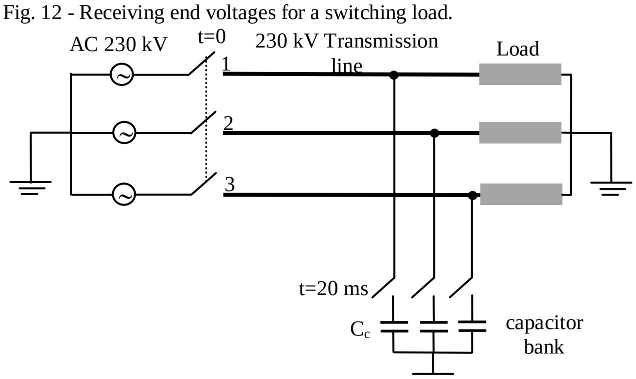

Fig. 13 - Switching of a capacitors bank.

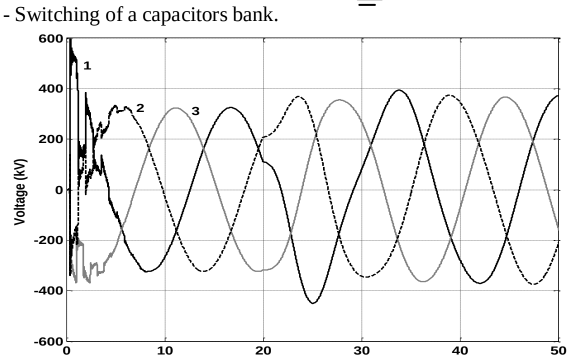

Fig. 14 - Receiving end voltages for a switching of a capacitors bank.

In other situation, in Fig. 14, it was considered the switching of a capacitor bank at the receiving end of the line. Initially the line shown in Fig. 10, with a resistive load per phase equal to 1 kΩ connected at its receiving end, was energized at t = 0. Then at time t = 20 there input from a three phase capacitor bank (C_c = 25μF).

Fig. 14 show the resulting voltages at the receiving end for the line, considering the switching capacitor bank. Curves 1, 2 and 3 show the voltages at the phases 1, 2 and 3, respectively.

Fig. 14 shows that after the inclusion of the capacitor bank, at time t = 20 ms, there was increase of the voltage at the receiving end of the line as it was expected.

IV. Conclusion

Lumped parameters transmission line models can be used to represent three-phase line directly in time domain and because it is developed directly in time domain, it is possible to use it in simulations of electromagnetic transients considering transmission lines with non-linear elements like as switching loads and short circuit faults originated by lightning.

However, this line representation only can be used in situations where the three-phase line is ideally transposed or a non-transposed line with a vertical symmetry plane. These lines can be decoupled in its propagation modes by using a real and frequency independent modal transformation matrix that can be easily represented in time domain. In this paper, this representation was denominated *classical model*.

The proposed lumped parameters transmission line model permits to represent the line directly in phase domain, without to use modal transformation matrix and, this way, can be used to represent a generic transposed or non-transposed three-phase line transmission line without to take into account its geometrical characteristics.

The proposed model was used to represent non transposed three-phase lines with and without vertical symmetry plane.

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