Robust Phase-Domain Transmission Line Representation Based on Time-Domain Fitting

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Abstract **–This work presents a methodology for deriving a phase-domain transmission line representation based on time-domain fitting. The resulting model is described by a polynomial matrix in the discrete-time domain. The robustness of the representation, its stability and passivity, is attained by imbedding a set of constraints in the solution of the fitting equations, which are solved using quadratic programming. Results demonstrating the features of the derived representation are presented for the case of a two-phase asymmetric, untransposed transmission line.**

Keywords – Electromagnetic transients, transmission line, discrete time, time-domain fitting, constrained least squares.

I. INTRODUCTION

The complexity and size of modern power systems have increasingly required electromagnetic transient studies to support decisions in both design and operation. The diversity and accuracy of the available models for power systems components are noticeable. Considering the modeling of transmission lines, the frequency dependence of the line parameters is modeled by rational function approximations either in S or Z domain fitted to frequency response data points [1-6]. It is very important to ensure stability and passivity for the fitted functions.

Such models can be separated into two large classes: modal-domain and phase-domain models. Usually they require the fitting of rational functions in the s-plane [2,3,4,5] and in the z-plane [6,7] to the admittance and to the propagation function frequency data points. The stability of solution in [4] is attained deleting the unstable poles. In [5], only stable poles are allowed. Important improvements to a Phase-Domain ARMA line model [6] are presented in [7]. Passivity for the approximated admittance matrices in the s-domain is taken into account in the fitting process in [8]. Techniques for obtaining transmission line representation (network equivalents) based on time-domain fitting have been reported in [9, 10].

In this work, the line is represented in the phase-domain based on time-domain fitting. Stability and passivity constraint equations are included in the fitting process by forcing the poles of the fitted functions to be inside the z-plane unity circle and by forcing any negative eigenvalue of the real part of the admittance function $G(\omega)$ to be positive. The methodology for deriving a robust phase-domain transmission line representation is based on time-domain fitting for the calculation of Network Equivalents [9-11]. A polynomial matrix in the discrete-time domain describes the resulting model. The robustness – stability and passivity – of the model is attained by imbedding a set of constraints in the solution of the fitting equations, which is solved using quadratic programming. The required data can be obtained either from measurements or a computed time-domain response of the transmission line. In the latter case, a highly accurate but complex and computational intensive model is used. The resulting representation retains the characteristics of the transmission line while providing a simple representation. As it is derived in the discrete-time domain, this representation can be easily integrated into transient calculation routines. Besides, it is closely related to the topology of digital filters. This makes the implementation of the derived model easier for the purpose of real-time transient calculation in computers with limited architecture, as in the case Digital Signal Processing (DSP) cards.

Section II presents the outline of the methodology. The topics of parameter identification, determination of the order and stability and passivity requirements of the representation are described in Sections III and IV. Digital simulation results are discussed in Section V. Conclusions are given in Section VI.

II. METHODOLOGY

The proposed methodology is based on the derivation of single-port and two-port network equivalents by means of time-domain fitting [9-11]. It was extended to allow the calculation of phase-domain transmission line representations. It is exemplified limiting the analysis to four-port networks, which allows the representation of two-phase transmission lines. This is not an intrinsic limitation of the proposed methodology and the results regarding three-phase transmission lines will be presented in a future paper.

The transmission line in study is treated as a linear network. Thus, assuming time-invariance and zero initial conditions, it can be fully characterized in discrete-time domain by a linear constant-coefficients difference equation [12] given as

$$\sum_{k=0}^{p} A_k i(n-k) = \sum_{k=0}^{q} B_k v(n-k) \qquad (n = 0, \ldots, N-1), \quad (1)$$

where p is related to the output, the current $i(n)$, and q is the number of past terms in the input, the voltage $v(n)$.

This difference equation of order p, which characterizes the transmission line representation, is used to build an overdetermined set of linear equations from computed time-domain response of the transmission line.

The fitting procedure uses the solution of this overdetermined system to obtain the parameters for the transmission line representation. However, this does not ensure the stability and passivity criteria. Therefore, a set of linear constraints is added to the set related to the time-domain response fitting. The general formulation is

$$\min_{x} \; \left\| Ax - B \right\| \qquad Dx \le e \ , \tag{2}$$

where A and B correspond to the fitting equations and D and e to constraint equations. The fitting and constraint equations are solved simultaneously by means of optimization techniques based on Quadratic Programming [13,14]. These equations are discussed below.

III. Transmission Line Representation: Fitting Equations

The voltage and current sequences in (1) are considered accurate information for deriving a two-phase transmission line representation, the determination of A_k and B_k . These voltage and current sequences of length *N*, considered as inputs and outputs, respectively, are taken at the four terminals of the network in study. They are obtained using phase-domain models available from transient calculation programs.

To represent a two-phase transmission line, $i(n)$ and $v(n)$, in (1), are 4×1 vectors and A_k and B_k , the parameters to be calculated, are 4×4 matrices. The poles, as proposed in [9-11], were assumed to be the same which makes easier to enforce stability (see Section V). The polynomial matrix A_k results in a diagonal matrix, where each nonzero element is a set of coefficients a_k . It is assumed $q = p$. The coefficient A_0 is defined as 4×4 identity matrix. Thus, the normalized equation to represent two-phase transmission line is given as,

$$i(n) = B_0 v(n) + \sum_{k=1}^{p} \left(B_k v(n-k) - A_k i(n-k) \right), \tag{3}$$

where B_0 has the admittance dimension and the summation is computed only from past values. Equation (3) represents admittance B_0 in parallel with a current source, accounting for the summation term. This form facilitates the integration of the line representation into transient calculation programs. The derivation of the fitting equation and the determination of the order *p* is discussed next.

A. Parameter Identification (A_k and B_k)

To determine A_k and B_k , it is necessary to take the voltage and current sequences at the terminals of the two-phase overhead transmission line, as shown in Fig. 1, obtained from digital simulations.

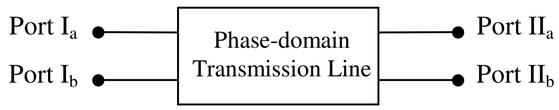

Fig.1 Two-phase transmission line representation.

Here, the currents at each terminal were obtained from the unit-step voltage response although a different input voltage could be used. Due to two-phase line configuration, it is not necessary to take voltage and current sequences at all ports, considering that some are identical.

Initially, the ports $\mathrm{I_b}$, $\mathrm{II_a}$ and $\mathrm{II_b}$ are short-circuited and a unit-step voltage is applied at port $\mathrm{I_a}$, taking the following sequences: $v_{\mathrm{I\,aa}}$ (voltage at port $\mathrm{I_a}$), $i_{\mathrm{I\,aa}}$, $i_{\mathrm{I\,ab}}$, $i_{\mathrm{I,II\,aa}}$ and $i_{\mathrm{I,II\,ab}}$ (currents at port $\mathrm{I_a}$, port $\mathrm{I_b}$, port $\mathrm{II_a}$ and port $\mathrm{II_b}$, respectively). Applying a unit-step voltage at port $\mathrm{I_b}$, with the remaining ports short-circuited, the following sequences are taken: $v_{\mathrm{I\,bb}}$ (voltage at port $\mathrm{I_b}$), $i_{\mathrm{I\,bb}}$ and $i_{\mathrm{I,II\,bb}}$ (currents at port $\mathrm{I_b}$ and port $\mathrm{II_b}$, respectively).

Rewriting (1) in matrix form one gets a set of linear equations in the form

$$I = \begin{bmatrix} 0 & 0 & . & 0 \\ i_0 & 0 & . & 0 \\ . & . & . & . \\ i_{p-2} & i_{p-3} & . & 0 \\ \hline i_{p-1} & i_{p-2} & . & i_0 \\ . & . & . & . \\ i_{N-2} & i_{N-3} & . & i_{N-p-1} \end{bmatrix}, V = \begin{bmatrix} v_0 & 0 & . & 0 \\ v_1 & v_0 & . & 0 \\ . & . & . & . \\ v_{p-1} & v_{p-2} & . & 0 \\ \hline v_p & v_{p-1} & . & v_0 \\ . & . & . & . \\ v_{N-1} & v_{N-2} & . & v_{N-p-1} \end{bmatrix}. \tag{4}$$

Each current and voltage sequence is used to build a corresponding convolution matrix. The subscripts in the variables *i* and *v*, in (4), indicate the time index in the sequences. Using the matrices *I* and *V* obtained from the voltage and current sequences, the sets of coefficients a_k , $b_{\mathrm{I\,aa}k}$, $b_{\mathrm{I\,ab}k}$, $b_{\mathrm{I,II\,aa}k}$, $b_{\mathrm{I,II\,ab}k}$, $b_{\mathrm{I\,bb}k}$ and $b_{\mathrm{I,II\,bb}k}$ are calculated from fitting equation given as

$$A\,x = B\,, \tag{5}$$

where,

$$A = \begin{bmatrix} I_{\mathrm{I\,aa}} & -V_{\mathrm{I\,a}} & 0 & 0 & 0 & 0 & 0 \\ I_{\mathrm{I\,ab}} & 0 & -V_{\mathrm{I\,a}} & 0 & 0 & 0 & 0 \\ I_{\mathrm{I,II\,aa}} & 0 & 0 & -V_{\mathrm{I\,a}} & 0 & 0 & 0 \\ I_{\mathrm{I,II\,ab}} & 0 & 0 & 0 & -V_{\mathrm{I\,a}} & 0 & 0 \\ I_{\mathrm{I\,bb}} & 0 & 0 & 0 & 0 & -V_{\mathrm{I\,b}} & 0 \\ I_{\mathrm{I,II\,bb}} & 0 & 0 & 0 & 0 & 0 & -V_{\mathrm{I\,b}} \end{bmatrix},$$

$$x = \begin{bmatrix} a_k & b_{\mathrm{I,\,aa}} & b_{\mathrm{I,\,ab}} & b_{\mathrm{I,II,\,aa}} & b_{\mathrm{I,II\,ab}} & b_{\mathrm{I,\,bb}} & b_{\mathrm{I,II\,bb}} \end{bmatrix}^T$$

and

$$B = \begin{bmatrix} -i_{\mathrm{I,\,aa}} & -i_{\mathrm{I,\,ab}} & -i_{\mathrm{I,II,\,aa}} & -i_{\mathrm{I,\,IIab}} & -i_{\mathrm{I,\,bb}} & -i_{\mathrm{I,\,IIbb}} \end{bmatrix}^T .$$

From the solution vector *x* and the structures of the diagonal matrix A_k and the matrix B_k , the parameters to represent the two-phase transmission line are given as

$$A_k = \begin{bmatrix} a_k & 0 & 0 & 0 \\ 0 & a_k & 0 & 0 \\ 0 & 0 & a_k & 0 \\ 0 & 0 & 0 & a_k \end{bmatrix}, B_k = \begin{bmatrix} b_{\mathrm{I\,aa}k} & b_{\mathrm{I\,ab}k} & b_{\mathrm{I,II\,aa}k} & b_{\mathrm{I,II\,ab}k} \\ b_{\mathrm{I\,ba}k} & b_{\mathrm{I\,bb}k} & b_{\mathrm{I,II\,ba}k} & b_{\mathrm{I,II\,bb}k} \\ b_{\mathrm{I,II\,aa}k} & b_{\mathrm{I,II\,ab}k} & b_{\mathrm{I\,aa}k} & b_{\mathrm{I\,ab}k} \\ b_{\mathrm{I,II\,ba}k} & b_{\mathrm{I,II\,bb}k} & b_{\mathrm{I\,ba}k} & b_{\mathrm{I\,bb}k} \end{bmatrix} \tag{6}$$

where $b_{\mathrm{I\,ba}k} = b_{\mathrm{I\,ab}k}$ and $b_{\mathrm{I,II\,ba}k} = b_{\mathrm{I,II}\,abk}$.

The fitting equation (5) results in the following dimensions: A is ($6N\times7p+6$), B is ($6N$) and x is ($7p+6$). It is used $N >> p$ to characterize an overdetermined system, for which a solution in the least square sense can be obtained for the unknowns. From the calculated A_k and B_k the accuracy can be evaluated and the stability and passivity of the representation must be checked.

B. Determination of the order p

An important step to build the matrices I and V, in (4), and, as a consequence, the matrix A, in (5), is to calculate the best value p which determines the number of variables to be calculated and the rank condition of (5). Two approaches to determine p were presented in [9-11]. Here, the Singular Value Decomposition (SVD) method is used.

For each matrix I, the upper partition (denoted by dashed line) contribute to the rank in (4) with p linearly independents rows, regardless how large is the value of p, due to upper triangles filled with zeros. To complete the rank, the remaining $N – p$ lines should have $p + 1$ linearly independent rows considering (4) is well conditioned. Therefore, the information about the rank of each matrix I, in (4) must be searched in its lower partition.

The SVD analysis is performed in the lower partitions of each matrix I corresponding $i_{\mathrm{I\,aa}}$, $i_{\mathrm{I\,ab}}$, $i_{\mathrm{I,II\,aa}}$, $i_{\mathrm{I,II\,ab}}$, $i_{\mathrm{I\,bb}}$ and $i_{\mathrm{I,II\,bb}}$. This procedure results in six different values for p, where each one is equal to the number of eigenvalues that are 10^4 times larger than the smallest singular value. Due to structure of matrix A_k , considering only a set of coefficient a_k , it is used only one value of p to characterize the elements of A_k and B_k . Therefore, it is chosen the largest value of p.

IV. TRANSMISSION LINE REPRESENTATION: CONSTRAINT EQUATIONS

Stability and passivity criteria must be satisfied for a passive network. The constraint equations are based on application of Z transform to the fitting equation. Thus, taking the Z transform of (1) results in

$$Y(z) = \left(\sum_{k=0}^{p} A_k z^{-k} \right)^{-1} \cdot \left(\sum_{k=0}^{q} B_k z^{-k} \right) \therefore Y(z) = A(z)^{-1} B(z) \tag{7}$$

Due to structure of the diagonal matrix A_k , the operation to obtain the inverse of $A(z)$ is simplified. The polynomial matrix $A(z)^{-1}$ is diagonal and each diagonal element is $1/a(z)$, where $a(z)$ is a scalar polynomial with coefficients a_k[1]. Thus, the rational admittance matrix $Y(z)$ is represented as

$$Y(z) = \begin{bmatrix} \frac{b_{\mathrm{I\,aa}}(z)}{a(z)} & \frac{b_{\mathrm{I\,ab}}(z)}{a(z)} & \frac{b_{\mathrm{I,II\,aa}}(z)}{a(z)} & \frac{b_{\mathrm{I,II\,ab}}(z)}{a(z)} \\ \frac{b_{\mathrm{I\,ba}}(z)}{a(z)} & \frac{b_{\mathrm{I\,bb}}(z)}{a(z)} & \frac{b_{\mathrm{I,II\,ba}}(z)}{a(z)} & \frac{b_{\mathrm{I,II\,bb}}(z)}{a(z)} \\ \frac{b_{\mathrm{I,II\,aa}}(z)}{a(z)} & \frac{b_{\mathrm{I,II\,ab}}(z)}{a(z)} & \frac{b_{\mathrm{I\,aa}}(z)}{a(z)} & \frac{b_{\mathrm{I\,ab}}(z)}{a(z)} \\ \frac{b_{\mathrm{I,II\,ba}}(z)}{a(z)} & \frac{b_{\mathrm{I,II\,bb}}(z)}{a(z)} & \frac{b_{\mathrm{I\,ba}}(z)}{a(z)} & \frac{b_{\mathrm{I\,bb}}(z)}{a(z)} \end{bmatrix}. \tag{8}$$

From the analysis of (7) and (8), the constraint equations are obtained. The method presented to enforce stability and passivity is based on linearization and constrained optimization using Quadratic Programming.

A. Stability Requirements

The stability analysis, that in the general case depends on the polynomial matrix $A(z)$, is restricted to the analysis of the roots of the scalar polynomial $a(z)$ [11],

$$\sum_{k=0}^{p} a_k z^{-k} = 0, \tag{9}$$

This is a consequence of using only one set of coefficients related to the output. Therefore, to ensure stability is necessary to have all roots of $a(z)$ with absolute value less than 1, so that each root is inside the z-plane unity circle.

Considering that an unstable solution, from (5), is obtained, a correction Δx_a is calculated to be added to x_a (the coefficients a_k in the solution vector x) in order to the absolute values of all roots of $a(z)$ become less than 1. Therefore, the set of constraint equations related to stability, can be formulated as

$$J_S \; \Delta x_a \leq 1 - z_U \tag{10}$$

where J_S is the Jacobian of the absolute values z_U (set of unstable roots of $a(z)$) related to the set of coefficients of a_k. According to [11], each element of J_S, can be calculated as

$$\frac{\partial |z_j|}{\partial a_i} = |z_j| \operatorname{Re} \frac{1}{\sum_{k=1}^{p} k a_k z_j^{-k+i}}. \tag{11}$$

B. Passivity Requirements

The absorbed power, for any exciting complex voltage v, by a generic admittance matrix $Y = G + \mathrm{j}B$ is given as [8]

$$P = \operatorname{Re}\left\{ v^* Y v \right\} = \operatorname{Re}\left\{ v^* G v \right\}. \tag{12}$$

Where * denotes transpose and conjugate. It can be ob-

[1] When spasity is used, many values of a_k are equal to 0. Then, it reduces the computacional time.

served in (12) that P is always positive if all eigenvalues of G are larger than zero. The passive behavior of the line representation is ensured if the matrix G is positive definite (PD)[15] and depends on the scalar polynomials a_k, $b_{\mathrm{I\,aa}k}$, $b_{\mathrm{I\,ab}k}$, $b_{\mathrm{I,II\,aa}k}$, $b_{\mathrm{I,II\,ab}k}$, $b_{\mathrm{I\,bb}k}$ and $b_{\mathrm{I,II\,bb}k}$, as shown in (8).

As discussed in Section IV.C below, the stability and passivity requirements are enforced separately: first stability and then passivity. Therefore, the passivity constraints to be included in (2) requires the calculation of corrections only for the coefficients b_k.

From a solution given in (5), the admittance matrix, (8), is calculated for a normalized frequency range, $0 \leq \omega < \pi$. A set of frequencies (ω_i) is taken, in which the eigenvalues of G are negatives (λ_i). Corrections $\Delta x_{b\mathrm{Iaa}}$, $\Delta x_{b\mathrm{Iab}}$, $\Delta x_{b\mathrm{I,IIaa}}$, $\Delta x_{b\mathrm{I,IIab}}$, $\Delta x_{b\mathrm{Ibb}}$ and $\Delta x_{b\mathrm{I,IIbb}}$ are calculated in such a way the eigenvalues of G, (λ_i), become positive.

Assuming linearity, the dependence of the eigenvalues of G (λ_i) with each set of b_k is established. They are the elements of the Jacobian matrices related to passivity and can be defined as the product of two partial derivatives, for each frequency in the set ω_i:

$$\frac{\partial \lambda_i}{\partial b_k} = \frac{\partial \lambda_i}{\partial G_{mn}} \frac{\partial G_{mn}}{\partial b_k}, \qquad (13)$$

In (13), λ_i represent the eigenvalues of matrix G, b_k is a set of coefficients and G_{mn} are the elements of matrix G.

The first partial derivative in (13) represents the relation of the eigenvalues of G to the element of G. This term is calculated numerically and must be observed that some elements of G are modified simultaneously.

The second partial derivative in (13) gives the relation between the elements of G to the correspondent set of b_k. It is calculated analytically [11] as

$$\frac{\partial G_{mn}}{\partial b_k} = \mathrm{Re}\left[\frac{e^{-j\omega_i k}}{A(z)}\right] \qquad (14)$$

The set of constraint equations related to passivity, which are included in D and e in (2), is formulated as

$$-J_{Pb}\ \Delta x_b \ < \ \lambda_i \ , \qquad (15)$$

where, $J_{\mathrm{P}b}$ represents the Jacobian matrix of passivity calculated from (13) and Δx_b is a correction to be added to the coefficients b_k to enforce passivity.

C. Procedure for the determination of A_k and B_k

Due to non-linearity relations in (2), the procedure to obtain a phase-domain line representation is iterative. The fitting and constraint equations are conjugated and submitted to a quadratic programming routine. An incremental solution, Δx, is calculated in each iteration. The final formulation of the problem (2) is

$$\min_x \ \left\| H\Delta x - h \right\| \qquad D\,\Delta x \leq e \ , \qquad (16)$$

where, the matrix H and vector h are obtained from A and B. The procedure continues until the stability and passivity requirements are satisfied. It is divided into two main steps: the stability criterion is achieved first and then the passivity is enforced. Therefore, in the first step, D and e in (16) are calculated using (10) and in the second step using (15). This is adopted to facilitate the quadratic routine convergence. The described procedure is adequate to calculate a robust two-phase line representation.

V. RESULTS

The asymmetric and untransposed two-phase transmission line, seen in Fig. 2, is used to demonstrate the technique.

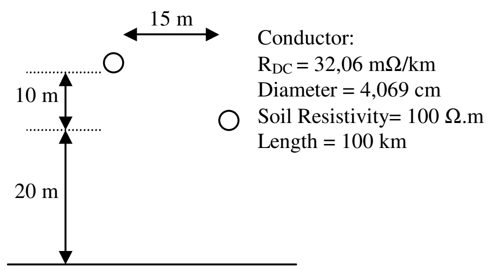

Fig.2 Two-phase overhead transmission line.

Transient simulations, regarding the line in Fig. 2, are carried out in PSCAD™/EMTDC®[16] using the phase-domain line model. These simulations serve as reference for the comparisons of accuracy when using the phase-domain line representation based on time-domain fitting and are also used to generate the voltage and current sequences necessary for the parameter identification. The phase-domain transmission line model implemented in PSCAD™/EMTDC® is based on [16-18] and is considered one of the most advanced phase-domain line models available in electromagnetic transients programs. The routines for obtaining the discrete-time transmission line representation and performing the electromagnetic transient calculations, using the calculated line representation, are developed in Matlab [19].

Voltage and current curves related to transient calculations, considering the phase-domain line model used in PSCAD™ and the obtained line representation, are compared. As a measure of accuracy (using voltage as example), the overall fitting error, F_{error}, is calculated as

$$F_{error} = \left\| V_m - V_{ps} \right\| / \left\| V_{ps} \right\| \qquad (17)$$

where m and ps subscripts refer to the sequences using the discrete-time line representation in phase-domain calculated in Matlab and the PSCAD™ model, respectively.

To calculate the parameters A_k and B_k for the line in Fig. 2, voltage and current sequences are obtained in the way described in Section III.A. The order of the line representation is determined based on the SVD approach, as seen in Section III.B. The singular values considering the currents $i_{\mathrm{I\,aa}}$, $i_{\mathrm{I\,ab}}$ and $i_{\mathrm{I,II\,ab}}$, respectively, are shown in Fig. 3. In this analysis the convolution matrices I are calculated for a value of p equal to 180.

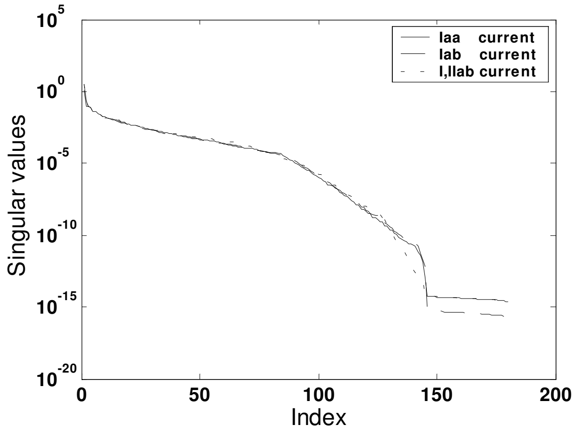

Fig.3 Singular values using SVD approach.

The curves seen in Fig. 3 are very close. It means that the values of the order to represent the self and mutual admittances for the transmission line are approximately the same. The computed value for the order p is equal to 142 and the parameters A_k and B_k are calculated. It is verified that the largest absolute value root of $a(z)$ is 0.9998, which means that the representation is stable. The lowest calculated eingenvalue of matrix G is 3.5695e-7, leading to a passive representation. Thus, for the considered case, the stability and passivity routines were not required.

The non-sparse representation used in this work may lead to heavy computational effort, thus the concept of sparsity can be applied to reduce this demand. The authors intend to extend this methodology to the determination of sparse representations, for which the enforcement of robustness is expected to be necessary.

As a measure of the accuracy of the representation during the identification of A_k and B_k , fitting errors are calculated comparing the current sequences obtained from (3) with the current sequences obtained from PSCAD™/EMTDC® simulations. The largest fitting error calculated, based on (17), is 1.1658e-4. Therefore, the resulting A_k and B_k represent the two-phase transmission line quite satisfactorily.

To further check the transmission line representation performance, transient calculations with resistances and voltage sources connected to the line terminals are obtained. The basic simulation diagram is seen in Fig. 4. The current and voltage curves taken at transmission line ports, either from the line representation in Matlab and in PSCAD™/EMTDC®, are compared. A 10 μs time step was used. If the time step changes it is necessary to do a refitting.

To provide a better accuracy analysis, the voltage sources shown in Fig. 4 are adjusted to excite differently the line and ground modes. The line mode is mainly excited, when V_1 and V_2 are unit-step voltages with opposite polarities, while the ground mode excitation requires V_1 and V_2 with the same polarity. For these simulations, ports II_a and II_b are left opened. Figures 5 and 6 show the obtained currents at port I_a and voltages at port II_b, in phase-domain, respectively. In these figures, LM and GM are related to line mode and ground mode excitation, respectively, obtained using PSCAD™model and the Discrete-Time phase-domain Line Representation (DTLR). Considering a single pole switching energization, a 60 Hz voltage source is used for V_1 with the ports I_b and II_a left opened and the port II_b short-circuited. Currents at port II_b and voltages at port II_a, in the phase-domain, obtained using PSCAD™/EMTDC® and DTLR models, are shown in figures 7 and 8. It can be verified from the results shown in figures 5 to 8 that the currents and voltages obtained from transient calculations using the DTLR present good accuracy.

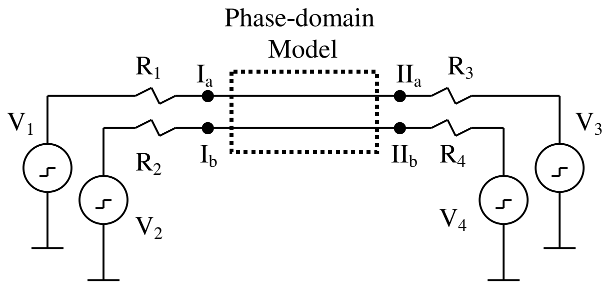

Fig.4 Electromagnetic transient calculations.

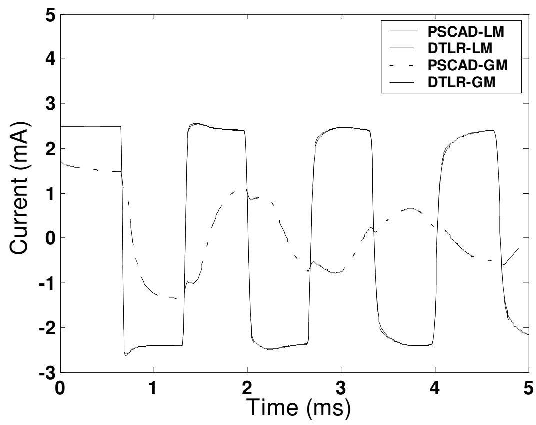

Fig.5 Current curves at port I_a.

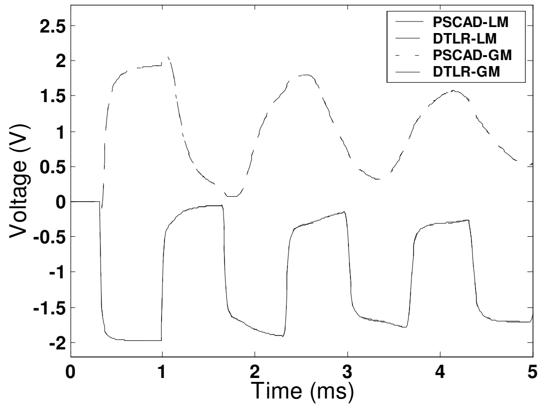

Fig.6 Voltage curves at port II_b.

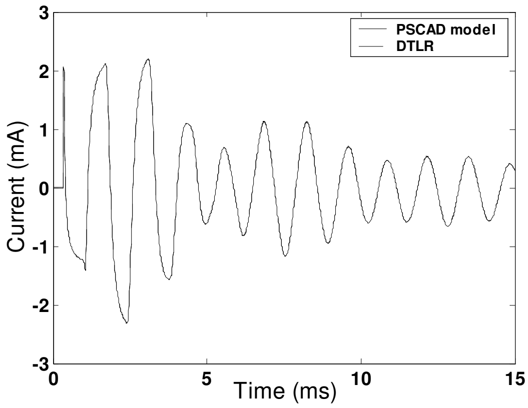

Fig.7 Current curves at port II_b-60Hz.

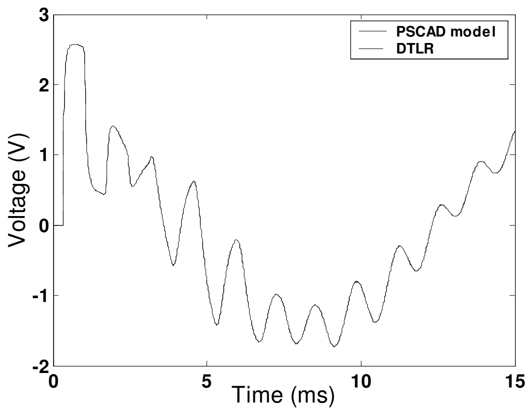

Fig.8 Voltage curves at port II_a-60 Hz.

VI. CONCLUSIONS

The paper has presented a methodology for deriving phase-domain transmission line representation based on time-domain fitting. Routines to enforce stability and passivity of the representation were formulated and included in the fitting procedure. The fitting and constraint equations are combined and submitted to quadratic programming routines. The procedure is iterative, due to non-linearities, and a solution is obtained when the fitting, stability and passivity conditions are satisfied.

To demonstrate the performance of the derived representation, transient calculations regarding a two-phase asymmetric and untransposed transmission line are used. Voltages and currents at the transmission line ports are compared for transient simulations using the discrete-time transmission line representation and phase-domain line model in PSCAD™/EMTDC®. The results presented good agreement. The authors intent to extend the methodology to a three-phase transmission line representation and also to the derivation of sparse representations.

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