ANALYSIS OF POWER TRANSFORMER MATRIX REPRESENTATION IN ELECTROMAGNETIC TRANSIENT STUDIES

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SCOPE

This paper presents some theoretical aspects of power transformers matrix representation, availables in EMTP and ATP programs, for the calculation of electromagnetic transients in power systems. Some results of simulations made with the program ATP (5.0 version for PC) are included, in these simulations the matricial models mentioned above were used. Finally a comparission is made between the results obtained with these models and those obtained from field tests.

KEY WORDS

Electromagnetic transients - Matricial models of power transformers.

1. INTRODUCTION

Electromagnetic transient studies give part of the necessary information for an appropiate planning and a correct operation of a power system. Such studies can be made through TNA (Transient Network Analyzer) and digital programs. The digital simulation of electromagnetic transients in a power system is made modelling each of their components. On account of that, the authors present in this paper some theoretical aspects of power transformers matrix representation, availables in EMTP and ATP programs, with the purpose of giving to the users a better comprehension of them. The matrix models [R]-[L] and [R]-$[L]^{-1}$ have the following characteristics:

- their parameters can be calculated from de data of usual short-circuit and excitation tests given by the manufacturer.
- they are flexible, they allow to model electromagnetic characteristics of transformer with different degrees of approximation on account of studies requirements and available data.
- they are not valid for studies involving high frequencies.

2. [R]-[L] AND [R]-$[L]^{-1}$ THREE PHASE TWO WINDINGS TRANSFORMER MODEL [1] [2] [3] [4] [5]

For the obtention of the models mentioned above the following hypotesis were assumed:

- the saturation curve λ x i is linear for the core of the transformer
- hysteresis and eddy current losses were ignored in this stage
- the capacitances distributed of the windings were neglected

2.1 Model [R]-[L]

Figure 1 shows a core type three phase transformer with two windings.

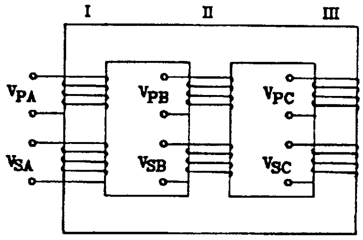

Figure 1 - Core type three phase transformer with two windings

where:

v_{PA}, v_{PB}, v_{PC} - instantaneus voltages between the terminals of the coils of the primary winding

v_{SA}, v_{SB}, v_{SC} - the same for secondary winding

This transformer can be considered like a set of six coils mutually coupled as shown in Figure 2, where

i_{PA}, i_{PB}, i_{PC} - instantaneus currents in the coils of the primary winding

i_{SA}, i_{SB}, i_{SC} the same for the secondary winding

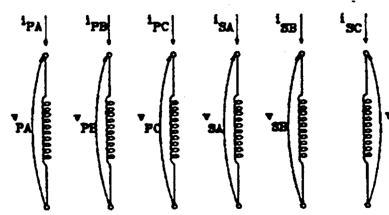

Figure 2 - Scheme for the three phase transformer of Figure 1

The differencial matricial equation that relates the branch voltages and currents of the transformer is :

$$\begin{bmatrix} v_{PA} \\ \cdot \\ \cdot \\ v_{SC} \end{bmatrix} = [R] . \begin{bmatrix} i_{PA} \\ \cdot \\ \cdot \\ i_{SC} \end{bmatrix} + [L] . \frac{d}{dt} \begin{bmatrix} i_{PA} \\ \cdot \\ \cdot \\ i_{SC} \end{bmatrix} \qquad (01)$$

where:

[R] - branch resistance diagonal matrix of the windings

[L] - branch inductance matrix of the winding

This equation leads to [R]-[L] model of the transformer.

2.1.1 Derivation of the matrices [R] and [L]

In the next section one way to obtain [R] and [L] matrices separately is described. The equation (01) for steady state solution can be written as:

$$\begin{bmatrix} \dot{V}_{PA} \\ \cdot \\ \cdot \\ \dot{V}_{SC} \end{bmatrix} = [\dot{Z}] \cdot \begin{bmatrix} \dot{I}_{PA} \\ \cdot \\ \cdot \\ \dot{I}_{SC} \end{bmatrix} \qquad (02)$$

where : $[\dot{Z}] = [R] + jw[L]$:

$$[\dot{Z}] = \begin{bmatrix} \begin{bmatrix} \dot{Z}^P_{AA} & \dot{Z}^P_{AB} & \dot{Z}^P_{AC} \\ \dot{Z}^P_{AB} & \dot{Z}^P_{BB} & \dot{Z}^P_{BC} \\ \dot{Z}^P_{AC} & \dot{Z}^P_{BC} & \dot{Z}^P_{CC} \end{bmatrix} & \begin{bmatrix} \dot{Z}^{PS}_{AA} & \dot{Z}^{PS}_{AB} & \dot{Z}^{PS}_{AC} \\ \dot{Z}^{PS}_{AB} & \dot{Z}^{PS}_{BB} & \dot{Z}^{PS}_{BC} \\ \dot{Z}^{PS}_{AC} & \dot{Z}^{PS}_{BC} & \dot{Z}^{PS}_{CC} \end{bmatrix} \\ \begin{bmatrix} \dot{Z}^{PS}_{AA} & \dot{Z}^{PS}_{AB} & \dot{Z}^{PS}_{AC} \\ \dot{Z}^{PS}_{AB} & \dot{Z}^{PS}_{BB} & \dot{Z}^{PS}_{BC} \\ \dot{Z}^{PS}_{AC} & \dot{Z}^{PS}_{BC} & \dot{Z}^{PS}_{CC} \end{bmatrix} & \begin{bmatrix} \dot{Z}^S_{AA} & \dot{Z}^S_{AB} & \dot{Z}^S_{AC} \\ \dot{Z}^S_{AB} & \dot{Z}^S_{BB} & \dot{Z}^S_{BC} \\ \dot{Z}^S_{AC} & \dot{Z}^S_{BC} & \dot{Z}^S_{CC} \end{bmatrix} \end{bmatrix} \qquad (03)$$

$\dot{Z}^P_{AA}, \ldots, \dot{Z}^S_{CC}$ - self impedances of primary and secondary coils

$\dot{Z}^P_{AB}$ - mutual impedance between primary coils A and B

$\dot{Z}^S_{BC}$ - mutual impedance between secondary coils B and C

$\dot{Z}^{PS}_{AC}$ - mutual impedance between primary and secondary coils A and C respectively

Figure 1 shows that the mutual inductances between legs I and II are different from the ones between legs II and III, consequently there will be necessary 6 excitation tests with 21 measurements ($L_{IK}=L_{KI}$) for derivation the matrix jw[L]. The following approximations are made because the above mentioned test are not given by the manufacturer:

- The mutual inductances between primary coils are all equal
- The mutual inductances between secondary coils are all equal
- The mutual inductances between the coils on the same leg are all equal
- The mutual inductances between primary and secondary coils on different legs are all equal

The partition of matrix [Z] from equation (02) in four 3 x 3 submatrices leads to:

$$\begin{bmatrix} [\dot{V}_P] \\ [\dot{V}_S] \end{bmatrix} = \begin{bmatrix} [\dot{Z}^P] & [\dot{Z}^{PS}] \\ [\dot{Z}^{PS}] & [\dot{Z}^S] \end{bmatrix} \cdot \begin{bmatrix} [\dot{I}_P] \\ [\dot{I}_S] \end{bmatrix} \qquad (04)$$

where:

$$[\dot{V}_P] = [\dot{V}_{PA} \ \dot{V}_{PB} \ \dot{V}_{PC}]^t$$

$$[\dot{V}_S] = [\dot{V}_{SA} \ \dot{V}_{SB} \ \dot{V}_{SC}]^t$$

$$[\dot{I}_P] = [\dot{I}_{PA} \ \dot{I}_{PB} \ \dot{I}_{PC}]^t$$

$$[\dot{I}_S] = [\dot{I}_{SA} \ \dot{I}_{SB} \ \dot{I}_{SC}]^t$$

Each submatrix in the above equation has only two different elements: diagonal and off-diagonal.
Figure 3 shows the circuit associated with the equation (04).

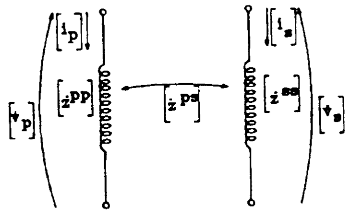

Figure 3 - Scheme of two-winding three phase transformer

For the two-winding phase unit the following tests are available: a) positive (1) and zero (0) sequence excitation tests b) positive (1) and zero (0) sequence short-circuit tests.
For excitation test the equation (04) in p.u. values, becomes:

$$[\dot{V}^{exc}_P] = j[X^P] \ . \ [\dot{I}^{mag}_P] \qquad (05)$$

where:

$[V_P^{exc}]$ - vector of primary excitation voltages
$[I_P^{mag}]$ - vector of primary exciting currents
$j[X^P]$ - imaginary part of matrix $[Z^P]$

The Fortescue's transformation on equation (05) gives for each sequence:

$$\dot{V}^{exc}_{P0} = jX^P_0 \ . \ \dot{I}^{mag}_{P0} \qquad (06)$$

$$\dot{V}^{exc}_{P1} = jX^P_1 \ . \ \dot{I}^{mag}_{P1} \qquad (07)$$

where:

X_0^P - zero sequence magnetizing reactance
X_1^P - positive sequence magnetizing reactance

From the data of excitation tests given by the manufacturer, is possible to calculate from equations (06) and (07) sequence magnetizing reactances.
The sequence reactances and phase coordinate reactances are related through:

$$X^P_s = \frac{1}{3}(X^P_0 + 2X^P_1) \qquad (08)$$

$$X^P_m = \frac{1}{3}(X^P_0 - X^P_1) \qquad (09)$$

For the secondary winding is reasonable to assume that the reactances in p.u. values are the same. The diagonal matrix [R] is derived from the data given by the manufacturer.
Finally $[Z^P]$ and $[Z^S]$ matrices have the following diagonal and off-diagonal elements, respectively:

$$\dot{Z}^P_s = R^P + jX^P_s \qquad \dot{Z}^P_m = jX^P_m$$

$$\dot{Z}^S_s = R^S + jX^P_s \qquad \dot{Z}^S_m = jX^P_m$$

For short-circuit test with winding resistances being ignored the equation (04) in p.u. values, becomes:

$$[\dot{V}_P^{short}] = j\,[X^P] \ . \ [\dot{I}_P^{short}] + j\,[X^{PS}] \ . \ [\dot{I}_s^{short}] \qquad (10)$$

$$[O] = j[X^{PS}] \ . \ [\dot{I}_P^{short}] + j[X^S] \ . \ [\dot{I}_s^{short}] \qquad (11)$$

where:

$$j\,[X^{PS}] = [Z^{PS}]$$

$j[X^S]$ - imaginary part of matrix $[Z^S]$

The Fortescue's transformation on equations (10) and (11) gives:

$$\dot{V}_{P1}{}^{short} = jX_1{}^{P} . \dot{I}_{P1}{}^{short} + jX_1{}^{PS} . \dot{I}_{S1}{}^{short}$$
$$O = jX_1{}^{PS} . \dot{I}_{P1}{}^{short} + jX_1{}^{S} . \dot{I}_{S1}{}^{short} \qquad (12)$$

$$\dot{V}_{P0}{}^{short} = jX_0{}^{P} . \dot{I}_{P0}{}^{short} + jX_0{}^{PS} . \dot{I}_{S0}{}^{short}$$
$$O = jX_0{}^{PS} . \dot{I}_{P0}{}^{short} + jX_0{}^{S} . \dot{I}_{S0}{}^{short} \qquad (13)$$

From the data of positive and zero short-circuit tests given by the manufacturer, is possible to calculate:

$$\frac{\dot{V}_{P1}{}^{short}}{\dot{I}_{P1}{}^{short}} = \dot{Z}_{PS1}{}^{short} \quad (14) \qquad \frac{\dot{V}_{P0}{}^{short}}{\dot{I}_{P0}{}^{short}} = \dot{Z}_{PS0}{}^{short} \quad (15)$$

The equations (12) and (13) together with imaginary parts of the impedances defined in equations (14) and (15) lead to:

$$jX_1{}^{PS} = \sqrt{(jX_1{}^{P} - jX_{PS1}{}^{short})\, jX_1{}^{S}} \qquad (16)$$

$$jX_0{}^{PS} = \sqrt{(jX_0{}^{P} - jX_{PS0}{}^{short})\, jX_0{}^{S}} \qquad (17)$$

The diagonal element $jX_s{}^{PS}$ and off diagonal element $jX_m{}^{PS}$ of matrix $[Z^{PS}]$ are derived from sequence reactance values $X_1{}^{PS}$, $X_0{}^{PS}$ as stated by equations (08) and (09).

2.1.2 Characteristics of the model [R]-[L]

The short-circuit reactances of the primary winding are represented indirectly in the matrix [Z] through the differences between the matrices $[Z^P]$ and $[Z^{PS}]$ in p.u. values. The short-circuit reactances of the secondary winding are represented indirectly in the matrix [Z] through the differences between the matrices $[Z^S]$ and $[Z^{PS}]$ in p.u. values. It's therefore important that the elements of matrix [Z] be calculated with very high accuracy,this would be an important restriction of he model. The exciting current must always be nonzero because matrix [Z] becomes infinite for zero exciting current.

2.2 [R]-[L]$^{-1}$ model

The equation (01) can be written as:

$$\frac{d}{dt}[i] = [L_{crm}]^{-1} . [v] - [L_{crm}]^{-1} . [R] . [i] \qquad (18)$$

where:

$[L_{crm}]$ - branch inductance matrix of the windings with magnetizing branches included

When the magnetizing inductances tend to infinite, the limit of equation (18) is:

$$\frac{d}{dt}[i] = [L]^{-1} . [v] - [L]^{-1} . [R] . [i \qquad (19)$$

where:

$$\underset{\text{without magnetizing branches}}{[L]^{-1}} = \lim_{[M] \to \infty} [L_{crm}]^{-1} \qquad (20)$$

The equations (19) and (20) lead to the "[R]-[L]$^{-1}$ model" of the transformer.

2.2.1 Derivation of the matrices [R] and [L]$^{-1}$

In the next section one way to obtain [R] and $[L]^{-1}$ matrices separately is described. The diagonal matrix [R] is derived from the data given by the manufacturer. In this section an extension from Dr.H.Dommel's procedure [2], [4], [5], for obtaining matrix $[L]^{-1}$ in the case of single phase N-coil transformer is made for two-winding three phase unit. From here on it is best to work with p.u. values and the winding resistances are ignored. From equation (04) the voltage drops between primary and secondary windings are expressed as:

$$[\dot{V}_P] - [\dot{V}_S] = ([\dot{Z}^P] - [\dot{Z}^{PS}]) . [\dot{I}_P] + ([\dot{Z}^{PS}] - [\dot{Z}^S]) . [\dot{I}_S] \qquad (21)$$

which can be written as:

$$[[\dot{V}_P] - [\dot{V}_S]] = [\dot{Z}'] . \begin{bmatrix} [\dot{I}_P] \\ [\dot{I}_S] \end{bmatrix} \qquad (22)$$

where:

$$[\dot{Z}'] = [[\dot{Z}^P] - [\dot{Z}^{PS}] \;\; \vdots \;\; [\dot{Z}^{PS}] - [\dot{Z}^S]]$$

(3 rows and 6 columns)

The magnetizing branches are ignored, then the sum of winding currents must be zero, or:

$$[\dot{I}_P] + [\dot{I}_S] = [O] \qquad (23)$$

From equations (22) and (23) results:

$$[[\dot{V}_P] - [\dot{V}_S]] = [\dot{Z}^{reduced}] . [\dot{I}_P] \qquad (24)$$

where matrix $[Z^{reduced}]$ has 3 rows and 3 columns. When the exciting currents are neglected the elements of matrix [Z] in equation (04) become infinites, however the matrix $[Z^{reduced}]$ does exist because their elements can be calculated from the short-circuit tests data which are not influenced by exciting currents. The Fortescue's transformation on equation (24) gives for each sequence:

$$\dot{V}_{P1} - \dot{V}_{S1} = \dot{Z}_1{}^{reduced} . \dot{I}_{P1} \qquad (25)$$

$$\dot{V}_{P0} - \dot{V}_{S0} = \dot{Z}_0{}^{reduced} . \dot{I}_{P0} \qquad (26)$$

For short-circuit tests the equations (25) and (26) become:

$$\dot{V}_{P1}{}^{short} = \dot{Z}_1{}^{reduced} . \dot{I}_{P1}{}^{short} \qquad (27)$$

$$\dot{V}_{P0}{}^{short} = \dot{Z}_0{}^{reduced} . \dot{I}_{P0}{}^{short} \qquad (28)$$

From the data of positive and zero short-circuit tests given by the manufacturer, is possible to use the equations (14) and (15), which give:

$$\dot{Z}_1{}^{reduced} = \dot{Z}_{PS1}{}^{short} \qquad (29)$$

$$\dot{Z}_0{}^{reduced} = \dot{Z}_{PS0}{}^{short} \qquad (30)$$

In this model the resistance and inductance parts of each branch must be separated.This is best accomplished by building matrix $[Z^{reduced}]$ only from the reactance part of the short-circuit test data. The diagonal element $jX_s{}^{red}$ and off diagonal element $jX_m{}^{red}$ of matrix $[Z^{red}]$ are derived from sequence reactance values $X_{PSO}{}^{short}$, $X_{PSO}{}^{short}$ as stated by equations (08) and (09).

In terms of admittance the equation (27) is rewritten as:

$$[\dot{I}_P] = [\dot{Y}^{reduced}] . [[\dot{V}_P] - [\dot{V}_S]] \qquad (31)$$

where :

$$[\dot{Y}^{reduced}] = [\dot{Z}^{reduced}]^{-1}$$

Equation (31) can be rewritten as:

$$[\dot{I}_P] = [[\dot{Y}^{reduced} \; \vdots \; - [\dot{Y}^{reduced}]] \cdot \begin{bmatrix} [\dot{V}_P] \\ \cdot \\ [\dot{V}_S] \end{bmatrix} \quad (32)$$

From equation (23) :

$$[\dot{I}_S] = - [\dot{I}_P] \quad (33)$$

Equations (32) and (33) give :

$$\begin{bmatrix} [\dot{I}_P] \\ [\dot{I}_S] \end{bmatrix} = [\dot{Y}^*] \cdot \begin{bmatrix} [\dot{V}_P] \\ [\dot{V}_S] \end{bmatrix} \quad (34)$$

where :

$$[\dot{Y}^*] = \begin{bmatrix} [\dot{Y}^{red}] & -[\dot{Y}^{red}] \\ -[\dot{Y}^{red}] & [\dot{Y}^{red}] \end{bmatrix}$$

Finally for two windings three phase transformer is valid :

$$[L]^{-1} = jw[\dot{Y}^*]$$

2.2.2 Characteristics of the model [R]-$[L]^{-1}$

In the last section 2.2.1 a matricial model of two windings three phase transformer was obtained in which the excitings currents were ignored. This could not be done in the model [R]-[L] of item 2.1. The matrix $[L]^{-1}$ is symmetric and singular (does not have inverse matrix of it), consequently this notation founded in different manual of EMTP does not have mathematical meaning, actually the notation [A] is used. The procedure for the obtention of [R]-[L] and [R]-$[L]^{-1}$ models for three or more windings of a three phase transformer is conceptually equal to the procedure used here for two windings three phase transformer.

3. ADDITTION OF OTHER CHARACTERISTICS [1] [2]

In this section a briefly description of how to add other characteristics of the transformer,s iron core is made.

3.1 Inclusion of magnetizing branches

For [R]-[L] model the excitings currents must always be nonzero, so the magnetizing branches are included.
For [R]-$[L]^{-1}$ model a procedure to incorporate this branches is developed in this section. From data of excitation tests given by the manufacturer, is possible to calculate from equations (06) and (07) zero and positive sequence magnetizing admittances: Y^m_0 and Y^m_1. The diagonal element jY_s^{mag} and off diagonal element jY_m^{mag} of matrix $[Y^{mag}]$ arederived from sequence reactance values Y_0^m, Y_1^m as stated by equations (08) and (09).

If the secondary winding is the closest to the core, the submatrix $[Y^m]$ is additioned to the matrix $[Y^*]$ of the section 2.2.1 as:

$$[\dot{Y}^*_{crm}] = \begin{bmatrix} [\dot{Y}^{red}] & -[\dot{Y}^{red}] \\ -[\dot{Y}^{red}] & [\dot{Y}^{red}] + [\dot{Y}^{mag}] \end{bmatrix}$$

Finally the new matrix $[L]^{-1}$ looks like as:

$$[L]^{-1} = jw[\dot{Y}^*_{crm}]$$

3.2 Inclusion of Hysteresis and Eddy Current Losses

The losses in the iron-core of the transforemr consist of two parts: a) Hysteresis losses b) Eddy Current losses. The sum of the two parts of losses is incorporated in the same way in the models [R]-[L] and [R]-$[L]^{-1}$ as explained here. From the zero and positive sequence excitation losses data given by the manufacturer is possible to obtain:

$$G_{m1} = \frac{P_{Fe\,1}}{S_b} \text{ p.u.} \qquad G_{m0} = \frac{P_{Fe\,0}}{S_b} \text{ p.u.}$$

where :
$P_{Fe\,0}$, $P_{Fe\,1}$ - zero and positive sequence excitation losses
S_b - power rating
$G_{m\,0}$,$G_{m\,1}$ - zero and positive magnetizing conductances
The self and mutual elements of the resistance matrix $[R_m]$ in phase quantities are:

$$R_{ms} = \frac{1}{3}\left(\frac{1}{G_{m0}} + \frac{2}{G_{m1}}\right) \qquad R_{mm} = \frac{1}{3}\left(\frac{1}{G_{m0}} - \frac{1}{G_{m1}}\right)$$

This matrix $[R_m]$, that represents excitation losses, is placed across the terminals of the winding closest to the core. This model of losses does not modify the matrix [R] of matricial models.

3.3 Inclusion of Saturation Effects

Often, saturation curves supplied by manufacturers give RMS voltages as a function of RMS currents, which has to be convert to a λ x i curve to represent saturation. In the references [1][2] a mathematical procedure is described which changes V_{RMS} x I_{RMS} into λ x i curves, this is made by an auxiliar program called SATURA (for ATP 5.0 version).
The representation of the characteristics λ x i is made taking into account two differents regions:

a) unsaturated region
b) saturation region

a) In this region the magnetic couplings between the coils are very strong,then the characteristics λ x i is represented as indicated in section 3.1.
b) In this region the magnetic couplings between the coils are weaks, then the modelling is made through three modified nonlinear inductances decoupled.

In the different versions of EMPT and ATP program are available several models for the representation of nonlinear elements [1] [2].

4. CASE STUDIES

In this section some results of simulations made with the program ATP (5.0 version for PC) are presented:
- Switching surges during energization of a transformer bank
- Saturation effects on power transformer due to temporary overvoltages

4.1 Switching surges

Switching surges were calculated due to energization of an unloaded transformer bank, voltages ratings 150/31.5/6.3 kV, apparent power ratings 50/50/15 MVA, type of connection Yyd. The neutral of the primary winding is directly earthed, while the neutral of the secondary winding is earthed through a 20 ohm resistance. This transformer belong to the 150 kV network transmission of Uruguay.

The following deterministic studies of energization were made from high voltage side.

Case 1 - The transformer bank was modelling through Saturable Transformer Component, the losses in the iron core were ignored.

Case 2 - The same model as in Case 1 but the losses in the iron core were taken into account.

Case 3 - The transformer bank was modelling through the matricial model $[R]-[L]^{-1}$, the losses in the iron core were ignored.

Case 4 - The same model as in Case 3 but the iron core losses were taken into account.

In all the cases the characteristic λ x i for each unit was used and the following values were chosen: - inicial voltage (before the energization) equal to 1.04 pu
- time step equal to 50 microseconds
- simulation time equal to 6 cycles

Figure 4 shows the voltage Phase B-Neutral in the 31.5 kV winding from Case 1. There are spurious numerical oscillations that crate transients overvoltages very high but not real.

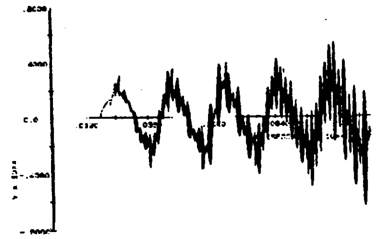

Figure 4 - Overvoltage Phase B - Neutral (31.5 kV)(Case 1)

Figure 5 shows the same voltage from Case 2. There is a damping of the numerical oscillations because the resistances that represent iron core losses are included.

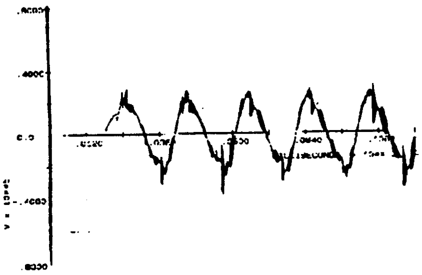

Figure 5 - Overvoltage Phase B - Neutral (31.5 kV)(Case 2)

Figure 6 shows the same voltage from Case 3, practically there are no numerical oscillations.

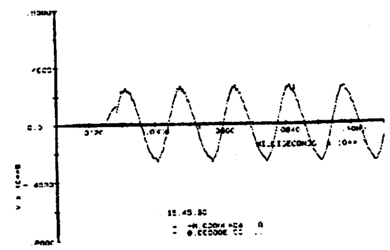

Figure 6 - Overvoltage Phase B - Neutral (31.5 kV)(Case 3)

For the different cases mentioned above the maximum and minimum values of the voltage Phase B-Neutral were obtained as indicated in Table I.

Table I - Voltage Phase B-Neutral (31.5kV)

Phase B - Neutral	Maximum (pu)	Minimum (pu)
Case 1	2.078	-2.497
Case 2	1.222	-1.474
Case 3	1.065	-1.049
Case 4	1.059	-1.043

From the results presented it can be concluded that:
- the matricial model has a better perfomance because it does not present numerical oscillations.
- the numerical oscillations that present the Saturable Transformer Component can be damped with the allocation of high resistances.
- the results obtained with matricial models in the Cases 3 and 4 are very similar.

4.2 Temporary overvoltages

In this section, for the power system of Figure 7, the values of temporary overvoltages derived from a simulation and those from field tests data are presented, with the objetive to evaluate the perfomance of the matricial model "$[R]-[L]^{-1}$".

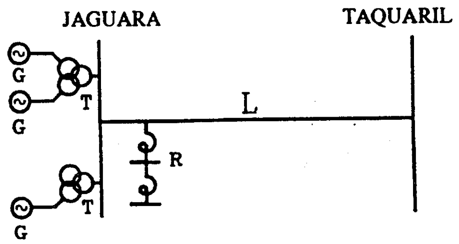

Figure 7 - Power network configuration

In the power network configuration of Figure 7:
- G - Generator of voltage rating 13.8 kV and power rating 112 MVA
- T - Transformer bank of voltage ratings 13.8/13.8/345 kV, and power rating 120/120/240 MVA
- L - Transmission line with length equal to 398 km
- R - Reactor bank of 56 MVAr

The data for the $[R]-[L]^{-1}$ model of the transformer bank T, and the other elements of the network were obtained of the reference [6]. In the simulation the curves λ x i and the losses in the iron core for each unit were taken into account, and the following values were adopted:
- time step equal to 50 microseconds
- simulation time equal to 9 cycles

Maximum and minimum values of line to ground voltage in Jaguará and Taquaril busbars are presented in the tables II and III.

Table II - Line to ground voltage in Jaguará terminal

Jaguará	Maximum (kV)	Minimum (kV)
Case	360.2	-361.0
Field test [8]	364.0	-360.0

Table III - Line to ground voltage in Taquaril terminal

Taquaril	Maximum (kV)	Minimum (kV)
Case	424.3	-422.8
Field test [8]	419.0	-414.0

Figures 8 and 9 show line to ground voltages in Jaguará and Taquaril busbars obtained from simulations.

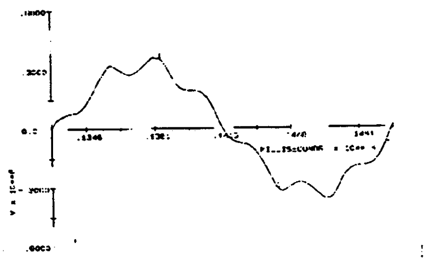

Figure 8 - Line to ground voltage in Jaguará

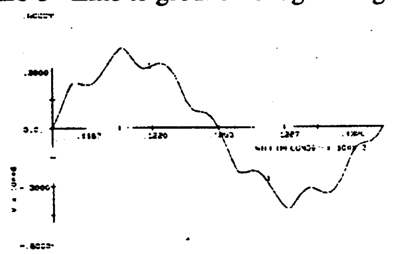

Figure 9 - Line to ground voltage in Taquaril

Figures 10 and 11 show line to ground voltages for the same terminals, from reference [6].

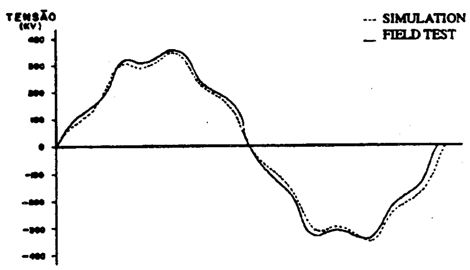

Figure 10 - Line to ground voltage in Jaguará terminal

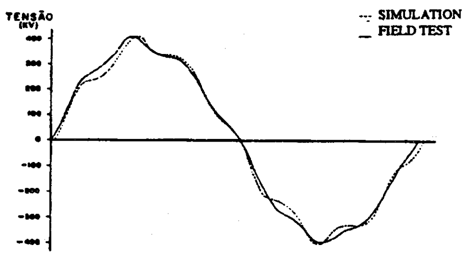

Figure 11 - Line to ground voltage in Taquaril terminal

From the results presented in this section it can be concluded that:

- the shapes of the curves obtained from simulations and field tests data are very similar
- the maximum difference calculated between the maximum values from simulations and field tests data was 2%. The same for minimum values

5. CONCLUSIONS

In the above studies the matrix representation,"[R]-[L]$^{-1}$ model" has a very good behavior for switching surges and temporary overvoltages:there weren,t numerical oscillations and there was a good agreement between the digital simulation and field tests data.

For representation of three phase core type transformer the matricial models didn't require the addition of extra delta-connected winding.

From the mentioned above the authors can conclude that the matricial models of power transformers become a better alternative in relation to others models availables in EMTP and ATP programs.

6. REFERENCES

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