Modeling, simulation and optimization of transmission lines. Applicability and limitations of some used procedures

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***Abstract* - The paper discusses the basic aspects of modeling, simulation and optimization of transmission lines, with emphasis in validity, applicability and limitations of some used procedures, and some guidelines for development of new procedures.**

1. INTRODUCTION

In this paper we discuss the basic aspects of modeling, simulation and optimization of transmission lines. As the subject can not be systematically covered within a single paper, we have chosen some specific points, as examples, which we discuss with emphasis in validity, applicability and limitations of some used procedures, and some guidelines for development of new procedures. Due to the vast bibliography about lines and its modeling, following the aim of this paper, we do not give a comprehensive list of references. We only indicate, also as examples, some references directly related with chosen specific points and the way they are presented. By no means, the choice of topics may be interpreted as a judgment of methodologies and procedures not dealt with in the paper.

The topics related to transmission lines modeling, simulation and optimization cover :

a. Physical evaluation of basic line parameters and associated analytical, numeric, analogous or test procedures, and accuracy requirements, according to foreseen applications.

b. Procedures to represent a line, considering its basic parameters and length, e. g. as seen from its terminals, and in a form adequate for the specific application.

c. Modeling and simulation of a line inserted in a network and interacting with the behavior of other elements.

d. Optimization of a line, according normal and transient operational constraints and effects, investment and operational cost, reliability, service quality, people and equipment safety, ambient impact, effects of eventual deviations from foreseen operational requirements.

In what concerns operational aspects and constraints, the following aspects must be taken into account:

A. In what concerns electromagnetic behavior:

A.1 Normal and contingency conditions and several types of transients, including slow transients, such as those involving electromechanical stability and related phenomena, voltage stability related to slow phenomena, sustained electrical overvoltages and related transients, fault and switching transients and fast transients, as those associated to lightning and to electric arc extinction, slow and fast ionization processes, disruptive and aging mechanisms.

A.2 Electromagnetic field and other parameters related to human and equipment safety, ambient impact, interference.

A.3 Interaction with mechanical, thermal, chemical, pollution and meteorological phenomena.

B. In what concerns mechanical, thermal, chemical and related meteorological phenomena:

B.1 Mechanical strength and aging, considering statistical aspects of temperature and meteorological phenomena, cascading effects and vandalism. Mechanical interaction with ground in towers' foundations.

B.2 Temperature resulting from load, transients and meteorological conditions, associated conductor displacements and effects in line parameters, including basic and insulation parameters, electromechanical forces, safety.

B.3 Electrochemical and surface aging, corrosion.

In order to situate the discussion of chosen points, avoiding some confusion resulting from different terminologies and assumptions, we present the *Appendix 1 - Traditional basic formulation of line parameters evaluation*, in which we do a very simple presentation, basically as example. Some of basic aspects are presented there, and, so, we do not repeat them. In order to simplify the presentation, we include in *Appendix 1* some procedures we have developed, e. g. in order to consider the electric permittivity of ground, the corona phenomena and lightning effects, and that are not used in common engineering practice.

In item 2. we discuss, as example, some basic aspects of usual procedures to evaluate line parameters, within the context of the simple formulation of *Appendix 1*.

In item 3. we deal with the effect of line transposition, trying, in this example, to illustrate a quite simple procedure of line modeling that avoids some frequent simplifications, and to discuss, in a concrete example, the effect of some modeling variants and simplifications, under the points of view of modeling procedures and of errors of obtained results. Some aspects that deal with a more detailed interpretation of modeling and errors are placed in *Appendix 2 - Modulus of immittance W in examples a , b , c , in function of frequency*.

In item 4. we discuss some aspects of modeling shield wire effects, related we the evaluation of the error that results from some usual simplifications and the definition of the conditions in which such error is acceptable.

In item 5. we discuss basic soil modeling, for line parameter evaluation purposes. We have chosen this topic because, typically, soil modeling assumptions, in line parameter evaluation, is far from reality.

In item 6. we present several aspects of very long distance transmission lines and systems, that are important for an adequate optimization of this type of transmission systems. In 6.1 we discuss some essential aspects of very long distance transmission. In 6.2, we comment basic physical aspects of very long lines operating conditions, and, in 6.3, basic physical aspects of very long lines switching.

In item 7. we discuss some aspects of transmission line optimization, with some concrete examples.

In item 8. we discuss the importance of joint optimization of line, network and operational criteria, also with a concrete example.

In item 9. we present a basic methodology to evaluate adequacy of line parameters and simulation procedures.

In item 10. we present some conclusions.

2. SOME BASIC ASPECTS OF USUAL PROCEDURES TO EVALUATE LINE PARAMETERS

In the most usual procedures to evaluate line parameters there are some explicit or implicit assumptions that imply in physical approximations. According the specific case or application, the errors resulting from such assumptions may be important and, even, may invalidate results obtained with such procedures.

The number of such assumptions is quite high. So, only two examples are discussed.

The first example is related with the implicit assumption of quasi stationary behavior of electromagnetic field, for directions orthogonal to line axis, that is considered in most (but not all) usual procedures of power engineering practice.

In order to simplify the discussion, let us consider a cylindrical conductor, with infinite conductivity, of infinite length, immersed in an homogeneous medium. Let us consider cylindrical space coordinates, $\mathbf{x}$, $\mathbf{r}$, φ , being $\mathbf{x}$ coincident with the axis of the conductor, $\mathbf{r}$ the distance to such axis and φ the angular cylindrical coordinate. Let us consider electromagnetic magnitudes at frequency $\mathbf{f}$, in complex representation.

Let us consider in such conductor a longitudinal current, $\mathbf{I}$, function of $\mathbf{x}$, and a total transversal current (including conduction current and displacement current), per unit length, $\underline{\mathbf{I}}_{\mathbf{t}}$. The electric charge, per unit length, in the conductor, $\mathbf{Q}$, is related with $\underline{\mathbf{I}}_{\mathbf{t}}$ by

$$\underline{\mathbf{I}}_{\mathbf{t}} = i\,\omega\,\mathbf{Q} \qquad (\omega = 2\,\pi\,\mathbf{f}\,)$$

The line parameters per unit length, $\mathbf{Z}$, $\mathbf{Y}$, are associated to electromagnetic fields, $\mathbf{E}$, $\mathbf{H}$, that can be obtained, e. g., through Lorentz potentials $\mathbf{V}$, $\mathbf{A}$ related with charge and current in the line.

The most used procedures to obtain parameters imply that, in a plane perpendicular to line axis, defined by a value of $\mathbf{x}$:

- $\mathbf{V}$, $\mathbf{A}$, $\mathbf{E}$, $\mathbf{H}$, depend on values of $\mathbf{I}$, $\mathbf{Q}$ (or related $\underline{\mathbf{I}}_{\mathbf{t}}$) for the same $\mathbf{x}$. This implies that the dependence on $\mathbf{x}$ of $\mathbf{I}$, $\mathbf{Q}$ have negligible effect on electromagnetic field, or, in other words, that the variation of $\mathbf{I}$, $\mathbf{Q}$ within the range $[\,\mathbf{x} - \Delta\,,\,\mathbf{x} + \Delta\,]$ of $\mathbf{x}$ is quite small, for Δ much higher that the distance from the conductor in which electromagnetic field is important.
- $\mathbf{V}$, $\mathbf{A}$, $\mathbf{E}$, $\mathbf{H}$, in air or with ideal ground, are related to values of $\mathbf{I}$, $\mathbf{Q}$ (or related $\underline{\mathbf{I}}_{\mathbf{t}}$) in the same instant $\mathbf{t}$, for the same $\mathbf{x}$, what implies to assume instantaneous propagation in directions perpendicular to $\mathbf{x}$.

Some very simple examples show the eventual importance of errors resulting from the most usual common assumptions:

- For ideal conductors and ideal ground (infinite conductivity) the longitudinal impedance per unit length, $\mathbf{Z}$, and the transversal admittance per unit length, $\mathbf{Y}$, with usual assumptions, would be

$$\mathbf{Z} = i\,\omega\,\mathbf{L} \qquad\qquad \mathbf{Y} = i\,\omega\,\mathbf{C}$$

with $\mathbf{L}$ and $\mathbf{C}$ frequency independent. However, the correct values of $\mathbf{L}$, $\mathbf{C}$, if defined through the previous expressions, are frequency dependent, although, at “low” frequency, they can be assumed frequency independent with acceptable error.

- With the usual assumptions there would be no radiation from transmission lines, what is not true.

To clarify the main aspects of quasi stationary approximation, in electromagnetic field evaluation, let us consider a linear, homogeneous isotropic medium, characterized by a propagation coefficient k , for electromagnetic magnitudes of frequency $\mathbf{f}$, in complex representation, associated to a factor $e^{-i\omega t}$, being $\omega = 2\,\pi\,\mathbf{f}$, and

$$k = \sqrt{\mu\,\varepsilon\,\omega^2 + \mu\,\sigma\,i\,\omega}$$

In air, $k \cong 3.337\;10^{-9}\;\mathrm{m^{-1}s}\,.\,\omega$ and, for 1 MHz, $k \cong 0.0219\;\mathrm{m^{-1}}$.

Let us consider a “punctual” electric charge, in a fixed position in space and varying sinusoidaly in time, of the form (in complex representation)

$$q = \mathbf{q}\;e^{-i\omega t}$$

Let us consider a generic point P , at distance r from such charge, and let $\mathbf{r}$ be the vector of point, referred to the center of the electric charge.

With some constraints and criteria of validation and interpretation, the electric field, $\mathbf{E}$, associated to such charge, in the generic point P , is

$$\mathbf{E} = \frac{q}{4\,\pi\,\varepsilon}\,\frac{1}{r^2}\;e^{-i\omega t}\;\frac{\mathbf{r}}{r}\;\left[1 - i\,k\,r\right]\;e^{i\,k\,r}$$

The “quasi stationary” approximation is equivalent to consider

$$|\,k\,r\,| << 1$$

and, so,

$$\mathbf{E} \cong \frac{q}{4\,\pi\,\varepsilon}\,\frac{1}{r^2}\;e^{-i\omega t}\;\frac{\mathbf{r}}{r}$$

Similar effects appear in the relations between elementary charge and current sources and associated $\mathbf{V}$, $\mathbf{A}$, $\mathbf{E}$, $\mathbf{H}$, without, or with, quasi stationary approximation.

To have a more concrete idea of the relative effect of the quasi stationary approximation, let us consider the relative error, $\Delta_{\mathbf{r}}$, of the transversal unitary impedance, defined as

$$\Delta_{\mathbf{r}} = \mathbf{Z_u} \,/\, \mathbf{Z_{u0}} - 1$$

being:

$\mathbf{Z_u}$ the transversal impedance, referred to an unitary length, between a charge straight linear filament, infinite in both senses, with uniformly distributed charge, and varying sinusoidaly in time (with equal phase along the filament) and a pair of linear filaments, parallel to the charge filament and at distances from it respectively $\mathbf{r_1}$ and $\mathbf{r_2}$, in a homogeneous, linear and isotropic medium.

$\mathbf{Z_{u0}}$ the transversal impedance, referred to an unitary length, in conditions similar to those indicated for $\mathbf{Z_u}$, but with the quasi stationary approximation (equivalent to assume k r = 0).

In Fig. 1 we represent the modulus, $|\Delta_r|$, of Δ_r , in function of modulus, $\boldsymbol{M}$, and argument, $\boldsymbol{A}$, of $k\,r_1 = \boldsymbol{M}\,e^{\,i\boldsymbol{A}}$, for $r_2 / r_1 = 10$. The values of $|\Delta_r|$ are indicated by numbers in white or blue, that identify the lines that separate value domains of $|\Delta_r|$, in a color scale.

In Fig. 2 we do a similar representation, for $r_2 / r_1 = 100$.

In Fig. 3 to 5 we represent $|\Delta_r|$ in function of $\boldsymbol{M}$, for a pure dielectric medium ($\sigma = 0$), in which k is real and, so,

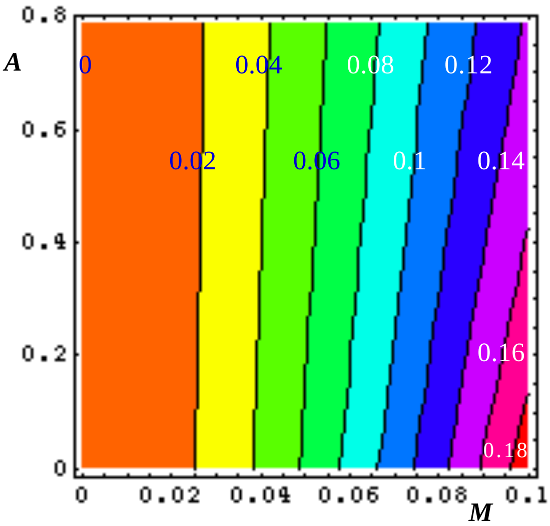


Fig. 1 - $|\Delta_r|$ in function of $\boldsymbol{M}$, and $\boldsymbol{A}$, for $r_2 / r_1 = 10$.

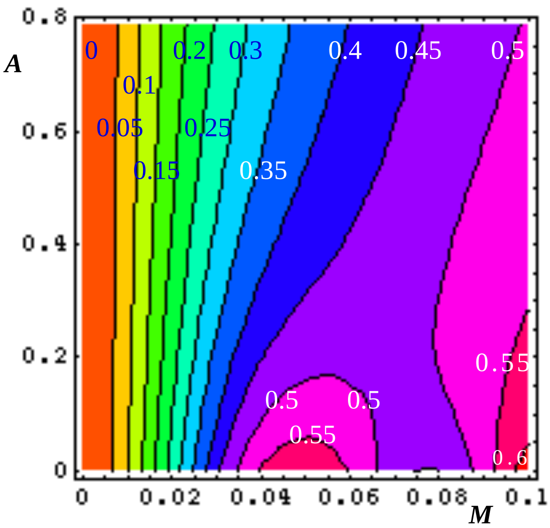


Fig. 2 - $|\Delta_r|$ in function of $\boldsymbol{M}$, and $\boldsymbol{A}$, for $r_2 / r_1 = 100$.

$\boldsymbol{A} = 0$. Fig. 3 , 4 and 5 refer to r_2 / r_1 equal to 10 , 100 , 1000 , respectively.

Let us consider, now, an apparently more restrictive concept of per unit length line parameters **Z** , **Y** , and the electromagnetic fields, **E** , **H** , associated with such definitions.

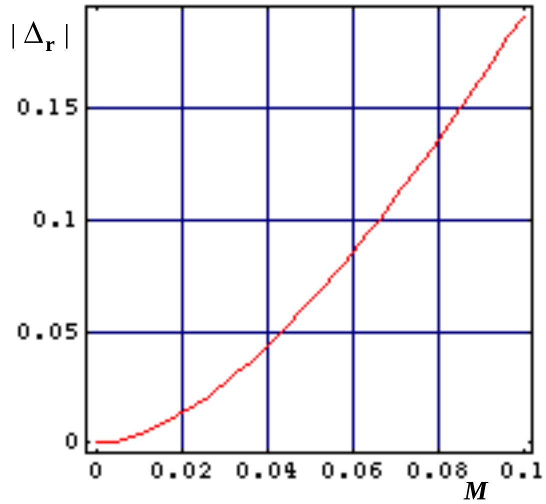


Fig. 3 - $|\Delta_r|$ in function of $\boldsymbol{M}$, for $\boldsymbol{A} = 0$, $r_2 / r_1 = 10$.

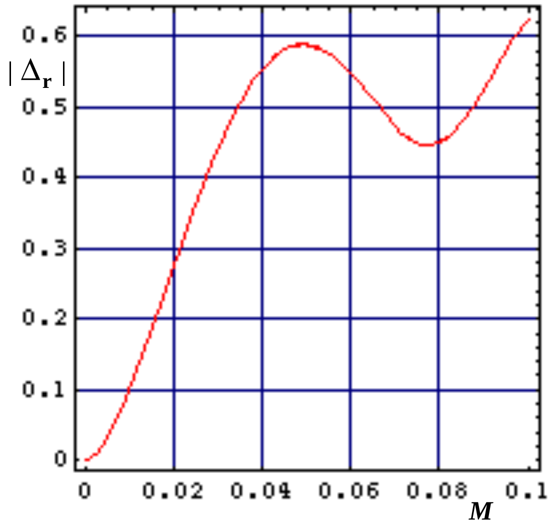


Fig. 4 - $|\Delta_r|$ in function of $\boldsymbol{M}$, for $\boldsymbol{A} = 0$, $r_2 / r_1 = 100$.

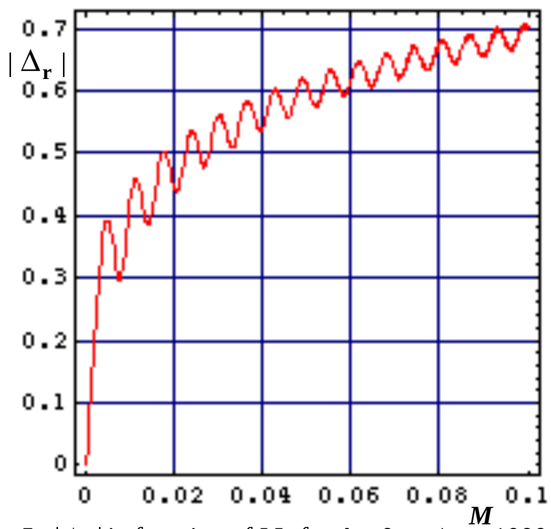


Fig. 5 - $|\Delta_r|$ in function of $\boldsymbol{M}$, for $\boldsymbol{A} = 0$, $r_2 / r_1 = 1000$.

In this concept, the evaluation of these parameters is associated with specific modes, in a propagation sense, along the line, treated separately. For each mode, longitudinal currents, transversal voltages, electric and magnetic fields, in any plane perpendicular to line direction, $\mathbf{x}$, maintain a fixed proportion, and vary along $\mathbf{x}$ according a common factor

$e^{\pm \gamma \mathbf{x}}$

So, parameters $\mathbf{Z}$, $\mathbf{Y}$, and the related electromagnetic fields, $\mathbf{E}$, $\mathbf{H}$, for that mode, apply to such proportion and variation with $\mathbf{x}$, and not to a "general" assumption of variation with $\mathbf{x}$ (apart eventual restrictions of "slow variation" with $\mathbf{x}$, or similar). It is out of the scope of this paper a deep discussion of the consequences of this apparently more restrictive concept of line parameters.

Let us consider a simple example, for which there is an "exact" solution of electromagnetic field. In this example we consider a metallic cylindrical conductor, with radius 10 mm, of infinite length, with a material with $\sigma = 35$ MS/m , $\varepsilon = 30\ \varepsilon_0$, $\mu = \mu_0$, immersed in vacuum.

Let us consider the relative error, $\Delta_{\mathbf{Er}}$, of the radial component, $\mathbf{E_r}$, of electric field, defined as

$$\Delta_{\mathbf{Er}} = \mathbf{E_r} / \mathbf{E_{r0}} - 1$$

being:

$\mathbf{E_r}$ the radial component of electric field, at a point, P , at distance r from conductor axis, for the electromagnetic field associated to a mode, propagating in one sense, along the conductor.

$\mathbf{E_{r0}}$ the radial component of electric field, at the same point, P , but with the quasi stationary approximation.

In Fig. 6 we represent the modulus, $\boldsymbol{M_{\mathrm{Er}}}$, and the argument, $\boldsymbol{A_{\mathrm{Er}}}$, in function of r (expressed in meter), for several frequencies, $\mathbf{f}$. It is interesting to mention that the transversal voltage, referred to a point at infinite distance, is finite in the "exact" solution, but infinite in the quasi stationary approximation.

A more detailed quantitative evaluation of this and other examples shows that, for most common applications, the error of assuming quasi stationary behavior, for directions orthogonal to line axis, can be accepted for frequencies till about 1 MHz. For some other applications, however, namely related to lightning effects, radio interference and induced effects far from the line, errors resulting from such assumption are too high, and more correct methods must be used.

Another example, of basic aspects of line parameters evaluation, is related to the fact that common formulas imply a distance, along line axis, from the point or orthogonal plane in which electromagnetic field or parameters are being evaluated, much higher that the distance from line axis till which the electromagnetic field is important for the parameter being evaluated. So, common formulas for line parameters evaluation do not apply to very short conductors or to the vicinity of line extremities. For such conditions, different procedures must be used, e. g. based in methods described in [1-2].

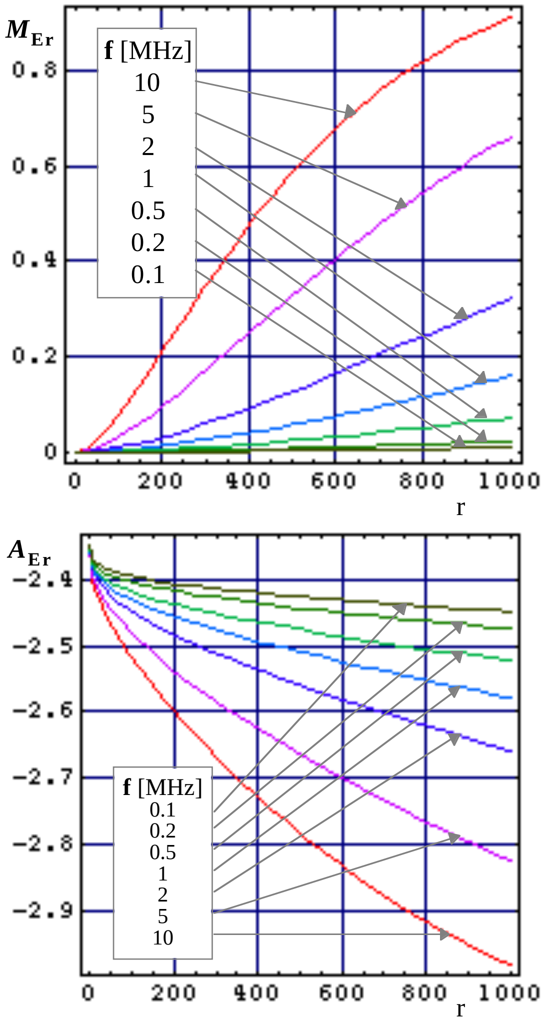


Fig. 6 - $\boldsymbol{M_{\mathrm{Er}}}$ and $\boldsymbol{A_{\mathrm{Er}}}$ in function of r and f , in example conditions.

3. EFFECT OF LINE TRANSPOSITION

In order to illustrate some aspects of modeling assumptions, and, also, a simple way of representing line behavior in frequency domain, directly in three phase, without the need of mode separation and phase-mode-phase transformation, we consider a three-phase, 500 kV , 400 km, 60 Hz , non-conventional line, with different conductor arrangement in central and lateral bundles, and considering soil parameters frequency dependent.

This line has been modeled directly in phase and frequency domain, in frequency range [0 , 20 kHz], considering 2161 frequencies, and with direct integration of line basic equations, in space, obtaining numerically the transfer function between voltages and currents at both extremities, using a fast procedure based in successive doubling of line length for which transference function is evaluated. When applicable, real transposition conditions are considered.

For an easier comparative analysis, it has been considered the switching on of one phase of such line, from an "infinite" busbar, whose phase voltage amplitude, $\hat{\mathbf{U}}$, is taken as unity, is presented graphics. One phase, $\mathbf{k}$, is switched on at $\mathbf{t} = 0$, when the busbar voltage of such phase ($\mathbf{u_{ak}}$) is maximum. The other two phases of switching line terminal were assumed open, during simulation time. At the other line terminal, the three phases were also assumed open, during simulation time. For several conditions, it is represented the voltage, $\mathbf{u}_{\mathbf{bk}}$, of switched phase (**k**) at line open terminal, in function of time.

The following alternatives for line transposition are illustrated as example:

a - Line "ideally" transposed.

b - Line transposed as indicated in Fig. 7.

c - Non transposed line, as indicated in Fig. 8.

For alternative **a**, the result is identical for any **k** value (1 , 2 , 3). For alternative **b**, it is given the result for **k** = 1 (external phase at transposition sectors near extremities) and **k** = 2 (central phase at transposition sectors near extremities). For alternative **c**, it is given the result for **k** = 1 (external phase).

The voltage $\mathbf{u}_{\mathbf{bk}}$, in function of time, **t** , is presented in Fig. 9 to 12. In this example, there are significative differences between the shape of voltage at open line terminal, according alternative and switched phase (when applicable). However, strictly in example conditions, in what concerns overvoltage and insulation coordination, the differences are moderate, and can be neglected for most application purposes. It is justified some caution in eventual generalization of the comparative results of this example. Namely, for conditions in which it occurs an eventual resonance type phenomena, involving line and network, assumptions concerning transposition modeling can be important. It is out of the scope of this paper a general discussion of eventual differences according specific conditions. For illustrative purposes, we present in *Appendix 2*, for the four conditions of Fig. 9 to 12, the amplitude of the immittance, or transfer function, $\mathbf{W} = \mathbf{U}_{\mathbf{bk}} / \mathbf{U}_{\mathbf{ak}}$ between voltages of switched phase, at both line terminals, in simulation conditions, in function of frequency, **f** , in the range [1 , 30 kHz] ($\mathbf{U}_{\mathbf{bk}}$, at open terminal, $\mathbf{U}_{\mathbf{ak}}$ at switched terminal, both in phase **k**).

The graphics of *Appendix 2* show important differences in immittance W , in frequency domain, except for low frequency. For the example conditions the frequency spectrum of disturbance is somewhat diffuse, and there is a reasonable compensation between differences of W in such spectrum. An eventual resonance type condition can imply in important differences according transposition modeling.

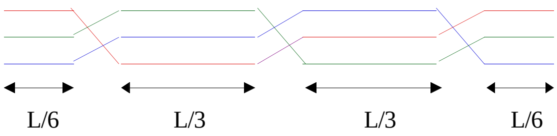


Fig. 7 - Line transposition scheme in alternative **b**. Phases 1 , 2 , 3 are represented in red, green and blue, respectively.

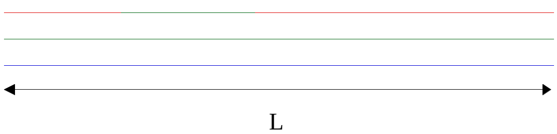


Fig. 8 - Line phase arrangement in alternative **c** . Phases 1 , 2 , 3 are represented in red, green and blue, respectively.

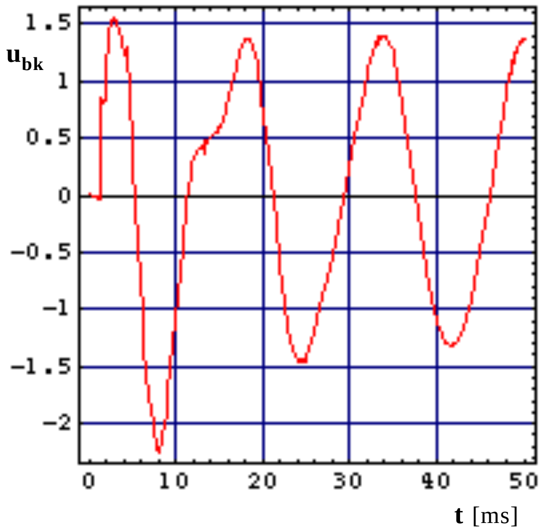


Fig. 9 - Example **a**. Line "ideally" transposed.

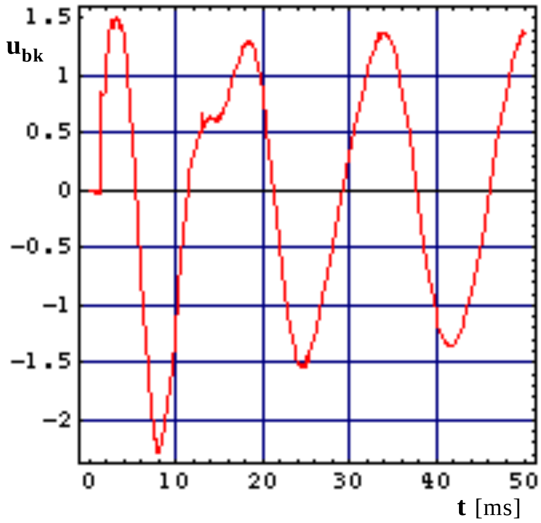


Fig. 10 - Example **b** . Line transposed, as indicated in Fig. 7. Switching on of phase 1.

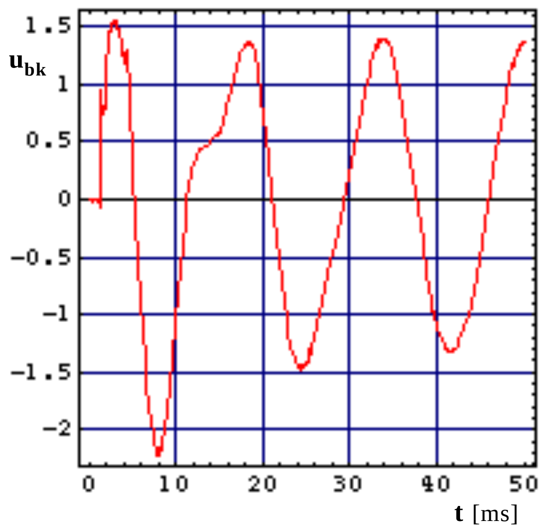


Fig. 11 - Example **b** . Line transposed, as indicated in Fig. 7. Switching on of phase 2.

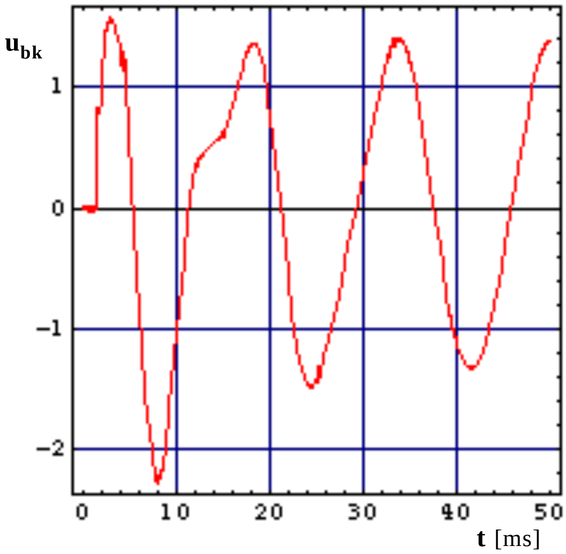


Fig. 12 - Example **c**. Line non transposed, as indicated in Fig. 8. Switching on of phase 1.

4. SOME ASPECTS OF MODELING SHIELD WIRE EFFECTS

As examples, we discuss briefly some aspects of modeling shield wire effects.

Quite often, shield wires are steel cables. It is essential to consider the fact that steel is a ferromagnetic material and, so, it is erroneous to represent it as a metal having a magnetic permeability, μ , practically equal to vacuum permeability, μ_0 . Some versions of commonly used programs do not allow easy access to a convenient choice of cable μ . For some applications, the error resulting from assuming $\mu = \mu_0$ may be very important.

Another important aspect is the eventual saturation of magnetic material of steel cables, that must be taken into account for high current values in shielding wires.

In the common practice, little attention is given to the adequate magnetic characterization of shielding cables, that is neither specified nor measured. Some specific practical cases of Brazilian lines have shown the need to represent correctly the magnetic properties of shielding cables.

Another aspect that needs some attention is the way shielding wires are considered in line simulation. For some purposes, shielding cables must be represented explicitly, together with phase conductors, for instance:

- To analyze lightning behavior, including effects of strikes in towers, shielding wires and phase cables, at least within several spans in both senses from impact point.

- Short-circuits involving ground or shielding wires, also, at least within several spans in both senses from fault point.

In case of shielding wires directly connected to all towers or structures, and excluding the conditions of the two types indicated above, it may be acceptable to consider shielding wires in an implicit way, “eliminating” shield wires of the explicit **Z** and **Y** matrices. This can be done, e. g. , with the assumption of null transversal voltage in shielding wires, what allows a very simple manipulation of matrices to consider the effect of shielding wires in matrices relating, directly, voltages and currents in phases. This procedure appears quite reasonable for frequencies such that a quarter wave length is much longer than line span, or, typically, till about 100 kHz. For higher frequencies, such procedure must be verified according the problem under analysis. As an example, we indicate a specific case in which such procedure can be applied at least till about 1 MHz.

The considered example is a 500 kV transmission line, with non conventional geometry, in which the aspect under analysis relates to β Clarke components, considering as reference the central phase. Due to symmetry of the line in relation to a vertical plane, in the interaction between phases and shielding wires, there is a pair of modes involving, only, β components in phases conductors and in shielding wires. Let us assume a frequency $\mathbf{f}$ = 1 MHz, and a span of 600 m (about two wave lengths), and consider, near a line terminal, the line open at such terminal, and longitudinal currents $\mathbf{i_1}$, $\mathbf{i_3}$, at external phases, at 741 m from line terminal:

$$\mathbf{i_1} = 1 \text{ A} \cos \omega t \qquad \mathbf{i_3} = -1 \text{ A} \cos \omega t \qquad (\omega = 2 \pi \mathbf{f})$$

As an example of computational procedures based in exact modes, the presented results were obtained computing the “exact” modes. Manipulating the line matrices considering phases and shielding wires, the exact eigenvalues and eigenvectors were obtained, relating phase and shielding wires voltages and currents along the line through exact modes. Conditions at two points of phase wires, along the line, and of transversal voltage of shielding wires at line towers, were imposed, obtaining voltages and currents along the line.

In Fig. 13 it is represented the amplitude of voltages to ground of external phases, $\mathbf{\hat{U}_p}$, and of shielding wires, $\mathbf{\hat{U}_s}$, in function of longitudinal line coordinate $\mathbf{x}$ (zero at line extremity).

For comparison purposes, it is also represented, in Fig. 14, $\mathbf{\hat{U}_p}$ in function of $\mathbf{x}$, assuming transversal voltage of shielding wires is null.

As shown by the Fig. 13 and 14, in the conditions of this example, for 1 MHz, the transversal voltage of phase conductors obtained with the assumption of shielding cables continuously grounded is quite similar to correct value, with shielding cables grounded only at towers. Naturally, for transversal voltage at shielding wires, such assumption is not adequate.

5. BASIC SOIL MODELING

One essential aspect of line modeling is the adequate representation of ground, that affects line parameters, per unit length, ahead of being a dominant aspect of for analysis and project of line grounding system. By historical and cultural reasons, the most used procedures assume that the ground may be assumed as having a constant conductivity, frequency independent, and an electric permittivity that can

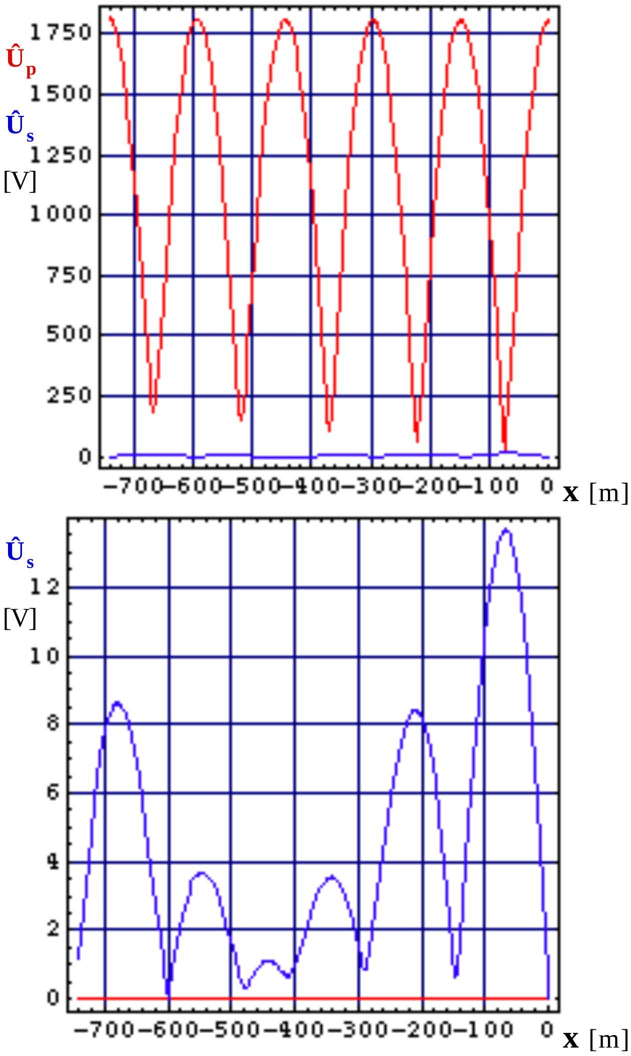


Fig. 13 - Amplitude of voltages, $\hat{\mathbf{U}}_p$ and $\hat{\mathbf{U}}_s$, in function of $\mathbf{x}$, in example conditions.

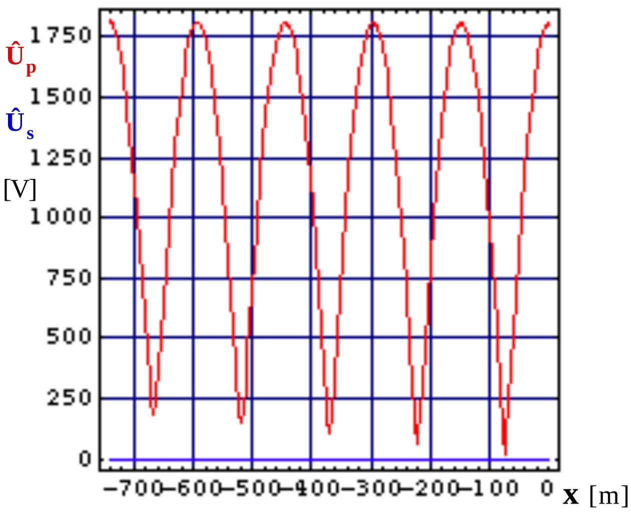


Fig. 14 - Amplitude of voltages, $\hat{\mathbf{U}}_p$ and $\hat{\mathbf{U}}_s$, in function of $\mathbf{x}$, assuming shielding wires continuously grounded.

be neglected ($\omega \ \varepsilon << \sigma$). These two assumptions are quite far from reality, and can originate inadequate line modeling.

Except for very high electric fields, that originate significative soil ionization, soil electromagnetic behavior is essentially linear, but with electric conductivity, σ , and electric permittivity, ε , strongly frequency dependent.

In [1-6] we have presented and justified several soil electric models, that:

- Cover a large number of soil measured parameters, with good accuracy, and within the range of confidence of practical field measurement.
- Satisfy coherence conditions.

From previous models, we have developed a basic and general model of electromagnetic parameters of a medium, that assures physical consistency, and which has shown to be quite useful to define models from measurement results. In particular, such model is very well adapted to soil modeling, with a small number of numerical parameters. For a very high number of soil samples, the dominant behavior, in the frequency range [0 , 2 MHz] , can be represented with such model, with only three numerical parameters. Also, the statistical analysis of a high number of field measurements has identified three parameters that can be assumed statistically independent, and their statistical behavior. One of them, σ_0 , is the soil conductivity at low frequency, that is or can be obtained by usual measurement procedures. The other two, α , Δ_i , whose meaning is described in Fig. 15, define frequency dependence of electric soil parameters.

The statistical distribution of parameters of electric soil model can be represented by Weibull distributions. A summary of statistical distribution of parameters that define frequency dependence is presented in Fig. 15.

If specific measurements of soil parameters, in function of frequency, have been done, procedures described in [1-8] allow to define grounding system behavior, to evaluate people and equipment safety, and to optimize means to obtain adequate behavior for lightning.

One eventual difficulty, specially for small grounding systems, is to evaluate soil parameters related to frequency dependence, that are not obtained by common procedures, and can be measured as described in [3-4].

In [9] we present some results of a systematic analysis of soil behavior for some basic examples related to fundamental aspects that influence the lightning behavior of grounding systems, covering the statistical range of parameters, with a statistical analysis of the effect of soil parameters in such behavior.

With such type of analysis, it is possible to have a basic approach to define, in a statistical sense, the importance of parameters related to frequency dependence, in conjunction with usually available information, and, so, to evaluate the need of specific measurements, or precautions to use parameter estimates, based in statistical distribution of such parameters, and information usually available about soil.

In Fig. 15 we present a summary of a basic soil model and the main aspects of the statistical behavior of frequency dependence of soil parameters.

Basic model :

$$\mathbf{W} = \sigma + i\,\omega\,\varepsilon = K_0 + K_1 \left[1 + i \tan\left(\frac{\pi}{2}\,\alpha\right)\right] \omega^{\alpha} =$$

$$= K_0 + K_{1*}\,\omega^{\alpha}$$

being $i = \sqrt{-1}$, $\omega = 2\,\pi\,\mathbf{f}$, σ the electric conductivity, ε the electric permittivity.

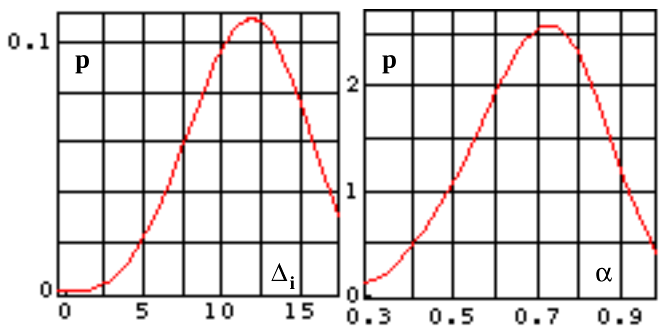
Formulation used in presentation of statistical analysis:

$$\mathbf{W} = \sigma + i\,\omega\,\varepsilon = \sigma_0 + \mathbf{k}\,(i\,\omega)^{\alpha} = \sigma_0 + \Delta\mathbf{W} = \sigma_0 + \Re + i\,\Im$$

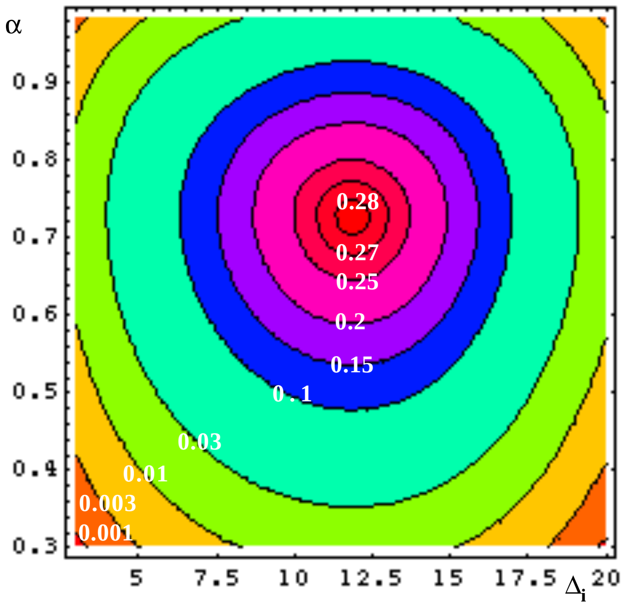
$$\mathbf{W} = \sigma + i\,\omega\,\varepsilon = \sigma_0 + \Delta_i \left[\operatorname{cotang}\left(\frac{\pi}{2}\,\alpha\right) + i\right] \left(\frac{\mathbf{f}}{1\,\mathrm{MHz}}\right)^{\alpha}$$

being σ_0 , Δ_i , α statistically independent, σ_0 the electrical conductivity at low frequency, and $\Delta\mathbf{W} = \Re + i\,\Im$ the increase of $\mathbf{W}$ between low frequency and frequency $\mathbf{f}$.

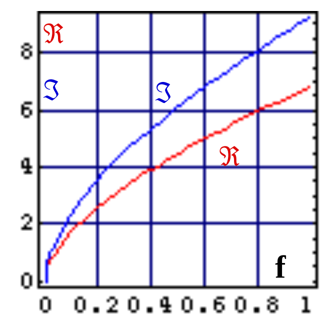
a - Basic definitions



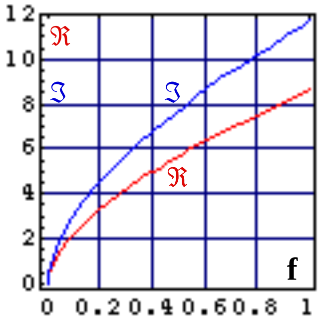
b - Probability density, **p** , of parameters Δ_i , α , considered separately, with Weibull approximations based in a high number of soil samples. Scale of **p** applicable to Δ_i is graduated in $(\mathrm{mS/m})^{-1}$. Scale of Δ_i is graduated in mS/m .



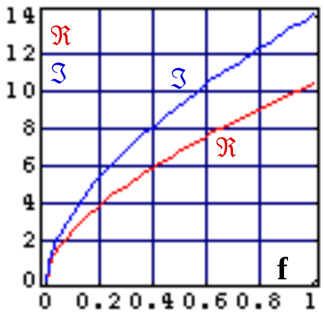
c - Probability density, **p** , of parameters [Δ_i , α] , considered together, with Weibull approximations based in a high number of soil samples. No correlation between Δ_i and α. Scale of Δ_i is graduated in mS/m . Values of **p** , in white, are expressed in $(\mathrm{mS/m})^{-1}$.



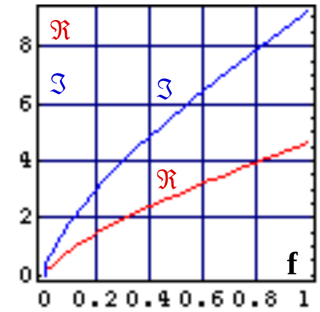
d.1 - $\mathbf{P}(\alpha) = 0.25$, $\mathbf{P}(\Delta_i) = 0.25$



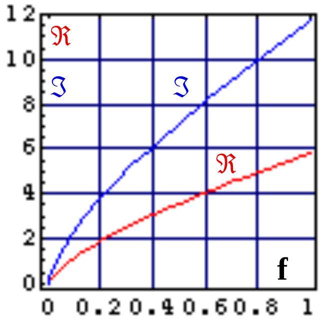
d.2 - $\mathbf{P}(\alpha) = 0.25$, $\mathbf{P}(\Delta_i) = 0.50$



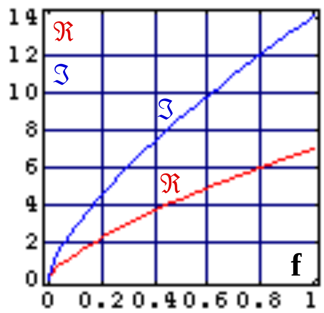
d.3 - $\mathbf{P}(\alpha) = 0.25$, $\mathbf{P}(\Delta_i) = 0.75$



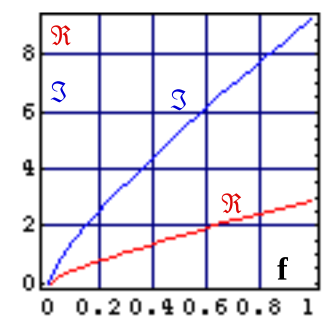
d.4 - $\mathbf{P}(\alpha) = 0.50$, $\mathbf{P}(\Delta_i) = 0.25$



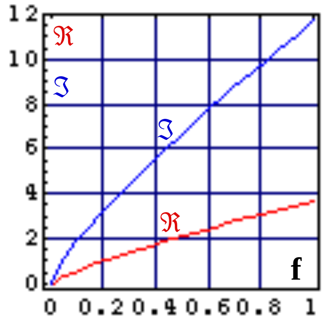
d.5 - $\mathbf{P}(\alpha) = 0.50$, $\mathbf{P}(\Delta_i) = 0.50$



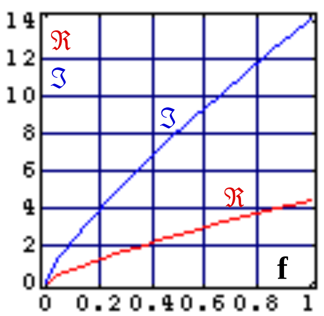
d.6 - $\mathbf{P}(\alpha) = 0.50$, $\mathbf{P}(\Delta_i) = 0.75$



d.7 - $\mathbf{P}(\alpha) = 0.75$, $\mathbf{P}(\Delta_i) = 0.25$



d.8 - $\mathbf{P}(\alpha) = 0.75$, $\mathbf{P}(\Delta_i) = 0.50$



d.9 - $\mathbf{P}(\alpha) = 0.75$, $\mathbf{P}(\Delta_i) = 0.75$

d - Examples of $\Re$, $\Im$ (in mS/m), in function of frequency, **f** (in MHz), for nine pairs of $\mathbf{P}(\alpha)$, $\mathbf{P}(\Delta_i)$, being:

$\mathbf{P}(\alpha)$ - probability of α to be lower than value considered in the graphic;

$\mathbf{P}(\Delta_i)$ - probability of Δ_i to be lower than value considered in the graphic.

Fig. 15. Summary of statistical distribution of soil parameters.

6. VERY LONG DISTANCE TRANSMISSION

6.1 Essential aspects of very long distance transmission

In [10-31], the problem of AC transmission at very long distance was studied using several methods to consider some transmission system alternatives, interpreting the dominant physical and technical phenomena, and using simulations to detail and confirm general analysis.

The results obtained were quite interesting. Namely, they have shown that: electric transmission at very long distance is quite different of what would be expected by simple extrapolation of medium distance transmission experience; to optimize a very long distance transmission trunk, a more fundamental and open approach is needed. By example:

- Very long distance lines do not need, basically, reactive compensation, and, so, the cost of AC transmission systems, per unit length, e.g., for 2800 km, is much lower than, e.g., for 400 km.

- For very long transmission systems, it is appropriate the choice of non conventional line conception, including eventually:
  - "Reduced" insulation distances, duly coordinated with adequate means to reduce switching overvoltages;
  - Non conventional geometry of conductor bundles, six-phase lines, surge arresters distributed along the line.

- Switching transients, for several normal switching conditions, are moderate, in what concerns circuit breaker duties and network transients severity, for lines and equipment. Namely, line energizing, in a single step switching, of a 2800 km line, without reactive compensation, originates overvoltages that are lower than, or similar to, overvoltages of a 300 km line with reactive compensation.

- Quite good results can be obtained with a careful coordination of circuit breakers with line and network, namely with synchronized switching, coordination of several circuit breakers and closing auxiliary resistors.

- There are some potentially severe conditions quite different from typical severe conditions in medium distance systems, e.g., in what concerns secondary arc currents, and requirements to allow fault elimination without the need of opening all line phases. The severity of such conditions is strongly dependent of circuit breaker and network behavior. Due to peculiar characteristics of long lines' transients, it is possible to reduce drastically the severity, with fast switching and appropriate protection schemes. Quite good results can be obtained with a careful coordination of circuit breakers with line and network, namely with synchronized switching, coordination of several circuit breakers and closing auxiliary resistors. Eventually, special schemes can be used to limit overvoltages for some quite unfavorable conditions of fault type and location.

Due to the lack of practical experience of very long transmission lines, and the fact that they have characteristics quite different of traditional power transmission lines and networks, a very careful and systematic analysis must be done, in order to obtain an optimized solution.

6.2 - Basic physical aspects of very long lines operating conditions

In order to clarify the most important aspects of very long lines characteristics, let us assume a line with no losses, total length $\mathbf{L}$, longitudinal reactance per unit length $\mathbf{X}$, transversal admittance per unit length $\mathbf{Y}$, both for non-homopolar conditions, at power frequency, $\mathbf{f}$. In case of longitudinal compensation, and or transversal compensation, at not very long distances along the line, such compensation may be "included" in "equivalent average" $\mathbf{X}$ and $\mathbf{Y}$ values. The electric length of the line, Θ , at frequency $\mathbf{f}$ (being $\omega = 2\,\pi\,\mathbf{f}$ and $\mathbf{v}$ the phase velocity), is

$$\Theta = \sqrt{\mathbf{X\,Y}}\ \mathbf{L} = \frac{\omega}{\mathbf{v}}\ \mathbf{L} \qquad\qquad \mathbf{v} = \frac{\omega}{\sqrt{\mathbf{X\,Y}}}$$

If $\mathbf{X}$ and $\mathbf{Y}$ values do not include compensation, the phase velocity, $\mathbf{v}$, is almost independent of line constructive parameters, and of the order of 0.96 to 0.99 times the electromagnetic propagation speed in vacuum.

The characteristic impedance, $\mathbf{Z}_c$, and, at a reference voltage, $\mathbf{U}_0$, the characteristic power, $\mathbf{P}_c$, are

$$\mathbf{Z}_c = \sqrt{\frac{\mathbf{X}}{\mathbf{Y}}} \qquad\qquad \mathbf{P}_c = \frac{\mathbf{U}_0^{\,2}}{\mathbf{Z}_c}$$

Let us consider eventual longitudinal (series) and transversal (shunt) reactive compensation, along the line, at distances not too long (much smaller than a quart wave length at power frequency), by means of "reactive compensation factors", ξ , η . Being $\mathbf{X}_0$, $\mathbf{Y}_0$ the, per unit length, longitudinal reactance and transversal admittance, of the line, not including compensation, and $\mathbf{X}$, $\mathbf{Y}$ the "average" per unit length corresponding values, including compensation, we have

$$\mathbf{X} = \xi\ \mathbf{X}_0 \qquad\qquad \mathbf{Y} = \eta\ \mathbf{Y}_0$$

Without reactive compensation, $\xi = 1$, $\eta = 1$. By example, in a line with 30 % longitudinal capacitive compensation and 60 % transversal inductive compensation, we have $\xi = 0.70$, $\eta = 0.40$.

The eventual longitudinal and transversal reactive compensation have the following effect:

$$\Theta = \sqrt{\xi\,\eta}\ \Theta_0 \qquad \mathbf{Z}_c = \sqrt{\frac{\xi}{\eta}}\ \mathbf{Z}_{c0} \qquad \mathbf{P}_c = \sqrt{\frac{\eta}{\xi}}\ \mathbf{P}_{c0}$$

The index $_0$ identifies corresponding values without reactive compensation ($\xi = 1$, $\eta = 1$).

By example, in a line with 600 km, at 60 Hz ($\Theta_0 = 0.762$ rad), using capacitive 40% longitudinal compensation ($\xi = 0.60$) and inductive 65% transversal compensation ($\eta = 0.35$), Θ is reduced to 0.349 rad (equivalent to 275 km at 60 Hz), characteristic impedance is multiplied by 1.31 and characteristic power by 0.76 .

In traditional networks, with line lengths a few hundred kilometers, the reactive compensation is used to reduce Θ to "much less" than $\pi/2$ (a quart wave length) and to adapt $\mathbf{P}_c$, that, together with Θ , define voltage profiles, some switching overvoltages and reactive power absorbed by the line.

In case of very long distances (2000 to 3000 km), to reduce Θ to much less than $\pi/2$ would imply in extremely high levels of reactive compensation, increasing the cost of transmission (doubling, according some published studies of "optimized" transmission systems), and with several technical severe consequences, due to a multitude of resonance type conditions.

The solution we have found, and discuss above, for very long distances, is to work with Θ a little higher than π , so avoiding the need of high levels of reactive compensation, and obtaining a transmission system much cheaper and with much better behavior.

Neglecting losses, the behavior of the line, at power frequency, in balanced conditions, is defined by Θ and $\mathbf{Z}_c$.

Let us assume that voltages at both extremities, $\mathbf{U}_1$, $\mathbf{U}_2$, in complex notation, are:

$\mathbf{U}_2 = \mathbf{U}_0$ $\qquad\qquad$ $\mathbf{U}_1 = \mathbf{U}_0\ e^{i\,\boldsymbol{\alpha}}$

Apart a proportionality factor $\mathbf{P}_c$, the active and reactive power, at both extremities and along the line, depend on Θ and α .

Let us consider lines with the following electric lengths:

a) $\Theta = 0.05\ \pi$ (about 124 km at 60 Hz)

b) $\Theta = 0.10\ \pi$ (about 248 km at 60 Hz)

c) $\Theta = 0.90\ \pi$ (about 2228 km at 60 Hz)

d) $\Theta = 0.95\ \pi$ (about 2351 km at 60 Hz)

e) $\Theta = 1.05\ \pi$ (about 2599 km at 60 Hz)

f) $\Theta = 1.10\ \pi$ (about 2722 km at 60 Hz)

For these six examples, we represent, in Fig. 16, in function of α :

- The transmitted active power, **P**.

- The reactive power, **Q** , absorbed by the line (sum of reactive power supplied to the line at both terminals).

- The transversal voltage (modulus), $\mathbf{U}_m$, at line midpoint.

Examples **a)** , **b)** correspond to "usual" lengths of relatively short lines. They must be operated in vicinity of $\alpha = 0$, in which an α increase increases transmitted power. Transmitted power may exceed characteristic power, with an increase of reactive power absorbed by the line.

Examples **c)**, **d)**, **e)**, **f)** correspond to very long lines. In examples **c)** , **d)** , the lengths are little shorter than half wavelength ($\Theta = \pi$) and, in examples **e)** , **f)** , they are a little higher than half wave length. Note the lengths of these examples **c)** , **d)** , **e)** , **f)** are longer than a quart wavelength ($\Theta = \pi/2$) .

For these examples **c)**, **d)**, **e)**, **f)**, in vicinity of $\alpha = 0$, voltage at central line region and reactive power consumption are extremely high, compared, respectively, with voltage at line extremities and transmitted power.

For examples **c)**, **d)**, In vicinity of $\alpha = \pi$, the derivative of transmitted power in relation to α is negative, and, so, it does not occur the natural stabilizing effect of a positive derivative, that is one of the reasons why alternating current electrical networks are basically stable (with few exceptions), considering electromechanical behavior of generating groups and loads. Unless extremely complex control systems are considered, affecting all main network power stations, it is not adequate to have transmission trunks with length between a quarter and a half wave length ($\pi/2 \le \theta \le \pi$).

For examples **e)**, **f)** In vicinity of $\alpha = \pi$, the derivative of transmitted power in relation to α is positive, and, so, it occurs the natural stabilizing effect of a positive derivative, similarly with the behavior of short lines near $\alpha = 0$. In vicinity of $\alpha = \pi$, the behavior of line, view from line terminals, is similar to the behavior of a short line, in the vicinity of $\alpha = 0$, for transmitted power in the range $-\mathbf{P}_c \le \mathbf{P} \le \mathbf{P}_c$. Reactive power consumption of line is moderate, and voltage along the line does not exceed $\mathbf{U}_0$. The main different aspect is related to voltage in middle of the line, that is proportional to transmitted power. If characteristic power is referred to maximum voltage along the line, the maximum transmitted power is limited to characteristic power (what does not occur in short lines).

At least for a point to point long distance transmission, the fact that voltage at middle of the line varies, between 0 and $\mathbf{U}_0$, has no major inconvenient.

If, for a mainly point to point long distance transmission, it is wished to connect some relatively small loads, in middle part of the line, there are several ways to do so. It is convenient to adopt some non conventional solution, adapted to the fact that, in central part of the line, the voltage is not "almost constant", but varies according transmitted power, and current is "almost constant". It is an easy task for FACTS technologies, and some useful ideas can be obtained with ancient transmission and distribution systems at "constant current".

Lines with an electric length almost equal to half wave length ($\Theta = \pi$), do not behave in convenient way. They are near a singular point, with changes of derivatives of some magnitudes in relation to others, what originates several important troubles, namely related to control instabilities and eventual physical basic instability.

In Fig. 17 it is presented an amplification of Fig. 16 , for examples **e)**, **f)**, in the range of "normal operating conditions", with maximum voltage along the line limited to $\mathbf{U}_0$.

As shown with previous simplified discussion, for long distance transmission, there are several important reasons to choose an electric length of the line, Θ , a little higher than half wave length, in what concerns normal operating conditions and inherent investment. The "exact" choice is not critical. A range $1.05\ \pi \le \Theta \le 1.10\ \pi$ is a reasonable first approach. Also for "slow" and "fast" transient behavior, this choice has very important advantages, as discussed below.

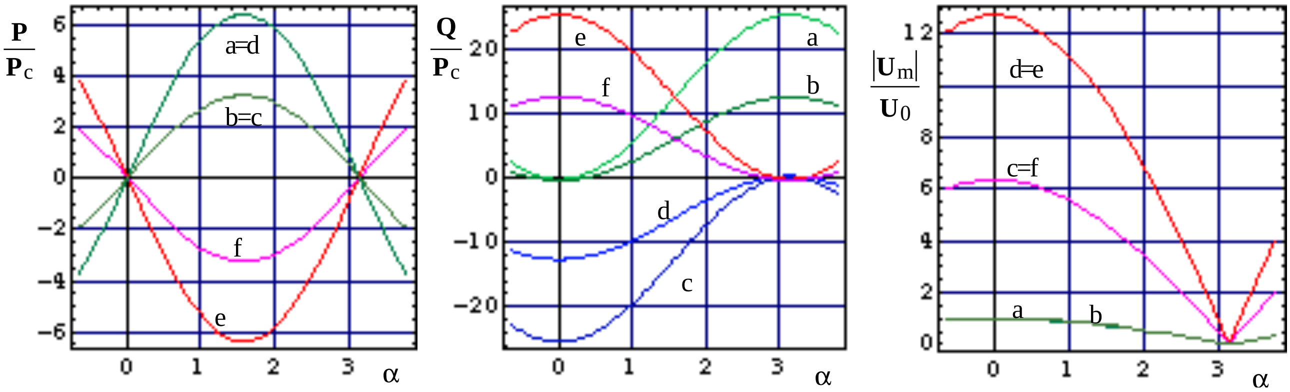


Fig. 16 - Transmitted power, $\mathbf{P}$, reactive power absorbed by the line, $\mathbf{Q}$, modulus of voltage at middle of the line, $|\mathbf{U}_m|$, in function of α, for six examples.

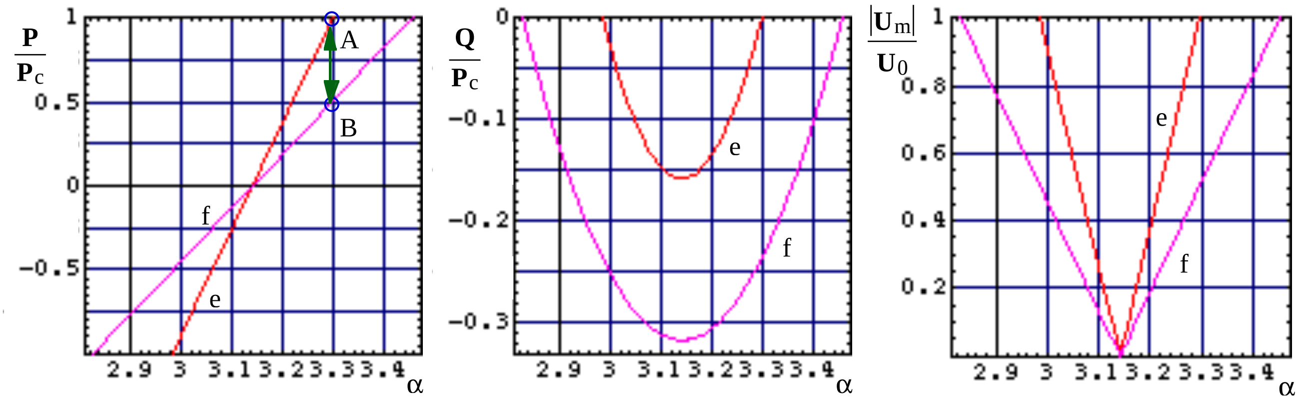


Fig. 17 - Transmitted power, $\mathbf{P}$, reactive power absorbed by the line, $\mathbf{Q}$, modulus of voltage at middle of the line, $|\mathbf{U}_m|$, in function of α, for two examples of very long lines, in normal operating range.

The solution of long distance transmission with Θ a little higher than π (e.g. $1.05\ \pi \leq \Theta \leq 1.10\ \pi$) is quite robust for electromechanical behavior and, also, for relatively slow transients, associated with voltage control. For example, a relatively small reactive control, equivalent to a change in Θ, allows a fast change in transmitted power, in times much shorter than those needed to change the mechanical phase of generators, as represented schematically in figure 17 by an arrow and "points" **A** , **B** . Let us assume the line of example **e)** , transmitting a power $\mathbf{P} = \mathbf{P}_c$ (operating point **A** of figure 17). A FACTS reactive control that changes Θ from 1.05 to 1.10, what can be done very rapidly, passing the operating point to **B**, changes the transmitted power from 1.0 $\mathbf{P}_c$ to 0.5 $\mathbf{P}_c$, maintaining the phase difference between line terminals. A FACTS system, control oriented for its effect on Θ, can be very efficient for electromechanical stability.

It must be mentioned that, for balanced conditions, reactive compensation does not need capacitors or reactors to "accumulate energy". In balanced conditions, for three or six phase lines, the instantaneous value of power transmitted by the line (in "all phases") is constant in time, and does not depend on reactive power (what is different of the case of a single phase circuit), and, so, reactive power behavior can be treated by instantaneous transfer among phases, e.g. by electronic switching, with no basic need of capacitors or reactors for energy accumulation (differently of what would be the case of a single phase line).

6.3 Basic physical aspects of very long lines switching

In order to allow a quite simple interpretation of the effect of line length on line switching overvoltages, it is convenient to consider a very simple line model [26], that allows to take into account the dominant physical effects, with a minimum number of parameters, and that, for most important effects, can be treated by very simple analytical procedures, directly in phase domain.

Main characteristics of long line switching are explained with such model, as it has been confirmed with extensive detailed simulation methods.

Let us consider the switching on of a three or six-phase line from an infinite busbar, with sinusoidal voltage of frequency f and amplitude $\hat{U}$, with simultaneous switching on of all phases, and neglecting loss effects in propagation. We have shown [26] that the maximum switching overvoltage (for most unfavorable switching instant), in successive time intervals $[(2\,n - 1)\ T < t < (2\,n + 1)\ T$, being T the "propagation time" along the line], associated to increasing number, n , of wave reflections, is

$$\mathrm{Max}_n[u_{2k}(t)] = \mathbf{S}^{*n}_{\max}\ \hat{U} \qquad\qquad \mathbf{S}^{*n}_{\max} = 2\,|\mathbf{S}_n| = 2\left|\frac{1-\mathbf{r}^n}{1-\mathbf{r}}\right|$$

The global maximum of $u_{2k}(t)$, $\mathrm{Max}[u_{2k}(t)]$, is the envelope of relative maxima, for all n values. Such envelope is

$$\mathrm{Max}[u_{2k}(t)] = \mathbf{S}^*_{max}\,\hat{U} \qquad \mathbf{S}^*_{max} = \frac{4}{|1-\mathbf{r}|} = \frac{4}{|1+e^{-i2\theta}|}$$

$$\mathbf{S}^*_{max} = 2\sec\theta$$

being

$\mathbf{r} = -e^{-i2\theta}$ $\qquad$ $\theta = \omega T$

θ "electric length" of line (in radians) at power frequency

In Fig. 18 we represent the coefficients $\mathbf{S}^{*n}_{max}$ and $\mathbf{S}^*_{max}$, in function of line electric length, θ .

This global maximum is the double of voltage at no load end, in stabilized conditions, at power frequency (whose value is $\hat{U}_0 = \sec\theta\,\hat{U}$).

So, in assumed conditions, the ratio of maximum overvoltage, at open line end, and source peak voltage, is function, only, of "electric line length", θ , at power frequency.

Let us consider two examples, Example 1 with $\theta = 1.0$, Example 2 with $\theta = 3.5$ (line lengths of about 788 km and 2760 km , at 60 Hz). Corresponding $\mathbf{S}^*_{max}$ values are, respectively, 3.70 and 2.14 .

In figure 19 we represent, for these two examples, open line terminal phase to ground voltage (taking source peak phase to ground voltage as unity), considering infinite source and simultaneous closing of all phases. In each graphic are represented two curves. For one curve, the closure, of represented phase, occurs when source voltage is zero, and, for the other, when such source voltage is maximum. The abscissa scales are graduated in $\tau = \omega t$.

Maximum overvoltages, found only with these two switching instants, are practically equal to values given by $\mathbf{S}^*_{max}$ formula.

For illustrative purposes, we represent, in figure 20, for examples 1 and 2, voltage in third phase to close, assuming a delay of 2 ms between second and first phase closures, and a delay of 2 ms between second and third.

In figure 21, we represent, for examples 1 and 2, voltages to ground in three phases of open end line terminal, for synchronized switching on. Comparison of this curves with those of figures 5 and 6, illustrates the order of magnitude of switching overvoltage reduction that results of synchronized switching on.

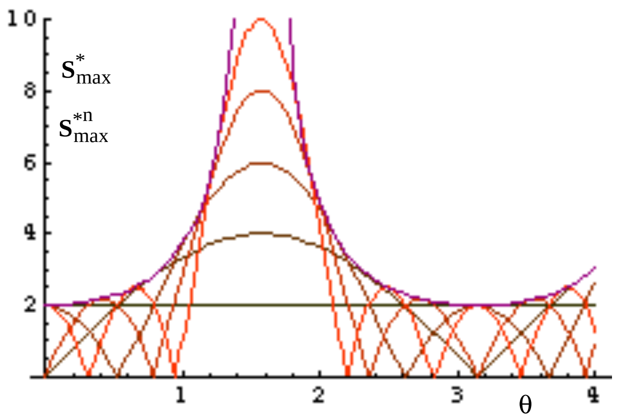


Fig. 18 - Coefficients $\mathbf{S}^{*n}_{max}$ and $\mathbf{S}^*_{max}$, in function of line electric length, θ .

The curves of figure 18, in the range of $\theta \le \pi/2$, express the well known fact that line switching on has an increasing severity with line length, what is the reason of traditional use of shunt reactors and or series capacitors in lines with a few hundred kilometers, in order to reduce the equivalent electric "length" , θ , of line and reactive compensation, together, and, so reduce switching overvoltages.

The range $\theta \ge \pi/2$ of those curves express, in a similar way, the main severity aspects of line switching on, for very long lines.

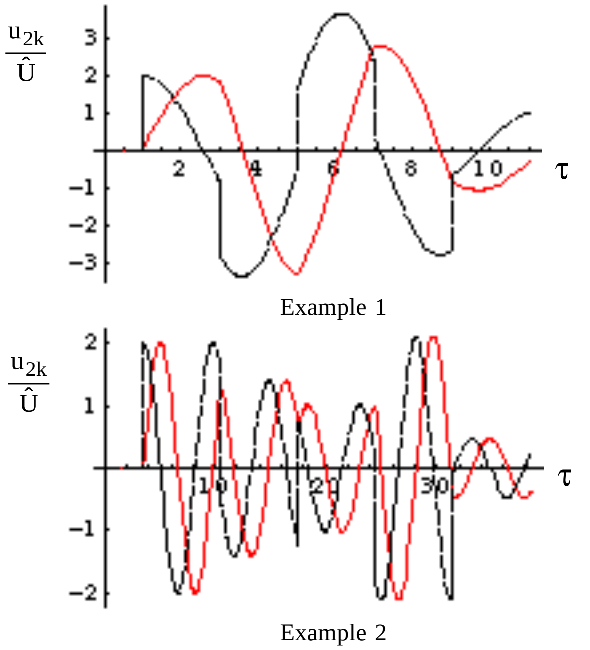


Fig. 19 - Voltage at open line end, for simultaneous closure or all phases, in example conditions.

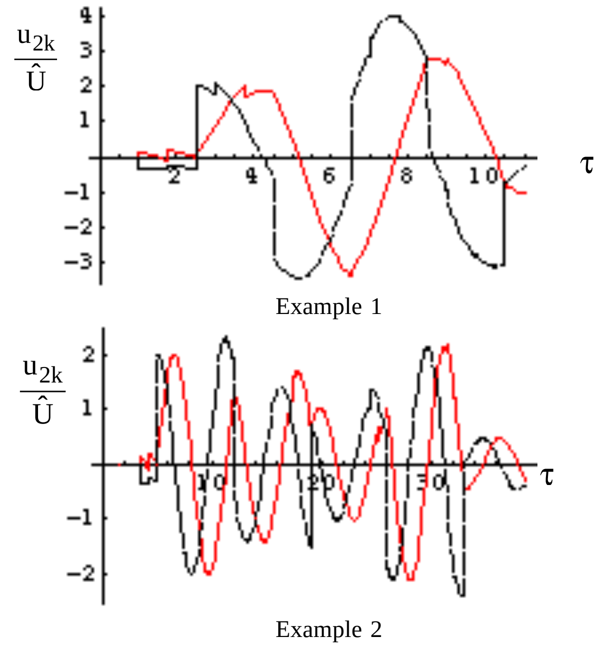
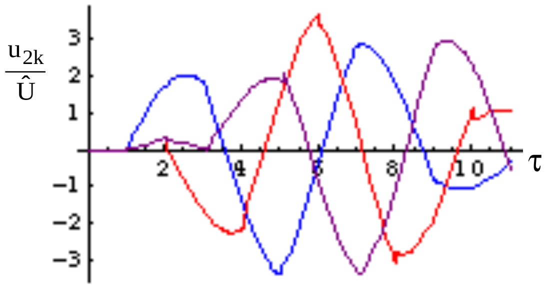
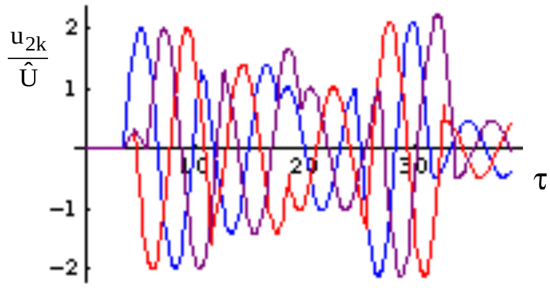


Fig. 20 - Voltage at open line end, for third phase to close, in example conditions.



Example 1



Example 2

Fig. 21 - Voltage at open line end, for synchronized switching on, in example conditions.

Electric line lengths between $\pi/2$ and π must be avoided, in principle, due to power frequency and power control aspects. Electric line length very close to π must also be avoided, due to the fact that it is a is “singular” condition, namely for power control of electric network. For electric line lengths a little higher than π (e.g. $3.2 < \theta < 3.5$), however, lines have quite interesting properties. Namely, switching overvoltages are quite moderate, and similar to those of relatively short lines.

So, for transmission at distances of the order of 2 500 to 3000 km, as is the case for transmission from Amazonian Region to Southeast Region, in Brazil, the natural way, for AC transmission, is to have transmission trunks with no basic reactive compensation, instead of extrapolating the traditional practice of line strong reactive compensation of long lines. In several aspects, the behavior of an uncompensated line is much better than the behavior of a strongly reactive compensated line, and the cost of an uncompensated line is much lower.

The main objective of the previous analysis is to identify and explain the dominant physical aspects of line switching on, and the influence of line length, for very long lines. It shows why it is not applicable the direct and simple extrapolation of common practices for relatively short lines. It also shows that and why direct switching on, in a single step, of a very long line, with no reactive compensation, originates moderate overvoltages, much lower than overvoltages obtained in switching on lines with a few hundred kilometers length.

A similar analysis explains, also, the several other aspects of very long lines behavior, for different transient phenomena, including those associated to various types of faults and secondary arc aspects for single phase faults.

Of coarse, some more detailed and correct analysis should be done for real conditions, considering the frequency dependence of line parameters and consequent attenuation and distortion of wave propagation, and different propagation characteristics of several line modes. However, for simultaneous closing of all phases, when switching on the line, the error of the previous analysis has been found to be quite small, in several cases of very long lines treated with much more detailed and rigorous procedures. One reason for the small error arises from the fact that, for simultaneous closing of all phases, only the non homopolar line modes interfere in switching transients, and such modes are affected by frequency dependence, attenuation and distortion, much less than homopolar modes. So, all interfering modes correspond to a transient behavior not "too far" of ideal line conditions.

Otherwise, even for transient conditions affected by homopolar modes, in very long lines, simplified analysis has been found to give approximate results, with some simple modifications of ideal line assumptions. The main reason for such behavior is that, along the total length of a very long line, homopolar components of high frequency are strongly attenuated. So, for some types of switching transients, a very detailed representation of phase-mode transformation dependence, and of frequency dependence of homopolar modes parameters, can be avoided.

7. TRANSMISSION LINE OPTIMIZATION

The transmission line should be optimized trying to obtain minimum total cost (including installation costs of line and associated equipment, and costs of operation, including losses) and maximum reliability in its operation in power system, taking into consideration several other aspects.

Some characteristics of conventional transmission line projects are:

- Standardized bundles of conductors, with a symmetrical circular shape;
- High values for insulating distances.

These characteristics lead to lines with a limited parametric variation for each voltage level. So, the traditional line optimization process do not interfere very much with the equipment and network optimization. In this case, it is possible to not consider the transmission line optimization in a planning study.

It is possible to increase the characteristic power of a line by varying the bundle shape and by decreasing the insulation distances, which would be very interesting for very long transmission distances.

The insulation distances can be reduced to low values with measures to reduce the overvoltages and the swing between phases.

Some actions to decrease overvoltages are, e. g. :

- Use of synchronized switching on of circuit breakers;
- Use of distributed arresters along transmission line.

Its is possible to reduce the swing between phases using insulated spacers.

Non conventional transmission lines, on the contrary of traditional lines, have a high range of eventual variation of parameters.

Some characteristics of five transmission line examples are shown in Table 1. The geometric line configuration of these examples are presented in Fig. 22, 23 and 24. The examples are, respectively, a conventional 500 kV three-phase line, two non conventional 500 kV three-phase lines, a non conventional double-circuit three-phase line and a non conventional six-phase line. In all these examples conductors have 483 mm^2 ("Rail"), and electric field in air, with voltage U_0 , is limited to 0.9 x 2.05 MV/m .

The non conventional lines have reduced insulation distance and non standardized bundles of conductors. The bundle geometries were optimized by a computational program. The program maximizes the characteristic power of a line respecting a maximum electric field on conductors' surface and some geometric constraints of bundles' shape and location.

In Table 1 , n_c is the number of conductors per bundle, D is the insulation distance, U_0 is the reference voltage (phase to phase for three-phase lines, phase to ground and between consecutive phases, for six-phase line), P_c is the characteristic power at voltage U_0 , J_c is the current density with power P_c and voltage U_0 .

The characteristic power of the non conventional 500 kV lines of examples 2 and 3 is much higher than that of the conventional 500 kV line (example 1). For a long distance transmission, the transmission power capacities of non conventional lines of examples 2 and 3 are greater than the double of conventional line capacity (example 1).

The three-phase double-circuit and the six-phase configuration allows to almost double the power capacity for long distance transmission, with a moderate increase of right of way area. The advantage of six-phase transmission is the possibility to decrease insulation distance, since the voltage phase-to-phase, for consecutive phases, is equal to phase-ground voltage, and is less than in the case of three-phase double-circuit line. Although, the optimized bundles for six-phase lines are greater than those of three-phase double-circuit line.

The methodology of line optimization is shown in details in [16-19].

The electric compensation of line, the switching and operational criteria must be optimized together with the line.

Table 1 - Main parameters of line examples

Example	D [m]	n_c	U_0 [kV]	P_c [MW]	J_c [A/mm^2]
1	11	3	500	924	0.736
2	5	6	500	1910	0.761
3	6	7	500	2295	0.783
4	7	5	$350\sqrt{3}$	4134	0.815
5	3	5	350	3955	0.779

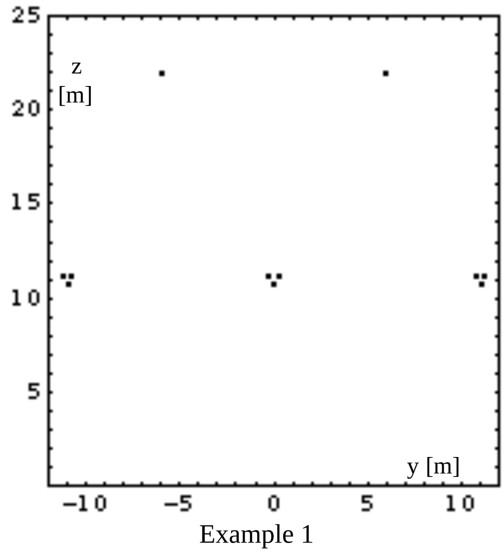


Fig. 22 - Conventional transmission line of 500 kV.

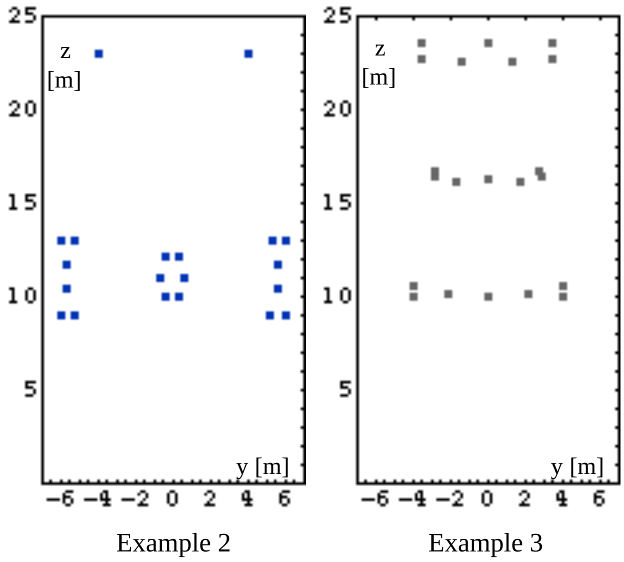


Fig. 23 - Transmission lines of 500 kV , with non conventional conductor bundles.

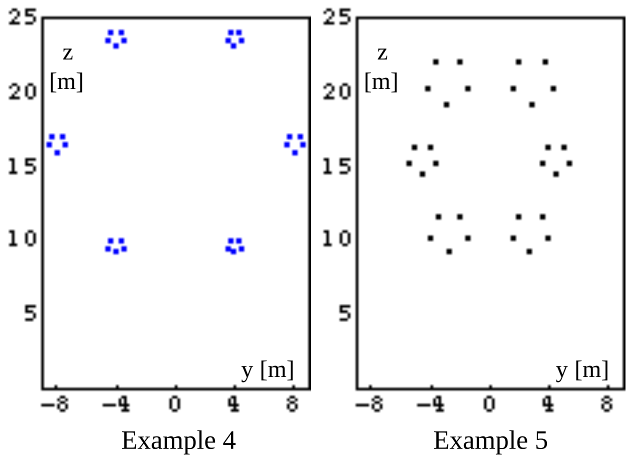


Fig. 24 - Double circuit three-phase and six-phase transmission lines, with non conventional symmetric conductor bundles.

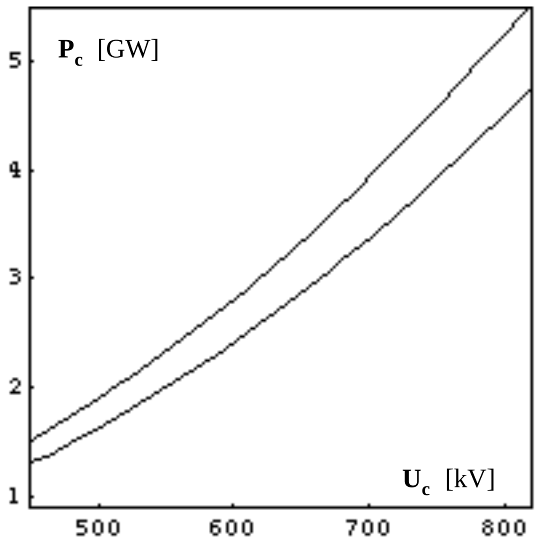


Fig. 25 - Characteristic power, $\mathbf{P_c}$, than can be obtained with optimized non conventional lines (NCL) within prudent criteria, in function of voltage, $\mathbf{U_c}$ (phase-phase, rms), for three-phase lines.

Table 2 - Feasible range of $\mathbf{P_c}$, with optimized non conventional three-phase lines (NCL), for three values of $\mathbf{U_c}$

U_c [kV]	P_c [GW]
500	1,6 a 1,9
525	1,8 a 2,1
750	3,9 a 4,6

In item 8. we present an example that illustrates the importance of joint optimization.

In order to give a concrete idea of the eventual impact of non conventional line, NCL. concept and consequent results of its use in line optimization, in Fig. 25 it is indicated the approximate range of characteristic power, $\mathbf{P_c}$, that can be obtained within prudent choices and criteria, without very special efforts. In Table 2 we indicate corresponding ranges for three base nominal voltages. It is feasible to project lines with characteristic power much higher than with traditional engineering practice, with optimized solutions, and with reduced ambient impact.

8. IMPORTANCE OF JOINT OPTIMIZATION OF LINE, NETWORK AND OPERATIONAL CRITERIA

To illustrate the importance of joint optimization of compensation of line, switching and operational criteria, we describe briefly some aspects of a specific project [21-22].

The analyzed transmission system is based on a 420 kV line, 865 km long, 50 Hz, with "non-conventional" concept, connecting Terminal 1 to Terminal 2, being its most important characteristics shown below :

- 420 kV "non-conventional" transmission line conception. The structure is external to the three phases, which allows to reduce the distance between the phases and to obtain more adequate line characteristics for the transmission analyzed.

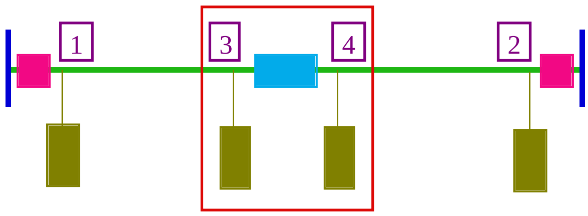
- Ground with frequency dependent parameters, being the conductivity at low frequencies around 0.5 mS/m.

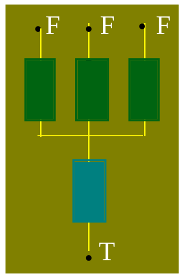
- Series compensation corresponds to 0.5 times the direct longitudinal line reactance.

- Shunt compensation (for direct and inverse components) corresponds to 0.8 times the direct line transversal admittance.

- Compensation system, both in series and shunt, as shown in Fig. 26, with a compensation installation in the middle of the line, as well as shunt compensation at both line terminals. It is worth mention that it is possible to have just one point of compensation along the line (besides the compensation at both line ends).

- Maximum eventual 800 MW load at Terminal 2.





Detail describing a shunt reactor.
F indicates a phase terminal and T the grounding terminal.

Symbol	Meaning
	Transmission line, with 865 km
	Busbar to which line is connected
	Line switching circuit breaker
	Shunt reactor (obtained with three phase reactors, one neutral reactor)
	Series capacitor
	Compensation system in middle of line
1 2 3 4	Points in which line is connected to compensation equipment

Fig. 26 – Line basic scheme, including series and shunt compensation system.

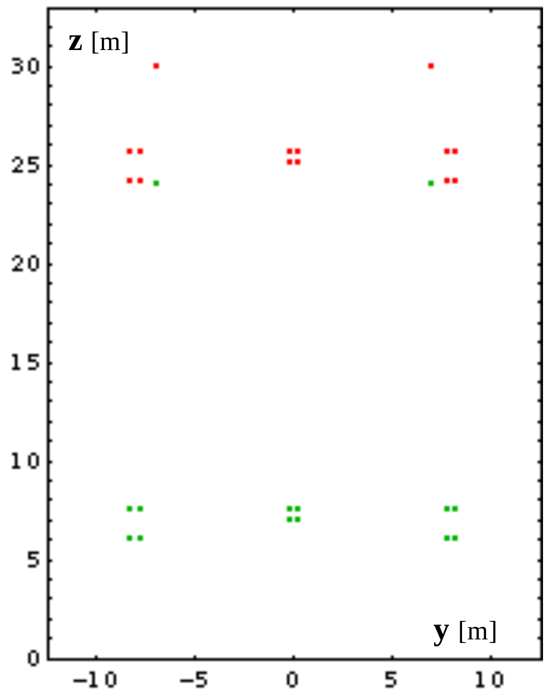


Fig. 27- Transmission line schematic representation. The green points represent the conductors at middle span, for a span 380 m and phase conductors at 60 ^{0}C . The red points represent the conductors near the structure.

In Fig. 26 it is shown the basic transmission scheme, including the series and shunt compensation equipment.

In Fig. 27 it is shown, schematically, the line considered.

This transmission system has some unfavorable constraints (e. g. 865 km), compared with "most common" transmission systems, and in order to obtain an optimized solution, it was necessary to perform a systematic analysis covering a large number of options and parameters. With the study procedure used it was found a solution with a non-conventional line, in which it was possible to conciliate apparently contradictory requirements and solutions.

These solutions allowed a relatively low cost transmission system with good operational quality.

Some interesting aspects of proposed transmission system are:

- There are reactive compensation only at line extremities and in an intermediate point.

- Switching of the 865 km transmission system directly from one extremity, without switching at intermediate points.

- Line arrangement optimized for the specific line length and transmitted power.

- Single-phase opening and reclosing, assuring high probability of secondary arc extinction, for single phase faults, in order to obtain high reliability of transmission.

- Joint optimization of project and operational criteria, allowing important cost reduction.

9. A BASIC METHODOLOGY TO EVALUATE ADEQUACY OF LINE PARAMETERS AND SIMULATION PROCEDURES

In order to validate modeling and simulation procedures, it is quite important to verify if the line parameters have been properly calculated in frequency domain and if the line model has an appropriate response within the transient simulation tool which is going to be used. Some simple analysis can be performed. We present some adequate and reasonably simple methods that allow a basic evaluation, reducing the probability of important non detected errors. For illustrative purposes, we present such methods through its application to some examples.

There are two main aspects to be observed. One is to assure that adequate physical formulation, mathematical procedures and programming instructions have been used. The other is, ahead of that, to verify the physical coherence of calculated parameters and of consequent line behavior.

In order to verify if the line parameters have been properly calculated, in what concern important mistakes, a rather expedite verification is to compare the obtained results with some simple and robust formulation, as it is the case of the complex distance formulation, described in *Appendix 1*.

We use as example the transmission line described in Fig. 28. It has a vertical symmetry plane, which is the most frequent type of geometry used in EHV lines. The line parameters were calculated using the JMarti procedure (ATP), which is widely used in Brazil, and compared with an external calculation called "exact", as described in *Appendix 1*. The designation "exact" means that only the assumptions and approximations indicated in *Appendix 1* have been used, without further simplifying assumptions. It does not mean exact in a strict sense. The results for per unit resistance and per unit inductance, for an ideally transposed line, are presented in Fig. 29 and 30.

There are significant differences between the results obtained with the two procedures ("exact" and JMarti), specially for the homopolar mode, or Mode 0. We comment briefly such differences for this mode:

- The JMarti model results present an "oscillation" in the per unit length resistance. Up to around 500 Hz, the model gives a higher resistance when compared with the "exact" calculation result, whilst for the following range, the resistance is lower.

- The inductance obtained with JMarti model is lower, for frequencies above 100 Hz.

- The damping effect in propagation, with JMarti model, is higher for frequencies below 800 Hz, and lower for higher frequencies.

An easy analysis, that allows to have a simple insight in some aspects of line behavior, is to compare the alternatives of non transposed line and ideally transposed line (with a transposition cycle assumed much shorter than a quart wave length, for the whole frequency spectrum analyzed). The unitary parameters of an ideally transposed line can be obtained doing the diagonal elements, and the non

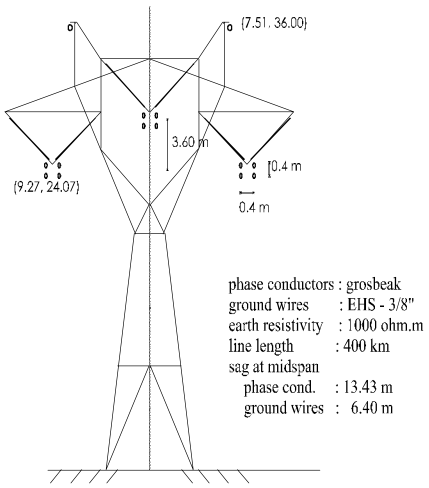


Fig. 28 - Schematic representation of the 440 kV three-phase line.

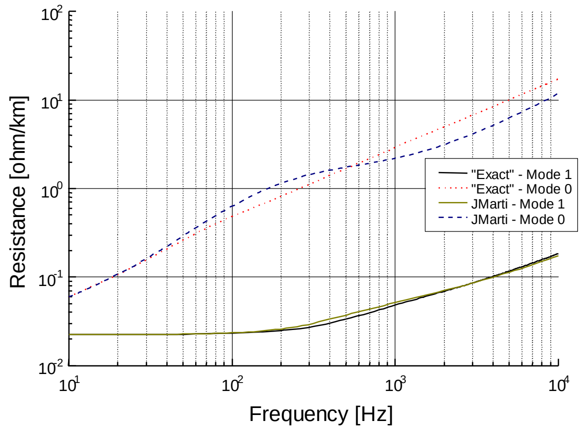


Fig. 29 – Comparing per unit length resistance in mode domain of a transposed single three-phase transmission line calculated with two different procedures : "Exact" calculation and JMarti Model (ATP).

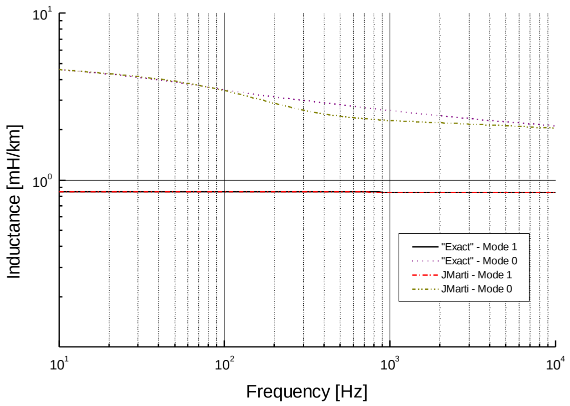


Fig. 30 – Comparing per unit length inductance in mode domain of a transposed single three-phase transmission line calculated with two different procedures : "Exact" calculation and JMarti Model (ATP).

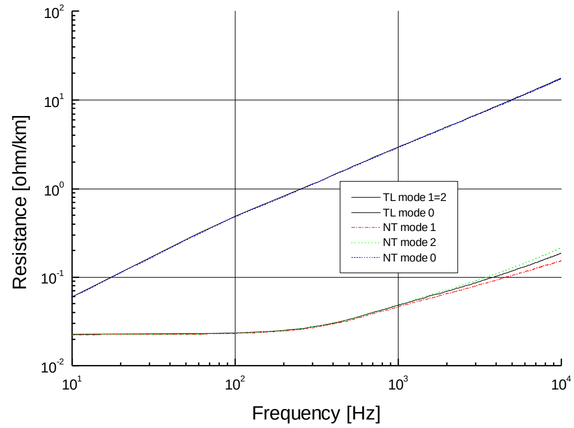


Fig. 31 - Per unit length resistance in mode domain of a single three-phase transmission line calculated with *Appendix I* formulae. Comparing the parameters of transposed line with non-transposed line.

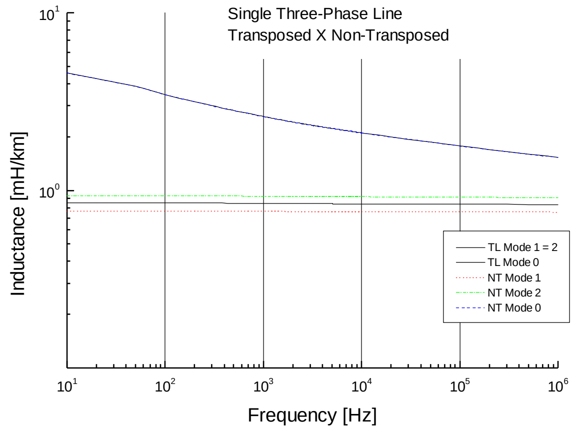


Fig. 32 - Per unit length inductance in mode domain of a single three-phase transmission line calculated with *Appendix I* formulae. Comparing the parameters of transposed line with non-transposed line.

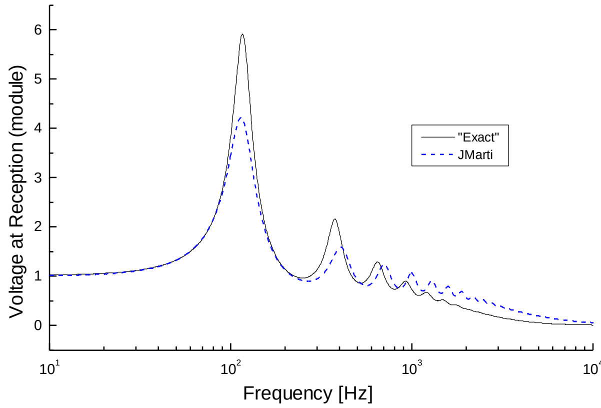


Fig. 33 – Frequency scan of zero sequence of a transposed three-phase line. Comparing the results between "exact" calculation and JMarti Model (ATP).

diagonal elements, of matrices **Z** and **Y** , equal to medium values of diagonal elements, and non diagonal elements, respectively, of matrices **Z** and **Y** in non transposed line.

In an ideally transposed line there are only two distinct propagation modes, as there are two equal "aerial" modes.

For a three-phase non-transposed line there are three distinct propagation modes. However the "aerial" modes are rather similar, whilst the homopolar mode has a quite different behavior.

Considering the line parameters for both ideally transposed and non-transposed lines, it is expected that :

- The homopolar mode are not equal, but similar;

- The aerial modes are not equal in the two lines, but should be also similar.

In Figs. 31 and 32 the resistance and inductance, per unit length, calculated with the formulae described in *Appendix 1*, are presented, for the line described in Fig. 28.

It can be observed that, for the example line, the homopolar modes are very similar when comparing a transposed line and a non-transposed line. The "aerial" modes also have some similitude but are not equal, as expected.

A frequency scan analysis is also an important test to be carried out. It allows to detect several types of important physical inconsistencies. An "exact calculation", concerning the aspects compared in the paper, was also realized, so the models could be more properly confronted, for the example line of Fig. 28. This so called "exact calculation" was performed by computing the line two-port elements (ABCD constants) for each frequency in mode domain and obtaining the exact eigenvectors to transform the mode quantities into phase, for both models. The sending terminal was assumed with a 1 V source and the receiving end was opened. The transfer functions between the line extremities were analyzed in the range of 10 Hz to 10 kHz. Some results for homopolar mode are shown in Fig. 33. The analysis of the frequency scan response represented in this Figure shows that the JMarti model has higher damping response for frequencies up to 500 Hz and lower damping for higher frequencies. This result agrees with the analysis of the per unit line parameters.

Another useful and reasonably simple test is to obtain and compare the mode and phase propagation line behavior, for some simple conditions, e. g. , a specific shape of voltage applied at one line terminal. The "exact" behavior, in the sense indicated above, is easily obtained by means of the transfer function, in frequency domain, and the use of integral Fourier transformation, to obtain the line response in time domain. This procedure has been applied in other examples of this paper.

This example and other similar ones show that some currently applied transmission line models, which intend to represent the frequency dependence of line parameters in time domain simulation program, have some inaccuracies.

According to predicted application, such inaccuracies may be important. There is the need of simple and robust guidelines and test methods, of the type indicated above, to validate line models for transient studies.

The main aspects of proposed guidelines to evaluate adequacy of line parameters and simulation procedures are :

- To analyze the per unit longitudinal parameters, comparing its results with a simplified complex distance formula;
- To compare the eigenvectors and eigenvalues obtained with the program under examination with the "exact" eigenvectors and eigenvalues, in the frequency domain.
- To do a frequency scan of line response, e. g. , for positive and zero sequence voltage applied to a line terminal.
- To do a comparison of results obtained directly with time domain simulation procedures with results obtained with transfer functions in frequency domain and Fourier integral transformation.

The proposed methodology has been applied to our model and to some established models, allowing us to identify some inaccuracies very promptly.

10. CONCLUSIONS

In order to identify the items related to the more detailed conclusions, we indicate, in bold, the number of the item related to each group of conclusions. In order to allow to have a basic idea of the conclusive aspects of the paper, through the reading of the conclusions, we some superposition occurs. At the end of this item, we present very shortly what we think to be the general aspects of the subjects dealt with in the paper.

1. - The paper discusses the basic aspects of modeling, simulation and optimization of transmission lines, with emphasis in validity, applicability and limitations of some used procedures, and some guidelines for development of new procedures. As the subject can not be systematically covered within a single paper, we have chosen some specific points, as examples, which, in general, are typical of groups of similar application problems and of groups of methodological aspects.

2. - A first type of examples, treated in item 2. , is related to some basic aspects of usual procedures to evaluate line parameters. In the most usual procedures there are some explicit or implicit assumptions that imply in physical approximations. According the specific case or application, the errors resulting from such assumptions may be important and, even, may invalidate the obtained results. In this paper, some examples have been discussed, including some numeric results.

One example, dealt with in item 2. , is related with the usual implicit assumption of quasi stationary behavior, for directions orthogonal to line axis. A detailed quantitative evaluation of this and other examples shows that, for most common applications, the consequent error can be accepted for frequencies till about 1 MHz. For some other applications, however, namely related to lightning effects, radio interference and induced effects far from the line, errors resulting from such assumption are too high, and more correct methods must be used.

Another example, of basic aspects of line parameters evaluation, is related to the fact that common formulas imply a distance, along line axis, from the point or orthogonal plane in which electromagnetic field or parameters are being evaluated, much higher that the distance from line axis till which the electromagnetic field is important for the parameter being evaluated. So, common formulas for line parameters calculation do not apply to very short conductors or to the vicinity of line extremities. For such conditions, different procedures must be used, e. g. based in methods identified in the paper.

3. - Some examples are related to the effect of line transposition, correlated modeling procedures, and methodologies adequate to deal directly with simulation in phase and frequency domain.

It has been presented an example that illustrates some aspects of modeling assumptions, and, also, a simple way of representing line behavior in frequency domain, directly in three phase, without the need of mode separation and phase-mode-phase transformation, allowing to consider non-conventional line, with different conductor arrangement, e. g. in central and lateral bundles, and with soil parameters frequency dependent.

In this example the line has been modeled directly in phase and frequency domain, in frequency range [0 , 20 kHz], considering 2161 frequencies. With direct integration of line basic equations, in space, the transfer function between voltages and currents at both extremities is obtained numerically, using a fast procedure based in successive doubling of line length for which transference function is evaluated. When applicable, real transposition conditions have been considered. Different alternatives of line transposition and modeling have been simulated, for line switching on. In this example, there are significant differences between the shape of voltage at open line terminal, according alternative and switched phase (when applicable). However, strictly in example conditions, in what concerns overvoltage and insulation coordination, the differences are moderate, and can be neglected for most application purposes. It is justified some caution in eventual generalization of the comparative results of this example. Namely, for conditions in which it occurs an eventual resonance type phenomena, involving line and network, assumptions concerning transposition modeling can be important.

We present in *Appendix 2*, for the four conditions analyzed, the amplitude of the immittance, or transfer function, between voltages of switched phase, at both line terminals, in simulation conditions, in function of frequency. There are important differences in immittance, in frequency domain, except for low frequency. For the example conditions the frequency spectrum of disturbance is somewhat diffuse, and there is a reasonable compensation between differences of immittance in such spectrum. An eventual resonance type condition can imply in important differences according transposition modeling. A careful examination of presented results may be quite useful to interpret the line behavior for switching phenomena and its interaction with applicable to specific conditions.

4. - In a set of examples, we discuss briefly some aspects of modeling shield wire effects.

Quite often, shield wires are steel cables. It is essential to consider the fact that steel is a ferromagnetic material and, so, it is erroneous to represent it as a metal having a magnetic permeability, μ , practically equal to vacuum permeability, μ_0 . Some versions of commonly used programs do not allow easy access to a convenient choice of cable μ . For some applications, the error resulting from assuming $\mu = \mu_0$ may be very important.

Another important aspect is the eventual saturation of magnetic material of steel cables, that must be taken into account for high current values in shielding wires.

In the common practice, little attention is given to the adequate magnetic characterization of shielding cables, that are neither specified nor measured. Some specific practical cases of Brazilian lines have shown the need to represent correctly the magnetic properties of shielding cables.

Another aspect that needs some attention is the way shielding wires are considered in line simulation. For some purposes, shielding cables must be represented explicitly, together with phase conductors, for instance:

- To analyze lightning behavior, including effects of strikes in towers, shielding wires and phase cables, at least within several spans in both senses from impact point.
- Short-circuits involving ground or shielding wires, also, at least within several spans in both senses from fault point.

In case of shielding wires directly connected to all towers or structures, and excluding the conditions of the two types indicated above, it may be acceptable to consider shielding wires in an implicit way, “eliminating” shield wires of the explicit **Z** and **Y** matrices, being **Z** the unitary (per unit length) longitudinal impedance matrix and **Y** the unitary transversal admittance matrix. This can be done, e. g. , with the assumption of null transversal voltage in shielding wires, what allows a very simple manipulation of matrices to consider the effect of shielding wires in matrices relating, directly, voltages and currents in phases. This procedure appears quite reasonable for frequencies such that a quarter wave length is much longer than line span, or, typically, till about 100 kHz. For higher frequencies, such procedure must be verified according the problem under analysis.

As an example of computational procedures based in exact modes, the presented results were obtained computing the “exact” modes. Manipulating the line matrices considering phases and shielding wires, the exact eigenvalues and eigenvectors were obtained, relating phase and shielding wires voltages and currents along the line through exact modes.

In the conditions of this example, for 1 MHz, the transversal voltage of phase conductors obtained with the assumption of shielding cables continuously grounded is quite similar to correct value, with shielding cables grounded only at towers. Naturally, for transversal voltage at shielding wires, such assumption is not adequate.

5. - We have discussed the very important problem of soil modeling.

One essential aspect of line modeling is the adequate representation of ground, that affects line parameters, per unit length, ahead of being a dominant aspect of for analysis and project of line grounding system. By historical and cultural reasons, the most used procedures assume that the ground may be considered as having a constant conductivity, frequency independent, and an electric permittivity that can be neglected ($\omega \varepsilon << \sigma$). These two assumptions are quite far from reality, and can originate inadequate line modeling.

Except for very high electric fields, that originate significant soil ionization, soil electromagnetic behavior is essentially linear, but with electric conductivity, σ , and electric permittivity, ε , strongly frequency dependent.

We have described a previously developed group of soil electric models, that:

- Cover a large number of soil measured parameters, with good accuracy, and within the range of confidence of practical field measurement.

- Satisfy coherence conditions.

From previous models, we have developed a basic and general model of electromagnetic parameters of a medium, that assures physical consistency, and which has shown to be quite useful to define models from measurement results. In particular, such model is very well adapted to soil modeling, with a small number of numerical parameters. For a very high number of soil samples, the dominant behavior, in the frequency range [0 , 2 MHz], can be represented with such model, with only three numerical parameters. Also, the statistical analysis of a high number of field measurements has identified three parameters that can be assumed statistically independent, and their statistical behavior. One of them, is the soil conductivity at low frequency, that is or can be obtained by usual measurement procedures. The other two define frequency dependence of electric soil parameters.

The statistical distribution of parameters of electric soil model can be represented by Weibull distributions. A summary of statistical distribution of parameters that define frequency dependence has been presented.

If specific measurements of soil parameters, in function of frequency, have been done, indicated procedures allow to define grounding system behavior, to evaluate people and equipment safety, and to optimize means to obtain adequate behavior for lightning.

One eventual difficulty, specially for small grounding systems, is to evaluate soil parameters related to frequency dependence, that are not obtained by common procedures, and can be measured as described in [3-4].

We indicate some results of a systematic analysis of soil behavior for some basic examples related to fundamental aspects that influence the lightning behavior of grounding systems, covering the statistical range of parameters, with a statistical analysis of the effect of soil parameters in such behavior. With such type of analysis, it is possible to have a basic approach to define, in a statistical sense, the importance of parameters related to frequency dependence, in conjunction with usually available information. With this procedure, it is possible to evaluate the need of specific measurements, or precautions, to use parameter estimates, based in statistical distribution of such parameters, and information usually available about soil.

We present a summary of a basic soil model and the main aspects of the statistical behavior of frequency dependence of soil parameters.

6. - We discuss some important problems related to very long distance transmission, including:

- Essential aspects of very long distance transmission.

- Basic physical aspects of very long lines operating conditions.

- Basic physical aspects of very long lines switching.

The problem of AC transmission at very long distance was studied using several methods to consider some transmission system alternatives, interpreting the dominant physical and technical phenomena, and using simulations to detail and confirm general analysis.

The results obtained were quite interesting. Namely, they have shown that: electric transmission at very long distance is quite different of what would be expected by simple extrapolation of medium distance transmission experience; to optimize a very long distance transmission trunk, a more fundamental and open approach is needed. By example:

- Very long distance lines do not need, basically, reactive compensation, and, so, the cost of AC transmission systems, per unit length, e.g., for 2800 km, is much lower than, e.g., for 400 km.

- For very long transmission systems, it is appropriate the choice of non conventional line conception, including eventually:
    - “Reduced” insulation distances, duly coordinated with adequate means to reduce switching overvoltages;
    - Non conventional geometry of conductor bundles, six-phase lines, surge arresters distributed along the line.

- Switching transients, for several normal switching conditions, are moderate, in what concerns circuit breaker duties and network transients severity, for lines and equipment. Namely, line energizing, in a single step switching, of a 2800 km line, without reactive compensation, originates overvoltages that are lower than, or similar to, overvoltages of a 300 km line with reactive compensation.

- Quite good results can be obtained with a careful coordination of circuit breakers with line and network, namely with synchronized switching, coordination of several circuit breakers and closing auxiliary resistors.

- There are some potentially severe conditions quite different from typical severe conditions in medium distance systems, e.g., in what concerns secondary arc currents, and requirements to allow fault elimination without the need of opening all line phases. The severity of such conditions is strongly dependent of circuit breaker and network behavior. Due to peculiar characteristics of long lines' transients, it is possible to reduce drastically the severity, with fast switching and appropriate protection schemes. Quite good results can be obtained with a careful coordination of circuit breakers with line and network, namely with synchronized switching, coordination of several circuit breakers and closing auxiliary resistors. Eventually, special schemes can be used to limit overvoltages for some quite unfavorable conditions of fault type and location.

Due to the lack of practical experience of very long transmission lines, and the fact that they have characteristics quite different of traditional power transmission lines and networks, a very careful and systematic analysis must be done, in order to obtain an optimized solution.

In order to clarify the most important aspects of very long lines characteristics, we present a parametric example with simplifying assumptions that allows an easy and clear formulation that identifies most important aspects. As shown in this discussion, for long distance transmission, there are several important reasons to choose an electric length of the line, Θ , a little higher than half wave length, in what concerns normal operating conditions and inherent investment. The "exact" choice is not critical. A range $1.05\ \pi \le \Theta \le 1.10\ \pi$ is a reasonable first approach. Also for "slow" and "fast" transient behavior, this choice has very important advantages.

The solution of long distance transmission with Θ a little higher than π (e.g. $1.05\ \pi \le \Theta \le 1.10\ \pi$) is quite robust for electromechanical behavior and, also, for relatively slow transients, associated with voltage control. For example, a relatively small reactive control, equivalent to a change in Θ , allows a fast change in transmitted power, in times much shorter than those needed to change the mechanical phase of generators. A FACTS system, control oriented for its effect on Θ , can be very efficient for electromechanical stability.

It must be mentioned that, for balanced conditions, reactive compensation does not need capacitors or reactors to "accumulate energy". In balanced conditions, for three or six phase lines, the instantaneous value of power transmitted by the line (in "all phases") is constant in time, and does not depend on reactive power (what is different of the case of a single phase circuit), and, so, reactive power behavior can be treated by instantaneous transfer among phases, e.g. by electronic switching, with no basic need of capacitors or reactors for energy accumulation (differently of what would be the case of a single phase line).

In order to allow a quite simple interpretation of the effect of line length on line switching overvoltages, we have shown results of a very simple line model, that allows to take into account the dominant physical effects, with a minimum number of parameters, and that, for most important effects, can be treated by very simple analytical procedures, directly in phase domain.

Main characteristics of long line switching are explained with such model, as it has been confirmed with extensive detailed simulation methods.

It has been shown that, in a group of simplifying conditions, representative of important aspects of line switching transients, the ratio of maximum overvoltage, at open line end, and source peak voltage, is function, only, of "electric line length", θ , at power frequency.

For transmission at distances of the order of 2 500 to 3000 km, as is the case for transmission from Amazonian Region to Southeast Region, in Brazil, the natural way, for AC transmission, is to have transmission trunks with no basic reactive compensation, instead of extrapolating the traditional practice of line strong reactive compensation of long lines. In several aspects, the behavior of an uncompensated line is much better than the behavior of a strongly reactive compensated line, and the cost of an uncompensated line is much lower.

The main objective of the previous analysis is to identify and explain the dominant physical aspects of line switching on, and the influence of line length, for very long lines. It shows why it is not applicable the direct and simple extrapolation of common practices for relatively short lines. It also shows that and why direct switching on, in a single step, of a very long line, with no reactive compensation, originates moderate overvoltages, much lower than overvoltages obtained in switching on lines with a few hundred kilometers length.

A similar analysis explains, also, the several other aspects of very long lines behavior, for different transient phenomena, including those associated to various types of faults and secondary arc aspects for single phase faults.

In order to give a concrete idea of the eventual impact of non conventional line, NCL, concept and consequent results of its use in line optimization, it is indicated the approximate range of characteristic power that can be obtained within prudent choices and criteria, without very special efforts. It is feasible to project lines with characteristic power much higher than with traditional engineering practice, with optimized solutions, and with reduced ambient impact.

7. - We discuss some important aspects of transmission line optimization, including several topics not frequently taken into account.

The transmission line should be optimized trying to obtain minimum total cost (including installation costs of line and associated equipment, and costs of operation, including losses) and maximum reliability in its operation in power system, taking into consideration several other aspects.

Some characteristics of conventional transmission line projects are:

- Standardized bundles of conductors, with a symmetrical circular shape;
- High values for insulating distances.

These characteristics lead to lines with a limited parametric variation for each voltage level. So, the traditional line optimization process do not interfere very much with the equipment and network optimization. In this case, it is possible to not consider the transmission line optimization in a planning study.

It is possible to increase the characteristic power of a line by varying the bundle shape and by decreasing the insulation distances, which would be very interesting for very long transmission distances.

The insulation distances can be reduced to low values with measures to reduce the overvoltages and the swing between phases.

Some actions to decrease overvoltages are, e. g. :

- Use of synchronized switching on of circuit breakers;
- Use of distributed arresters along transmission line.

Its is possible to reduce the swing between phases using insulated spacers.

Non conventional transmission lines, on the contrary of traditional lines, have a high range of eventual variation of parameters.

Some characteristics of five transmission line examples are shown in the paper. The examples are, respectively, a conventional 500 kV three-phase line, two non conventional 500 kV three-phase lines, a non conventional double-circuit three-phase line and a non conventional six-phase line.

The non conventional lines have reduced insulation distance and non standardized bundles of conductors. The bundle geometries were optimized by a computational program. The program maximizes the characteristic power of a line respecting a maximum electric field on conductors' surface and some geometric constraints of bundles' shape and location.

The characteristic power of the non conventional 500 kV lines of examples is much higher than that of the conventional 500 kV line. For a long distance transmission, the transmission power capacity of the non conventional lines of examples is greater than the double of conventional line capacity.

The three-phase double-circuit and the six-phase configuration allows to almost double the power capacity for long distance transmission, with a moderate increase of right of way area.

The methodology of line optimization is shown in details in references.

The electric compensation of line, the switching and operational criteria must be optimized together with the line.

In order to give a concrete idea of the eventual impact of non conventional line, NCL, concept and consequent results of its use in line optimization, it is indicated the approximate range of characteristic power, $\mathbf{P_c}$, that can be obtained within prudent choices and criteria, without very special efforts. in function of voltage.

It is feasible to project lines with characteristic power much higher than with traditional engineering practice, with optimized solutions, and with reduced ambient impact.

8. - To illustrate the importance of joint optimization of compensation of line, switching and operational criteria, we describe briefly some aspects of a specific project.

The analyzed transmission system is based on a 420 kV line, 865 km long, 50 Hz, with maximum eventual 800 MW load at one line terminal.

This transmission system has some unfavorable constraints (e. g. 865 km), compared with "most common" transmission systems, and in order to obtain an optimized solution, it was necessary to perform a systematic analysis covering a large number of options and parameters, and using several non traditional methodologies. With the study procedure used it was found a solution with a non-conventional line, and several other non-conventional solutions, with which it was possible to conciliate apparently contradictory requirements and solutions. These solutions allowed a relatively low cost transmission system with good operational quality.

Some interesting aspects of proposed transmission system are:

- There are reactive compensation only at line extremities and in an intermediate point.
- Switching of the 865 km transmission system directly from one extremity, without switching at intermediate points.
- Line arrangement optimized for the specific line length and transmitted power.
- Single-phase opening and reclosing, assuring high probability of secondary arc extinction, for single phase faults, in order to obtain high reliability of transmission.
- Joint optimization of project and operational criteria, allowing important cost reduction.

9. - We have presented a basic methodology to evaluate adequacy of line parameters and simulation procedures, giving some example results.

The given examples and other similar ones show that some currently applied transmission line models, which intend to represent the frequency dependence of line parameters in time domain simulation program, have some inaccuracies.

According to predicted application, such inaccuracies may be important. There is the need of simple and robust guidelines and test methods, of the type indicated above in the paper, to validate line models for transient studies.

The proposed methodology has been applied to our model and to some established models, allowing us to identify some inaccuracies very promptly.

A.1 - In order to clarify terminology, we indicate, in *Appendix 1*, in a very simplified form, some of the basic assumptions in several of most used formulations to obtain line parameters. There are some variants, but a more generic discussion would be out of the scope of this paper.

In order to simplify the presentation, we include in this Appendix some procedures we have developed, e. g. in order to consider the electric permittivity of ground, the corona phenomena and lightning effects, and that are not used in common engineering practice.

In the Appendix 1, we comment the following aspects:

- Basic line equations, in frequency domain.
- Geometric simplifying assumptions.
- Electromagnetic field behavior simplifying assumptions.
- Longitudinal unitary impedance matrix Z .
- Transversal unitary admittance matrix Y .
- Procedure to consider conductivity and permittivity of soil.
- Line modes referred to unitary parameters.

- Ideal line behavior.
- Line modeling in frequency domain.
- Line modeling in p (or s) domain.
- Modeling corona effects.
- Grounding modeling procedures.
- Line modeling for lightning phenomena.
- Basic constraints of modeling procedures.

In a few points we discuss some relevant aspects of line modeling, including some alternative procedures.

In what concerns methodological aspects not included in common used procedures, we deal with the following problems:

- Procedures to consider effect of ground permittivity.

- Some basic problems related to phase-mode transformation, to the use of quasi-modes and to peculiarities of some eventual assumptions.

- Some basic aspects of ideal line behavior, of procedures aiming to simulate directly in time domain and of the use of propagation functions.

- Some basic aspects of line modeling in frequency domain, and of procedures trying to conciliate frequency domain formulations with time domain procedures.

- A simple and efficient procedure to model a line in phase and frequency domain, without the need to deal explicitly with hyperbolic functions of matrices.

- Line modeling in p (or s) domain.

- Procedures to model corona phenomena.

- The use of a tensorial formulation that, within some eventually acceptable errors, allows to consider some types of non linear behavior (e. g. , associated to corona), interaction among different frequencies and the incremental parameters dependence on "phase" in relation to a reference condition. Also, some type of superposition may be dealt with, using hybrid time-frequency simulation procedures.

- A simple physical model of corona, in connection to spatial field distribution in time and space in vicinity of line conductors. This simple model satisfies naturally to experimental main behavior of corona according to shape of voltage in vicinity of conductor, and allows to take into account interaction between conductors and phases.

- Grounding modeling procedures, including several aspects that are frequently treated with non adequate assumptions, that may originate very important errors, namely for unfavorable lightning and soil behavior characteristics, as it happens in most of Brazil. We indicate procedures to treat such aspects with adequate methodologies that, however, are not applied in common engineering practice.

- Line modeling for lightning phenomena, with emphasis in identification in several common practices that can originate important errors and deficient project and design.

Within the diversity of modeling procedures and application problems, there is not a single method with important advantages for all application problems. An adequate choice must be done, according dominant aspects.

The most used programs for modeling transient phenomena are based in direct time simulation procedures, and, so, an important amount of algorithms try to concentrate in time domain.

In many aspects, frequency domain and **p** domain have important advantages that, in authors' opinion, have not been exploited fully. It appears justified an important effort in frequency domain, **p** domain in and hybrid procedures, to allow a more adequate optimization of methods. For some aspects, time domain procedures have relevant advantages that justify their use, inclusive in hybrid methods using frequency domain, **p** domain and time domain analysis.

10. - As an overview of the questions discussed in the paper, we emphasize the following:

- Most used procedures used in modeling, simulation and optimization of transmission lines, have validity and applicability limitations, whose importance depends on the specific application. It is quite important to have a correct idea of such limitations.

- There is a wide spectrum of metodologies and procedures. The corresonding validity and applicability limitations are quite different. Also several of them have important advantages and drawbacks, whose importance depends on the specific application and its requirements and constraints.

- There is no specific methdology best suited for all applications.

- It is essential to have a clear idea of the limitations of used procedures. Otherwise there is a risk of erroneous results with eventual important consequences.

- There are some usual assumptions quite far from reality, that have been identified in the paper. It is justified an effort to avoid the use of those assumptions.

- The most used programs for modeling transient phenomena are based in direct time simulation procedures, and, so, an important amount of algorithms try to concentrate in time domain. For some applications, time domain methods are a convenient choice. For other applications, other procedures may be more convenient.

- In many aspects, frequency domain and **p** domain have important advantages that, in authors' opinion, have not been exploited fully. It appears justified an important effort in frequency domain, **p** domain in and hybrid procedures, to allow a more adequate optimization of methods. For some aspects, time domain procedures have relevant advantages that justify their use, inclusive in hybrid methods using frequency domain, **p** domain and time domain analysis.

- There are ways through which it is possible to optimize transmission lines, that may allow, in many conditions, great improvement in project, including transmission capability, total cost, ambiental impact and operational behavior. It is justified an open mind attitude, considering alternatives to common engineering practice.

- Very long distance transmission, e. g. , at 2500 km, has characteristics, discussed in the paper, much different of usual long lines (e. g. , 400 km). It is essential to consider such characteristics, and to consider jointly the transmission trunk and the network, to obtain an optimized project of very long distance transmission.

APPENDIX 1 - TRADITIONAL BASIC FORMULATION OF LINE PARAMETERS EVALUATION

Introduction

In order to clarify terminology, we indicate, in a very simplified form, some of the basic assumptions in several of most used formulations to obtain line parameters. There are some variants, but a more generic discussion would be out of the scope of this paper.

In order to simplify the presentation, we include in this Appendix some procedures we have developed, e. g. in order to consider the electric permittivity of ground, the corona phenomena and lightning effects, and that are not used in common engineering practice.

Basic line equations, in frequency domain

For sinusoidal alternating electrical magnitudes, of frequency **f** and pulsation $\omega = 2\,\pi\,\mathbf{f}$, with complex representation of sinusoidal alternating electrical magnitudes, and with several approximations and validity restrictions, the basic equations of a transmission line are

$$-\frac{d\mathbf{U}}{d\mathbf{x}} = \mathbf{Z}\,\mathbf{I} \qquad\qquad -\frac{d\mathbf{I}}{d\mathbf{x}} = \mathbf{Y}\,\mathbf{U}$$

being:

Z the longitudinal unitary impedance matrix, referred to the line cables, of generic element $\mathbf{Z}_{mn}$, function of **f**

Y the transversal unitary admittance matrix, referred to the line cables, of generic element $\mathbf{Y}_{mn}$, function of **f**

U the matrix of transversal voltages of the line cables, function of longitudinal coordinate **x**

I the matrix of longitudinal currents in the line cables, also function of **x** .

Geometric simplifying assumptions

Soil surface is assumed plane and line cables are assumed horizontal, parallel among themselves.

Distance between any pair of conductors is assumed much higher than the sum of their radius.

Electromagnetic effects of structures and insulators are neglected.

Electromagnetic field behavior simplifying assumptions

Some simplifying assumptions are usually done about electromagnetic field behavior, e. g. , quasi stationary type assumptions in what concerns transversal behavior, e. g. equivalent to:

- Neglect propagation time in a direction perpendicular to line axis.
- To relate electric and magnetic field strictly to currents and charges per unit length in the line conductors in a plane perpendicular to line axis, at the same instant.
- To accept some simplifications in border conditions at surfaces separating air from conductors and from ground.
- To assume soil strictly homogeneous or with homogeneous layers separated by horizontal planes. Distance between any pair of conductors is assumed much higher than the sum of their radius.
- Ferromagnetic materials in cables treated assuming an “equivalent” magnetic permeability, μ .

Longitudinal unitary impedance matrix Z

Let **m** , **n** be general indices of any two line conductors, varying **m** , **n** from 1 to the number of conductors, $\mathbf{n}_{max}$, and being, eventually, $\mathbf{n} = \mathbf{m}$.

Let us assume a plane soil surface and cylindrical conductors horizontal and parallel among them, and let be (considering a pair of conductors of indexes **m** , **n** , as represented schematically in Fig. 34),

$\mathbf{h}_m$ the height of conductor **m** from ground (and referred approximately to conductor axis).

$\mathbf{r}_m$ the external radius of conductor **m** .

$\mathbf{y}_{mn}$ the distance between the vertical planes that include the axis of conductors **m** , **n** .

$\mathbf{R}_{mn} = \mathbf{R}_{nm}$ the distance between the axis of conductors **m** , **n** (for $\mathbf{m} \neq \mathbf{n}$).

$\mathbf{R}'_{mn} = \mathbf{R}'_{nm}$ the distance between the axis of conductors **m** and the axis of the image, in relation to ground surface, of **n** , or inversely (for $\mathbf{m} \neq \mathbf{n}$).

$\mathbf{Z}^0$ the longitudinal unitary impedance matrix, **Z** , referred to the line conductors, of generic element $\mathbf{Z}^0_{mn}$, in the assumption that the conductors and the soil behave like perfect conductors (infinite conductivity); in this assumption we would have an ideal line, without losses and dispersion (assuming air permittivity and magnetic permeability uniform and frequency independent), with propagation velocity equal to electromagnetic propagation velocity in air.

$\mathbf{Z}^i$ parcel of **Z** additional to matrix $\mathbf{Z}^0$ that expresses the effect of line conductors not behaving like perfect conductors.

$\mathbf{Z}^s$ of **Z** additional to matrix $\mathbf{Z}^0$ that expresses the effect of ground not behaving like perfect conductor.

$\mathbf{Z}^e$ parcel of **Z** that expresses the effect of electromagnetic field external to the cables, in the assumption that the line cables behave as perfect conductors.

i imaginary unit ($\mathbf{i} = +\sqrt{-1}$).

We have:

$$\mathbf{Z} = \mathbf{Z}^e + \mathbf{Z}^i = \mathbf{Z}^0 + \mathbf{Z}^s + \mathbf{Z}^i$$

In indicated assumptions, we have

$$\mathbf{Z}^0 = \frac{\mu_0}{2\,\pi}\,\mathbf{i}\,\omega\,\mathbf{M}$$

being **M** one matrix that characterizes the line geometry, of generic element $\mathbf{M}_{mn}$, and

$$\mathbf{M}_{mm} = \log\frac{2\,\mathbf{h}_m}{\mathbf{r}_m}$$

(for the diagonal elements of matrix **M** , such that $\mathbf{m} = \mathbf{n}$)

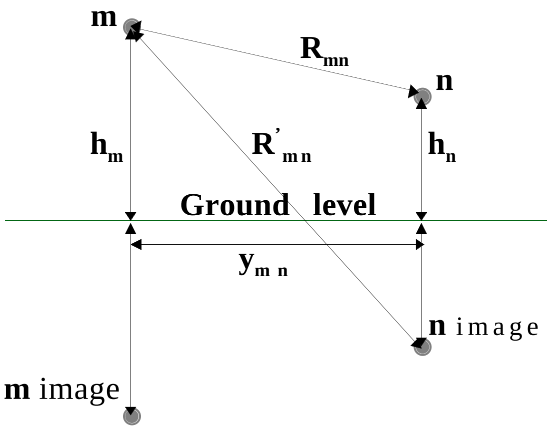


Fig. 34 - Relative position of two line conductors, **m** , **n** , in a plane perpendicular to line axis.

$\mathbf{M}_{mn} = \log \dfrac{\mathbf{R}'_{mn}}{\mathbf{R}_{mn}}$ (for the non-diagonal elements of matrix **M** , such that $\mathbf{m} \neq \mathbf{n}$)

$\mathbf{R}_{mn} = [\ (\mathbf{h}_m - \mathbf{h}_n\ )^2 + \mathbf{y}_{mn}{}^2\ ]^{1/2}$ (for $\mathbf{m} \neq \mathbf{n}$)

$\mathbf{R}'_{mn} = [\ (\mathbf{h}_m + \mathbf{h}_n\ )^2 + \mathbf{y}_{mn}{}^2\ ]^{1/2}$ (for $\mathbf{m} \neq \mathbf{n}$)

Let us consider, as example, the Carson formulation [32], to obtain the effect of non ideal soil. Due to formal coherence aspects, we consider a variant of Carson formulation, that does not affect its important aspects. Carson formulation assumes that, in soil,

$\omega\ \varepsilon << \sigma$

Although, by mistake, Carson states that its formulation applies to magnetic permeability of soil, μ , different of vacuum magnetic permeability, μ_0 , approximate validity of Carson (within some parameters range) implies that, in soil, it is

$\mu \cong \mu_0$

Within the assumptions of this formulation, let it be

$\alpha = [\ \mu_0\ \omega\ \sigma\ ]^{1/2}$ $\mathbf{h}^*_m = \alpha\ \mathbf{h}_m$ $\mathbf{h}^*_n = \alpha\ \mathbf{h}_n$

$\mathbf{y}^*_{mn} = \alpha\ \mathbf{y}_{mn}$ $\mathbf{R}^*_{mn} = \alpha\ \mathbf{R}_{mn}$ $\mathbf{R}'^*_{mn} = \alpha\ \mathbf{R}'_{mn}$

Within this formulation (with Carson approximate results, and with the conditions of its approximate validity), the elements of matrix $\mathbf{Z}^s$ defined above are

$\mathbf{Z}^s_{mm} = \dfrac{\mu_0}{2\pi}\ \omega\ \mathbf{J}_v\ [\ 2\ \mathbf{h}^*_m\ ,\ 0\ ]$ (for diagonal elements of $\mathbf{Z}^s$, such that $\mathbf{m} = \mathbf{n}$)

$\mathbf{Z}^s_{mn} = \dfrac{\mu_0}{2\pi}\ \omega\ \mathbf{J}_v\ [\ \mathbf{h}^*_m + \mathbf{h}^*_n\ ,\ \mathbf{y}^*_{mn}\ ]$ (for non-diagonal elements of $\mathbf{Z}^s$, such that $\mathbf{m} \neq \mathbf{n}$)

being $\mathbf{J}_v$ a function of two arguments, η , ζ , defined by

$$\mathbf{J}_v\ [\ \eta\ ,\ \zeta\ ] = 2 \int_0^\infty \left(\sqrt{\xi^2 + i}\ - \xi \right)\ e^{-\eta \xi}\ \cos\ (\ \zeta\ \xi\ )\ d\xi$$

The function $\mathbf{J}_v$ can, also, be expressed in function of arguments δ , θ , being

$\delta = \sqrt{\eta^2 + \zeta^2}\ = \mathbf{R}'^*_{mn}$

$\theta = \text{atang}\ \dfrac{\zeta}{\eta} = \text{atang}\ \dfrac{\mathbf{y}_{mn}}{\mathbf{h}_m + \mathbf{h}_n} = \text{atang}\ \dfrac{\mathbf{y}^*_{mn}}{\mathbf{h}^*_m + \mathbf{h}^*_n}$

In principle, with an acceptable small error for aerial transmission lines, the effect resulting from non-ideal conductors may be taken into account by means of parcel $\mathbf{Z}^i$ of matrix **Z** , assuming that only diagonal elements of $\mathbf{Z}^i$ are non-null (neglecting mutual effect resulting from non ideal behavior of conductors).

In these conditions, the element of matrix $\mathbf{Z}^i$ corresponding to a specific conductor may be defined as the ratio between the longitudinal component of electric field at the external surface of the conductor and the longitudinal current at such conductor. This definition is relatively robust and satisfies several coherence conditions.

Due to approximate cylindrical symmetry, the internal impedance is naturally expressed in terms of Bessel functions. With some simplifying assumptions, reasonable for most applications, such formulation is relatively simple.

Once obtained the matrix **Z** referred to all line conductors, with some simplifying assumptions (reasonable for some conditions, but not for others), it is easy to reduce such matrix to a matrix referred to phases, relating longitudinal currents and transversal voltages per phase (by a routine manipulation of the matrix **Z** referred to all line conductors), e. g. assuming that:

- The transversal voltages of the several conductors of each phase are equal.
- Transversal voltages of grounded earth wires are null.

A more simple procedure to evaluate matrix **Z** , that is also frequently used [34], and gives results similar to Carson formula, although, in principle, with higher error margin, is to consider an equivalent complex penetration distance, **d** , above ground, at which an ideal ground is assumed, as represented schematically in Fig. 35, being

$\mathbf{d} = 1\ /\ \sqrt{\sigma\, i\, \omega\, \mu_0}$

“External” impedance, obtained with such “equivalent” soil level, considers, with eventually acceptable error, soil effect.

These procedure assumes that, in soil,

$\omega\ \varepsilon << \sigma$

A different method, which avoids most of simplifying assumptions of Carson’s method, as been presented [35-36]. It appears potentially interesting. Apparently some revision mistakes have occurred in published formulae, that must be corrected for obtaining correct results. The practical implementation of this method has, in principle, some numerical difficulties, that impose some particular precautions.

Transversal unitary admittance matrix Y

Let us consider the matrix **D** of transversal voltage coefficients, of generic element $\mathbf{D}_{mn}$, and **C** the matrix of transversal capacitance, per unit length, both referred to line conductors, such that

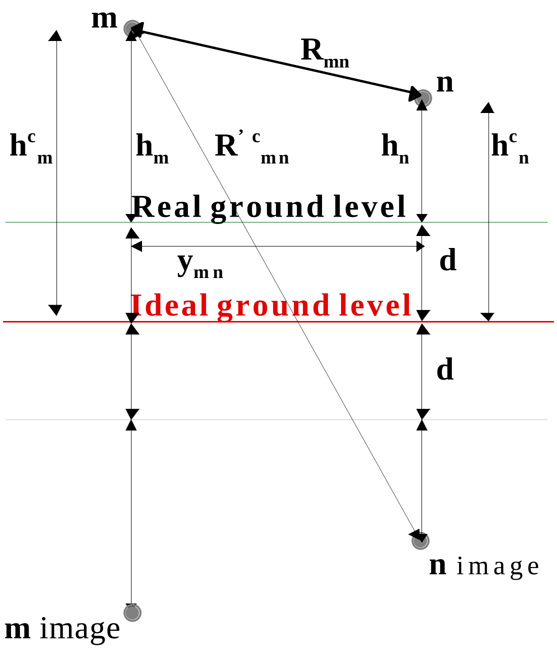


Fig. 35 - Relative position of two line conductors, **m** , **n** , in a plane perpendicular to line axis, considering an ideal ground level at a complex distance, **d** , from real ground level.

$\mathbf{U} = \mathbf{D\ Q} \qquad \mathbf{Q} = \mathbf{D}^{-1}\,\mathbf{U} = \mathbf{C\ U} \qquad \mathbf{C} = \mathbf{D}^{-1}$

$- \dfrac{d\mathbf{I}}{d\mathbf{x}} = \mathbf{i}\,\omega\,\mathbf{Q} = \mathbf{i}\,\omega\,\mathbf{D}^{-1}\,\mathbf{U} \qquad - \dfrac{d\mathbf{I}}{d\mathbf{x}} = \mathbf{Y\ U}$

$\mathbf{Y} = \mathbf{i}\,\omega\,\mathbf{C} = \mathbf{i}\,\omega\,\mathbf{D}^{-1}$

In usual simplifying assumptions, it is

$$\mathbf{D} = \frac{1}{2\pi\varepsilon_a}\,\mathbf{M}$$

$\mathbf{Y} = \mathbf{i}\,\omega\,\mathbf{C} = \mathbf{i}\,\omega\,\mathbf{D}^{-1} = 2\,\pi\,\varepsilon_a\,\mathbf{i}\,\omega\,\mathbf{M}^{-1}$

being **M** one matrix that characterizes the line geometry, of generic element $\mathbf{M}_{mn}$, identical to matrix **M** indicated above, about the computation of matrix **Z** .

The usual assumptions imply, ahead of electromagnetic field behavior simplifying assumptions indicated above, that, for transversal effects, the soil is equivalent to an ideal conductor (infinite conductivity). This last assumption, in what concerns matrix **Y** , may be reasonable for some typical conditions, namely if and when the ground parameters σ and ε are such that

$|\,\sigma + \mathbf{i}\,\omega\,\varepsilon\,| >> \mathbf{i}\,\omega\,\varepsilon_0$

A procedure to evaluate matrix **Y** without the assumption of ideal soil has been presented [37], but does not appears to be widely used.

Procedure to consider conductivity and permittivity of soil

Currently used methods indicated above neglect effect of ground permittivity. This hypothesis is quite far from reality, even for low frequency. It is immediate from Maxwell equations interpretation that, to consider effect of ground permittivity, with otherwise assumptions equivalent to those adopted in such methods, it is adequate:

- In Carson or equivalent formulae, to consider

$\alpha = [\,\mu_0\,\omega\,(\sigma + i\,\omega\,\varepsilon)\,]^{1/2}$ instead of $\alpha = [\,\mu_0\,\omega\,\sigma\,]^{1/2}$

- In complex distance or equivalent formulae, to consider

$\mathbf{d} = 1/\sqrt{(\sigma + i\,\omega\,\varepsilon)\,i\,\omega\,\mu_0}$ instead of $\mathbf{d} = 1/\sqrt{\sigma\,i\,\omega\,\mu_0}$

This procedure is a very simple way to avoid the important error of neglecting soil permittivity effects in line parameters, as it is typically assumed in common engineering practice.

Line modes referred to unitary parameters

In order to allow a simple interpretation, let us consider a three-phase line. The formal transposition for a line with an arbitrary number of phases or poles is immediate.

From the pair of first order differential equations, in **U** and **I** , it is immediate to obtain the second order differential equations, in **U** and **I** , separately:

$\dfrac{d^2\,\mathbf{U}}{d\,\mathbf{x}^2} = \mathbf{Z\ Y\ U} \qquad \dfrac{d^2\,\mathbf{I}}{d\,\mathbf{x}^2} = \mathbf{Y\ Z\ I}$

It is worth to mention that the product of matrices is not commutative, in general.

Let us search solutions characterized by an exponential variation (with a complex exponent, in general) of voltage or current, with distance **x** , along the line:

$\mathbf{U} = \mathbf{U}_0\,e^{\pm\gamma\,\mathbf{x}} \qquad \mathbf{I} = \mathbf{I}_0\,e^{\pm\gamma\,\mathbf{x}}$

In the expressions above, **U** and **I** are functions of **x** , but not of time, **t** . The variation of voltage and current in function of time, in complex representation, $\underline{\mathbf{u}}$, $\underline{\mathbf{i}}$, is expressed by an additional factor that, as it affects all voltages and currents, in complex representation, was not included in previous expressions. Such factor can be expressed by

$e^{\pm\mathbf{i}\,\omega\,\mathbf{t}}$

and, so, the complexes associated to instantaneous values of voltages and currents (function of **x** and **t**), in complex domain, are

$\underline{\mathbf{u}} = \mathbf{U}_0\,e^{\pm\gamma\,\mathbf{x}}\,e^{\pm\mathbf{i}\,\omega\,\mathbf{t}} \qquad \underline{\mathbf{i}} = \mathbf{I}_0\,e^{\pm\gamma\,\mathbf{x}}\,e^{\pm\mathbf{i}\,\omega\,\mathbf{t}}$

In real domain, voltage and current, **u** , **i** , in function of **x** , **t** , are

$\mathbf{u} = \Re\,[\,\underline{\mathbf{u}}\,] = \Re\,[\,\mathbf{U}_0\,e^{\pm\gamma\,\mathbf{x}}\,e^{\pm\mathbf{i}\,\omega\,\mathbf{t}}\,]$

$\mathbf{i} = \Re\,[\,\underline{\mathbf{i}}\,] = \Re\,[\,\mathbf{I}_0\,e^{\pm\gamma\,\mathbf{x}}\,e^{\pm\mathbf{i}\,\omega\,\mathbf{t}}\,]$

We have

$\dfrac{d^2\,\mathbf{U}}{d\,\mathbf{x}^2} = \mathbf{Z\ Y\ U} = \gamma^2\,\mathbf{U} \qquad \dfrac{d^2\,\mathbf{I}}{d\,\mathbf{x}^2} = \mathbf{Y\ Z\ I} = \gamma^2\,\mathbf{I}$

For a more compact notation, let be

$\mathbf{A} = \mathbf{Z\ Y} \qquad \mathbf{B} = \mathbf{Y\ Z}$

For the exponential type solutions under analysis, it must be

$$\det \begin{vmatrix} \mathbf{A}_{11} - \gamma^2 & \mathbf{A}_{12} & \mathbf{A}_{13} \\ \mathbf{A}_{21} & \mathbf{A}_{22} - \gamma^2 & \mathbf{A}_{23} \\ \mathbf{A}_{31} & \mathbf{A}_{32} & \mathbf{A}_{33} - \gamma^2 \end{vmatrix} = 0$$

$$\det \begin{vmatrix} \mathbf{B}_{11} - \gamma^2 & \mathbf{B}_{12} & \mathbf{B}_{13} \\ \mathbf{B}_{21} & \mathbf{B}_{22} - \gamma^2 & \mathbf{B}_{23} \\ \mathbf{B}_{31} & \mathbf{B}_{32} & \mathbf{B}_{33} - \gamma^2 \end{vmatrix} = 0$$

or, in other words, γ^2 must be an eigenvalue of matrices $\mathbf{A} = \mathbf{Z}\,\mathbf{Y}$ and $\mathbf{B} = \mathbf{Y}\ \mathbf{Z}$. Although, in general, $\mathbf{A}$ and $\mathbf{B}$ are different, they have the same eigenvalues (but, in general, different eigenvectors).

To obtain the $\mathbf{j}$ solutions, γ_j^2, of the two previous equations, it is enough to obtain the solutions of any of them. For each value of γ_j^2 there are two values of γ_j, what can be expressed by $\pm\gamma_j$, being γ_j one of the two square roots of γ_j^2. Each pair of roots of one of solutions γ_j^2 is associated to propagation and attenuation in opposed senses.

For each value, γ_j^2, of previous solutions, and for that solution (or solution pair), the corresponding voltages or currents are in a certain proportion. Such proportion defines, apart an arbitrary complex factor, the eigenvector associated to γ_j^2.

Let

$$\mathbf{U}_{FMj} = \begin{vmatrix} k_{uj1} \\ k_{uj2} \\ k_{uj3} \end{vmatrix}$$

be the eigenvector of voltages in phase coordinates (respectively phases 1 , 2 , 3) corresponding to the voltage, in mode coordinate, associated to the eigenvalue γ_j. It must be

$$(\mathbf{A}_{11} - \gamma_j^2)\, k_{uj1} - \mathbf{A}_{12}\, k_{uj2} - \mathbf{A}_{13}\, k_{uj3} = 0$$

$$\mathbf{A}_{21}\, k_{uj1} - (\mathbf{A}_{22} - \gamma_j^2)\, k_{uj2} - \mathbf{A}_{23}\, k_{uj3} = 0$$

$$\mathbf{A}_{31}\, k_{uj1} - \mathbf{A}_{32}\, k_{uj2} - (\mathbf{A}_{33} - \gamma_j^2)\, k_{uj3} = 0$$

Due to the fact that γ_j^2 is one of the roots of the determinant of the coefficients of previous equations system, such equations are not distinct, and one of them is a linear combination of the other two.

So two (any) of previous equations define the proportion of k_{uj1}, k_{uj2}, k_{uj3}, or, in other words, apart a proportionality factor, in principle arbitrary, define the transversal voltages eigenvector associated to γ_j.

Let

$$\mathbf{I}_{FMj} = \begin{vmatrix} k_{ij1} \\ k_{ij2} \\ k_{ij3} \end{vmatrix}$$

be the eigenvector of currents in phase coordinates (respectively phases 1 , 2 , 3) corresponding to the current, in mode coordinate, associated to the eigenvalue γ_j.

It must be

$$(\mathbf{B}_{11} - \gamma_j^2)\, k_{ij1} - \mathbf{B}_{12}\, k_{ij2} - \mathbf{B}_{13}\, k_{ij3} = 0$$

$$\mathbf{B}_{21}\, k_{ij1} - (\mathbf{B}_{22} - \gamma_j^2)\, k_{ij2} - \mathbf{B}_{23}\, k_{ij3} = 0$$

$$\mathbf{B}_{31}\, k_{ij1} - \mathbf{B}_{32}\, k_{ij2} - (\mathbf{B}_{33} - \gamma_j^2)\, k_{ij3} = 0$$

Any two of previous equations define the proportion of k_{ij1}, k_{ij2}, k_{ij3}, or, in other words, apart a proportionality factor, in principle arbitrary, define the longitudinal currents eigenvector associated to γ_j.

In general, the eigenvector of voltages and the eigenvector of currents, associated to the same eigenvalue γ_j, are distinct (ahead of the "freedom" of choosing different proportionality factors for the two eigenvectors).

If two of the three roots γ_j^2 are coincident, in the systems of three linear equations that define the eigenvectors, for that double root, only one equation (in each system of three equations) is "distinct". The other two do not impose additional proportionality conditions among k_{uj1}, k_{uj2}, k_{uj3}, and among k_{ij1}, k_{ij2}, k_{ij3}. So, there is an infinity of eigenvalues associated to the eigenvalue of multiplicity two. Expressed in another form: given two distinct eigenvectors (ahead the arbitrary complex proportionality factors) for the double root γ_j^2, any linear combination of such eigenvectors is also an eigenvector, for the same eigenvalue.

If the three roots γ_j^2 are equal, the systems of three linear equations that define the eigenvectors do not impose additional relation among k_{uj1}, k_{uj2}, k_{uj3}, and among k_{ij1}, k_{ij2}, k_{ij3}, and any linear combination of phase voltages or currents is an eigenvector, with eigenvalue $\pm\gamma_j$. This condition corresponds to the case of an ideal line, without losses and dispersion (ideal conductors and ideal ground), for which any pair phase voltage-current, or linear combination, propagates according air parameters, assumed without losses (σ null) and with ε constant and frequency independent.

In principle, transversal voltages and longitudinal currents can be expressed in terms of "phase coordinates" or in terms of "mode coordinates", corresponding each "mode" to an eigenvalue γ_j, to a pair of "complex scalar" transversal voltage and "complex scalar" longitudinal current (both for the same eigenvalue and in mode coordinates), and to a pair "eigenvector transversal voltage" and "eigenvector longitudinal current" (both for the same eigenvalue and in phase coordinates).

Let us identify the mode coordinates and the phase coordinates by the indexes $\mathbf{M}$ e $\mathbf{P}$, respectively, and let us consider the phase-mode and mode-phase transformation matrices, for transversal voltages and longitudinal currents, $\mathbf{T}_{uMP}$, $\mathbf{T}_{uPM}$, $\mathbf{T}_{iMP}$, $\mathbf{T}_{iPM}$, such that

$$\mathbf{U}_{M1} = \mathbf{Z}_{oM1}\, \mathbf{I}_{M1} \qquad \mathbf{U}_{M2} = \mathbf{Z}_{oM2}\, \mathbf{I}_{M2} \qquad \mathbf{U}_{M3} = \mathbf{Z}_{oM3}\, \mathbf{I}_{M3}$$

$$\mathbf{U}_M = \mathbf{T}_{uMP}\, \mathbf{U}_P \qquad \mathbf{U}_P = \mathbf{T}_{uPM}\, \mathbf{U}_M$$

$$\mathbf{I}_M = \mathbf{T}_{iMP}\, \mathbf{I}_P \qquad \mathbf{I}_P = \mathbf{T}_{iPM}\, \mathbf{I}_M$$

We have

$$\mathbf{T}_{uMP} = \mathbf{T}_{uPM}^{-1} \qquad \mathbf{T}_{iMP} = \mathbf{T}_{iPM}^{-1}$$

$$\mathbf{T}_{uPM} = \begin{vmatrix} k_{u11} & k_{u21} & k_{u31} \\ k_{u12} & k_{u22} & k_{u32} \\ k_{u13} & k_{u23} & k_{u33} \end{vmatrix}$$

$$\mathbf{T}_{iPM} = \begin{vmatrix} k_{i11} & k_{i21} & k_{i31} \\ k_{i12} & k_{i22} & k_{i32} \\ k_{i13} & k_{i23} & k_{i33} \end{vmatrix}$$

Let us consider the relations, expressed in phase coordinates,

$$-\frac{d\,\mathbf{U}}{d\,\mathbf{x}} = \mathbf{Z}\ \mathbf{I} \qquad -\frac{d\,\mathbf{I}}{d\,\mathbf{x}} = \mathbf{Y}\ \mathbf{U}$$

or

$$-\frac{d}{d\,\mathbf{x}}\ \mathbf{U}_P = \mathbf{Z}_{PP}\ \mathbf{I}_P \qquad -\frac{d}{d\,\mathbf{x}}\ \mathbf{I}_P = \mathbf{Y}_{PP}\ \mathbf{U}_P$$

We obtain

$$-\frac{d}{d\,\mathbf{x}}\ \mathbf{T}_{uPM}\ \mathbf{U}_M = \mathbf{Z}_{PP}\ \mathbf{T}_{iPM}\ \mathbf{I}_M$$

$$-\frac{d}{d\,\mathbf{x}}\ \mathbf{T}_{iPM}\ \mathbf{I}_M = \mathbf{Y}_{PP}\ \mathbf{T}_{uPM}\ \mathbf{U}_M$$

and

$$-\frac{d}{d\,\mathbf{x}}\ \mathbf{T}_{uPM}^{-1}\ \mathbf{T}_{uPM}\ \mathbf{U}_M = \mathbf{T}_{uPM}^{-1}\ \mathbf{Z}_{PP}\ \mathbf{T}_{iPM}\ \mathbf{I}_M$$

$$-\frac{d}{d\,\mathbf{x}}\ \mathbf{T}_{iPM}^{-1}\ \mathbf{T}_{iPM}\ \mathbf{I}_M = \mathbf{T}_{iPM}^{-1}\ \mathbf{Y}_{PP}\ \mathbf{T}_{uPM}\ \mathbf{U}_M$$

from which

$$-\frac{d}{d\,\mathbf{x}}\ \mathbf{U}_M = \mathbf{T}_{uPM}^{-1}\ \mathbf{Z}_{PP}\ \mathbf{T}_{iPM}\ \mathbf{I}_M$$

$$-\frac{d}{d\,\mathbf{x}}\ \mathbf{I}_M = \mathbf{T}_{iPM}^{-1}\ \mathbf{Y}_{PP}\ \mathbf{T}_{uPM}\ \mathbf{U}_M$$

So, the longitudinal impedance per unit length, in mode coordinates, $\mathbf{Z}_{MM}$, and the transversal admittance per unit length, in mode coordinates, $\mathbf{Y}_{MM}$, such that

$$-\frac{d}{d\,\mathbf{x}}\ \mathbf{U}_M = \mathbf{Z}_{MM}\ \mathbf{I}_M \qquad -\frac{d}{d\,\mathbf{x}}\ \mathbf{I}_M = \mathbf{Y}_{MM}\ \mathbf{U}_M$$

are related with the matrices longitudinal impedance per unit length, in phase coordinates, $\mathbf{Z}_{PP}$, and the transversal admittance per unit length, in phase coordinates, $\mathbf{Y}_{PP}$, by

$$\mathbf{Z}_{MM} = \mathbf{T}_{uPM}^{-1}\ \mathbf{Z}_{PP}\ \mathbf{T}_{iPM} = \mathbf{T}_{uMP}\ \mathbf{Z}_{PP}\ \mathbf{T}_{iPM}$$

$$\mathbf{Y}_{MM} = \mathbf{T}_{iPM}^{-1}\ \mathbf{Y}_{PP}\ \mathbf{T}_{uPM} = \mathbf{T}_{iMP}\ \mathbf{Y}_{PP}\ \mathbf{T}_{uPM}$$

$$\mathbf{Z}_{PP} = \mathbf{T}_{uPM}\ \mathbf{Z}_{MM}\ \mathbf{T}_{iPM}^{-1} = \mathbf{T}_{uPM}\ \mathbf{Z}_{MM}\ \mathbf{T}_{iMP}$$

$$\mathbf{Y}_{PP} = \mathbf{T}_{iPM}\ \mathbf{Y}_{MM}\ \mathbf{T}_{uPM}^{-1} = \mathbf{T}_{iPM}\ \mathbf{Y}_{MM}\ \mathbf{T}_{uMP}$$

The matrices $\mathbf{Z}_{MM}$ and $\mathbf{Y}_{MM}$ are diagonal (with non diagonal elements null). So, the voltage and current of each mode are related with the current and the voltage of the same mode, and, within the line, there is no interaction among distinct modes. Such interaction may occur in line terminals, in points in which there are modification of mode-phase relations, such as transposition points, and in points in which external conditions are imposed, e. g. , line faults, interrupted phases. For some problems in which shield wires must be considered explicitly, towers, tower grounding, and specific aspects of shielding wires connection may originate eventual interaction among modes.

It is, also,

$$\mathbf{Z}_{MM11}\ \mathbf{Y}_{MM11} = \mathbf{Y}_{MM11}\ \mathbf{Z}_{MM11} = \gamma_1^2$$

$$\mathbf{Z}_{MM22}\ \mathbf{Y}_{MM22} = \mathbf{Y}_{MM22}\ \mathbf{Z}_{MM22} = \gamma_2^2$$

$$\mathbf{Z}_{MM33}\ \mathbf{Y}_{MM33} = \mathbf{Y}_{MM33}\ \mathbf{Z}_{MM33} = \gamma_3^2$$

The characteristic impedances of modes, $\mathbf{Z}_{oM1}$, $\mathbf{Z}_{oM2}$, $\mathbf{Z}_{oM3}$, are

$$\mathbf{Z}_{oM1} = (\ \mathbf{Z}_{MM11}\ /\ \mathbf{Y}_{MM11}\ )^{1/2}$$

$$\mathbf{Z}_{oM2} = (\ \mathbf{Z}_{MM22}\ /\ \mathbf{Y}_{MM22}\ )^{1/2}$$

$$\mathbf{Z}_{oM3} = (\ \mathbf{Z}_{MM33}\ /\ \mathbf{Y}_{MM33}\ )^{1/2}$$

and the characteristic admittances of modes, $\mathbf{Y}_{oM1}$, $\mathbf{Y}_{oM2}$, $\mathbf{Y}_{oM3}$, are

$$\mathbf{Y}_{oM1} = (\ \mathbf{Y}_{MM11}\ /\ \mathbf{Z}_{MM11}\ )^{1/2} = \mathbf{Z}_{oM1}^{-1}$$

$$\mathbf{Y}_{oM2} = (\ \mathbf{Y}_{MM22}\ /\ \mathbf{Z}_{MM22}\ )^{1/2} = \mathbf{Z}_{oM2}^{-1}$$

$$\mathbf{Y}_{oM3} = (\ \mathbf{Y}_{MM33}\ /\ \mathbf{Z}_{MM33}\ )^{1/2} = \mathbf{Z}_{oM3}^{-1}$$

being

$$\mathbf{U}_{M1} = \mathbf{Z}_{oM1}\ \mathbf{I}_{M1} \qquad \mathbf{U}_{M2} = \mathbf{Z}_{oM2}\ \mathbf{I}_{M2} \qquad \mathbf{U}_{M3} = \mathbf{Z}_{oM3}\ \mathbf{I}_{M3}$$

and

$$\mathbf{I}_{M1} = \mathbf{Y}_{oM1}\ \mathbf{U}_{M1} \qquad \mathbf{I}_{M2} = \mathbf{Y}_{oM2}\ \mathbf{U}_{M2} \qquad \mathbf{I}_{M3} = \mathbf{Y}_{oM3}\ \mathbf{U}_{M3}$$

In general, the matrices defining relations between phase domain and mode domain voltages, currents and per unit longitudinal impedances and transversal admittances are frequency dependent. This fact creates some difficulties in time domain simulation procedures using simultaneously mode simulation, e. g. , for lines, and phase simulation, e. g. for switching conditions and surge arresters. The need to consider a phase-mode transformation frequency dependent, that can not be expressed, at least directly and in a simple form, in time domain, reduces or eliminates most advantages of mode domain use, in time simulation. Some common used procedures consider a phase-mode "transformation" assumed frequency independent, e. g. equal to the correct transformation matrices evaluated for a specific frequency. The error of this assumption may be more or less important according the specific application.

In lines having a vertical symmetry plane, as it occurs in most transmission lines, there are two groups of eigenvalues, as an immediate result of such symmetry. In a three-phase representation, one of such groups corresponds to β Clarke's component, that is an exact mode, and the other group joins α Clarke's component and homopolar component, $\mathbf{h}$, that are not exact modes, and may, eventually, be treated as quasi-modes.

The use of Clarke's components as quasi-modes (one of them, β , an exact mode, if the line has a vertical symmetry plane), has the advantage that phase-"mode" transformation matrices are frequency independent and real, and, so, can be applied directly in time domain. Additionally, the Clarke's transformation, being "a priori" frequency independent, has not the risk of introducing errors associated to peculiarities of a particular frequency. Clarke's components have also the advantage that "quasi-mode"-phase transformation can be simulated, in common time domain simulation programs, by means of ideal transformers, allowing the use of such programs in most of their models and tools, but allowing specific choice of line modeling, eventually different of line models available in such programs.

Another assumption, that, when acceptable, has many practical advantages, is to assume "ideal" transposition of line. With this assumption, homopolar component (corresponding, in phase domain, to voltages or currents, identical in the three phases) is an exact mode. The other two modes have the same eigenvalue, and, so, there is a degree of freedom in choosing the eigenvectors of such modes. They can be chosen, e. g. , like α , β Clarke's components, that have the advantage of being real. They can be chosen, also, as direct (positive) and inverse (negative) symmetrical components. In fact, any linear combination of voltages and currents to which, in phase domain, corresponds a null sum of magnitudes of three-phases is also a mode with the same eigenvalue.

Ideal line behavior

Let us consider an ideal line with conductors and ground with infinite conductivity, and general assumptions similar to those indicated above.

The basic equations of a transmission line are

$$-\frac{d\mathbf{U}}{d\mathbf{x}} = \mathbf{Z}\,\mathbf{I} \qquad\qquad -\frac{d\mathbf{I}}{d\mathbf{x}} = \mathbf{Y}\,\mathbf{U}$$

being:

$\mathbf{Z} = \mathbf{Z}^0 = \mathbf{i}\,\omega\,\mathbf{L} = \frac{\mu_0}{2\pi}\,\mathbf{i}\,\omega\,\mathbf{M}$ the longitudinal unitary impedance matrix, referred to the line cables, of generic element $\mathbf{Z}_{mn}$, function of $\mathbf{f}$

$\mathbf{Y} = \mathbf{i}\,\omega\,\mathbf{C} = 2\,\pi\,\varepsilon_a\,\mathbf{i}\,\omega\,\mathbf{M}^{-1}$

$\mathbf{M}$ one matrix that characterizes the line geometry, defined above

So,

$\mathbf{Z}\,\mathbf{Y} = \mathbf{Y}\,\mathbf{Z} = \varepsilon_a\,\mu_0\,(\,\mathbf{i}\,\omega\,)^2\,\boldsymbol{U}$

being $\boldsymbol{U}$ an unitary matrix (with all diagonal elements equal to 1 and all non-diagonal elements equal to 0), and all eigenvalues are equal to

$\gamma = \pm\,\mathbf{v}^{-1}\,\mathbf{i}\,\omega$

being $v = (\varepsilon_a\,\mu_0)^{-1/2}$ the speed of electromagnetic propagation in air.

So, in complex domain, voltages and currents (in conductors, or phases), in function of $\mathbf{x}$ and $\mathbf{t}$, are

$\underline{\mathbf{u}} = \mathbf{U}_0\,e^{\pm\gamma\,\mathbf{x}}\,e^{\pm\mathbf{i}\,\omega\,\mathbf{t}} = \mathbf{U}_0\,e^{\pm\mathbf{i}\,\omega\,(\,\mathbf{t}\mp\mathbf{x}/\mathbf{v}\,)}$

$\underline{\mathbf{i}} = \mathbf{I}_0\,e^{\pm\gamma\,\mathbf{x}}\,e^{\pm\mathbf{i}\,\omega\,\mathbf{t}} = \mathbf{I}_0\,e^{\pm\mathbf{i}\,\omega\,(\,\mathbf{t}\mp\mathbf{x}/\mathbf{v}\,)}$

In real domain, voltage and current, $\mathbf{u}$, $\mathbf{i}$, in function of $\mathbf{x}$, $\mathbf{t}$, are

$\mathbf{u} = \Re\,[\,\underline{\mathbf{u}}\,] = \Re\,[\,\mathbf{U}_0\,e^{\pm\mathbf{i}\,\omega\,(\,\mathbf{t}\mp\mathbf{x}/\mathbf{v}\,)}\,]$

$\mathbf{i} = \Re\,[\,\underline{\mathbf{i}}\,] = \Re\,[\,\mathbf{I}_0\,e^{\pm\mathbf{i}\,\omega\,(\,\mathbf{t}\mp\mathbf{x}/\mathbf{v}\,)}\,]$

So, due to the fact that the result is formally independent of ω and $\mathbf{x}$, except in what concerns the exponential factors, in expression above, and the relation between $\mathbf{t}$ and $\mathbf{x}$ that appears, only, in the factor, in exponent,

$\mathbf{t} \mp \mathbf{x}\,/\,\mathbf{v}$

the propagation along the line is characterized by any arbitrary function of $\mathbf{t} - \mathbf{x}\,/\,\mathbf{v}$ or of $\mathbf{t} + \mathbf{x}\,/\,\mathbf{v}$, what represents ideal waves of arbitrary shape (in function, e. g. , of $\mathbf{t}$ or of $\mathbf{x}$) propagating with speed $\pm\,\mathbf{v}$, without attenuation and distortion

Choosing, by example, as "current mode" for mode of index $\mathbf{m}$, the current, $\mathbf{i}_{\mathbf{m}}(\,\mathbf{x} - \mathbf{v}\,\mathbf{t}\,)$, in conductor (or phase) of index $\mathbf{m}$, the transversal voltage, in conductor or phase of index $\mathbf{n}$, for that mode, will be

$\mathbf{u}_{\mathbf{n}}(\,\mathbf{x} - \mathbf{v}\,\mathbf{t}\,) = \boldsymbol{Z}_{\mathbf{nm}}\,\mathbf{i}_{\mathbf{m}}(\,\mathbf{x} - \mathbf{v}\,\mathbf{t}\,)$

being

$$\boldsymbol{Z}_{\mathbf{nm}} = \mathbf{v}\,\mathbf{L}_{\mathbf{nm}} = \sqrt{\frac{\mu_0}{\varepsilon_a}}\;\mathbf{M}_{\mathbf{nm}}$$

the surge mutual impedance (real) between conductors or phases $\mathbf{m}\,\mathbf{n}$.

In this very simple case, it could have been used a manipulation directly in time domain. We have presented a manipulation in frequency-time domain, to emphasize frequency-time aspects.

The simulation of an ideal line in time domain is quite simple. In each terminal, at time $\mathbf{t}$, "arrives" a wave from the other terminal, that was "defined" at the other terminal at time $\mathbf{t} - \tau$, being τ the propagation time. The terminal conditions, considering the "arriving" wave and other constraints, "define" the wave sent in the sense of the other terminal, that will arrive there at time $\mathbf{t} + \tau$.

For non-ideal lines, there are attenuation and distortion, and the simulation of the line, in time domain, is less simple.

Several programs that work in time domain have incorporated procedures to simulate lines, in time domain, trying to adapt the basic concepts that apply to ideal lines. In some cases, some simplifications have been used, and, some of them, imply in physical validity restrictions. Most used procedures can give good or bad results according the specific application and, also, according additional precautions to limit errors. It is out of the scope of this paper a general discussion of methods and procedures used in time domain simulation programs [46-58].

We present an example, quite simple, that illustrates clearly some of the reasons of the difficulty of line simulation procedures directly in time domain. Let us consider a single conductor or a single mode whose unitary (per unit length) parameters are assumed equivalent to constant $\mathbf{R}$, $\mathbf{L}$ in series, for longitudinal $\mathbf{Z}$, and to constant $\mathbf{G}$, $\mathbf{C}$ in parallel, for transversal $\mathbf{Y}$, what, in frequency domain, corresponds to

$\mathbf{Z} = \mathbf{R} + \mathrm{i}\,\omega\,\mathbf{L}$

$\mathbf{Y} = \mathbf{G} + \mathrm{i}\,\omega\,\mathbf{C}$

and being, in general,

$\mathbf{R}\,/\,\mathbf{L} \neq \mathbf{G}\,/\,\mathbf{C}$

There is an "exact" analytical solution [33], in function of time, for a step voltage applied at one line extremity, e. g. at time $\mathbf{t} = 0$, and propagation only in one sense (e. g. , infinite line). Such "exact" solution involves integrals whose arguments include Bessel functions whose arguments contain $\sqrt{\mathbf{t}^2 - \mathbf{x}^2/\mathbf{v}^2}$, being $\mathbf{x}$ the space coordinate along the line and

$\mathbf{v} = 1 / \sqrt{\mathbf{L\,C}}$

The parameter $\mathbf{v}$ may be interpreted as a propagation velocity, in a restrict sense, associated to "first" arrival of voltage and current impulses at point $\mathbf{x}$. A dual solution is obtained immediately for a step current in one line terminal and propagation only in one sense. In [39] it is presented a systematic analysis of the propagation characteristics of this simple condition, in graphic form.

It is quite interesting that there is attenuation and distortion, and that line and current, for the same voltage or current step, at one terminal, present different "shapes", either in function of $\mathbf{t}$ or of $\mathbf{x}$.

The "exact" solution for an "arbitrary" voltage or current at one line terminal can be obtained from the solution for a step voltage or a step current, by a convolution procedure.

Apart formal details, the difference between the reply of the "assumed" line and the "corresponding ideal line" (with parameters $\mathbf{L}$, $\mathbf{C}$ equal to those of considered line and $\mathbf{R}$ and $\mathbf{G}$ null) may be associated to a propagation function.

A similar procedure can be applied to a more general case, in which unitary parameters are frequency dependent. From the "propagation" line characteristics in frequency domain, it is easy to obtain the reply to a step voltage or to a step current, or to another "basic function", using Fourier integral transformation. View in this way, the treatment in time domain can de done by means of a numerical procedure, without "formal" additional error, and with eventual numerical error or computational processing difficulties.

If it is desired to obtain a simple analytical formulation of propagation functions, in time domain, errors, either of physical consistency type, or numerical accuracy type, or both, are introduced. Several used procedures consider propagation functions that present some validity restrictions. According the specific application, such restrictions may be acceptable, or not.

Line modeling in frequency domain

Let us consider a <u>mode</u> or "<u>quasi-mode</u>" of a transmission line, in complex formulation of alternating current magnitudes (e. g., voltages and currents), of frequency $\mathbf{f}$,

$$-\frac{d\mathbf{U}}{d\mathbf{x}} = \mathbf{Z_u}\,\mathbf{I} \qquad\qquad -\frac{d\mathbf{I}}{d\mathbf{x}} = \mathbf{Y_u}\,\mathbf{U}$$

being (for such mode):

$\mathbf{Z_u}$ the longitudinal unitary impedance

$\mathbf{Y_u}$ the transversal unitary admittance

$\mathbf{U}$ the transversal voltage, in function of longitudinal coordinate $\mathbf{x}$

$\mathbf{I}$ the longitudinal current, also function of $\mathbf{x}$.

From the previous equations pair, we also have the second order differential equations, separately for $\mathbf{U}$ and $\mathbf{I}$:

$$\frac{d^2\mathbf{U}}{d\mathbf{x}^2} = \mathbf{Z_u}\,\mathbf{Y_u}\,\mathbf{U} \qquad\qquad \frac{d^2\mathbf{I}}{d\mathbf{x}^2} = \mathbf{Y_u}\,\mathbf{Z_u}\,\mathbf{I}$$

Differently of what happens, in general, for the matrices applicable to the line together, for a mode we have

$\mathbf{Z_u}\,\mathbf{Y_u} = \mathbf{Y_u}\,\mathbf{Z_u}$

We have

$$\frac{d^2\mathbf{U}}{d\mathbf{x}^2} = \mathbf{Z_u}\,\mathbf{Y_u}\,\mathbf{U} = \gamma^2\,\mathbf{U}$$

$$\frac{d^2\mathbf{I}}{d\mathbf{x}^2} = \mathbf{Y_u}\,\mathbf{Z_u}\,\mathbf{I} = \gamma^2\,\mathbf{I}$$

being

$$\gamma = (\pm)\sqrt{\mathbf{Z_u}\,\mathbf{Y_u}} = (\pm)\sqrt{\mathbf{Y_u}\,\mathbf{Z_u}}$$

the propagation coefficient that defines the variation with $\mathbf{x}$ of exponential type solutions.

For the exponential solutions of exponent $\pm\gamma\,\mathbf{x}$,we have

$\mathbf{U} = \pm\,\mathbf{Z_c}\,\mathbf{I}$

being

$$\mathbf{Z_c} = (\pm)\sqrt{\frac{\mathbf{Z_u}}{\mathbf{Y_u}}}$$

the characteristic impedance.

The line behavior, for the frequency $\mathbf{f}$, may be characterized, in alternative:

a - By parameters $\mathbf{Z_u}$, $\mathbf{Y_u}$

b - By parameters $\mathbf{Z_c}$, γ

From one of these two parameter pairs, the other pair is obtained immediately.

Let us consider a line or line part of length $\mathbf{L}$.

Let us consider a modeling modulus representing a line or line part of length $\mathbf{L}$ and the corresponding equivalent π scheme, as represented in Fig. 36 .

This modulus, in what concerns the relations among voltages and currents in respective terminal <u>pairs</u>, may be represented correctly by a π scheme, as represented in Fig. 36 , being the impedance $\mathbf{Z_e}$ and each one of the two admittances $\mathbf{Y_{e2}}$ of this scheme

$$\mathbf{Z_e} = \mathbf{Z_c}\,\mathbf{sinh}\,[\,\gamma\,\mathbf{L}\,]$$

$$\mathbf{Y_{e2}} = \mathbf{Z_c}^{-1}\,\mathbf{tanh}\,\frac{\gamma\,\mathbf{L}}{2}$$

In principle this equivalent scheme is exact, in the sense that it corresponds exactly to line differential equations, for any values of $\mathbf{L}$ and $\mathbf{f}$, if $\mathbf{Z_e}$ and $\mathbf{Y_{e2}}$ have the values resulting from previous equations. So, a single π can be used to represent a line with any length.

For an analysis in frequency domain there is no significative obstacle to modeling a line with a "long" π , in the sense that $|\,\gamma\,\mathbf{L}\,|$ might have a large value, inclusive much larger than 1 .

The conversion between frequency and time domains is simple, in principle, using, e. g. , Fourier integral transformation.

A variant of the previous formulation is to consider the admittance matrix of the line, as view at their terminals, $\boldsymbol{Y}$. Using the signals definition of Fig. 37, we have

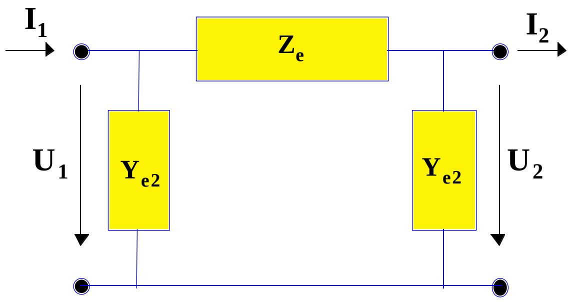


Fig. 36 - Model π of a line modulus.

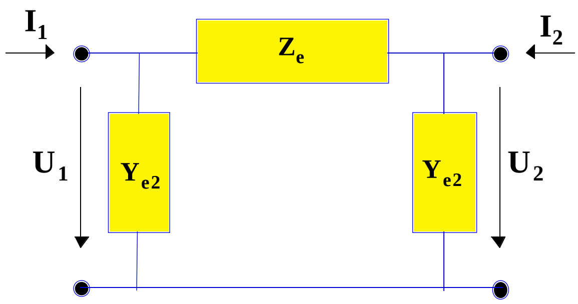


Fig. 37 - Model π of a line modulus.

$$\begin{vmatrix} \mathbf{I}_1 \\ \mathbf{I}_2 \end{vmatrix} = \boldsymbol{Y} \begin{vmatrix} \mathbf{U}_1 \\ \mathbf{U}_2 \end{vmatrix}$$

being

$$\boldsymbol{Y} = \mathbf{Y_c} \begin{vmatrix} \cot\text{anh}(\gamma \mathbf{L}) & -\cos\text{ech}(\gamma \mathbf{L}) \\ -\cos\text{ech}(\gamma \mathbf{L}) & \cot\text{anh}(\gamma \mathbf{L}) \end{vmatrix}$$

Another variant is to consider the transfer function, $\boldsymbol{W}$, between voltages and currents at one line terminal and voltages and currents at the other terminal. Using the signals definition of Fig. 36, we have

$$\begin{vmatrix} \mathbf{U}_2 \\ \mathbf{I}_2 \end{vmatrix} = \boldsymbol{W} \begin{vmatrix} \mathbf{U}_1 \\ \mathbf{I}_1 \end{vmatrix}$$

being

$$\boldsymbol{W} = \begin{vmatrix} \cosh(\gamma \mathbf{L}) & -\mathbf{Z_c} \sinh(\gamma \mathbf{L}) \\ -\mathbf{Y_c} \sinh(\gamma \mathbf{L}) & \cosh(\gamma \mathbf{L}) \end{vmatrix}$$

The use of the π scheme indicated above, or similar formulations, for analysis directly in time domain, has some difficulty that can be interpreted as associated to the hyperbolic functions of previous expressions of $\mathbf{Z_e}$ and $\mathbf{Y_{e2}}$. They impose a formal characterization degree that is not compatible with some types of circuit models. In a numeric point of view, the dual aspect of such formal constraint is the need to use more complex computational procedures in order to obtain enough small errors. There are different types of procedures and attitudes aimed to solve the problem in an acceptable form. It is out of the scope of this paper to discuss such procedures.

There is a simple procedure that allows to use programs based in time domain simulation, but allowing a specific line modeling, independent of line models of such programs.

The basic aspect of that procedure is the fact that, for a model of the type of the π scheme of Fig. 36 , for **L** reasonably shorter than a quarter wave length, the hyperbolic functions have a small effect in impedance $\mathbf{Z_e}$ and in admittances $\mathbf{Y_{e2}}$, that may be assumed proportional to per unit length parameters **Z** and **Y** . Within most common assumptions:

- **Y** is proportional to frequency (in time domain) or to **p** (in **p** domain). So, $\mathbf{Y_{e2}}$ can be represented by a capacitance (in mode representation) or a matrix of capacitances (in phase representation). This type of representation is quite easy in most time domain simulation programs.

- **Z** has, typically, a minimum phase shift type, or similar, behavior, that can be represented by simple equivalent circuit schemes, whose parameters are easily obtained directly from per unit longitudinal impedance in function of frequency, with desired accuracy. As the frequency dependence is of minimum phase shift type, the real and imaginary parts are adjusted in a dual form, and, in principle and apart constants, it is enough to adjust one of them.

For the typical case of common switching transient simulation, with a representative frequency range till about 5 to 10 kHz, it is adequate to consider a π length of about 10 to 5 km, and, in each one, to consider, per mode, a capacitance per π (associating $\mathbf{Y_{e2}}$ circuits in consecutive πs) and a number of the order of 10 resistors and inductors. By example, the $\mathbf{Z_e}$ element of a “short” π circuit may be represented by a series R , L circuit in series with nine parallel R , L circuits. “Connections” phase-mode can be done, e. g. , by means of ideal transformers.

In some simplifying assumptions, or using symmetry conditions, this type of scheme can be used directly in phase domain, almost without additional modeling constraints.

In more general conditions, this type of modeling can also be used, with some simple additional precautions, e. g. , using ideal transformers, to allow different modeling procedures in the line and in other network elements.

This procedure has been used in a large number of simulations, considering several constructive types of AC and DC lines, detailed modeled, e. g. , considering frequency dependence of ground parameters. Also, several of most commonly used simulation programs, in time domain, have been used. The line simulation was quite easy, in all cases.

In principle, the modeling with π scheme can be done directly in conductor or phase domain, dealing with hyperbolic functions of matrices.

The equivalent scheme of a line length **L** , in frequency domain, as seen at their terminals, in conductor, phase or mode domain, may be interpreted as a direct linear relation between **n** terminal (transversal) voltages and **n** terminal (longitudinal) currents, in each of both terminals. So, line equations can be treated as a relation between the **2 n** terminal voltages and the **2 n** terminal currents, equivalent to **2 n** linear relations between the **4 n** complexes defining such voltages and currents. There are **2 n** degrees of freedom in the currents and voltages at line terminals. By example, any set of **2 n** of such complexes can be imposed. As a result, the line will define the other **2 n** .

Using this point of view, the line can be defined by means of several matricial formulations, to use in order to have a convenient simulation procedure.

One example of such manipulation is to consider a matrix relating voltages and currents at one terminal with voltages and currents at the other terminal. This formulation allows to consider successive short lengths. Multiplying successively this type of matrices, the linear relation among the **4 n** magnitudes at terminals of a long line are obtained in a very simple and computational efficient way, without the need of using mathematical formulations to obtain directly hyperbolic functions of matrices.

For a "short" line of length $\Delta\mathbf{x}$, the line equations allow to obtain almost immediately the matrix $\mathbf{M}_\Delta$ relating voltages and currents in "points" $\mathbf{x}$ and $\mathbf{x} + \Delta\mathbf{x}$. In a "simplified" way: in principle, from basic line equations

$$-\frac{d\mathbf{U}}{d\mathbf{x}} = \mathbf{Z\,I} \qquad\qquad -\frac{d\mathbf{I}}{d\mathbf{x}} = \mathbf{Y\,U}$$

we obtain

$$\Delta\mathbf{U} = \mathbf{U}_{\mathbf{x}+\Delta\mathbf{x}} - \mathbf{U}_\mathbf{x} = -\,\mathbf{Z}\,\Delta\mathbf{x}\,\mathbf{I}$$

$$\Delta\mathbf{I} = \mathbf{I}_{\mathbf{x}+\Delta\mathbf{x}} - \mathbf{I}_\mathbf{x} = -\,\mathbf{Y}\,\Delta\mathbf{x}\,\mathbf{U}$$

and, so,

$$\mathbf{U}_{\mathbf{x}+\Delta\mathbf{x}} = \mathbf{U}_\mathbf{x} - \mathbf{Z}\,\Delta\mathbf{x}\,\mathbf{I}$$

$$\mathbf{I}_{\mathbf{x}+\Delta\mathbf{x}} = \mathbf{I}_\mathbf{x} - \mathbf{Y}\,\Delta\mathbf{x}\,\mathbf{U}$$

In principle, these relations allow to express the matrix $\zeta_\mathbf{b}$, formed by the complexes defining voltages and currents in terminal **b** , as the product of a transfer matrix $\mathbf{W}_{\Delta\mathbf{x}}$ multiplying the matrix $\zeta_\mathbf{a}$, formed by the complexes defining voltages and currents in terminal **a** :

$$\zeta_\mathbf{b} = \mathbf{W}_{\Delta\mathbf{x}} \cdot \zeta_\mathbf{a}$$

Several numerical details allow a good accuracy with a fast computational procedure. They are not discussed here.

By **p** successive squaring of such matrix, it is obtained the transfer matrix applicable to a line length

$$\mathbf{L} = \Delta\mathbf{x}\ 2^\mathbf{p}$$

By example, the matrix applicable to an 100 km line can be obtained from the transfer matrix applicable to a "line" of 100 km / 1024 , squared 10 times. For the frequency range adequate to model most switching transients, for a "line" of 100 km / 1024 , the hyperbolic functions **tangh** and **sinh** coincide with their arguments, and **cosh** is practically 1, with high numerical accuracy. So, the hyperbolic functions of a line with 100 km, or more, are considered in the numerical results, with a very simple and fast procedure.

Line modeling in p (or s) domain

The basic physical aspects that characterize line behavior are, or can be, related to analytical functions of complex variables. Such functions appear naturally in most physical robust formulations and can be considered an important evidence of the validity or robustness of a physical formulation. It applies, namely, to the following aspects of line formulation that we use:

- Maxwell equations.
- Soil electromagnetic model.
- Carson basic formulation.
- Formulation of parameters related to cables, through Bessel functions.
- Complex distance concept to evaluate effects of ground and conductors in line parameters.

For non linear phenomena, namely in ferromagnetic materials saturation and hysteresis effects, and in corona effects, the straight application of usual forms of manipulation of analytical functions of complex variables is not adequate, at least in a macroscopic point of view. Even for non linear phenomena, some tensorial procedures allow to expand the applicability of the most important aspects of analytical functions of complex variables [38]. This generalization [38,31] is not dealt with in this paper.

Some important aspects of phenomena that can be described in terms of analytical functions of complex variables are related to the following aspects, that are expressed in a simplified form, to give an easier insight in main concepts implied in some computational procedures:

- There is an intrinsic duality time-frequency, in describing, measuring or observing physical phenomena, in time-frequency-space domain, including the behavior of human and animal senses.
- There are basic relations in the value of any physical magnitude expressed in function of time, **t** , in function of frequency, **f** , or $\omega = 2\,\pi\,\mathbf{f}$. The relation between a frequency, $\mathbf{G}(\mathbf{f})$ or $\mathbf{G}(\omega)$, and a time $\mathbf{g}(\mathbf{t})$, description of a physical magnitude, ***g*** , can be expressed, e. g. , by means of the dual Fourier complex transformation, or, in a "compact" way, and with some manipulation and interpretation rules, in terms of a factor $e^{\pm i\omega\mathbf{t}}$.
- The properties in time-frequency domain can also be analyzed in terms of a complex variable **p** (equivalent to an explicit complex form $i\,\omega$), sometimes represented by **p** , others by **s** , and with some variants of definitions and manipulation rules, e. g. associated with Laplace transformation or with Heaviside transformation. In a "compact" way, and with some manipulation and interpretation rules, the relation between **p** and **t** domains can be expressed in terms of a factor $e^{\pm\mathbf{pt}}$.

In **p** domain transfer functions can be expressed, in principle, in function of its zeros and poles. In case of a finite number of zeros and poles [38,59], this fact allows to identify such function by a finite number of complex parameters (e. g. , zeros, poles and a proportionality factor, or poles and corresponding residues), what is more compact than a continuous function of **f** . There are some eventual drawbacks, however, in identifying functions by means of its zeros and poles.

Some functions, by example hyperbolic functions, have an infinite, but numerable, number of zeros and poles.

Some other functions imply in an infinite non numerable number of zeros and poles. This is the case, e. g., of the described soil model, than considers a continuous distribution of relaxation time of soil particles whose effect is the frequency dependence of soil electromagnetic parameters.

Modeling corona effects

When there is corona phenomena, they may affect line behavior in a significative way. The modeling of corona has some peculiar aspects, namely related to its non-linear character, and to the fact that the ionization associated to plasma is not related in a simple way to voltage and current, having some characteristics of hysteresis type.

It is possible to use some properties of linear type phenomena by means of a tensorial formulation [38-39] that, within some eventually acceptable errors, allows to consider some types of interaction among different frequencies and the incremental parameters dependence on “phase” in relation to a reference condition. Also, some type of superposition may be dealt with, using hybrid time-frequency simulation procedures [38-45,23,29-30].

Although with accuracy restrictions, we have obtained reasonable results assuming a simple physical model of corona, in connection to spatial field distribution in time and space in vicinity of line conductors [44]. This simple model satisfies naturally to experimental main behavior of corona according to shape of voltage in vicinity of conductor, and allows to take into account interaction between conductors and phases. Anyhow, the simulation time is relatively high if this model is used in long lines simulation. We expect that, whit a reasonable effort, this type of procedure may be an attractive way to include corona in several studies in which it is important. In present day common practice, corona is typically considered only in special cases.

Grounding modeling procedures

Grounding of line structures is extremely important for lightning line behavior, and, also, for fault consequences and people safety.

The adequate modeling of grounding is extremely important in regions of high lightning intensity, as it occurs in most of Brazil, and of unfavorable ground parameters, as it is also the case of most of Brazil, e. g. compared with “typical” conditions in most European countries and United States and Canada. One of the problems of some used procedures is the fact that they resulted from practice in countries with quite favorable ground parameters and low lightning activity, and, so, the effect of some basic errors or approximations are not “detected” by practical operational results.

Among the errors we have found in concrete cases, and that have originated important consequences, we mention the following ones:

- To ignore the effect of foundations in grounding parameters. The foundations of mechanical structures and stays have an important influence in grounding line behavior and must be considered, with adequate precision, in analysis of line grounding.

- To ignore frequency dependence of ground electric parameters. It is essential to consider frequency dependence of soil parameters to simulate grounding behavior for lightning effects. In several cases in which computed and measured results have been compared, important differences have been found. Frequently, such differences are attributed to soil ionization, that is important only for high current values in ground. The main reason of discrepancies, at least in cases we have examined, was the fact that frequency dependence of ground parameters had not been taken into account in computational simulation.

- To use computational models used for power frequency, inadequate for fast phenomena, such as lightning.

- To treat grounding of several structures considering average parameters, not taking into account the dispersion of ground parameters and its effect, of statistical type, in grounding of line structures, e. g. , in what concerns line behavior in consequence of lightning.

There are methods that allow an adequate modeling of the grounding system of transmission lines [1-2]. However, they are not generally applied in common engineering practice.

Line modeling for lightning phenomena

Line modeling for lightning phenomena involves some specific aspects, that we comment briefly.

A first group of problems is related to the need of adequate estimation of statistical distribution of lightning parameters including statistical distribution of incidence point, amplitude and time front, related to:

- Lightning impulses striking the structures and guys, phase conductors and shield wires.

- Lightning impulses striking the ground, near the line, and originating induced overvoltages.

For this group of problems, important methodological requirements are related to an adequate model of lightning incidence, by example by means of electrogeometric model, with conveniently selected parameters [7-8,39], and an adequate modeling of line location considering important orography aspects.

In regions of low lightning intensity, high conductivity of soil and strongly meshed networks, with relatively short lines, lightning is not a difficult problem to deal with. This situation as lead to the use of very simplified assumptions, eventually wrong, but whose effects are not detected or do not deserve much attention. Unfortunately, some widely used procedures have resulted of this type of assumptions. In cases, as it occurs in most of Brazil, with high lightning intensity, low conductivity of soil and not strongly meshed networks, with long lines, lightning is a difficult and very important problem to deal with. In some cases, the use of “international” practices has lead to wrong results, with severe practical consequences. By example, some simplifying assumptions of some methods and programs developed within some international organizations have lead to order of magnitude errors in the number of faults originated by lightning.

A second group of problems relates to line modeling, for lightning phenomena. This aspect imposes to model several spans, considering explicitly the shielding wires, the applicable spans length, and the variation along the span of distance among phases and shielding wires, and, eventually, details of towers or structures, insulators and "accessories" affecting electromagnetic field distribution. It may be important, also, to model corona effects, and eventually, to take into account variation of relevant parameters along a span. With some adequate precautions, it is possible, in several types of application studies, to avoid the need of a systematic simulation procedure including corona. Also, it may be convenient to take advantage of the fact that several relevant lightning effects are related to front of wave phenomena, with time domain of the order of 10^0 to 10^1 µs , and frequency spectrum of the order of 10^5 to 10^6 Hz . Within these ranges, an almost assimptotic approach for evaluation of line parameters is adequate.

A third group of problems is related to modeling requirements for structures, towers and stays, in connection to currents between shielding wires and ground. Some frequently used models were obtained by analogy with line behavior, for propagation along the line. In several of such models, however, such analogy is applied not respecting the basic conditions applicable to lines that justify the validity of such models. So, several of commonly used models are not valid.

A fourth group of problems is related to modeling of the effects of a lightning strike in the ground, near the line. Some of used models are affected by a mistake in used Maxwell equations, including applied fields. Such mistake leads to wrong results.

A fifth group of problems is related to adequate modeling of structures or towers grounding systems. This question has been commented above.

Basic constraints of modeling procedures

Within the diversity of modeling procedures and application problems, there is not a single method with important advantages for all application problems. An adequate choice must be done, according dominant aspects.

The most used programs for modeling transient phenomena are based in direct time simulation procedures, and, so, an important amount of algorithms try to concentrate in time domain.

In many aspects, frequency domain and **p** domain have important advantages that, in authors' opinion, have not been exploited fully. It appears justified an important effort in frequency domain, **p** domain in and hybrid procedures, to allow a more adequate optimization of methods. For some aspects, time domain procedures have relevant advantages that justify their use, inclusive in hybrid methods using frequency domain, **p** domain and time domain analysis.

APPENDIX 2 - MODULUS OF IMMITTANCE W IN EXAMPLES a , b , c OF ITEM 3. , IN FUNCTION OF FREQUENCY

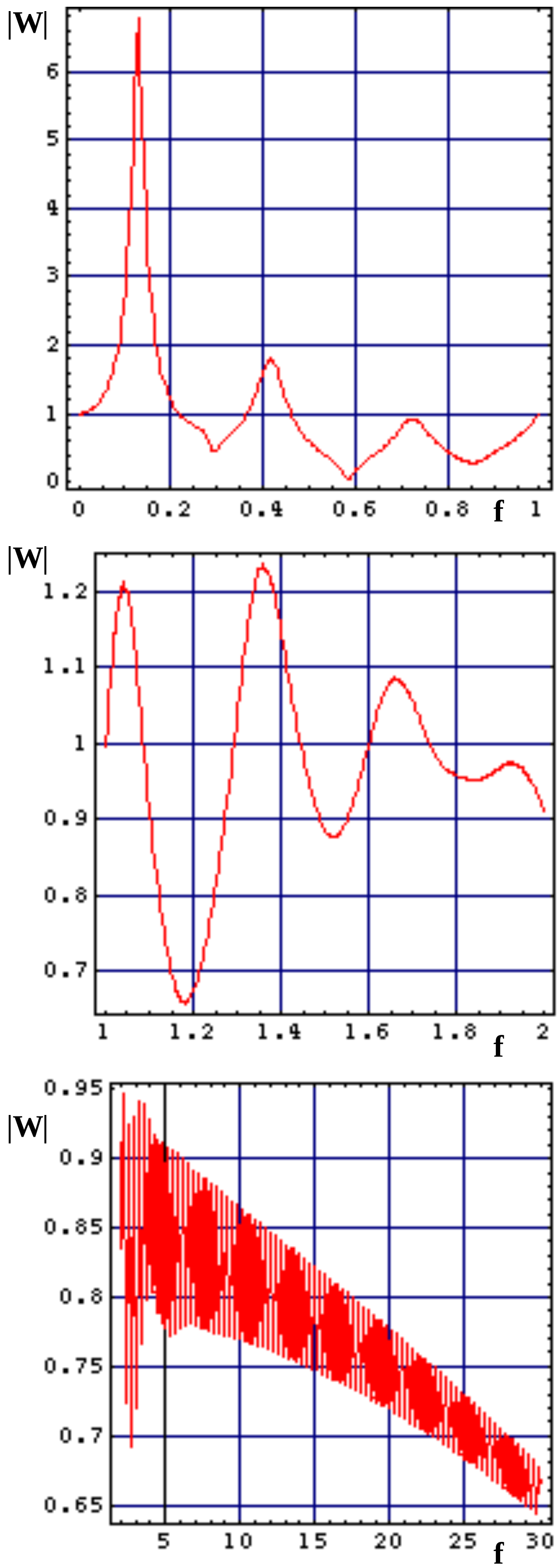


Fig. 38 - Example **a** . Line "ideally" transposed. In abscissa it is indicated the frequency, **f** , in kHz. The graphics represent the modulus, |**W**| , of $\mathbf{W} = \mathbf{U}_{bk} / \mathbf{U}_{ak}$, in function of **f** .

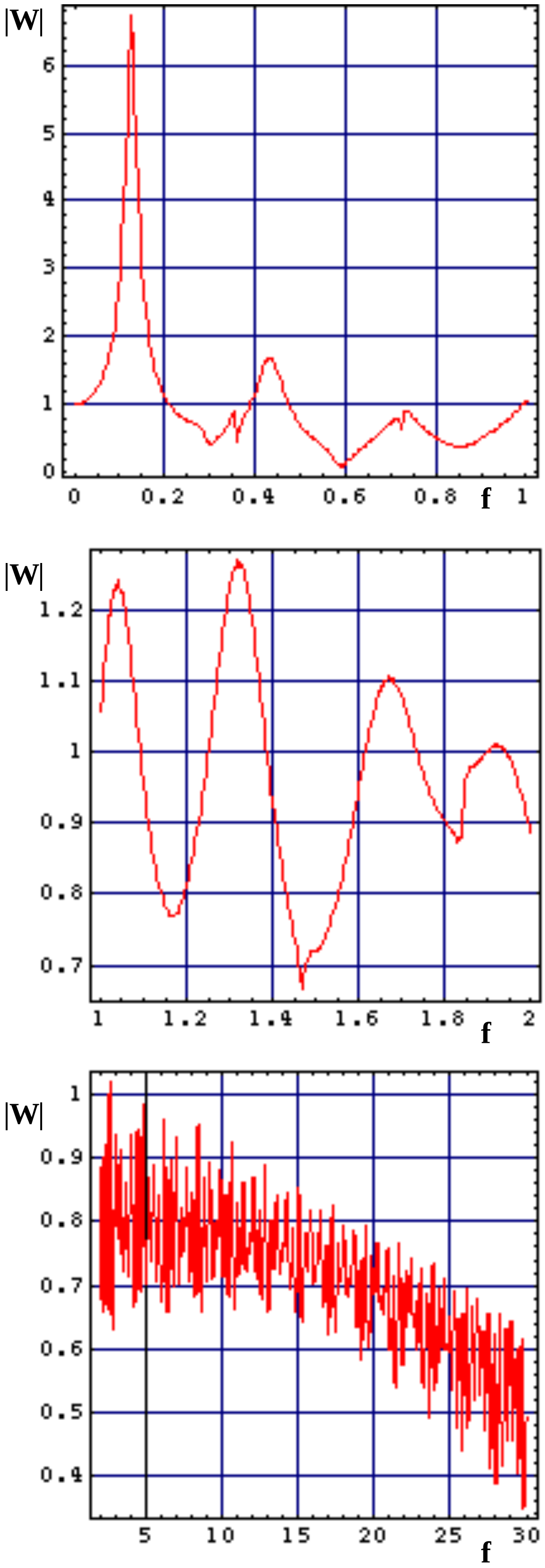


Fig. 39 - Example **b** . Line transposed as indicated in Fig. 7 . Switching on of phase 1. In abscissa it is indicated the frequency, **f** , in kHz. The graphics represent the modulus, |**W**| , of $\mathbf{W} = \mathbf{U}_{bk} / \mathbf{U}_{ak}$, in function of **f** .

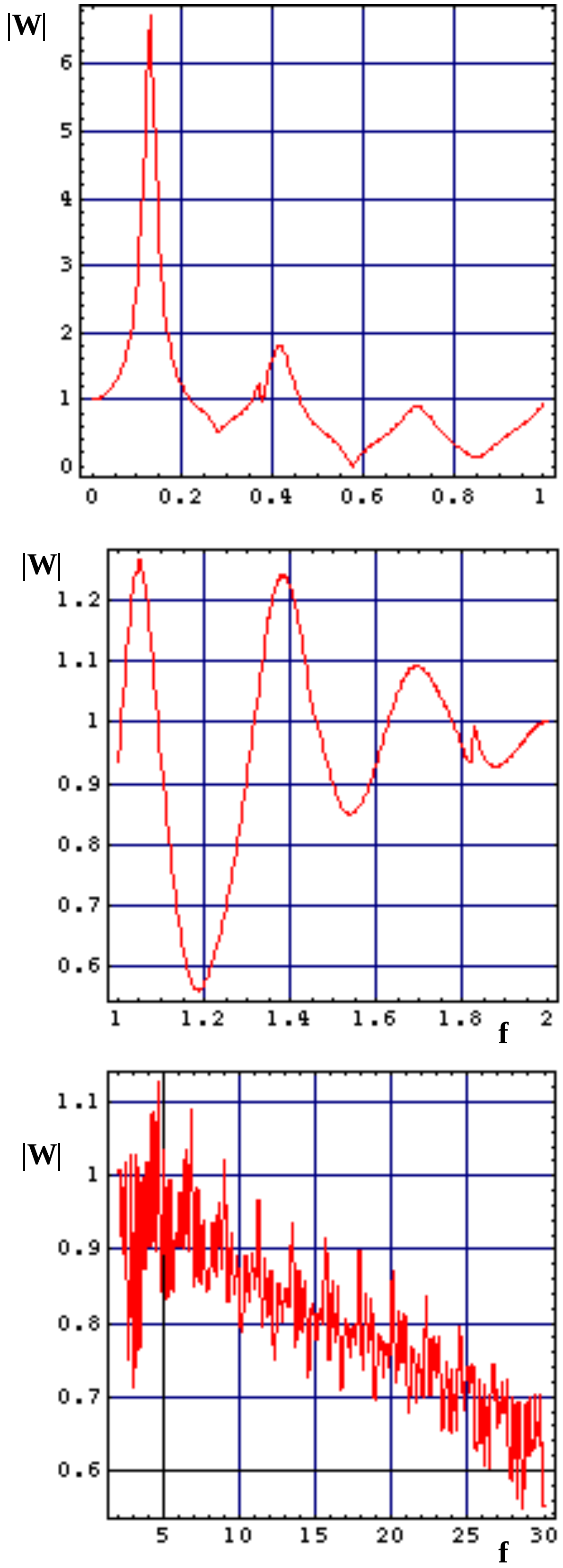


Fig. 40 - Example **b** . Line transposed as indicated in Fig. 7 . Switching on of phase 2. In abscissa it is indicated the frequency, **f** , in kHz. The graphics represent the modulus, |**W**| , of $\mathbf{W} = \mathbf{U}_{bk} / \mathbf{U}_{ak}$, in function of **f** .

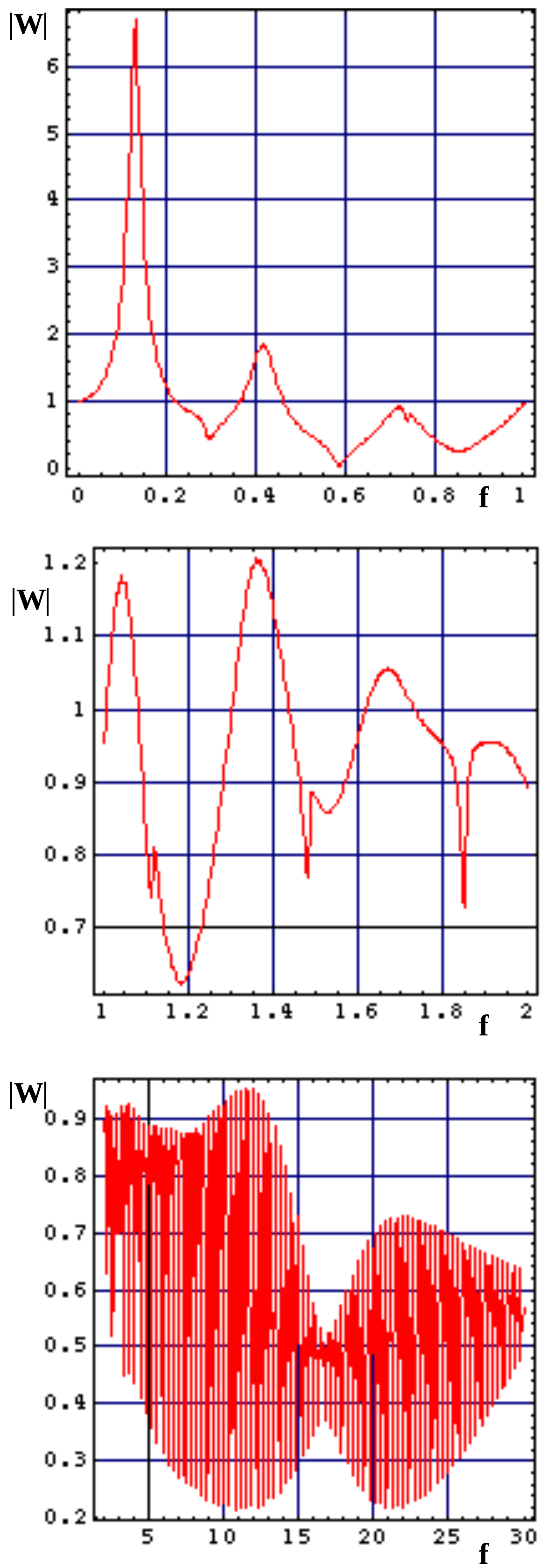


Fig. 41 - Example **c** . Line non transposed as indicated in Fig. 8 . Switching on of phase 1. In abscissa it is indicated the frequency, **f** , in kHz. The graphics represent the modulus, |**W**| , of $\mathbf{W} = \mathbf{U}_{bk} / \mathbf{U}_{ak}$, in function of **f** .

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