COMPUTATIONAL ROUTINE FOR DYNAMIC ANALYSIS OF TRANSMISSION LINE STRUCTURES

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Abstract. *In the design of transmission line (TL) structures usually a static analysis is used. Dynamics actions, as wind or cable rupture, are considered through 'equivalent static actions'. However, it is known that a dynamic analysis is necessary to obtain an accurate response of efforts and displacements that occur in the structures of TL subjected to variable actions in time. Commercial programs specifically developed for design of TL structures do not carry out any type of dynamic analysis. Within this context, the present paper deals with the development of a computational routine for: (a) automatic generation of the input data of a TL segment, (b) dynamic analysis of the TL segment subjected to dynamic actions, using direct integration method of the equations of motion, through explicit form by central finite differences, and (c) visualization of results through animations of nodal displacements, besides it making available efforts and displacements along the time of analysis. It can be affirmed that the developed routine is very efficient and of easy handling. A tool capable to generate and analyze a whole segment of a TL, including all their components, subjected to dynamic actions is very useful. Therefore, it could become an excellent tool for designers interested in dynamic response of transmission line structures, in order to verify the design obtained with a conventional static analysis, mainly when new types of towers and disposition of cables are proposed.*

Keywords*: Computational Routine, Dynamic Analysis, Central Finite Differences, Transmission Line Structures, Metallic Towers, EPS Wind.*

1. INTRODUCTION

Usual procedures for analysis and design of transmission line (TL) metallic structures of electric power are presented in Brazilian codes NBR 5422 (1985) and NBR 8842 (1985), in American codes ASCE Standard 10 97 (2000), in the international recommendations of IEC 60826 (2003) and in the technical literature, (e.g., Labegalini *et al.*, 2005). Static analysis is used in all of these cases, *i.e.*, dynamic actions, such as wind and cable rupture, are considered through 'equivalent static actions'. However, it is known that in order to obtain more accurate values of efforts and displacements that occur in these structures, when subjected to the dynamic actions, an analysis that supplies such results along the time (dynamic analysis) is indispensable.

Within such context, a computer program to carry out a dynamic analysis in TL structures, in a simplified way, becomes necessary. The Central Finite Differences method, an explicit numerical integration method of the equations of motion, which presents a formulation relatively simple, can be used to obtain the response along the time in the bars of the towers, in the elements of the cables and insulators of a TL, allowing to deal with physical and geometrical non-linearities with relative easiness, besides the advantage of not requesting the assembly of the stiffness global matrix, since the integration is carried out at element level (Menezes *et al.*, 1998).

In this paper computational routines to generate automatically the input data of a TL segment, including towers, cables and insulators, to analyze the structure subjected to dynamic actions, using the central finite differences method, and finally to visualize the results (efforts and displacements) in selected elements of the towers, cables and insulators along the time are developed.

2. OBJECTIVE, JUSTIFICATION AND METHODOLOGY

The main objective of this paper consists of developing a computational routine in FORTRAN language for:

- Automatic generation of the input data of a TL segment, including towers, cables and insulators, in which the user just informs the tower topology, the conductor cable and shield wire type, the insulator string length, the spans and unevenness between towers and the mechanical parameters of the materials, so that the program can generate all the input data of the TL segment in study;
- Analysis of the structure subjected to dynamic actions, such as wind and cable rupture, using the central finite differences method;

- Visualization of the results, *i.e.*, the efforts in selected elements of the towers and cables and displacements in the top of the towers along the time of analysis, besides animations of displacements of all nodes and bars of the TL segment.

Commercial programs specifically developed for design of TL structures, such as iTowers Designer (2007) and PLS Tower (2000), do not carry out any type of dynamic analysis. Thus, a tool capable to generate and analyze a TL segment, including all their components, subjected to dynamic actions, should have a significant importance in verification of design results obtained with a conventional static analysis, mainly when new types of towers and cable dispositions are proposed.

The paper was developed in three stages:

- In the first stage, denominated pre-processing, routines in FORTRAN language to generate automatically the input data of a complete TL segment, including towers, cables and insulators, with discretizations previously defined by the user were programmed.
- These data serve as input data for the dynamic analysis of the structure in the routine developed in FORTRAN, using the central finite differences method. This second stage is denominated processing.
- In the final stage, denominated post-processing, output files are generated, which will be used for visualization of the results, with animations of the displacements of the TL components along the time of analysis. For that, specific post-processing software denominated TECPLOT is used.

3. CENTRAL FINITE DIFFERENCES METHOD

The dynamic response is obtained by direct explicit numerical integration of the equations of motion in the time domain, using the finite central differences scheme, because it does not require assembling or updating the system global stiffness matrix. Integration is accomplished at element level, which constitutes an advantage in non-linear problems. When the system mass and damping matrices **M** and **C** are both diagonal, the method becomes explicit and the expression in central finite differences for the displacement at any node in either the x, y or z direction, at time t + Δt, may be written as:

$$q(t+\Delta t) = \frac{1}{1+c_m \Delta t/2}\left[\frac{f(t)\,\Delta t^2}{m} + 2\,q(t) - (1 - c_m \Delta t/2)\,q(t-\Delta t)\right] \tag{1}$$

in which q denotes the nodal coordinate in either the x, y or z direction, f(t) the resultant nodal force component in the corresponding direction at the time t, $c_m = c/m$ is a constant, m the nodal mass and c the nodal damping coefficient, proportional to mass m. The resultant nodal force f(t) consists of the gravitational forces (dead weight and external nodal forces), and axial forces in the truss elements. It is important to quote that geometrical non-linearity is always considered, since the nodal coordinates are updated after each integration step Δt.

Convergence and accuracy of the solution depend basically on the integration time interval Δt. Since the method is only conditionally stable (Bathe, 1996), it is necessary that $\Delta t \leq \Delta t_{crit}$. For latticed structures, the critical time interval Δt_{crit} can be estimated by (Groehs, 2005):

$$\Delta t \leq \Delta t_{crit} = \frac{L_{min\ (0)}}{\sqrt{E/\rho}} \tag{2}$$

in which $L_{min(0)}$ is the initial length (in t = 0) of the smallest truss element, E is the Young's modulus and ρ is the material mass density. More details about this numerical integration method, applied to dynamic analyses of TL towers and cables, can be found in Miguel *et al.* (2005), Kaminski *et al.* (2005) and Kaminski (2007).

4. APPLICATION EXAMPLE

The application example was elaborated with a TL segment formed by four towers and five 400m spans, without unevenness among the towers (Figure 1). The system is subjected to the wind action. For that, the structure characteristics were supplied, such as: nodal coordinates, connectivities, geometrical properties of the towers, cables and insulators and mechanical properties of the materials. The characteristics of the wind (imposed action) should also be prescribed so that the numerical results can be obtained with the use of the developed FORTRAN program.

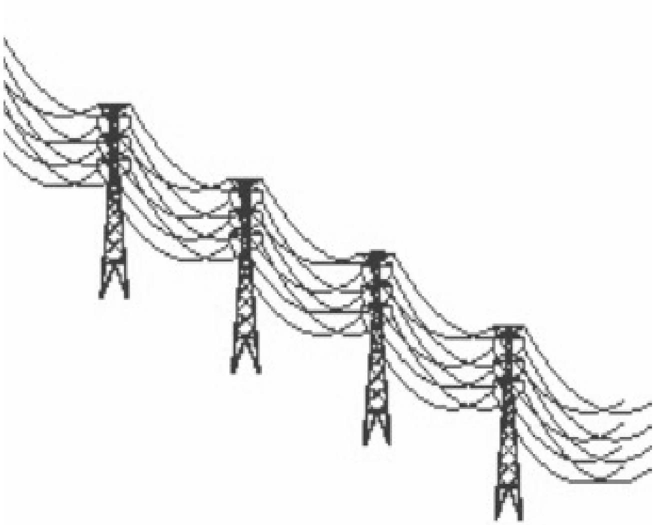

Figure 1. TL segment with four towers and five spans.

4.1. Description of the towers and insulator strings

Transmission line segments consisting of towers known as SY, insulator strings, conductor cables and shield wires were analyzed in the present study. The SY tower is a self-supporting suspension tower, for 138kV double circuit, 33.4 meters high and 5.0 meters at the base (Figure 2). The tower is composed by eight different L sections and it was modeled with 174 nodes and 415 bars. The insulator strings are 1.65 meters high and each one of them was modeled with a single element.

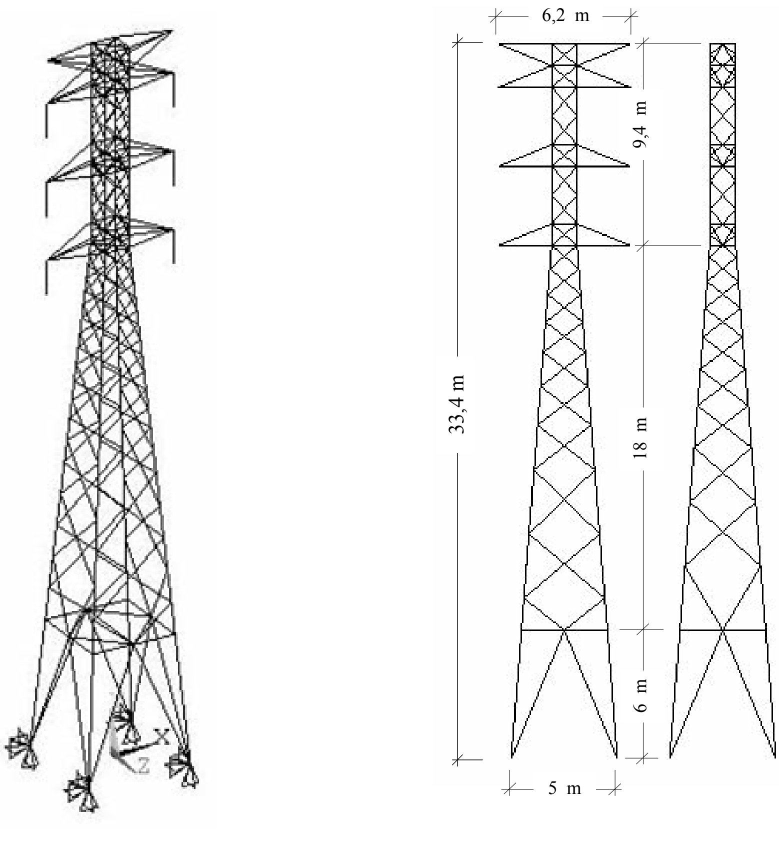

Figure 2. Layout of the SY tower.

4.2. Description of the conductor cables and shield wires

The conductor cables are made of aluminum with steel core (Aluminum Conductor Steel Reinforced - ACSR) and the shield wires are type Extra High Strength (EHS) steel cables. The cables are formed by the association of threads, able to carry only tension forces.

The conductor cables (CC) and shield wires (SW) present the following constitutive laws:

$$F_{CC} = 10^7 A_{CC} (16.3254\, \varepsilon_{CC}^4 - 6.1854\, \varepsilon_{CC}^3 - 44.6718\, \varepsilon_{CC}^2 + 68.5004\, \varepsilon_{CC} - 0.625) \quad (3)$$

$$F_{SW} = 10^7 A_{SW} (234.339\, \varepsilon_{SW}^4 - 441.98\, \varepsilon_{SW}^3 + 196.734\, \varepsilon_{SW}^2 + 128.332\, \varepsilon_{SW} + 1.123) \quad (4)$$

in which A_{CC} denotes the total area of the conductor cable (aluminum + steel), equal to 3.75×10^{-4}m^2; F_{CC} the tensile force (N); and ε_{CC} the elongation of the cable expressed in percent of the cable unstressed length ($L_{0\,CC}$). In connection with shield wires: A_{SW} represents the area, equal to 5.11×10^{-5}m^2; F_{SW} the tension force (N); and ε_{SW} the elongation expressed in percent of the shield wire element unstressed length ($L_{0\,SW}$).

Suspended cables in transmission lines present the form of a cathenary. In the condition EDS (Every Day Stress) the conductor cables are designed for a tension around 20% of its capacity (UTS - Ultimate Tension Stress), and the shield wires around 14% of UTS.

When the suspension points of the cable has the same height, the cathenary is symmetrical in relation to the center of the span (central axis), where the vertex is located, which is the point where the maximum sag occur. In the case of supports with different heights, the cathenary is not symmetrical and the maximum sag f_e does not occur in the center of the span, as shown in Figure 3. The sag depends on the span length, on the temperature and on the applied tension in the cable when this is fastened in the supports.

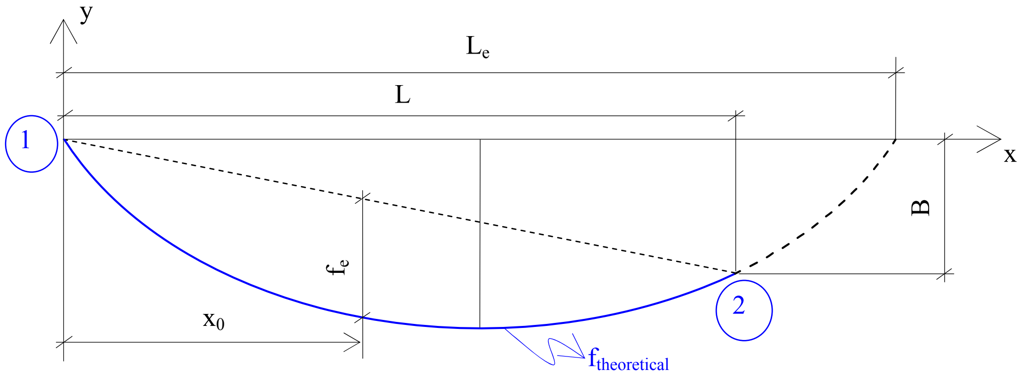

Figure 3. Suspended cable between the supports “1” and “2” with different heights (B ≠ 0).

In the beginning of the analysis (initial condition, t = 0s) the cable should be in a position such that, after the application of the weight force, this is subjected to the design tension force, equivalent to a percentile of the rupture force in the tension of the cable, with the theoretical cathenary ($f_{theoretical}$) and the maximum sag (f_e). The formulation used to determine the theoretical cathenary, the maximum sag, the position of the maximum sag (x_0) and the theoretical length of the cables is presented in Kaminski (2007). Additional details can be found in Irvine and Caughey (1974).

Figure 4 shows the positions of the conductor cable ACSR in the initial condition (before the application of the weight force) and theoretical (after the application of the weight force), for a L = 400m span and without unevenness between the supports (B = 0m), obtained applying the referred formulation.

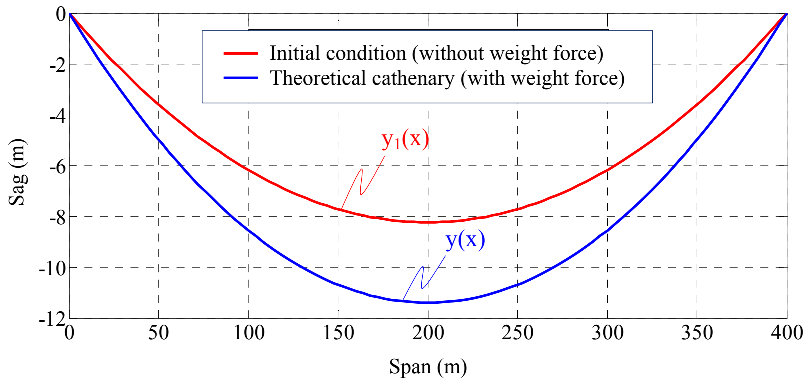

Figure 4. Positions of the conductor cable ACSR in the initial and theoretical condition.

The constitutive equation of cables composed by more than one material is obtained through a combination of the stress-strain curves of each one of the materials. In the case of conductor cables ACSR, whose external material is the aluminum and the internal (soul) is the steel, the stress-strain curve is obtained by the sum of the aluminum curve, multiplied by the area of the cross section of aluminum A_{al}, with the steel curve, multiplied by the area of the cross section of steel A_a. This equation can be normalized dividing by the total area of the cross section of the cable A_t, as shown in equation below:

$$\sigma = \sigma_{al}\left(\frac{A_{al}}{A_t}\right) + \sigma_a\left(\frac{A_a}{A_t}\right) \tag{5}$$

In which:

$$A_t = A_{al} + A_a \tag{6}$$

$$\sigma_{al}\left(\frac{A_{al}}{A_t}\right) = a_4\,\varepsilon^4 + a_3\,\varepsilon^3 + a_2\,\varepsilon^2 + a_1\,\varepsilon + a_0 \tag{7}$$

$$\sigma_a\left(\frac{A_a}{A_t}\right) = b_4\,\varepsilon^4 + b_3\,\varepsilon^3 + b_2\,\varepsilon^2 + b_1\,\varepsilon + b_0 \tag{8}$$

In which: ε is the strain in %.

The properties of the conductor cable ACSR used in the application example are presented in Table 1.

Table 1. Properties of the conductor cable ACSR.

External diameter	25.146 mm
Area of the cross section (aluminum + steel)	374.709 mm^2
Ultimate tension force	11209.5 daN
Weight by meter	1.27726 daN/m
Young's modulus	74.515 $daN/mm^2/100$

The coefficients of the non-linear constitutive equations (polynomial of 4th degree) of the conductor cable and of the aluminum and steel materials are given in Table 2. While the properties of the shield wire, type EHS, can be found in Kaminski (2007).

Table 2. Coefficients of the constitutive equations of the conductor cable and of the materials aluminum and steel.

	Coefficients of the polynomial of 4th degree				
	a_4	**a_3**	**a_2**	**a_1**	**a_0**
Aluminum	11.5156	4.52157	-41.635	40.5326	-0.6087
Steel	4.80977	-10.707	-3.0368	27.9678	-0.0163
Combined	16.32537	-6.18543	-44.6718	68.5004	-0.625

4.3. Description of the EPS wind load

It is admitted that EPS winds can be described by a 3D stationary and homogeneous turbulent flow, characterized by mean wind velocity with constant orientation throughout the region of interest. The vertical profile of the mean wind velocity is also assumed invariant with the horizontal coordinates. Thus, the wind field is defined by a reference velocity at the standard 10m height, by the vertical profile and by the spectra of the two horizontal and the vertical fluctuating velocity components, which are assumed independent random processes. Samples of the wind velocity field are generated at pre-selected points forming a 3D grid within the volume of interest. The spacing of the points in the along-wind, transversal and vertical directions must be set equal to the corresponding correlation lengths of the fluctuating velocity components. Components of the fluctuating wind velocity vector elsewhere are then determined by the interpolation procedure proposed by Riera and Ambrosini (1992) for analyzing 1D structures, extended herein to two or three-dimensional fields. For wind normal to the TL, the largest dimensions of system in the along-wind direction, typically less than 10m, are negligible in relation to the corresponding correlation length, which largely exceeds 100m. Thus, only the fluctuating wind components in the two-dimensional field defined by the TL plane of symmetry must be simulated. More details can be found in Miguel *et al.* (2007).

4.4. Results

The dynamic response of TL segments consisting of four towers, considering also insulator strings, conductor cables and shield wires, as well as the exterior adjacent spans (Figure 1), is numerically determined. The TL segment is subjected to EPS winds characterized by a mean 10min velocity at 10m height equal to 21.6m/s, surface roughness corresponding to IEC 60826 (2003) terrain type B.

The stationary load *vs.* time graphs for selected bars of the analyzed towers and cables are shown, for illustration purposes, in Figures 5 to 8. The transient segments at the beginning of the records were disregarded.

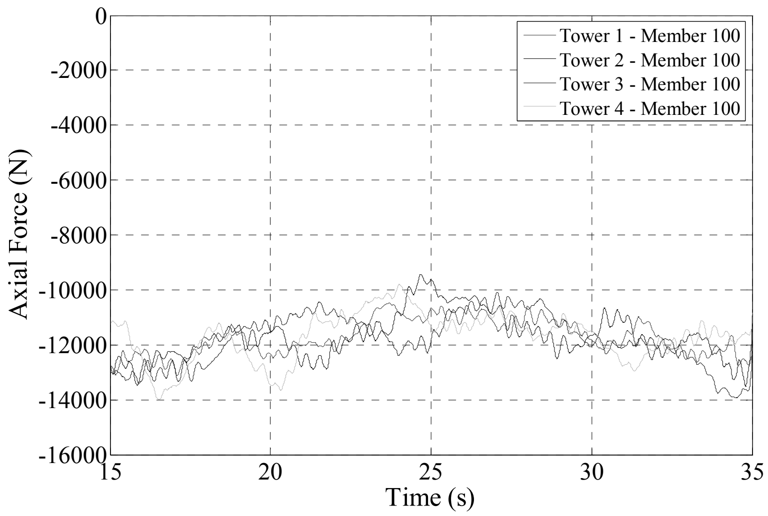

Figure 5. Axial force in same main member of four adjacent towers (20s samples in EPS event).

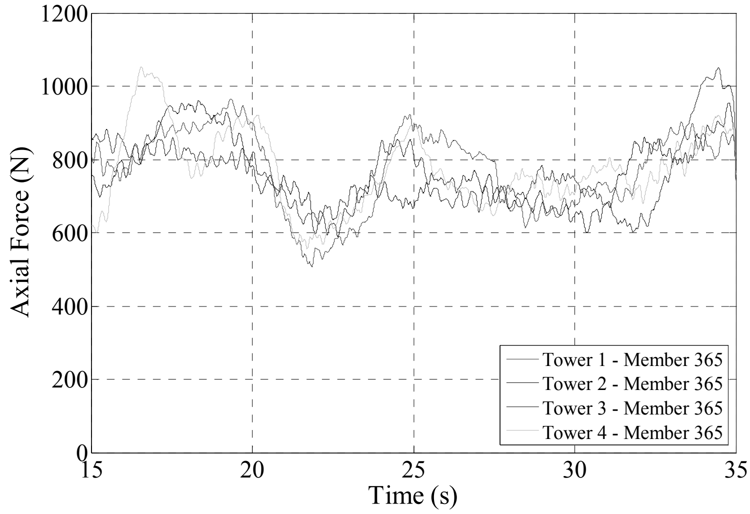

Figure 6. Axial force in same diagonal member of four adjacent towers (20s samples in EPS event).

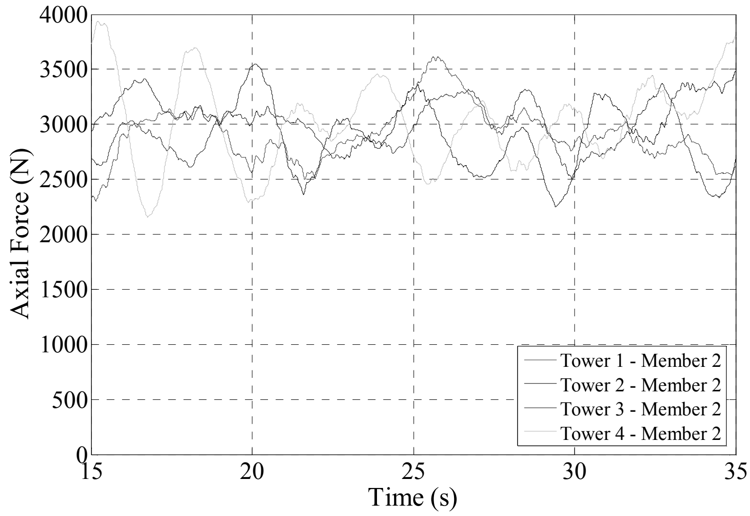

Figure 7. Axial force in same secondary member of four adjacent towers (20s samples in EPS event).

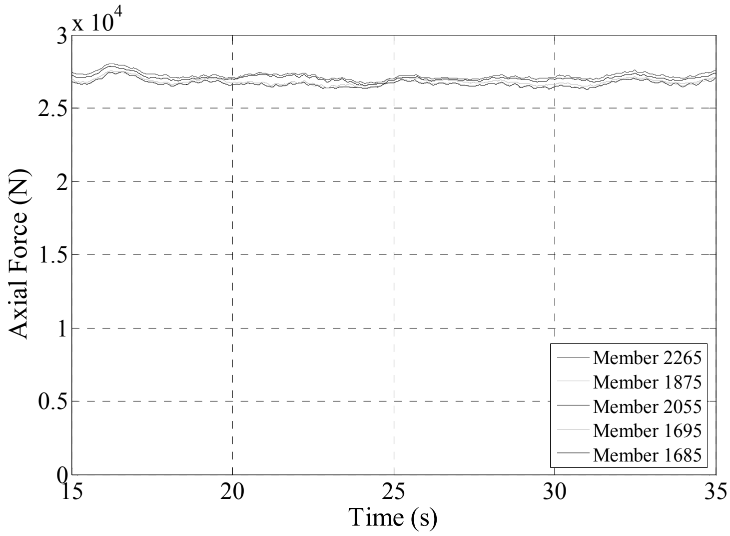

Figure 8. Axial force at five different locations of conductor cable (20s samples in EPS event).

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5. CONCLUSIONS

The present paper presented a computational routine developed in FORTRAN language capable to generate and analyze a complete TL segment, including all their components, subjected to dynamic actions.

It can be affirmed that the routine was shown very efficient and of easy handling. So, it could become an excellent tool for designers interested in dynamic response of TL structures, in order to verify the design obtained with a conventional static analysis, mainly when new types of towers and disposition of cables are proposed.

6. ACKNOWLEDGEMENTS

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