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SENSITIVITY OF WIND INDUCED DYNAMIC RESPONSE OF A TRANSMISSION LINE TO VARIATIONS IN WIND SPEED

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ABSTRACT

This paper studies the dynamic behavior of a multi-span transmission line system under synoptic wind considering various speeds to determine the range of wind speeds in which the system experiences resonance. A finite element numerical model was developed for the purpose of this study. This model is employed to assess the dynamic behavior of a self-supported lattice tower line under various wind speeds. Dynamic Amplification Factor (DAF), defined as the ratio between the peak total response to the peak quasi-static response, is evaluated. It is found that conductors' responses exhibit large DAF compared to the towers especially at low wind speeds ($v \leq 25$ m/s). This results from the low natural frequency of the conductors (0.19 Hz) which is close to the wind load frequency while the natural frequency of the tower is equal to 2.36 Hz. In addition, the conductors' aerodynamic damping decreases with the decrease of wind speed which leads to higher dynamic effect while the tower's aerodynamic damping plays a minor role. The results of the dynamic analysis conducted in this study are also used to compare the gust response factors (GF_T), defined as the ratio between peak total response to the mean response, to those obtained from the ASCE code ($GF_{T\text{-}ASCE}$). It has been noticed that the gust response factors obtained from the ASCE code lead to conservative peak responses for both towers and conductors of the chosen line.

Keywords: Transmission lines; synoptic wind; dynamic analysis; quasi-static analysis; self-supported towers

1. INTRODUCTION

Previous studies performed on the dynamic response of transmission line (TL) systems (Davenport 1962, Momomura et al. 1997, Loredo-Souza and Davenport 1998, Holmes 2008, Lin et al. 2012, Aboshosha et al. 2016) showed that the natural frequencies of typical transmission line towers are usually higher than the frequencies that correspond to the maximum turbulence energy. The towers' natural frequency is usually higher than 1 Hz. This leads to negligible resonant tower responses. The studies have also shown that the tower conductors and the turbulent winds might have close frequencies, however the resonant effect is almost also negligible due to the effect of high aerodynamic damping resulting from the conductors' behavior. This holds true under high speed winds, however for low wind speeds the aerodynamic damping decreases and thus resonant effects can possibly occur. This topic needs further investigations as current codes and standards fail to account for resonance in the design of TL systems. Accordingly, the current paper focuses on the following objectives:

1- Developing a numerical model portraying a multi-span transmission line system to study its dynamic behavior.
2- Conducting dynamic analysis on a self-supported steel lattice tower transmission line system considering various synoptic wind speeds to be able to determine the range of velocities at which resonance occurs.

This paper is divided into five sections. In section 1, introduction and main objectives of the study are outlined. In section 2, a brief description of the transmission line system considered in the study is provided. A detailed description of the finite element model of the TL is described in section 3. In section 4, the results of the dynamic analysis of the considered transmission line system are shown and interpreted. Finally the main conclusions drawn from the study are presented in section 5.

2. CONSIDERED TL SYSTEM

In this study, a transmission line system consisting of self-supported steel lattice towers is considered. Figure 1 shows the dimensions and geometry of the self-supported tower under consideration. Table 1 also shows in further details the dimensions of the tower as well as the conductor properties.

Table 1: Tower and Conductor Properties

	Tower Properties				Conductor Properties					
System	H (m)	W* (m)	E (GPa)	Freq.** (Hz)	L (m)	S (m)	w (N/m)	v (m)	A_p (m^2)	Freq.** (Hz)
Self-supported lattice	52	13	200	2.36	299	8.5	11.6	3.2	0.042	0.19

* The reported width is the width of the cross arms.

** The frequencies are evaluated at wind speed V = 25 m/s.

As shown in Table 1, The total height of the tower H = 52 m, while the tower width W = 13 m, E is the elasticity modulus, and the L is the span length, S is the sag length, w is the conductor weight, v is the insulator length, A_p is the projected area of the conductor.

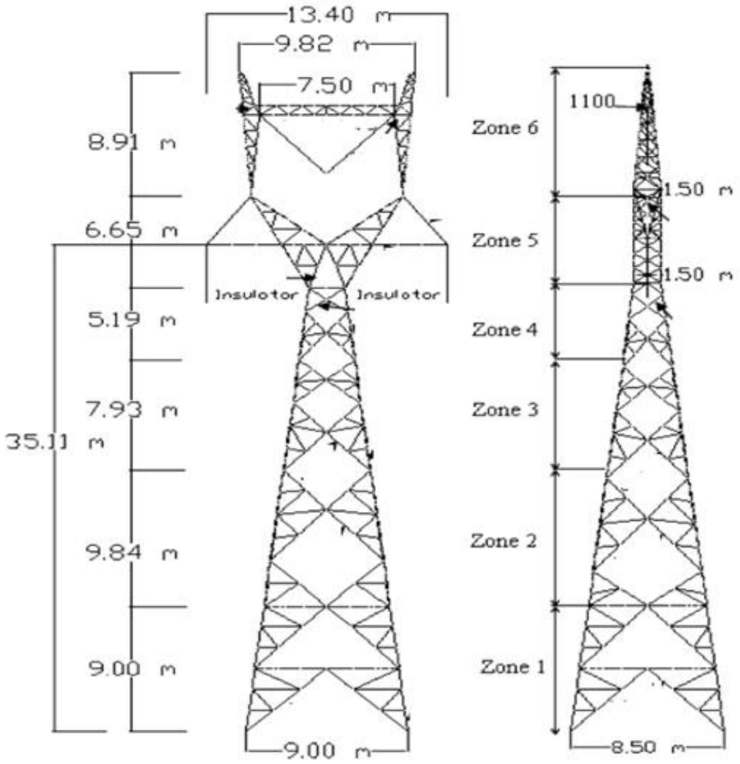


Figure 1: Self-supported Steel lattice tower dimensions

3. NUMERICAL MODEL

3.1 Wind Field

Synoptic winds can be defined by two different velocity components; mean and fluctuating wind components. In this study, a technique proposed by Chen and Letchford (2004 a, b) and Chay *et al.* (2006) was implemented to numerically generate the fluctuating wind velocities component of the wind field. The Power Spectrum Density (PSD) proposed by von Karman (1948) which defines the energy of the wind fluctuations in a frequency domain is utilized to generate the turbulent wind speeds. Using the relationship between the turbulent length scale L_u and turbulent length scale of the longitudinal fluctuations along the transverse direction L_{uv} ($L_u = L_{uv}/3$), a value for L_u was obtained. According to the ASCE 74 (2010), the value for L_{uv} was taken as 67 m considering an open terrain exposure. Based on the coherency decay function (Davenport 1979, 1980), correlations between the fluctuating components were presented and a coherency decay constant value of 10 was used. Using an aerodynamic roughness $z_0 = 0.03$ m, the mean velocity turbulence intensity profiles were acquired from the ESDU (2001, 2002). Figures 2 and 3 show two samples of the fluctuating velocity versus time at heights 14 m and 30 m, respectively. Fluctuating velocities are generated numerically for a number of 6 zones along the tower heights (shown in Figure 1) and 5 locations along each conductor span.

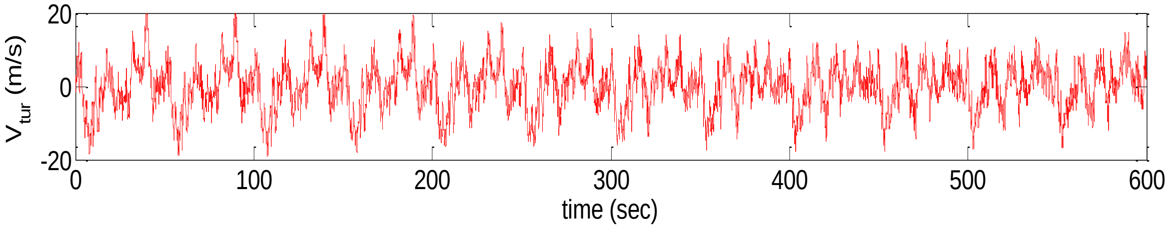


Figure 1: Turbulence Velocity Variation at 14 m height

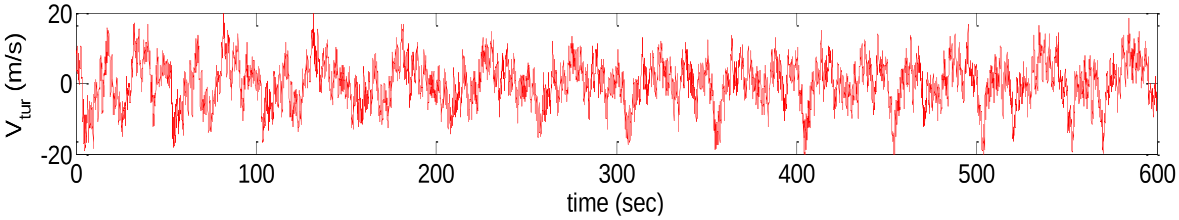


Figure 2: Turbulence Velocity Variation at 30 m height

3.2 Finite Element Analysis

In order to accurately predict the dynamic response of the TL system under synoptic wind considering the non-linear behaviour which is mainly because of the conductors, a comprehensive finite element model is developed using the commercial program SAP2000. In this model, as shown in Figure 4, all TL components are modelled where 3D frame elements are used to model the tower members, while the conductors are modelled using non-linear cable element. To accurately depict the response of the insulators, the moment resisting connection between the tower nodes and the insulators is released.

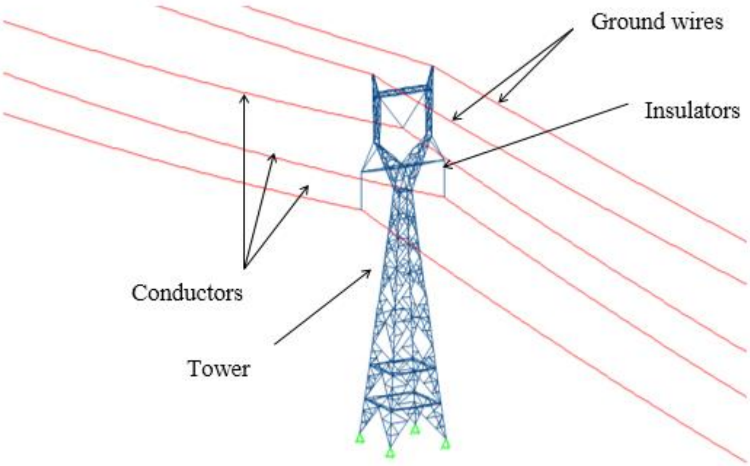
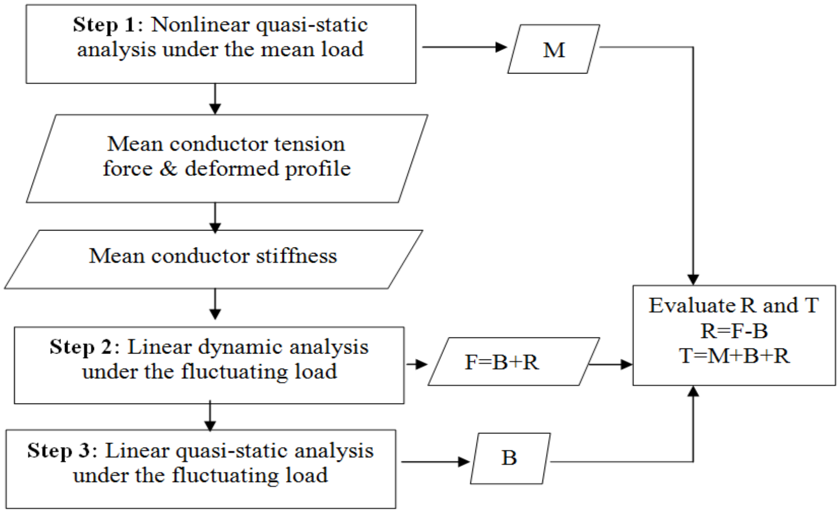


Figure 4: Finite Element Model of the transmission Line System

In order to accurately simulate the forces acting on the TL system due to fluctuating synoptic wind, non-linear dynamic analysis under instantaneous wind load can be used where the wind load includes both mean and fluctuating wind components. Despite the major usage of this method, it is impractical and time consuming. As such, a different approach suggested by Sparling and Wegner (2007) using two steps is implemented, where the time required to analyze the response is reduced significantly while maintaining the high accuracy of the results. The first step in this approach involves studying the mean response of the transmission line system by performing non-linear analysis when the system is subjected to mean wind loading. The second step of the method involves finding the fluctuating response of the system under fluctuating load using linear analysis. The use of linear analysis is acceptable in this case considering the small ratio between the mean and the fluctuating components. Further steps can be performed in order to identify the subcomponents of the fluctuating load; the background component and the resonant component. Finding the background component involves evaluating the system quasi-statically when subjected to fluctuating winds. Since the total fluctuating component is a resultant of the background and the resonant components, the resonance can be obtained by subtracting the background response from the total fluctuating response. A flow chart summarizing the main steps conducted in this approach is presented in Figure 5, as shown below.



M: mean response; F: fluctuating response; B: background component; R: resonant response; T: total response

Figure 5: Steps of the Method for Analyzing the System's Response (Aboshosha and El Damatty 2015)

4. RESULTS OF DYNAMIC RESPONSE

The method described above was implemented in the finite element model described earlier where the following results were obtained. It is worth mentioning that the developed finite element model is validated with the results obtained from an investigation conducted by Aboshosha *et al.* (2016).

4.1 Analyzing The Conductor's and Tower's Natural Frequencies

The conductor's and the tower's natural frequencies can be identified using the spectra shown in Figure 6 below. The first natural frequencies of the conductor and the tower correspond to the peaks shown in the spectra graphs. As can be seen from Figure 6(a), the conductor's first natural frequency is identified as 0.19 Hz and from 6(b), the tower's natural frequency is identified as 2.36 Hz. It should be noted that the excitation coming from Figure 6(a) is due to the conductors only, whereas the excitation peak in Figure 6(b) is a combination of the tower and conductor's excitation. The first natural frequencies are summarized in Table 1.

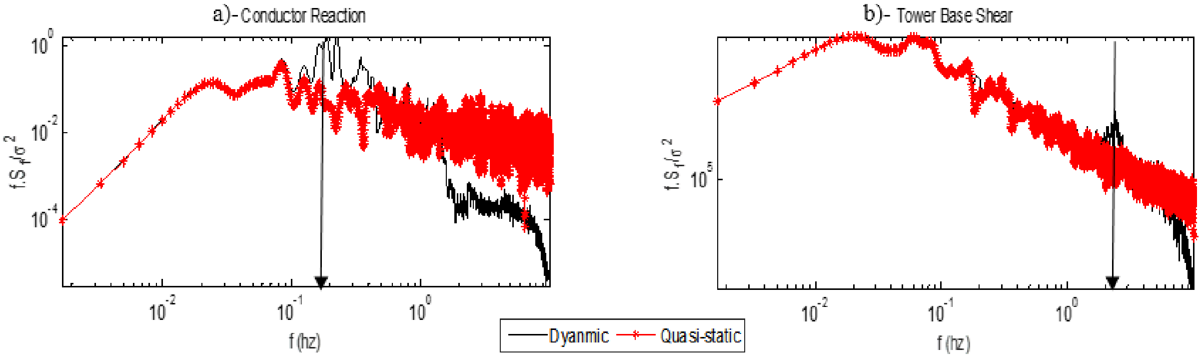


Figure 6: Spectra Showing (a) Conductor's and (b) Tower's Frequencies

4.2 Dynamic Amplification Factor (DAF)

Considering the method described above to determine the total response of the system, the time history of the conductor reaction at the insulator as well as the tower base shear are analyzed. The total response contains the mean, background, and resonant components. The total response includes the dynamic behavior of the system. An estimation of the quasi-static response of the system without considering the dynamic effect can be produced by summing the mean and the background components. Sample of total, mean, background and resonant response time histories of the conductor reaction are shown in Figure 7.

The dynamic amplification factor (DAF) is a ratio between the peak total response and the peak quasi-static response as shown in Equation 1.

$$[1] \qquad DAF = \frac{\hat{R}_T}{\hat{R}_{QS}}$$

Where $\hat{R}_T$ is the peak total response and $\hat{R}_{QS}$ is the peak quasi-static response. For the TL system in this study, five different responses were recorded for measuring the DAF and are shown in Figure 8 below.

The five considerations are the (1) conductor reaction R_y in the direction of wind, (2) the displacement of the conductor at the mid-span, (3) the tower base shear, (4) the tower base moment, and (5) the tower top deflection.

Analyzing the figure above, the following information can be deducted. The figure shows that the tower behaves very differently compared to the conductors. As expected, the tower does not experience large resonant responses due its high natural frequency. The conductors however can be seen to experience high amounts of resonance shown in the figure as large DAF values. DAF values larger than 1.1 are considered as high.

Another apparent trend shown in the figure is the decrease of DAF values with the increase in wind velocity. This is due to the increase in aerodynamic damping due to the movement of the conductors with the increase in wind speed. In cases of low wind speeds (v < 25 m/s) the resonant component is considered to be large and must be taken into account when designing for the TL system. Values for the conductors' reactions' DAF range between 1.18 and 1.35 with an average value of 1.25. Values for the conductors' mid-span displacements' DAF vary between 1.22 and 1.39 with an average value of 1.31.

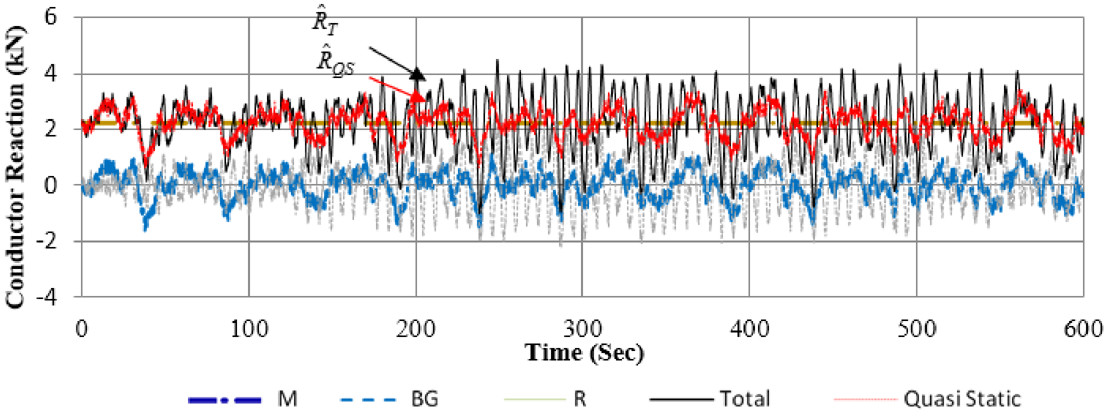


Figure 7: Sample conductor reaction response

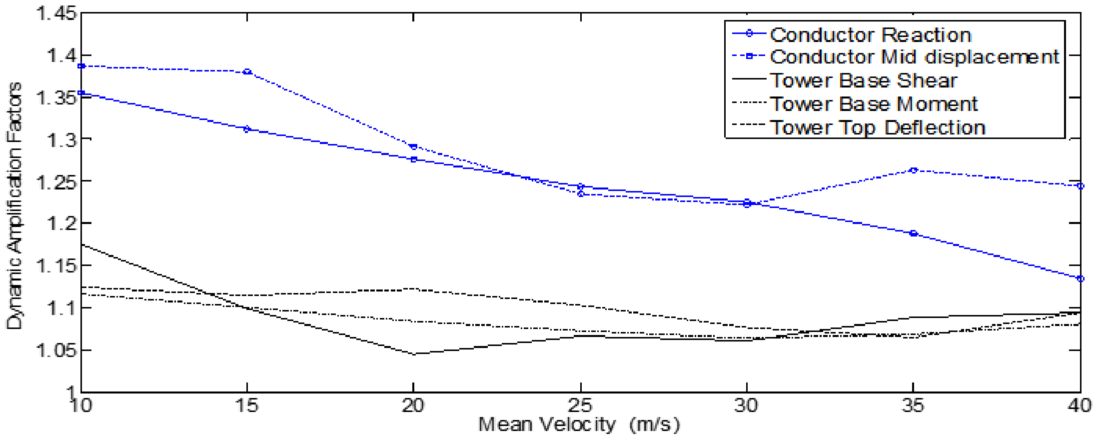


Figure 8: DAF vs. Mean Velocity

4.3 Gust Response Factor (GRF)

Another factor that is evaluated in this study is the gust response factor which is defined as the ratio between the peak total response and the mean response. This factor is referred to as GF_T. Another gust factor considered in the study is the ratio between the peak quasi-static response and the mean response, referred to as GF_{QS}. Other factors such as $GF_{T\text{-}ASCE}$ and $GF_{QS\text{-}ASCE}$ which correspond to values from the ASCE 74 (2010) which in turn are based on Davenport's expressions (1979) are also considered for this study. The factors for the tower base shear and the conductor reaction are plotted in Figure 8 in comparison with mean wind speed. As expected, GF_T values are higher than GF_{QS} since the values for GF_T include the resonant component.

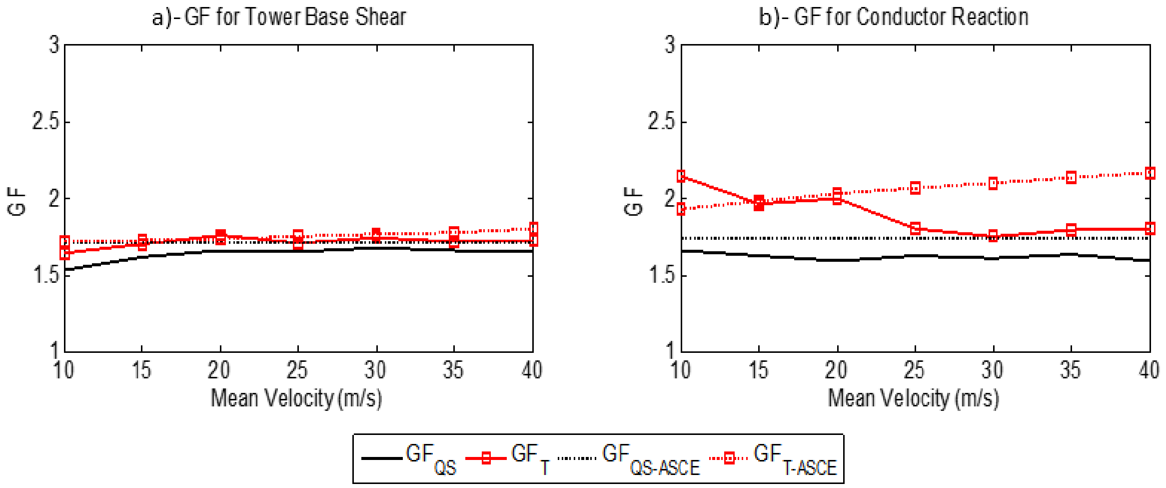


Figure 9: Gust Response Factor Values vs. Mean Wind Velocity for (a) Tower Base Shear and (b) Conductor Reaction

In addition, the gust factors obtained from the dynamic analysis conducted in the current study are compared to the values obtained from the ASCE. It is concluded that $GF_{T\text{-}ASCE}$ values obtained from the ASCE have larger values than GF_T obtained from the nonlinear dynamic analysis, proving that ASCE values are conservative. It is also apparent in Figure 9(a) but more clearly shown in Figure 9(b) that the difference between GF_T and GF_{QS}, as well as $GF_{T\text{-}ASCE}$ and $GF_{QS\text{-}ASCE}$ is large which shows that the dynamic effect has to be accounted for in evaluating the conductors' peak response especial for low wind speeds less than or equal to 20 m/sec.

5. CONCLUSIONS

A finite element model of a multi-span TL system was developed in order to assess its dynamic behavior under synoptic winds with varying speeds. The towers of the system consisted of self-supported steel lattice towers. The model was validated using responses obtained from an aeroelastic TL previously testes at the Boundary Layer Wind Tunnel Laboratory at Western University. The values for conductors' reactions as well as tower's base shear are recorded and evaluated in order to determine the peak total responses and peak quasi-static responses. Moreover, the mean, background, and resonant components of the response were analyzed. Dynamic amplification factors as well as gust response factors are evaluated and the following conclusions are drawn from the study:

- The tower behaves differently compared to the conductors. The tower experiences less dynamic amplification factor compared to the conductors which experience higher dynamic response especially at low wind speeds.
- The dynamic amplification factor of the conductors decreases with the increase in wind speed. Such a reduction is attributed to the increase in aerodynamic damping.
- The dynamic amplification factor for the conductors' reactions' is found to range between 1.18 and 1.35 with an average value of 1.25.
- The dynamic amplification factor for the conductors' mid-span displacements' is found to be vary between 1.22 and 1.39 with an average value of 1.31.
- It is concluded that the total gust response factor GF_T values are higher than the quasi-static gust response factor GF_{QS} values since the GF_T values include the resonant component.
- Gust response factors obtained from ASCE considering the dynamic effect $GF_{T\text{-}ASCE}$ are higher than those obtained from dynamic analysis conducted in the current study GF_T .
- Gust response factors obtained from ASCE considering only the background effect $GF_{QS\text{-}ASCE}$ are compatible with those obtained from dynamic analysis GF_T for the tower as well as for the conductor responses at high speeds. At low speeds (i.e. < 25 m/s), $GF_{QS\text{-}ASCE}$ for the conductor are less than GF_T, which indicates the importance of considering the dynamic effects for the conductors at low speeds.

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