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Behaviour of transmission line conductors under tornado wind

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Abstract. Electricity is transmitted by transmission lines from the source of production to the distribution system and then to the end users. Failure of a transmission line can lead to devastating economic losses and to negative social consequences resulting from the interruption of electricity. A comprehensive in-house numerical model that combines the data of computational fluid dynamic simulations of tornado wind fields with three dimensional nonlinear structural analysis modelling of the transmission lines (conductors and ground-wire) is used in the current study. Many codes of practice recommend neglecting the tornado forces acting on the conductors and ground-wires because of the complexity in predicting the conductors' response to such loads. As such, real transmission line systems are numerically simulated and then analyzed with and without the inclusion of the lines to assess the effect of tornado loads acting on conductors on the overall response of transmission towers. In addition, the behaviour of the conductors under the most critical tornado configuration is described. The sensitivity of the lines' behaviour to the magnitude of tornado loading, the level of initial sag, the insulator's length, and lines self-weight is investigated. Based on the current study results, a recommendation is made to consider conductors and ground-wires in the analysis and design of transmission towers under the effect of tornado wind loads.

Keywords: transmission lines; conductors; ground-wire; tornado; F2; CFD simulation; wind loads

1. Introduction

Tornadoes are high intensity wind (HIW) events that produce strong and damaging wind forces in various directions. Those events are localized and have a narrow width. Most structures are not designed to resist tornado loads since the probability of being exposed to a tornado is quite small. This is not the case of long span structures like transmission lines that extend for kilometers. When a tornado occurs at a transmission line location, the probability that it hits one of the towers is quite high. The failure of one tower can trigger a cascade failure because of the unbalanced loads resulting from the conductors' tension. Dempsey and White (1996) reported that 80% of all weather related transmission line failures worldwide are due to HIW events. Despite this fact, very little information about tornado loads is available in transmission line codes of practice and guidelines. The limited information available in some codes ASCE (2010) and CIGRE` (2009) states that the tornado forces acting on the conductors can be neglected. The reason behind that, as

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stated in those guidelines, is that the prediction of the conductor response to such loads is complicated. As such, the purpose of the current study is to assess the effect of tornado loads acting on conductors on the overall response of transmission towers. The study is conducted numerically using results of computational fluid dynamics (CFD) simulations for the tornado wind field and finite element modelling for the conductors. The CFD simulations were conducted by Hangan and Kim (2008) and validated using field measurements reported by Sarkar *et al.* (2005) and Lee and Wurman (2005) for the 1998 spencer South Dakota F4 tornado and the 1999 Mullhall F4 tornado, respectively. The CFD data was processed by Hamada *et al.* (2010) to simulate the wind field for F2 tornadoes. The finite element modelling of the conductors is based on the four-noded three dimensional curved cable element that was developed by Koziey (1993) and then extended by Hamada and El Damatty (2014) to include the geometric nonlinear effect.

Few attempts have been made in the literature to investigate the overall behaviour of transmission line systems under high intensity wind events, such as tornadoes and downbursts. Savory *et al.* (2001) investigated the failure of a self-supported lattice tower under analytical tornado wind model that was developed by Wen (1975). Only the horizontal wind profile corresponding to F3 tornado was used without considering the vertical component of the tornado wind field. The study was conducted only for a single tower without the conductors and ground-wires. Loredo-Souza and Davenport (1998) investigated experimentally the dynamic behaviour of the transmission line conductors. The study concluded that the dynamic behaviour of the conductors is attenuated significantly by large aerodynamic damping, which can be as high as 60% of the critical damping, and that the background response is the main contributor for the total fluctuating response. Darwish *et al.* (2010) concluded that for the case of downbursts, the resonant component due to turbulence is also negligible as a result of the large aerodynamic damping. The same conclusion regarding the dynamic effect was reached by Holmes *et al.* (2008), Holmes (2008), and Hamada and El Damatty (2011). Hamada *et al.* (2010) and Hamada and El Damatty (2011) conducted comprehensive studies to understand the behaviour of transmission line systems under tornado loading. The studies investigated the variation of the tower members' internal forces with the tornado location relative to the transmission line system, and provided an insight about the structural response of lattice towers under tornado wind loads. Hamada and El Damatty (2015) extended an in-house numerical model to study the progressive failure of lattice transmission towers under tornado wind loads. The study investigated the resilience of transmission line system against failures when experiencing F2 tornado wind fields, described the failure modes using different material models, and assessed the effect of inclusion of geometric nonlinearities in the failure analysis of the towers.

The current study concentrates on the behaviour of conductors under tornado loading. It focuses on F2 tornadoes since the majority of tornadoes are equal or less than this magnitude, and it is not actually practical to design structures to resist higher levels of tornadoes (ASCE 2010 and CIGRE` 2009). The study starts by describing the tornado wind field. Real transmission towers are numerically simulated and then analyzed with and without the inclusion of the lines (conductors and ground-wires). The results are used to assess the importance of including the lines in the analysis of transmission lines under tornado loads. The behaviour of the conductors under the most critical tornado configuration is described. Finally, the sensitivity of the conductors' behaviour to the magnitude of loading, the level of initial sag, the insulator string's length, and the lines self-weight is assessed.

2. F2 tornado wind field on tower and conductors

The current study assess the forces transferred from the lines (line's reactions) to the supporting towers under F2 tornado wind loads. Two main components are essential to conduct the current study: a) the F2 tornado wind field, and b) the modelling of transmission line systems used to assess the effect of the conductors on the overall behaviour. The current section summarizes the tornado wind field and the following section discusses the nonlinear three dimensional finite element model of the transmission line system. The wind field used in the current study is based on the procedures developed by Hamada *et al.* (2010) to estimate a velocity field for F2 tornadoes from the computational fluid dynamics (CFD) simulations conducted by Hangan and Kim (2008). The CFD analyses are conducted with smooth surface and the resulting tornado wind field represents the steady state, i.e. does not vary with time. The velocity field V(r, θ, z) has a three dimensional spatial variation and is given as a function of the cylindrical coordinates r, θ, and z. The tornado velocity field has three velocity components: the radial velocity Vr (r, θ, z), the tangential velocity Vt (r, θ, z), and the axial velocity Va (r, θ, z). The maximum tangential velocity of F2 tornado is 78 (m/sec) and occurs at a radius r = 96 (m) and a height z = 19 (m). The maximum radial velocity is 49 (m/sec) and corresponds to a radius r = 146 (m) and a height z = 6 (m). The maximum axial velocity is 37 (m/sec) and corresponds to a radius r = 171 (m) and a height z = 127 (m).

In order to gain an insight about the F2 tornado wind field, the profile of the tangential velocity component along the height is plotted in Fig. 1 for different values of r, where r is the distance from the tornado center. The near ground region, Z less than or equal 100 (m), is the main interest of transmission line design. In addition, the vertical profile of the three velocity components for radii r = 100 (m) and r = 150 (m) are provided in Figs. 2 and 3. The dotted lines shown in these figures indicate the location of the transmission lines (conductors) for the two transmission towers considered in the current study.

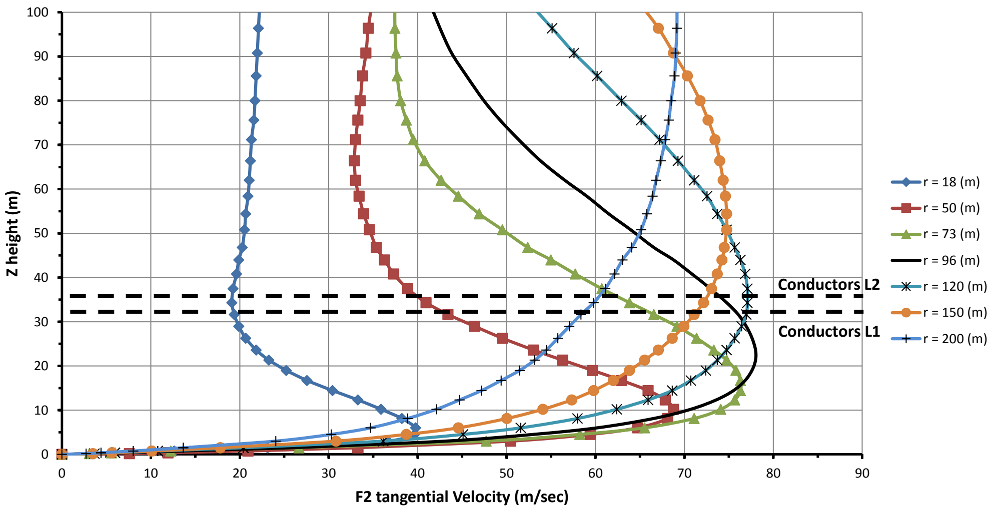


Fig. 1 Vertical Profile of Tangential Velocity Component for Different Radial Distances from Tornado Center (F2 Tornado)

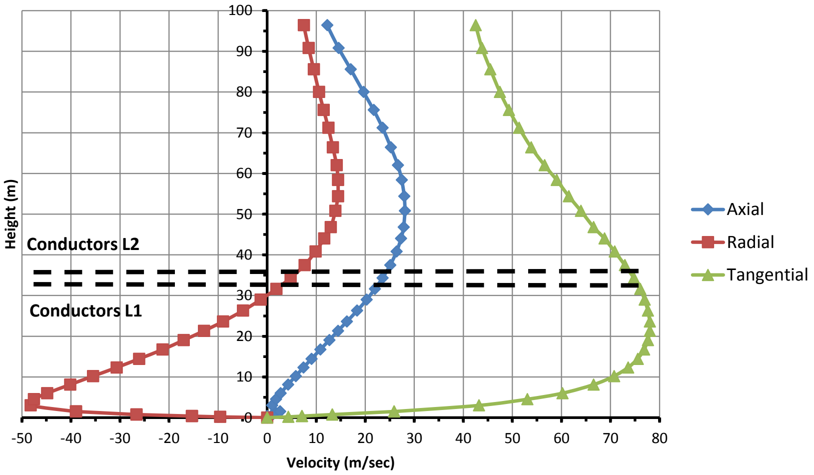


Fig. 2 Variation of the Three Velocity Components of F2 Tornado along the Height at Distance 100 (m) from Tornado Center

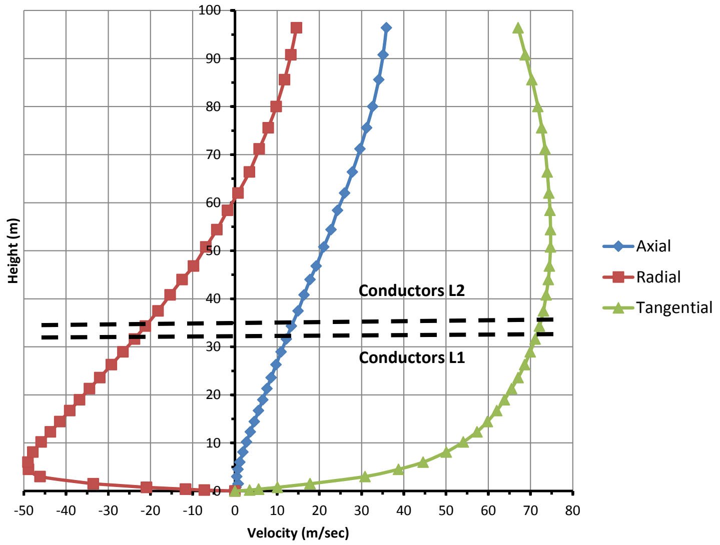


Fig. 3 Variation of the Three Velocity Component of F2 Tornado along the Height at Distance 150 (m) from Tornado Center

As shown in the figures, the tornado wind profile is significantly different than the conventional boundary layer wind profile. The peak velocities are close to the ground and the velocities change direction with height. The tornado wind profiles in the tangential, radial, and vertical directions are different for each distance r from the tornado center. The evaluation of the F2 tornado wind forces on the lines is described in detail by Hamada *et al.* (2010) and Hamada and El Damatty (2011).

3. Description of transmission lines and finite element mode

Two different transmission lines are selected to assess the forces transferred from the lines to the supporting towers under F2 tornado wind loads. The first guyed transmission line is labelled as L1 and has a line span of 480 (m). Two conductors and one ground-wire are connected to the supporting guyed towers T1 as shown in Fig. 4. The tower height is 44.39 (m) and is supported by four guys attached to the tower guy's cross-arms at an elevation of 38.23 (m). The geometric and material properties of the conductors and ground-wires are provided in Table 1. The second guyed transmission line is labelled as L2 and has a line span of 460 (m). The guyed tower height is 46.57 (m) and is supported by four guys attached to the tower bridge. Three conductors and two ground-wire are connected to tower T2 as shown in Fig. 4. The conductors in transmission lines L1 and L2 are connected to the tower cross-arms using a 4.27 (m) insulators. The geometric and material properties of the conductors and ground-wires are provided in Table 1.

The tower of interest refers to the middle tower as shown in Fig. 4, where the conductors' forces transferred to the supporting tower are studied. The modelling of the conductors is based on the four-noded cable element developed by Hamada and El Damatty (2014) and shown in Fig. 5. It follows the same procedures adopted Hamada and El Damatty (2014) where the stiffness of the towers and insulators are simulated using a three dimensional nonlinear spring system.

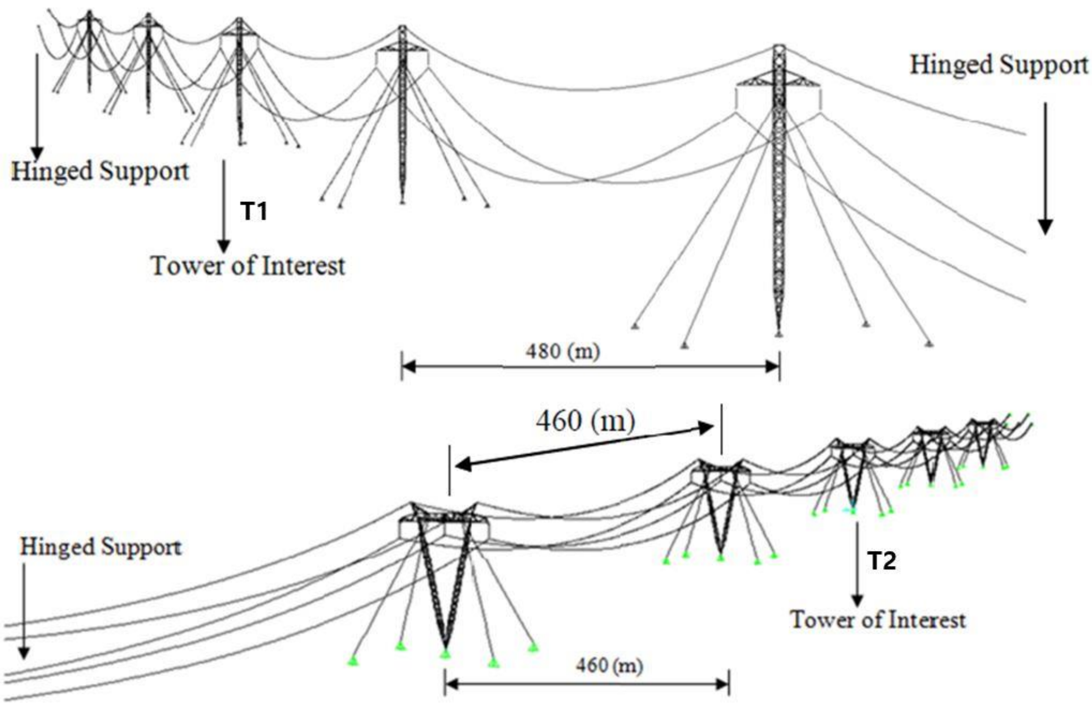


Fig. 4 Geometry of the Modelled Guyed Transmission Lines

Table 1 Physical Parameters Employed for Conductors and Ground-wires

Parameters		L1 Lines		L2 Lines	
		Conductor	Ground-wire	Conductor	Ground-wire
Name		1843.2 MCM 72/7 Nelson ACSR	9 mm Grade 1300 Steel Skywire	1Kcmil 4×495 0.85"(22×7) ACSR	3/8" Steel (GR 180)
Wind Span	m	480	480	460	460
Diameter	mm	40.64	9	21.59	9.53
Weight	N/m	28.97	3.9	35.83	3.9
Modulus of Elasticity	N/m^2	6.23×10^{10}	1.86×10^{11}	5.177×10^{10}	2×10^{11}
Sag	m	20	13.54	16	16

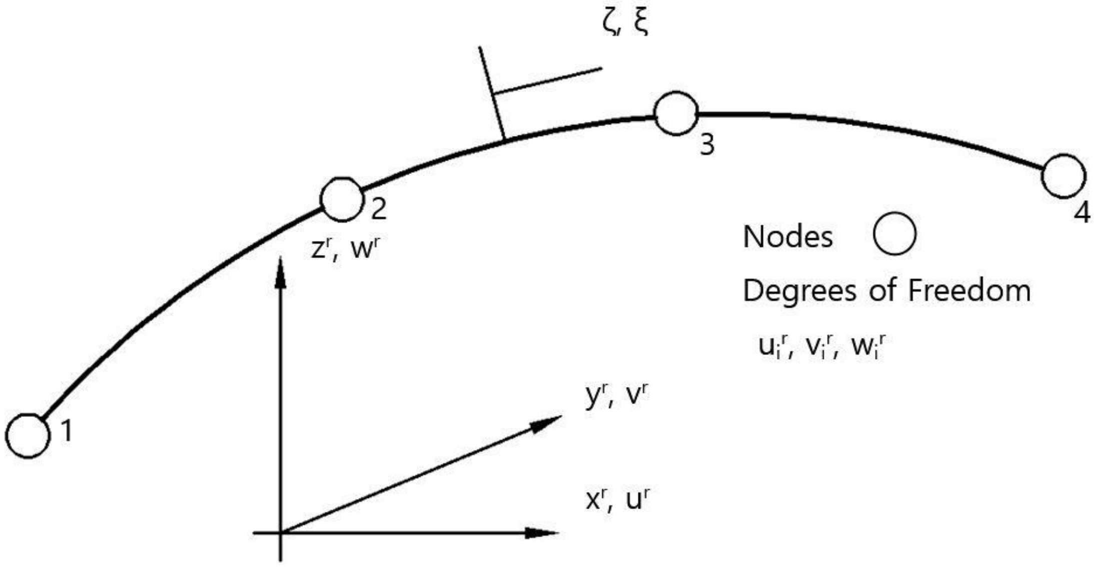


Fig. 5 Cable Element Coordinate and Systems and Nodal Degrees of Freedom

Three spans from each side of the tower of interest are included in the analysis as suggested before by Shehata *et al.* (2005) and Hamada (2009). The forces in the intermediate spring obtained from the nonlinear analyses are evaluated and then reversed representing the effect of the conductors on the supporting towers when the system is subjected to an F2 tornado. These forces have three components: a) transverse component associated with drag loads, b) longitudinal component related to the nonlinear behaviour of the conductors and resulting from the differential tension between the two span adjacent to the tower, and c) vertical component associated with the lift loads. These forces are referred to as lines' (conductors) reactions in the rest of the study. The tower is analyzed under the combined effects of the conductors' forces and the tornado forces acting on the main body of the tower. More details about the three dimensional nonlinear finite element model of the two transmission line systems are provided by Hamada *et al.* (2010) and Hamada and El Damatty (2011).

4. Effect of conductors on the transmission towers behaviour

The importance of considering the conductors and ground-wires in the analysis of transmission line systems under tornado loading is assessed in this section. ASCE (2010) states that tornado loading applied to the lines can be neglected because of the small tornado path widths (150 m in the case of the F2 tornado) and the complexity of the wind force mechanism applied to the lines. Extensive parametric studies are conducted for transmission line systems L1 and L2. For each system, the parametric study is repeated twice; with and without considering the tornado loads acting on the lines (conductors and ground-wire). The difference between the two sets of analyses conducted for each system represents the effect of the conductor forces. Such a study will assist in assessing the validity of the recommendation made in some codes of practice for neglecting such forces. Similar to the investigation done by Hamada *et al.* (2010) and Hamada and El Damatty (2011), the parametric study for each transmission line system involves a large number of quasi-static analyses by considering different values for the tornado configurations (R and θ) as shown in Fig. 6; R and θ define the tornado location relative to the tower of interest. Combinations of thirteen values for R and sixteen values for θ are considered in each parametric study. The considered values for R are 50, 75, 90, 100, 125, 150, 200, 250, 300, 350, 400, 450, and 500 (m) and for the angles θ are 0, 30, 45, 60, 90, 120, 135, 150, 180, 210, 225, 240, 270, 300, 315, and 330^o.

The results of the parametric studies conducted for transmission line systems L1 and L2 are provided in Tables 2 and 3, respectively. Each table reports the peak forces in selected members of both towers that result from the entire parametric study. Those peak forces are given for the case of with and without lines. Different zones at which the internal forces are reported are illustrated in Figs. 7 and 8 for towers T1 and T2, respectively. The term diagonal (1) and diagonal (2) used in Tables 2 and 3 represent diagonal members located in plans parallel and perpendicular to the lines, respectively. Zone 6 for tower T1 includes the guys and conductors' cross-arms and the internal forces are reported in an upper and a lower chord members for each cross-arm. Similarly, the conductors' cross-arms is located in Zone 4 for tower T2. In addition to the peak internal forces, the tables provide also the tornado configurations corresponding to those peak forces for each of the reported members. By comparing the results reported in Tables 2 and 3, the following observations can be concluded:

- The chords' peak internal forces increase by 22% to 140% due to the inclusion of the lines (conductors and ground-wires) in the analysis of transmission towers under tornado wind loads.
- Some diagonal members experience higher internal forces when the conductors and ground-wires are excluded.
- The critical tornado configurations R and θ that lead to peak internal forces in both cases of with and without transmission lines generally coincides. The inclusion of the lines results in variation in the critical configurations for few members.
- The reduction in the cross-arms members' peak internal forces, due to the exclusion of the conductors and the ground-wires, is significant. This is expected, as the cross-arms and the upper part of the towers (Zone 6 for tower T1 and Zone 4 for Tower T2) are mainly responsible of carrying the lines loads. The critical tornado configurations that lead to the peak internal forces in these two zones when the conductors are included are R = 125 (m) and $\theta = 180^o$ and R = 450 (m) and $\theta = 90^o$.

Table 2 Results of the Parametric Study Conducted for Transmission Tower T1

Member		No.	Type	F2 Tornado: Parametric Study with Lines (W.L.) Axial (KN)	Tornado Configuration	F2 Tornado: Parametric Study with Lines (WO.L.) Axial (KN)	Tornado Configuration	Percentage (W.L.-WO.L.)/W.L. %*
Zone 1		F14	Chord	-144	R=125 θ=330	-118	R=100 θ=270	22
Zone 1		F43	Diagonal (1)	2	R=75 θ=150	2	R=90 θ=330	0
Zone 1		F45	Diagonal (2)	-11	R=125 θ=240	-11	R=125 θ=240	2
Zone 3		F141	Chord	-225	R=125 θ=30	-174	R=90 θ=330	30
Zone 3		F183	Diagonal (1)	-16	R=100 θ=30	-16	R=100 θ=0.0	4
Zone 3		F172	Diagonal (2)	-5	R=90 θ=60	-7	R=125 θ=60	-23
Zone 5		F318	Chord	-215	R=125 θ=30	-150	R=125 θ=0.0	44
Zone 5		F368	Diagonal (1)	15	R=150 θ=150	14	R=100 θ=150	5
Zone 5		F359	Diagonal (2)	-23	R=100 θ=240	-22	R=100 θ=270	4
Zone 6	Tower	F215	Chord	-78	R=450 θ=90	-33	R=125 θ=180	140
Zone 6	Tower	F398	Diagonal (1)	47	R=125 θ=30	26	R=125 θ=0.0	81
Zone 6	Tower	F406	Diagonal (2)	-37	R=200 θ=60	-13	R=125 θ=90	198
Zone 6	Guy	F437	Upper Chord	227	R=125 θ=180	148	R=125 θ=180	53
Zone 6	Guy	F422	Lower Chord	-134	R=125 θ=210	-82	R=125 θ=225	62
Zone 6	Conductor	F118	Upper Chord	40	R=450 θ=90	5	R=125 θ=180	634
Zone 6	Conductor	F538	Lower Chord	-47	R=450 θ=90	-8	R=125 θ=180	510

%* Negative values-peak forces due to exclusion of the lines are higher than with lines

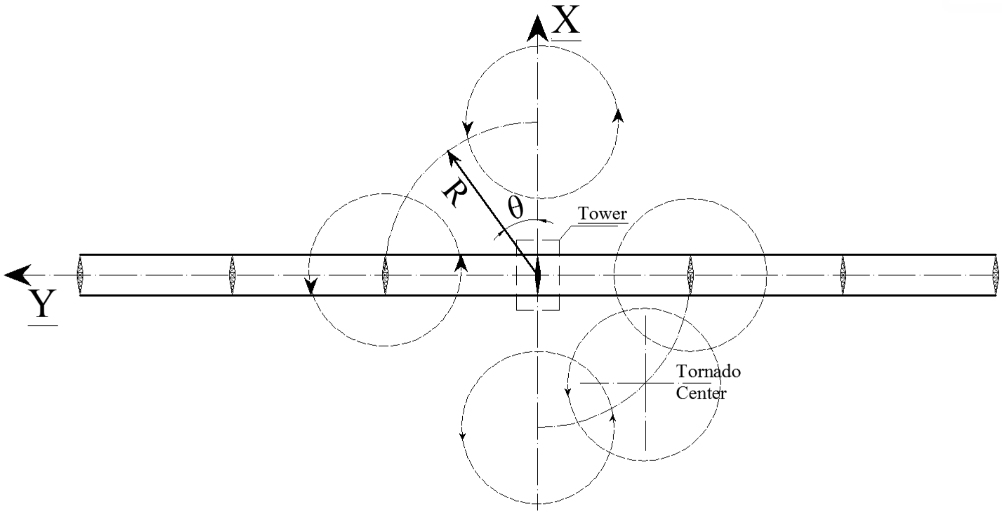


Fig. 6 Tornado Parameters (Configurations) *R* and *θ*

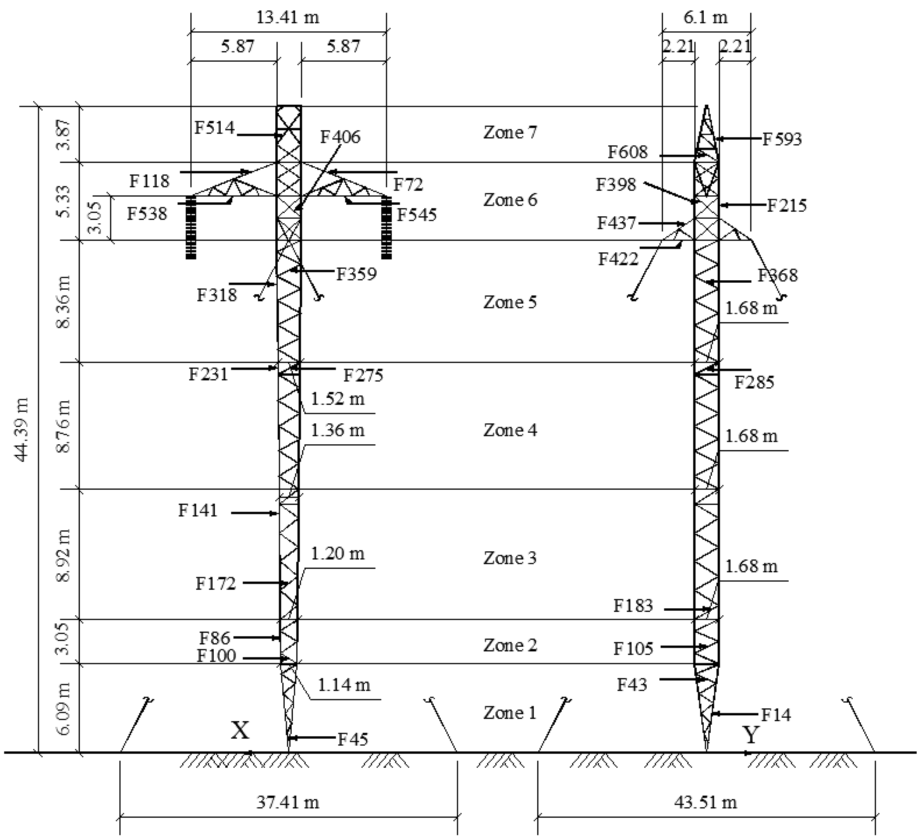


Fig. 7 Geometry of Guyed Tower T1 – Transmission Line L1

Table 3 Results of the Parametric Study Conducted for Transmission Tower T2

Member				F2 Tornado				Percentage
		No.	Type	Parametric Study with Lines (W.L.)		Parametric Study with Lines (WO.L.)		(W.L.-WO.L.)/W.L.
				Axial (KN)	*Tornado Configuration*	Axial (KN)	*Tornado Configuration*	%*
Zone 1		F1558	Chord	-282	R=100, θ=180	-290	R=75, θ=150	-3
Zone 1		F1460	Diagonal (1)	-9	R=100, θ=180	-10	R=75, θ=150	-6
Zone 1		F1804	Diagonal (2)	-8	R=100, θ=180	-3	R=150, θ=150	138
Zone 2		F1725	Chord	-545	R=90, θ=330	-412	R=90, θ=330	32
Zone 2		F1647	Diagonal (1)	-12	R=150, θ=45	-17	R=100, θ=45	-28
Zone 2		F1911	Diagonal (2)	-18	R=150, θ=330	-17	R=125, θ=0.0	-5
Zone 2		F1662	Chord	-49.5	R=100, θ=180	-469	R=125, θ=180	6
Zone 2		F1589	Diagonal (1)	-14	R=90, θ=330	-16	R=150, θ=330	-14
Zone 2		F1865	Diagonal (2)	12	R=100, θ=225	19	R=75, θ=225	-35
Zone3		F1688	Chord	-25.7	R=100, θ=180	-215	R=100, θ=180	20
Zone3		F1611	Diagonal (1)	53	R=100, θ=180	52	R=125, θ=180	2
Zone3		F1887	Diagonal (2)	7	R=125, θ=180	11	R=100, θ=150	-35
Zone 4	Conductor	F1228	Upper Chord	49	R=125, θ=180	20	R=125, θ=135	145
Zone 4	Conductor	F1213	Lower Chord	-58	R=400, θ=270	-25	R=125, θ=0.0	131
Zone 5		F1229	Upper Chord	47	R=100, θ=30	59	R=125, θ=0.0	-21
Zone 5		F1194	Lower Chord	-81	R=125, θ=180	-56	R=125, θ=0.0	45

%* Negative values-Peak forces due to exclusion of the lines are higher than with lines

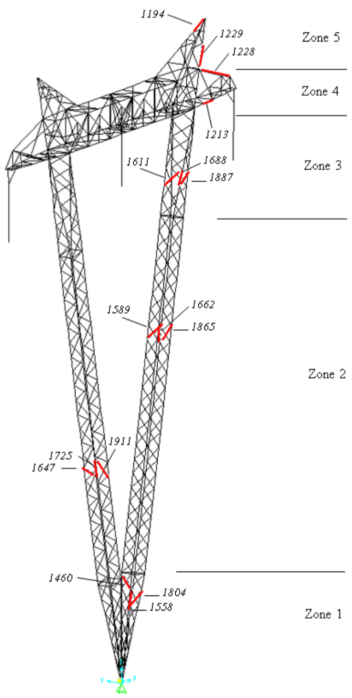


Fig. 8 Geometry of Guyed Tower T2 – Transmission Line 2

5. Effect of various parameters on conductors' longitudinal reaction

Having recognized the importance of including the conductors in the analysis of transmission lines under tornadoes, the study proceed by conducting a parametric study for the conductor reactions. The study focuses on the longitudinal reaction resulting from the unbalanced loads that might result from a tornado configuration. Such a reaction is not easy to evaluate and requires nonlinear analyses unlike the transverse and vertical reactions, which can be evaluated accurately enough based on tributary area. Also, the parametric study focuses mainly on one tornado configuration (R=125 (m) and $\theta = 180^o$), which is shown to be critical for many tower members. However, some other angles "θ" are considered in the parametric study for this critical value of R. A schematic showing the location of the tornado relative to the tower of interest for the configuration (R=125 (m) and $\theta = 180^o$) is shown in Fig. 9. The distribution of the transverse and vertical wind field velocity due to this configuration and along a distance of 1500 (m) from both side of the tower are provided in Figs. 10 and 11, respectively. Fig. 10 shows that the transverse velocity change directions along the opposite sides of the tower. The distribution is shown for values of θ = 30, 45, 60, 90, 180_o. The longitudinal reaction result from the difference between the magnitudes of transverse velocities along the opposite spans. As shown in Fig. 10, the tornado configurations of R = 125 (m) with $\theta = 180^o$ leads to the maximum unbalanced load between the two adjacent spans. The vertical profile shown in Fig. 11 is almost symmetric, and it acts upward against the weight of the conductors. As shown in the Figure, the vertical velocity can reach up to 40% of the maximum transverse velocity.

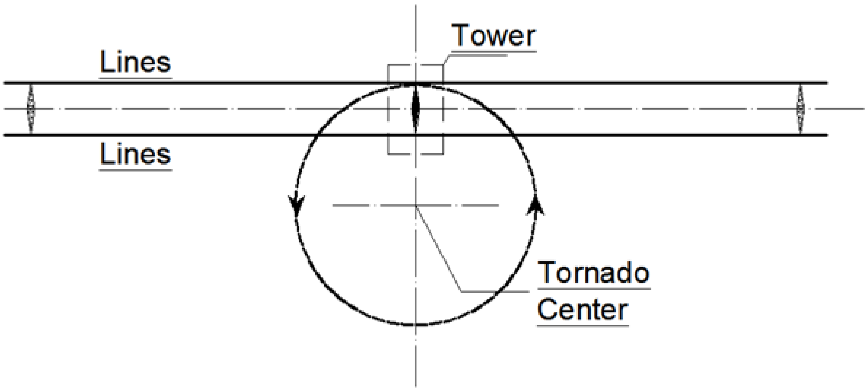


Fig. 9 Horizontal Projection of F2 Tornado Located at Relative Distance R = 125 (m) and θ = 180^o

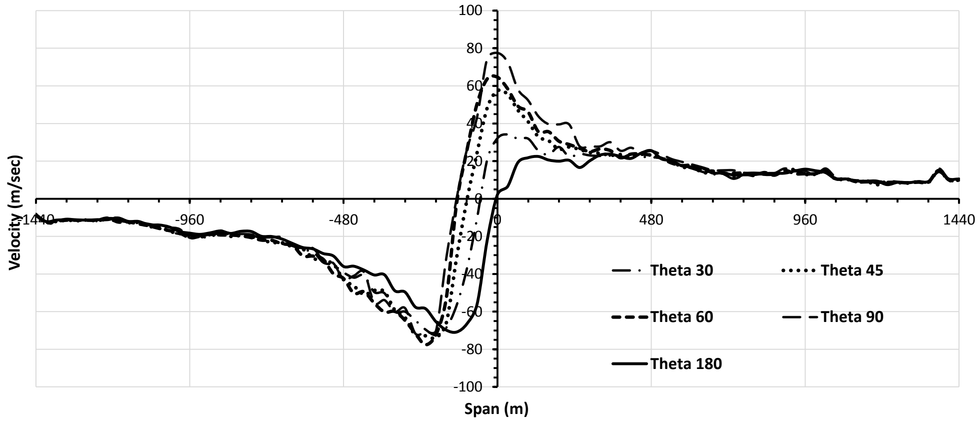


Fig. 10 Transverse Velocity Distribution along the Conductors – R = 125 (m) and θ = 30, 45, 60, 90, 180^o

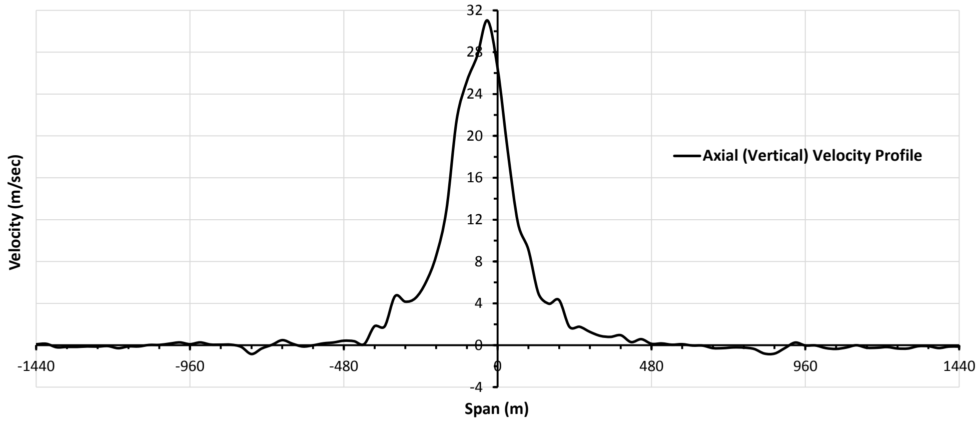


Fig. 11 Vertical Velocity Distribution along the Conductors – R = 125 (m) and θ = 180^o

The deformation of the conductors due this wind field, as obtained from the finite element analysis, are provided in Figs. 12 and 13 for the lines L1 and L2, respectively. In each figure, the projection of the deformed shape are provided in a vertical and horizontal plan reflecting the effects of the vertical and transverse velocities, respectively. For this tornado configuration, the longitudinal reaction obtained from the analysis is comparable to the transverse reaction. Longitudinal reaction of 9,006 (N) and 7,700 (N) are calculated for lines L1 and L2, respectively. The transverse reactions for the same lines are 15,422 (N) and 11,841 (N), respectively. The ratio between the longitudinal and transverse reactions is in the order of 65%.

Various parameters can affect the values of the longitudinal reactions. Those include the magnitude of loading, the pretension force, the insulator length, and the own weight of the conductor. The variation of the longitudinal reactions with those parameters is assessed in the following subsections.

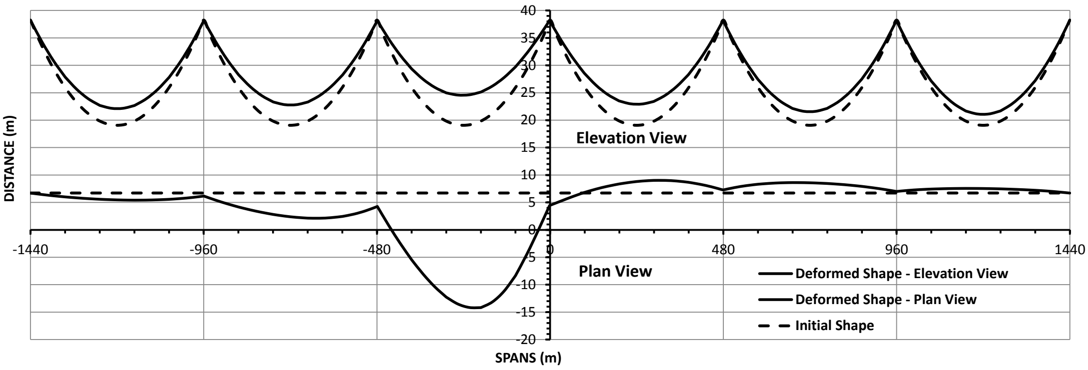


Fig. 12 Deformed Shape of Transmission Line L1 due to F2 Tornado Configurations R = 125 (m) and θ = 180^o

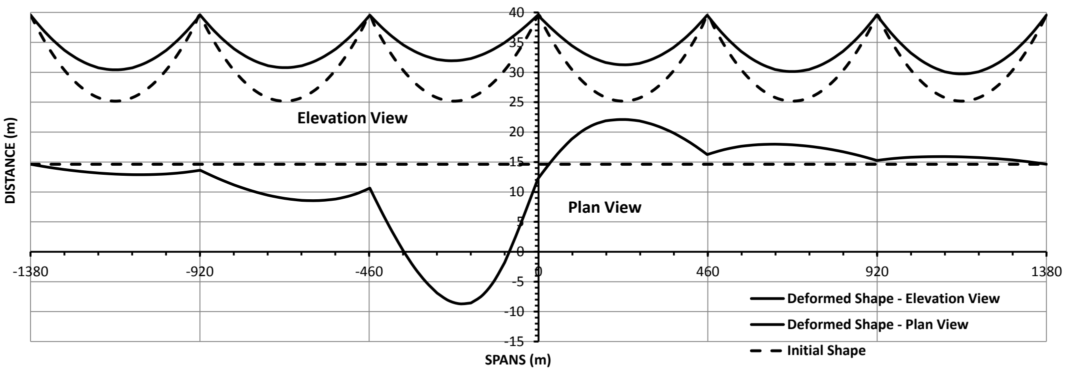


Fig. 13 Deformed Shape of Transmission Line L2 due to F2 Tornado Configurations R = 125 (m) and θ = 180^o

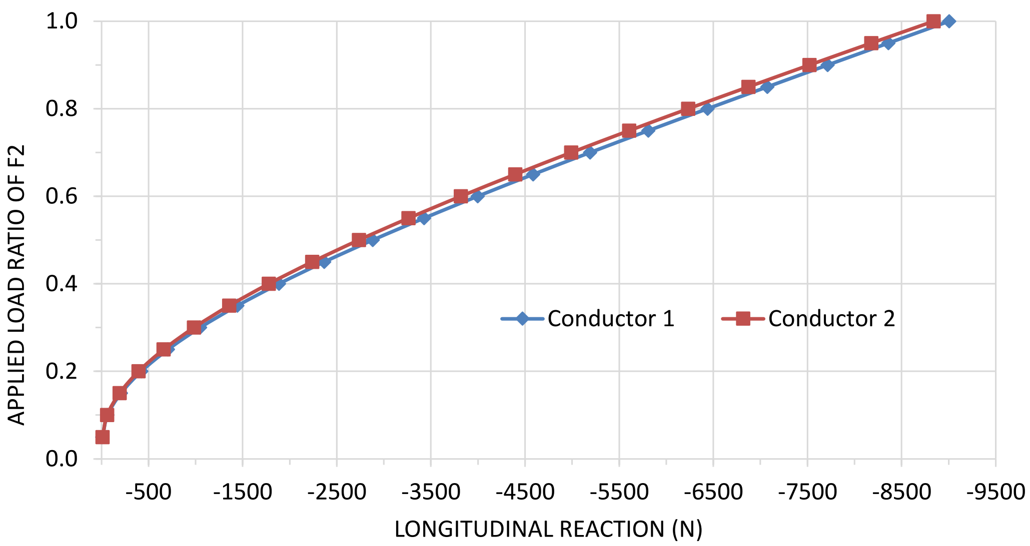


Fig. 14 Transmission Line System L1 Longitudinal Reactions due to the Variation of the Applied F2 Tornado Loads

5.1 Effect of magnitude of load

The variation of the conductors' longitudinal reactions with the magnitude of F2 tornado loads is investigated in this part. The F2 tornado wind load is applied incrementally in a quasi-static manner using a load increment of 5%. The variation of the longitudinal reactions with the magnitude of F2 tornado loads is plotted for transmission line systems L1 and L2 in Figs. 14 and 15, respectively. The figures show the plots for the two conductors belonging to line L1 and the three conductors belonging to line L2. For each line, the conductors are located at similar height while there locations varies along the transverse direction of the cross-arms as shown in Figs. 7 and 8. The variation in the reaction values between different conductors belonging to same system is due to the difference in their horizontal location relative to the tornado. This difference is small for line L1, where the cross-arm is relatively narrow (13 (m) width). Meanwhile, a large difference is shown for line L2, where the cross-arm has a width of 29.3 (m). All plots show a nonlinear variation of the longitudinal reactions with the magnitude of load, especially at the early stage of loading.

For illustration, the transverse and vertical reactions for the conductors of the two lines are plotted in Figs. 16 and 17 versus the magnitude of applied load. As shown in the figures, those reactions exhibit a linear behaviour with variation in magnitudes again due to the difference in the transverse location of the conductors. The 29.3 (m) distance between the two edge conductors in transmission line system L2 leads to significant change in the F2 tornado forces applied on the conductors.

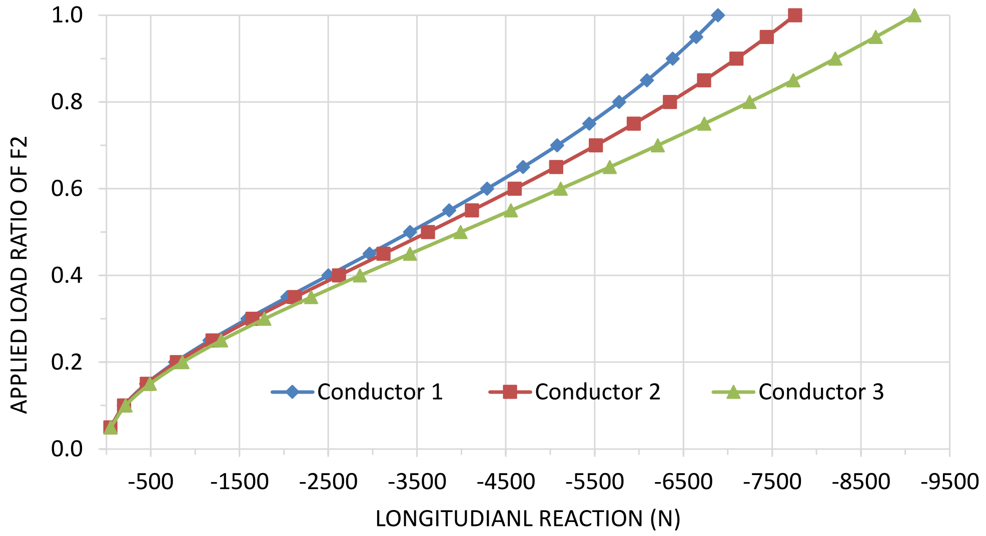
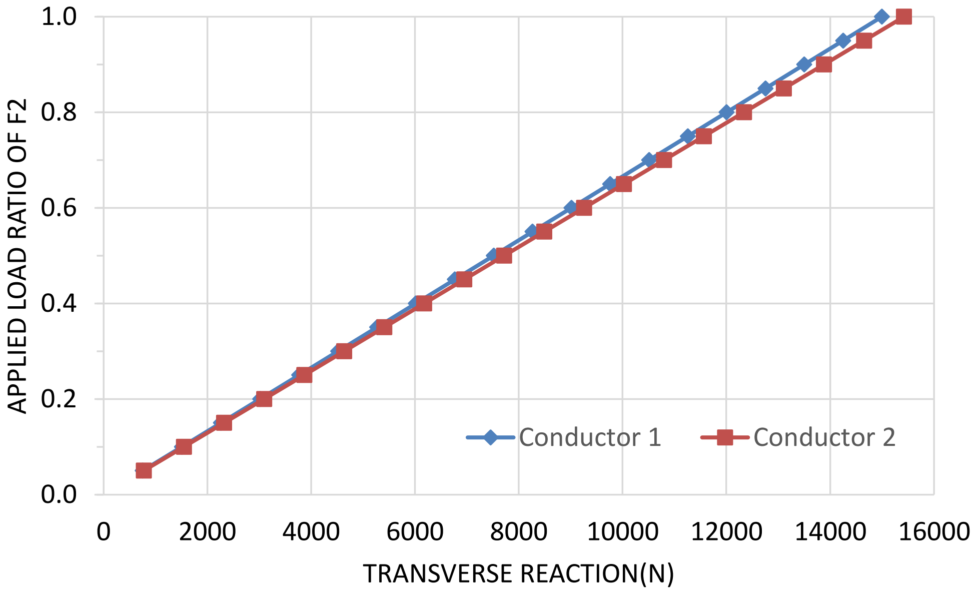


Fig. 15 Transmission Line System L2 Longitudinal Reactions due to the Variation of the Applied F2 Tornado Loads

Consequently, a difference in the conductor's reactions of 25% occurs in the longitudinal direction, and 33% occurs in the transverse direction. The results conclude that the horizontal and vertical F2 tornado forces change significantly in space. In addition, this significant change in the lines' reactions leads to an additional torsional moment on the supporting towers and significant additional forces in some of the supporting guys.

5.2 Effect of conductors' pretension and sag

In this part of the parametric study, both the value of the pre-tension force and yaw angle θ are varied, while the tornado location distance R is kept constant at a value of 125 (m). Only one conductor of line L1 is shown in the results presented in the current study, with similar behaviour for all other conductors in this parametric study. The pretension force is varied from 60 (kN) to 200 (kN). Figs. 18-20 show that the three reaction components vary with angle θ, especially the transverse and longitudinal components. Regarding the effect of pretension force, negligible variation for the transverse and vertical reactions, and significant variation for the longitudinal reactions are exhibited. Fig. 20 shows that the maximum value for the longitudinal reaction occurs at θ = 180o. Fig. 21 indicates that the longitudinal reaction decreases nonlinearly with the increase of the pretension force.



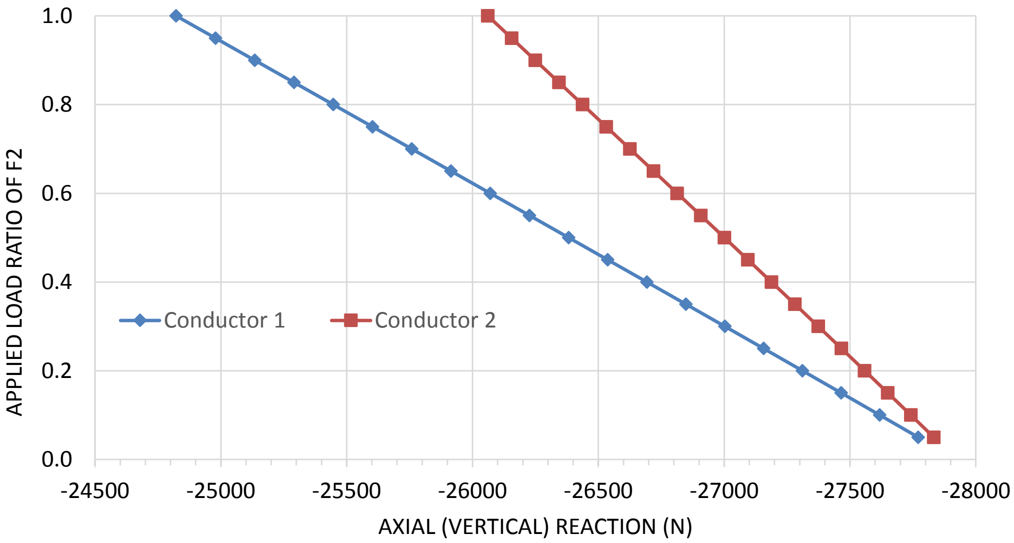


Fig. 16 Transmission Line System L1 Transverse and Vertical Reactions due to the Variation of the Applied F2 Tornado Loads

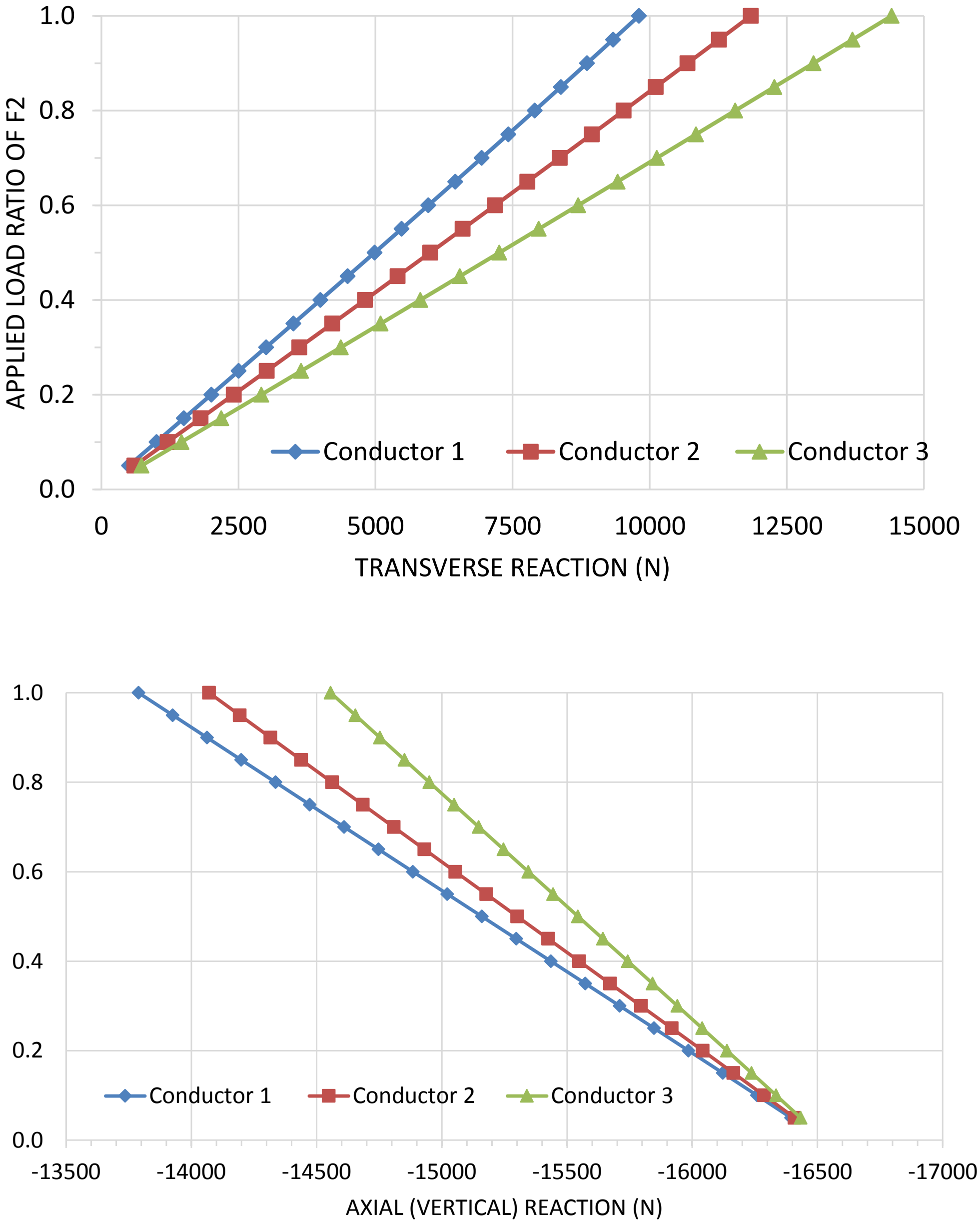


Fig. 17 Transmission Line System L2 Transverse and Vertical Reactions due to the Variation of the Applied F2 Tornado Loads

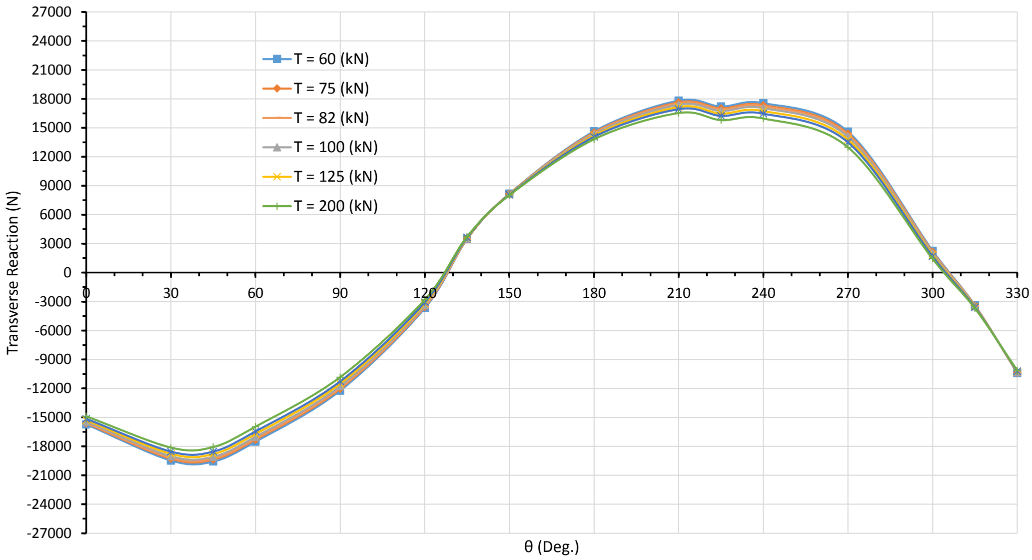


Fig. 18 Variation of Transmission Line's Transverse Reaction with Pretension Force and Sag – R = 125 (m) (Transmission Line System L1)

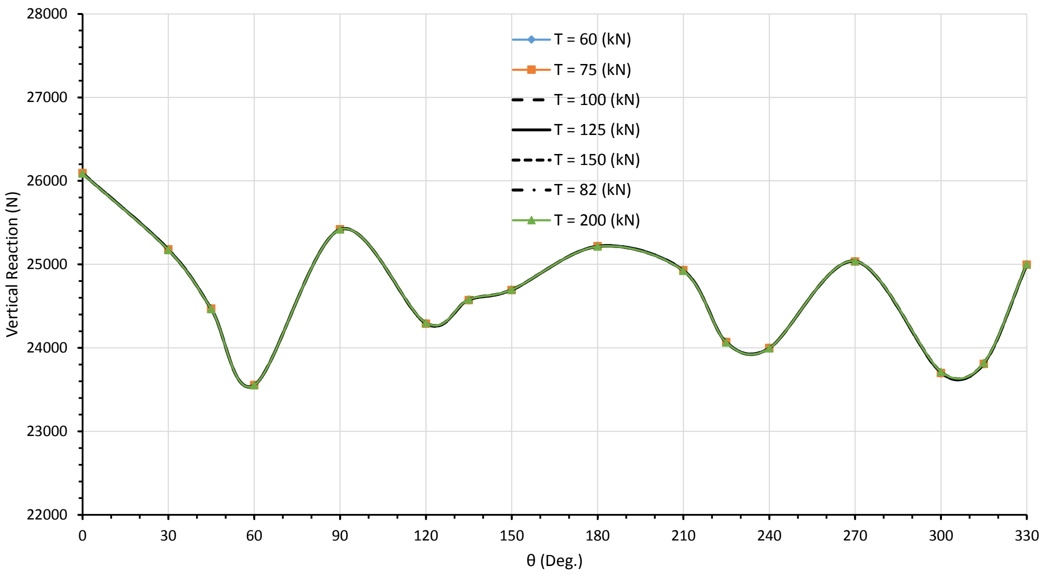


Fig. 19 Variation of Transmission Line's Vertical Reaction with Pretension Force and Sag – R = 125 (m) (Transmission Line System L1)

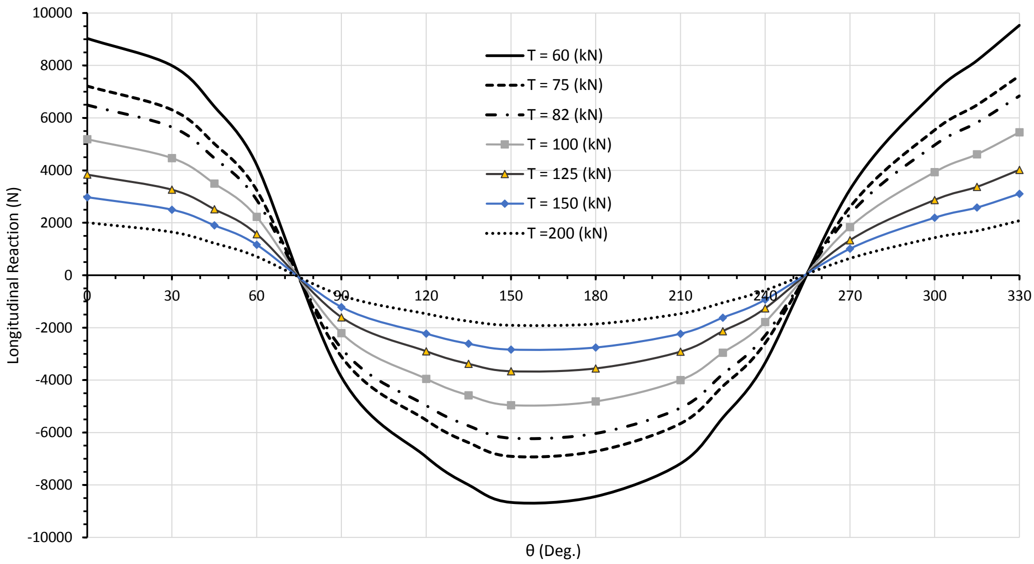


Fig. 20 Variation of Transmission Line's Longitudinal Reaction with Pretension Force and Sag – R = 125 (m) (Transmission Line System L1)

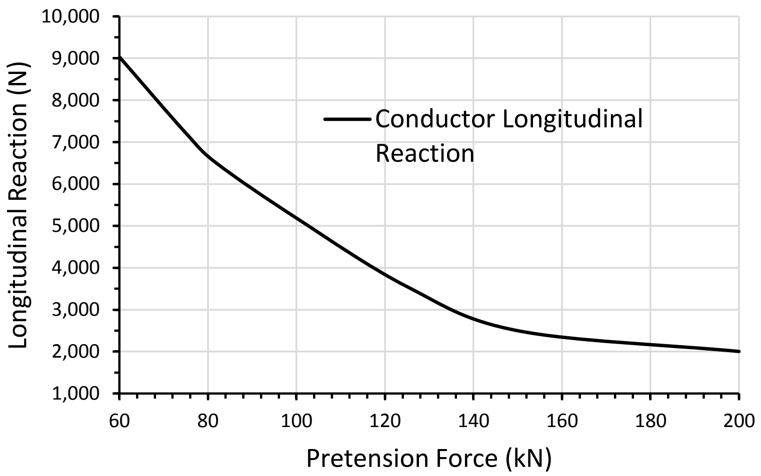


Fig. 21 Variation of Longitudinal Reaction with Pretension force

5.3 Effect of insulator length

Insulators are responsible of transferring the transmission line loads to the supporting towers. Insulators used in the industry can have different lengths. Based on industry recommendations, the range of insulator's length is 1 to 4.27 (m). In order to assess the effect of the insulators length on the longitudinal reaction of transmission lines during a tornado event, the analyses are repeated by varying the insulator length within this range. Both transmission line systems L1 and L2 are considered in this parametric study. The results of this parametric study are provided in Fig. 23, which illustrates that the longitudinal reaction changes significantly and in a nonlinear manner with the change of the insulator length. Shorter insulators lead to higher longitudinal reactions. The nonlinear behaviour is due to the nonlinear change of the insulators stiffness with movement as explained in detail in Hamada and EL Damatty (2011 and 2014).

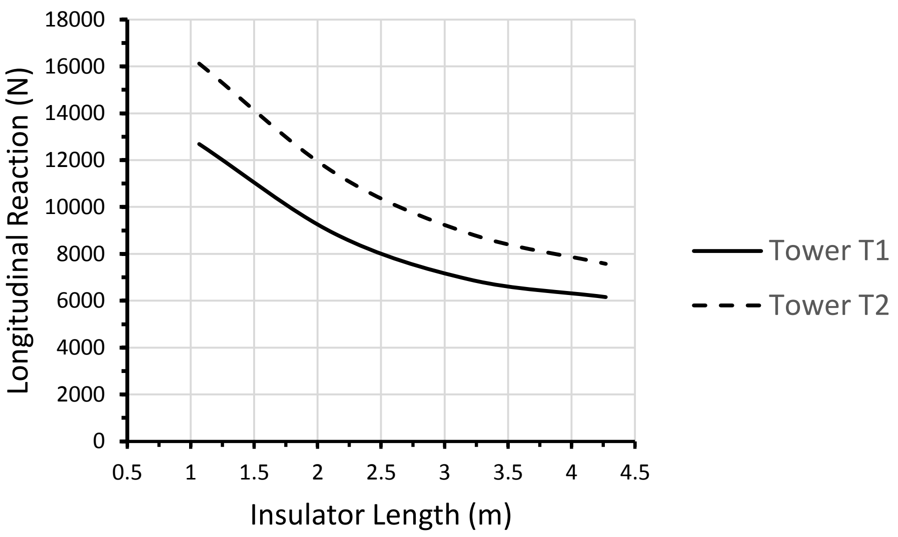


Fig. 22 Variation of Longitudinal Reaction with Insulator Lengths

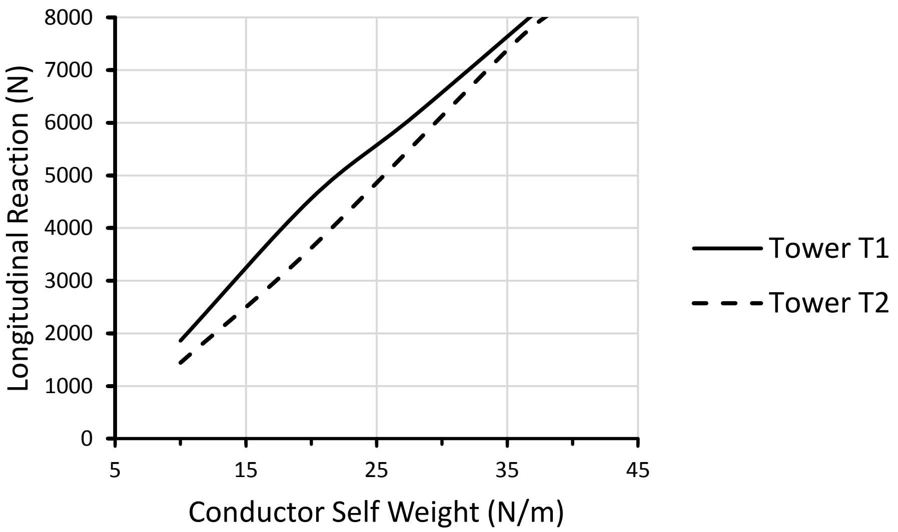


Fig. 23 Variation of Longitudinal Reaction with Conductor's self-weight

5.4 Effect of conductor self-weight

Transmission lines (conductors) are made of different composite materials. The selection of the lines material is based on different factors, such as the span, weather parameters, and method of installation. The self-weight of these lines varies from one hydro company to another and from country to another. Accordingly, the current section investigates the effect of the conductors self-weight on the longitudinal reactions. Both transmission line systems L1 and L2 are considered in this investigation. The results of this parametric study are shown in Fig. 23, which indicates that the longitudinal reaction change linearly with the variation of the conductor's self-weight.

6. Conclusions

The following conclusions can be drawn from the conducted study:

- The F2 tornado force (velocity) distribution on transmission lines, such as conductors and ground-wires, is highly non-uniform and varies nonlinearly. In addition, the applied tornado velocities on transmission lines can change directions within one line span, which leads to a high nonlinear behaviour and a more complex behaviour.
- The vertical (uplift and downdraft) velocity component of F2 tornado is significant and can be up to 40% of the transverse velocity component. Accordingly, nonlinear three dimensional analysis, involving coupling between the transverse and the vertical responses, is recommended for the studying transmission lines under tornado wind loads.
- The study investigates the validity of the recommendation made in some codes of practice to neglect the tornado loads acting on the lines. The results show that chord's peak internal forces increase by 22 to 140% due to the inclusion of the lines in the analysis under tornado loads.
- The length of transmission tower's cross-arms has a significant effect on the conductor's reactions associated with tornado loads. For the same tower, differences of 25% and 33% in the longitudinal and transverse reactions, respectively, are reported due to a horizontal distance between the two edge conductors of 29 (m). This difference in reactions leads to an additional torsional moment on the supporting towers.
- Significant longitudinal line's reaction leads to compression forces in tower's cross-arms that are not typically considered in the design of those cross-arm's members. Accordingly, the current study investigates the effect of different parameters on the longitudinal reactions of transmission lines. The study shows that the longitudinal reaction:
    a) has a nonlinear variation with the magnitude of the applied F2 tornado wind loads.
    b) changes significantly and in a nonlinear manner with both the value of the initial pretension force and sag, and the length of the insulator springs attached to the line.
    c) varies linearly with the change of the conductor's self-weight

In view of these conclusions, transmission lines' conductors and ground-wires are recommended to be considered in the analysis and design of transmission towers subjected to tornado wind loads.

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