Dynamic Response Analysis of Transmission Tower under Thunderstorm Downburst

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Abstract

Many transmission towers around the world collapsed due to thunderstorm downbursts. It is essential to understand mechanisms of downbursts and to predict dynamic responses of transmission towers under downbursts. In this regard, a deterministic-stochastic hybrid model of downbursts is employed to simulate the time history of wind speed caused by a downburst at the site of a tower. The hybrid model is factorized as a time-varying mean wind speed component and a fluctuating wind speed component. The former is represented by the product of a vertical profile and a time function, and the latter is treated as the amplitude modulated stationary stochastic process. Both wind speeds are transformed into downburst loads acting on the tower at different levels, taking consideration of flow accelerations induced by varying wind speed and direction. A 50.5 m tall transmission tower is selected as a case study. A finite element model of the tower is established using the commercial software ANSYS, and dynamic responses of the tower subjected to downburst load are analyzed using the Newmark's method. The results show that the dynamic responses of the transmission tower under downburst taking wind direction into consideration are different from that without considering wind direction. The sensitive locations of the goblet-type transmission tower to damage under downburst are the corner of the goblet head and the first level of the mast tower.

Key words: Thunderstorm downburst, Transmission tower, Dynamic response, Critical location

1. Introduction

Downburst is described as "a strong downdraft which induces an outburst of damaging winds on or near the ground"(1). It is one of the high intensity winds (HIWs), ranging from various forms of downbursts and micro-bursts all the way up to fully mature tornadoes(2). They are seldom recorded because of its relatively small spatial and temporal scales, but there are plenty records of transmission line and tower failures induced by HIWs in Argentina, Australia, South Africa, Brazil, the United States, Canada, and many other countries in the world. Many of the utilities reported that 80-100% of their weather-related facility failures were the result of HIWs. A survey of transmission line failures conducted by the CIGRE Study Committee 22, Working Group WG.06 for Line Reliability and Security essentially confirmed this finding. The committee report revealed that 139 of the 229 failures reported from 20 countries over the last 10 years were caused by thunderstorms and tornados (2).

In the current design codes of transmission towers, the traditional boundary layer winds such as monsoon winds are considered rather than HIWs for the design wind loads(3),(4),(5),(6),(7). However, downburst is different from traditional boundary layer wind in several aspects:

(1) Vertical wind speed profile: The average maximum wind speed of a downburst occurs at a height of proximate 80 m within a range from 50 to 100 m at a distance of about 1.5 km from the point of impact for an average downburst diameter of 1.8 km(8).

(2) Wind speed time history: The time history of traditional boundary layer wind speed can be regarded as a stationary process, whereas the time history of downburst wind speed is non-stationary. For a downburst, its mean wind speed is time varying and its fluctuating wind speed is non-stationary.

(3) Wind structure: A downburst is a local wind event. Its impacts range from the storm center to about 2 times the downburst diameter. The downburst moves forward with a translation speed.

(4) Wind data: Downbursts have been seldom recorded by meteorological stations whereas the traditional boundary layer wind data are fruitful. This is mainly attributed to relatively small spatial and temporal scales and severe damage characteristics.

The inherent differences between the downburst and traditional boundary layer winds may cause very different responses of transmission towers. However, the shortage of downburst data makes it difficult to predict return-period wind speeds based on extreme-value projections, although some progress is being made toward quantifying the risk of some HIW events. This is the reason why the current design codes for transmission towers consider the traditional boundary layer winds only but not the downburst. As a result, the transmission towers which are adequately safe under the boundary layer winds may fail to the downburst.

Therefore, this paper first employs a deterministic-stochastic hybrid model of downbursts to simulate the time history of wind speed caused by a downburst at the site of a tower. The hybrid model is factorized as a time-varying mean wind speed component and a fluctuating wind speed component. The former is represented by the product of a vertical profile and a time function, and the latter is treated as the amplitude modulated stationary stochastic process. Both wind speeds are transformed into downburst loads acting on the tower at different levels, taking consideration of flow accelerations induced by varying wind speed and direction. A 50.5 m tall transmission tower is selected as a case study. A finite element model of the tower is established using the commercial software ANSYS. Dynamic responses of the tower subjected to downburst load are analyzed using the Newmark's method and sensitive locations of the tower to damage due to the downburst are identified.

2. Downburst Model

The downburst model presented by Chen and Letchford(8) is adopted in this study. In their model, the wind speed time history of a downburst at any height is a non-stationary process and can be expressed as a sum of the time varying mean wind speed and the fluctuating wind speed. The time varying mean wind speed is factorized as the product of an Oseguera and Bowles's vertical velocity profile(9) and a time function, which respectively describe the changes of vertical and horizontal profiles with time. The time function with a maximum value of 1 is the ratio of the combined wind speed to the maximum combined wind speed. The combined wind speed is assumed to be the vector summation of the radial impinging jet velocity(10) and the storm translation speed(11). The fluctuating wind speed is obtained by an amplitude-modulated stationary Gaussian stochastic process with a standard deviation of 1. The Kaimal power spectral density (PSD) model and Davenport coherence function are utilized to form the PSD matrix. The eigen-decomposition based on the spectral representation method is utilized to generate wind speed time histories from the stationary Gaussian stochastic process.

The track of the downburst is such that the storm center of the downburst is right ahead of the tower and passes by the transmission tower at zero-angle in the y direction (see Fig.1). Hence, the line between the storm center and the tower center is parallel to the y-direction of the transmission tower and the windward face of the tower is normal to the moving path of the storm center. The downburst is assumed to come from a distance of 4000 m with a translation speed of 12 m/s.

The downburst is modeled with a horizontal radial wind speed profile shown in Fig. 2. Its maximum radial jet velocity is 33 m/s, occurring at a distance of 1120 m from the stagnation point (the storm center), with a characteristics radius of 1000m and a radial length scale of 700 m. The normalized vertical wind speed profile is displayed in Fig. 3, in which the characteristic height out of the boundary layer is 300 m, the characteristic height in the boundary layer is 24 m, and the scaling factor is 0.14/s(9).

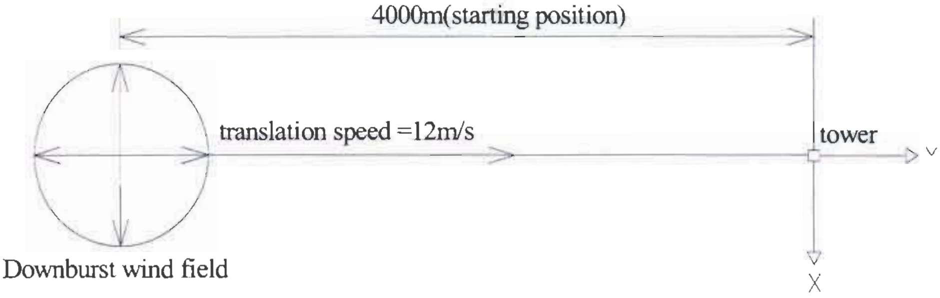

Fig.1 Track of downburst.

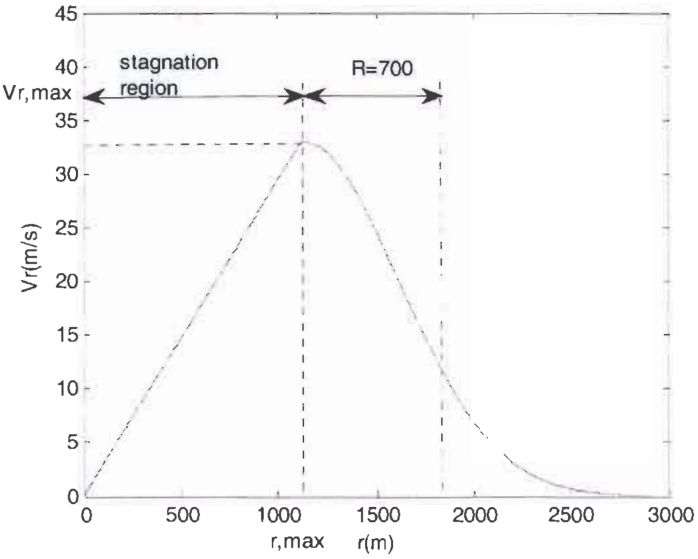

Fig.2 Horizontal radial wind speed profile.

The time function and the combined wind speed time history which is the vector combination of radial and translation velocities, at the position of the tower along the path of the downburst, are simulated and shown in Fig.4 and Fig.5, respectively. The time histories of the mean wind speed and the fluctuating wind speed at 47 m high of the tower along the downburst path are illustrated in Fig. 6 and Fig. 7, respectively. The time history of the downburst wind speed V_c, the summation of mean wind speed and fluctuating wind speed, at any height of the tower can be simulated using the downburst model. Fig. 8 illustrates the downburst wind speed time history at 47 m high of the tower.

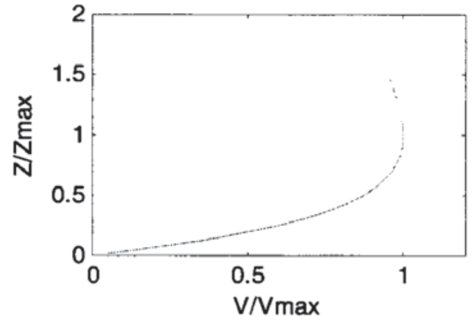

Fig.3 Vertical Profile of horizontal radial outflow.

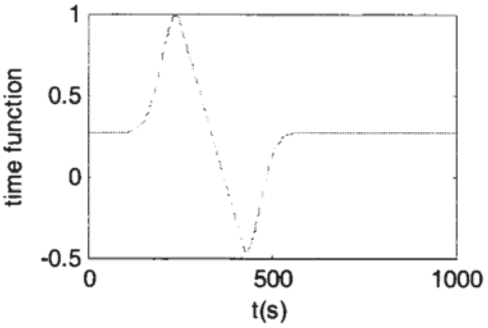

Fig.4 Simulated time function.

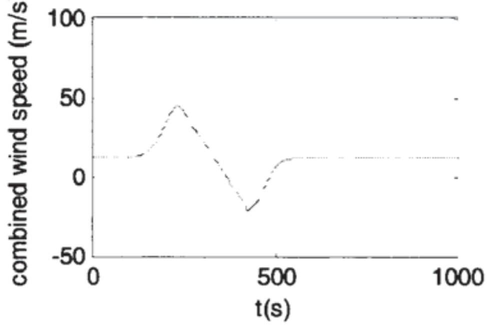

Fig.5 Simulated combined wind speed time history.

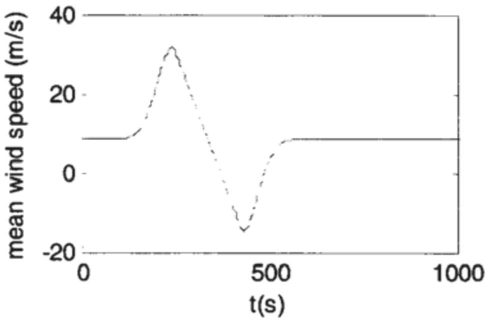

Fig.6 Simulated mean wind speed time history at height 47 m.

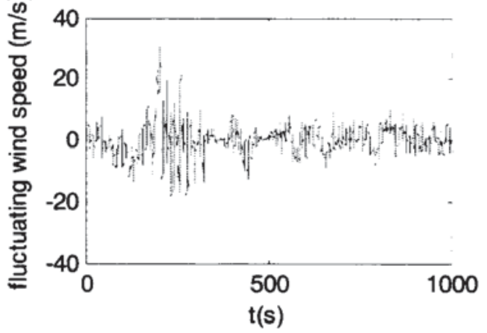

Fig.7 Simulated fluctuating wind speed time history at height 47m.

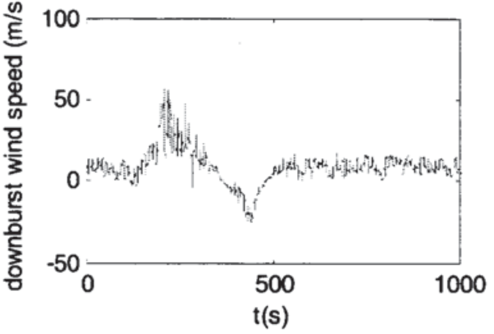

Fig.8 Simulated downburst time history at height 47m

3. Loading Model

Wind loads on a lattice transmission tower under traditional boundary layer winds depend on wind speed and wind direction as well as the size, shape and solidity ratio of the tower. Wind loads on a lattice transmission tower due to downburst are more complex than those due to traditional boundary layer winds. Nevertheless, there is no sophisticated way at present to ascertain wind loads on the lattice tower due to downburst. Most investigators(8),(12) just simply adopted the quasi-steady assumption and used the traditional way to calculate the downburst-induced wind loads on the lattice transmission tower. Some investigators considered also the inertia loads due to the accelerations in the wind flow as the downburst wind speed magnitude and direction are time varying(13). Consequently, the wind force on the transmission tower is the summation of the drag force and inertia force(14),(15). The latter method is used to calculate the wind force acting on the transmission tower induced by thunderstorm downburst in this study with the following equation.

$$F(t)=\frac{1}{2}\rho C_d D V_c \left|V_c\right|+\frac{\pi}{4}\rho C_m D^2 \frac{dV_c}{dt} \tag{1}$$

where C_d is the drag coefficient, which is approximately equal to 3.0 according to the UK Code of Practice for a lattice tower(3) with a solidity ratio of 19.04%; C_m is the inertia coefficient, which could be determined from experiments and taken as 1.0 here according to the previous study(14); ρ is the air density, which is 1.29Kg/m^3; D is the projected width of the transmission tower normal to wind direction; and V_c is the downburst wind speed in the y-direction as shown in Fig. 1.

4. Tower Model

The transmission tower selected in this study is a 110-500 KV goblet type self-supported transmission tower (see Fig.9). The tower is 50.5 m high with a square base of 9.0×9.0 m. The base tower is 9 m high, the mast tower is 23.15 m high, and the mast head is 18.35 m high. The tower is characterized as being wide at the base, then tapering from the bottom up to the top of the mast tower, and finally with a goblet type mast head. The dimension of the tower can be found in Fig. 9. The structural members of the main tower are made of equal steel angles and connected by bolts. The steel type is Q235 and Q345. There are a total of 24 types of cross sections of the structural members in the tower.

A finite element model is established using commercial software ANSYS, as shown in Fig. 10. The tower members are modeled by Beam188 elements, which are Timoshenko type beams including tension, compression, torsion, bending, and shear-deformation effect. This type of elements has six or seven degrees of freedom at each node, i.e., translations in the x, y, and z directions, rotations about the x, y, and z directions, and the optional warping degree of freedom. The tower model has 6318 elements, 11701 nodes and 70182 degrees of freedom in total. The modal analysis of the transmission tower shows that the first three natural frequencies are 1.992, 2.036, and 2.886 Hz, respectively. Fig. 11 shows the first three modal shapes.

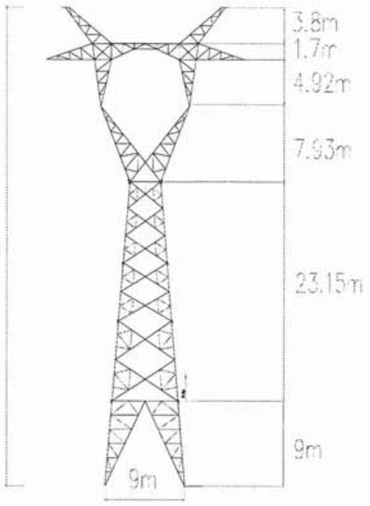

Fig.9 Schematic diagram of transmission tower.

Fig.10 Finite element model of tower.

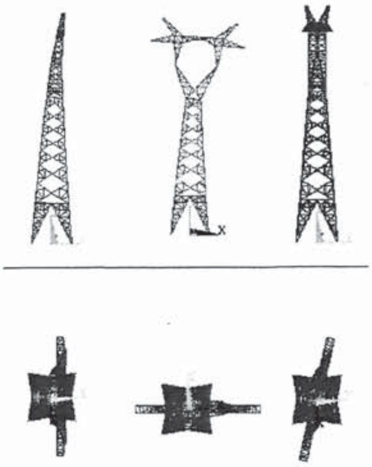
Fig.11 First-three mode shapes of the tower.

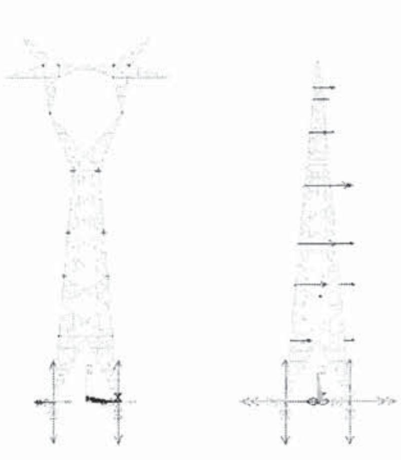
Fig.12 Wind loads on the tower.

Downburst loads are applied to 36 nodes of the tower model as illustrated in Fig. 12 with red color dots. Taking into account the shielding of leeward members by windward ones, the windward members take 2/3 of the total load and the leeward members take about 1/3 of the total load(13),(16). Consequently, the windward nodes receive 2/3 of the total load and the leeward nodes receive 1/3 of the total load. The load time history of the downburst on the transmission tower at node 33 is shown in Fig. 13

5. Response of Transmission Tower

Dynamic responses of the tower to downburst loads without considering transmission lines are computed using the Newmark's method. Different from traditional boundary layer winds, downburst wind magnitude and direction change with time. By looking at the downburst path illustrated in Fig.1 and with reference to the tower, the downburst radial wind changes its direction when the storm center passes through the tower. Wind loads on the tower are affected by wind direction. Therefore, if the wind changes its direction, the direction of wind load on the tower changes as well. However, in most previous studies the effect of downburst wind direction is often ignored. Fig.14 and Fig.15 illustrate the downburst-induced displacement response time histories at the top of the transmission tower without and with consideration of the downburst wind direction. It can be seen from the two figures that the consideration of downburst wind direction causes different displacement responses of the transmission tower from those without considering downburst wind direction.

Maximum displacements at windward and leeward nodes along the height of the tower in the y-direction are illustrated in Fig. 16 and Fig. 17. The maximum displacement at the top of the tower is 0.146 m. The maximum displacement does not increase linearly with height. In particular, the increasing rates of maximum displacements at 13.35 m and 40.08 m are high, indicating that the tower sections at the height of 13.35 m and 40.08 m are sensitive to the downburst.

The stress levels of the transmission tower under the thunderstorm downburst are also computed using the software ANSYS in order to evaluate the possible yielding positions of the tower by using the Tresca's yielding criterion, which assumes that shear stresses lead to the plastic flow and the element yields when the maximum shear stress reaches the yielding stress. The results show that the maximum shear stress occurs at positions i and j. We can conclude that positions i and j are the possible yielding positions, as illustrated in Fig. 18.

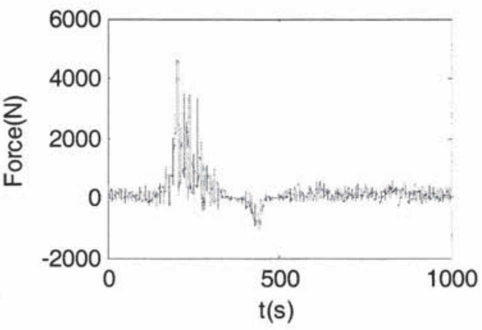

Fig. 13 Downburst load time history at height 47 m.

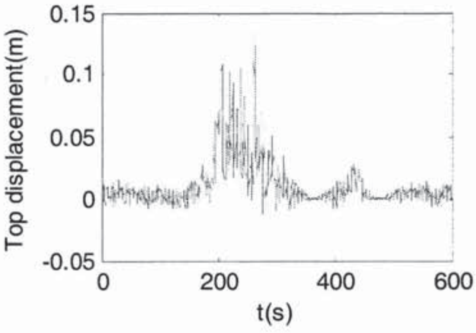

Fig.14 Top displacement of transmission tower (without considering wind direction)

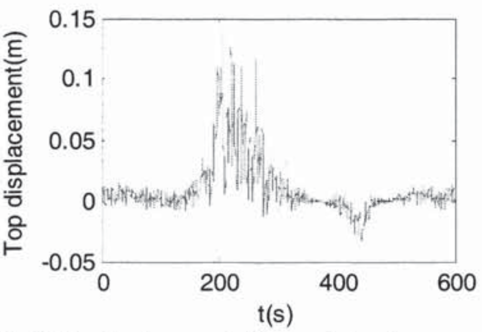

Fig.15 Top displacement of transmission tower (with considering wind direction).

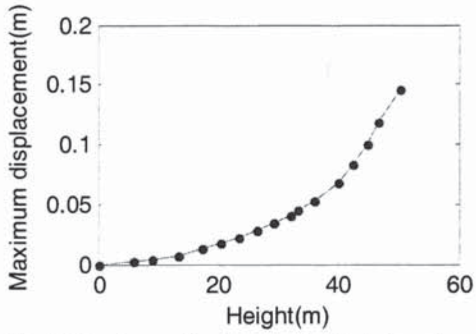

Fig.16 Maximum displacements of windward nodes along the height of the tower.

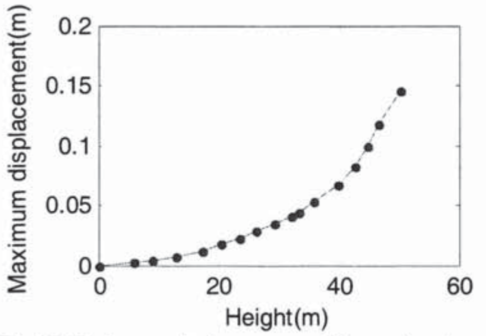

Fig.17 Maximum displacements of leeward nodes Along the height of the tower.

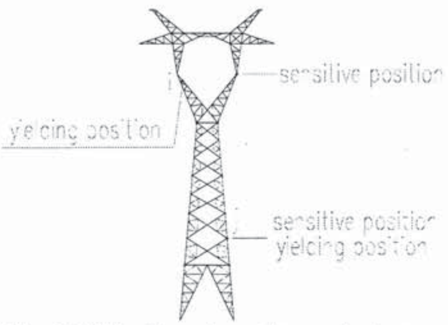

Fig. 18 Critical locations of transmission tower.

6. Conclusions

The deterministic-stochastic hybrid model of downbursts has been employed to simulate the time history of wind speed caused by a downburst at the site of a tower. Downburst winds have then been transformed into downburst loads acting on the tower at different levels, taking consideration of flow accelerations induced by varying wind speed and direction. A 50.5 m tall transmission tower has been selected as a case study with a finite element model established and the commercial software ANSYS used. The results show that the dynamic responses of the transmission tower under downburst taking wind direction into consideration are different from that without considering wind direction. The downburst-induced maximum displacement at the top of the transmission tower with wind direction considered is 0.146 m. The sensitive locations of the goblet-type transmission tower to damage under downburst are the corner of the goblet head and the first level of the mast tower.

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