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Ground wires longitudinal forces on end transmission tower subjected to downbursts

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SUMMARY

Most weather-related transmission line failures are caused by High Intensity Wind events such as downbursts. A crucial element of transmission lines' structural integrity is the end towers that contains the incidents of cascade failure. The most challenging aspect in modelling the transmission lines is the cables since they possess highly nonlinear structural behaviour. These cables can be conductors attached to the tower through insulators, or ground wires attached directly to the tower to protect the line during lightening. The current study aims to provide simplified practical methods to estimate the longitudinal reactions of the ground wires on an end tower. Firstly, the critical downburst configuration that causes maximum longitudinal reactions on an end tower is determined through a parametric study. Then, the effect of different ground wires' parameters on their longitudinal reactions is studied. Consequently, two methods are developed considering practical ranges of different parameters governing the ground wires' behaviour.

Keywords: *High Intensity Wind, Cables, Sheild wires, Geometric nonlinearity, Multiple variable regression*

1. INTRODUCTION

High Intensity Wind (HIW) events, such as downbursts and tornadoes, cause most of the reported weather-related transmission line failures around the globe. The importance of the structural integrity of transmission lines under downburst winds motivated many researchers to investigate this topic. Mara et al. (2010) and Shehata et al. (2005) concluded that the downburst size, strength, and location relative to the structure have a significant effect on the structure's behaviour.

Savory et al. (2001) studied the failure of a transmission tower under tornado and downburst wind. They predicted a failure in the case of the tornado. However, no failure was evident in the case of the downburst. In contrast, Shehata et al. (2005) presented three failure modes for a transmission tower under downbursts. Aboshosha et al. (2016) explained that the first study did not take the cables' reactions into account while the later one included the cables' reactions and revealed that a critical failure mode was due to the significant variation in the longitudinal cables' forces transmitted to the tower. This finding casted light on the importance of including the cables' forces when studying transmission towers. These cables can be conductors attached to the tower through insulators, or ground wires attached directly to the tower to protect the line during lightening.

El Damatty and Elawady (2018) conducted a study to provide practical design provisions for tangent transmission towers. They introduced three load cases resulting from an extensive parametric study of the downburst locations and sizes. These load cases were adopted by ASCE-74 (2020) guidelines. The most challenging aspect of these load cases is the estimation of the cables' longitudinal reactions resulting from the unbalanced tension forces. This task requires conducting nonlinear analysis of the cables using the non-uniform downburst forces. As a result, Elawady and El Damatty (2016, 2018) developed sets of charts and a three-dimensional interpolation technique that can be used to estimate the longitudinal reaction without conducting nonlinear analysis. Their method for both the conductors and the ground wires was also incorporated in the ASCE-74 (2020) guidelines.

While a typical transmission line consists of a series of transmission towers supporting the conductors and the ground wires, end transmission towers are usually stronger towers used within the line to limit cascading towers collapses. Also, end transmission towers are used when the line terminates when it is connected to a substation equipment or transitions to underground cables. While most of the conducted studies focused on the typical tangent towers. Recently, Ahmed and El Damatty (2025) conducted a study where they investigated the behaviour of the end towers under downburst loading through experiments conducted at WindEEE (Wind Engineering, Energy and Environment) facility. They also conducted a numerical study where they concluded that the current tangent towers guidelines are not adequate for designing the end towers under downburst winds. This fact is the motivation of the current study to evaluate ground wires' longitudinal forces acting on an end tower. The evaluation of ground wires' longitudinal forces is a challenge since it requires conducting nonlinear analysis for the ground wires under the non-uniform downburst loading. The aim of the current study is to provide simplified methods to estimate the ground wires' longitudinal forces on end towers for engineering practitioners.

In the current study, the critical downburst configuration resulting in maximum longitudinal forces is first evaluated. Then, the parameters controlling the behaviour of the ground wires are studied. Moreover, two methods are suggested to estimate the ground wires' longitudinal reaction based on the most significant ground wires' parameters. The first method relies on the three-dimensional linear interpolation technique previously introduced by Elawady and El Damatty (2016, 2018). The second method introduces the use of multiple variable regression analysis approach to develop a simple yet accurate empirical expression for the ground wires' longitudinal forces.

2. METHODOLOGY

High Intensity Wind events such as downbursts are localized events. Therefore, conventional methods are not suitable to measure their characteristics in the field. As such, the Computational Fluid Dynamics (CFD) introduces an alternative that can be used to model these extreme events. The current study utilizes the CFD model developed and validated by Kim and Hangan (2007). They provided a time series of the mean wind speed for a small-scale model. A scaling-up technique is proposed by Shehata et al. (2005) in order to estimate the full-scale downburst wind field. The downburst wind field depends on a reference velocity called the jet velocity (V_J) and it varies between 50 m/s and 70 m/s. The downburst wind profile depends on the downburst size referenced by the jet diameter (D_J) and the distance from the center of the downburst (R).

The semi-closed form solution developed and validated by Aboshosha and El Damatty (2014) was used in the current study due to its computational efficiency compared to the nonlinear finite element analysis. An efficient technique is crucial in the current study where approximately 2900 analysis cases were conducted. This semi-analytical technique was found to be 185 times faster than the nonlinear finite element analysis. Despite its computational efficiency, this technique was proven to be accurate taking into account the cables' highly nonlinear behaviour in addition to the insulator's flexibility (Aboshosha and El Damatty, 2014).

3. CRITICAL DOWNBURST CONFIGURATION

A parametric study covering different possible downburst parameters and locations is conducted. Two cable configurations of three different spans were used in this parametric study. The analysis is conducted through the following ranges and the maximum longitudinal reactions along with their corresponding downburst parameters are recorded.

- D_J from 500 to 1500 m with an increment of 250 m
- R/D_J from 0.8 to 2.0 with an increment of 0.2
- θ from -90º to 90º with an increment of 15º

These ranges result in 455 different analysis cases. The conducted parametric study on the 6 cables revealed that the critical case resulting in maximum longitudinal cable reaction is when D_J is equal to 1500 m, R/D_J of 1.2, and θ has a value of 15º.

4. EFFECT OF GROUND WIRES' PARAMETERS ON THE LONGITUDINAL FORCES

The effect of the ground wire's different parameters on its longitudinal reaction when it is subjected to downbursts is examined. The ground wires are studied under the critical downburst configuration. The five parameters that define the ground wire's nonlinear behaviour and longitudinal reactions on the end tower, are the wind pressure, the sag ratio, the cable's weight per unit length, the cable's axial stiffness, in addition to the span. Six cables are introduced in Table 1 and are used by changing one parameter at a time to examine its effect on the longitudinal reaction (R_x) through a practical range for each parameter as reported by Elawady and El Damatty (2018).

Table 1: Ground wires used to identify the effect of each cable's parameter on the cable's reactions.

Ground wire index	Weight per unit length w (N/m)	Projected diameter d_P (mm)	Axial stiffness EA (N)	Sag ratio s%	Span L (m)
GW1	3	5.9	2.00E+07	4.0%	300, 400, and 500
GW2	15	20.2	6.00E+07	2.5%	300, 400, and 500

A summery of the studied ground wire's parameters and their effect on its longitudinal reaction on an end tower, is presented in Table 2. As this table suggests, the relationship between the ground wire's longitudinal reaction and its different parameters can be assumed linear.

Table 2: The effect of the ground wire's different parameters on its longitudinal reaction acting on an end tower subjected to downbursts.

Parameter	Effect on R_x
The wind pressure (α)	Linear variation within α range of 18 kg/sec^2 to 62 kg/sec^2
The sag ratio (s%)	Linear variation when s% is 2.5% up to 4.0%
The cable's weight per unit length (w)	Linear variation through a range from 3 N/m to 15 N/m
The cable's axial stiffness (EA)	Linear variation within the range between 2.0E+7 N and 6.0E+7 N

5. PROPOSED METHOD FOR ESTIMATING GROUND WIRES' LONGITUDINAL REACTIONS

This section highlights the development of two practical methods that can be used to estimate the ground wires' longitudinal reactions as function of the cables' parameters as an alternative of conducting nonlinear analysis under the downburst time series load. The first method is an adoption of the three-dimensional interpolation technique by Elawady and El Damatty (2016, 2018) and Yao and El Damatty (2024). The second method utilizes multiple variable regression analysis to develop an equation that can be used to estimate the ground wires' longitudinal reactions within the studied practical ranges. To validate the use of these methods, test cases are analyzed and estimated using the suggested methods, each one at a time, and the error percentage is calculated. The maximum error does not exceed 5% indicating the adequacy of these methods.

6. CONCLUSIONS

The current study suggests practical methods to estimate the longitudinal ground wires' reaction acting on an end tower due to downbursts. Firstly, the critical downburst configurations that causes maximum longitudinal reaction are revealed to have R/D_J of 1.2, θ of 15^o, and D_J equals to 1500. Ground wires' longitudinal reactions depend on their nonlinear structural behaviour. As such, these reactions depend on the structural properties of the ground wire. The effect of different ground wire's parameters on its longitudinal reaction is studied. Then, two practical methods for estimating the longitudinal reaction are developed. The first method uses a three-dimensional linear interpolation technique through a set of 8 charts. The second method uses an equation that was developed through multiple variable regression analysis.

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