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Engineering method for estimating the reactions of transmission line conductors under downburst winds

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ABSTRACT

In this study, a closed form solution to calculate the reactions of transmission line conductors subjected to downburst loads is derived. The derivation is conducted using a simplified multi-spanned conductor–insulator system, where the insulators to the right and to the left of the tower of interest are modeled using a combination of roller supports and linear springs. The considered system allows for the interaction between the spans without the need of solving a set of non-linear equations to avoid the complexity. The closed form solution is derived to be applicable for downbursts with arbitrary size and location relative to the line. The solution is then focused on a critical downburst case that is previously recommended for the line design. Accuracy of the derived solution is assessed under both downbursts with arbitrary size and location and downbursts corresponding to the critical case. The assessment is carried out by comparing the conductor reactions obtained using the proposed solution with those from the Finite Element Analyses (FEAs). It is found that the predicted reactions by the proposed solution are in a very good agreement with those from the FEA in both the transverse and the longitudinal directions. For example, the highest differences for the critical case are found equal to 2% and 8% for the reactions in the transverse and the longitudinal directions, respectively. This indicates that the solution is reasonably accurate given the complexity of both the downburst wind field and the structure behavior of the conductor system. The proposed solution represents a practical and useful tool for practitioner engineers involved in the design of transmission lines, particularly under downburst winds.

1. Introduction

Electricity is carried by Transmission Lines (TL) from sources of production to end customers. Transmission Lines (TLs) consist mainly of towers, conductors and insulators. Conductors, which are supported by the towers through the insulators, are responsible for transmitting the electricity. The economic losses associated with the failure of a TL do not only result from the repairing costs but also from the interruption of power, which can extend for few months. It is reported that High Intensity Winds (HIW), in the forms of downburst or tornadoes, are responsible for more than 80% of the weather-related failures of TLs worldwide [12]. A downburst is a strong downdraft that induces an outburst of damaging winds near the ground as described by Fujita [15]. In September 1996, Manitoba Hydro Company, Canada, reported a failure of 19 transmission towers due to a downburst event [21]. In Australia, Li [20] stated that downbursts are responsible for more than 90% of the weather-related failures.

Shehata et al. [23] conducted a failure study on a guyed transmission line subjected to downbursts. They utilized the downburst wind field obtained by Kim and Hangan [18] using a Computational Fluid Dynamics (CFD) simulation, in which the downburst was treated as an impinging jet. Their study showed that the most critical failure mode happens due to a downburst with a jet diameter, D_j, (i.e. diameter of the downdraft) equals to twice the conductor span length, L_x, which is located at a radial distance, $R = 1.60\ D_j$, and an angle $\Theta = 30°$ measured from the tower of interest, as shown in Fig. 1. This leads to a large differential tension between the conductor spans on the sides of the tower of interest which leads to a large longitudinal forces transmitted from the conductors to the tower. Design standards are now at an early stage of including HIW in the design of TLs. For example, the AS/NZS [5] provides a map showing the areas where downbursts have to be included in the design. The standard uses a uniform load to model the downburst effect on the conductor spans. Although, this can be used to reasonably obtain the transverse reactions, it

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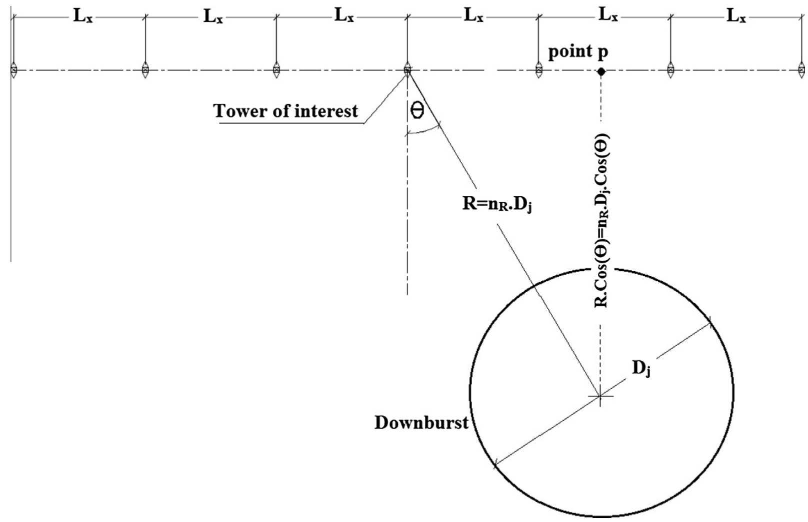

Fig. 1. Downburst parameters.

does not allow for the prediction of the differential conductor tension between the spans, which was found to be important. The studies performed by El Damatty and Aboshosha [13], Aboshosha and El Damatty [1], El Damatty et al. [14] manifested the importance of accounting for the differential conductor tension while studying the downburst effect on the TLs.

Finite Element Analysis (FEA) was utilized in most of the previous studies to predict the behavior or the failure of transmission lines under downbursts [23,24,11]. Their studies showed that analyzing the conductors using FEA and predicting the critical longitudinal forces transmitted to the towers due to downburst loading is a time consuming task. This is due to the following: (1) Conductors are highly flexible structure elements. Therefore, their behavior under transverse loading associated with downbursts is highly non-linear due to the large deformations and the P-delta effect. (2) Since downbursts are localized events, their size and location can vary, which lead to altering the loads acting on the conductors and consequently the transmitted forces from the conductors to the towers. As such, the determination of the maximum forces transmitted requires a long parametric study that involves altering the downburst size and location.

Other than FEA, Irvine [17] proposed a closed-form solution to obtain the reaction for a single spanned conductor, which is subjected to loads that can be fitted by a 3rd degree polynomial. Yu et al. [28], also proposed a closed-form solution for a single spanned conductor subjected to high concentrated loads. However, both solutions do not consider the flexibility of the insulators, which has a significant effect on the forces transmitted to the towers [11]. The method of the rolling span, proposed by Winkelman [27], accounts for the insulator flexibility. However, it neglects the differences between the conductors' tensile forces in the adjacent spans and, consequently, fails to predict the longitudinal forces transmitted to the towers. Ahmadi-Kashani and Bell [4], Wie et al. [26] developed cable elements that are able to simulate a whole span based on the analytical solution of elastic centenary. Modeling a whole span using those elements reduces the number of degrees of freedom significantly compared with discretizing the span using multiple regular cable elements. However, those elements were developed for uniform wind loads only, which is not the case for downburst winds. This motivated Aboshosha and El Damatty [2] to develop a semi-analytical technique to solve for the conductor reactions under a general non-uniform distribution of loading. Aboshosha and El Damatty [2] showed that this technique is quite efficient and accurate in predicting the conductor's response under downburst loading. The drawback of this technique is that it involves solving simultaneous nonlinear equations with a relatively large number of unknowns, and this requires an iterative technique. This might not be easy to handle by practitioner engineers. The first objective of the current study is to simplify this technique in order to reach a closed form solution that can used to calculate the forces transmitted from the conductors to the towers due to a downburst with a general size and location in space. The second objective is to focus the solution to calculate the longitudinal forces for the critical downburst case recommended for the line design by El Damatty et al. [14]. The margin of error resulting from the assumptions incorporated in the developed closed form solution is quantified. The paper starts by laying down the mathematical formulations describing the problem and deriving the closed form solution step by step for both the transverse and the longitudinal reactions due to a general downburst configuration as shown in Section 2. The closed form solution obtained in Section 2 requires some factors that depend on the downburst size and location. These factors are obtained in Section 3. In Section 4, the formulation focuses on the critical downburst case that is responsible for inducing the maximum longitudinal conductor reaction and previously recommended for the line design. A parametric study is then conducted in Section 5 to assess the accuracy of the closed form solution. Accuracy is estimated by comparing the reactions obtained from the closed form solution with the reactions obtained from non-linear finite element analyses.

2. Formulation

Based on how the conductors are supported, transmission towers can be classified into three categories: supporting towers, tension towers and end towers. For the supporting towers, conductors at both sides of the tower are supported by a single insulator to balance most of the tension forces between the two sides. This category of towers is used in the straight portion of the line and represents the majority of the towers. Tension towers are typically used when there is a change in the inclination of the line direction. Different than the supporting towers, conductors at both sides of the tension towers are supported by individual insulators. This arrangement leads to a resultant tension that needs to be resisted by the tower. Therefore, tension towers are typically stiffer than supporting towers. A tension tower can also serve as a stop-breaking tower resisting the tension force in the case of broken wires preventing the progressive collapse of supporting towers. End towers are used at the end of