Engineering Structures 123 (2016) 490–500

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Nonlinear inelastic responses of transmission tower-line system under downburst wind

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ARTICLE INFO

Article history:
Received 1 December 2015
Revised 22 April 2016
Accepted 26 May 2016
Available online 14 June 2016

Keywords:
Capacity curve
Downburst
Electrical transmission tower
Inelastic systems
Nonlinear dynamic analysis
Wind forces

ABSTRACT

Electrical transmission tower-line systems transport the needed electrical energy. These systems are spatially distributed and subjected to extreme natural environmental events such as downbursts. The capacity curve of a single tower has been reported under the downbursts but neglecting the turbulent wind component and potential dynamic tower-wire interaction. This study is focused on the assessment of capacity curve of a tower within the tower-line system considering the turbulent winds and the tower-wire interaction. The incremental dynamic analysis and the nonlinear static pushover analysis are employed to estimate the capacity curve. Moreover, comparison of such a capacity curve to that of a single tower is also presented. It was shown that the turbulent winds introduce variability in the capacity curve. The estimated capacity curve by using the nonlinear static pushover analysis is in close agreement to the average capacity curve obtained based on the curves estimated using the incremental dynamic analysis. Most importantly, it is shown that the capacity curve of a single tower represents adequately that of a tower within a tower-line system, and the effect of the dynamic interaction between the tower and the wires on the capacity curve is negligible.

1. Introduction

Electrical transmission tower-line systems are critical for the transportation of electrical energy. The design of tower-line systems is often governed by the wind load, although the ice load could be important for cold regions. The wind loads acting on the transmission tower, conductors and ground wire are specified in the CSA C22.3 No. 60826-10 [1], the Guidelines for Electrical Transmission Line Structural Loading [2], the ANSI National Electric Safety Code [3], and the International Electrotechnical Commission (IEC) Standard 60826:2003 [4]. The specifications are typically developed based on an atmospheric boundary layer (ABL) wind profile. The design of the tower-line systems is carried out by considering the elastic responses under wind loading and neglecting the inelastic behaviour of transmission towers. The latter can be justified since the duration of extreme ABL winds is long and the ductility demand associated with such winds is large [5,6]. The ductility demand is reduced for high intensity wind events with short durations such as tornados and downbursts. Therefore, there is value in assessing the nonlinear inelastic force-deformation relation (or capacity curve) of the tower and tower-line systems under wind loads due to high intensity wind events by considering the inelastic behaviour.

The evaluation of the responses of a tower under tornado and microburst-induced wind loading was given in [7] by neglecting the turbulent fluctuating winds. They showed the value of using numerical modeling of the tower under high intensity wind events to identify the failure mode observed in the field. They also suggested that the influence of the conductor loads and the effects of high intensity winds on different types of towers need to be investigated. In addition to this study, other studies focused on assessing the responses of tower or tower-line systems under high intensity wind events include those reported in [8–11]. In all cases, these studies did not consider nonlinear inelastic behaviour. The assessment of inelastic responses and the capacity curve for a single tower was presented in [12–14]. For their assessment, the incremental dynamic analysis (IDA) and the nonlinear static pushover analysis (NSPA), that are often applied to evaluate the performance and capacity of structures under seismic loading [15], are employed. The NSPA is carried out by monotonically increasing the lateral loads with a predefined height-wise lateral load distribution, while the IDA procedure requires a series of linear/nonlinear dynamic analyses to be carried out for a few selected load-time histories that are scaled using an intensity measure.

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http://dx.doi.org/10.1016/j.engstruct.2016.05.047
0141-0296/

Nomenclature

A	cross-sectional area of the wire
$A(\boldsymbol{p},t)$	amplitude modulating function at point $\boldsymbol{p}$ and time t
C_x	exponential decay coefficients along X-axis
C_{xc}	drag coefficient for the wire
C_{xti}	drag coefficient for the i-th face
C_z	exponential decay coefficients along Z-axis
$\mathrm{Coh}(\boldsymbol{p}_i,\boldsymbol{p}_j,f)$	coherence function
D_{jet}	jet diameter of simulated downburst
D_T	tip displacement of the tower obtained from time history analysis
d	diameter of the wire (m)
E	elastic modulus of the wire (kPa)
F_c	total load on the wire
F_t	total wind load on the panel along the wind direction
f	frequency (Hz)
G_c	combined wind factor for the wire
G_L	span factor for the wire
G_t	combined wind load factor for the tower panel accounting for roughness of terrain and height of the panel
K_{st}	stiffness of the end-spring
$\kappa(\boldsymbol{p},t)$	normalized fluctuating wind speed
L	span between adjacent towers
L_e	effective wire length
ΔL	length of the two-node link element
p and q	the orders of the AR and MA components order of the ARMA model
q_y	gravity load of wire per unit length
r	distance from the center of the downburst to a point of interest
S_B	base shear of the tower obtained from time history analysis (kN)
$S(f)$	power spectral density function
S_{ti}	total surface area projected normally on the corresponding i-th face (m^2)
s_L	sag to span ratio
T_0	horizontal tension of the wire (kN)
t_s	time step used in downburst simulation
Δt	time interval for ARMA algorithm
V_{hor}	horizontal wind speed resulting from downburst
V_{jet}	jet velocity of simulated downburst
$\overline{V}(\boldsymbol{p})$	maximum mean wind speed at the point $\boldsymbol{p}$
V_R	reference wind speed
$v(\boldsymbol{p},t)$	fluctuating wind speed
z	height
Ω	angle of attack (yaw angle) between the wind direction and the wires
β_i	moving average (MA) coefficient
γ_i	autoregressive (AR) coefficient
ε_i	n-variate Gaussian white noise
τ	density correction factor
μ	density of air
θ	angle of attack (yaw angle) between the wind direction and the tower

The results from these analyses are used to evaluate the force-deformation relation, and to identify the capacities of the tower at incipient yield and at incipient collapse. A comparison of the results from a nonlinear finite element model to full-scale push-over data of a tower is given in [12], showing good agreement between the analysis and test results of the tower. It was found in [13] that the capacity curve, defined by the tip displacement of the tower versus the base shear of the tower, can be adequately estimated using the NSPA, and that the capacity curve obtained by the NSPA agrees well with that obtained by the IDA. The results reported in [14] are focused on the downburst wind loads considering that the model given in [16] is appropriate. They showed that the capacity curve of a single tower is influenced by the loading profile and wind direction, that the capacity curves for any given wind direction under downburst winds are approximately bounded by those obtained for the ABL and rectangular wind profiles, and that the capacity curve or surface for the ABL wind profile could be used as a conservative approximation to that for the downburst wind loading. These observations can be used as basis to simplify the task of checking newly designed towers and evaluating existing towers under downbursts if approximate results are desired. It must be emphasized that only a single tower is considered in these mentioned studies; the investigation of the impact of dynamic interaction due to the conductors and ground wire on the capacity curve of the tower is not available in the literature. An extensive review on dynamic responses of tower-line system can be found in [17].

This study is focused on the nonlinear inelastic responses of tower-line system subjected to downburst wind loading. The main objectives of the study are to develop the capacity curve of a tower within the tower-line system (i.e., considering the dynamic tower-wire interaction) under downburst wind loading, and to compare such a capacity curve to that obtained for a single tower without incorporating the dynamic effects of the conductors and ground wire. The comparison is aimed at suggesting a simple procedure to assess capacity curve of a tower within the tower-line system.

2. Modeling of transmission tower-line system under downburst wind loads

2.1. Modeling of transmission tower-line system

A tower-line system with self-supported lattice transmission towers is illustrated in Fig. 1. Details on the section properties of the structural members of the tower and the geometric variables are the same as those given in [14,18]. The material nonlinearity of the tower members is considered using bilinear model with the ratio of the post-yield stiffness to initial stiffness equal to 0.05. The tower is modeled in ANSYS [19], where the tower members are modeled using 2-node nonlinear 3-dimensional frame elements assuming rigid connections (representing multi-bolted moment-resisting connections). A 3-dimensional numerical model of the tower is shown in Fig. 1b and c; the tower model consists of 959 elements and 405 nodes. The geometric nonlinearity is accounted for through the use of a large deformation analysis. The tower is assumed to have fixed base and the soil-structure interaction can be neglected.

The overhead wires are pre-tensioned; the pretension depends on the sag to span ratio [20]. The properties of conductors and ground wire are shown in Table 1, and the span length between two adjacent towers is 488 m. For the finite element modeling, each wire within a span is represented using 30 two-node link elements, where each node has three translational degrees of freedom and the element is specified to take the tension only along the direction of the wire. To define initial geometry of the wire profile and the coordinates of the nodes, a sag to span ratio, s_L, of 0.03 is considered to be adequate [21], and an iterative procedure is used