ICONHIC2022
3rd International Conference on Natural Hazards & Infrastructure
5-7 July 2022, Athens, Greece

Modular modeling and risk assessment of power transmission lines under extreme weather hazards

Angeliki Gerontati[1]
Institute of Steel Structures, National Technical University of Athens, Athens 15780, Greece

Dimitrios V. Bilionis
RISA Sicherheitsanalysen GmbH, Xantener Straße 11, Berlin-Wilmersdorf 10707, Germany

Dimitrios Vamvatsikos
Institute of Steel Structures, National Technical University of Athens, Athens 15780, Greece

Mike Tibolt
ArcelorMittal Belval & Differdange SA – AMBD, Esch-sur-Alzette, Luxembourg

ABSTRACT

Power transmission lines are the “highways” of electricity, consisting of conductors supported on steel towers. Transmission towers are categorized as support or angle/dead-end based on their capability to resist along-line loads transmitted by the conductors. They are vulnerable to severe weather and in particular the combination of high winds and ice accretion that could lead to catastrophic failures. It is thus of great interest in the system design to arrest the propagation of a single tower failure that may trigger a series of failures of adjacent ones, considerably lengthening the duration of power outage. A modular multi-span model of a power line is proposed for the assessment of the behavior of the tower-line system and the severity evaluation of such failures. Fault tree analysis is employed to examine the failure propagation to adjacent towers under extreme weather hazard, which allows the assessment of consequences at the level of an entire system of interleaved support and angle/dead-end transmission towers. The aggregated economic losses for an operational lifetime of 60 years are investigated using the proposed model versus a simplified approach, where all towers are exclusively characterized as support ones without considering successive failures.

Keywords: risk assessment, power line, failure propagation, lattice towers

INTRODUCTION

Risk assessment is a process to identify potential hazards and analyze the possible impacts to a structure if the hazard occurs. The process consists of a sequence of steps that can be applied to a wide range of structures and systems; herein the focus is on the risk assessment of power transmission lines. A transmission line is a part of the electric power utility system, transmitting electricity from power plants to consumers over long distances and as a result it is constantly exposed to weather hazards. Several researchers have studied this subject over the years, but the scale of the system usually leads to simplifications in assessment, as will be discussed in the following.

Of significant importance when assessing the risk of a power line, is to accurately determine its constituent components and the hazard they are exposed to. The way different components are affected by the same hazards changes the performance of the overall system. Specifically, a transmission line is composed of different types of lattice towers. Support/suspension towers provide the bulk of the transmission line towers; they are light structures, employed at linear sections, mainly supporting gravity loads and transverse lateral

---

[1] E-mail address: agerontati@mail.ntua.gr

loads, e.g., due to wind. Dead-end towers are placed at the end-points of the line, while angle towers are placed at the points where the direction of the conductors changes as they are both capable of resisting along-line, one-sided, or eccentric lateral loads. Thus, they are also interspersed at regular intervals (say every 3-5 towers) along the line to support conductor axial forces and arrest cascading failures. Usually dead-end and angle towers have similar or even the same geometry and consequent behavior, being able to support much higher lateral loads than support towers.

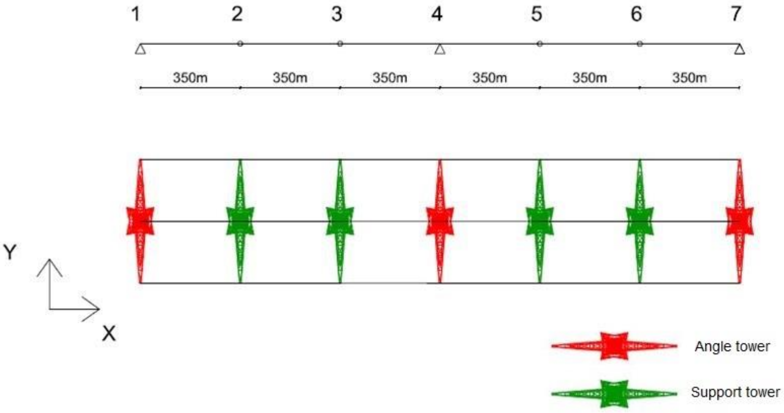


Figure 1. *Power transmission power line geometry*

When it comes to hazards for transmission lines, weather is the governing factor. Several studies, among which those of Liang et al. (2015) and Savory et al. (2001), claim that strong winds are the main cause of transmission tower collapse; as a result, wind speed is the most common intensity measure for this type of analysis. Wind direction is also very important, not so much with respect to the structure of the tower itself but in respect to the resulting conductor lateral load. Another critical loading condition, mostly observed in northern latitudes, is accumulated ice on towers and conductors, increasing not only gravity loads but also changing their shape resulting in increased lateral loads and potential aerodynamic instabilities for conductors. Furthermore, assessing a single tower is not necessarily enough. By design a collapse can propagate to adjacent towers; such cascading events are often characterized by a single initiating failure event followed by complex sequences and are the main reason for large-scale blackouts on series systems such as a transmission line (Abdalla et al, 2008; Zimmerman et al, 2017).

Considering the significance and need of uninterrupted supply of energy, the development of a framework for the performance-based assessment of power transmission networks is essential. The ultimate goal is the risk estimation of transmission lines under “all” combinations of wind and icing conditions; for this reason, a power line consisting of different types of towers subjected to cascading failures is studied via fault tree analysis. At the last step, the results of the risk assessment of the transmission line are used to calculate the total cost over a 60-year lifetime and compared with the results of a simplified approach. The latter approach assumes that dead-end/angle towers are invulnerable, and only employs support towers without considering successive collapses.

CASE STUDY TRANSMISSION LINE

The hypothetical six-span transmission line under study is shown in Fig.1. The power line has a length of 2.1 km and consists of both angle/dead-end and support Danube-type towers (Tibolt et al, 2021). Each tower is 50 m high and it carries two 380 kV circuits, each circuit consisting of three phases. A phase is made of a bundle of four conductors; in the case of a support tower, conductors are supported by insulators hanging vertically, while for angle/dead-end towers they hang at an angle. Also, a single lightning protection wire is installed at the top of the towers. Both support and angle/dead-end towers have the same geometry; the overall plan is square with dimensions at the base of 6.84m × 6.84m and decreasing upwards. The structural parts comprise equal-leg angles of various sizes of S355J2 steel; an interested reader should refer to Bilionis et al. (2020a) for more detailed information.

FRAGILITY ANALYSIS

Three-dimensional (3D) models of the towers were developed on the OpenSees platform (OpenSees 2006), where a large number of dynamic analyses were performed for discrete values of the intensity measures (IMs). The IMs used in this study are wind speed, wind direction and ice thickness. Each wind speed value is used as a reference 10-min average value in TurbSim (Jonkman and Kilcher, 2012) to generate multiple 10-min timehistories; each timehistory is associated with a wind direction. The transmission towers under study are symmetric with respect to the structure's (local) principal axes, *x* and *y* (Fig.2), which per Fig.1 are perfectly aligned with the global axes, with *x* running along the line. Thus, a wind angle of 0° is considered to be longitudinal to the power line and a wind angle of 90° is transversal. Therefore, only winds of 0°/45°/90° are considered adequate to convey the full picture. Furthermore, five ice accretion values of 0, 1, 5, 10 and 15mm are utilized in the fragility analysis. Examining the performance of each tower type the residual displacement at the top of the tower is recorded; when this displacement exceeds the value of 0.01m, associated with local member buckling a tower is considered to have failed, as global collapse invariably follows. The structural fragility is estimated using the number of failures over the total number of analyses for different values of wind speed. Then, a lognormal distribution is fitted to the results and the set of fragility curves (parameterized on wind speed) characterizing each tower under multiple combinations of wind and/or ice conditions is estimated. Fig.3 illustrates the resulting fragility curve sets for both support and angle towers given the wind direction and ice thickness.

In addition, fragility curves are estimated for angle towers whose neighboring support towers on one side of the power line have collapsed. Such towers receive eccentric loading due to conductors surviving only on one side and their capacity to sustain lateral loads is clearly reduced; thus, symmetry exists only around the x-axis and five wind direction angles (0°, 45°, 90°, 135°, 180°) are utilized to produce the corresponding fragilities in Fig.4. A wind angle of 0° is considered to be longitudinal to the line from the side where conductors exist and a wind angle of 180° is considered to be longitudinal to the line from the side where support towers have collapsed.

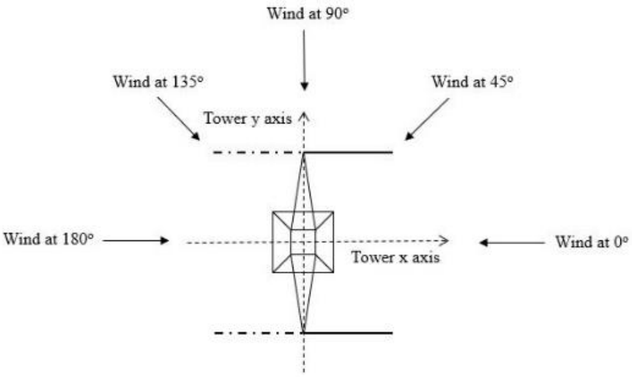
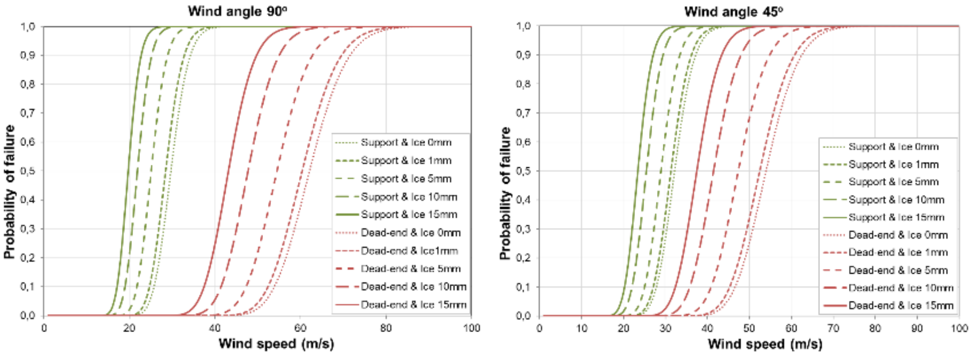


Figure 2. *Wind incidence angle with respect to the local tower coordinate system*



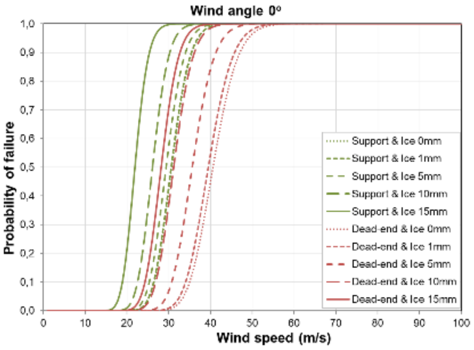


Figure 3. *Wind fragility curve sets characterizing the support (green color) and angle/dead-end towers (red color).*

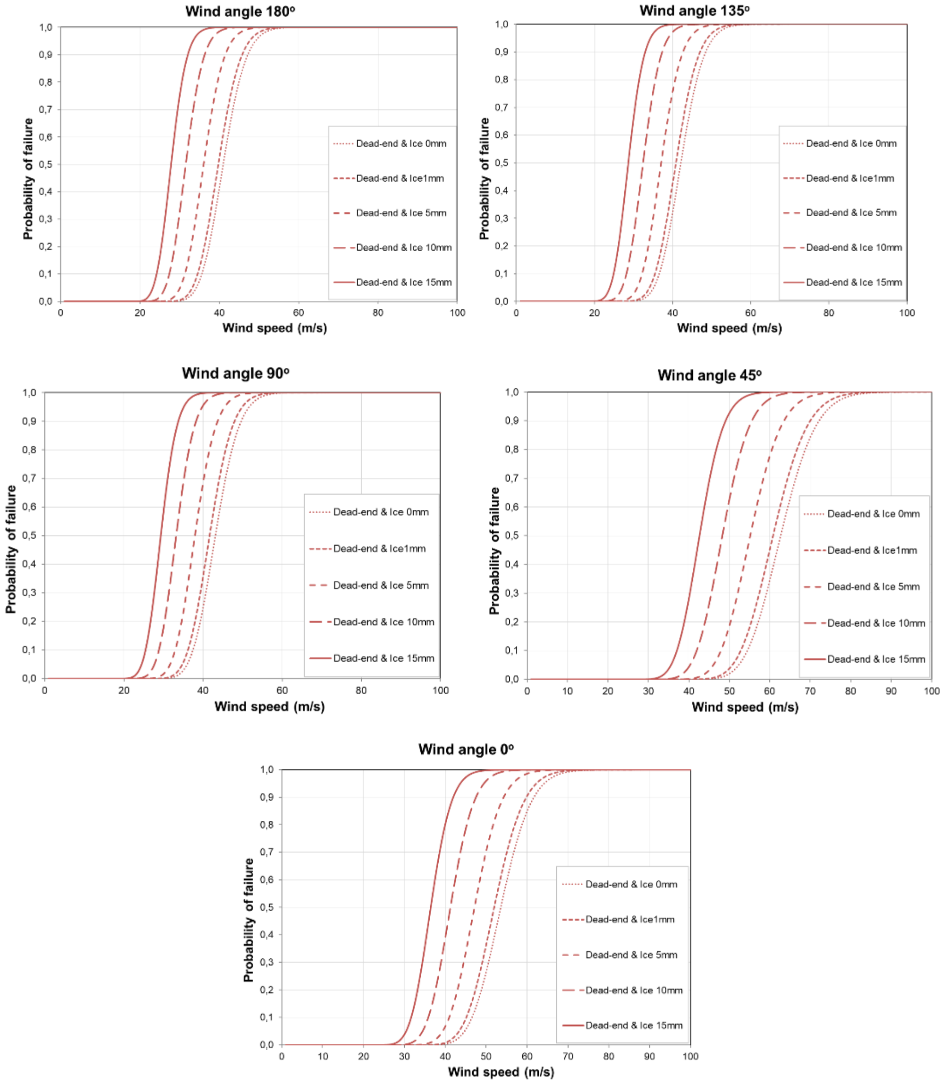


Figure 4. *Wind fragility curve sets for eccentrically loaded angle/dead-end towers when the conductors are not present on one side or have gone slack due to adjacent tower collapse.*

WEATHER HAZARD

The transmission line studied (Fig.1) is located in the region of Annaberg-Buchholz, in the eastern part of Germany. Twenty-year records of wind speed and wind direction are available in 10min resolution from the closest weather station located in Marienberg. Ice accretion measurements are not available. Instead, the procedure proposed by Jones (1998) is employed to estimate the accumulated ice from freezing rain events using the available records of wind speed, atmospheric temperature and precipitation rate.

To isolate storm events, so called episodic periods, timehistories of successive wind speed recordings in 10min resolution enclosed by values higher or equal to 15m/s are isolated from the recordings; these timeseries are accompanied by values of wind direction and ice thickness. Each set of the three parameter timeseries forms a single episodic period, characteristic of the site. In general, their duration is short, with most of them lasting less than 2 days and only a few lasting 2 to 5 days.

To replicate a sufficient number of extreme events, a stochastic catalogue with 1.000.000 potential realizations of a single year is generated, where each year contains a different number of episodic periods based on a Poisson distribution assumption, assuming an average annual rate of events per the historical record. The individual episodic periods assigned to each poissonian event are randomly selected from the recorded ones and scaled according to a Gumbel distribution of winds, fitted to the recorded data.

RISK ASSESSMENT

An event-based probabilistic weather hazard assessment (PWHA) is performed for the case study of a transmission line. The aim is the estimation of the mean annual frequency (MAF) of failure. The main steps followed by the proposed methodology are described below.

The first step of the process is the characterization of transmission towers as angle/dead-end or support based on the topology of the power line and the estimation of the fragility functions per tower type. Angle and dead-end towers are considered to have the same behavior and therefore fragility against weather hazards. From now on, angle and dead-end transmission towers will simply be referred to as angle towers.

At the next step, the performance of transmission towers exposed to episodic periods of the stochastic catalogue is examined per each 10-min interval of the event timeseries; each interval is characterized by a specific combination of wind speed, wind direction and ice thickness. The latter two intensity measures lead to the selection of the appropriate fragility curve (Fig.3), whereas the wind speed ultimately determines each tower's probability of failure. Given the relatively short length of the line, the same weather hazard is imposed along its entire length.

Given the probability of failure, 100 potential realizations are simulated for each tower. For each iteration a random value of 0 or 1 is generated according to the Bernoulli distribution defined by the probability of failure to characterize whether the tower has collapsed or not. Furthermore, cascading failures are propagated. When a tower collapses, it automatically leads to the failure of all neighboring support towers; collapse propagation momentarily stops at the nearest angle towers bracketing the failed one. Then, these angle towers themselves are re-evaluated for the same 10-min interval to check for collapse under eccentric loads; their fragility functions in this case are illustrated in Fig. 4. This procedure is repeated for all intervals of the episodic period.

Power transmission lines are series systems: Whenever a single tower collapses, the power line fails to transmit electricity. The line's probability of failure per episodic period is estimated as the ratio of the number of line failures to the total number of realizations. Accordingly, the probability of failure (P_c) of the line can be calculated as follows:

$$P_C = \frac{1}{N}\sum_{i=1}^{N} L_i \tag{1}$$

where L_i is 0 if the line is functional and 1 otherwise, and N = 100 is the number of realizations employed.

The next step is the computation of the MAF of power line failure; this procedure is straightforward using the available stochastic catalogue and the number of failures of the power line per each yearly realization. In this case, the MAF of failure of the transmission line equals 0.0098 and the associated mean return period (MRP) of failure is 103 years. Also, the probability of failure of different number of failed towers is calculated, using Equation 1 as in case of the transmission line, only setting L_i = 1 if the designated number of towers have simultaneously failed. Actually, a single tower loss is not possible, as the weakest link is a set of two adjacent support towers per Fig.1. When one of them collapses it causes the failure of its neighbor. Failure of four towers is clearly the most frequent occurrence (Table 1), given the assumed uniformity of wind speeds, and it always involves the two pairs of support towers. Three collapsed towers correspond to failure of one of the two angle towers at the ends of the line, together with its adjacent supports, while five towers may fail when the central angle tower collapses together with all four supports.

Table 1. *Mean Annual Frequency of simultaneous failure for different numbers of transmission towers*

2 towers	3 towers	4 towers	5 towers	6 towers	7 towers
3.19E-03	1.30E-07	**6.36E-03**	1.32E-04	5.16E-05	1.57E-05

LOSS ESTIMATION

An important factor of interest to power plant operators is the expected cost of repairing tower collapses during their lifetime, which in this case is considered to be 60 years. The total cost is the sum of the direct average annual loss of repairing the power line (AAL_D) and the indirect average annual loss of non-operation of the line (AAL_I) multiplied by the lifetime T expressed in years:

$$LC_T = (AAL_D + AAL_I) \cdot T \tag{2}$$

Where $T = 60$ years is employed for our purposes.

The average annual direct loss results from the restoration of the collapsed towers is calculated as:

$$AAL_D = \sum_{j=2}^{M} MAF_j \cdot GC_j \tag{3}$$

where MAF_j is the mean annual frequency of $j = 2\ldots M$ towers failing ($M = 7$ here) and GC_j is the total (or group) cost of the j collapsed towers, taking into account the number of towers to be replaced from each type, support or angle. Replacing a tower incurs the cost of the superstructure and the cost of transportation and installation of the tower, assuming that the foundation is fully reusable; the overall cost for a support tower is 68,439€ and for an angle tower it is 223,378€.

On the other hand, the annual indirect loss due to service disruption is estimated as the product of the cost of a disruption and the MAF of failure of the power line. The cost of a disruption depends on the size of the population served, the average revenue of the power company per month and person, and finally the duration of an electric power outage. The average revenue for the power company is taken to be 125€/month per person, incorporating both transmission and generation costs. For the duration of an electric power outage the instructions of HAZUS-MH (2012) are adopted. Accordingly, 3 days are necessary to restore a transmission line with extensive damages; in our case this corresponds to 2, 3, or 4 collapsed towers. This rises to 7 days for complete damage, taken to correspond to 5 or more failed towers. Still, the most important factor is the size of the population served by the power line; thus, one small and one large-scale scenario are considered. For the first scenario the regions of Annaberg-Buchholz and Marienberg with a combined total number of residents of 36,525 are studied. At a larger scale, the overall region of Erzgebirgskreis, which contains the aforementioned towns, is considered; it has 334,948 total residents.

The results of this Approach A, which entails some non-negligible complexity, appear in Table 2. In comparison, the evaluation of the risk of the transmission line is also estimated using a simpler Approach B, commonly used in the literature. The transmission line is assumed to exclusively consist of a single type of tower and specifically the support type. Of course, in this case cascading failures are not considered because the assumption of a collapsed support tower leading to failure of all the adjacent support ones would produce rather armageddonic results. The MAF of failure of the power line in this case is 0.0112 and the expected costs are presented in Table 2. The results are in favor of Approach A, as version B is on the conservative side.

Table 2. *Comparative direct/indirect average annual loss and aggerated lifetime cost for the two competing approaches. The simpler Approach B tends to overestimate the overall cost.*

	Direct AAL_D	**Indirect AAL_I**		**Lifetime Cost LC_{60}**	
		Annaberg	**Erzgebirgskreis**	**Annaberg**	**Erzgebirgskreis**
Approach A	2,296€	4,575€	41,954€	412,279€	2,655,001€
Approach B	1,830€	8,411€	77,131€	614,476€	4,737,322€

CONCLUSIONS

The performance of a six-span power transmission line consisting of two types of towers under weather hazard was estimated, considering the effect of successive towers collapses. For the analyses, timehistories of wind speed and direction as well as ice accretion values were created; the associated fragility functions for wind and ice conditions were also developed. Using the estimated Mean Annual Frequency (MAF) of failure, the expected cost of 60-years transmission line lifetime is calculated.

In addition, a simplified approach was used for the same power line, this time entirely consisting of support towers, was analyzed without considering cascading failures. The same weather hazard and the appropriate fragility curves were used to estimate the MAF of failure and the overall cost.

The results show that following the proposed methodology the MAF of failure is by 15% lower; as for the expected costs the values are by 49% and 78% lower than the simpler approach for both the short and large-scale scenarios. It is concluded that the proposed approach can lead to improved estimates of cost, but it clearly requires more details on the power line (e.g., the location and structural details of angle/dead-end towers), as well as an increased analytical effort and expenditure of computational resources. Whether this is worth the gains in accuracy is a choice best left to the analyst. A simpler solution would be to employ statistics of past wind-induced failures, where available, to appropriately adjust the analytical fragilities and the overall transmission line model. This calibration would ensure that predictions better match observations, improving the fidelity without overly increasing the computational effort.

ACKNOWLEDGMENTS

This research has been financed by the European Commission through the Programs: a) "ANGELHY - Innovative solutions for design and strengthening of telecommunications and transmission lattice towers using large angles from high strength steel and hybrid techniques of angles with FRP strips" with Grant Agreement Number: 753993 (Research Program of the Research Fund for Coal and Steel), b) "PANOPTIS - development of a decision support system for increasing the resilience of transportation infrastructure based on combined use of terrestrial and airborne sensors and advanced modelling tools" with Grant Agreement number: 769129 (HORIZON 2020) and c) "HYPERION - development of a decision support system for improved resilience & sustainable reconstruction of historic areas to cope with climate change & extreme events based on novel sensors and modelling tools" with Grant Agreement number: 821054 (HORIZON 2020).

REFERENCES

Abdalla O.H., Alkhusaibi T.M., Awlad-Thani M., Al-Mazrouey M.N. (2008). Restoration of a 132-kV overhead transmission line affected by tropical cyclone Gonu in Oman. 2008 IEEE/PES Transmission and Distribution Conference and Exposition, Chicago, IL, USA.

Bilionis D., Gerontati A., Vamvatsikos D. (2020b). Safety estimates and cost benefit analyses of case studies, Deliverable 4.2, ANGELHY Project. URL: http://angelhy.ntua.gr/deliverables/WP4/4.2%20-%20D4.2%20-%20Safety%20estimates%20and%20cost-benefit%20analyses%20of%20case%20studies.pdf

Bilionis D., Vlachakis K., Vamvatsikos D. (2020a). Parametric models of case studies and loads, Deliverable 4.1, ANGELHY Project. URL: http://angelhy.ntua.gr/deliverables/WP4/ANGELHY%20-%20D4.1%20-%20Parametric%20models%20of%20case%20studies%20and%20loads.pdf

FEMA (2012). HAZUS-MH 2.1: Technical Manual, Federal Emergency Management Agency, Washington D.C.

Jones, K. (1998). A simple model for freezing rain ice loads. Cold Atmospheric Research, 46, 97-97.

Jonkman B.J. & Kilcher L. (2012). TurbSim User’s Guide. Technical Report NREL/TP-xxx-xxxx. NREL Technical Report, National Renewable Energy Laboratory, Golden, Colorado.

Liang S., Zou L., Wang D., Cao H. (2015) Investigation on wind tunnel tests of a full aeroelastic model of electrical transmission tower-line system. Engineering Structures, 85, 63–72.

OpenSees (2006). Open System for Earthquake Engineering Simulation. Pacific Earthquake Engineering Research Center, University of California, Berkeley, URL: http://opensees.berkeley.edu/

Savory E., Parke G.A., Zeinoddini M., Toy N., Disney P. (2001). Modelling of tornado and microburst-induced wind loading and failure of a lattice transmission tower. Engineering Structures, 23(4), 365–375.

Tibolt M., Bezas M.Z, Vayas I., Jaspart J.P. (2021). The design of a steel lattice transmission tower in Central Europe. Engineering Structures, 23(4), 243-248.

Zimmerman R., Zhu Q., de Leon F., Guo Z. (2017). Conceptual modeling framework to integrate resilient and interdependent infrastructure in extreme weather. Journal of Infrastructure Systems, 23(4), 04017034.