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# Proposed Generally Applicable Fragility curve parameters for 154kV Transmission Towers under Extreme Wind Load

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## 1. Introduction

Extreme wind events driven by climate change pose significant threats to the stability of power grids, and structural damage to transmission towers—one of their key components—can lead to localized outages and even large-scale blackouts [1]. For instance, Typhoon Maemi in 2003 caused the collapse of 12 transmission towers in South Korea, resulting in power outages, while Typhoon Mujigae in China in 2014 damaged 206 towers, leading to widespread blackouts [2,3]. These cases highlight the necessity of conducting fragility analyses for transmission towers in system-level safety assessments of power grids; however, such analyses are constrained by substantial time and cost requirements. To address this challenge, the present study proposes generally applicable fragility parameters for 154 kV transmission towers, which are the most widely deployed in the Korean power grid.

## 2. Nonlinear Pushover Analysis

### *2.1 154kV Tower Model and Wind Load Calculation*

The representative 154kV transmission tower model was adopted from the study of Kim et al. [4] and corresponds to the most widely used tower type in the main transmission network of South Korea. The front and side elevations of the tower are presented in Fig. 1, where the tower was divided into panels according to IEC 60826 in order to define the wind load application zones [5]. For wind load estimation, the procedures specified in IEC 60826 were followed, and three equations were employed to calculate the wind loads acting on both the transmission tower and the conductors.

$$q_0 = 0.5\tau\mu(K_R V_{RB})^2 \tag{1}$$

$$A_t = q_0(1 + 0.2sin^2 2\theta)(S_{t1}C_{xt}\ cos^2\theta +_{t2} C_{xt}\ sin^2\theta)G_t \tag{2}$$

$$A_c = q_0 C_{xc} G_c G_L dLsin^2\Omega \tag{3}$$

Here, $q_0$ denotes the dynamic reference wind pressure, while $A_t$ and $A_c$ represent the wind loads acting on the external panels of the tower and on the transmission lines, respectively. The parameters $\tau$ and $\mu$ correspond to the air density correction factor and the air mass per unit volume, for which conservative values of 1.19 and 1.225 kg/m³ were adopted. $K_R$ denotes the roughness factor, and $V_{RB}$ is the 1-minute mean wind speed measured at a height of 10 m above ground in terrain category B. $S_t$ represents the projected area of the tower members within each panel, and $C_{xt}$ refers to the drag coefficients in the x- and y-directions. $G_t$ is the combined wind factor, while $C_{xc}$, the drag coefficient for conductors, was conservatively set to 1. The conductor diameter (*d*) was taken as 28 mm, $G_L$ denotes the span factor, and $\Omega$ is defined as 90°-$\theta$. The $\theta$ between the transmission line and the wind direction was assumed to be perpendicular for wind load estimation.

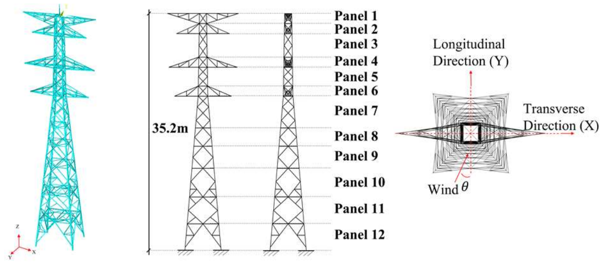


Fig. 1. 154kV transmission tower model.

### *2.2 Aleatory and Epistemic Uncertainties Variables*

To derive generally applicable fragility parameters, both epistemic and aleatory uncertainty variables were represented using probability distributions, as summarized in Table I. A total of 100 sample models were generated through Latin Hypercube Sampling (LHS). For epistemic uncertainty variables, the yield strength ($f_y$), ultimate strength ($f_u$), elastic modulus (*E*), Poisson's ratio (*v*), and ultimate strain ( $\varepsilon_u$) were considered, each assumed to follow a lognormal distribution. The mean values of these variables were obtained from the Korean Design Standard (KDS 14 31

05), while their coefficients of variation (COV) were determined based on the *Probabilistic Model Code* published by the Joint Committee on Structural Safety (JCSS) [6,7].

Among the aleatory uncertainty variables, the wind direction was modeled using a uniform distribution ranging from 0° to 90°. This accounts for the fact that, in addition to straight-winds, non-uniform wind conditions such as typhoons can impose loads on transmission towers from various wind direction. Furthermore, the span length between towers was incorporated as an input variable, extracted from spatial data provided by OpenStreetMap [8].

Table Ⅰ. Considered aleatory and epistemic variables.

| Material parameter | Probability distribution | Mean value | Coefficient of variation |
|---|---|---|---|
| Yield Stress | Lognormal | 275 MPa | 0.07 |
| Ultimate Stress | | 410 MPa | 0.04 |
| Poisson's ratio | | 0.3 | 0.03 |
| Elastic modulus | | 210,000 MPa | 0.03 |
| Ultimate strain | | 0.02 | 0.06 |
| Wind direction | Uniform | 367.7m | 0.58 |
| Span length | Fisk | 512.3m | 0.42 |

*2.3 Results of Nonlinear Pushover Analysis*

For the nonlinear analysis of the 154 kV transmission tower, numerical modeling was performed using PyMAPDL. Each structural member was modeled with BEAM188 elements, and the material properties were defined as SS275 and SS410. A bilinear steel model was employed to capture the inelastic behavior. The wind speed range was set from 10 m/s to 100 m/s, with increments of 5 m/s, and the analyses were conducted accordingly. To determine failure, the displacement limit was defined as 1.5% of the tower height, following precedents in prior studies [9,10]. For the 154 kV tower, this corresponded to a failure displacement of 528 mm.

Figure 3 presents the nonlinear analysis results for the 154 kV transmission tower model. The red solid line represents the average response across all simulations and indicates the average capacity curve derived through curve fitting. The analysis results showed that at a top displacement of approximately 0.6 m, the corresponding average base shear was about 580 kN.

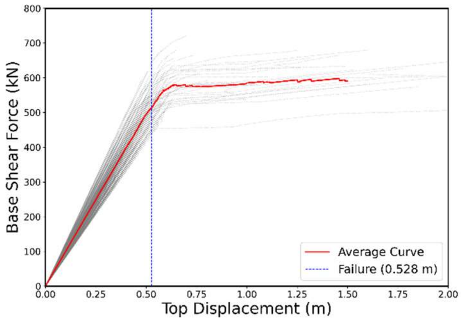

Fig. 3. Pushover curve for 154kv tower

## 3. Fragility analysis for 154kV tower

Based on the nonlinear analysis results, a fragility analysis of the 154 kV transmission tower model was conducted. The fragility curves, presented in Figure 5, were derived for wind direction angles in 30° intervals. For the range of 0°–30°, the parameters were obtained as $V_m$ =51.63 m and $\beta$ =0.109. For 30°–60°, the results were $V_m$ =50.77 m/s and $\beta$ =0.130. In the 60°–90° range, $V_m$ slightly increased to 50.97 m/s, while $\beta$ decreased to 0.111. For the overall range of 0°–90°, the fragility parameters were $V_m$ =51.13 m/s and $\beta$ =0.117, indicating relatively consistent behavior across all wind directions.

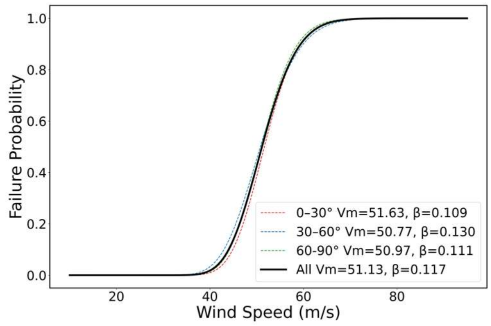

Fig. 4. Fragility curve for 154kV transmission tower

## 4. Proposed Fragility Curve Parameters and Discussion

The consideration of uncertainty factors is essential to propose generally applicable fragility curves for 154 kV transmission towers under extreme wind conditions. Such consideration enhances the reliability of fragility analyses and power grid safety assessments. In this study, two additional sources of uncertainty were incorporated, and the final combined logarithmic standard deviation, $\beta_{Proposed}$, was formulated as the sum of variances, as presented in Equation (4).

$$\beta_{proposed}{}^{2} = \beta_{Analysis}{}^{2} + \beta_{WM}{}^{2} + \beta_{MDL}{}^{2} \qquad (4)$$

Here, $\beta_{Proposed}$ refers to the logarithmic standard deviation derived from the fragility analysis results presented in Chapter 3 (Fig. 4). $\beta_{WM}$ represents modeling uncertainty, and $\beta_{MDL}$ denotes the uncertainty associated with the representative 154 kV transmission tower model.

First, $\beta_{WM}$ was taken as 0.05, following the coefficient proposed by Ellingwood (1978) [11]. This coefficient accounts for modeling uncertainties arising during structural analysis, reflecting the possibility that the numerical model may not fully capture the actual structural capacity of the transmission tower.

Second, $\beta_{MDL}$ was determined with reference to the *Quality Rating of Index Archetype Models* provided in FEMA P695 [12]. This table quantifies uncertainties associated with representative models by classifying them into High, Medium, and Low categories based on two evaluation criteria, and assigning corresponding values of $\beta_{MDL}$. In this study, a value of 0.35, corresponding to the medium category, was adopted.

Finally, as summarized in Table II, generally applicable fragility parameters are proposed for 154 kV transmission towers. The proposed parameters are based on 10-minute mean wind speeds but can be converted to 3-second gust wind speeds by applying the appropriate gust factor to $V_m$ .

Table II. Proposed fragility curve variables for 154kV tower

| | | $V_m$ (m/s) | $\beta_{Proposed}$ |
|---|---|---|---|
| Proposed variables | 154kV | 50.77 | 0.38 |

## 5. Conclusions

In this study, nonlinear analysis and fragility assessment were performed for 154 kV transmission towers commonly used in the Korean power grid, yielding the median capacity ($V_m$) and logarithmic standard deviation ($\beta$). In addition, modeling uncertainty and the uncertainty associated with the representative 154 kV tower model were further incorporated. Ultimately, generally applicable fragility parameters were proposed for 154 kV transmission towers. These parameters can provide useful guidance for practical decision-making in system-level safety assessments of power grids.

## 6. ACKOWLEDGEMENT

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