

Research Progress on Disaster Resilience of Transmission Lines: Postprint

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Abstract

Current research and literature on transmission line disaster resistance predominantly focus on the impact of a single disaster type on transmission lines, primarily emphasizing the effects of earthquakes and wind hazards, while lacking a systematic review that covers the entire chain from disaster damage mechanisms to probabilistic assessment and further to resilience assessment for transmission lines under various disasters. To systematically summarize the current research progress on transmission line disaster resilience, this study first investigates the damage mechanisms of transmission lines under four individual disasters (earthquake, wind, flood, landslide) and two typical coupled disasters (wind-earthquake, wind-ice), as well as the corresponding structural models and disaster models. It then systematically reviews the probabilistic assessment of transmission lines under these disasters, summarizing current research on hazard assessment, structural probabilistic assessment under disaster actions, and loss assessment caused by disasters, and reviews the research achievements of several domestic research teams working on transmission line disaster resistance. On this basis, it systematically reviews research on regional transmission line resilience assessment, identifying the key issues and existing research gaps in regional transmission line resilience studies. Finally, it provides an outlook on future development directions for transmission line disaster resilience research, and draws conclusions regarding transmission line damage mechanism models, structural probabilistic assessment methods under disasters, research keys for regional transmission line resilience, and future development directions for transmission line disaster resilience research.

Full Text

Preamble

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Abstract

Current research and literature on transmission line disaster resistance primarily focus on the impact of individual hazards, with major emphasis on earthquake and wind disasters. A systematic review covering the entire spectrum from damage mechanisms to probabilistic assessment and resilience evaluation for transmission lines under various disasters is lacking. This study provides a comprehensive summary of research progress on transmission line disaster resilience. First, we examine damage mechanisms of transmission lines under four single hazards (earthquake, wind, flood, landslide) and two typical coupled hazards (wind/earthquake, wind/ice), along with corresponding structural and hazard models. Subsequently, we review probabilistic assessment approaches for transmission lines under these hazards, summarizing research on hazard risk assessment, structural probabilistic assessment under disaster actions, and disaster-induced loss evaluation, while also reviewing contributions from domestic research teams. Based on this foundation, we examine regional transmission line resilience assessment research, identifying key challenges and existing gaps. Finally, we propose future research directions for transmission line disaster resilience, addressing critical issues including damage mechanism models, probabilistic assessment methodologies, regional resilience evaluation, and development trends.

Keywords: transmission lines; disaster resilience; damage mechanism; disaster action model; probabilistic assessment; hazard risk; regional power grid

1. Introduction

Transmission lines constitute critical equipment in power systems and essential components of electrical grids that have undergone rapid development in recent years. However, most transmission lines are exposed to complex and variable outdoor environments, making them vulnerable to various natural disasters such as lightning, ice and snow, wind, earthquakes, floods, landslide-debris flows, and wildfires. While lightning causes the highest proportion of transmission line trips and anomalies, its impact is primarily on electrical equipment rather than structural components, with only rare instances of structural damage like insulator detachment or conductor breakage. Although earthquake occurrence

frequency is much lower than wind disasters, strong seismic events can cause severe damage to transmission lines. In the 2008 Wenchuan earthquake, transmission lines and power facilities were severely damaged, and the power grid collapsed. For example, transmission line failures triggered by disasters are often unpredictable. In such scenarios, evaluating transmission line damage and disaster resilience has become a major concern for scholars.

China is among the world's most disaster-prone countries, where power system resilience directly impacts post-disaster emergency response and people's livelihoods. In recent years, with the continuous development of China's economy and society, the demand for electricity in social production and daily life has been increasing. Current research has established computational models for transmission lines under different hazards, but a key challenge remains balancing model accuracy with computational efficiency to develop simplified models that are both realistic and computationally efficient. Furthermore, existing studies predominantly focus on probabilistic assessment of single transmission lines or line sections, with limited research on regional grid impacts. This study systematically reviews damage mechanisms under single and coupled hazards, summarizes probabilistic assessment methodologies, and addresses critical issues in transmission line disaster resilience research, introducing the concept of "resilience" to evaluate power system capacity in responding to extreme events.

2. Disaster Damage Mechanisms and Models

Disaster damage mechanisms establish relationships between hazard actions and structural responses. Scholars have proposed various models for transmission lines under different hazards, including structural models and disaster action models. Common structural models include tower-line system models and single-tower models.

The Tongji University team (Li Jie and Xie Qiang) has conducted extensive research on wind and seismic responses of transmission lines, while the Shandong University team (Tian Li) has performed wind tunnel tests and shaking table experiments on seismic and wind-induced vibration responses of long-span transmission tower-line coupling systems. During earthquakes, interaction exists between transmission towers and conductors, as well as between towers and foundation soils. Ge Xuzhang established a finite element model of the tower-line system, using static analysis and modal assessment to evaluate broken wire effects and determine the most unfavorable broken wire conditions for progressive collapse analysis.

Simplified models have also been proposed. X2+Y et al. developed a simplified model for tower/insulator/line coupling systems considering soil-structure interaction, where the tower is simplified as a multi-degree-of-freedom (MDOF) system, single-layer transmission lines as mass-assembled MDOF rigid bar combinations, and single-layer insulators as mass points. Analysis using this model demonstrates that soil-structure interaction significantly affects seismic perfor-

mance, while tower-line interaction markedly influences tower top displacement. Some scholars adopt single-tower models for seismic response studies, modeling towers individually without conductors. While theoretically conductors affect tower response, their influence is relatively small under seismic action, making single-tower models generally conservative and computationally efficient.

For wind load simulation, scholars have conducted wind tunnel tests to obtain structural wind dynamic characteristics and wind-induced response data. The Zhejiang University team (Lou Wenjuan) has performed extensive theoretical analysis, experimental research, and numerical simulation on wind-induced vibration and conductor icing. Wind load simulation is complex, particularly under combined wind and rain where conductors may experience rain-wind induced vibration, seriously threatening normal operation.

Z2/⁴SW2+J et al. established a finite element model for double-circuit vertical steel lattice towers, applying loads at midpoints of lattice units. Compared with tower-line system models, simplified single-tower models offer higher computational efficiency but are generally used for problems focusing only on specific tower responses under wind loads. For transmission lines, tower-line system models are typically employed, with domestic overhead transmission line load specifications providing calculation methods for conductor wind loads.

For seismic analysis, artificial non-stationary earthquake wave time histories conforming to statistical characteristics are synthesized. Specifications require at least three ground motion time histories for dynamic time-history analysis, including at least one artificial wave. For large-span, high-rise transmission tower-line systems with large distances between supports, spatial effects of seismic wave arrival time differences and intensity variations cannot be ignored, necessitating multi-point, multi-dimensional seismic response studies. Additionally, scholars have investigated tower damage under mainshock-aftershock sequences, selecting real mainshock-aftershock sequences and ground motion intensity measures to analyze their impact on tower deformation and damage. Performance states are classified based on deformation development and bearing capacity degradation.

3. Probabilistic Assessment Under Various Hazards

3.1 Wind Hazard Assessment

For wind hazard assessment, scholars have established vulnerability models for transmission towers under hurricanes. The process involves: (1) establishing the wind field at the structure location, selecting appropriate wind speed discrete points, wind profile models, and power spectral density functions to model fluctuating wind speed using the spectral method; (2) calculating equivalent wind loads and aerodynamic damping for the tower-line system, performing time-domain finite element analysis to extract wind-induced responses including tower displacement, base shear, and bending moment; and (3) defining failure modes based on these responses and code limits, applying probability

density evolution theory to obtain probability density evolution curves and analyze wind resistance reliability. Some scholars have also conducted probabilistic assessment of fatigue life under wind loads.

3.2 Flood Hazard Assessment

Research on probabilistic assessment of transmission lines under flood is relatively limited. 3H,G et al. proposed a probability flow-based risk assessment method for quantitatively evaluating power system operation under extreme precipitation conditions. OH4+ et al. developed a comprehensive risk probability assessment framework for flood-affected transmission towers using airborne LiDAR 3D point cloud data to extract geometric structures, designing novel point cloud segmentation and fitting algorithms to estimate tower inclination angles and assess flood damage risk.

3.3 Landslide Hazard Assessment

For landslide probability assessment, Liu Shuhao studied key factors for transmission line landslide disasters based on historical disaster samples and geological/geographical data, establishing a landslide risk evaluation factor index system. Han Bo proposed a vulnerability analysis framework for power grids under landslide disasters, using interpretable classification models to predict tower collapse probabilities under multiple hazards and generate vulnerability surfaces. Machine learning has also been applied, with Y4 et al. using correlation and sensitivity analysis for parameter screening, employing backpropagation neural networks and support vector machines validated through receiver operating characteristic curves and cumulative landslide percentage curves to predict spatial landslide distribution and create susceptibility maps.

3.4 Ice Hazard Assessment

gJ2, et al. proposed a method for assessing bearing capacity and vulnerability surfaces of transmission tower-line systems under combined ice and wind loads based on nonlinear static pushover analysis. By comparing pushover curves with incremental dynamic analysis curves, ice thickness and 10-minute mean wind speed were identified as intensity measures for vulnerability surfaces, with correction coefficients introduced to account for wind spatiotemporal variation uncertainties.

4. Coupled Hazard Assessment

4.1 Wind-Earthquake Coupling

IJ et al. established a time-varying uncertainty numerical model based on wind-then-earthquake damage mechanisms, analyzing tower responses under combined seismic and wind loads. Dynamic analysis was performed using artificial

ground motions meeting code requirements, with performance states classified based on deformation development and bearing capacity degradation.

4.2 Wind-Ice Coupling

For wind-ice coupling, scholars combined joint probability distribution models of ice thickness and wind speed to calculate failure probabilities under different service lives. Machine learning has been employed to construct risk assessment models for transmission lines under icing conditions.

5. Resilience Assessment of Regional Transmission Lines

The concept of resilience, originally proposed by Holling in 1973 for ecology to describe ecosystem stability and recovery capacity after disturbances, has recently become a research focus for regional transmission lines. Quantitative analysis centers on evaluating power system robustness, self-healing capacity, and rapid recovery capability when facing natural disasters, human attacks, or other interference events. China is among the earliest countries to propose the concept of “resilient power grid,” emphasizing resilience in smart grid construction.

Current research gaps include: (1) limited studies on regional grid impacts despite extensive single-line probabilistic assessments; (2) challenges in balancing model accuracy and computational efficiency; (3) insufficient consideration of coupled hazards; and (4) need for standardized resilience evaluation frameworks. Future directions should focus on developing refined damage mechanism models, efficient probabilistic assessment methods, regional resilience evaluation systems, and integrated multi-hazard approaches.

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