Electronics, Communications and Networks
A.J. Tallón-Ballesteros (Ed.)

doi:10.3233/FAIA241319

Transmission Line Hazard Analysis and Structural Resilience Methods: A Comprehensive Review

Jianping CHENG[a,1], Xinmin YU[a] and Yifan WU[a]
[a] *State GRID Fujian Economic Research Institute, No. 68 Road Chayuan, Fuzhou 350013, Fujian Province, China*

Abstract. The safety and reliability of power transmission lines are the cornerstone of the stable operation of the national economy. However, in recent years, with the frequent occurrence of extreme weather events and geological disasters, the damage suffered by transmission lines is increasing, which poses a serious challenge to the stable operation of the power system. In order to promote the progress and development of the theory of disaster-resistant design of transmission lines, this paper discusses in depth the disaster cases that have occurred, analyses in detail their causes and damage modes, and comprehensively evaluates the various methods and measures currently adopted to ensure the safe operation of transmission lines. Through the systematic summary and conclusion of these issues, it aims to uncover design flaws. Based on this, targeted suggestions are proposed to enhance transmission lines' resistance to external loads.

Keywords. Transmission line, disaster analysis, structural design, experimental validation

1. Introduction

The safe operation of transmission lines, as a medium that carries the task of transmitting high loads of electrical energy, has traditionally been a matter of deep concern to all sectors of the community, as any failure or damage can lead to huge economic losses [1]. Compared to conventional building structures, transmission lines exhibit unique attributes: high towers, wide spanning distances, and often traversing areas with complex and variable terrain. As the height of the tower increases, the overall structural flexibility of the transmission line shows a non-linear growth trend. Rao et al [2] observed different types of premature failures during comprehensive testing of transmission line towers at the Tower Testing and Research Station, Structural Engineering Research Centre in Chennai. In addition, the tower and conductor work together under a variety of dynamic characteristics that span different orders of magnitude.

China is one of the most frequent natural disasters in the world, deeply affected by multiple factors such as geographical and climatic environments, resulting in some areas becoming the high incidence of a variety of natural disasters and areas of concentration, which constitutes a serious challenge to the safe operation of the transmission line project

[1] Corresponding Author, Jianping Cheng, State GRID Fujian Economic Research Institute, No. 68 Road Chayuan, Fuzhou, Fujian Province, China; E-mail: 313136188@qq.com.

structure, resulting in the frequent occurrence of accidents such as collapses, tilting, serious damage, etc., and the trend is increasing [3]. With the accelerated pace of power grid construction, transmission lines have to traverse extreme environments such as heavy ice-covered areas, high intensity seismic zones, high altitude zones, and areas with poor geological conditions. This trend has directly led to a significant increase in the height and span length of transmission line towers, complex structural forms, and more variable and unpredictable external load excitation and dynamic response characteristics [4]. At the same time, the geographic and meteorological conditions of the different geographical areas traversed by the line corridor vary significantly, which puts forward higher requirements for the overall safety level and continuous operation time of the transmission line system.

Therefore, this paper focuses on the disasters that have occurred on transmission lines at home and abroad, analyses their causes and damage patterns in depth, and systematically discusses the contributions and achievements of transmission line structural systems in ensuring safe operation from the three dimensions of structural design optimisation, application of numerical analysis methods and experimental verification practice. By synthesizing safety issues, it aims to uncover design flaws and propose targeted measures to enhance the structure's resistance to external loads.

2. Transmission line disaster analysis

2.1. Wind disaster

Among the many natural disasters, wind disasters pose a particularly significant threat to the security of power systems. According to statistics, up to 70 percent of power supply interruptions in Japan are attributed to failures of overhead transmission lines, with wind-induced disasters dominating the list [5]. Despite the fact that the collapse of transmission tower structures and tower falling incidents have long attracted widespread attention from all sectors of the community, such accidents are still commonplace and have so far failed to achieve fundamental improvements and upgrades. For example, the wind accidents in 1992 and 1993 were particularly serious, with two consecutive tower collapses in China, especially the Ge double circuit which collapsed 7 towers in a row at one time, resulting in serious economic losses. in April 1996, transmission towers in Victoria, Australia and Ontario, Canada both collapsed during downburst storms. in 2005, a total of more than 50 transmission towers collapsed in China, including the 500 kV Renmin tower in Siyang, Jiangsu Province, and the 500 kV Renmin tower in Siyang, China. In 2005, a total of more than 50 transmission towers collapsed in China, including the collapse of the 500 kV Renshang 5237 line in Siyang, Jiangsu Province, which was caused by strong winds from a thunderstorm, knocking down 10 towers at once [5]. In 2006, Typhoon Sangmei caused serious damage to power grids and equipment in Wenzhou, Zhejiang Province and Fuding, Fujian Province, resulting in 3 downed poles on 220 kV lines and 98 downed poles on 110 kV lines. In May 2018, 2 transmission towers collapsed in Yueyang, Hunan Province, when the local area was struck by a level 8 gust of wind.

2.2. Ice-covered disaster

Ice cover is a serious natural disaster for high-voltage transmission lines, and the threat of ice-covered loads on transmission lines is very serious. In many areas, ice cover from freezing rain and fog significantly increases the load on transmission lines, which in turn triggers safety accidents such as broken lines and fallen towers. In addition, transmission line ice cover may also induce a series of problems such as conductor dancing, tripping, communication interruption and equipment damage. According to incomplete statistics, in terms of transmission line dancing, from 1957 to early 1992, a total of 44 conductor dances occurred in China, involving 161 lines, causing damage to 66 conductors and leading to more than 119 line trips [6]. On 5 January 1998, freezing rain fell in the northeastern United States and southeastern Canada, accumulating more than 80 mm, resulting in the near total collapse of the transmission network in southwestern Quebec and eastern Ontario [7]. Between December 2004 and February 2005, freezing rain in some parts of China led to widespread ice cover on transmission lines, with three lines having a total of 24 towers down and 3 deformed; six 220 kV lines had 18 towers down and 9 deformed [8]. In 2008, most parts of southern and eastern China suffered unprecedented rain, snow and ice disasters. As of 12 February of that year, a total of 17 provinces in the country had 35,968 lines out of service and 1,731 substations out of service due to the disaster. Among them, the number of fallen towers of 110 kV to 500 kV lines was as high as 8709. The thickness of ice cover on many lines reached 30 mm to 60 mm, and some lines even reached 80 mm [9].

2.3. Earthquake disaster

Earthquakes are one of the major natural hazards facing mankind, and the nature of the transmission tower-line system, with its combination of towering structures and large spans, means that it is highly vulnerable to earthquakes. the 1971 San Fernando earthquake in the United States, which resulted in the total paralysis of the electric power system, triggered the first time that attention was paid to the assessment of the performance of lifeline engineering systems in earthquakes [10]. The 1994 Northridge earthquake, which resulted in the complete destruction of two consecutive large transmission towers and the interruption of multiple circuits of power supply [11]. The 1995 Kobe earthquake in Japan caused the foundation of about 20 transmission towers to sink and the towers to tilt, resulting in the interruption of power supply to 2.6 million customers. In October 2004, a magnitude 6.8 earthquake occurred in Niigata, Japan, causing 1 transmission tower to collapse, 3 tilted and 20 slightly tilted due to landslides, etc. On 12 May 2008, the Wenchuan earthquake caused the collapse of 110 kV lines with more than 20 towers; 8 towers of 500 kV Maotan line and 2 towers of 220 kV Maoyong line were damaged.

2.4. Coupling of wind and rain disasters

In the transmission tower design code and building structure code, wind load is a very important design and calculation index, while rain load is rarely mentioned. However, whether it is a typhoon or a hurricane, the wind and rain loads are often combined when it occurs, and the dynamic response characteristics under this combined action will be significantly larger compared to a single design criterion, which increases the risk of structural system damage and collapse. 10 500 kV transmission towers collapsed in the

Jilin provincial grid on 21 July 2000, and in July 2002, thunderstorms and gusty winds occurred several times in Liaoning province, causing damage to many lines of the Liaoning power grid. In July 2002, there were many thunderstorms and winds in Liaoning Province, which caused many lines of the Liaoning power grid to suffer damage one after another. According to statistics, 80% of transmission line damage in Australia in 2005 was caused by storms [12]. Typhoon Haiyan, which made landfall off the coast of Dulag, Leyte Province, Central Philippines, on 8 November 2013, caused the most severe damage to the Ormoc-Isabel and Panit-an-Nabas lines on Leyte and Panay islands, which suffered from a large number of consecutive tower failures. Although the condition of functional failure of transmission towers is very common, only a few scholars at home and abroad have been engaged in this work.

3. Resilience methods

3.1. Structural design

The design specifications and methods are the basis for the safety of transmission lines, as well as the necessary basis for the production and construction of transmission lines. At present, the design process of transmission tower structure at home and abroad generally includes the following three aspects: firstly, the tower is selected according to the requirements of the load of the conductor line and meteorological conditions. Secondly, professional software is applied to design, calculate, and test the true type of the structure's rods. For the transmission tower structure, the loads acting on the structure can be divided into permanent loads, variable loads and special loads according to their nature. Permanent loads include the tower's self-weight, guide wires, insulators, fittings of gravity loads, as well as a variety of other fixed equipment on the tower of gravity loads, etc.; variable loads including wind loads, snow and ice loads; guide wires and tension of the wire, construction and maintenance of temporary loads, structural deformation caused by secondary loads, etc.; while the special loads, including conductive line breakage of the line caused by the load, caused by earthquakes, and in the mountainous areas or special terrain.

Transmission line design is based on the tower structure as the core, using space truss system model and static calculation methods to carry out comprehensive design and analysis [13]. The core of this method lies in the fact that the loads of conductor and ground wire under various working conditions and the impact load of broken wire are equivalent to the static loads acting on tower nodes; meanwhile, the random pulsating wind load is simplified to the static average wind load for calculation.

3.2. Numerical analysis

In recent years, the finite element method, as a representative of numerical simulation methods, has been rapidly developed and widely used in the engineering field. With the continuous evolution of the finite element method and the continuous improvement of computer performance, the analysis model of transmission tower structure has been upgraded from a single tower model to a more complex tower-line system model.

Currently, the linear dynamic analysis techniques have matured, both for the single tower model and the more complex tower-line system model. Yasui et al. [14] successfully analysed the dynamic response of a transmission tower line using the time domain method by simplifying the transmission tower into beam and truss units and the conductors and insulators into truss units. Battista et al. [15] used the frequency domain approach to explore in depth the dynamic characteristics and stability of the transmission tower-wire system. Ozono et al. [16] started to consider the effects of various factors on the dynamic response of the tower-wire system, such as the number of spans of the tower line, boundary conditions, conductor mass and vertical span ratio, in their study. However, linear analysis has some limitations in simplifying the load effects and inter-structural interactions, etc., and the possible errors brought by this simplification still need to be explored in depth.

Nonlinear analyses have likewise undergone an evolution from single tower models to tower-line system models. El-Ghazal [17] and Rao et al. [18] discussed the structural dynamic response of transmission towers under wind vibration using different approaches, the former considering factors such as accidental fracture of the bars and temperature, and the latter taking into account the effects of component eccentricity and local deformation. Wang et al. [19] provided a systematic solution for geometric defects in transmission towers, where the effect of geometric defects on tower capacity and fault location can be clearly observed.

3.3. Experimental validation

The reliability of the tower and steel structure of the transmission line, as the infrastructure supporting the conductor line, is crucial to the safe and stable operation of the power grid. At present, the test of transmission tower-line system mainly includes two aspects: real type test and model test. Among them, the model test can also be divided into: wind tunnel test and shaking table test. In the early days, the wind effect and dynamic characteristics of transmission tower structures were mostly determined by rigid models, while elastic model tests were relatively few. Although the testing of thin-walled steel components faces challenges such as the large number of bars, the cumbersome production of air-elastic models and the difficulty of measurement, with the advancement of technology, it is now possible to carry out air-elastic model wind tunnel tests for the tower-wire system [20]. In order to study the dynamic behaviour of the tower-column system at different wind speeds, Xie et al. [21] conducted wind tunnel tests on an aeroelastic model of an extra-high voltage transmission tower-line system. In particular, the effect of power line vibration on the tower is discussed.

Seismic simulation shaker tests allow visual observation of the damage mechanisms of structures under seismic action. This method is currently the most direct and relatively accurate test method for assessing the seismic performance of structures. Filiatraut et al. [22] investigated the interaction between conductors of different stiffness and insulators of different stiffness under seismic excitation by means of shaking table tests. He et al. [23] proposed and validated a numerical solution method for the seismic response of multi-span flexible conductor-pile equipment coupling system based on the equation of motion. The influence laws of various interconnecting factors on the seismic response of the equipment provide a basis for the seismic design of the substation.

True-type test is a key link to assess the overall load carrying performance of the tower, deformation, member and node load carrying capacity, structural force transfer mechanism, as well as to verify the consistency between the computational model and the actual project. Momomura [24] and Okamura et al. [25] carried out two-year-long sustained observation on the wind vibration characteristics of the full-size true-type tower wire system, not only monitoring the strains of the main members of the tower body and the eight-split conductor tension, but also analysed its wind vibration law in depth. Savory [26] carried out field observations of a linear tower in the south of England over a period of four years and investigated in detail the effect of wind loads on the foundation forces at the base of the tower. Tian et al. [27] conducted full-size tests on a transmission tower and then used ABAQUS to build a material model to simulate its strength capacity and verify the validity of their method. Fu et al. [28] analysed the stress and displacement distribution of a tensioned tower under eight different load cases based on full-scale tests. The tower successfully passed the 100% load step test for the first 7 load cases and collapsed under overload for the 8th load case. Xie et al. [29] proposed a diagonal support modification technique to improve the load carrying capacity of existing transmission towers based on in-depth investigation of the damage mechanism of transmission tower working conditions.

4. Conclusions

(1) Wind loads, ice-covered loads, seismic loads, and wind and rain loads are the main threats to transmission lines. In view of the frequent occurrence of extreme weather, how to reasonably increase extreme conditions based on the conventional design of the work conditions, while avoiding excessive increase in the weight of the tower will be the future trend in the design of transmission towers.

(2) The current transmission line design is mainly based on the spatial truss model and static calculation method of the tower structure, but the structure is in a dynamic state in actual operation. Therefore, how to effectively and reasonably consider the influence of structural dynamic characteristics and dynamic effects on the operation of the tower has become an important direction of research.

(3) There is a relative lack of experimental research on transmission tower members and nodes, and the damage criterion is not comprehensively considered. Accurate damage criterion is the key to ultimate bearing capacity analysis, and all influencing factors need to be considered comprehensively.

(4) Although experimental verification can accurately reflect the mechanical properties of the transmission tower-wire system, the high cost of true-type tests and the similarity theory of simplified models have yet to be improved, which limits its wide application.

Acknowledgments

This study was supported by State Grid Corporation of China technology project (No. B3130N240003).

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