申请同济大学工学博士学位论文

高压输电塔–线耦联体系风致非线性振动研究

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Research on Wind Induced Nonlinear Vibration of High Voltage Transmission Tower-Line Coupling System

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摘要

高压输电塔线体系的风致破坏问题一直是困扰世界各国线路工作者的难题，自首条线路投入使用以来，对该问题的研究就从未间断，但至今仍未能真正解决。另一方面，作为重要的生命线工程，高压输电线路的风致破坏会给国民经济的建设和人民生活的安定造成巨大损失，甚至会威胁到国家社会局面的稳定性。因此，对高压输电线路体系的风致破坏问题进行深入研究具有重要的社会意义。本文采用有限元分析、风洞试验、非线性振动分析相结合的方式，对高压输电塔线体系的风致响应做了详细分析，建立了输电塔线耦合体系的非线性动力学分析模型，研究揭示出塔线耦联体系风致振动的本质非线性响应特点，并给出了高压输电塔线体系风致破坏的理论解释。

建立了较为准确的高压输电塔线体系的三维有限元模型，采用基于随机Fourier 波数谱的脉动风场数值模拟技术得到输电线路的设计风速场，同时根据现场观测风速数据，对单根输电线、单杆输电塔及塔线体系的自振特性和风振响应进行了详细分析。研究发现，对于输电线路中的单体结构，其自振频率之间有近似 1:1 和近似整数倍的关系存在，在风致振动过程中，输电线与输电塔成为一个整体振动，风速愈大，线与塔之间的耦合振动愈强，输电线路的风致振动是本质非线性的，强风时，输电塔与输电线的耦合非线性振动可使结构的动力响应显著增加，输电塔结构的内力增加受输电线的影响显著，线路的破坏是由于输电塔塔腿受压侧主材构件的弹塑性状态的失稳破坏引起的，按传统线性动力分析理论设计输电塔结构时，未考虑塔架与输电线耦合振动对塔架动力特性的影响，使得既有的输电塔结构在强风环境中偏于不安全。

设计制作了高压输电塔线体系的气动弹性模型，对塔线体系的风振响应进行了风洞试验研究，观测到了塔线体系中的输电塔在强风时的破坏现象，其破坏特点与现场调查的高压输电塔的破坏较为相像。对于塔身无附加横隔的输电塔组成的输电线路，在输电塔破坏前可以看到塔身背风面构件在顺风向的强烈振动，在短时间内，塔体振动部位的杆件发生破坏，最终导致输电线路破坏。可知，强风时输电塔破坏既有弹塑性状态的失稳破坏，也有输电塔结构的气弹稳定性破坏。试验结果分析进一步证明，高压输电塔线体系在强风时的风致振动具有较强的非线性振动特性，输电线与输电塔之间的模态耦合作用较强；输

电线路结构设计时，需考虑非线性振动对输电塔结构动力特性的影响。

从非线性动力学入手，建立了输电线与输电塔的三维非线性运动方程，对输电线的面外与面内的非线性耦合振动做了研究；根据输电线与输电塔的连接条件，得到了简化的塔线体系耦合非线性动力模型，进一步研究了输电塔与输电线之间的非线性振动特点，揭示出输电塔与输电线组成的耦合体系的非线性振动易出现 1:1 和 1:2 的内共振模式，并讨论了不同内共振模式对塔线耦联体系振动能量及输电塔内力的影响特点，揭示出输电线与输电塔之间的非线性内共振是造成线路中输电塔在强风时破坏的一个重要原因。

最后，对今后的研究工作方向进行了简要讨论。

关键词：高压输电塔线耦连体系，风致非线性振动，有限元分析，风洞试验，内共振，稳定破坏，破坏机理

ABSTRACT

The wind-induced damage of the High voltage transmission tower-line coupling system (HVTLS) is a challenging issue that bewilders researchers in the worldwide. It has been investigated for a long time since the first transmission line was erected. It, however, still remains an open challenge up to now. As one of the important lifeline engineering, on the other hand, the HVTLS with wind-induced damage might cause huge economic losses that is an adverse factor to the social stability and people's lives, even to the national security. Therefore, it has practical meaning to make a monographic research on the wind-induced damage problem of the HVTLS. In the present thesis, the characteristics of the wind-induced dynamic response of the HVTLS are investigated in detail using finite element methods, wind tunnel test and nonlinear dynamics methods, respectively. A nonlinear dynamic analysis model of the HVTLS is established. The investigation results reveal the wind-induced vibration of the HVTLS exhibits the nature of nonlinearity, and a theoretical explanation on the wind-induced damage mechanism of the HVTLS is given as well.

In this paper, an accurate three-dimensional finite element model of the HVTLS is presented. The characteristics of free vibration and wind-induced vibration of the single transmission conductor, single transmission tower and tower-line system are studied in detail. The wind velocity data used in analysis is obtained involving two approaches. One is the field observation, and the other is numerical simulation technology on the fluctuated wind which employs the stochastic Fourier wave-number spectrum as the target power spectrum. The results show that the natural frequencies of the monomer structure of the HVTLS approximately exhibits a relationship with 1:1 or integral multiple. The vibrations of transmission conductors and towers are coupled together under winds, especially under the strong wind. It is remarked that the coupling is strengthened with increasing of the wind speed, and the wind-induced vibration of the HVTLS exhibits natural nonlinearity. Under the strong wind, moreover, the coupling nonlinear vibration of the towers and conductors would lead to the internal forces of the tower increasing significantly, and this increment strongly relies on the vibration of conductors. The failure of the HVTLS, meanwhile, is resulted from the destabilization of the principle components of the compression-side tower leg with elastoplastic state. The impact of the dynamic characteristic caused by the coupling vibration between the tower and the conductors, however, is not taken into consideration in the traditional design method of transmission tower based on the linear dynamic analysis, which would result in the constructed transmission tower being unsafe in the condition of strong winds.

The aero-elastic model of the HVTLS is designed for the investigation of the wind-induced vibrations in TJ-3 wind tunnel. The phenomena of tower faultier appears in the test when the testing wind speed is higher, and the destructive characteristics are similar to that observed in the field. Strong along-wind vibration of the leeward components of tower without additional diaphragm is observed before the tower was damaged. The components of the vibrating region are then damaged immediately, resulting in the eventual destruction of the transmission tower. It is noted from the FEM analysisthat the tower damage exhibits structural instability, as well as aero-elastic instability characteristics. The test results proves again that the wind-induced vibrations of the HVTLS subjected to the strong wind features the characteristics of nonlinear vibration, and the coupling effect between tower and conductors is very intensive. When designing the structures of transmission tower- system, the contribution of the nonlinear vibration of conductors to the tower dynamic characteristics should be taken into account.

Based on the nonlinear dynamics, three-dimensional nonlinear dynamic equations of the conductor and the tower are deduced. Following that, the out-of-plane and in-plane nonlinear coupling vibrations of the conductor are studied. According to the connecting condition of the conductor and tower, the simplified coupling nonlinear dynamic model of the tower-line system is constructed, whereby the nonlinear characteristics of the coupling system are further studied. The results reveal that the nonlinear vibration of tower-line system is apt to carry out as 1:1 and 1:2 internal resonance modes. The impact behaviors of different internal resonance modes on the transfer of system vibration energy and the increasing of tower inner force are investigated. It shows that the nonlinear internal resonance between tower and conductors is a significant factor resulting in the damage of transmission tower under the strong wind.

Finally, all the results and findings of the research are summarized and the work for further investigation is discussed.

Key words: high voltage transmission tower-line coupling system, wind-induced nonlinear vibration, finite element analysis, wind tunnel test, internal resonance, stability failure, damage mechanism

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