申请同济大学工学博士学位论文

高压输电塔-线耦联系统随机风振响应与动力可靠度研究

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Wind-induced Dynamic Behavior and Reliability Analysis of Transmission tower-lines system

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摘 要

强风荷载下高压输电塔线耦联系统的风振响应计算是电网线路设计中的重要问题，结构在风荷载（通常风荷载为控制荷载）作用下的动力可靠度则为研究的内容。围绕上述两个问题，本文提出导线动张力荷载计算模型和耦联系统理论模型，从解耦和不解耦两个角度给出了频域和时域的计算方法，并基于广义概率密度演化理论开展了输电塔线耦联系统在随机风荷载作用下的体系动力可靠度分析研究。

以某实际高压输电塔线为对象。基于随机 Fourier 谱仿真获得风场，通过精细化的有限元模型，计算了设计风速作用下，塔－线耦联体系结构的风振动力响应。比较了塔线荷载分离，塔线结构解耦等五种工况下塔顶位移、关键主材应力，导线位移的动力响应的时域及频域分布特点和概率特性。在一定程度上揭示塔线系统的中导线和塔体之间风荷载传递和相互作用的动力机制。表明：导线动张力是塔—线耦联体系解耦计算的关键所在。

从解耦的角度出发，研究了导线风致振动在支座处动张力产生的物理机制。按照悬索连续体系动力方程，将导线在风荷载作用下分成三种状态：自重状态、平均风作用下几何大变形的非线性静力状态—平均风偏状态、脉动风下的导线以平均风偏状态为平衡位置的动力状态。将脉动风荷载在导线平均风偏状态下，在面内和面外分解，考虑面外一阶和面内对称一阶振动是导线脉动风下线性振动的卓越振型，根据非耦合两自由度线性动力方程，得到位移和弦向张力解，考虑支座处反力的矢量条件，可以建立风荷载下导线的动张力时域计算模型。推导了对导线动力响应影响显著的气动阻尼的理论解，通过流固耦合的数值计算对理论解进行了讨论和修正。

在导线动张力时域解的基础上，依据随机振动理论，进一步推导了水平动张力的功率谱密度解析解。引入设计应用中常用的工程参数，通过适当的简化推导和提炼，建立了动张力的标准差响应谱表达式，在此基础上给出了设计等效荷载公式，并与我国规范和 IEC 规范做了比较。

介绍了基于广义概率密度演化方法进行动力可靠度分析的一般步骤，说明了其中涉及的关键技术，如数论选点法，等价极值事件原理等。将非线性结构随

机动力响应的概率密度演化方法与体系可靠度等价极值事件理论相结合，在不引入任何假定的情况下，依据随机 Fourier 谱模型生成风场，运用动张力模型荷载，计算了塔体的随机动力响应，给出了输电塔线体系风振随机响应时变的概率密度精确演化特征，获得了复杂失效准则下，高压输电塔线耦联系统的体系可靠度。

以耦联系统风致振动的物理规律和主要频域特征为基础，基于分析力学原理，以塔架和平均风偏状态下导线的广义自由度的方式，结合平均风下塔架的静力非线性性能，建立了强风下耦联系统的非线性力学理论模型，并运用等效线性化方法，给出系统在强风荷载下的非线性随机动力响应频域近似解和临界平均风速的判断方式。

关键词：输电塔-线耦联系统；风致动力响应；输电线；动态张力；随机振动；随机 Fourier 谱；广义概率密度演化方程；等价极值事件；动力可靠度；体系可靠度

ABSTRACT

Wind induced dynamic response of high-voltage transmission tower-lines system is an important issue in grid structural design computation. Dynamic reliability of gird structure under stochastic wind load (usually wind is the dominate load) is the core content. Around the two main issues, from the coupling and decoupling perspective, the thesis presents a new method for dynamic tension of transmission line under wind load and a coupled transmission tower-lines system idealized model. Thus, frequency domain and time domain solution of dynamic response of transmission tower-lines system are analyzed. Moreover, based on the generalized probability density evolution theory, reliability analysis of transmission tower-lines system under stochastic wind load is developed.

Taking a practical high-voltage transmission towers and lines as prototype of fine finite element model, under design wind load simulated by stochastic Fourier spectrum method, the wind-induced dynamic response of transmission tower-lines system is commutated. Comparison of the top displacement, strain of key member and their probability of tower and line under five wind loads cases, such as: separation of wind load on towers and lines, structural decoupling of towers and lines, reveal the dynamic mechanism of transfer of wind loads from lines to tower and interaction between the tower and lines. Solution shows that dynamic tension of line to tower is the key of decoupling analysis of transmission tower-lines system under wind load.

From the decoupling view, the mechanical mechanism of wind-induced dynamic tension of line on the support is explored. Based on motion equation of a continuous cable system, dynamic tension of the transmission line caused by along-wind loading was decomposed into two parts, nonlinear static effects by mean wind and linear dynamic effects by turbulence wind in its equilibrium plane. Because the first out-of-plane mode and the first symmetric in-plane mode are two dominant modes which contribute the most to the dynamic tension force of the transmission line, the motion equation is decoupled and the time domain solutions of dynamic tension then be obtained. Besides, as a significant influence factor in dynamic tension, theoretical solution of aerodynamic damping is deduced. Then, through the comparison with the fluid-solid coupling numerical computation, the theoretical solution is discussed and a amendment is proposed.

According to the linear stochastic vibration theory, the frequency domain solution of dynamic tension is developed. Introducing the common engineering design parameters to the solution, the expression is refined and simplified to a root mean squarer (RMS) response spectrum. Based on it, a design equation for line wind load is set up and then its solution is compared with the IEC60826 (International Electricity Commission code) and China specification DL/T5154-2002.

After a brief introduction of the general procedure to evaluate dynamic reliabilities with general probability density evolution method (GPDEM) and several key techniques, such as: strategy for selecting representative points via numerical theory and equivalent extreme-value event, the dynamic responses of the wind-induced dynamic responses of transmission tower-lines system are analyzed. During the processes, dynamic tension model deduced previously and wind field simulated by stochastic Fourier spectrum is applied to calculate the wind load on system. Probability density evolution processes, time-varying mean values and deviations of these stochastic responses are also presented. Based on the equivalent extreme-value event, the dynamic reliability of transmission tower-lines system under complex failure criteria is evaluated

Based on the previous analysis on mechanical mechanism and domain frequency characteristics of dynamic vibration of tower-lines system under wind, by Analytical Mechanics, a nonlinear idealized MDOF (multiple degree of freedom) model for coupled system is proposed, including the in-plan and out-plan generalized freedom of lines under mean wind, the first along-wind model of tower and the nonlinear behaviors of tower under monotonous mean wind load. Using the method of statistical linearization, an approximate frequency domain solution of steady state response of the model is obtained. The criteria design mean wind velocity of the tower-lines system can be evaluated by whether the iterative procedure of the statistical linearization ceases to obtain positive solution.

Key Words: High-Voltage transmission tower-lines system, Wind-induced dynamic response, transmission lines, Dynamic tension, Stochastic vibration, Stochastic Fourier spectrum, General probability density evolution method, Equivalent extreme-value event, Dynamic reliability, System reliability

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