Uncertainty Quantification of the Lines Excited by Transient Electromagnetic Disturbances Based on Stochastic Models

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ABSTRACT

The transient electromagnetic disturbance (TED), such as lightning electromagnetic pulse (LEMP), high altitude electromagnetic pulse (HEMP), and high power microwave (HPM) may couple into the power system through various conductors, such as power lines, communication cables, and other transmission line structures. The coupling responses may cause failure or even damage to the equipment connected with the lines. For TED events with low probability, deterministic simulation based on certain parameters cannot predict the possible variation and distribution of the responses, and it is hard to provide reasonable evaluations for the TED impact. To address the above problems, this dissertation takes HEMP as an example, stochastic models are developed for uncertainty quantification of the responses under HEMP.

To study the impact of uncertainties in the source of HEMP and the environment, an accurate and efficient iterative self-consistent simulation scheme is developed for the simulation of HEMP generation and propagation. Compared with the conventional non-iteration method, the simulation efficiency is improved up to tens of times. Since the full simulation of HEMP has no analytical expression, a physical-based stochastic surrogate model is derived from the simplified model of magnetic dipole and electric quadrupole. The proposed model can address the accuracy problem of constructing non-intrusive surrogate models, when the spatial distribution of the HEMP electric field amplitude and polarization angle is not smooth. Compared to the conventional uncertainty quantification based on Monte Carlo (MC), the proposed stochastic surrogate model of HEMP requires fewer full simulations, and it can reduce the time-consuming from days to hours. The statistical results show that the probability distributions of the amplitude, the rise time, and the polarization angle of the HEMP are strongly correlated.

In order to simulate the potential coupling responses of lines with nonlinear loads (such as metal-oxide arresters, MOA), when the coupling responses may vary in a large range due to the uncertainty of TED. Based on the analog behavior modeling, the macromodels of field-to-lines coupling are established to deal with the frequency-dependent characteristics as well as the nonlinear load of the lines; An equation-based dynamic nonlinear model of MOA is proposed to represent the behavior of the MOA that may be less nonlinear when the rise time of the induced current is faster. These two models can be easily combined together in the simulation. Based on the deterministic model of field-to-lines coupling responses, by expanding the telegraph equations through the polynomial chaos expansion method (PCE), the stochastic models of transmission line coupling responses are intrusively constructed. The time-consuming of the stochastic models is about 70 times faster than MC. However, the stochastic models for field-to-line coupling response are available only when the

uncertainty variables are assumed as mutually independent variables.

When the uncertainty quantification results of the HEMP are used as the inputs of the field-to-line coupling problem, the variables are no longer mutual independence. To address the problem of transferring arbitrary correlated multidimensional variables in the hierarchical stochastic models, we proposed a PCE method based on the kernel density estimation (KDE), that the orthogonal polynomial basic functions can be constructed for the arbitrary correlated variables. The proposed KDE-PCE does no transformation for the input variables, it has the advantage of high efficiency and fast convergence speed, which is suitable for the uncertainty quantification problem that can be divided into several independent physical processes with uncertainties. From the uncertainty quantification based on the proposed hierarchical stochastic model, the conducted environment for transmission lines are less severe.

To evaluate the equipment connected with the transmission lines considering the uncertain coupling responses, and to address the problem of equivalent characterization of the coupling responses and the equipment strength, the expression method based on the equivalent injection current is proposed. The equivalent injection current is extracted from the distributed-parameter model for the test platform. It is validated that the equivalent injection current is not affected by the length and loads of the injected line, which avoids the influence of the unknown input impedance of the equipment under test. Since the effect tests usually result in few data, in order to overcome the effects caused by sampling variability and estimation errors, a distribution-free vulnerability evaluation method is proposed, according to the framework of the quantification of margins and uncertainties (QMU) method. Two non-parametric estimation/ regression methods are proposed to estimate the quantiles and the tolerance bounds for the equipment strength. These methods are applicable for the effect data and binary state data, respectively, and are not constrained by the preset probability distribution. By using the distribution-free QMU metric based on quantiles and tolerance bounds, reasonable vulnerability assessment conclusions can be provided with certain confidence levels.

This dissertation systematically studied the uncertainty quantification of the transmission line under the HEMP, the method proposed in the dissertation can be expended to carry out studies about the impact of other types of TEDs.