Study on Modeling and Efficient Algorithms for Geomagnetic Induction in AC Transmission Grids and Gas Pipeline Networks

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By

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ABSTRACT

Geomagnetic disturbances (GMDs) are wide-area natural hazards caused by solar activity, which induce low-frequency geoelectric fields on the earth's surface. The resulting geomagnetically induced currents (GICs) in the power grid can lead to the half-wave saturation of transformer, and the pipe-to-soil potential may interfere with the cathodic protection system, which may pose a potential threat to the reliable operation of large-scale AC transmission grids and gas pipeline networks. Therefore, understanding the induced voltage and current levels in the energy system due to extreme GMDs is of great significance for further assessment and mitigation of geomagnetic hazards. The increasingly interconnected and coupled transmission grids and gas pipeline networks are subject to complex spatially distributed geoelectric fields, which requires more efficient and generalized geomagnetic induction models. In this respect, this dissertation studies the wide-area spatiotemporal distribution characteristics of the geoelectric fields, proposes several reduced geomagnetic induction models for power grids and pipeline networks, and further establishes a comprehensive induction model that considering the coupling between these two networks.

First, the evaluation scenarios of the geoelectric fields induced by extreme GMD are constructed for the geomagnetic induction analysis of energy networks, considering the intensity of geomagnetic activity and the distribution of three-dimensional earth conductivity. Typical scenarios such as 100-year, 200-year and 10,000-year events are constructed for extreme geomagnetic variations, by combining the extreme value statistical method with the theoretical upper limit of the disturbance storm time index. Then, a Bayesian inversion method for horizontally layered earth structure is proposed, which can quantify the impact of measurement noise and shielding effects on the estimation performance from a statistical perspective. In addition, the nonuniform wide-area geoelectric fields on the earth's surface are calculated considering complex earth resistivity distribution such as the coast.

Then, this study proposes a model reduction method for GIC calculation in lumped parameter circuits of the power grids. A reduced nodal admittance matrix method is proposed for GIC calculation in power grids based on Kron reduction, which reduces the size of GIC model while retaining the positive definiteness and sparsity of the design matrix. Moreover, the impact of transformer reactive power loss caused by GIC on the voltage security of the power system is

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evaluated. A compressed surrogate computational model for multiple AC voltages is established based on the generalized polynomial chaos expansion method and principal component analysis, which can speed up the uncertainty quantification of AC voltages in bulk transmission systems during GMD compared to traditional Monte Carlo method.

Furthermore, this study proposes a reduced method for the distributed parameter circuit of buried pipelines. A modified equivalent pi-circuit model for pipelines excited by nonuniform geoelectric field is derived based on transmission line theory, which can efficiently solve the geomagnetic induction in large-scale interconnected pipeline networks in the cases of nonuniform geomagnetic source field and complex earth conductivity distribution. Furthermore, the proposed equivalent circuit can be used to efficiently evaluate the nonlinear polarization effects of coating breakdown. The proposed equivalent circuit is then extended to the calculation of other types of electromagnetic interference on buried pipelines, such as the conductive interference caused by the HVDC earth return currents.

Finally, this study proposes a novel geomagnetic induction calculation model that considers the coupling between the AC transmission system and the pipeline network. The substation grounding currents may interact with the leakage currents from nearby buried pipelines through the earth during GMD, which is not fully considered in classical geomagnetic induction studies. Hence, a more comprehensive nodal voltage analysis is conducted to evaluate the geomagnetic induction in integrated systems, where the conductive coupling between grounded nodes is characterized by ground transfer resistances. The results of several test cases indicate the need to account for the coupling between the substation grounding grid and the buried pipeline in order to predict the distribution of the geomagnetic response accurately.

In summary, in this research activity, more generalized modeling methods are developed for the geomagnetic induction in transmission grids, gas pipeline networks and their integrated systems, by considering the influence of nonuniform geoelectric fields, uncertain input parameters, nonlinear components, and conductive coupling. And the proposed algorithms enable more rigorous evaluation of the response in energy networks and are promising for online applications, which lays the foundation for further GMD risk assessment and mitigation.

KEY WORDS: Geomagnetic disturbances; Geomagnetically induced currents; Pipe-to-soil potentials; Integrated power-gas systems; Model reduction; Uncertainty quantification

TYPE OF DISSERTATION: Application Fundamentals