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Modeling of geomagnetic induction in power grids and pipeline networks

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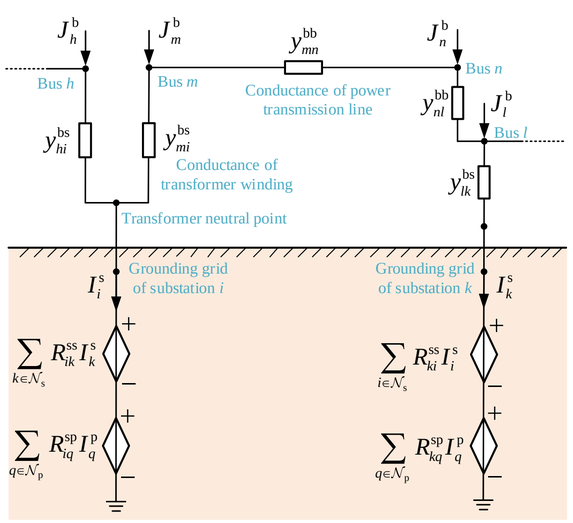
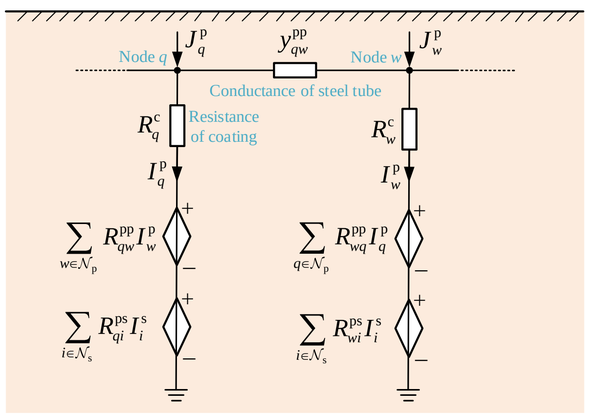
Research context and motivation

- Geomagnetic disturbance (GMD) hazards initiated by space weather can induce low-frequency (0.1 mHz–0.1 Hz) geoelectric fields, which may pose a threat to the reliability of the ground-based technological systems, including power grids and pipeline networks.
- Geomagnetic induction can lead to adverse effects on the critical equipment. Geomagnetically induced currents (GIC) give rise to half-cycle saturation of the transformers in power grids. The pipe-to-soil potentials (PSP) may accelerate the corrosion of the pipeline and interfere with the cathodic protection system.
- Nowadays, large-scale interconnected energy infrastructures, e.g. 1000 kV ultra-high-voltage power grid in China, are built for long-distance energy transmission. These systems with long conductor lines and low resistances are more vulnerable to the GMD.
- Therefore, rigorous and efficient assessment of geomagnetic induction in energy systems is extremely important for long-term/online risk assessment and mitigation.

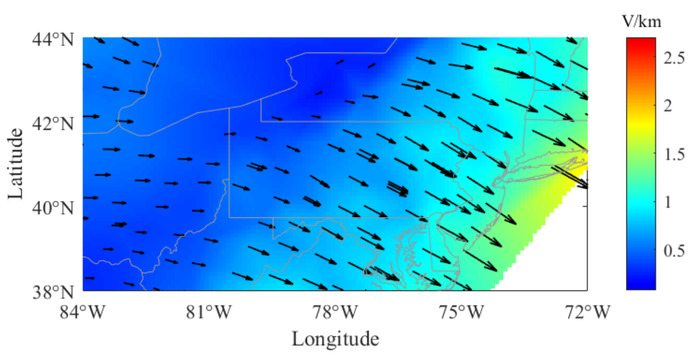
Addressed research questions/problems

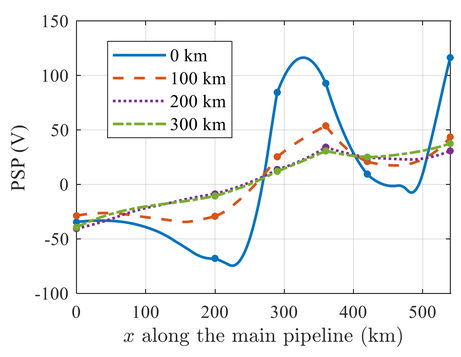
- Wide-area distributed geoelectric fields affect energy systems spanning thousands of kilometers. Efficient methods should be developed to solve the induction model of large-scale systems.
- There are a large number of uncertain parameters in the induction model, e.g. soil resistivity, substation grounding resistance, etc. Statistical methods are required to quantify the resulting uncertainty of the GIC and PSP.
- Modern power systems and natural gas pipeline networks are increasingly coupled both functionally and spatially. The integrated power-gas systems hold promise for improving the flexibility of energy supply. Moreover, common corridor of power transmission lines and buried pipelines are built to save land use and construction costs. Thus, the influence of their interaction on geomagnetic induction deserves attention.





- The developed induction model needs to be suitable for any given nonuniform spatial distribution of geoelectric field. The influence of the spatial granularity of the geoelectric field needs to be investigated.



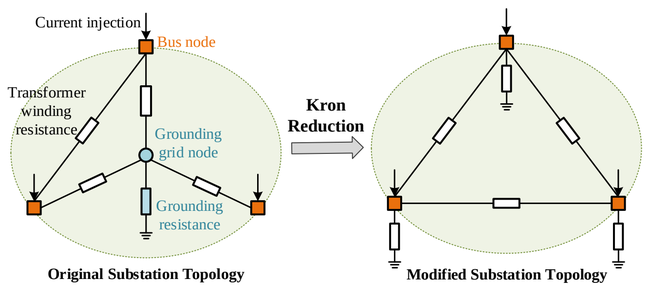


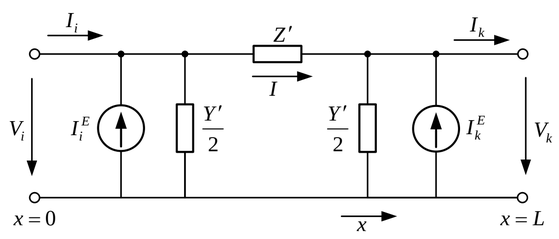
Novel contributions

- A novel reduced nodal admittance matrix method for probabilistic GIC analysis in power grids. It can save about 25%-40% of the simulation time compared with the classical full-node admittance matrix method.
- Geomagnetic induction analysis in power grids and pipeline networks considering the nonuniform geomagnetic source field and the lateral soil resistivity variation.
- First attempt to consider the interaction between the power grids and buried pipelines in geomagnetic induction analysis.

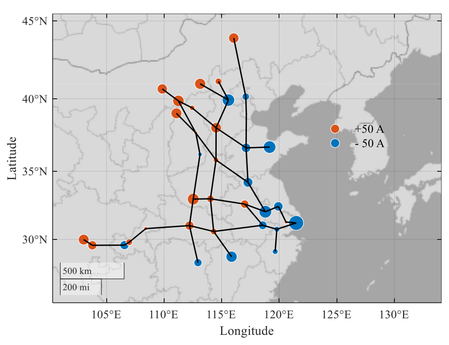
Adopted methodologies

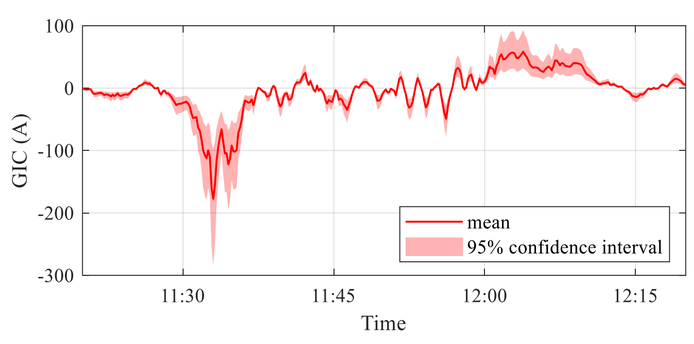
- Kron reduction is adopted to reduce the size of the computational model of power grid and preserve the positive definiteness of the design matrix, thus the power grid GIC can be efficiently solved by utilizing Cholesky decomposition.
- A modified equivalent-pi circuit is derived for the geomagnetic induction analysis in pipeline networks with nonuniform geoelectric fields for model order reduction.



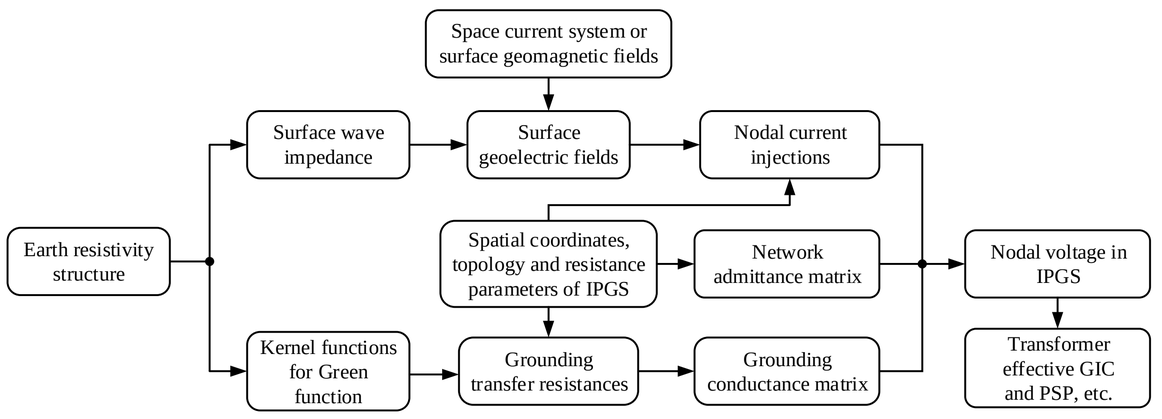


- Monte Carlo method is used for probabilistic GIC analysis in power grid considering the uncertain substation grounding resistance parameters.





- A nodal voltage analysis method is proposed to evaluate the geomagnetic induction in the integrated power-gas systems (IPGS) considering their interaction.



Future work

- Uncertainty quantification of the effects of GIC on voltage security of power systems. The additional reactive power loss of transformer can be combined with the power flow model to calculate the risk metrics, such as the probability of AC voltage exceeding specified limits, the probability distribution of the voltage margin, etc.
- Evaluate the effect of GIC on the transformer hot-spot heating. A time-domain model will be established for the transformer structural parts to simulate the probability distribution of the temperature rise.
- The performance of several uncertainty quantification methods, e.g. Monte Carlo method and polynomial chaos expansion, will be compared.

Submitted and published works

- **M. -Z. Liu**, Y. -Z. Xie, N. Dong, Z. -Y. Wang and Y. -F. Yang, "Numerical Analysis of Nonuniform Geoelectric Field Impacts on Geomagnetic Induction in Pipeline Networks," *IEEE Transactions on Electromagnetic Compatibility*, vol. 64, no. 4, pp. 999-1009, Aug. 2022.
- **M. -Z. Liu**, Y. -Z. Xie, Y. -H. Chen and Q. Liu, "Modeling the 10,000-Year Geomagnetic Disturbance Scenarios Based on Extreme Value Analysis," *IEEE Letters on Electromagnetic Compatibility Practice and Applications*, vol. 2, no. 4, pp. 156-160, Dec. 2020.
- Y. -h. Chen, Y. -z. Xie, **M. -z. Liu**, Z. -y. Wang, Q. Liu and A. -c. Qiu, "Geomagnetically Induced Current Calculation of High Voltage Power System With Long Transmission Lines Using Kriging Method," *IEEE Transactions on Power Delivery*, vol. 37, no. 1, pp. 650-657, Feb. 2022.
- **M. -Z. Liu**, Y. -Z. Xie, Y. -F. Yang, R. Trinchero and and I. S. Stievano, "Reduced Nodal Admittance Matrix Method for Probabilistic GIC Analysis in Power Grids," *IEEE Power Engineering Letters* (Submitted, Under Review).

List of attended classes

- Enrolled in co-directed thesis project between PoliTo and Xi'an Jiaotong University (XJTU), courses are taken in XJTU.

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