GICs resulting from ground electric fields induced by GMDs above 3-D Earth conductivity structure - assimilating magnetotelluric array and ionospheric data sets

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The electric power grid is exposed to geomagnetically induced currents (GICs) that arise in response to geomagnetic disturbances (GMDs). During large GMDs, strong electric currents enter the grounding of transformers and saturate the cores, thus distorting the power signal AC waveforms. This can lead to system relay interference, reactive power loss, and total system collapse, including cascading failures that can propagate over a wide area. The lack of resilience of power grids to GICs presents a grave risk to the economy and to public safety. Efforts from the research and development perspective, the regulatory agencies, and from the power utilities are underway to mitigate against potential damage from these events.

We illustrate key geophysical factors that determine the intensity of ground electric fields, and hence GICs, that arise from GMDs above a crust and mantle whose electrical structure is 3-D. We apply real-world examples from temporary regional and continental-scale arrays of ground electric and magnetic field (i.e. magnetotelluric) monitoring stations that demonstrate the intensification of ground electric fields associated with strong 3-D conductivity variations, which are ubiquitous across the continental US.

We discuss two approaches to predicting the intensity of ground electric fields. The first is to solve the fully coupled, reduced form of Maxwell’s Equations in the quasi-static approximation in the time domain, given knowledge of the ionospheric source fields in both time and space domains. In order to accomplish this, constraints on ionospheric source fields were obtained from the Poker Flat Incoherent Scattering Radar (PFISR) system at a facility north of Fairbanks, Alaska. In 2015 we operated a synchronous array of 25 long-period magnetotelluric (MT) stations beneath the ionospheric footprint of PFISR. We developed a solution for the fully coupled Maxwell’s Equations using the Finite Difference Fictitious Wave Domain (FDFWF) method, that when combined with a cascade decimation approach to represent the time domain waveform of ground electric and magnetic fields in a low-loss compressed form, speeds the solution and reduces memory requirements by many orders of magnitude relative to conventional FDTD approaches. We report on forward and inverse solutions for determining 3-D ground conductivity structure and the resulting ground electric fields, as applied to the Alaska data set.

Our second approach avoids solving Maxwell’s equations, and instead makes direct use of the MT impedance functions that are generated for each MT station location using well-established frequency domain methods. We have obtained approximately 1000 MT impedance functions for sites across approximately half of the area of the continental US, and using these we have constructed a set of two linear filters that: a) project real time measurements of ground magnetic fields from distant magnetic observatories onto the locations of the (former) temporary MT stations, and then b) project the predicted electric fields through the site-specific MT impedance functions to predict the real-time electric fields at those locations. These electric fields are then projected onto the path of the power grid and integrated along the path length to determine the forcing function for the GICs. We applied this Cascading Linear

Filter Algorithm (CLFA) to predicting electric fields for power grids in two regions of the US, and compare our predictions with some indirect measurements of GICs in those grids. We describe the impact of varying distance from remote magnetic observatories on the fidelity of the electric field predictions, and demonstrate the importance of factoring in 3-D variations in ground conductivity in order to produce electric field predictions that more accurately represent the GIC threat to power grids.

Keywords: GIC, GMD, Magnetotelluric, Electric Field, Impedance, Space Weather

