AMS100

ABSTRACT

6.4: Mitigating Impacts of Space Weather: Advances in Real-Time Prediction of Reactive Power Loss on Power Transformers due to Geomagnetic Disturbances

Wednesday, 10 January 2018 **09:15 AM - 09:30 AM**

Austin, Texas - Salon J (Hilton)

Geomagnetic disturbances (GMDs) arising from space weather events induce electric fields in the Earth's crust, mantle, and oceans that drive quasi-DC geomagnetically induced currents (GICs) in conductive infrastructure such as electric transmission lines and transformers. Strong GICs can saturate transformer cores, distorting the AC waveform of the power signal that can lead to system relay interference, reactive power loss, or even total system collapse such as the Hydro-Quebec system-wide blackout of 1989.

As an aid to planning and facilitate better resilience to GMDs, operators have tools that provide indications of potential "hotspots," based on statistical models of likely GMD storm scenarios and power distribution grounding models that assume that the electrical conductivity of the Earth's crust and mantle varies only with depth within a broad region. The adoption of such assumptions has been called into question; the US National Science Foundation EarthScope Magnetotelluric Program operated by Oregon State University has mapped real-world 3-D ground electrical conductivity structure across more than half of the continental US. Large deviations are seen in calculated GICs that employ this information relative to previous models that approximate the Earth conductivity as 1-D. One goal of our research is to provide a toolset that uses the best available information about 3-D ground conductivity and other information from power grid sensor networks, to allow power grid operators to make dynamic control decisions to help mitigate against damage to power transformers. We demonstrate that use of 3-D ground conductivity information significantly improves the fidelity of GIC predictions over current models employed by the power industry.

There are two approaches to modeling the intensity of electric fields at ground level that drive GICs through the power grid. The first approach is to numerically solve the coupled system of differential equations that represents the physics of electromagnetic induction above a 3-D conducting Earth, given a model of the inducing electric or magnetic fields in the ionosphere and an existing model of the 3-D variations in electrical conductivity of the Earth's crust and upper mantle. The result is a time-series of vector electric fields, at ground level, along the pathways of power transmission lines. This approach is computationally expensive and demands large amounts of fast computer memory to implement. The underlying ground conductivity models are ultimately derived through inverse modeling of observations of time variations in ground level electric and magnetic fields determined through magnetotelluric measurements and are intrinsically inexact, volume-averaged estimates of real-world conductivity variations. Furthermore, exact knowledge of the instantaneous complex form of ionospheric electric fields that induce GICs in the grid is illusive at best. A second approach to solving this problem lies in eliminating use of ground conductivity models entirely, but rather directly using the magnetotelluric information from which those models were subsequently derived. We have taken this second branch to solving the GIC prediction problem, and show that real-time predictions of ground level electric fields can be obtained on consumer-class personal computers.

The foundation of this modeling approach comes from the 3-D mapping of the electrical conductivity of the Earth's crust and mantle through the NSF's EarthScope magnetotelluric (MT) program. MT data are obtained by measuring the naturally occurring time variations in the Earth's vector electric and magnetic fields at ground level on a grid of temporary observation locations. These electric and magnetic field measurements are used to determine the MT impedance tensor for each site (the ratio of horizontal vector electric and magnetic fields at ground level expressed as a complex-valued frequency domain quantity), which provides information on the electrical conductivity structure of the Earth's crust and mantle. We project real-time magnetic field data streams from US Geological Survey (and other) permanent networks of magnetic observatories, into a cascading set of two linear filters that:

1. Finds the best fitting (in a robust least squares sense) linear filter coefficients that map ground magnetic field data recorded previously on temporary (typically, operating for ~3-4 weeks) rolling networks of 10-30 MT stations at a time (such as the aggregated collection ~1000 temporary/portable MT stations that have covered half of the area of the continental US under the support of the NSF EarthScope Program) and magnetic field data recorded over the same time interval by the much sparser network of permanent magnetic observatories that most closely surrounds the region of interest, and that then

2. applies that linear filter to real-time magnetic observatory data to generate real-time predictions of ground magnetic field values at the locations where EarthScope (or other) magnetotelluric stations had previously operated, following which

3. the predicted magnetic fields are projected through MT impedance tensors previously calculated from the MT data collected at the MT stations (equation 1 below), thus yielding predictions of ground electric fields at those sites; such predicted fields are then

4. projected to the line paths of high voltage lines that lie inside the aperture of the MT array, using a nearest neighbor distance-based weighted interpolation. The electric fields are then integrated along the line paths to yield a time varying voltage which is used as input to an equivalent circuit that describes the power grid configuration, yielding a real-time GIC prediction.

These steps describe our Cascading Linear Filter Algorithm. In the present work, we illustrate how the method may be applied to predicting the reactive power loss at individual power transformers on regional-scale electric transmission grids, and show how use of real-world 3-D ground conductivity information as contained within the MT impedance tensors leads to substantial deviations from existing 1-D-based methods. We also demonstrate that peak reactive power loss and hence peak risk for transformer damage from GICs does not necessarily occur during peak GMD storm times, but rather depends on the time-evolution of the (directional) polarization of the GMD's inducing fields and the complex ground (3-D) electric field response, and the resulting alignment of the ground electric fields with the power transmission line paths.

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