2014 Status of EPRI Geomagnetic Disturbance Research and Future Plans

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ABSTRACT

The Electric Power Research Institute's (EPRI's) geomagnetic disturbance (GMD) research project continued in earnest in 2013 and the first half of 2014. Working in close cooperation with participating utilities and the North American Electric Reliability Corporation (NERC), EPRI has continued to deliver a range of tools and information spanning GMD scenario definition, geomagnetically induced current (GIC) modeling, GIC measurement, power system and equipment vulnerability assessment, mitigation, risk management, and industry awareness. This effort aims to maintain high bulk power system reliability by shortening customer interruptions, as well as minimizing the risks of damage to long-lead-time equipment and limiting macroeconomic costs. This important work is continuing through 2014 and beyond, with specific goals for enhanced understanding of GMDs and practical guidance for utilities. EPRI also plans to deliver guidance to aid industry compliance with NERC Reliability Standards on GMDs, which are being developed in response to a Federal Energy Regulatory Commission (FERC) directive. This report summarizes the GMD regulatory activity, EPRI GMD work completed in 2013, current EPRI GMD work under way, and planned EPRI work in this area.

Keywords

Geomagnetic disturbances (GMDs)
Geomagnetically induced currents (GICs)
Solar storms

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INTRODUCTION

Summary of Regulatory Activity

Geomagnetic disturbances (GMDs) have demonstrated their potential to adversely impact the reliable operation of power systems. GMD events can cause geomagnetically-induced current (GIC) to flow in power transformers. This can lead to half-cycle saturation in the transformers. Potential consequences include generation of harmonic currents, increased absorption of reactive power, and hotspot heating in the transformers. These harmonic currents and the reactive power absorption, in turn, can result in misoperation of protection systems and reactive power source loss. This combination can result in voltage collapse of power systems [1].

This potential adverse impact to the reliability of North American power systems has motivated significant regulatory activity on GMDs in the last two years. On October 18, 2012, the Federal Energy Regulatory Commission (FERC) issued a Notice of Proposed Rulemaking (NOPR) on GMDs [2]. After addressing many filed comments on the NOPR, FERC issued Order 779 on May 16, 2013, which directed the North American Electric Reliability Corporation (NERC) to submit two stages of proposed reliability standards on GMDs [3].

In response, NERC developed the Stage 1 Standard, EOP-010-1, which requires “applicable registered entities to develop and implement operating procedures that can mitigate the effects of GMD events.” Also in response to the FERC Order, NERC is developing the Stage 2 Standard, TPL-007-1, which requires “applicable registered entities to conduct initial and ongoing assessments of the potential impact of benchmark GMD events on their respective system.” This Standard must identify the “benchmark GMD events.” For each entity, if the assessments identify potential impacts from the benchmark events, then entities must “develop and implement a plan to mitigate the risk of instability, uncontrolled separation, or cascading as a result of a benchmark GMD event.” The plan must consider not only operating procedures and training, but also “contain strategies for mitigating the potential impact of GMDs based on factors such as the age, condition, technical specifications, system configuration, or location of specific equipment.” FERC requires this Stage 2 Standard to be filed by January 2015 [1].

EPRI Project: Providing Industry Support for Compliance with the Stage 2 GMD Standard

In its 2015 Annual Research Portfolio, EPRI has initiated an effort (project P40.023) to provide a single, easy-to-follow reference, guidance on the forthcoming Stage 2 Standard, and example case studies illustrating the analysis techniques and mitigation strategy evaluation. As the Stage 2 Standard is expected to require reporting of initial analysis results to NERC in 2019 or 2020, the creation of easily assessable technical material that provides instruction and guidance when performing the newly developed GMD studies is expected to be timely.

This effort will leverage recent EPRI supported research related to the development and advancement of GMD assessment and planning tools. Industry experience, system studies, and expert guidance will be compiled for planners, operators, and analysts in evaluating potential system vulnerability to GMD as well as potential mitigation options, along with the development of illustrative examples. The research conducted and the associated guidelines to be developed from this effort will work in concert with the existing NERC GMD guidelines and forthcoming standards [4].

2
EPRI GMD WORK COMPLETED

The EPRI GMD project has delivered a range of tools and information in the areas of GMD scenario definition, GIC modeling, power system and equipment vulnerability assessment, mitigation, risk management, and industry awareness (see Figure 2-1).

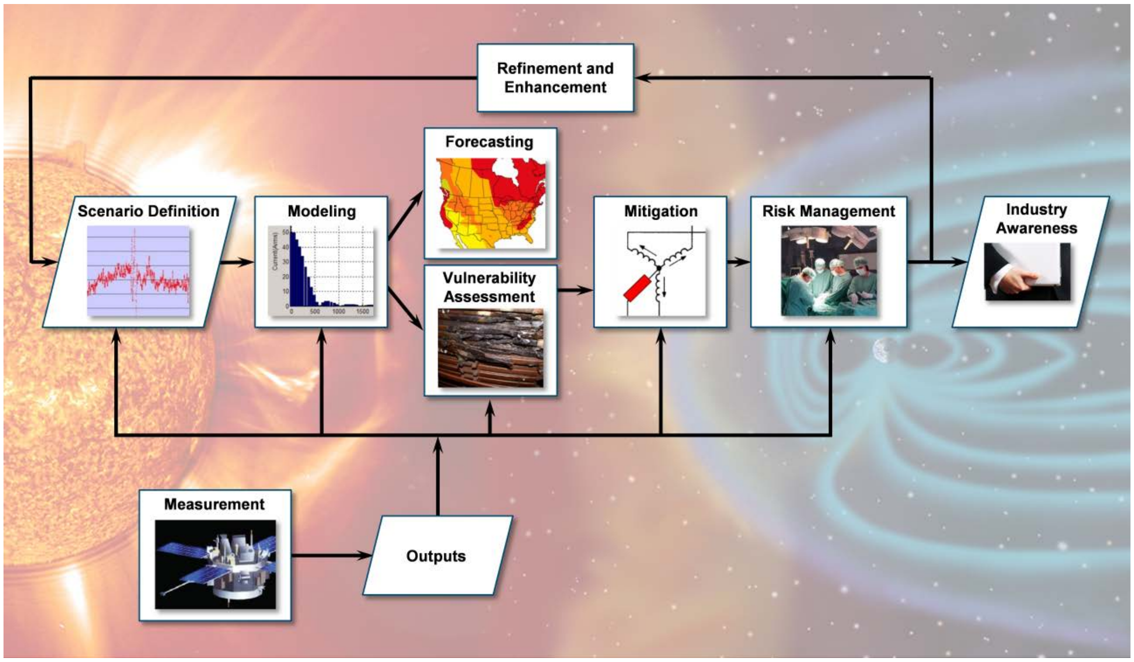

Figure 2–1
EPRI has delivered important GMD research results in a variety of areas.

GMD Research Results

EPRI has recently delivered significant GMD research results, and documented these results in published reports, in the following areas:

- **Storm Scenario Definition**. In 2013, EPRI carried out a study of extreme geomagnetic storm and GIC scenarios, and also continued its studies to further understanding of the theoretical extreme geoelectric fields. In 2014, EPRI is further refining this work to enable utility application [5].
- **GIC Calculation**. In 2013, EPRI completed work on improved methods of calculating GICs [6]. In related work, EPRI assessed the impact of using uniform (versus non-uniform) geology assumptions on GIC calculations. In particular, a 2013 EPRI study examined the impact of land mass boundary conditions (i.e., GIC calculations near coastlines) [7].
- **GIC Modeling**. In 2013, EPRI presented a methodology for the modeling and analysis of GMDs and GICs on the power grid. The methodology integrated the effects of GICs into the power flow to assess the impact on system voltage stability. EPRI provided the results of studies performed on EPRI benchmark models and large-scale power system models. The

report also proposed a technique to perform sensitivity analysis of transformer GICs to electric fields and induced line voltages, to determine how much of a large power flow model is needed to accurately determine the GICs in transformers of interest [8].

In related ongoing work in 2014, EPRI is providing GIC modeling for a particular member utility. To do this, EPRI is using reference storms and calculating GIC flows in lines and transformers.

- **Vulnerability Assessment**. In 2014, EPRI documented the application of state-of-the-art GMD vulnerability assessment tools, models, and methods for a representative main transmission system model at a particular utility. By testing the available assessment methods using actual system models and data, a better understanding of the nature of likely system impacts can be gained along with the real world capabilities of available analysis tools and models. The study process and findings from dc network model development, system vulnerability assessments, and modeling sensitivity analyses were provided.
- **Transformer Modeling**. In 2013, EPRI reported on transformer modeling to simulate GICs using electromagnetic transient (EMT) studies. This research presented a new topological model for a single-phase, three-winding core-form autotransformer; proposed a method for developing a model of a three-phase, three-legged transformer; and located data and models in the literature for a five-legged transformer [9].
- **Mitigation**. In 2013, EPRI supported NERC in assessing the impact of devices that mitigate the impact of GIC flows on hardware such as transformers (i.e., blocking devices) [10].

EPRI SUNBURST Research Network

In parallel, EPRI has enhanced its SUNBURST research network that measures GICs in real time. In 2013 alone, with support from the U.S. Department of Energy (DOE), EPRI has worked with numerous utilities across North America to install almost 30 new SUNBURST measurement nodes, bringing the total number of measuring stations to about 36 and providing more complete coverage across the continent. The SUNBURST network will continue to act as a valuable research tool in support of industry GMD efforts.

GMD Summit

In conjunction with the North American Transmission Forum (NATF), EPRI conducted a GMD Summit September 24-25, 2013 at EPRI's Charlotte offices. The Summit provided a non-public forum for information sharing and discussion of the practical aspects of preparing for a GMD event (studies, monitoring, operations, mitigation, etc.). This Summit enabled approximately 50 experts and stakeholder representatives from NERC, the Edison Electric Institute, the utility industry, government, and EPRI to review completed and ongoing GMD research projects and identify remaining needed efforts.

Close Cooperation with NERC

EPRI has worked closely with NERC in its GMD research. This collaboration has led to significant progress on important GMD deliverables through the end of 2013. EPRI's GMD research initiative has supplied and will continue to provide both research and engineering expertise in support of developing a set of GMD-related guidelines that the NERC GMD Task Force is producing. These documents will provide both general guidelines as well as non-traditional issues power engineers need to consider when performing GMD-related studies. The four guideline documents being produced are the following:

- **Transformer Modeling Guide,** which summarizes the transformer models that are available for GMD planning studies
- **GIC Application Guide,** which provides the theoretical background for calculating GIC and underlying assumptions used in modern GMD simulation tools [11]
- **Operating Guide**, which provides guidance on the operating procedures that can be used in the management of a GMD event [12]
- **Planning Application Guide,** which provides guidance and non-traditional considerations for performing GMD-related assessment studies [13]

In 2014 and beyond, EPRI proposes to continue its close collaboration with NERC on GMD research. Specifically, this project's 2014 objectives follow:

- Provide guidance to planners at electricity delivery companies when considering installation of GIC blocking devices
- Provide guidance to planners at electricity delivery companies to comply with the NERC GMD standards
- Assess the potential harmonics consequences of GICs

This project's objectives for 2015 and beyond follow:

- Provide updated guidance to planning engineers on how to incorporate the effects of GMDs in system planning studies
- Provide guidance to planners to assess the implications of harmonics caused by GICs
- Validate earth conductivity models
- Develop and refine generic thermal and electrical transformer models for various transformer types

Benefits of This Research

The understanding developed in this project is intended to help utilities prepare for large solar storms and to operate the grid through such events. The aim is to maintain high bulk power system reliability by shortening customer interruptions, as well as minimizing the risks of damage to long-lead time equipment, and limiting macroeconomic costs. In addition, this work may identify gaps in forecasting and mitigation solutions, and provide guidance on the economic feasibility of available mitigation technologies.

3
EPRI ONGOING AND NEW GMD EFFORTS WITH NERC

EPRI ongoing and new GMD work with NERC is in the following four areas:

- GIC mitigation planning guide (initiate in 2014)
- Potential harmonics consequences of GIC (initiate in 2014)
- Earth conductivity validation using direct measurement (initiate in 2014; deliver in 2015)
- Develop generic transformer thermal and electrical models (continue in 2014; deliver in 2015 or later)

For this work, as well as subsequent planned work, EPRI plans to deliver quarterly newsletters and quarterly webcasts on the latest GMD information, including research activity, solar activity, system measurements, technology advancements, and regulatory developments. The webcasts will also serve to solicit industry feedback and suggestions. EPRI will also deliver annual summary technical updates and semi-annual white papers to transfer information to all stakeholders in understandable forms, and a final summary technical report at project conclusion.

GIC Mitigation Planning Guide

EPRI will support NERC in developing a guide for the application of GIC mitigation devices. This guide is intended for use by electricity delivery companies and their consultants who are considering the installation of devices to block, or substantially impede, the flow of quasi-dc GIC through power transformer neutrals and through transmission lines. This guide will describe the potential consequential impacts of such devices on other equipment and system performance. It will define the studies needed to specify the ratings of the devices, evaluate their effectiveness, and assess the risks of consequential impacts. Study descriptions will include sufficient background for the user to understand the purpose and objectives of the studies, describe the study tools and types of data needed to perform the studies, and provide suggested criteria for evaluating the study results. The guide will cover at least short-circuit performance, insulation coordination, and resonances. Consideration will be given to both the normal modes of device operations, as well as failure modes.

The guide will primarily focus on capacitive and resistive GIC mitigation devices installed between the neutrals and grounds of transformers, but the guide will also provide application considerations for low-impedance series capacitor devices specifically applied for blocking GIC through transmission lines. Devices or design modifications to transformers with the purpose of cancelling the direct impacts of GIC on transformers (e.g., dc flux nulling devices) are specifically excluded from this scope. The development of the application guide will be informed and supported by a 2013 EPRI report on GIC mitigation device consequential impacts (EPRI report 3002003392, see Figure 3-1) [10], as well as earlier published EPRI reports.

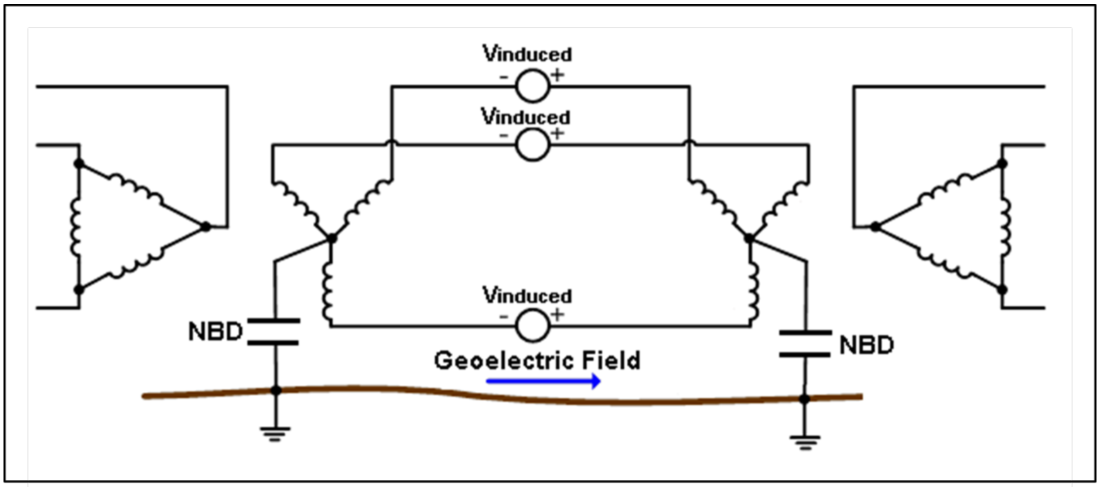

Figure 3–1
Simplified power system with neutral blocking devices—a GIC mitigation device for power transformers [10]

Potential Harmonics Consequences of GIC

EPRI will develop a reference guide for the evaluation of high-level harmonic voltages and currents resulting from a severe GMD. An early 2014 EPRI report describes how asymmetric saturation of transformers during a GMD causes potentially large amounts of harmonic currents to be injected into the power grid [14]. This prior report describes the methodologies and requirements for modeling the harmonic voltages and currents (see Figure 3-2). However, the prior report does not provide the background and criteria needed by utilities and transmission system operators to evaluate the risks to transmission system reliability and equipment integrity posed by potentially exceptional values of harmonic voltage distortion. While there are various standards and references regarding the routine power quality impacts of harmonics, these routine power quality concerns are of relative insignificance compared to the potential for major transmission component damage and/or tripping due to the very levels of distortion that may be present during GMDs.

The new 2014 guide will describe the impacts of high-level distortion on capacitors, generators, protection system, power electronics controllers (e.g., flexible ac transmission systems [FACTS]), high-voltage direct current (HVDC) systems, and surge arresters, as well as other affected bulk power system components.

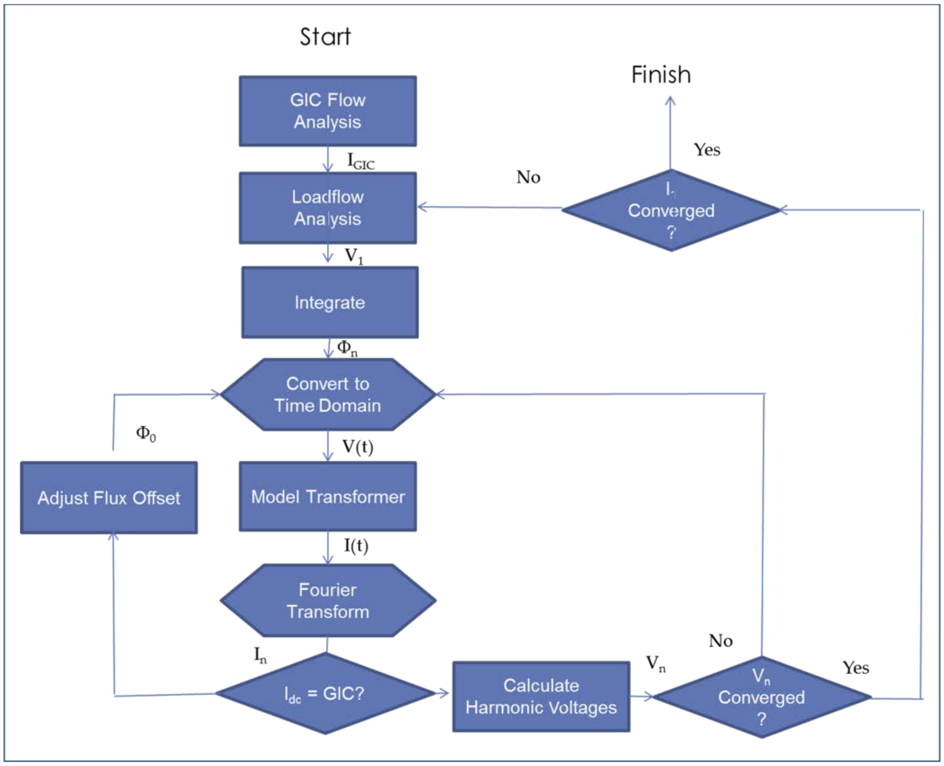

Figure 3–2
Iterative process for system analysis of harmonics during GMD [14]

Earth Conductivity Validation Using Direct Measurement

In 2012, EPRI published a report on one-dimensional (1D) earth resistivity models for various physiographic regions (reflecting the bedrock geology) of the continental United States and parts of Alaska [15]. Although the earth's internal structure can have a complex three-dimensional distribution of electrical resistivity, a 1-D model provides a useful first-order approximation for modeling gross resistivity structure and its effect on surface electric field in a particular region. Each 1-D model consists of a "layer-cake" figure showing the change of resistivity with depth, and a table detailing the information sources and justifications for the assigned conductivity/resistivity values and layer thicknesses. The values presented were based on the author's judgment and interpretation using publicly available information currently available, and could conceivably change as a result of other interpretation or subsequent geophysical surveys. Nineteen models for selected continental United States physiographic areas were prepared, as well as five models covering parts of Alaska (see Figure 3-3).

The purpose of this new work is to potentially enhance the accuracy of earth conductivity/resistivity using a method of actually directly measuring the earth conductivity/resistivity. EPRI will use this direct measurement approach to refine the earth conductivity models and their effect on surface electric field. EPRI will validate these models as possible with GIC measurements from the EPRI Sunburst system, magnetic field variance measurements from USGS, Natural Resources Canada, and EPRI, and system topology models of transmission systems in North America. EPRI will initiate this work in 2014 and deliver it in 2015.

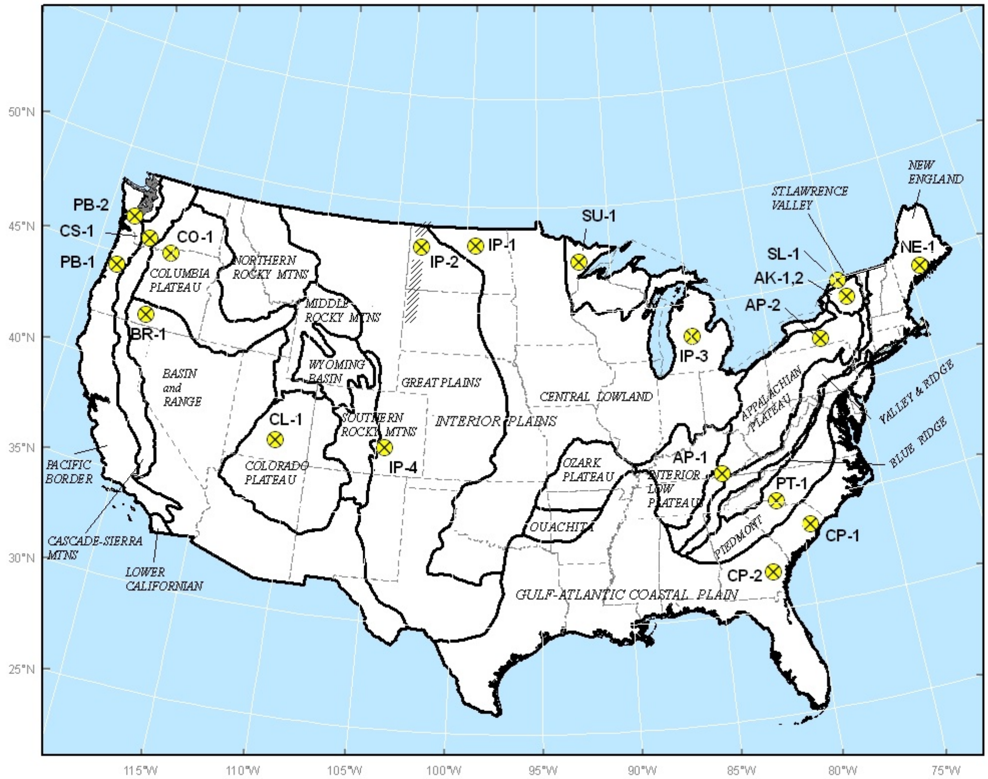

Figure 3–3
Location of 1-D earth resistivity models with respect to physiographic regions of the contiguous United States [15]. EPRI is using a direct measurement method to potentially enhance the accuracy of earth resistivity.

Generic Transformer Thermal and Electrical Models

Work currently proposed for funding by DOE includes preparation of a test plan specification for thermal and electrical testing of transformers in the presence of GICs, and conduct of actual transformer thermal (hotspot) and electrical (aka magnetic, including harmonics and var generation) testing. This work will feed into this effort, which is to develop refined generic transformer thermal and electrical models. Only a small handful of transformer tests and models have been completed to date. It is important that additional data can be developed and gathered to refine models for various transformer types. The overall purpose of these activities is to determine transformer vulnerability to GICs and determine transformer electrical response to GICs to assess power system vulnerability and develop mitigation strategies.

This work involves contracting with OEMs (transformer manufacturers) to obtain validated thermal and electrical models. Transient thermal models are required to simulate the dynamic temperature behavior of critical hotspot components caused by increases in losses (e.g., tie-plates, windings). In previous industry work, researchers have fit an analytical function to the measured thermal response of a transformer design at its hotpot locations to a step dc excitation, which can be provided by the manufacturer, as proposed in this task [16]. Researchers can then use this function to simulate the hotpot temperature profile for transformers of this design when subjected to GICs.

Electrical/magnetic models (e.g., network-model, finite element models in 3-D) of the transformers are necessary (with all involved components) to model effects such as increases in losses and increase in reactive power consumption and harmonics. Both effects are caused by additional stray flux inside the transformer. EPRI will then refine and enhance the models to form generic transformer models, including the following:

- 1-phase transformer models
- 3-phase, 3-limb transformer models
- 3-phase, 5-limb transformer models

EPRI will continue work initiated in 2014 and deliver this work in 2015 or later.

4
CONCLUSIONS

In addition to the planned quarterly newsletter, quarterly webcasts, technical updates, white papers, and final project report, EPRI plans to deliver the following in the remaining portion of this project:

- A guide (technical report) for the application of GIC mitigation devices for use by electricity delivery companies that are considering installation of devices that block GIC flow
- A reference guide (technical update) describing the impacts of high-level harmonics protection systems and sensitive components
- A technical update that describes the results of research into a direct measurement method of Earth conductivity determination
- A set of validated thermal and electrical models of transformers that address GIC impacts, including the following types of transformers: 1-phase transformer models; 3-phase, 3-limb transformer models; and 3-phase, 5-limb transformer models

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ABBREVIATIONS AND ACRONYMS

1-D	one-dimensional
3-D	three-dimensional
DOE	U.S. Department of Energy
EMT	electromagnetic transient
EPRI	Electric Power Research Institute
FACTS	flexible ac transmission systems
FERC	Federal Energy Regulatory Commission
GIC	geomagnetically induced current
GMD	geomagnetic disturbance
HVDC	high-voltage direct current
NATF	North American Transmission Forum
NERC	North American Electric Reliability Corporation
NOPR	Notice of Proposed Rulemaking
OEM	original equipment manufacturer
USGS	United States Geological Survey

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