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Industry Requirements for Geomagnetic Disturbance Models

Interim Progress Report for PNNL Project 78599

July 29, 2022

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U.S. DEPARTMENT OF ENERGY
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Abstract

This research project will address the most pressing uncertainties in modeling and measuring the electric power grid effects of geomagnetic disturbances (GMDs) and the E3 portion of nuclear electromagnetic pulse (EMP). The primary goal is to help decision-makers in the electric power sector have the knowledge and tools they need to most effectively mitigate GMD effects on our nation's electric grid, with a secondary focus on EMP. Comprehensive modeling, model assessment through sensitivity analysis, and validation with field measurement data will be the primary tasks undertaken. The goal will be a more widespread adoption of these modeling approaches, namely characterizing the uncertainty associated with these models and how that uncertainty will affect decision-making by industry. This document summarizes industry requirements for better decision-making tools, informed by feedback from an industry advisory board. These requirements help guide planning and execution of the project's remaining tasks.

Executive Summary

This document is an interim progress report for PNNL Project 78599, Enhanced Geomagnetic Disturbance Modeling Tools, conducted for the U.S. Department of Energy, Office of Cybersecurity, Energy Security, and Emergency Response. PNNL is partnering with the Electric Power Research Institute (EPRI) and Texas AM University (TAMU) in the conduct of this research. In addition, the project team has assembled an industry advisory board (IAB) to help guide this research. This focus of this research is enhancing the accuracy of geomagnetic disturbance (GMD) modeling for power system impacts. This report provides a summary of GMD modeling tools, a gap analysis for how those tools can be enhanced, and a synopsis of the first project IAB meeting conducted in July 2022. The report summarizes the research findings associated with fiscal year 2022 and outlines the planned research for fiscal year 2023 and byondbeyond.

Acronyms and Abbreviations

AC	alternating current
ATP	Alternative Transients Program
BP	budget period, typically corresponds to one fiscal year
CESER	DOE Office of Cybersecurity, Energy Security, and Emergency Response
DC	direct current
DOE	U.S. Department of Energy
E3	slow component of EMP, occurring over at least several seconds
EMP	electromagnetic pulse
EMT	electromagnetic transient
EMTP®	one of the commercial EMT tools
EPRI	Electric Power Research Institute
ETTM	EPRI Transformer Thermal Screening tool
FERC	Federal Energy Regulatory Commission
FWP	field work plan
GIC	geomagnetic induced current
GICharm	GIC harmonics program
GMD	geomagnetic disturbance
GMLC	Grid Modernization Laboratory Consortium
GridPACK™	open-source power system analysis software for high-performance computing
HELICS	Hierarchical Engine for Large-scale Infrastructure Co-Simulation
HEMP	high-altitude electromagnetic pulse
IAB	industry advisory board
IEEE	Institute of Electrical and Electronics Engineers
NERC	North American Electric Reliability Corporation
OpenETran	Open Electromagnetic Transients program
PNNL	Pacific Northwest National Laboratory
PowerWorld	a power system simulation software tool with GMD functions
PSS/E	Power System Simulator for Engineering
SUNBURST	EPRI project for monitoring GIC on power systems
SVC	Static VAR Compensator
TAMU	Texas A&M University
VAR	volt-amperes reactive
Xyce	open-source electronic circuit simulator for high-performance computing

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1.0 Geomagnetic Disturbance Effects on Electric Power Systems

The power grid is one of our most critical infrastructures and it is now widely recognized that GMDs and HEMPs have the potential to severely disrupt the operation of the electric grid. While these two event types are certainly different, both can impact the electric grid in a similar manner. GMD causes relatively low-frequency (much less than 1 Hz) changes in the earth's magnetic field. Interaction of a changing magnetic field with the deep earth conductivity induces an electric field at the earth's surface, which in turn causes quasi-DC current, known as GICs, to flow in long conductors with earth connections, such as the power grid. The impact of a HEMP attack, specifically the E3 component, creates a similar induced current. These can have adverse effects on major power system components, especially transformers.

While the potential for GICs to impact the grid has been known since the 1940s [1, 2], over the last decade tremendous progress has been made by the electric power community in understanding the impact of GICs on the grid and in the development of tools to help with their modeling and mitigation. Many of these new developments are documented in a wide variety of papers, including many by project team members, and several NERC reports including [3]. This new progress has also led to the creation of NERC Standard TPL-007-4 "Transmission System Planned Performance for Geomagnetic Disturbance Events" [4] that is now being implemented. This work has also developed the now well-established GMD assessment process shown in Fig. 1. The research presented here builds on this strong foundation, addressing the areas in which there is a critical need for new research.

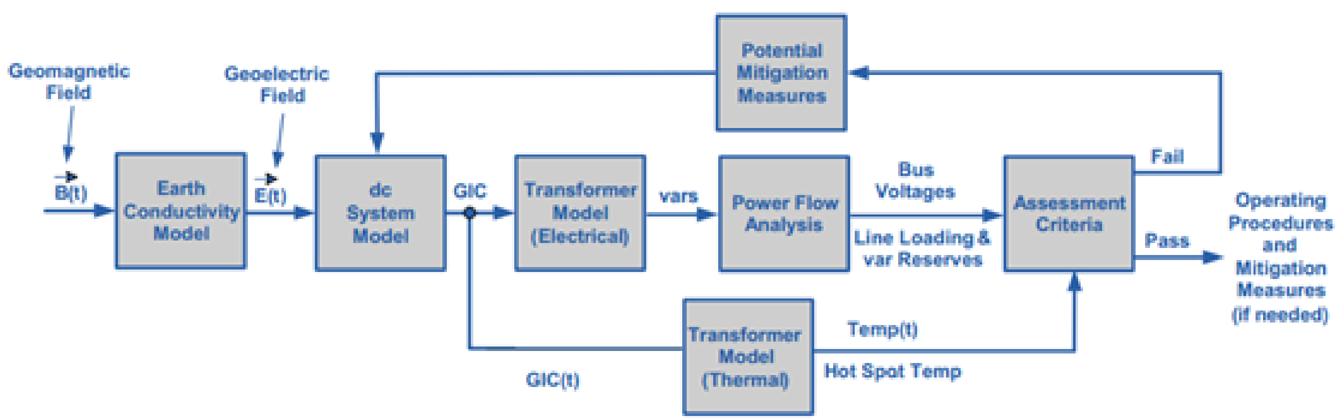

Figure 1. Integrated View of the NERC GMD Assessment Process.

As has been widely reported, two primary grid risks are associated with GIC: (1) the potential for widespread damage to high-voltage transformers, and (2) the potential for voltage collapse due to GIC-induced reactive power losses [5]. In particular, GICs can cause overheating and damage to the transformers, with high harmonic currents caused by the saturation of transformers. GICs can also cause relays, capacitive components such as SVCs, and other protection devices to trip, thereby contributing to grid instability; this effect is compounded by the fact that transformers already absorb extra reactive power due to GICs. Tripping of several reactive power devices was the main cause of the blackout affecting millions of people in Quebec in 1989.

Protecting the electric grid from GICs requires their consideration both beforehand in the longer-term planning time frame and in real-time operations. The research presented here addresses both. Building on the foundation of the industry's prior work in this area we believe there are four key needs that we propose to address—the first two in the planning time frame, the third overlapping planning and operations, and the last one in operations.

First, there is a need for more effective models and tools in essentially all aspects of Figure 1. For example, building on the foundation of [5], GICs were first integrated into a commercial power flow with [6] and into dynamics simulations in [7]. Other GIC-related modeling tools exist including harmonic generation and propagation, and transformer thermal models to relate levels of GIC with equipment overheating. While over the last few years these tools have been improved, more research is needed (details provided later in this section). Also, the advantages, limitations, impact of assumptions, as well as usage of each type of model are not always fully understood in the power industry, and some of the models could be better coupled. There are also various sources of modeling uncertainty in factors like the probability of damage to equipment for a given GMD event, ground resistivity, substation grounding resistance [8, 9], and degree of impact of equipment failure on a large interconnection, as well as the characteristics of GMD events for which it is reasonable to prepare.

Second, there is a need for a better understanding of the relative benefits of various GIC-related investment decisions. These investment decisions include the deployment of various GIC-related sensors including magnetometers, devices to directly measure the GICs flowing in different locations in the grid (e.g., in the transformer neutral connections), additional transformer sensors (e.g., to measure GIC-related hotspots), potentially GIC transformer neutral blocking devices, and the development of additional GIC-related remedial action schemes.

Third, a key uncertainty in the assessment methodology shown in Fig. 1 is the spatial and time-varying characteristics of the input magnetic field shown as B(t) in the figure. While an assumed B(t) input is provided in [4], it is virtually certain that any future event will not be identical to this input, and could be substantially different. The research challenge is to ensure that the sensors, controls, and software available operationally are sufficient so that electric utilities are prepared to deal with events that could be much more severe than given in [4]. The intent of this work is not to advocate that the assumed waveform of [4] be changed, but rather a recognition that, as was dramatically demonstrated in Texas in February 2021, outlier events occur and they need to be considered in planning even if their impacts cannot be fully mitigated.

Fourth, there is a need for better near real-time decision-making environments. GMD events can last for hours to days, and during these time spans system conditions could be rapidly changing. Hence, there could be severe operational challenges in maintaining situational awareness and in making informed decisions. Research is needed in the development of what could be best described as a GIC state estimator, in which a number of measurements associated with the GICs (including those from magnetometers, transmission system GIC flows, and transformer monitors) [10, 11] are combined with power system state estimator results to provide a complete estimate of how the GICs are affecting the system in real-time. The results of this could be used for maintaining better situational awareness and for determining appropriate control responses.

The remainder of this section provides more specifics for all of these research needs. Overall, we propose a modeling framework (Fig. 2) to help decision-makers in the electric power sector choose the most effective investments, modeling tools, measurements, and operating practices to mitigate GMD- and longer-term GIC-related EMP effects. The main objectives are:

- Characterize modeling uncertainties and their impacts on decision-making for GIC mitigation planning.
- Validate the different types of models: (1) against field measurements from both individual equipment and system wide; and (2) across models of various levels of accuracy and required computational effort.
- Develop recommendations for when and how to use each type of GIC model available.
- Identify the most important set of assumptions for each type of model.
- Develop a probabilistic approach based on asset fragility for probability of equipment failure related to various GMD data sets.

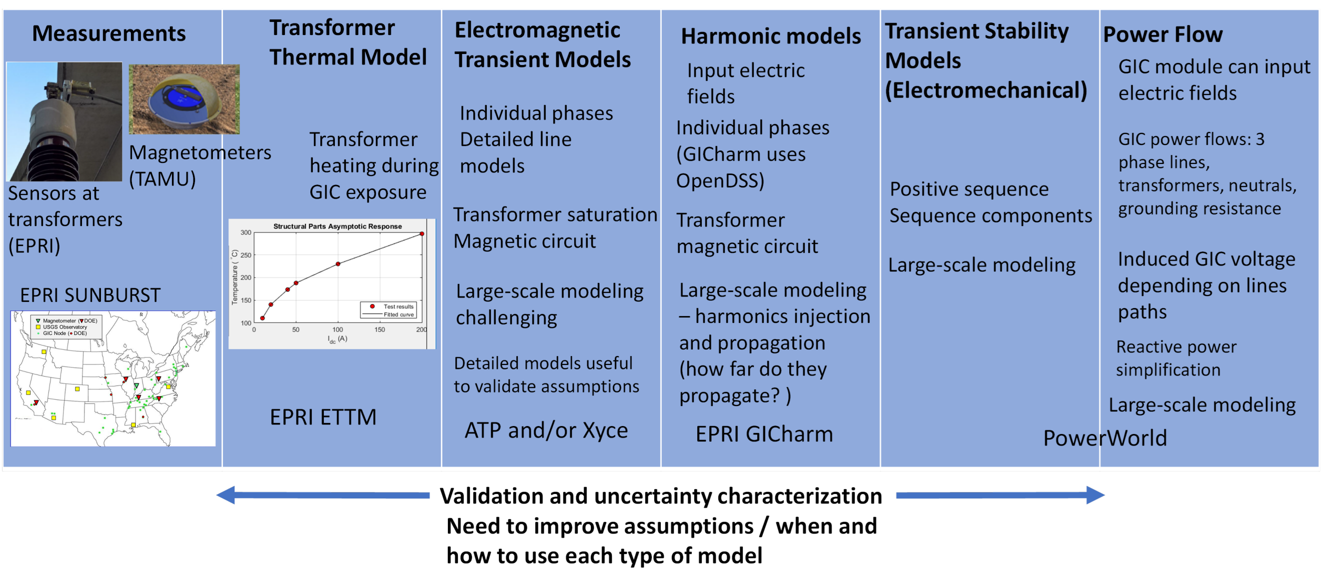

Figure 2. Some tools that may help characterize uncertainties in modeling and measuring GIC.

This modeling work looks to move the industry toward a complete, near real-time simulation of GIC flow along with its effects on system assets and performance. Currently, analysis is conducted in different platforms, and this project will work to provide a seamless interface between them. The integration of these platforms will lead to a more effective real-time impact-mitigation decisions and a reduction in the likelihood of ending with equipment damage and widespread power blackouts due to a major GMD event.

Currently, GMD vulnerability assessments are conducted in a platform such as PowerWorld, the GIC harmonic analysis is conducted in GICharm, and the transformer thermal analysis is conducted in EPRI's Transformer Thermal Module. Each of these platforms relies on information from the GMD vulnerability assessments; however, these analyses are conducted independently of each other.

2.0 Inventory of GMD Tools and Models

Some of the existing tools for modeling GMD effects on power systems were identified in the project planning phase. Based on further evaluation, a subset of these has been selected for use in this project, as presented in Table 1. This project will examine and update some of the fundamental assumptions used in these tools.

Table 1. Some Tool Selections for GMD Modeling

Name	Description
PowerWorld[a]	Power system load flow and stability with GMD analysis functions.
SUNBURST[b]	Collaborative GIC monitoring network.
GICharm[c]	Harmonic power flow analysis with GIC.
ETTM[d]	Transformer thermal assessment model.
EMTP[e]	A commercial EMT tool that comes with a GMD test system.

(a) https://www.powerworld.com/training/online-training/geomagnetic-disturbance-modeling
(b) https://www.epri.com/research/products/000000000001015938
(c) https://www.epri.com/research/products/000000003002021347
(d) https://www.epri.com/research/programs/027540/results/3002022749
(e) https://www.emtp.com/support/technical-presentations?recherche=geomagnetic

A previous Los Alamos National Laboratory report surveyed transmission line model improvements for EMP studies [12]. Based on those suggestions, new transmission line models to be investigated in this project for GMD studies include Agrawal's model [13, 14], a full-wave model [15], and transmission line super-theory [16].

Modern techniques for transformer hot-spot monitoring are summarized in [17, 18]. These may provide a starting point for planning a new program in transformer hot-spot monitoring.

We also identified a standard GMD test case [19, 20, 21] that has power system, transmission line, transformer, generator, and geographic data in the public domain. Simulation results on this test system can help validate our modeling extensions, and would be replicable by other investigators.

3.0 Gap Analysis

This section describes work underway in budget period one (BP1) to meet gaps identified at the proposal stage. The industry advisory board (IAB) provided guidance on electric utility requirements for GMD modeling, which informs the delivery of BP1 results and planning for BP2.

3.1 Fundamental Modeling Assumptions

Task 1 will explore, validate, and possibly enhance key assumptions that GMD and EMP grid assessments rely upon. This approach will reduce the risk that widely adopted tools and methods may produce inaccurate results, especially during extreme events that haven't been measured before.

1. Compare the performance of newer line models (super-theory, full-wave transmission line) to the model for electromagnetic coupling. Identify use cases for improved models of coupling for GMD and EMP effects on power systems. Use ATP and/or EMTP for comparison.

2. Investigate the impact of transmission line ground wires, tower grounding, soil layer characteristics, and phase unbalance on the assumptions made for positive-sequence modeling of GMD and EMP effects on power systems. Use EMT simulation compared to PowerWorld and the GICharm engine.

3. Investigate the impact of DC offset on the definition of reactive power, which remains a key concept embedded in positive-sequence modeling tools. How does it affect predictions of voltage collapse or rise from these tools? Use EMT simulation compared to PowerWorld and the GICharm engine.

4. Investigate the impact of harmonics on positive-sequence modeling. How does it affect predictions of voltage collapse or rise during extreme events? Use EMT simulation compared to PowerWorld.

5. Specify the gaps and essential updates to the point tools used in Tasks 2 and 3, which contribute to the integrated impact assessments in Task 4.

3.2 Modeling Transformer Impacts

Task 2 will provide quantified and verified modeling inputs needed by power system planners and operators. This approach will allow for the integration of these quantified and verified modeling inputs into a platform that will allow for system operators to make quick and accurate decisions to mitigate the adverse effects of GIC.

1. Assess the impact of modeling uncertainties in GIC planning parameters. A common modeling assumption is that the GIC flow is balanced in the three phases. However, slight differences in transmission line resistance will produce unbalanced DC bias excitation. This fact has been identified in recent GIC measurements conducted on all three phases. This will have a big impact in 3-phase transformer design where it is assumed that each phase is producing

equal flux. In addition, the GIC bias produced by geomagnetic storms fluctuates with time. These fluctuations are frequency dependent, making them system dependent. These effects will be investigated by means of the transformer and system models developed in EPRI's GICharm software package.

2. Perform model validation with existing GIC measurements. The results of this investigation will be correlated with all available field data from transformers that have been equipped to record the effects of GIC, including the EPRI SUNBURST network.

3. Integrate GIC vulnerability assessment tools to allow for near real-time mitigation strategies.
   a. NERC TPL-007 planning studies and remedial operational measures are based on assumptions about extreme events and may not be directly applicable to actual conditions (network configuration and storm strength). Therefore, it is critical that the GIC and load-flow calculations during an actual event account for the present (as opposed to TPL-007 planning) system configuration. This is like using simulations for outage management, but with GIC-enabled software. To provide an accurate picture to system operators, the GIC-enabled software needs to account for all aspects that are of concern to the system operator.
   b. These simulations need to account for the transformer "hot spot" heating. This form of heating is caused by stray flux due to asymmetrical saturation. This effect will be accounted for by the integration of the EPRI Transformer Thermal Screening (ETTM) tool into the GIC and load-flow tools.
   c. These simulations need to account for the presence of even and odd harmonics in the system. This can lead to tripping of reactive power resources such as capacitor banks and SVCs. This effect will be considered by the integration of the GICharm tool.

3.3 Modeling System Impacts

Task 3 will ultimately provide a tested and validated methodology for doing real-time GIC mitigation. Some aspects of the task are as follows:

1. Develop more robust power flow algorithms for handling the usual reactive power transformer loadings associated with high GICs. Part of this work will focus on detecting and correcting situations in which the power flow solves to an alternative (non-operable) solution.

2. Develop improved input and parameter sensitivity analysis techniques, and use them to break new ground in the understanding of how GICs can affect electric grids.

3. Couple the power flow (positive sequence) based approaches with Task 2's harmonic analysis.

4. Develop improved algorithms for doing model validations, and then use the models and real data provided by SUNBURST and other magnetometers to do actual system model validation. Associated with this will be algorithms to determine what measurement kinds and locations provide the most value to GMD assessments.

5. Develop algorithms for real-time GIC mitigation that combine models with actual measurements, and then demonstrate these algorithms in a simulation environment with a focus on ensuring situational awareness. This may lead to a new state estimator developed in year 2 of the project.

3.4 Industry Advisory Board Feedback

The IAB met from 9:00-10:30 Mountain time on July 18, 2022, with a virtual option provided for those unable to attend in person. The agenda was:

1. Project objectives, overview, schedule, and deliverable.
2. Industry requirements for GMD modeling and tools.
3. DOE plan to monitor transformer thermal response.

During the second and third meeting segments, we discussed the following subtopics for perceived gaps in GMD assessment tools:

1. How do positive sequence power flow programs and other modeling tools, including GMD phenomena consideration, help estimate reactive power demand and risk of voltage collapse?

   There is a consensus that positive power flow programs, such as PowerWorld and PSS/E, help to estimate reactive power demand and risk of voltage collapse. That said, there is also a concern as to the lack of guidance on the selection of worst case storm scenarios for GMD studies. Regarding modeling tools, there is a concern on data trustfulness used in GMD studies such as Earth's magnetic field and var consumption values. It was also highlighted that the nonlinear relationship between GIC and var consumption, due to transformer saturation, isn't modeled well in power flow programs. Power flow models have standard var consumption per amp of GIC, but this parameter may not be accurate. The need to consider substation grounding resistances, shield wires and the unbalanced operation was further highlighted as a question regarding their potential effect on GMD studies. Finally, the validation of modeling tools used, was also a general concern of the IAB.

2. What assumptions are made about power system models that can be detrimental during GMD events? How can we test these assumptions and validate models to mitigate GMD event risks?

   There was a general perception that the linear model of var consumption and GIC could be detrimental for the GMD studies. The selection of worst case scenarios, which impact the input data use on the GMD studies, can also have a great impact of GMD event risks evaluation. Values of system parameters used in GMD studies, as resistance of wires, which can vary significantly with temperature, and system topology not being exact, were also highlighted as potentially detrimental during GMD events analyses. Lack of field data, such as observations from existing field transformers, was also highlighted as model validation constraint.

   Validation of models requires field data, which is generally not available to the industry. Regardless, some IAB members are currently doing model verification with data collected in a recent K-8 GIC level event recorded in the US and Canada. GIC monitoring shows little or noise-level currents and can spike inexplicably without associated GMD events. It is not clear if there are other phenomena that can drive DC currents.

   The modeling assumption of balanced operation and the consideration of substation grounding and shield wires were presented as a question, and of unclear impact on GMD events.There was a general perception that substation grounding could impact GMD studies, as well as potentially shield wires. It was not clear though for IAB members, the extend of the impact of the lack of consideration of such modeling in GMD studies. Considering load flow studies based on positive sequence modelling, it is clear that those models are not considered, thus the importance of such is not clear.

3. How can GMD effects, such as harmonic generation and propagation, be useful for the industry? How can we validate the models of these GMD effects?

   There is a concern regarding the correlation between GMD and transformer hotspots. It is not clear to IAB members if this is a strong correlation, or to what extent this affects transformers. There was also a concern regarding the use of harmonic tools, and the impacts such could have on the industry. The use of sensors regarding validation of models was also a concern, as there are not many in service currently, as well as the most appropriate mechanism to fund such investment on existing and new transformers. Regarding GMD effects, there is knowledge between IAB members of transformers in service that should be monitored.

4. How can transformer thermal modeling, considering GMD effects, be useful for the industry? How can we validate transformer thermal modeling with GMD effects?

   There is a concern on the industry use for transformer thermal modeling, considering GMD effects. Correlation of transformer hotspot effect and GMD is not clear. There are several utilities which have transformer monitoring in place, thus potentially having data one can use to validate thermal models. There were questions regarding how one can effectively implement thermal monitoring of a transformer when there is uncertainty regarding which parts of the equipment will have issues.

5. What effects do transformer hotspots have on transformer performance, and how can monitoring of hotspots mitigate risks specific to GMD events?

   There were questions regarding the extend of risks imposed on transformers hotspot due to GMD events. Several utilities have transformer monitoring implemented; thus, analysis of such data may provide an explanation. Risk mitigation strategies associated with transformer degradation do not exist, and prevalence of voltage collapse due to GMD events is not clear.

6. Are you aware of any notable GMD events? What were the ramifications of such events, and did they affect operations or standards in your industry?

   Overall IAB members were aware of notable GMD events as well as ramification of such evens in the industry. IAB members were also aware of effects on industry standards and operations.

7. How can awareness of GMD events be used to make investment decisions for GMD resilience? What are the benefits of GMD-related investment decisions? What kind of cost-benefit analysis can be performed to justify such investments?

   There was a consensus that better modeling of GMD events can translate to increased system resilience. It is not clear how to mitigate the GMD effects on the system through related investment approaches once model uncertainties are quantified. Further, it is not clear what type of cost-benefit analysis should be performed to justify such investments.

8. What are methods to increase situational awareness during GMD events, and are they sufficient?

   A state estimator which incorporates GMD events can increase situational awareness during GMD events. Validation of such program, as well as sufficiency of such an approach for decision making is not clear for IAB members. Increased observability of the system through sensors deployed on existing transformers and installed on new transformers is seen as a method to increase situational awareness of the grid to GMD events. It was mentioned that real-time monitoring tools, which considers GMD effects, can also increase situational awareness of the power grid.

4.0 Next Steps

The project team will complete BP1 tasks as planned. The IAB meeting provided information to define an economical approach to transformer hot-spot monitoring in Task 5.

4.1 Follow-on Work

The project tasks for BP2 are tentatively planned as follows, with funding and details to be determined:

1. Integrated Probabilistic Risk Assessment: This task will build a probabilistic model to estimate the probability of transformer damage and the probability of voltage collapse based on the combination of models from Tasks 2 and 3, with enhanced assumptions from Task 1.

2. Transformer Monitoring: This task will create an instrumentation program to measure transformer thermal response compared to actual GIC flows. The program will include a plan to set up, cost share, implement, collect, and evaluate data collected from the transformers. The BP1 effort will focus on:
   a. Categorize transformers into types that are representative of new transformers installed in the U.S. grid. Working with transformer manufacturers, determine the numbers, types, and locations of the instrumentation for the transformers. Create a susceptibility location criterion for instrumenting a transformer in this program. For example, if the new transformer is installed in a location not subject to high GICs, then the transformer is not a good candidate for inclusion in the program. Determine the GIC monitor requirements, including model, type and cost, for each new transformer.
   b. Work with DOE to create and detail the cost share, contracting, and data sharing arrangements for utility partners who participate in the program. Work with DOE to engage utility associations, so that the program details get to all potential partners at utilities as well as transformer manufacturers.

3. Technology Integration and Transfer: This task will develop continuation plans for budget periods BP2 and BP3, if applicable. The task goal is to integrate all the separate threads of research from the other tasks, delivering coherent results to stakeholders. This approach enables flexibility in planning out-years, with a go/no-go decision point each year.

4.2 Transformer Hot-Spot Monitoring

From the IAB meeting, we learned that it won't be necessary to monitor dozens of transformers for hot spots. From analytical work, the most vulnerable transformers can be identified for monitoring; these are located in the Northern latitudes, and are predicted to experience High GIC values. It's also useful to monitor a few more transformers, for model validation purposes. The IAB utilities were willing, or at least open to the idea, of monitoring transformers for model validation.

The cost of providing hot-spot monitors, on a transformer under construction, is about the same as for providing a GIC monitor, i.e., no more than $20K. The decision can be made relatively late in the transformer manufacturing process, and the cost is a small fraction of the total transformer cost. The cost of retro-fitting a transformer in service would be higher, with some savings possible if done in conjunction with scheduled maintenance. However, at this cost level, DOE may consider funding the sensors and model validation work for a complete program that involves 10-12 new transformers. Participating vendors and utilities could provide cost share, e.g., for installation labor. The same transformers are likely to have GIC monitors, which could share the data collection infrastructure.

One or two existing transformers may be considered for hot-spot monitoring as well. The team would have to develop more detailed cost estimates for this, based on specific transformers considered to be vulnerable. Model validation provides an alternative, i.e., if the monitoring and thermal model validation leads to confidence in the modeling process, then it wouldn't be necessary to monitor existing transformers if they have trustworthy models.

5.0 References

[1] Vernon D. Albertson, John M. Thorson, Roger E. Clayton, and Sarat C. Tripathy. Solar-induced-currents in power systems: Cause and effects. *IEEE Transactions on Power Apparatus and Systems*, PAS-92(2):471–477, 1973.

[2] A. G. McNish. The magnetic storm of march 24, 1940. *Terrestrial Magnetism and Atmospheric Electricity*, 45(3):359–364, 1940.

[3] Lawrence J. Zanetti. Review of north american electric reliability corporation (nerc) interim report: Effects of geomagnetic disturbances on the bulk power system—february 2012. *Space Weather*, 11(6):335–336, 2013.

[4] NERC. Tpl-007-4 transmission system planned performance for geomagnetic disturbance events. https://www.nerc.com/pa/Stand/Reliability%20Standards/tpl-007-4.PDF, 2020.

[5] V. D. Albertson, J. G. Kappenman, N. Mohan, and G. A. Skarbakka. Load-flow studies in the presence of geomagnetically-induced currents. *IEEE Transactions on Power Apparatus and Systems*, PAS-100(2):594–607, 1981.

[6] Thomas J. Overbye, Trevor R. Hutchins, Komal Shetye, Jamie Weber, and Scott Dahman. Integration of geomagnetic disturbance modeling into the power flow: A methodology for large-scale system studies. In *2012 North American Power Symposium (NAPS)*, pages 1–7, 2012.

[7] Trevor R. Hutchins and Thomas J. Overbye. Power system dynamic performance during the late-time (e3) high-altitude electromagnetic pulse. In *2016 Power Systems Computation Conference (PSCC)*, pages 1–6, 2016.

[8] Uyen Bui, Thomas J Overbye, Komal Shetye, Hao Zhu, and James Weber. Geomagnetically induced current sensitivity to assumed substation grounding resistance. In *2013 North American Power Symposium (NAPS)*, pages 1–6. IEEE, 2013.

[9] Maryam Kazerooni, Hao Zhu, and Thomas J Overbye. Improved modeling of geomagnetically induced currents utilizing derivation techniques for substation grounding resistance. *IEEE Transactions on Power Delivery*, 32(5):2320–2328, 2016.

[10] Cecilia Klauber, Komal Shetye, Thomas J. Overbye, and Katherine Davis. A gic estimator for electric grid monitoring during geomagnetic disturbances. *IEEE Transactions on Power Systems*, 35(6):4847–4855, 2020.

[11] Cecilia Klauber, Komal S. Shetye, Zeyu Mao, Thomas J. Overbye, Jennifer Gannon, and Mike Henderson. Real-time monitoring applications for the power grid under geomagnetic disturbances. In *2020 IEEE Electric Power and Energy Conference (EPEC)*, pages 1–5, 2020.

[12] Michael Kelly Rivera, Scott N. Backhaus, Jesse Richard Woodroffe, Michael Gerard Henderson, Randall J. Bos, Eric Michael Nelson, and Andjelka Kelic. Emp/gmd phase 0 report, a review of emp hazard environments and impacts. https://www.osti.gov/biblio/1330652, 11 2016.

[13] Ashok K. Agrawal, Harold J. Price, and Shyam H. Gurbaxani. Transient response of multiconductor transmission lines excited by a nonuniform electromagnetic field. *IEEE Transactions on Electromagnetic Compatibility*, EMC-22(2):119–129, 1980.

[14] H.K. Hoidalen. Analytical formulation of lightning-induced voltages on multiconductor overhead lines above lossy ground. *IEEE Transactions on Electromagnetic Compatibility*, 45(1):92–100, 2003.

[15] A. G. Chiariello, A. Maffucci, G. Miano, F. Villone, and W. Zamboni. A transmission-line model for full-wave analysis of mixed-mode propagation. *IEEE Transactions on Advanced Packaging*, 31(2):275–284, 2008.

[16] H. Haase, J. Nitsch, and T. Steinmetz. Transmission-line super theory: A new approach to an effective calculation of electromagnetic interactions. *URSI Radio Science Bulletin*, 2003(307):33–60, 2003.

[17] A. B. Lobo Ribeiro, N. F. Eira, J. M. Sousa, P. T. Guerreiro, and J. R. Salcedo. Multipoint fiber-optic hot-spot sensing network integrated into high power transformer for continuous monitoring. *IEEE Sensors Journal*, 8(7):1264–1267, 2008.

[18] Abhisek Ukil, Hubert Braendle, and Peter Krippner. Distributed temperature sensing: Review of technology and applications. *IEEE Sensors Journal*, 12(5):885–892, 2012.

[19] Aboutaleb Haddadi, Afshin Rezaei-Zare, Luc Gérin-Lajoie, Reza Hassani, and Jean Mahseredjian. A modified ieee 118-bus test case for geomagnetic disturbance studies–part i: Model data. *IEEE Transactions on Electromagnetic Compatibility*, 62(3):955–965, 2020.

[20] Aboutaleb Haddadi, Luc Gérin-Lajoie, Afshin Rezaei-Zare, Reza Hassani, and Jean Mahseredjian. A modified ieee 118-bus test case for geomagnetic disturbance studies—part ii: Simulation results. *IEEE Transactions on Electromagnetic Compatibility*, 62(3):966–975, 2020.

[21] Aboutaleb Haddadi, Reza Hassani, Jean Mahseredjian, Luc Gérin-Lajoie, and Afshin Rezaei-Zare. Evaluation of simulation methods for analysis of geomagnetic disturbance system impacts. *IEEE Transactions on Power Delivery*, 36(3):1509–1516, 2021.

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