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CIGRE US National Committee
2013 Grid of the Future Symposium

Modeling, Monitoring and Mitigating Geomagnetically Induced Currents

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Introduction

This paper addresses the American Electric Power (AEP) approach to understanding and responding to geomagnetically induced currents (GIC) and their impact on the power grid. Along with its engagement in several collaborative efforts within the power industry, AEP's internal approach is to model simulated events and their impact on the grid, monitor the actual impact at several key locations, and develop procedures to avoid or mitigate any potential lasting adverse impacts.

When solar storms occur, they eject a mass of charged particles. In the few cases when these ejections are hurled earthwards, these ejections interact with earth's magnetic field causing geomagnetic disturbances (GMDs). GMDs induce voltage and drive GICs of very low frequency onto transmission grid, accessible through grounded connections of substation and generating station transformers. These interactions vary in intensity and result in electric fields (E-fields) oriented in a direction which can vary for each event. Thus the impact from GMDs will be different for each storm scenario.

Transformers may experience half-cycle saturation due to the quasi-DC nature of GIC. If such saturation occurs, harmonics are generated, and reactive power demand increases in the transformers [1]. If a storm reaches great enough intensity, voltage collapse is possible in the affected area. AEP has monitored GIC activity through the current solar cycle 24 (SC24), as well as through a portion of each of the prior two cycles. AEP EHV transformer specifications have also addressed GIC performance requirements over the last two decades. No lasting impacts have been observed to date on the AEP system [10].

Interest in GMD, and concern for its impact within the USA, has tracked along with the roughly 11-year solar cycle itself during the last several cycles. Solar activity in March 1989 resulted in widespread outages in Quebec and was cited as a factor in internal damage to a generating transformer (of a particularly susceptible design) in New Jersey near the Eastern Coast of the US.

During a solar storm in March 1989, transformer half-cycle saturation in Quebec caused high reactive power demand and harmonic generation. Protection and control equipment associated with static VAR compensation (SVC) systems removed SVCs from service at a time when voltage support was most needed. This occurred in response to harmonic peaks. Contemporary protective systems today would filter out those harmonics.

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The GSU that experienced overheating in New Jersey was a shell type transformer with a crossover lead arrangement that was not well-suited to endure high stray flux fields seen during heavy loading. The half-cycle saturation of the transformer exacerbated this susceptibility due to greater stray flux and resulted in high temperature damage to the local insulation. This damage was then detected by dissolved gas-in-oil analysis (DGA) and the unit was removed from service.

During the past two solar cycles, AEP installed GIC monitoring at key locations to observe the impact of GMD. As reported earlier [10], peak GIC in a transformer neutral connections was observed to be 87 A. Most observed events caused GICs of much less magnitude. No lasting impacts to the system or system transformers, due to GMD have been observed on the AEP system to date. As the predicted peak of SC24 approached over the last several years, however, interest in GMD phenomenon has once again surged.

In preparation for the peak of this solar cycle, AEP expanded both its collaborative and internal activities in order to better understand and endure GMD events and their impact on the system. In addition to monitoring at key locations, modeling has now been added. To supplement mitigation techniques already employed, operating procedures have also been developed.

GIC Modeling

In 2011, AEP contracted a consultant to model sensitivity of the AEP system transformers (138 kV and above) to GMD. Using proprietary software, information was provided to indicate greatest predicted GIC for each location for GMD scenarios of various E-field orientation and intensity. This supported initial placement of permanent monitoring facilities for GIC.

AEP has worked subsequently with others using now commercially available software to simulate steady state system behavior during GMD events focused on the AEP system [13]. Expected GIC flows for various GMD scenarios were developed as a sensitivity analysis. Simulated maximum neutral currents, for a 2V/km E-field at earth's surface, were on the order of 260 A. The greatest currents observed during GIC monitoring of the AEP system over nearly three decades has been 87 A. As will be explained later, AEP's transformer specifications require that transformers be designed to withstand GIC currents greater than this magnitude.

Depending upon the E-field orientation, voltage collapse conditions may be possible for E-field intensity of from 13 V/km to 18 V/km for angles of 135 degrees and 45 degrees (with North being 0 degrees), respectively. Figure 1 shows a comparison of voltage deviation between base case conditions and the case of base case loading in the presence of GIC from a constant E-field of 5 V/km directed to the Southeast (135^o).

AEP is now independently using the same commercial software package to further model and assess grid performance. The models will be adapted and refined over time based upon results obtained from monitored GIC values. Monitoring methodology is described in the following section of this paper. In addition to validating and refining the model using measured GIC currents, many assumptions made in the earliest analyses are being separately evaluated and validated. Among the most important of these values are the substation ground grid resistance, transformer winding resistances and confirmation of transformer core types for a number of locations. Assumed values will be replaced with recorded data to improve the model accuracy.

The power industry is also pursuing an improved understanding of non-uniform behavior of the E-field due to changes in earth geology and resistivity. Until such time that this improved detail is obtained and modeled, assumptions will continue to be made concerning constant E-fields.

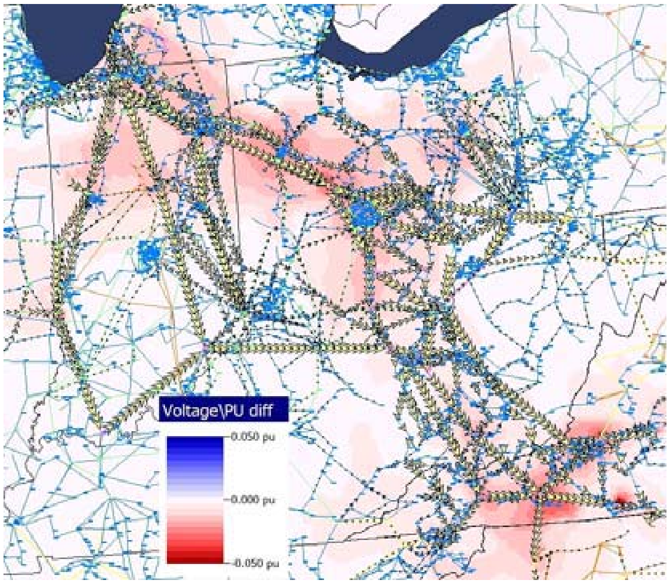

Figure 1. PU Bus Voltage Comparison between Base Case and Case with GICs for 5 V/km @135°

GIC Monitoring

In prior solar cycles, GIC monitoring was installed at several sites around the AEP system. These installations were removed some time after the peak of each solar cycle. During this current solar cycle, SC24, permanent installations have been designed for 12 locations. In addition to monitoring GIC currents, the monitoring systems capture and archive harmonics, MVAR demand, bus voltage, and transformer temperature. DGA information is being captured separately.

All of these values except DGA are being visually displayed via a GIC dashboard. Certain events, such as GIC above a certain threshold, or events with Kp index of 7 and above, will trigger automatic reports forwarded for notification and review by individuals who are subscribed to the reports. Figure 2 is an illustration of one of the views from this dashboard system.

AEP is also installing magnetometers at three locations, to supplement measurements made by others, and to provide more specific information at sites relevant to the AEP system. Thus far, during SC24, the greatest value observed at the 12 monitoring locations is approximately 26 A.

Based upon sensitivity analyses from the simulations mentioned above, additional monitoring installations are being identified in order to record more comprehensive information that will be used to monitor GIC impacts, and to aid in validating simulation models. Some refinements are also necessary in the instrumentation and recording of data due to occasional false readings which have been observed during certain switching events on the system.

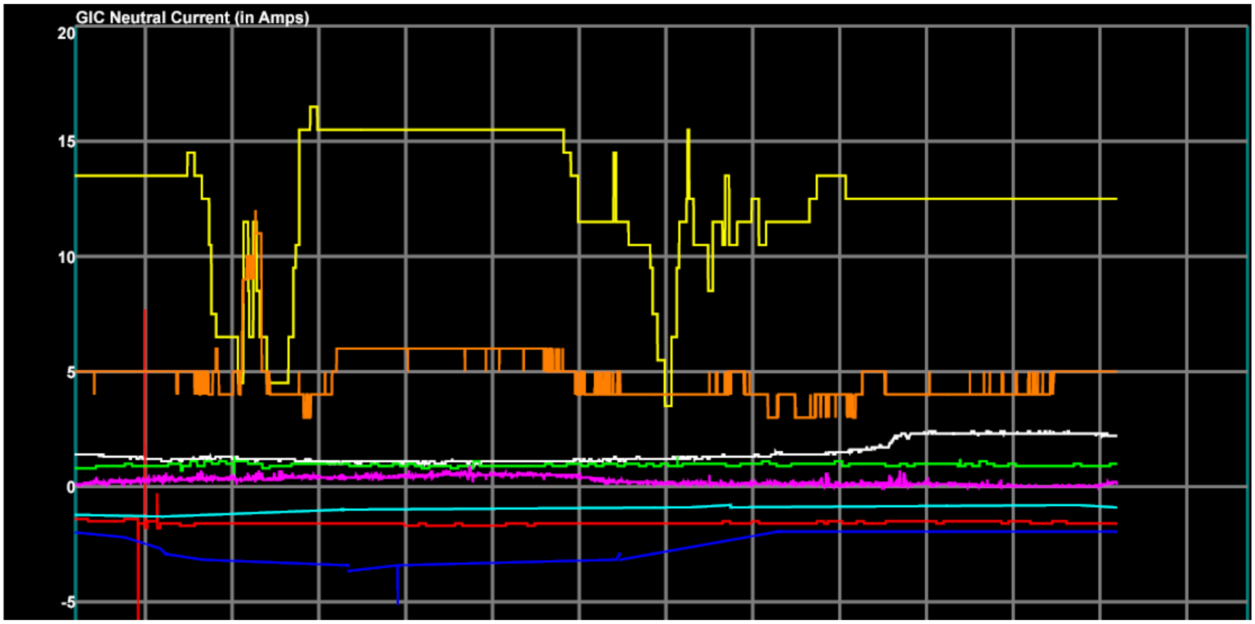

Figure 2. An Illustration of GIC Dashboard Display at AEP Showing Neutral Currents at Several Locations

GIC Mitigation

GIC mitigation consists of the following measures: GIC-related requirements in transformer specifications; an asset health center which includes transformer condition assessment; implementation of the aforementioned modeling work and monitoring systems; maintaining an ample supply of spare transformers; and development and implementation of operating procedures to address GIC-related contingencies.

Transformer specifications for AEP's Transmission system include design and performance requirements to withstand 120 A neutral current for single phase transformers in transformer neutrals, and 300 A (or 100 A per phase) for three-phase transformers. AEP transformers rated 765 kV and 500 kV are generally single phase, and transformers rated 345 kV are generally three phase. No restriction is placed on core configuration. Design review requirements are extensive and include a review of the GIC design.

An ample number of EHV transformer spares is maintained at AEP. AEP transformer ratings are highly standardized and this greatly simplifies transformer spare requirements and interchangeability. It would take nearly simultaneous failure on the order of 20% of the EHV transformer population in order to cause significant risk to the system. No foreseeable GMD scenarios would result in such an extreme impact on transformer failures at AEP. Operating procedures are expected to limit widespread impacts. System voltage collapse is far more likely to precede widespread permanent damage to insulation due to high temperatures. Those transformers with lead structures or flux shields most susceptible to stray flux heating have been identified and modified through the years.

Operating procedures for GMD events affecting the PJM footprint (the northernmost portion of the AEP system) were developed in 2011 and are intended to limit system and transformer impacts. For simplicity, these procedures are as similar as possible to other transformer related precautions for overheating or loss of cooling conditions. The procedures rely upon reducing load, if excessive GIC impacts are observed, such as high temperature, high harmonics, or heavy MVAR demand by the transformer.

An Asset Health Center (AHC) is now being implemented at AEP [14]. There are many benefits of this system, which assesses condition of transformers, breakers and batteries. The AHC is intended to prevent failures, optimize maintenance activity and prioritize replacement of aging or poorly performing assets. GIC related transformer impacts are included in the real time monitoring systems for EHV transformers over time. Although this solar cycle will pass before all AHC installations are completed on the bulk system, steady progress is expected in monitoring installation. Automated condition assessment will include algorithms to evaluate any GIC impacts.

In addition to these internal measures, AEP is actively engaged in collaborative activities regarding GMD through EPRI and the NERC GMD Task Force and standards drafting process.

Conclusions

A great deal remains to be learned about the impact of GMD on power systems. AEP has positioned itself to address GMD impacts during this current solar cycle, and also has taken steps to contribute to the industry's growing knowledge of system and transformer response to GMD. Modeling, using the best available knowledge and tools, provides an evaluation of grid sensitivity to various GMD scenarios and identifies locations of greatest interest on the system. Monitoring records specific impacts at locations of interest, documents actual experience and enables validation of and improvement in accuracy of models over time. Mitigation measures ensure that the system is built and operated in a robust manner in order to endure typical GMD events, and mitigate more extreme events should they occur.

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