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Geomagnetic Disturbance Impacts and AEP GIC/Harmonics Monitoring System

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SUMMARY

Solar surface eruption emits plasma, generating Corona Mass Ejection (CME). When the mass of particles ejected during a solar flare (a.k.a., solar storm) strikes Earth, it will distort Earth geomagnetic fields. The interaction between the solar storm particles and Earth's magnetic fields can induce slowly varying electric fields on Earth's surface, which in turn drive geomagnetically induced currents (GIC) through power transformers and onto transmission lines. If sufficient in intensity and duration, these quasi-DC currents may cause transformer saturation and overheating, which in the extreme can lead to transformer damage or failure. The transformer saturation will also increase transformer reactive power consumption, resulting in lower system voltage and possible outages. The Earthly effect of eruptions on the sun's surface is called geomagnetic disturbance (GMD). The solar storm impacts on transmission facilities depend on many factors, including:

- The intensity of solar storm activity
- Whether and where the mass of particles ejected during a solar storm strikes Earth
- The facilities' geography (proximity to Earth's poles) and local geology
- Length and orientation of lines and the winding connection of connected transformers
- The design of connected transformers and their power loading during the GMD

The solar activity cycle has a period of about 11 years. American Electric Power (AEP) has experienced many solar cycles. Over the concerns of the blackout and other adverse experiences of Hydro Quebec and other utilities during earlier geomagnetic disturbances, AEP installed temporary monitoring systems to detect GMD in transmission connected power transformers and to assess its vulnerability in two past solar cycles. Transformer neutral currents have been observed during GMD events, but AEP appears to have been less susceptible than utilities closer to the Earth's poles, and no lasting adverse impact has been found. However, for the anticipated 2013 peak of solar cycle 24, and to learn more about the phenomenon, AEP Transmission is: 1) collaborating with EPRI, NERC and others to develop a GIC simulation model for AEP transmission grid; 2) conducting independent GMD study of AEP transmission grid to identify areas of greatest potential vulnerability for transformer impacts; 3) installing permanent GIC/Harmonics monitors to detect and evaluate GMD impacts at multiple locations; 4) developing visualization and decision tools to assist operators

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to take appropriate actions; 5) developing/refining operating procedures based in part on a combined GMD Index; 6) developing GMD data reporting & notification tool; 7) enhancing new EHV transformer specifications by quantifying GIC current withstand capacity; and 8) retaining the best of retired EHV transformers as emergency spares.

This paper first presents historical GMD events and the observed impacts on the AEP system, then a GMD mitigation approach, together with the architecture of a GMD Monitoring System that monitors and evaluates the GMD impacts on selected AEP EHV transformers, as well as power system behavior during geomagnetic disturbance are described.

The detailed implementation considerations such as monitoring parameters, alarm configurations, equipment specifications & testing are addressed. As an integrated part of the GMD Monitoring System, an Automated GMD Event Reporting & Notification tool is proposed to generate GMD event reports and provide automatic notifications based on defined parameters, hence disseminating the GMD information among stakeholders. Finally, future possible studies and collaborations are proposed.

KEYWORDS

Geomagnetic Disturbance (GMD), Geomagnetically Induced Currents (GIC), GMD Impact, GMD Monitoring, GIC Monitoring, Harmonics Monitoring

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Introduction

Solar surface eruption emits plasma, generating Corona Mass Ejection (CME). When the mass of particles ejected during a solar flare (a.k.a., solar storm) strikes Earth, it will distort Earth's geomagnetic fields. The interaction between the solar storm particles and Earth's magnetic fields can induce slowly varying electric fields on Earth's surface, which in turn drive geomagnetically induced currents (GIC) through power transformers and onto transmission lines. If sufficient in intensity and duration, these quasi-DC currents may cause transformer saturation and overheating, which in the extreme can lead to transformer damage or failure. The transformer saturation will also increase transformer reactive power consumption, resulting in lower system voltage and possible voltage collapse. The Earthly effect of eruptions on the sun's surface is called geomagnetic disturbance (GMD). The solar storm impacts on transmission facilities depend on many factors, including:

- The intensity of solar storm activity
- Whether and where the mass of particles ejected during a solar storm strikes Earth
- The facilities' geography (proximity to Earth's poles) and local geology
- Length and orientation of lines and the winding connection of connected transformers
- The design of connected transformers and their power loading during the GMD

GMD Monitoring History

As one of the largest electric utilities in the United States, American Electric Power operates the nation's largest electricity transmission system with a nearly 39,000-mile network in 11 states, including more than 2,100 miles of 765 kV extra-high voltage (EHV) transmission lines, 8,300 miles of 345kV EHV lines, 18,000 miles of 138kV lines, and tens of thousands of lines below 138kV. AEP's PJM EHV grid is located above 35th parallel, and some EHV grid areas are on or near resistive igneous rock. The relatively high latitude, along with the long, interconnected, low resistance EHV lines across high resistive areas, make the AEP EHV grid theoretically susceptible to GMD impact; however, with more than 40 years of operations at 765 kV and more than 60 years of operation at 345 kV, AEP has experienced no history of transformer failure or damage due to GMD. Over the concerns of the blackout and other adverse experiences of Hydro Quebec and other utilities during earlier geomagnetic disturbances, AEP installed temporary monitoring systems on the neutrals of some vulnerable EHV transformers to detect GIC and to assess its vulnerability in two past solar cycles. From 1989 to 1994, GIC currents were monitored at four locations during the peak of Solar Cycle 22. For the March 13, 1989 K9 solar storm, less than 10 amps of GICs were recorded. Other observations, such as high audible noise at one GSU, high harmonics, and voltage fluctuations were reported during the major storm. No other special system behavior or visible equipment damage was observed at the monitored sites. Also, regular DGA were performed showing no evidence of transformer damage from the GMD events. For the peak of Solar Cycle 23, from 1999 to 2002, GIC monitors were installed at three locations, with the highest GIC observed at 87A at the Jefferson 765kV transformers on July 15, 2000 during a K9 GMD event, while typical readings were much lower. Figure 1 shows the GIC measurements at three 765kV substations (Jefferson, Kammer, and Jackson's Ferry) during the K9 GMD event. Again, no failures, gassing or lasting impacts were attributed to the GMD. GMD appeared to have limited impacts on AEP than on utilities closer to the Earth's poles, and the GIC monitors were removed after the cycle peak for the past two cycles.

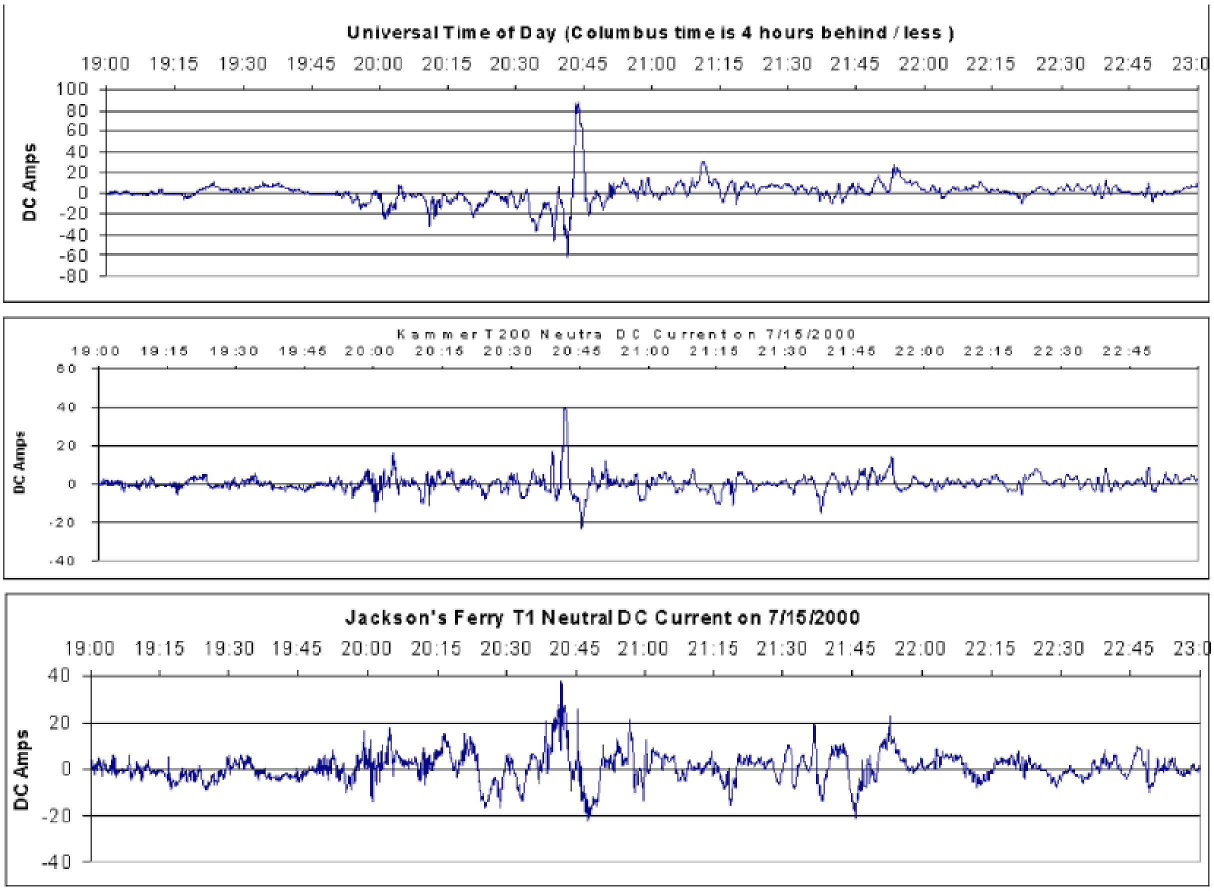

Figure 1 GIC Currents Observed During a Kp=9 GMD Event

GMD Mitigation Approach

Boosted by massive development of renewable energy and the incentives to invest in the build-out of new transmission lines directed by FERC Order 1000, the high voltage transmission grid is expanding at a quicker rate across the United States during the past decade than that of the previous three decades. For example, the AEP grid over last solar cycle has added 10% more miles at 345 kV and 4% more miles at 765kV, which has rendered the AEP system with rising vulnerability to GMD impacts.

For the anticipated 2013 peak of solar cycle 24, and to learn more about the phenomenon, AEP Transmission is:

1) collaborating with EPRI, NERC and others to develop a GIC simulation model for AEP transmission grid to share observations and insights
2) conducting independent GMD study of AEP transmission grid to identify areas of greatest potential vulnerability for transformer impacts
3) installing permanent GIC/Harmonics monitors to detect and evaluate GMD impacts at multiple locations
4) developing visualization and decision tools to assist operators to take appropriate actions based on a combined GMD Index consisting of GIC levels, harmonics currents, transformer reactive power consumptions, transformer temperature rises, NOAA GMD alerts, etc.
5) developing/refining operating procedures based in part on the combined GMD Index
6) developing GMD data reporting & notification tool to automatically generate GMD event reports and to facilitate post-event correlation analysis correlated to solar storm activity, GIC model validation and transformer health evaluation

7) enhancing new EHV transformer specifications by quantifying GIC current withstand capacity
8) retaining the best of retired EHV transformers as emergency spares

Architecture of GMD Monitoring System [1][2][3]

In order to mitigate the risk of GMD impacts on transformers and AEP system operations, an effective and reliable GMD monitoring system, comprising GIC monitoring and harmonics monitoring, is being implemented to provide assistance to Transmission Operators to protect transformers and prevent system blackout. The functional diagram of the GMD Monitoring system is represented below in Figure 2. Transmission Operators monitor the GIC and harmonic information from multiple sites via existing Supervisory Control and Data Acquisition (SCADA) system. The monitoring sites were selected based on a set of criteria including network configuration, asset criticality, historical GIC observations, ground resistivity, GIC sensitivity, AEP grid coverage, etc. The geomagnetic disturbance K-indices from the National Oceanic and Atmospheric Administration (NOAA)'s multiple geomagnetic observatories are also monitored, and AEP Transmission is currently receiving K Alerts and Warnings of 5 or higher from NOAA's Space Weather Prediction Center[1] and PJM. Based on the monitored GIC/harmonics information and GMD alerts, AEP Transmission coordinates its operating actions with Generator Operators, Cook Nuclear Plant operators, PJM, etc.

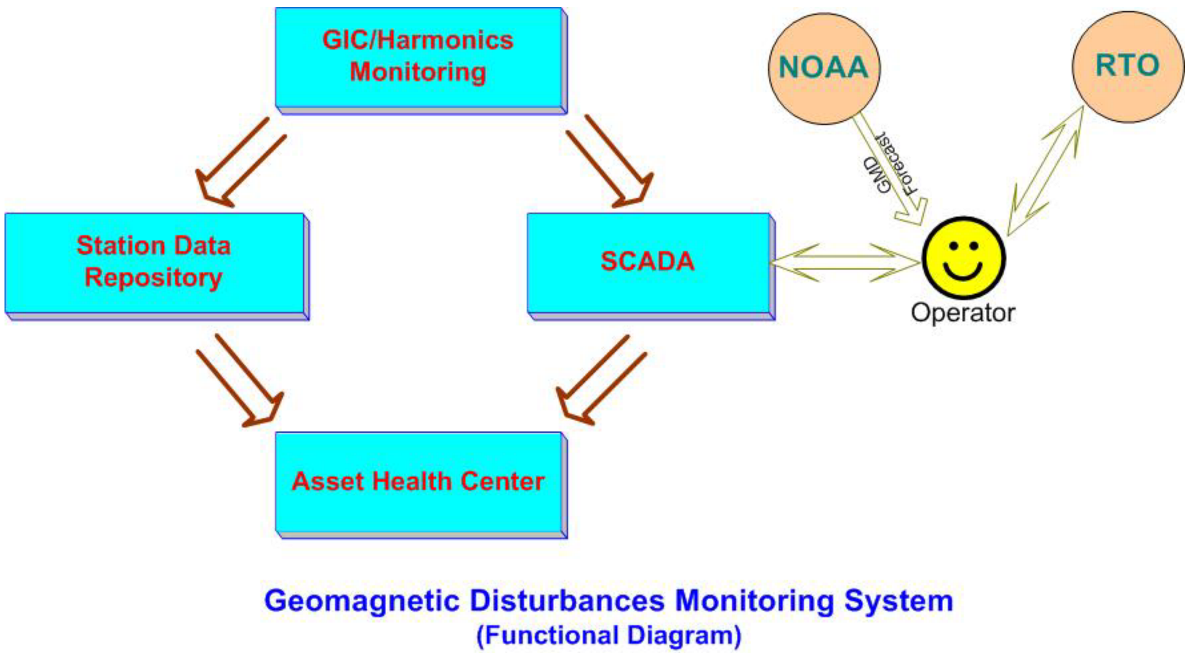

Figure 2 Functional Diagram of Geomagnetic Disturbances Monitoring System

The GMD monitoring system is a substation-based corporate-wide area monitoring network. There are two layer networks within the GMD monitoring system: the corporate level and the substation level, which are described below.

GMD Monitoring System – Corporate Level

The GMD monitoring system at the corporate level is comprised of a System Control Center (SCC), a few Regional Control Centers (RCCs), and a number of GIC/Harmonics Monitoring (GHM) systems located at key substations. Figure 3 provides a company-wide overview on the

[1] AEP is monitoring K-indices from NOAA observatories at Bolder CO. and Fredericksburg, VA, as well as Kp-index

configuration of the GMD monitoring system. The number of Regional Control Centers depends on a utility's geographical service territories, practice, etc. The Geomagnetic Disturbance Database (GMD DB) can be located at the system control center, and connected to the backup server of the SCC to minimize interventions to other key functions of the SCC, such as monitoring and control functions. The GMD database may be accessed by authorized users from the corporate-wide area network.

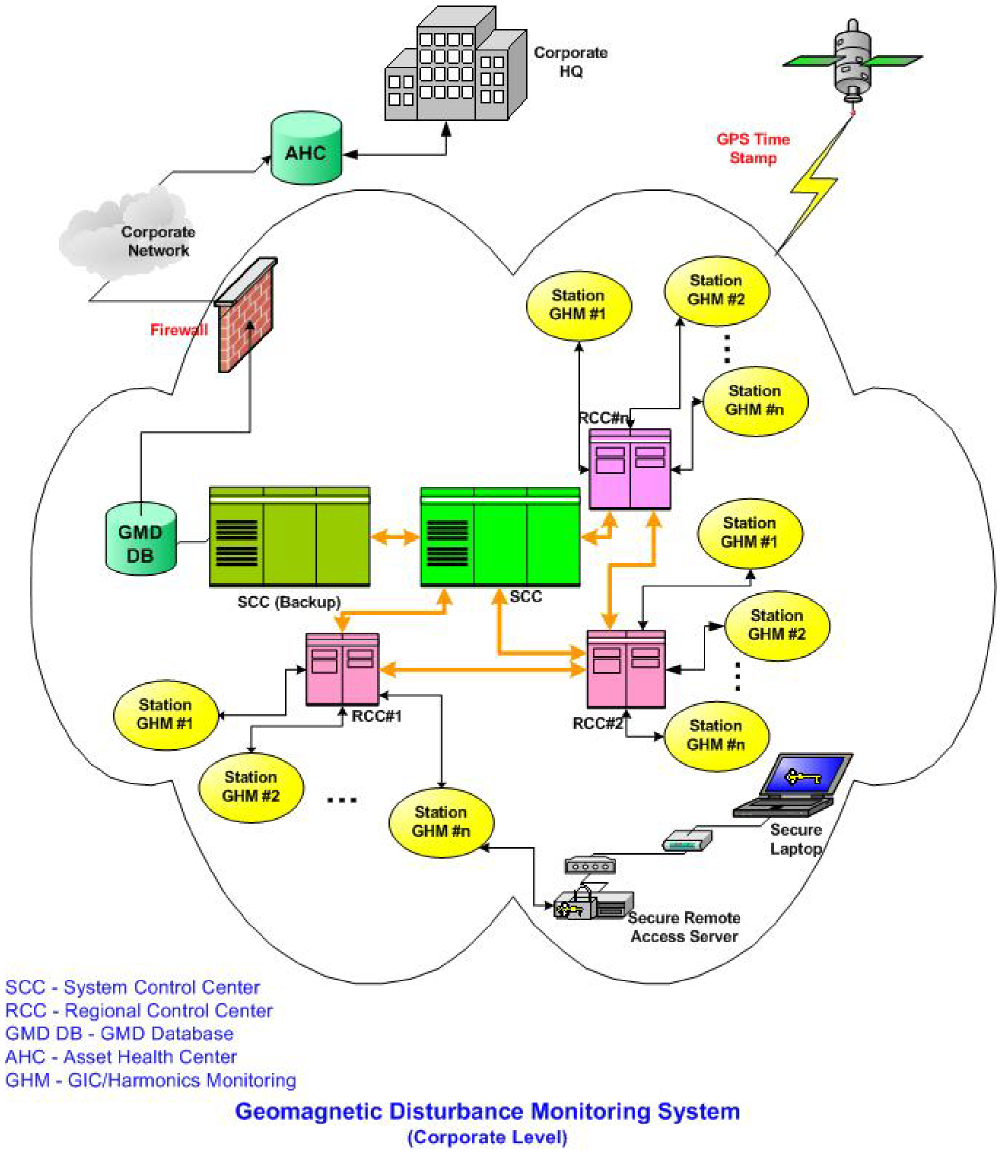

Figure 3 Geomagnetic Disturbances Monitoring – Overview

GIC/Harmonics Monitoring System – Substation Level

As shown in Figure 4, a typical GHM configuration at substation comprises two parts: 1) GIC detection in the yard; and 2) GIC data collection and harmonics monitoring in the control house. It is recommended to use fiber to connect the GIC relay in the yard and the Remote Terminal Unit (RTU) in the control house to minimize interference to GIC data. If a substation network is identified as Critical Cyber Assets per NERC CIP Standards, serial-to-fiber converters such as RMC20s can be used in the GIC cabinet and at the RTU/Station Data Repository (SDR) panel to provide serial connection over fiber.

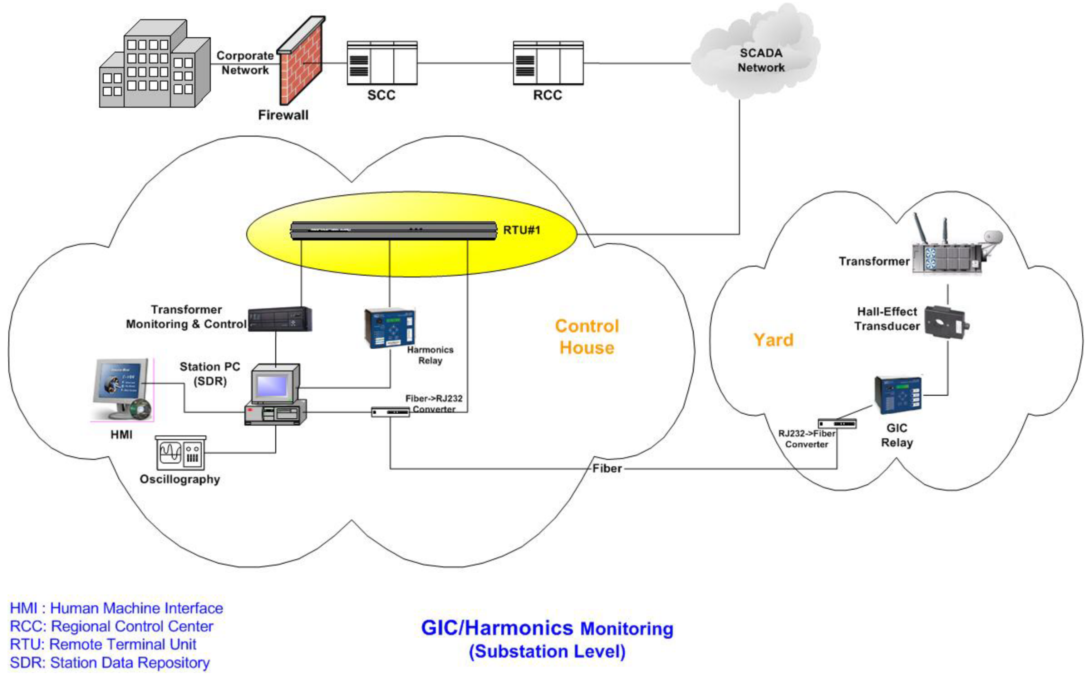

Figure 4 GIC/Harmonics Monitoring (GHM) System – Substation Level

GIC Detection

The GIC detection includes 1) a Hall-effect DC current transducer installed on transformer neutral to measure three-phase total GIC current and 2) a GIC relay to filter out AC components. Typically, pole-mounted cabinets close to a monitored transformer or common grounding structure for three single-phase transformers are used to house the Hall-effect DC current transducer, the GIC relay & GPS receiver, and fiber splicing.

Hall-Effect DC Current Transducer

The DC current transducer utilizes a Hall-effect sensor capable of measuring both AC and DC currents. The integrated output amplifier provides standard outputs of either AC/DC current (e.g., 4 ~ 20 mA) or DC voltage (e.g. +/- 5Vdc or +/- 10Vdc). It is preferable to choose +/- 10Vdc output to feed into a GIC relay[4].

There are different design options available such as solid-core or split-core[5]. For new transformer, it is desirable to choose the sold-core design. The split-core design can be used for retrofit installation without outage requirement. The Hall-effect sensor can be chosen from different sizes based on the range of DC currents to be measured. Appropriate sensor size must be chosen to fit transformer neutral insulated cables. It is recommended that the DC sensor accommodate at least +/-500A DC current with a 0.5% accuracy over an extended temperature range from -40°C to +60°C.

Hall-effect transducers should be tested for accuracy. Additional tests such as environmental tests, measuring DC with an AC background should also be performed to determine acceptance.

GIC Relay

The GIC relay converts transducer analog output signals into numerical values. A transformer neutral lead may have significant 60Hz current (maybe as high as more than 100A) due to system imbalance induced by un-transposed lines, mismatched single phase equipment, or unbalanced loading; hence, a built-in low pass filter with cutoff frequency of 2-3 Hz is required to filter out the AC components. The GIC relay will pass GIC monitoring data via fiber to RTU or station computer in the control house (Figure 4) using DNP 3.0 or IEC 61850 protocol over multi-mode fiber. DNP 3.0 protocol can be used to meet NERC CIP requirements. A GPS receiver is housed in the GIC relay cabinet to provide time-stamps for GIC data and event recording.

Depending on a transformer's design, age, loading, health condition, to name a few, the same level of GIC flow may have different impacts (e.g., saturation, heating, etc.) on different transformers. The programmable logic in the GIC relay can set up multiple alarms to alert system operators to take appropriate actions when the detected GIC current reaches a trigger threshold for a sustained period of time, say, 30 seconds. Due to the lack of detailed transformer assessment, the alarm thresholds are to be set with considerable margin based on historical GIC observations and inputs from transformer Subject Matter Experts and vendors. However, it should be cautious not to generate too many unnecessary alarms to compete for the operator's attention, and the alarm settings should be evaluated and refined once we gain more insight on the transformer GIC response. It is desirable to have two levels of GIC alarms, with a Level I alarm (a lower level GIC threshold) to alert the operator for elevated GMD activities at the monitoring site, and a Level II alarm (signaling significant risk to the equipment or system operation if not respond accordingly) to trigger necessary operator's actions prescribed in GMD operating procedures.

GIC Monitor Installation

It is not easy to get a transformer outage for GIC monitoring device installation, especially for an EHV transformer. Fortunately, temporary safety grounds can be placed on transformer grounding structure for GIC installation without taking the transformer out of service. The structure will be at ground potential at all times, but neutral current will be circulating on the neutral bus. The construction crew should be aware of this during the installation.

Depending on individual utility's practice, transformer ground leads may be replaced with insulated appropriate size cables (e.g., 4/0 cable) that will enter the DC transducer cabinet through a weatherhead, pass through the DC current transducer, and through conduit to the ground grid. The new grounds should be checked to solidly connect the grounding structure and the ground grid. Once the new grounds are verified the existing grounds can be removed. The other option is to install a split-core design transducer on existing grounding neutral to avoid a transformer outage request.

For a typical GIC installation, a DC transducer cabinet and a GIC relay cabinet will be added to existing transformer neutral structure. Mutlimode fiber in interduct must be run with AC and DC cables to the GIC relay cabinet through existing cable trench and new conduit connecting the GIC relay to a RTU and/or a local substation computer in the control house.

Harmonics Monitoring

The transformer half-cycle saturation due to GIC flow can generate harmonics into power grid, increase transformer reactive power losses, and overheat a transformer if significant higher GIC presents for a sufficiently long period. Relay misoperations may occur for some relay schemes responding to peak value voltage/current inputs or depending harmonics restraint for proper operation. Hence, harmonics monitoring can provide insightful assessment on the GMD impacts on substation equipment and system operations

Modern IED relays for transformer protection[6][7] can provide information on 2nd, 4th, and 5th harmonics currents, and it is preferable to utilize the capability of the existing IED relays to minimize hardware installation and maintenance costs associated with harmonics monitoring. If the existing transformer protection uses old electric-mechanic relays such as BDD relays, a standalone harmonics monitoring device can be installed to provide harmonics monitoring to the 50th order, as well as MVar, MW, voltage information. Oscillography waveforms can also be captured from a transformer IED relay triggered by the GIC level. The waveforms can be stored in the local computer and uploaded to a centralized server for post-event correlation analysis.

Combined GMD Index

In addition to the GIC and harmonics monitoring, it is recommended that the transformer temperature rise, transformer reactive power loss, NOAA GMD warnings, etc. be monitored, which enhance the situational awareness to system operators to defend against a severe GMD event. A combined GMD Index comprising these monitoring parameters helps operators take appropriate actions effectively and timely. The existing GMD operating procedures can be further refined based in part on the combined GMD index.

Visualization of Monitoring Data and GMD Event Reporting

It is recommended to create a data repository to store GMD monitoring data in a centralized location for post-event analysis, so a GMD event report including GMD K-indices, GIC levels, harmonics data, voltage fluctuations, transformer reactive power losses, transformer temperature rises, etc, can be easily generated and correlated to solar storm activity.
An automated GMD event reporting & notification tool is being implemented to generate GMD event reports posted to a Sharepoint portal, and to provide automatic notifications (e.g., email and/or text message) based on defined parameters to alert AEP personnel, hence timely disseminating the GMD information among stakeholders. The tool will also facilitate GMD information sharing with EPRI, NERC or others externally to AEP in a controlled/authenticated manner.

Future Studies and Collaborations

The GMD monitoring system provides GIC data to verify the GIC model to be developed, and the GIC/harmonics information will be integrated into AEP's Asset Health Center to evaluate the GMD impacts on transformer health.

In addition to GIC model validation, another area of interest for further studies and collaborations is to build a ground model for the AEP grid using GIC and magnetic field measurements to generate site-specific extreme GIC scenarios. Finally, GIC forecasts and system impact studies can also be beneficial to AEP transmission operations.

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