ELECTRIC POWER
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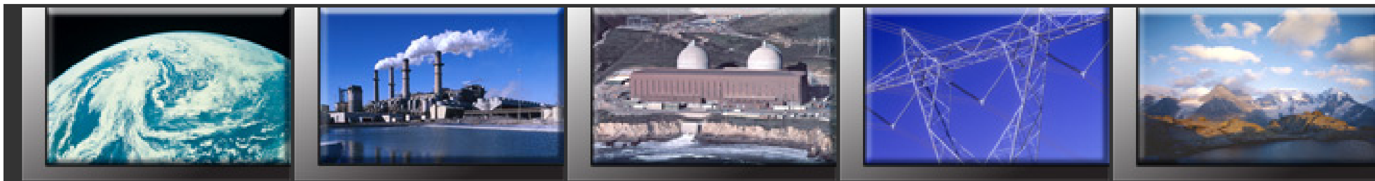
GMD News and Observer

Your View into EPRI Research on Geomagnetic Disturbance Vulnerabilities, Impacts, and Mitigation



An EPRI Newsletter **Issue 8, April 2014**

EPRI EXECUTIVE UPDATE

Welcome to the eighth issue of our newsletter, *GMD News and Observer.* Published approximately quarterly, this newsletter provides progress reports and insights for the industry on the geomagnetic disturbance (GMD) area. This issue summarizes three key research areas, in which EPRI has recently or will soon issue a report: 1) an analysis of neutral blocking devices to mitigate geomagnetically induced currents (GICs), 2) an assessment of use of uniform geology assumptions in GIC calculations, and 3) an analysis of GMD related harmonics.

Previous issues of this newsletter can be downloaded from epri.com (Issue 1: ID# 1025857; Issue 2: ID#1025858; Issue 3: ID#1025859; Issue 4: ID#3002000847; Issue 5: ID#3002000848; Issue 6: ID#3002000849; and Issue7: ID#3002000850). In subsequent issues, we will discuss emerging research on GMDs and proposed mitigation plans by various industry leaders.

In close collaboration with the North American Electric Reliability Corporation (NERC), EPRI is continuing its research on GMDs through the end of 2014. We are now welcoming new participants to our existing team, so please contact me if you are interested in collaborating with us in this fascinating and important area.

We welcome your feedback.

Best regards,
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GMD Mitigation: Analysis of Neutral Blocking Devices

EPRI recently completed and is documenting an analysis of neutral blocking devices as a form of mitigation for GICs.

Background

During GMDs, variations in the geomagnetic field induce quasi-dc voltages in transmission lines that drive GICs along transmission lines and through transformer windings to ground wherever there is a path for them to flow (see Figure 1). A capacitor presents a high impedance to GIC, and therefore alters both its flow and magnitude. As such, capacitors are often used to block the flow of GIC. This can be accomplished by inserting a neutral blocking device (NBD) in the neutral path of the transformers. This prevents the flow of the GIC through the transformer (see Figure 2) and prevents the transformer from entering half-cycle saturation that can lead to increased transformer hotspot heating, harmonic generation, and reactive power absorption. In the case of autotransformers, including an NBD in the neutral does not eliminate the flow of GIC in the series winding. Thus, an autotransformer can still enter into half-cycle saturation even if an NBD is installed.

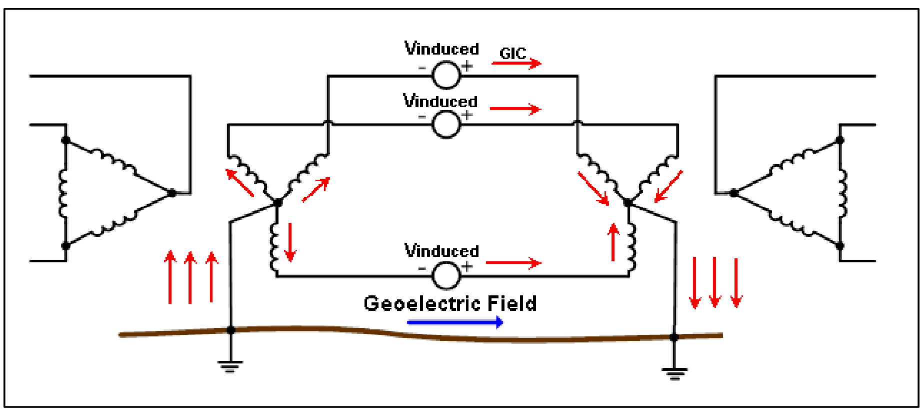

Figure 1. GIC flow in a simplified power system without neutral blocking devices

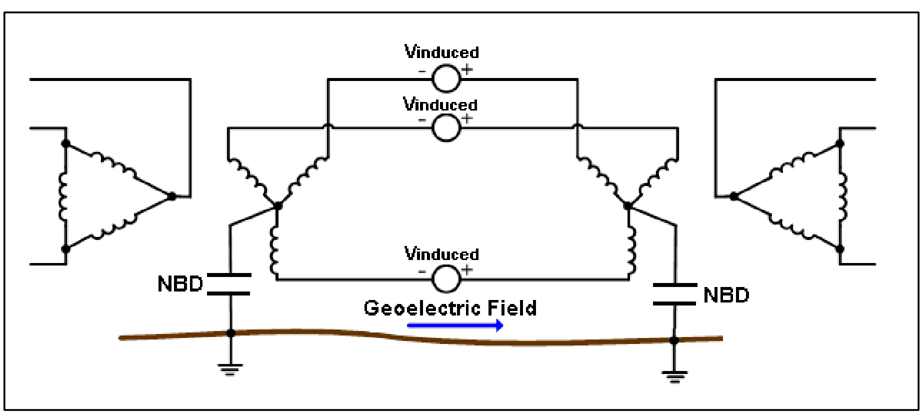

Figure 2. Simplified power system with neutral blocking devices.

Objective and Approach

The objective of this research under the direction of North American Electric Reliability Corporation (NERC) Task Force #3 has been to examine the impact of an NBD on the transmission system. This study did not involve evaluating the effectiveness of the NBD to improve system performance during a GMD. Additionally, the study did not input a reference storm to determine GIC flows with and without blocking devices. Rather, it focused on any unintended consequences of NBDs on the system.

The approach of the task force was to develop an example circuit that would be a reasonable representation of a transmission system in which NBDs would be placed and to study their potential impact on the bulk power system. The purpose of aligning on a task force approved test circuit was to allow other participants to examine the same circuit, and thus provide a common foundation for any discussions. The team evaluated various system operating conditions and EPRI agreed to study a series of scenarios developed by the task force on this test circuit and present the results.

Results

The analysis completed during this study includes a number of representative operating conditions using a benchmark transient simulation model. There may be many additional operating conditions and system contingences that should be studied during an NBD evaluation, including different equipment ratings, transformer connections (e.g., autotransformer, three-winding), and operating conditions. The simulation results and corresponding observations and conclusions are applicable only for the studied benchmark system model and assumed NBD component ratings and operating conditions. Nevertheless, the benchmark case was configured to reasonably represent conditions planners must address, and the results of the specific benchmark study do provide valuable insights and direction for additional research.

EPRI GMD RESEARCH

Assessing Geological Assumptions in GIC Calculations

Overview

Geomagnetic induction results in electric fields and currents being produced in the Earth and in long conductors, such as power systems, at the Earth's surface. The amplitude of these electric fields and currents depends on the amplitude and frequency of the geomagnetic field variation and the conductivity structure of the Earth. Away from the lateral conductivity structure, the electric fields and currents are simply related to the local one-dimensional conductivity structure. However, lateral changes in conductivity, such as at a coastline, can produce local distortions of the electric field. A recently published EPRI report describes a two-dimensional forward modeling code and applies it to an example to illustrate how the conductivity contrast between the sea and the land influences the geoelectric fields produced at the coast (EPRI report 3002000821, December 2013).

Approach

The electric current density of induced currents in the sea is considerably greater than in the land because of the greater conductivity of seawater. For currents flowing across the coast, the difference in current densities results in accumulation of charge at the coast that modifies the local electric fields to produce current continuity across the coast. The net result is that the electric field on the land side of the coast is increased compared to its value inland away from the coast.

Determining the electric field enhancement at the coast requires computer modelling of the electric and magnetic fields in the Earth. This can be achieved using a variety of techniques: finite-element, finite-difference, integral equations, each with their own strengths and limitations. These techniques have undergone many developments and improvements over the past forty years. Recently developed modelling software now allows modelling of realistic situations. To model the coastline, this report describes the utilization of the two dimensional (2-D) forward modelling code developed by Wannamaker et al.[1] This has many refinements over earlier codes that provide more stable computations and reliable results.

Results

Model calculations for a hypothetical coast with a 328 ft (100 m) deep sea show that the amplitude of the electric field enhancement as well as the extent inland changes with frequency. Overall, the electric field values (both inland and at the coast) decrease with decreasing frequency. However, the relative size of the coastal enhancement and its extent inland both increase as the frequency decreases. Further model calculations are needed to examine the coast effect for a range of geological and seawater depth scenarios.

Calculation complexity is reduced if planners were to assume that the electric field was constant, and ignored the coastal effect. Additional research is underway to determine the impact of the simplified assumption of system stability studies and transformer vulnerability studies.

GMD Related Harmonics: An Analysis

A recently published EPRI report (ID#3002002985) documents an investigation of the characteristics of harmonic distortion caused by transformers during a GMD, and describes a scoping assessment of tools needed by the industry to perform an adequate assessment of GMD-related distortion impacts.

[1] P.E. Wannamaker, J.A Stodt, and L. Rijo, "A Stable Finite Element Solution for Two-Dimensional Magnetotelluric Modelling," *Geophysical Journal of the Royal Astronomical Society*. Vol. 88, pp. 277-296 (1987).

Background

Recognized, but perhaps underappreciated, is the role that harmonic currents and voltages can play during a GMD event. Asymmetrically-saturated transformers act as potential sources of high-magnitude harmonic currents at harmonic orders not normally seen at any significant magnitude in the power system other than during transient events, such as the inrush phenomenon immediately following transformer energization. Because severe GMDs events are wide-scale, numerous transformers throughout a transmission system will be simultaneously saturated. Thus, during a severe GMD, the transmission system will have many sources of harmonic current. As a result, the various injections create harmonic current and voltage components at a particular location that may superimpose destructively, such as to cancel each other, or constructively such as to increase the magnitudes of harmonic voltage and current components. The injected harmonics also may interact with system resonances that have the potential to greatly amplify, or attenuate, harmonic voltages and currents.

Ordinary power quality criteria are not the critical concern during a severe GMD. Nonetheless, potentially extreme values of harmonic voltage and current distortion, can impose substantial physical stresses on power system components and may cause misoperation of protection and control systems. The most vulnerable power equipment includes capacitor banks and synchronous generators. High harmonic current levels can either damage this equipment or force their protective tripping. In addition to physically vulnerable equipment, control and protection systems are vulnerable to incorrect operation, potentially removing critical system components during the midst of a GMD. The harmonics injected into the system during GMD can potentially aggravate fundamental-frequency voltage stability issues. Thus, the critical concern regarding harmonics during GMD is not their impact on power quality in the conventional sense, but rather the potential impact of the harmonics on grid security.

System harmonic performance evaluation for GMD events, however, is particularly challenging due to the following factors:

- A GMD results in a large number of coherent harmonic sources distributed throughout the transmission grid (coherent meaning that the phase relationships between the various harmonic sources are deterministic, rather than stochastic). Many harmonic analysis tools are not configured to accommodate numerous sources.
- Current injections are over a range of harmonic frequencies, including both even and odd orders.
- Harmonic voltage distortion interacts with the transformers to alter the magnitude and phase of the injected harmonic currents (i.e., saturated transformers do not behave as ideal harmonic current sources).
- The harmonic source characteristics of three-phase transformers are complex, and the sequence components of the harmonics produced do not appear exclusively in the classic pattern (e.g., positive and negative sequence components of three-phase transformer exciting currents include triplen harmonics, and non-triplen harmonics have zero-sequence components).

- Propagation of the harmonics produced by GIC saturation is in both the ground mode (zero sequence) as well as the line modes (positive and negative sequence). Many harmonic analysis tools are not configured to model ground mode propagation, as conventional harmonic sources (e.g., industrial facilities, static var compensators, high voltage direct current, etc.) are isolated from the power grid by transformer connections which do not couple the zero sequence (e.g., wye-delta).
- The performance and physical withstand of various power equipment and systems under conditions of extreme harmonic distortion are neither well defined nor adequately documented. Thus, there is difficulty in interpreting the results of a harmonic analysis.

Report Objectives

The EPRI report describes an investigation of the characteristics of harmonic distortion caused by transformers during a GMD, and a scoping assessment of tools needed by the industry to perform an adequate assessment of GMD-related distortion impacts. When the results of a properly performed harmonic assessment are combined with the fundamental frequency analyses, a much more accurate evaluation of grid security during GMD can be obtained.

The report provides technical background and a tutorial discussion on the basics of asymmetric saturation. Harmonic current generation by GIC-saturated transformers is characterized, as well as the relationships of these currents to significant parameters such as GIC magnitude and transformer characteristics. Injection of transformer exciting current into the grid results in voltage distortion, and this voltage distortion affects the generation of harmonics. The non-ideal nature of GIC-saturated transformer harmonic current source characteristics is extensively explored.

Both time-domain and frequency-domain techniques for analysis of GMD-related distortion are assessed. Gaps and shortfalls of presently-available tools for performing GMD harmonic analysis are pointed out, and suggestions are made for future research and tool development.

While the following two topics are not addressed in the report, they represent areas of continuing and further research in this area:

- Modeling of three-phase transformers and the harmonic currents they produce. A number of transformer tests have been initiated in recent years to measure the full harmonic and thermal responses as well as the development of electromagnetic transient transformer models that can be used to derive harmonic current versus GIC relationships.[2]
- Guidance for harmonic impact assessment following the analytic determination of harmonic voltages and currents. For some equipment, such as capacitors and generators, existing standards provide sound guidance. For other equipment, such as protective relays, power

[2] Electromagnetic Transient-Type Transformer Models for Geomagnetically-Induced Current (GIC) Studies, EPRI, Palo Alto, CA. 3002000832.

electronics equipment, and HVDC systems, the vulnerabilities are more complex, specific to designs, and not well defined by existing standards.

NEWS and OPPORTUNITIES

EPRI-DOE Magnetometer Project Launched

EPRI recently entered into an agreement with the U.S. Department of Energy (DOE) to install three-axis magnetometer sensors between existing magnetic observatories to improve magnetic field resolution throughout the United States. Magnetometer sensor implementation offers concerned utilities the ability to closely observe magnetic fields in their service territory. Furthermore, the research will provide important information for validating deep earth geology. The goal of this installation will be to find the correlation between magnetic field changes and electric fields/GIC currents, which are determined by ground conductivity models, storm strength and orientation. EPRI is seeking utility participation in this important work. For more information, please contact EPRI Senior Technical Executive Rich Lordan, rilordan@epri.com, (650) 855-2435.

Opportunities for Participation

To find out about opportunities to participate in EPRI GMD research, please contact EPRI Senior Technical Executive Rich Lordan, rilordan@epri.com, (650) 855-2435.

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