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High-Level Harmonic Distortion During Geomagnetic Disturbances - a Hidden Threat to Grid Security

R.A. WALLING
Walling Energy Systems Consulting, LLC
USA

J. TAYLOR
Electric Power Research Institute
USA

SUMMARY

Geomagnetic disturbances (GMD) induce quasi-dc geomagnetically-induced currents (GIC) in transmission systems. This GIC can cause asymmetric saturation of many transformers across a transmission grid, resulting in thermal stress to the transformers, absorption of large amounts of fundamental-frequency reactive power, and the injection of large amounts of even- and odd-order harmonic currents into the transmission grid. Concerns have been raised that very severe GMD could cause power system voltage collapse or widespread transformer damage. While the risks of transformer material impact, and voltage instability caused by GMD are widely recognized, the industry is only beginning to recognize that harmonic issues created by GMD may rise far above ordinary power quality concerns. The harmonic distortion may substantially increase the operational severity of GMD events by causing the tripping of critical grid components such as reactive power resources. The impacts of severe GMD-related harmonic distortion on various types of power system equipment and systems including capacitor banks, protection systems, generators, power electronic systems (FACTS and HVDC), and surge arresters are summarized in this paper.

Harmonic currents injected by transformers during a GMD have magnitude and phase angles that are a function of the amount and polarity of the GIC, the fundamental voltage magnitude and phase angle, and transformer parameters. In the case of single-phase transformers, the harmonic current components can be calculated using analytical expressions. For three-phase transformers, time-domain analysis is necessary. Because many transformers will be saturated simultaneously during a GMD, and the harmonic currents propagate beyond the point of injection, analysis of GMD-related harmonic impacts must be performed on a system basis.

A case study of harmonic impacts, based on a simple transmission system model, is described in this paper. The results of this study indicate harmonic distortion could potentially cause tripping or damage to generators and capacitor banks during GMD events that may only result in only relatively minor fundamental-frequency voltage depressions. Additionally, significant harmonic analysis tool and model advancements are needed to fully evaluate system vulnerability to severe GMD events.

KEYWORDS

Geomagnetic Disturbance – Geomagnetically-Induced Current – Transformer – Saturation – Harmonic Distortion

rwalling@wesconsult.com

1. INTRODUCTION

Solar disturbances, such as coronal mass ejections, emit charged particles that can potentially disturb Earth's geomagnetic field. Geomagnetic disturbance results in slowly changing electrical currents, known as auroral electrojets, in the earth's upper atmosphere. These very-low frequency auroral currents induce ground-mode longitudinal voltages on power transmission lines, driving low-frequency currents that are superimposed on the power transmission system [1]. These currents, having spectral content in the milli-Hertz range, can be considered quasi-dc from the standpoint of power system impacts. Because the currents are induced in the ground mode, they seek to flow through the neutrals of grounded-wye transformers and autotransformers. The quasi-dc current flow, known as geomagnetically-induced current (GIC), results in asymmetric saturation of the transformers through which they flow.

Attention has been focused on the potential risk that a very severe geomagnetic disturbance (GMD) could result in widespread disruption of bulk power grid operations and permanent damage to major power system equipment assets. In the United States, the Federal Energy Regulatory Commission has ordered the North American Electric Reliability Corporation (NERC) to develop standards that require the owners and operators of the bulk power system to perform initial and on-going assessments of the potential impacts of GMD on the bulk grid, and to develop strategies to mitigate these risks including operational procedures and system modifications [2].

The primary transmission system impacts of the asymmetric transformer saturation caused by GIC can be divided into three categories: (1) direct impact to transformers, primarily in the form of thermal stress, (2) absorption of reactive power from the grid due to the lagging fundamental-frequency components of transformer exciting currents, and (3) injection of the harmonic components of transformer exciting currents into the grid.

The potential impact of GIC on transformer material integrity is a subject of considerable current debate. Some opine that a severe GMD event could cause widespread failure of critical transformers, and assert that recovery of grid operations following a severe GMD could take many months to execute due to the long lead time and constrained capacity of transformer manufacturers [3]. Others conclude that risks of transformer thermal failure from GIC are much more limited, and widespread failures are unlikely [4].

A GMD can be disruptive to a power system even if transformers are not damaged. Typically, many transformers will be simultaneously saturated during a severe GMD, with each transformer potentially absorbing a significant fraction of its MVA rating as reactive power. The cumulative effect of this unusual reactive demand can be grid voltage collapse. The voltage collapse phenomenon is currently the primary focus of the industry's evaluations of GMD operational impact. To aid this analysis, each of the major load flow software tools used for transmission planning in North America have had the capability added to calculate GIC flow and the resulting fundamental-frequency voltage impacts.

The industry is also beginning to recognize that the very high level of harmonic distortion caused by numerous GIC-saturated transformers may also have an important impact on grid security during GMD. This is not a routine power quality issue, and normal criteria for acceptable harmonic distortion are not particularly relevant. High levels of harmonic distortion can cause capacitor bank tripping, damage generators, trigger misoperation of FACTS device controls, and may also result in excessive peak voltages leading to metal-oxide surge arrester failure. At a time when a grid is heavily stressed due to unusual reactive power demand, critical reactive power resources such as capacitor banks, static compensators and generators may be removed from service as a result of GMD related harmonics. Thus, it is possible for harmonics to substantially aggravate fundamental-frequency voltage issues. Consideration of harmonic impacts may be decisive in an evaluation of grid security during severe GMD events. The only large-scale power system collapse in North America that has been attributed to GMD was the 1989 blackout of the Hydro Quebec system. Harmonic-related impacts were determined to be the cause of this collapse, via misoperation of static var compensator control and protection systems. Inclusion of harmonic impacts in GMD vulnerability assessments, however, is hampered by the lack of adequate models, software tools, and sufficiently-skilled engineering resources.

This paper describes the characteristics of harmonic currents injected into a grid during asymmetric saturation caused by GIC, and how the harmonic contributions of many transformers propagate and superimpose. A case study using a very simple transmission model is used to illustrate the potential impact of GMD harmonics. These impacts are placed in perspective by comparison with the fundamental-frequency voltage impacts in the same scenario. The paper concludes with a discussion of the significant impacts on grid security related to the high levels of harmonic distortion present during severe GMD events.

2. HARMONIC CURRENT INJECTION DURING GMD

GIC flow through transformers is associated with asymmetric saturation, meaning the transformer is saturated for a portion of alternate half-cycles in the same polarity. For GIC to flow to ground through a transformer, the transformer's flux linkage must be biased to the degree such that the average (or dc) value of the transformer's exciting current is equal to the net GIC, as explained in [6]. The resulting exciting current is composed of a semi-sinusoidal pulse, with one pulse per cycle as shown in Figure 1. This current clearly exhibits significant distortion.

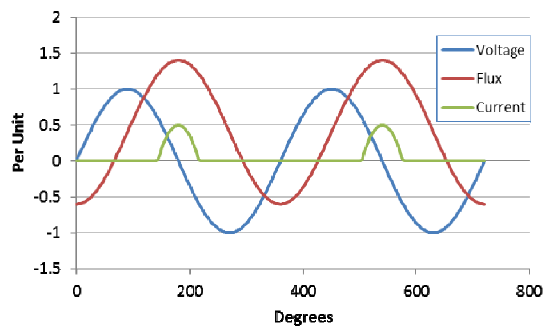

Figure 1 – Voltage, flux linkage, and exciting current relationships for a single-phase transformer with asymmetric saturation caused by GIC

The relationships between GIC, flux offset, and the fundamental and harmonic components of the exciting current are illustrated in an example where the dc flux offset (λ_0) is 0.4 p.u., the same offset as shown previously in Figure 1. In this example, the saturation threshold, or flux-axis intercept of the saturation curve (λ_s) is 1.2 p.u., and the slope of the curve in the fully-saturated region, or air core reactance (X_{ac}), is 0.3 p.u. on the transformer rating base. For single-phase transformers, these are the only transformer parameters of practical relevance to GIC behavior. Fourier analysis of the exciting current in Figure 1 reveals a dc (or average) component, a fundamental component, and a series of harmonic components at both even and odd multiples of the fundamental frequency as shown in Figure 2. The dc component magnitude of 0.068 p.u. indicates that a net GIC of this magnitude is necessary to produce the 0.4 p.u. flux bias. The magnitude of the harmonic distortion current (root-sum-square of the individual components) is 0.167 p.u., which is substantially greater than the fundamental reactive current component magnitude of 0.13 p.u. Because harmonic currents produced by GIC-saturated transformers exceed the fundamental component, and the fundamental (reactive) component is widely recognized to have potentially serious impacts on bulk power grids during severe GMD, it is logical to expect that harmonic components may also pose serious implications.

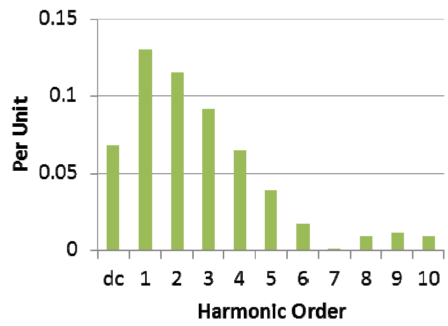

Figure 2 – Spectral components of the exciting current shown in Figure 1.

2.1. SINGLE-PHASE TRANSFORMERS

The harmonic currents injected by single-phase transformers conducting GIC can be defined using analytic expressions, for which the derivations can be found in [7]. Equation (1) defines the per-unit magnitude and sign of the harmonic current at order *n*, in terms of the fundamental per-unit voltage applied to the transformer V_f, per-unit air core reactance X_{ac}, and saturation delay angle α (in radians). The saturation delay angle is the electrical angle, at fundamental frequency, between the peak of the voltage wave and the onset of significant saturation.

$$\bar{i}_n = \frac{\bar{V}_f}{\pi \cdot \bar{X}_{ac}} \cdot \left[-\frac{\cos\left(n\pi/2 + (n-1)\cdot\alpha\right)}{n-1} + \frac{\cos\left(n\pi/2 + (n+1)\cdot\alpha\right)}{n+1} + 2\cdot\frac{\sin(\alpha)}{n}\cdot\sin\left(n\cdot\left(\pi/2 + \alpha\right)\right)\right] \quad (1)$$

The delay angle α is related to the GIC magnitude i_{GIC}, fundamental voltage and air-core inductance by Equation (2), which is transcendental, and must be solved iteratively to define α in terms of i_{GIC}.

$$\bar{i}_{GIC} = \frac{1}{2\pi}\cdot\frac{\bar{V}_f}{\bar{X}_{ac}}\left[2\cdot\cos(\alpha) - \pi\cdot\sin(\alpha) + 2\alpha\cdot\sin(\alpha)\right] \quad (2)$$

Harmonic current magnitudes are plotted in Figure 3 as a function of GIC for a transformer with 0.3 p.u. air-core reactance (typical of core-form construction) and with nominal fundamental voltage applied. The harmonic magnitudes do not monotonically increase with GIC, but rather they exhibit a "beating" behavior with the oscillations in magnitude more repetitive at the higher harmonic orders. The beating of the magnitude is due to reversals in polarity of the components, as illustrated in Figure 4 for the case of the seventh harmonic.

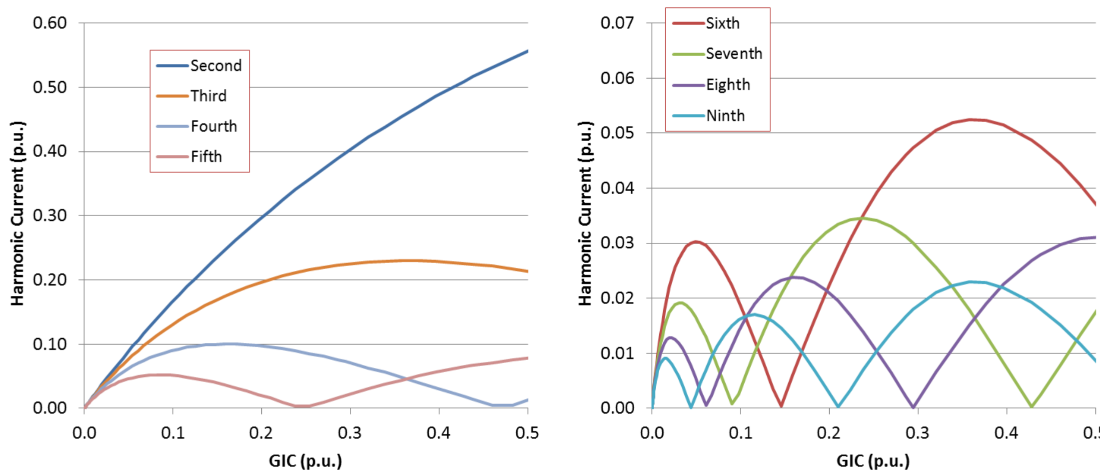

Figure 3 – Exciting current harmonic component magnitude as a function of GIC.

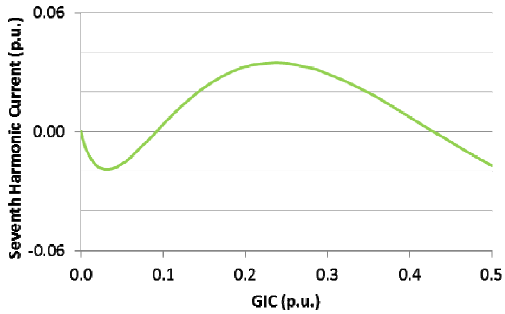

Figure 4 – Seventh order harmonic component as a function of GIC for the same conditions as Figure 3.

The polarity of exciting current harmonic components is also a function of the polarity of the net GIC in a transformer. Figure 5 compares the harmonic components for GIC flow from the tranformer neutral to earth (positive GIC polarity) and from the earth to the neutral (negative GIC polarity). Reversal of the GIC polarity results in reversal of the even-order harmonic polarities, but the odd-order polarities remain unchanged.

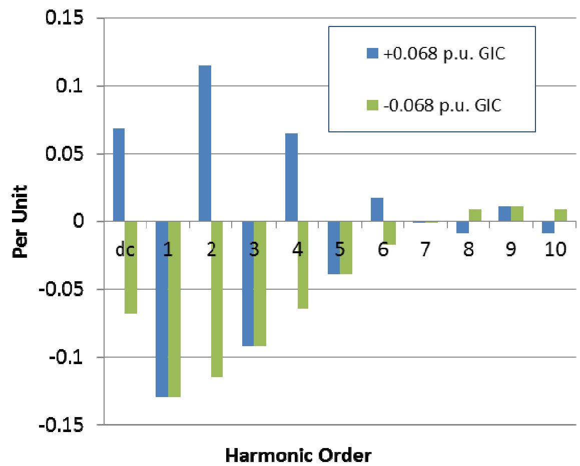

Figure 5 – Comparison of harmonic components for reversal of GIC polarity.

The phase angle of the harmonic current components injected into the grid by a GIC-saturated transformer are also dependent on the phase angle of the fundamental-frequency voltage applied to the transformer. Relative to an absolute phase reference, a shift of the fundamental voltage by angle ϕ results in a shift in the n^{th} harmonic component's phase angle by $n\cdot\phi$. In order to perform a network analysis if the superimposed harmonic impacts of many GIC-saturated transformers in a grid, the harmonic analysis must be linked to a fundamental loadflow analysis in order to correctly determine the phase angle and magnitude of each harmonic injection.

Because a bank of single-phase transformers is magnetically identical on all phases, and GIC flows equally in all three phase, the harmonic currents injected by a GIC-saturated transformer will fall into the classic sequence component pattern provided that the applied fundamental voltage is balanced; current components at orders that are multiples of three ($3\cdot k$) will be zero sequence, orders such as 4^{th} and 7^{th} ($3\cdot k+1$) are positive sequence, and order such as 5^{th} and 8^{th} ($3\cdot k-1$) are negative sequence. This is important to the analysis of propagation of these harmonics in the grid because the zero-sequence components flow in a network of substantially different parameters and topology than the line-mode (positive and negative sequence) harmonic components. This adherence to the classic sequence component pattern is exclusive to banks of single-phase transformers, however. As will be discussed later, three-phase transformers are magnetically unbalanced, and the classic pattern does not apply.

2.2. Three-Phase Transformers

Although banks of single-phase transformers are commonly used at EHV levels, most transformers in typical transmission systems are three-phase units. There are various three-phase transformer core types, each using some of the magnetic branches of the core to provide flux paths for multiple phases. Common types include the conventional three-phase shell form, three-leg core form, and five-leg core form designs. The resulting interaction between the phases, and the fact that the magnetic paths are different for the center and outer phases, results in a much more complex magnetic structure. Consequently, the exciting current components while carrying GIC cannot be defined by analytic equations as was demonstrated for single-phase transformers.

Analysis of GIC saturation behavior of three-phase transformers requires time-domain magnetic circuit modelling. An electrical circuit model based on the principle of electric-magnetic circuit duality was utilized to evaluate harmonics produced by various types of three-phase transformers carrying GIC. An example of the results for a 5-leg core form transformer is shown in Figure 6. The harmonic currents are substantially unbalanced between the phases.

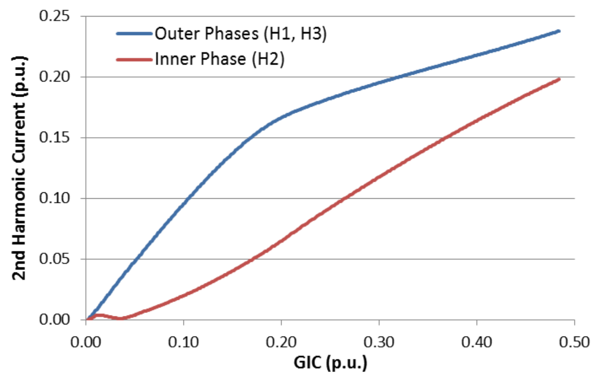

Figure 6 – Second exciting current components vs. GIC for a 5-leg three-phase transformer.

3. CASE STUDY

To illustrate how harmonic currents and voltages superimpose during a GMD, and the resulting levels of distortion, a case study was performed using a very simple transmission grid model. The parameters of this model were arbitrarily selected, based on typical characteristics of a system having a relatively low short-circuit capacity and long transmission lines. This selection tends to create resonances in the low-order harmonic range, tending to amplify the harmonic impacts. Thus, this model cannot be considered as necessarily representative of most typical transmission systems, but is used here for illustrative purposes. More extensive studies are presently underway using detailed models of an actual transmission system.

The five-bus system model and the base conditions used for this case study are illustrated in Figure 7. A quasi-dc electric field strength of 6.2 V/km, oriented along the direction of the long transmission lines, was then assumed to be caused by a GMD. As a result, a large amount of GIC flow results, with 449 A per phase of GIC in the transformers at both the generation and load ends of the system, and these transformers each absorb reactive power in excess of 483 MVAR. The fundamental-frequency loadflow conditions in the GMD scenario are shown in Figure 8. Because of the reactive power reserve of the generator, and the fact that the transmission line shunt reactors are assumed to be switchable and thus could be removed, the fundamental voltage depression was not to an alarming level as the least bus voltage is in excess of 0.95 p.u. In contrast, the degree of harmonic distortion in the model for this level of GMD is quite significant, as are the potential consequences of this distortion to power system equipment. Harmonics performance was analyzed using an iterative frequency-domain approach because the levels of harmonic voltage distortion present at the transformers interacts with the transformer saturation such that the harmonic current injections are different than for the ideal undistorted condition [7]. Levels of voltage distortion for each bus and current distortion stress on the generator and capacitor bank are indicated in Figure 9.

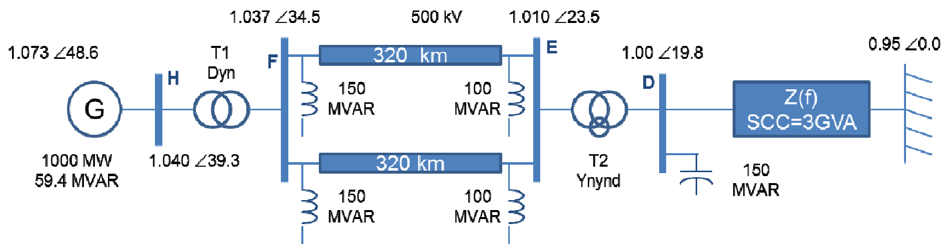

Figure 7 – Base model for network harmonic impact case study.

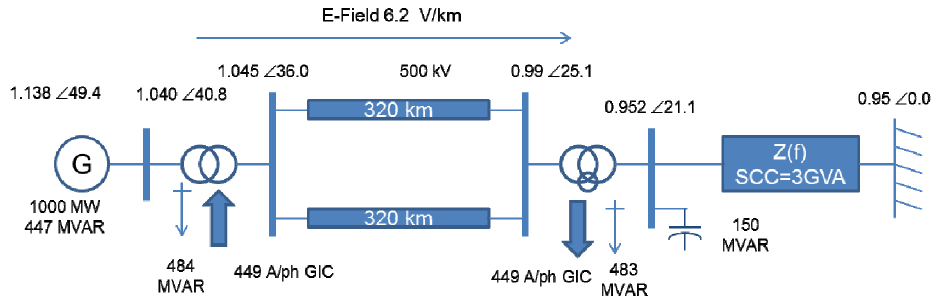

Figure 8 – Fundamental-frequency conditions with GMD producing 6.2 V/km.

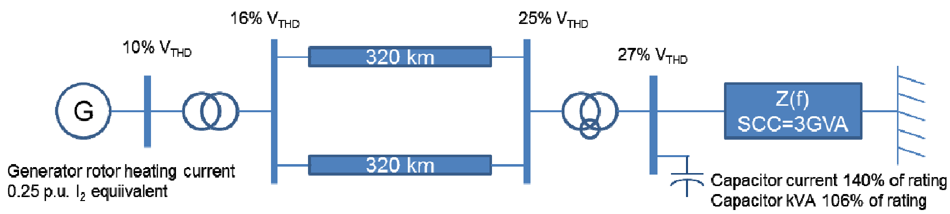

Figure 9 – Distortion conditions for same GMD case shown in Figure 8.

The harmonic currents flowing into the generator were evaluated by the methodology specified in ANSI C50.13 to determine an equivalent fundamental-frequency negative sequence current that produces comparable rotor heating. This methodology weights the respective components according to their harmonic order and sequence component. In this example, the generator currents are more than 2.5 times the acceptable limits specified by C50.13 for continuous duty.

Analysis of the spectral content of the voltage at Bus H (generator terminals) indicates that the second harmonic voltage is the dominant distortion component. Further analysis of the contributions to this distortion by transformer T1 (the generators step-up unit) and T2 at the remote end of the system makes the remarkable revelation that the majority of the harmonic current driven into the generator is produced by the remote transformer T2, 320 km away. The contribution of T1 actually is predominately in opposition to the T2 contribution, partially diminishing the resultant second-harmonic current magnitude as illustrated in the phasor diagram shown in Figure 10. While the parameters of this case study model may be neither typical nor realistic, these results clearly show that harmonic impacts during GMD must be analyzed on a system-wide basis. Any method of assessment of generator harmonic impacts during GMD that are based on only the saturation performance of its own GSU, is clearly inadequate.

The capacitor bank total rms current is well above the limits established by IEEE Std 18. While it is widely recognized that harmonic distortion during GMD can readily cause false tripping of certain types of capacitor protection schemes, the harmonic distortion may also cause failures of capacitor units or capacitor fuses, thus causing correct capacitor bank tripping as well.

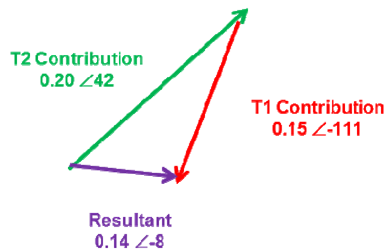

Figure 10 – Phasor diagram of the contributions to the generator bus 2nd harmonic voltage.

While GMD tends to cause depression of fundamental-frequency voltage, due to unusual reactive power demand, harmonic distortion may cause crest voltages that are much higher than the fundamental magnitude, potentially reaching magnitudes that could result in equipment damage. In the case study, the peak (crest) voltage at the generator 500 kV bus is 1.23 p.u. while the fundamental voltage is only 1.045 p.u. Metal-oxide surge arresters, due to their highly nonlinear characteristics, are primarily sensitive to the crest value of voltage, and this magnitude is far greater than the maximum continuous operating voltage (MCOV) capabilities of arresters typically applied to 500 kV systems. This poses the potential for thermal instability of the arresters, which typically culminates in a ground fault being applied to the system and the consequential tripping of the equipment that the arrester protects.

4. HARMONIC IMPACTS DURING GMD

The very high levels of harmonic distortion possible during a severe GMD can have a number of impacts that generally tend to exacerbate system stresses caused by the more widely recognized issue of unusual reactive power demand. Harmonic currents and voltages can cause misoperation of critical equipment and system, or may cause direct physical damage to the equipment. The various ways that harmonics during GMD might impact a bulk system are summarized below:

Protection Systems– Some power system protection systems are vulnerable to false operation due to high levels of harmonic distortion. This includes electromechanical relays used for negative sequence protection, and capacitor protection schemes based on neutral overcurrent or neutral overvoltage using relays that are responsive to harmonics. False tripping during GMD can result in the loss of critical power system components at a time when the system is severely stressed.

Capacitor Banks – Capacitor banks, due to their small and negative reactance at harmonic frequencies, tend to have very high levels of harmonic current during and event such as GMD where there are large-scale injections of harmonic current. Capacitor banks may trip due to false protection operation, or capacitor units may fail or fuses blow due to overload, resulting in a necessary trip to prevent cascading unit failures. Loss of capacitor banks during GMD removes a critical reactive power source at a time when they are most needed.

Generators – As illustrated in the case study, sufficient harmonic currents may be forced into generators to cause excess rotor heating during a severe GMD. Modern digital generator protection relays are typically designed to ignore non-fundamental currents. Thus, there may be a gap in the protection of these critical machines. Loss of a generator deprives the system of a reactive power resource, as well as a real power resource, introducing an additional challenge to both voltage and angular stability. A common misconception is that only negative sequence harmonics cause rotor heating; this is false, as any harmonic current other than the zero-sequence component will produce a stator magnetic field that has apparent rotation relative to the rotor, inducing currents in the rotor that result in heating. (Zero-sequence harmonics are blocked by the delta GSU transformer.)

Power Electronic Systems - The controls for FACTS and HVDC equipment are highly complex, and there are many possibilities for severe harmonic distortion to adversely interact with control performance. The 1989 Hydro-Quebec blackout was caused by such a control vulnerability to distortion [5]. Harmonic distortion will also tend to cause HVDC inverters to advance their firing angle in order to maintain commutation margin, thus increasing the reactive power demand of the

HVDC converter terminal. Harmonic filters applied at HVDC and SVC installations may overload due to the excessive distortion caused by transformer saturation during a GMD, and these filters may trip protectively trip, depriving the grid of their reactive power.

Surge Arresters – Crest voltages exceeding surge arrester MCOV, due to voltage distortion during a severe GMD, increases the risk of arrester thermal instability. This can cause faults that provide an undesirable dynamic stimulus to an already-stressed system, as well as the trip out of the equipment that the arresters protect (e.g., transformer, bus section, etc.).

5. CONCLUSIONS

GIC flow through transformers during a severe GMD results in the injection of large amounts of harmonic current into the grid. Because the injected harmonic currents have a defined relationship with respect to the fundamental voltage, the grid's transformers are coherent harmonic sources whose contribution components will constructively and destructively superimpose throughout the grid in a complex manner. Analysis of the harmonic behavior, therefore, must be on a system basis as the harmonic distortion at any point is dependent on distant, as well as nearby, transformers.

The case study described in this paper implies that harmonic distortion can be a very significant factor in the overall power grid impact of a severe GMD event. While the simplicity of the model does not support sound quantitative generalizations, the study does support a compelling argument that harmonic performance during GMD cannot be dismissed as unimportant. In order to make more accurate assessments of grid vulnerability to GMD, it is evident that additional attention is required in the form of additional research using detailed, realistic models, and further development of analytical tools to support analysis of GMD-caused harmonic impacts.

ACKNOWLEDGMENT

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