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Chairman Bay, Commissioners, FERC staff, and fellow panelists.

My name is Randy Horton, and I am the Manager of the Transmission Planning – Stability and Special Studies group at Southern Company Services in Birmingham, AL. I earned the PhD degree in electrical engineering from the University of Alabama, the Master of Electrical Engineering (M.E.E.) degree from Auburn University and the Bachelor of Science in Electrical Engineering (B.S.E.E.) degree from the University of Alabama at Birmingham, all with specialization in electric power systems. I have over 17 years of experience in modeling and simulation of protection systems, transients and power quality phenomenon. Additionally, I am a Senior Member of the Institute of Electrical and Electronics Engineers (IEEE) and have held leadership positions in various working groups including: Secretary of IEEE Std. 519 Working Group, Secretary of IEEE Flicker Task Force and Chair of the IEEE Working Group on Field Measured Overvoltages and Their Analysis. Thank you for the opportunity to share my thoughts with you today regarding the proposed TPL-007-1 standard.

1.0 Introduction

Over the past several years, NERC and the electric utility industry have made significant progress in understanding and addressing the reliability risk that geomagnetic disturbance (GMD) events pose to the bulk-power system. The proposed TPL-007-1 is an important addition to the body of Reliability Standards for the North American electric grid. This standard is based on the most advanced information available, and is supported by rigorous scientific and technical analysis. The standard is key in that it focuses on protection against wide-spread Bulk Electric System concerns, such as voltage collapse, Cascading, or uncontrolled islanding, thereby adding to the overall resiliency of the grid. For these reasons, the Southern Companies encourage the Commission to approve the proposed TPL-007-1 standard as submitted. Approving the standard now provides applicable entities with the regulatory certainty needed to move forward with these important assessments while encouraging applicable entities, manufacturers and vendors to develop risk mitigation solutions. The Southern Companies also support the Commission's objectives for continued research and development efforts regarding GMD impacts to reliability.

My testimony here today will focus on harmonics and vibrational effects during benchmark GMD events. There are three main points that I would like to make, and they are:

- more work is needed to develop commercially available computer modeling tools that can be used to assess the harmonic impacts of benchmark GMD events;
- vibration and audible noise do not appear to be damaging to transformers, and do not need to be considered in the assessment process. Additionally, models and commercially available computer model tools do not currently exist;
- analysis of protection systems is an important aspect of assessing the impact of benchmark GMD events on the bulk-power system; however, without the proper tools and expertise such analysis can be unwieldy, and can yield erroneous results (either overly optimistic or overly pessimistic).

The following technical discussion will be used to support these important considerations.

2.0 Harmonics and Vibrational Effects During Benchmark GMD Events

2.1 State of Knowledge and Modeling Capability Regarding Harmonics and Vibrational Effects

Analysis capability for assessing the impacts of harmonics created by non-linear loads and other system components on the bulk-power system is mature. Both frequency-domain and time-domain techniques and computer tools exist to perform harmonics analysis, and such tools have existed for decades. However, the assessment of harmonics created by an extreme GMD event presents some significant challenges that must be resolved by the industry before such studies can be done on a large scale such as required for benchmark GMD assessments. The following remarks describe the current modeling capability of the industry and some of the challenges associated with assessing the harmonic impacts of extreme GMD events.

2.1.1 Frequency-Domain Analysis

Harmonics analysis of the bulk-power system is commonly performed using frequency-domain techniques. This modeling technique is less complex than time-domain simulation, and assumes that the system is operating in the steady-state. The harmonic current injection of harmonic producing element (e.g. transformer experiencing half-cycle saturation) is modeled using an ideal current source.

There are numerous computer tools available to perform harmonics analysis in the frequency-domain including many of the time-domain tools that will be listed in the following section. Specific frequency domain tools include (but are not limited to): Siemens SINCAL, ETAP, OpenDSS, DIgSILENT, SuperHarm and others.

Although frequency-domain analysis is the most common harmonics analysis technique, there are some important difficulties and modeling gaps when the method is used to the assess the harmonic impact of a benchmark GMD event. Such issues include (but are not limited to):

- the effective GIC flow in all transformers in the network must be known beforehand , and a non-linear mapping between GIC and the harmonics that are created due to half –cycle saturation is required (see single-phase 500 kV GSU example in Figure 1). This capability is not currently offered in any commercially available computer tools.
- the magnitude and phase angle of the injected harmonic currents is affected by local voltage distortion; thus, the harmonic current injection of the transformer cannot, in a strict sense, be modeled as an ideal current source, and; thus, an iterative technique must be employed. This capability is not currently offered in any commercially available computer tools.
- because transformers subjected to GIC inject zero sequence harmonics, standard positive sequence power flow data cannot be used alone as a basis for assembling the system model.
- harmonic resonance created by shunt capacitor banks, and the damping effects of load must be considered. When large geographic areas are studied such as required for benchmark GMD events, considering such effects can be extremely difficult and requires a considerable amount of expertise and engineering judgement.

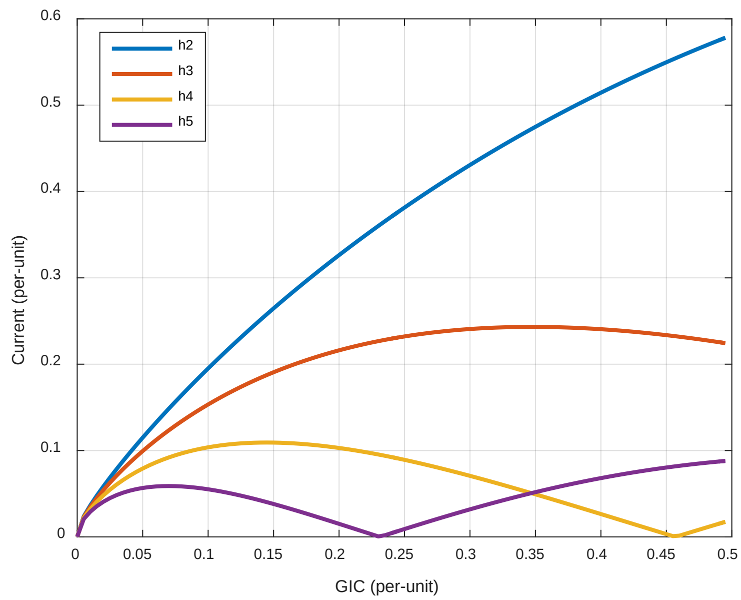

Figure 1. Harmonic current versus GIC for a 500 kV 400 MVA single-phase GSU.

2.1.2 Time Domain Analysis

In time-domain analysis, the power system is modeled by differential equations which describe the physics of each individual element in the system. The corresponding differential equations are solved numerically, and the results (waveforms) are plotted and analyzed. Many of the modeling limitations that are experienced when using frequency domain analysis (e.g. non-linear mapping of harmonics and GIC) are handled automatically. If a time-domain model is assembled correctly, it yields the most accurate solution.

There are numerous computer tools available to model power systems in the time-domain which include (but are not limited to): the electromagnetic transients program (EMTP), EMTDC/PSCAD, the alternative transients program (ATP), and others.

Although time-domain analysis is very powerful and can be used to perform harmonics analysis, there are considerable difficulties which arise when using this technique to assess the harmonic impacts of benchmark GMD events. Such difficulties include (but are not limited to):

- time-domain analysis requires very specialized expertise that may not be common to all applicable entities associated with the proposed standard;

- time-domain models are very detailed and labor intensive to construct. Creating models large enough to simulate the effects of a benchmark GMD event would be unwieldy;
- there are modeling gaps with regards to transformers subjected to geomagnetically induced current (GIC). Time-domain models of single-phase transformers are mature, and in general, the necessary parameter data (e.g. short circuit impedance, saturation characteristic, air-core reactance, etc.) are available or can be estimated from nameplate data. However, both models and the necessary parameter data for three-phase transformers are limited. There are some models available, but some of the input data is either not available or difficult to estimate (for example the zero sequence magnetizing reactance of three-phase, three-legged core transformers).

2.1.3 Important Considerations in Modeling Harmonic Impacts of Benchmark GMD Events

The following example is used to illustrate some of the difficulties in performing harmonic assessments of benchmark GMD events. Figure 2 shows a simplified 500 kV network which consists of a 500 kV:230 kV autotransformer and a 500 kV – 134 Mvar capacitor bank. For the purposes of this example, various levels of GIC were injected into the autotransformer and the corresponding harmonic current flow in the shunt capacitor bank was evaluated. All simulations were performed using time-domain techniques.

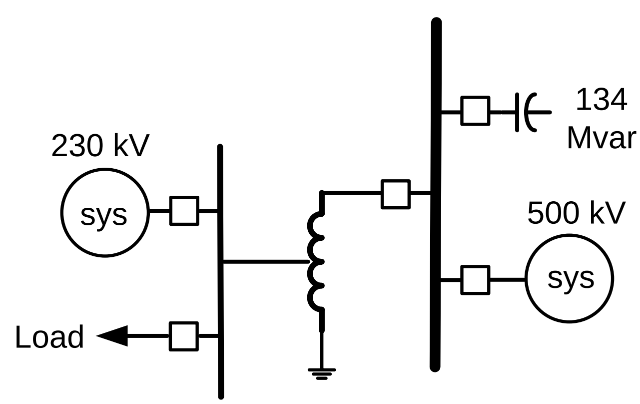

Figure 2. Simplified 500 kV Network

The resulting transformer exciting currents for four different levels of GIC, namely 100A/phase, 200A/phase, 300A/phase and 400A/phase, are provided in Figure 3.

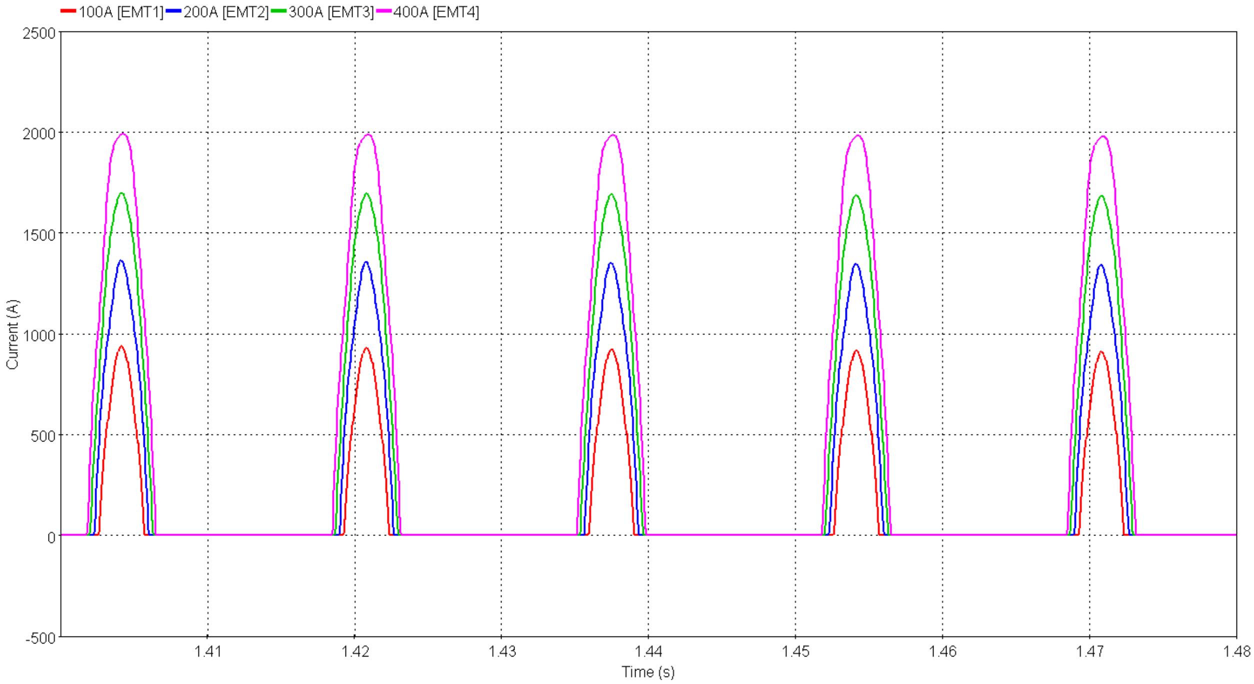

Figure 3. Autotransformer exciting current for various level of GIC.

The corresponding current flows in the 500 kV capacitor bank for these same levels of GIC are shown in Figure 4.

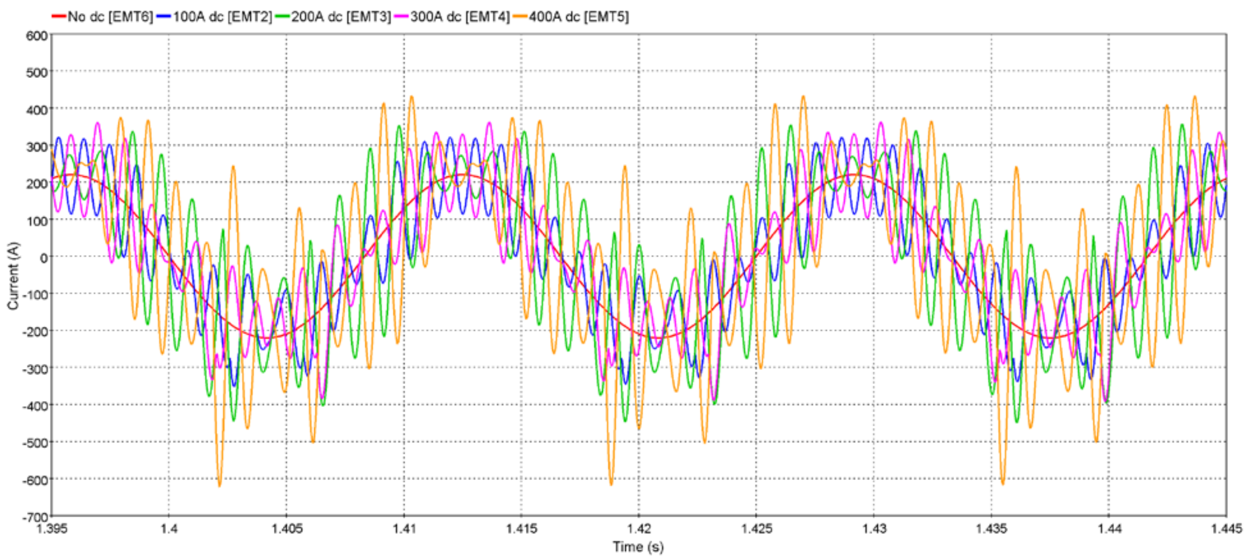

Figure 4. Current flow in 500 kV capacitor bank corresponding to various levels of GIC in the 500 kV: 230 kV autotransformer.

Fourier methods were employed to obtain the harmonic content of the capacitor bank currents. The results of this analysis are provided in Figure 5.

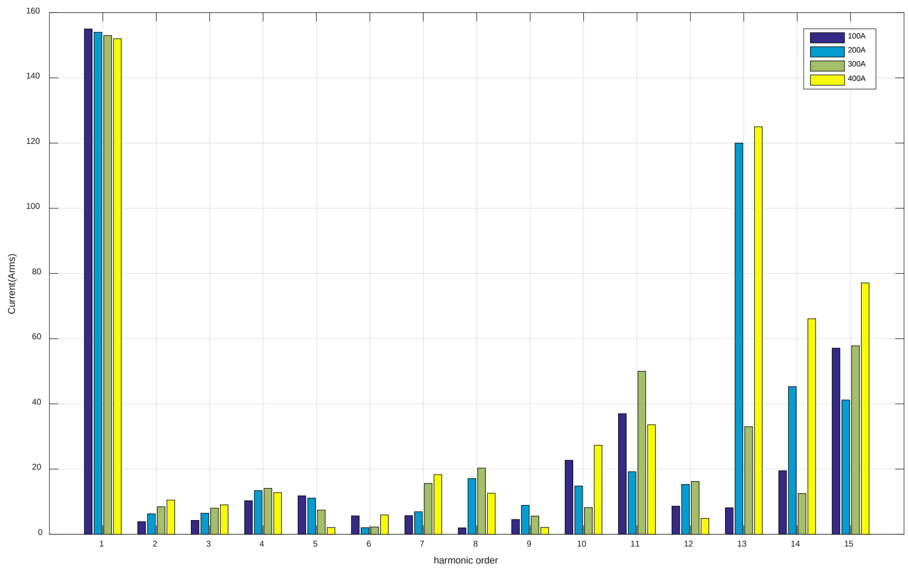

Figure 5. FFT of capacitor bank current for various levels of GIC in autotransformer

The addition of the capacitor bank creates a harmonic resonance between the 12th and 13th harmonics. The effects of the resonance are clearly seen in Figure 5. Because of the resonance, significant higher order harmonics are absorbed by the capacitor bank. Another important observation is that the harmonic current absorption of the capacitor bank appears to be non-linear, meaning that higher levels of harmonics are not always experienced with higher levels of GIC. Figure 6 shows the relative non-linear relationship of the 13th harmonic component of the exciting current with GIC flow in the autotransformer. As seen in Figure 6, the transformer will "inject" larger quantities of 13th harmonic with 200A/phase of GIC than it will with 300A/phase of GIC. This effect is clearly seen in FFT results presented in Figure 5.

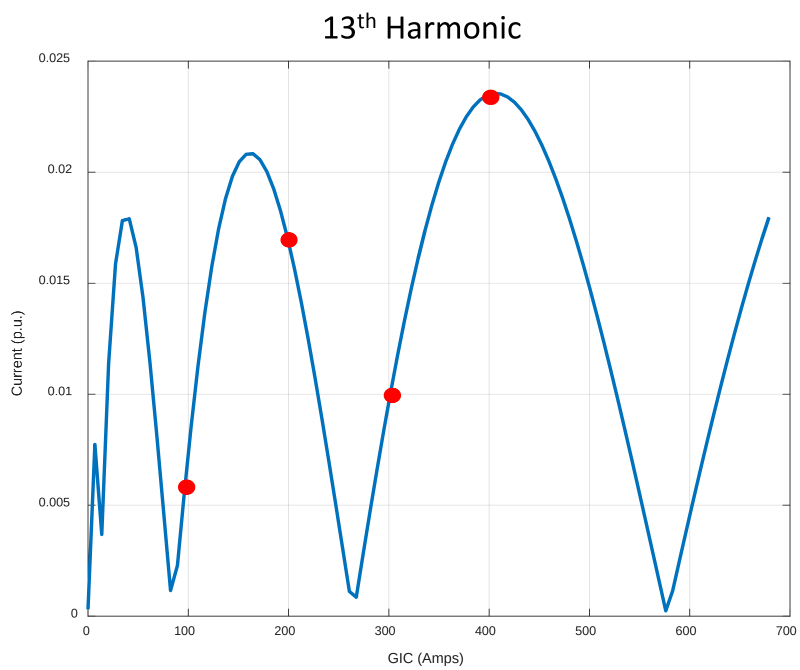

Figure 6. 13th harmonic current generated by the 500 kV autotransformers for various levels of GIC.

The resulting current distortion, *THDi*, *rms* current, and % of nameplate rating of the capacitor bank for various levels of GIC were computed and the results are provided in Table 1.

Table 1. Harmonic Current Distortion and *rms* current in capacitor bank.

GIC	100A	200A	300A	400A
THDi (%)	50.2	91.3	60.2	111.4
rms (A)	173	208	179	228
% of Rating	112	135	116	148[1]

Although the *rms* current flow in the capacitor bank exceeds the maximum *continuous* rating specified in IEEE Std. 18, it may be acceptable due to the short duration of such an event.

[1] Capacitors designed to meet IEEE Std. 18-2012 – IEEE Standard for Shunt Capacitors, are required to be capable of *continuous operation* at 135% of nominal current. Short-term ratings such as those needed for benchmark GMD assessments should be obtained from the capacitor manufacturer.

Specific ratings information for short-term capability should be obtained from the capacitor manufacturer.

Another item that is often misunderstood is whether or not current and voltage distortion should meet IEEE Std. 519[2] limits during a benchmark GMD event. Figures 7 and 8 show the resulting bus voltage and corresponding harmonic components, respectively, for varying amounts of GIC.

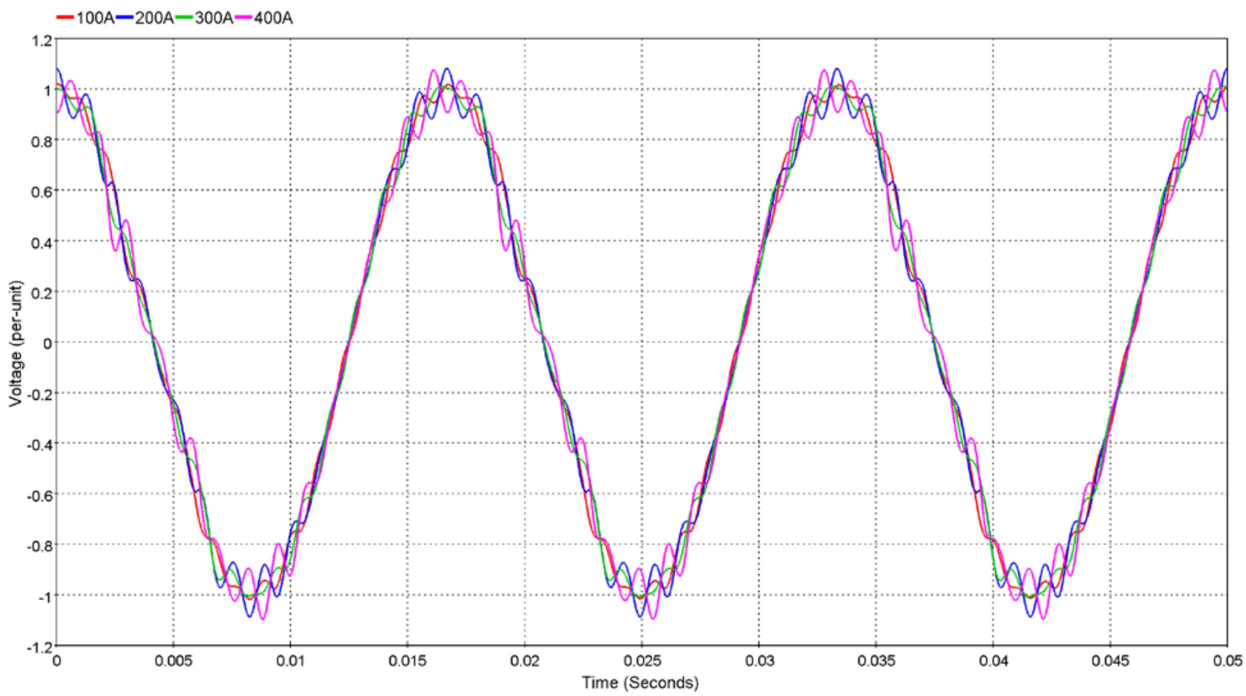

Figure 7. 500 kV bus voltage corresponding to various levels of GIC in the 500 kV: 230 kV autotransformer

[2] 519-2014 - IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems

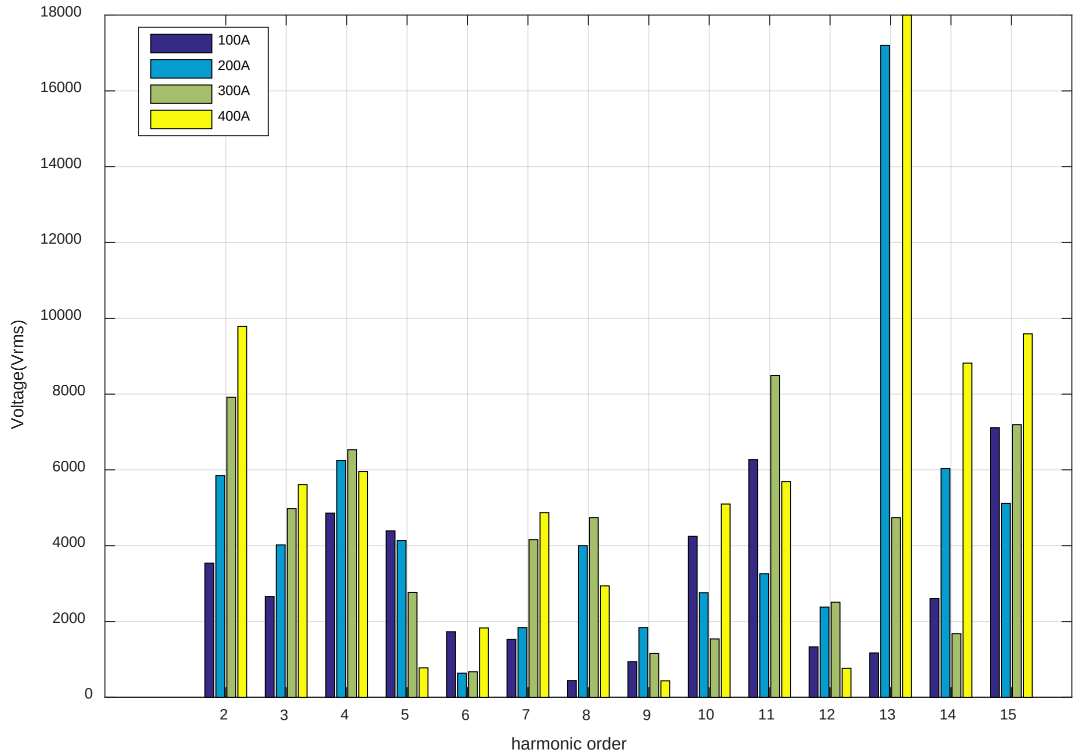

Figure 8. FFT of bus voltage for various levels of GIC in autotransformer

Using the information provided in Figure 8. The corresponding *THDv* and *rms* voltage was computed. The results of these computations are provided Table 2.

Table 2. Harmonic Voltage Distortion at 500 kV Bus

GIC	100A	200A	300A	400A
THDv (%)	4.7	7.8	6.4	9.5
rms (p.u.)	1.0	1.0	0.99	0.99

Although the total harmonic voltage distortion exceeds the IEEE Std. 519 recommended levels for a 500 kV bus, it does not necessarily pose a reliability issue for bulk-power system components because of its short duration. The intent of IEEE Std. 519 is that the harmonic limits be statistically maintained (e.g. *99th* percentile) over long periods of time, example one week, and were never intended to be applied to short duration events such as a benchmark GMD event.

The previous example illustrates the importance of considering harmonic resonance and how the non-linear nature of the harmonic current generated by half-cycle saturation can affect the results in ways that seem counterintuitive. Additionally, performance criteria that are intended to be utilized for *continuous* operation are not suitable for benchmark GMD events; thus, the industry needs additional guidance regarding the short-term harmonic capability of the bulk-power system and its components. Although analysis can be performed on small-scale systems, more work is needed to develop approaches and computer modeling tools for accurately assessing the harmonic effects of benchmark GMD events.

2.1.4 Vibrational Effects

Transformer noise and vibration is created by a phenomenon called magnetorestriction. The laminated steel core of a power transformer can be thought of as being comprised of microscopic magnets each having a North and South pole. When a transformer is energized with a 60 Hz voltage (resulting in a 60 Hz exciting current), the resulting magnetic field causes these microscopic magnets to flip back and forth - once in the positive half of the cycle and once in the negative half of the cycle (see Figure 9).

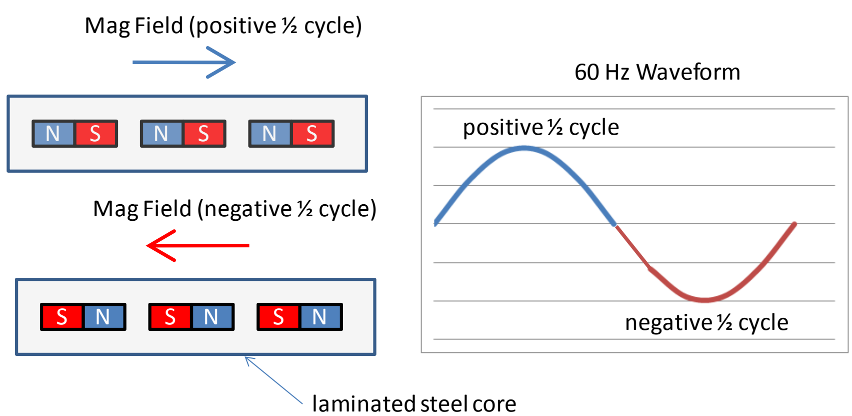

Figure 9. Illustration of magnetorestriction

The movement of these microscopic magnets causes the steel core to vibrate. Since the magnets flip back and forth at twice the frequency of the excitation source, the resulting vibration is also at twice the 60Hz power frequency (120 Hz in North America). The resulting core vibration is transferred to the transformer tank through bolted connections and the transformer oil, which eventually results in the movement of air (sound) outside of the transformer tank. It should be pointed out that vibration (and corresponding noise) also occurs at integer multiples of 120 Hz, i.e. 240 Hz, 360 Hz and so on. Harmonic currents created by half-cycle saturation cause magnetorestriction in the core just like 60 Hz current described above, and again the resulting sound is at twice the frequency of the excitation. For example, 3rd harmonic current (180 Hz) resulting from half cycle saturation will create vibration and noise at 360 Hz, 720 Hz, 1080 Hz and so on. Other harmonic currents are also present during half-cycle saturation, and create vibration and noise. The resulting noise is in the frequency range that the human ear is most sensitive (500 – 5000 Hz), and is often described as "growling".

From my own personal experience testing a large autotransformer at the Siemens plant in Austria, these transformers do produce a tremendous amount of noise when they are operating in a half-cycle saturated mode caused by the injection of dc current. However, the technical community at large is not aware of any transformer failures or reliability issues that have been directly attributable to GIC induced vibration. From an assessment standpoint, there are no known commercially available models or computer tools for evaluating the effects of vibration caused by half-cycle saturation of power transformers. Because there are no known documented cases of vibrational damage caused by GMD events, and there are no commercially available computer tools or performance criteria available to perform an assessment, the effects of GIC induced vibration should not be included in the assessment process described in the proposed TPL-007-1 standard.

2.2 Impacts of Harmonics on Bulk-Power System Components

The flow of harmonic currents in the power system can affect bulk-power system components such as protective relays, reactive power devices and generators. The following sections provide a brief discussion of potential effects.

2.2.1 Protection Equipment

The potential impact of harmonic currents on system protection devices is influenced by three principal factors: 1) relay type (e.g. microprocessor, electromechanical, solid-state), 2) the element being protected (e.g. transformer, transmission line, capacitor bank, etc.) and the type of protection scheme employed, and 3) the frequency response of the instrument transformers that the relays are connected to.

Microprocessor-based (or numerical) relays generally employ an analog low-pass filter and digital filtering to remove all dc and harmonic components contained in the voltage or current measurements. A typical signal flow diagram of a microprocessor-based relay is shown in Figure 10.

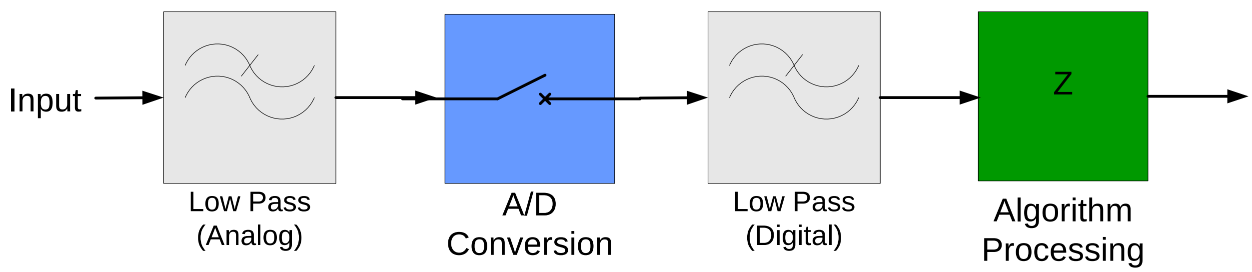

Figure 10. Generic Signal Flow Diagram of a Microprocessor-based Relay

Modern microprocessor based relays, which utilize digital signal processing techniques to remove dc and harmonic content, are theoretically immune to harmonic distortion.

Electromechanical relays are still employed in numerous locations in the bulk-power system. Electromechanical relays do not employ harmonic filtering, and the response of the relay is typically based on the true *rms* quantity which includes harmonics. Thus, electromechanical relays are vulnerable to misoperation due to harmonics.

Relay elements based on solid-state technology generally operate on peak value detection. At each cycle, they utilize analog electronics to measure the waveform magnitude, and use the largest absolute value presented by the waveform to determine trip decisions. Some solid state relays employ low-pass filtering to remove higher order harmonics, but some do not. When harmonics are present in a waveform, the peak value may be increased (refer to Figures 4 and 7) which can result in misoperation.

The type of element being protected and the type of protection scheme employed have a significant influence of the performance of the protection system during a benchmark GMD event. One of the protection schemes most vulnerable to the flow of harmonics is the neutral unbalance scheme of a grounded wye capacitor bank. Such a scheme is illustrated in Figure 11.

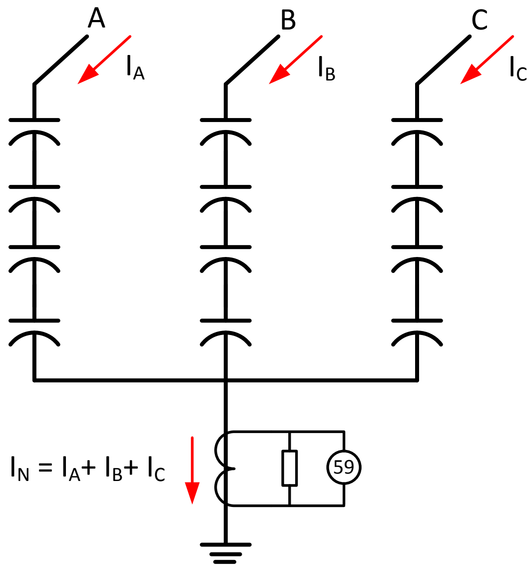

Figure 11. Unbalance protection scheme of a grounded-wye capacitor bank

The protection scheme shown in Figure 11 is vulnerable to misoperation due to harmonics if it employs either an electromechanical or solid-state relay. Balanced triplen harmonics (3rd, 6th, 9th, etc.) are zero sequence, and; thus, can flow in the neutral of the capacitor bank. The unbalance protection scheme can misinterpret these currents as being the result of a capacitor can failure and trip the capacitor bank off-line. Other types of configurations, e.g. split-wye grounded, are less prone to misoperation due to harmonics because they inherently filter out system imbalance that is not caused by capacitor failures[3]. Some capacitor banks and harmonic filter banks also employ overvoltage protection schemes. Because of their peak detection sensing algorithm, solid-state relays can be vulnerable to misoperation if the voltage waveform contains considerable harmonic components, and is believed to the cause of the SVC tripping which led to the March 13, 1989 blackout in HydroQuebec[4].

Large power transformers are commonly protected using a differential scheme (see Figure 12). If the scheme employs harmonic restraint (used to minimize misoperation during transformer energization), it can become de-sensitized during a severe GMD event. This can result for any

[3] R. Horton, et al, "Unbalance Protection of Fuseless, Split-wye, Grounded, Shunt Capacitor Banks", *IEEE Transactions on Power Delivery*, July 2002, pp. 698-701.
[4] March 13, 1989 Geomagnetic Disturbance, North American Electric Reliability Corporation, http://www.nerc.com/files/1989-Quebec-Disturbance.pdf

relay type (microprocessor, electromechanical or solid-state). However, most schemes also employ instantaneous tripping which would provide protection during fault events.

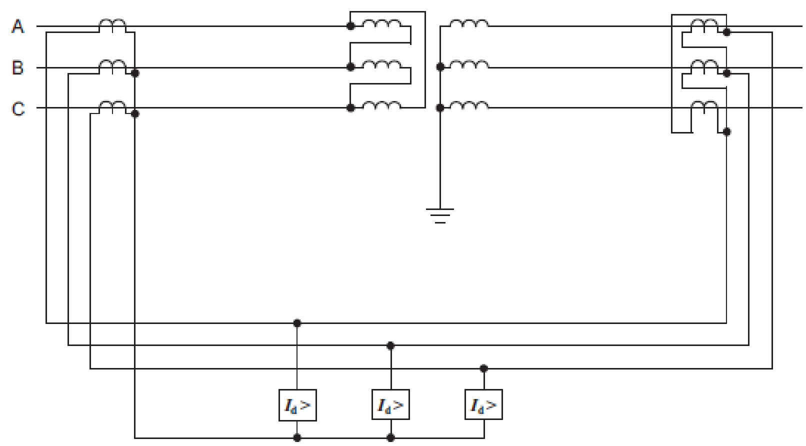

Figure 12. Example transformer differential protection scheme.

Protection schemes employ instrument transformers to step-down voltages and currents to levels that are appropriate (e.g. 120V and 5A). When primary voltage and current waveforms contain harmonics, the ability of the instrument transformer to provide an accurate representation of the primary signal becomes very important in determining the response of the protection system. The circuit diagram and corresponding frequency response of a typical 230 kV capacitively-coupled voltage transformer (CCVT), commonly used in bulk-power system protection schemes, is provided in Figure 13.

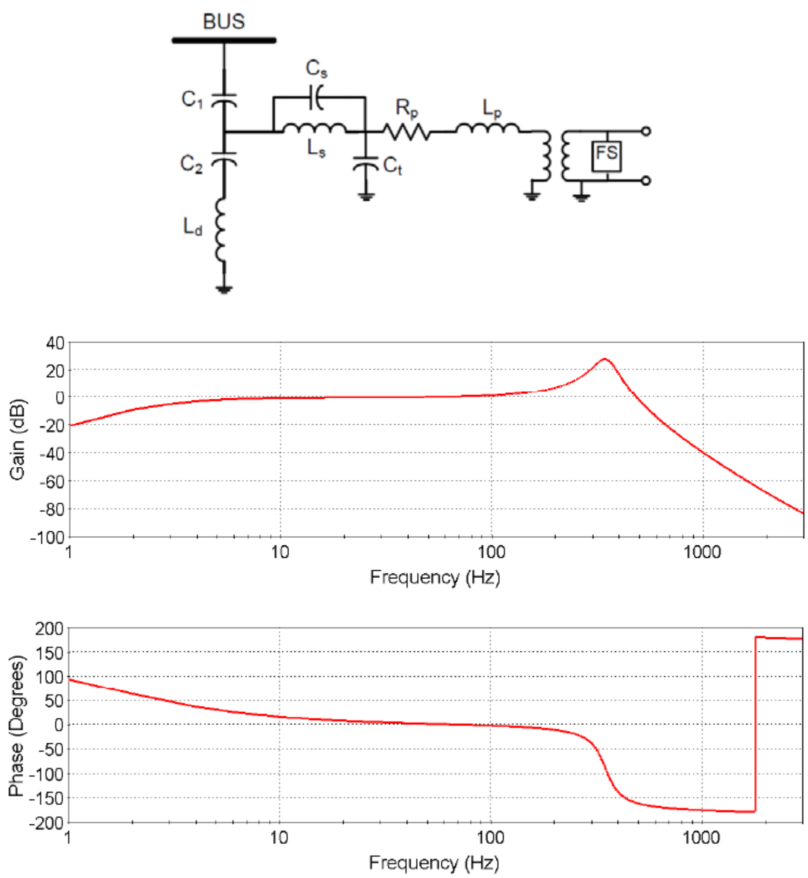

Figure 13. Circuit diagram and corresponding frequency response of a typical 230 kV capacitively-coupled voltage transformer (CCVT)[5].

The frequency response shown in Figure 13 illustrates the potential effect of instrument transformers. For example, at 300 Hz, the output of the CCVT would show that 300 Hz component of the primary voltage is approximately 1143% larger than it actually is. Although such effects are minimized with the use of microprocessor based relays, electromechanical and solid-state type relays could be vulnerable to misoperation depending on the type of protection scheme that is employed.

2.2.2 Impacts on Reactive Power Resources

As illustrated in the previous example, reactive power resources such as capacitor banks can and will absorb harmonic currents during a benchmark GMD event. Effects can include additional

[5] Understanding Harmonics and Interharmonics, EPRI PQ TechWatch, November 2011.

heating and misoperation of protection systems which can take these resources off-line when they are needed most. Harmonic filters, SVCs, and STATCOMs, are also vulnerable to poor performance during a benchmark GMD event. Thus, an assessment of these devices is necessary; however, additional criteria and improved tools are necessary to provide a realistic view of their operation during a severe GMD event.

2.2.3 Impacts on Generators

Although synchronous generators do not, in theory, generate harmonic currents, their windings do provide a path for them to flow. Harmonic current flow in the stator of a synchronous generator induces harmonic currents in the rotor which increases rotor heating. Fundamental frequency, negative sequence current also induces harmonic current in the rotor (120 Hz). To minimize their effect, IEEE Std. C50.13[6] provides limits for negative sequence current flow in synchronous generators. Negative sequence relays are generally employed to insure that the generators do not operate above the limit that could cause damage. Because most negative sequence relays operate off of fundamental frequency (60 Hz) quantities, they are unable to detect the equivalent negative sequence heating caused by the flow of harmonics in the stator winding of a generator. IEEE Std. C50.13 has been updated to include harmonic current in the calculation of negative sequence current limits. Detailed harmonics studies are required to provide an accurate assessment of harmonics that the generator would be exposed to during a benchmark GMD event. Additionally, a protective relay that includes harmonics in the calculation of an "equivalent" negative sequence current may need to be considered in some cases.

2.3 Power System Impacts Related to Reactive Power Demand

The flow of geomagnetically induced current (GIC) in the windings of power transformers creates an offset in the magnetic flux in the transformer core. This causes the transformer core to become saturated for one half of the power cycle; thus, the phenomenon is referred to as half-cycle saturation. The resulting exciting current can be obtained by mapping the resulting flux to the non-linear saturation characteristic of the transformer. Such a mapping is illustrated in

[6] C50.13-2005 - IEEE Standard for Cylindrical-Rotor 50 Hz and 60 Hz Synchronous Generators Rated 10 MVA and Above

Figure 14. Fourier analysis of the resulting waveform (see bottom left quadrant of Figure 14) shows that the exciting current contains a significant 60 Hz component and harmonics.

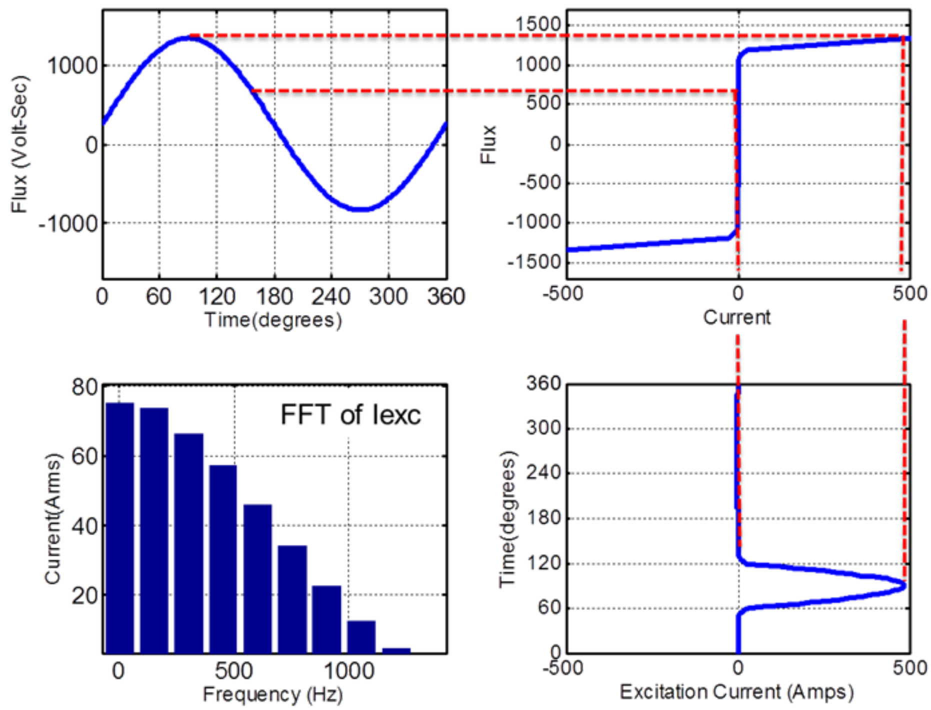

Figure 14. Half-cycle saturation of a power transformer due to the flow of GIC

The 60 Hz component of the exciting current corresponds to the reactive power absorption of the transformer. In effect, all of the transformers experiencing half-cycle saturation appear as large inductive loads to the bulk-power system. The result is wide-spread voltage depression that can result in voltage collapse during extreme GMD events if sufficient reactive power resources are not available.

3.0 Summary

In summary, the Southern Companies encourage the Commission to approve the proposed TPL-007-1 standard as submitted. Approving the standard now will provide the regulatory certainty needed to allow applicable entities to focus limited resources on the assessment process and on future R&D efforts; thus, encouraging applicable entities, manufacturers and vendors to develop comprehensive solutions to this important issue.

The key take-aways regarding vulnerability assessments performed under the proposed standard are as follows. First, more work is needed to develop commercially available computer modeling tools and performance criteria that can be used to assess the harmonic impacts of benchmark GMD events. Second, transformer vibration and audible noise that result from half-cycle saturation do not appear to be damaging to power transformers, and; thus, do not need to be considered in the proposed standard. Finally, the analysis of protection systems is an important aspect of assessing the impact of benchmark GMD events on the bulk-power system; however, without the proper computer modeling tools and expertise necessary to determine the harmonic levels that such devices may be exposed to during a benchmark GMD event, results can vary widely. Interpreting such results and determining whether or not they identify a potential reliability risk requires considerable expertise and engineering judgment.

Thank you for the opportunity to provide these comments in this important docket.