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Case Study – Effects of Geomagnetically Induced Current (GIC) Neutral Blocking Device

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SUMMARY

The North American Electric Reliability Corporation (NERC) is developing Geomagnetic Disturbance (GMD) Stage II reliability standard to address the impact of GMD to ensure continued reliable operation of the nation's Bulk-Power System. Based on the GMD vulnerability assessments of the potential effects of specified "benchmark GMD events" on equipment, as well as the Bulk-Power System as a whole, the GMD reliability standards will require applicable entities to develop and implement plans to protect against instability, uncontrolled separation or cascading failures of the system. The work presented here is an important part of AEP's GMD impact assessment efforts to address the potential of negative impacts on the reliable operation of AEP transmission systems. The paper presents results of Geomagnetically Induced Currents (GIC) flow simulation based on a uniform rotating geo-electric field and GIC re-distributions due to transformer Neutral Blocking Device (NBD).

The evaluation included:

- (a) Impact of transformer neutral GIC (N-GIC) blocking device on transformer effective GIC (E-GIC) and GIC redistribution
- (b) Impact of GIC blocking device on transformer reactive power absorption and its effectiveness in reducing total transformer reactive power absorption

The paper demonstrates that the GIC blocking device will block GIC flow through a transformer neutral. However, GIC flow will find its paths to other locations where transformer high-side winding is wye-grounded and electrically adjacent to the more active transformers that are now blocked, so GIC levels might increase in these neighboring transformers, particularly those that exhibit lower levels of GIC participation under the no blocking condition. Hence, the total system effective GIC does not reduce proportionally to the GIC blocked.

When the blocking device is added to an autotransformer, this primarily only reduces the GIC flow in the common winding and has limited impact on the series winding GIC flows; in fact, the GIC flow in the series winding might actually increase.

Finally, it is recommended that sensitivity analysis is performed to evaluate the factors, such as grid ground resistance, network topological changes, etc., that have the most impact on the

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effective GIC redistribution and reactive power consumption. GMD Operation Procedures can be further refined with the sensitivity analysis.

KEYWORDS

Geomagnetic Disturbance (GMD), Effective Geomagnetically Induced Currents (E-GIC), GMD System Vulnerability Assessment, Benchmark GMD Event, Transformer Thermal Assessment, Transformer Neutral Blocking Device (NBD), Transformer Reactive Power Consumption

1. Introduction

The North American Electric Reliability Corporation (NERC) is developing Geomagnetic Disturbance (GMD) Stage II reliability standard ^[1] to address the impact of GMD to ensure continued reliable operation of the nation's Bulk-Power System. Based on the GMD vulnerability assessments of the potential effects of specified "benchmark GMD events" on equipment, as well as the Bulk-Power System as a whole, the GMD reliability standards will require applicable entities to develop and implement plans to protect against instability, uncontrolled separation or cascading failures of the system^{[1]-[3]}. The work presented here is an important part of AEP's GMD impact assessment efforts ^{[4]-[8]} to address the potential to negatively impact the reliable operation of AEP transmission systems. The paper presents results of Geomagnetically Induced Currents (GIC) flow simulation based on a uniform rotating geo-electric field and GIC re-distributions due to transformer Neutral Blocking Device (NBD).

As indicated in some previous GIC system vulnerability studies, many of the AEP Grid transformers have low-levels of GIC flow under a severe geomagnetic storm, and some transformers may be subject to higher GIC flow. Therefore the focus of this analysis was to examine the efficacy of deployment of the neutral GIC blocking device on transformers with a maximum effective GIC (E-GIC) exceeding 15 amps per phase in the studied system. The GIC re-distribution phenomenon was also studied in detail to identify the potential negative impacts on those transformers without NBD.

The evaluation included:

- (a) Impact of transformer neutral GIC blocking device on transformer effective GIC and GIC redistribution
- (b) Impact of GIC blocking device on transformer reactive power absorption and its effectiveness in reducing total transformer reactive power absorption

2. GMD System Vulnerability Assessment

Benchmark GMD Event

Based on statistical analysis using geomagnetic field measurements from geomagnetic observatories, a conservative peak geo-electric field amplitude of 8 V/km for the Quebec region was determined as the reference geo-electric field and was defined as the benchmark GMD event with an estimated frequency of occurrence to be approximately 1 in 100 years. The geo-electric field peak amplitude, E_{peak} , can be calculated for other locations based on geomagnetic latitude (scaling factor α) and ground conductivity model (scaling factor β) using the following formula recommended in the NERC Benchmark GMD Whitepaper.^{Error! Reference source not found.}

$$E_{\text{peak}} = 8 \times \alpha \times \beta \text{ (V/km)} \quad (1)$$

The E-field peak value of the uniform field for the studied system was estimated at 3.52V/km using the geomagnetic latitude scaling factor of the northern part of the system and the corresponding scaling factor β for its ground conductivity model (a conservative approach).

Effective GIC I_{E-GIC}

For a two-winding transformer with high-side, wye-grounded winding such as generator step-up transformers (GSUs), the effective I_{EGIC} is simply the current in the grounded coil. If a blocking device is applied to the neutral of a GSU, it can effectively block the GIC flow through the GSU, resulting in zero GIC flow for the GSU. However, GIC flow in an autotransformer represents more complex patterns because of actual GIC flowing through both the series and common windings of this autotransformer.

Since the GIC flow in the series winding is different from that of common winding in an autotransformer, an effective GIC is calculated as a product of the series and common winding GICs taking into consideration the winding ratios to represent the overall impact on the autotransformer.

The effective GIC can be calculated as follow [5] [9] [11]:

$$I_{E-GIC} = \left| \frac{\alpha_i I_H + I_L}{\alpha_i} \right| = I_H + (I_N / 3 - I_H) V_X / V_H \quad (2)$$

where,

I_H is the per phase DC current going into either the high side winding or the series winding of an autotransformer

I_L is the per phase DC current going into either the low side winding or the common winding of the autotransformer

I_N is the neutral DC current (3-phase);

α_i is the transformer turns ratio, $\alpha_i = V_H / V_X$;

V_H is the rms rated voltage at HV terminals;

V_X is the rms rated voltage at the LV terminals.

The GIC flows in the neutral, series and common windings, and effective GICs for autotransformer A with and without the neutral blocking device are illustrated in Figure 1-1. For comparison, Figure 1-2 shows the E-GIC and MVar Loss changes for autotransformer B after applying a neutral blocking device. The NBD in Autotransformer B has very limited effect in reducing the E-GIC and the maximum E-GIC of Autotransformer B was reduced by less than 8% from 36.7 amps to 33.8 amps.

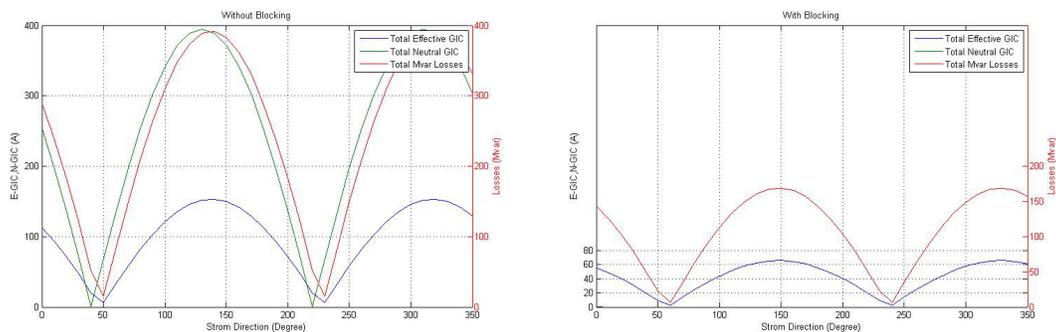


Figure 1-1 GIC Flow Pattern for Autotransformer A – No NBD vs. w/ NBD

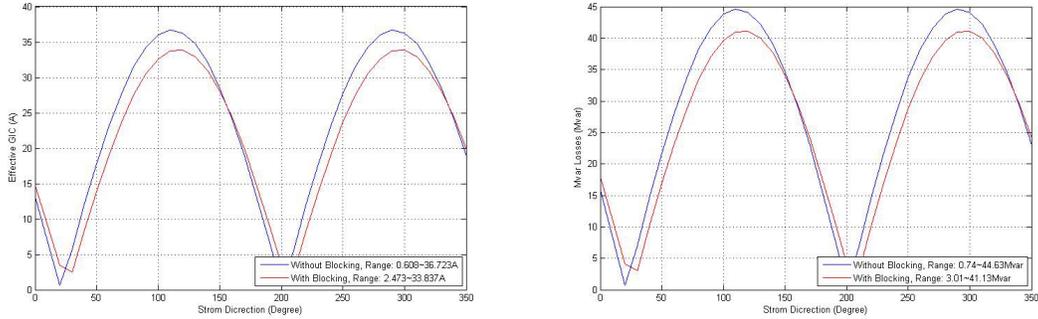


Figure 1-2 E-GIC & MVar Loss Comparison for Autotransformer B: No NBD vs. w/ NBD

GIC Simulations Based on Benchmark GMD Event

In the proposed draft NERC Stage II GMD Reliability Standard ^[1], each transformer owner shall conduct a thermal impact assessment for applicable power transformers where the maximum effective GIC value is 15 Amperes or greater per phase when subject to a benchmark solar storm.

GIC flows were simulated by applying a rotating uniform geo-electric field of 3.52 V/km to the studied system based on the NERC GMD benchmark event. A list of transformers with a maximum effective GIC greater than 15 amps per phase, named as “15-amp E-GIC List”, is identified when the system GIC is at its maximum. Figure 2-1 illustrates the total system effective GIC, total neutral GIC and total increased MVar in the transformers for 360 degree rotation. As shown in Figure 2-, the highest total system effective GIC is 3448 amps when the storm direction is at ~140 degrees, while the maximum total neutral GIC is 10768 amps. The maximum total increased transformer reactive power loss is 4785 MVar for the storm at 140 degrees.

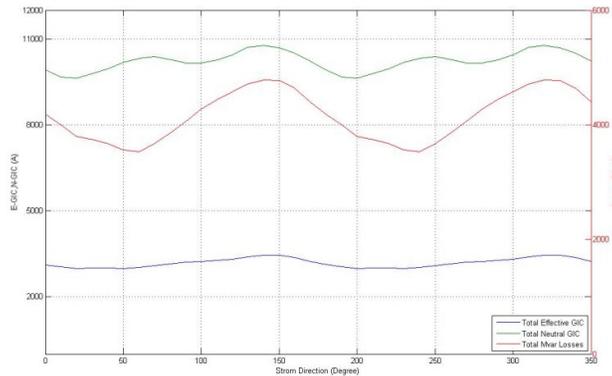


Figure 2-1 Total E-GIC, N-GIC and MVar Loss Vs. Storm Direction (No Blocking Case)

3. Effects of GIC Neutral Blocking Device (NBD)

As one of the potential measures to mitigate the negative impacts of GIC on a transformer, the transformer neutral blocking device is also well known to divert the GIC flow to its neighboring ground paths where transformers with high-side wye-grounded winding are electrically adjacent to the blocked transformers. In order to quantify the effect of NBD, transformer NBD is applied to the top 20% ~ 100% of the identified transformers on the 15-amp E-GIC list.

As shown in Table 1, when NBDs are applied to the top 20% of transformers experiencing the highest E-GIC (~14 transformers, which is referred as Top 20% Blocking thereafter) in the vulnerable transformer list, the effective GIC in 119 transformers increases, and the neutral GICs in 122 transformers are elevated, which accounts for 47% and 48%, respectively, of the total 253 transformers.

Table 1 Number of Transformers with Negative Impact due to Blocking

XF (E-GIC>15A) w/NBD	Effective GIC Elevated		Neutral GIC Elevated		MVar Loss Elevated	
	Ave. XF #	Elevated%	Ave. XF #	Elevated%	Ave. XF #	Elevated%
Top 20%	119	47.2	122	48.3	93	36.9
Top 33%	119	47.1	119	47.1	98	38.6
Top 66%	120	47.3	106	41.9	105	41.4
Top 100%	121	48.0	99	39.1	109	42.9

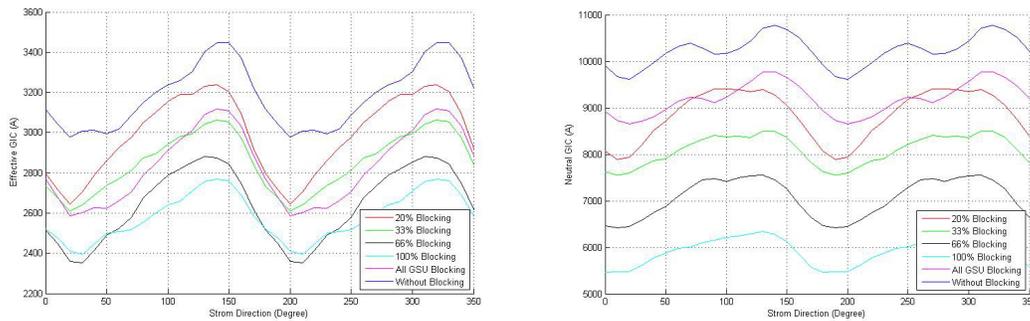


Figure 3-1 Total E-GIC & N-GIC vs. Various Blockings vs. Storm Direction

Figure 3-1 illustrates the total system E-GIC & N-GIC for the rotating benchmark geo-electric field and the blocking effect for various blocking scenarios. Figure 3-2 shows the percentages of system E-GIC (left) and N-GIC (right) for various percentage blockings compared to those in the no blocking base case. With 100% blocking, the average E-GIC reduction is less than 20%, which the N-GIC reduction achieve a little more than 40%.

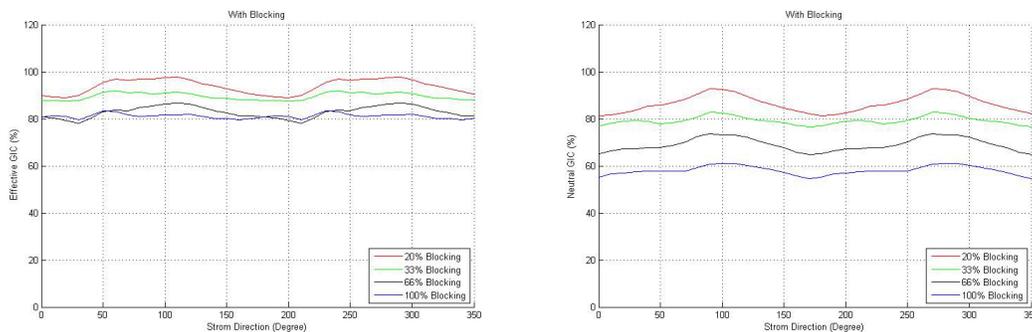


Figure 3-2 Percentages of Total E-GIC and N-GIC against Storm Direction for Various Blocking

The blocking performance for reactive power loss reduction is illustrated in Figure 3-3. For the storm directions when the system total MVar loss is at its minimum (~60 & 240 degrees), the NBDs achieve the lowest percentage MVar loss reduction, and while in the 20% Blocking case, there is almost no effect at all on reducing the system MVar loss.

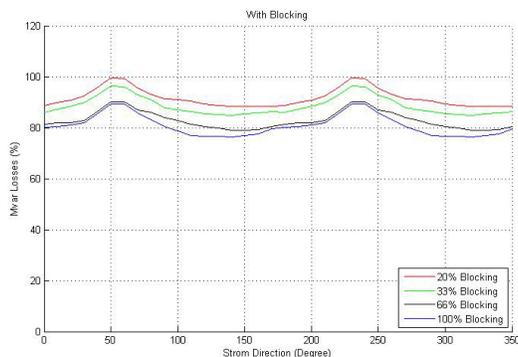


Figure 3-3 Percentage of MVar Losses after Blocking against Storm Direction

As expected, the total system neutral GIC has the most reductions ranging from 1378 amps (Top 20% Blocking) to 4287 amps (top 100% blocking) shown in Table 2; however, the NBD is much less effective in reducing the total system effective GIC, with only 195 amps reduction for the top 20% transformers with the highest effective GICs being blocked. Even with all the transformers with a maximum effective GIC greater than 15 amps per phase being blocked, the total system effective GIC is reduced by a mere ~600 amps. Compared to system neutral GIC reduction, system effective GIC reduction can only achieve average ~15% of that of the system neutral GIC reduction, in other words, every 6.67 amps of neutral GIC reduction contributes to only 1 amp of effective GIC reduction. Also indicated in Table 2, every 2 amps of effective GIC reduced at one location causes ~1 amp effective GIC increase in somewhere in the system. The relationship also holds true for transformer reactive power losses.

Table 2 Changes of Total Effective GIC, Neutral GIC and MVar Loss after Blocking

Blocking%	Average System Effective GIC Elevated					Average System Neutral GIC Elevated				Average System MVar Loss Elevated			
	Sys. E-GIC Reduced	Sys. E-GIC Elevated	Net Change	$\Delta E-GIC / \Delta N-GIC$	Elevated/Reduced	Sys. N-GIC Reduced	Sys. N-GIC Elevated	Net Change	Elevated/Reduced	Sys. MVar Reduced	Sys. MVar Elevated	Net Change	Elevated/Reduced
Top 20%	477	281	195	14%	59%	2102	723	1378	34%	819	458	360	56%
Top 33%	679	347	332	16%	51%	3154	1025	2128	33%	1009	521	488	52%
Top 66%	988	445	543	17%	45%	4555	1395	3161	31%	1299	580	719	45%
Top 100%	1216	615	601	14%	51%	5991	1704	4287	28%	1470	660	809	45%

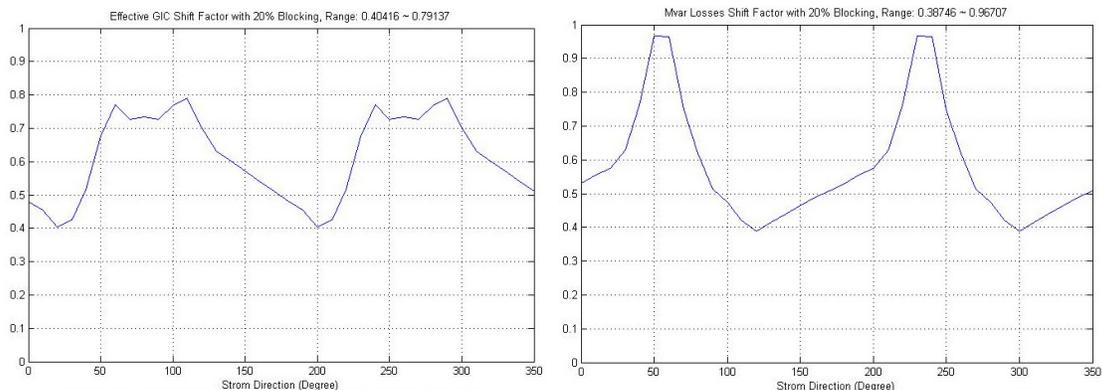


Figure 4-1 Shift Factor for E-GIC and MVar Loss against Storm Direction

Corresponding to Table 2, an index called Shift Factor was calculated as a percentage of the total system E-GIC (or MVar Loss) elevated compared to total system E-GIC (or MVar Loss) reduced for the rotating uniform E-field. Figure 4- shows that 40% to 79% of E-GIC reductions due to NBD deployment for the Top 20% Blocking case were offset by E-GIC increases elsewhere in the system. At some storm direction, the total transformer reactive power loss was barely changed with a shift factor as high as 0.97.

GIC re-distribution caused by the NBDs also changes the list of transformers with a maximum E-GIC greater than 15 amps per phase. Table 3 shows the total number of transformers in the 15-amp E-GIC List for various percentages of blocking. In the Top 20% Blocking case, although five transformers drop from the initial List due to their E-GICs falling below the 15-amp/phase threshold, the E-GIC of additional five transformers exceeds the 15-amp threshold, resulting the total number of transformers in the List unchanged. Even with all the transformers in the initial List with their N-GICs being blocked, the total number of transformers with E-GIC greater than 15 A/phase decreased by only 27%.

**Table 3 Number of Transformers w/ E-GIC > 15A
(At Maximum System GIC)**

Blocking%	Number of XFs w/ E-GIC > 15A			
	In the base list	Not in the base list	Total # of XF	# of XF Decreased
Base - 0%	70	0	70	0
Top 20%	65	5	70	0
Top 33%	62	6	68	2
Top 66%	54	8	62	8
Top 100%	41	10	51	19

The NBD effects on maximum/minimum/average system E-GIC are listed in Table 4. The system E-GICs were reduced by from 6.1% for Top 20% Blocking to less than 20% with NBD on all 70 transformers in the initial 15-amps E-GIC List.

Table 4 NBD Effects on System E-GIC

XF (E-GIC>15A) w/NBD	Maximum System GIC		Minimum System GIC		Average System GIC	
	GIC	Reduction%	GIC	Reduction%	GIC	Reduction%
Base - 0%	3448	0	2977	0	3183	0
Top 20%	3238	6.1	2645	11.1	2988	6.1
Top 33%	3062	11.2	2608	12.4	2851	10.4
Top 66%	2874	16.6	2360	20.7	2640	17.1
Top 100%	2766	19.8	2410	19.0	2583	18.9

The maximum E-GIC of a transformer in the studied system for the NERC benchmark event is ~153 amps per phase; with Top 20% Blocking, the maximum E-GIC of a transformer in the system was reduced to ~100 amps. Increasing the number of transformers with NBDs cannot further reduce the maximum E-GIC of that transformer (Table 5).

Table 5 NBD Effects on Maximum Transformer E-GIC

XF (E-GIC>15A) w/NBD	Maximum GIC	Reduction%	XF Rank in Base Case List
Base - 0%	152.9	0	1
Top 20%	100.2	19.2	3
Top 33%	100.2	19.3	3
Top 66%	101.7	18.1	3
Top 100%	101.9	17.9	3

Table 6 lists the percentage of transformer with NBD verse the total transformer MVar loss when the system is at the maximum, minimum or average MVar loss. As shown in the table, the maximum total transformer MVar loss was reduced from 11.6% to 23.8% with the percentage of transformer with NBD increasing from top 20% to 100%. It is less effective for the storm direction when the total transformer MVar loss is at its minimum.

Table 6 NBD Effects on System Reactive Power Loss

XF (E-GIC>15A) w/NBD	Max. System MVar Loss		Min. System MVar Loss		Ave. System MVar Loss	
	MVar Loss	Reduction%	MVar Loss	Reduction%	MVar Loss	Reduction%
Base - 0%	4785	0	3533	0	4148	0
Top 20%	4228	11.6	3511	0.6	3787	8.7
Top 33%	4060	15.2	3390	4.0	3659	11.8
Top 66%	3777	21.1	3183	9.9	3428	17.4
Top 100%	3646	23.8	3150	10.8	3338	19.5

4. Conclusions and Future Studies

The concept of neutral blocking devices such as capacitors or low-ohmic resistors have been proposed by some researchers and a prototype was installed in a pilot project, but none of these device has been proved to be reliable to effectively mitigate the risk of GMD impact on the reliability of BPS.

The paper demonstrates that a GIC blocking device will block the GIC flow through the neutral of a transformer at a substation; however, the GIC flow will find its paths to other locations where transformer high-side winding is wye-grounded and electrically adjacent to the more active transformers that are now blocked, so GIC levels might increase in these neighboring transformers, particularly those that exhibit lower levels of GIC participation under the no blocking condition. Hence, the total system effective GIC does not decrease proportionally to the neutral GIC blocked. When the blocking device is added for an autotransformer, this primarily only reduces the GIC flow in the common winding and has limited impact on the series winding GIC flows, in fact, the GIC flow in the series winding might actually increase. Other potential risks associated with the blocking device, such as negative impact on the reliability of protection systems, maintenance and compliance risks of blocking device operated as Special Protection System are not within the scope of this paper.

Finally, it is recommended that sensitivity analysis is performed to evaluate other factors, such as grid ground resistance, network topological changes, etc., that have the most impact on the effective GIC redistribution and reactive power consumption. GMD Operation Procedures can be further refined based the sensitivity analysis.

BIBLIOGRAPHY

- [1] NERC Reliability Standards, TPL-007-1 – Transmission System Planned Performance for Geomagnetic Disturbance Events (Draft), June, 2014
- [2] FERC Final Rule Order 779, Reliability Standards for Geomagnetic Disturbances, Docket No. RM12-22-000, Issued May 16, 2013
- [3] NERC GMDTF, “2012 Special Reliability Assessment Interim Report: Effects of Geomagnetic Disturbances on the Bulk Power System,” February 2012
- [4] Q. Qiu, J. Fleeman, Geomagnetic Disturbance Impacts and AEP GIC/Harmonics Monitoring System, CIGRE, 2012 Grid of the Future Symposium, Kansas City, Missouri, October 2012
- [5] K. Shetye, T. Overbye, Q. Qiu, J. Fleeman, Geomagnetic Disturbance Modeling Results for the AEP System: A Case Study, presented at IEEE PES 2013 General Meeting, Vancouver, BC, Canada, July 2013
- [6] T. Overbye, K. Shetye, T. Hutchins, Q. Qiu, et al., Power Grid Sensitivity Analysis of Geomagnetically Induced Currents, IEEE Transactions on Power Systems, July 2013
- [7] J. Fleeman, Q. Qiu, and L. Anderson, Modeling, Monitoring and Mitigating Geomagnetically Induced Currents, accepted to 2013 CIGRE Grid of the Future Symposium, Boston, Massachusetts, October 20~22, 2013

- [8] Q. Qiu, D. Ball, et al, Effect of GIC and GIC Capability of EHV Power Transformers – A Case Study on an AEP 765 kV Power Transformer Design, presented at 2013 CIGRE Grid of the Future Symposium, Boston, Massachusetts, October 20~22, 2013
- [9] NERC, Benchmark GMD Event Description White Paper, June, 2014
- [10] K. Zheng, et. al., “Influence of System Characteristics on the Amplitudes of Geomagnetically Induced Currents,” Submitted to IEEE Trans on Power Delivery, March 2012.
- [11] NERC, Transformer Thermal Impact Assessment White Paper, June, 2014

