Network Applicability
Project 2013-03 (Geomagnetic Disturbance Mitigation)
EOP-010-1 (Geomagnetic Disturbance Operations)

Summary Determination

The purpose of EOP-010-1 (Geomagnetic Disturbance Operations) is to mitigate the reliability impacts of geomagnetic disturbance (GMD) events by implementing Operating Plans, Processes, and Procedures. The proposed standard is applicable to Reliability Coordinators and Transmission Operators with networks that contain power transformers with high side grounded wye windings above 200 kV. The drafting team concluded that this is the minimum network voltage for which a reliability benefit can be expected from the application of GMD Operating Procedures. This lower-bound threshold is consistent with operating experience and modeling guidance provided in the literature, as explained below.

Background

On May 16, 2013 FERC issued Order No. 779, directing NERC to develop Standards that address risks to reliability caused by geomagnetic disturbances in two stages:

- Stage 1 Standard(s) that require applicable entities to develop and implement Operating Procedures. Stage 1 Standard(s) must be filed by January 2014. An implementation period of six-months was recommended in the FERC Order.
- Stage 2 Standard(s) that require applicable entities to conduct assessments of the potential impact of benchmark GMD events on their systems. If the assessments identify potential impacts, the Standard(s) will require the applicable entity to develop and implement a plan to mitigate the risk of instability, uncontrolled separation, or Cascading. Stage 2 Standards must be filed by January 2015. A specific implementation period for Stage 2 was not addressed in Order 779.

EOP-010-1 is a new standard to specifically address the stage 1 directives in Order No. 779.

Justification

Because transmission line resistance decreases by a factor of 10 from 69 kV to 765 kV and lower voltage lines tend to be shorter (115 kV lines are typically less than 15 miles in length), the resulting geomagnetically-induced current (GIC) generated by lines rated less than 200 kV are significantly less than those of higher voltages and are typically ignored in GIC analysis. Conversely, using a voltage threshold higher than 200 kV, such as 345 kV, for a lower-bound threshold could potentially create a reliability gap by excluding a portion of the network that can be significantly affected by GMD. Results of sensitivity analysis conducted by the drafting team are presented in the appendix. It shows that the GIC contribution from the 230 kV portion of the network can result in system impacts during a GMD event.

Network Definition Considerations

Key parameters in the definition of a network for assessing GMD impacts are:
- Transformer grounding and core construction
  - Only wye-grounded power transformer windings provide a path for GIC
  - Transformer core construction (e.g., single-phase, three-phase, autotransformer) has an effect on the magnitude of var absorption and generated harmonics. Single-phase transformers are more susceptible to half-cycle saturation due to GIC relative to three-phase 3-leg units; however, the var absorption in 3-legged three-phase core units cannot be neglected.
  - Regardless of core construction, all grounded wye transformers have an effect in the distribution of GIC in the network
- System topology
- Geographical location
- Resistance values of the elements of the DC network used to evaluate GIC distribution within the network
  - Transmission line resistances per unit length increase as the voltage level decreases (see typical values in Table 1). (With the resistances shown in Table 1, the maximum neutral GIC contributed by a single 230 kV circuit is of the order of 30 A, as opposed to 75 A for a single 345 kV circuit.)

Selection of a network where the cut off is selected on the basis of wye-grounded power transformers with HV terminals > 200 kV

- Almost all peer-reviewed studies on the effects of GIC include networks > 200 kV [1-13].
- When lower voltage levels are included, the effects of including network elements < 200 kV are in most cases minimal [9]. (The Appendix shows an example of the effects of the inclusion/exclusion of the 115 kV network.)
- The absorption of reactive power in a saturated transformer depends on the system operating voltage and GIC. It does not depend on the nameplate rating of the transformer. In the case of single-phase power transformers, var absorption and harmonic generation are very insensitive to air-core reactance [11].

TABLE 1
TYPICAL NETWORK RESISTANCES FOR DIFFERENT VOLTAGE-LEVEL POWER GRIDS IN NORTH AMERICA

System Voltage Levels (kV)	DC Resistances of the Transformers (ohm)	Grounding Resistances of the Substations (ohm)	DC Resistances of the Transmission lines (ohm/km)
230	0.692	0.563	0.072
345	0.356	0.667	0.037
500	0.195	0.125	0.013
735	0.159	0.258	0.011

- Reactive power absorption of a saturated transformer is proportional to its HV voltage rating. Transformers < 200 kV have a relatively lower influence in the reactive power balance of the system (see Figure 1).
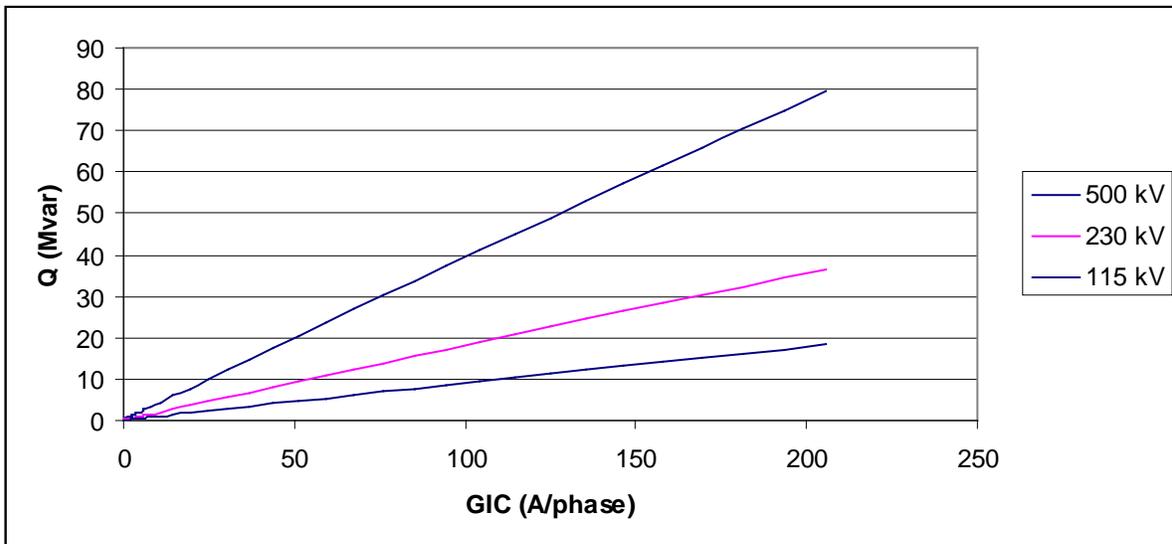

Figure 1: Reactive power absorption of a single-phase transformer vs. GIC

System Impact Considerations

A key element in a GMD event is the absorption of reactive power of high side wye-grounded transformers experiencing half-cycle saturation.

- In many jurisdictions bulk power transmission includes voltages > 200 kV. Tripping a transformer with high side voltage > 200 kV or reconfiguring > 200 kV circuits can impose serious constraints on operating limits; therefore, such operating scenarios must be considered in GMD impact studies.
- Generator step-up transformers are typically situated at electrical end points of the network where GIC tends to be highest. GSUs with high side voltages > 200 kV are not uncommon. On the other hand, GIC injected by circuits < 200 kV is limited because of the higher resistances of GSUs connected to < 200 kV networks
- Autotransformers are often used in networks above > 200 kV. The flow of GIC depends heavily on the relative resistances of various network elements and the geographical orientation of nearby transmission lines [14]. Considering a 500/230 kV autotransformer with one 500 kV and one 230 kV circuit, modelling GIC flow without taking into consideration the 230 kV circuit results in GIC overestimation between 20% and 30%. In a more complex configuration, the estimated GIC

ignoring the 230 kV circuits can over or underestimate GIC and the effects of GIC in transformers significantly. The appendix shows an example of this effect.

- From the point of view of GIC distribution in the network, transformer vulnerability is not a consideration. Including only transformers with high side windings > 300 kV would result in unrealistic GIC flow assessments (see Appendix)
- In systems where the bulk transmission voltages are 230 kV and 500 kV, neglecting circuits rated less than 300 kV would misrepresent GIC flows and var absorption, especially because GIC flow-through in 500 kV autotransformers would be neglected (see Appendix).

Appendix

This Appendix describes two examples where:
- The exclusion of 230 kV circuits at a station with 500/230 kV autotransformers cause significant errors in the estimation of GIC effects.
- The inclusion/exclusion of the 161 kV and 115 kV networks in a large utility within the Eastern Interconnect has minimal impact on the estimation of the effects of GIC in the system

Example 1: Exclusion of 230 kV circuits in a 500/230 kV transmission station

The distribution of GIC in a network, for a given geomagnetic latitude and earth structure, depends on a number of factors such as resistances of various circuit elements, induced voltages and network topology. There are times when a complex network topology can lead to non-intuitive results, such as the presence of a series capacitor causing an increase of GIC in a transformer.

To illustrate, consider the topology of the circuits connected to Transmission Station (TS) shown in Fig. A1. If a transmission circuit is sufficiently long it can be represented by a constant current source (since both induced voltage and line resistance are proportional to line length). In the case of a 500 kV circuit, GIC tends to be fairly constant for lengths > 150 km. A simplified representation is shown in Fig A2. The station has several autotransformers which have been lumped into a single equivalent autotransformer. The series capacitor bank is assumed to be out of service (bypassed).

Currents $I1$ and $I2$ represent the GIC contribution of the 500 kV circuits to the HV bus. Then,

$$I3 = I1 - I2 \qquad\qquad\qquad\qquad \text{(A.1)}$$

where $I3$ is the total contribution of the 500 kV circuits to the series winding. The total contribution to the common winding is given by

$$Ig = I3 + I4 + I5 + I6 - I7 \qquad\qquad\qquad\qquad \text{(A.2)}$$
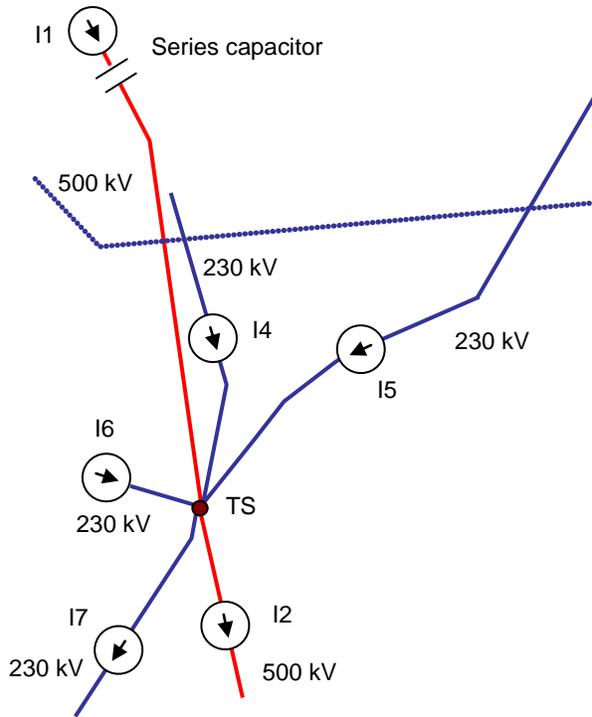
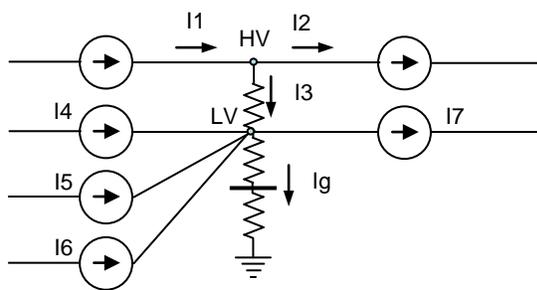Fig. A1: HV transmission lines connecting to Essa TS.

Fig. A2: Circuit representation of induced geoelectric fields and equivalent transformer representation.

Let us assume that the earth can be represented by a laterally-uniform earth model, and that the 500 kV circuits are in the same or similar orientation geographically with the same resistance per unit length, so that the injected GIC I1 and I2 are nearly identical (see Fig. A1). Then I3 will be small or zero and only the 230 kV circuits will contribute to the current in the transformer common winding Ig. If the 230 kV circuits were excluded, (i.e., I4 = I5 = I6 = I7 = 0) then I3 = Ig would be very small and the estimated effects of GIC on the autotransformer would be minimal.

If the 500 kV series capacitor bank in Fig. A1 is placed in service, then I1 = 0 and I2 = I3. The common-winding GIC is now equal to the sum of the GIC contributed by the 230 kV circuits and the remaining 500 kV circuit. Depending on the relative values of the contributions, the net GIC through the transformer may increase or decrease. Simulations show that in the network shown in Figure A1 when the series capacitors are in service, the effective GIC through the transformer increases by a factor of 30. This is not a general result, but rather a consequence of Kirchhoff's current law and a particular system topology.

If the series capacitor bank is in service and the 230 kV circuits are not taken into consideration all the GIC from the remaining 500 kV circuit would flow into the autotransformer and describe a completely different situation from in terms of the saturation of the autotransformer.

The cases described above were simulated with a GIC analysis tool and summarized in Table A1. Note that there are two 500/230 kV autotransformers in service in this simulation.

Table A1: Summary of the Effects of 230 kV Circuits in a Station with Two 500/230 kV Autotransformers				
Geoelectric field 5 V/km	230 kV and 500 kV 500 kV Series caps in service	230 kV and 500 kV 500 kV Series caps bypassed	No 230 kV 500 kV Series caps in service	No 230 kV 500 kV Series caps bypassed
Transformer GIC/phase (A/phase)	99.9	2.8	127	5.5
I1 (A/phase)	0	365	0	338
I2 (A/phase)	146.8	334	254	349
Incremental metallic hot spot temperature (C°)	89	1.6	60	7.6
var absorption (Mvar)	128	14	151	12.5
THD (%)	17	2.5	18	2.2

The conclusion from this example is that it is not always possible to make generalizations in a network of relatively complex topology.   While it is true that a series capacitor blocks GIC in the transmission line

where it is employed, it does not necessarily reduce GIC in system transformers. Furthermore, not taking into account the effects of the 230 kV circuits in this network would lead to inaccurate conclusions, such as a 33% underestimation of the hot spot temperature rise[1].

Example 2: Effects of the inclusion/exclusion of circuits below 200 kV

A portion of the Eastern Interconnect that contains 500 kV, 230 kV, 161 kV, and 115 kV facilities was modeled using PowerWorld software. When the GIC contribution of the 161 kV and 115 kV circuits was excluded, the effects on the network above 200 kV where found to be minimal. Table A2 summarizes the effects of including/excluding GIC contributions from the 161 kV and 115 kV network assuming a 5 V/km East-West geoelectric field. The differences in the results assuming a North-South geoelectric field are very similar, and are not reproduced in here.

Table A2: GIC Effects on the Network Above 200 kV Assuming an East-West 5 V/km Geoelectric Field			
	Including 115 kV	Excluding 115 kV	Difference
Maximum transformer GIC (A/phase)	134.65	133.78	0.6 (%)
Average transformer GIC (A/phase)	13.79	13.46	2.4 (%)
Maximum transformer var absorption (Mvar)	150.3	149.5	0.7 (%)
Average transformer var absorption (Mvar)	7.16	7.08	1.1 (%)
Minimum bus voltage (pu)	0.98204	0.98548	0.4 (%)
Average bus voltage (pu)	1.01858	1.01897	0.04 (%)
Total system var loss due to GIC (Mvar)	3,935	3,801	3.4 (%)

These results are consistent with observations made in peer-reviewed technical publications such as [9].

---

[1] Hot spot heating was estimated using the methodology described in [15]

References

[1] Boteler, D., Bui-Van, Q., & Lemay, J. (1994). Directional sensitivity to geomagnetically induced currents of the Hydro-Quebec 735 kV power system. *Power Delivery, IEEE Transactions on, 9*(4), 1963-1971.

[2] Boteler, D., Watanabe, T., Shier, R., & Horita, R. (1982). Characteristics of Geomagnetically Induced Currents in the B. C. Hydro 500 kV System. *Power Apparatus and Systems, IEEE Transactions on, PAS-101*(6), 1447-1456.

[3] Mäkinen, T. (1992). *Geomagnetically induced currents in the Finnish power transmission system.* Helsinki, Finland: Finnish Meteorological Institute.

[4] Mohan, N., Albertson, V., Speak, T., Kappenman, K., & Bahrman, M. (1982). Effects of Geomagnetically-Induced Currents on HVDC Converter Operation. *Power Apparatus and Systems, IEEE Transactions on, PAS-101*(11), 4413-4418.

[5] Picher, P., Bolduc, L., Dutil, A., & Pham, V. (1997). Study of the acceptable DC current limit in core-form power transformers. *IEEE Transactions on Power Delivery, Vol 12, No1*, 257-265.

[6] Pirjola, R. (2000). Geomagnetically induced currents during magnetic storms. *Plasma Science, IEEE Transactions on, 28*(6), 1867-1873.

[7] Pirjola, R., & Boteler, D. (2006). Geomagnetically Induced Currents in European High-Voltage Power Systems. *Electrical and Computer Engineering, 2006. CCECE '06. Canadian Conference on* (pp. 1263-1266). Ottawa, Canada: IEEE.

[8] Pirjola, R., Liu, C.-m., & Liu, L.-g. (2010). Geomagnetically Induced Currents in electric power transmission networks at different latitudes. *Electromagnetic Compatibility (APEMC), 2010 Asia-Pacific Symposium on* (pp. 699-702). Beijing, China: IEEE.

[9] Prabhakara, F., Hannett, L., Ringlee, R., & Ponder, J. (1992). Geomagnetic effects modelling for the PJM interconnection system. II. Geomagnetically induced current study results. *Power Systems, IEEE Transactions on, 7*(2), 565-571.

[10] Viljanen, A., Pirjola, R., Wik, M., Adam, A., Pracser, E., Sakharov, Y., et al. (2012). Continental scale modelling of geomagnetically induced currents. *J. Space Weather Space Clim., 3*, A171-A1711.

[11] Walling, R., & Khan, A. (1991). Characteristics of transformer exciting-current during geomagnetic disturbances. *Power Delivery, IEEE Transactions on, 6*(4), 1707-1714.

[12] Viljanen, A., & Pirjola, R. (1994). Geomagnetically Induced Currents in the Finnish High-Voltage Power System: A Geophysical Review. Netherlands: *Surveys in Geophysics,* 15, 383-408.

[13] Wik, M., Viljanen, A., Pirjola, R., Pulkkinen, A., Wintoft, P., & Lundstedt, H. (2008). Calculation of Geomagnetically Induced Currents in the 400 kV Power Grid in Southern Sweden. *Space Weather, Vol. 6*, S07005, 1-11.

[14] Overbye, T. J., et al, "Power Grid Sensitivity Analysis of Geomagnetically Induced Currents", IEEE Transactions on Power Delivery, 2013, Accepted for inclusion in a future issue, Digital Object Identifier 10.1109/TPWRS.2013.2274624.

[15] Marti, L., Rezaei-Zare, A., Narang, A. , "Simulation of Transformer Hotspot Heating due to Geomagnetically Induced Currents," IEEE Transactions on Power Delivery, vol.28, no.1, pp.320-327, Jan. 2013