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Description of document:	Unpublished Bonneville Power Administration (BPA) records concerning threats to the electric grid system from solar electromagnetic storm activity, 2015-2016
Requested date:	November 2016
Released date:	03-January-2017
Posted date:	16-January-2017
Source of document:	Freedom of Information Act request FOIA/Privacy Act Officer Mail Stop DK CGI-7 Bonneville Power Administration PO Box 3621 Portland, OR 97208 Online FOIA Request Form

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Department of Energy

Bonneville Power Administration
P.O. Box 3621
Portland, Oregon 97208-3621

FREEDOM OF INFORMATION ACT/PRIVACY PROGRAM

January 3, 2017

In reply refer to: FOIA #BPA-2017-00212-F

This communication serves as the Bonneville Power Administration's (BPA) response to your request for agency records made under the Freedom of Information Act, 5 U.S.C. § 552 (FOIA). Your records request was received in this office on November 20, 2016 and acknowledged on December 8, 2016.

Request

"...any unpublished BPA reports or memoranda concerning threats to the electric grid system from solar electromagnetic storm activity such as a Carrington Event type phenomenon, and/or any steps being taken by BPA to address this potential problem."

Response

In accord with the FOIA requirements and practices, BPA has conducted electronic searches of records associated with the following agency offices:

Transmission Service Planning
Operations Support
Technology Innovation
Trans Infrastructure Development Planning
Transmission Project Mgmt.
Operations Control
Substation Engineering
System Operations
National Relations
Org. Delivery & Performance

A total of 97 pages of agency records responsive to your request were located; these records were previously posted on BPA's FOIA web portal at this Internet location: https://www.bpa.gov/news/FOIA/library/Pages/2016-FOIA.aspx

You will find the records at this location in the following on-line index: BPA-2016-00637-F - Meyer - BPA records re significant impacts on the grid from EMP/GMD/GIC - FOIA Release in Full.

In addition, BPA's Transmission Operations Support (TOO) organization offers the following information and Internet links, which you may find useful:

> BPA has an operating plan for GMDs, which includes how to receive advanced warning from the Space Weather Prediction Center (see www.swpc.noaa.gov), and BPA monitors Geomagnetically-Induced Currents (GIC) at more than a dozen locations. The public has access to the last four days of GIC data at: http://transmission.bpa.gov/Business/Operations/gic/gic.aspx.
>
> A previous BPA Officer, Mr. Earl Gjelde, served on the Commission for the April, 2008 "Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack". http://www.empcommission.org/docs/A2473-EMP_Commission-7MB.pdf

In accord with the FOIA, BPA is herein providing you with 97 pages of previously released responsive agency records. Your FOIA request BPA-2017-00212-F is closed with all available agency records provided. Pursuant to 10 C.F.R. § 1004.7(b)(2), I am the individual responsible for the determinations described above.

FOIA Fee

There are no FOIA fees applicable to the fulfillment of your request for BPA records.

FOIA Appeal

This decision, as well as the adequacy of the search, may be appealed within 90 calendar days from your receipt of this letter pursuant to 10 C.F.R. § 1004.8. Appeals should be addressed to:

Director, Office of Hearings and Appeals,
HG-1, L'Enfant Plaza
U.S. Department of Energy
1000 Independence Avenue, S.W.
Washington, D.C. 20585-1615

The written appeal, including the envelope, must clearly indicate that a FOIA appeal is being made. You may also submit your appeal to OHA.filings@hq.doe.gov, including the phrase "Freedom of Information Appeal" in the subject line. The appeal must contain all of the elements required by 10 C.F.R. § 1004.8, including a copy of the determination letter. Thereafter, judicial review will be available to you in the Federal District Court either: 1) in the

district where you reside; 2) where you have your principal place of business; 3) where DOE's records are situated; or 4) in the District of Columbia.

You may also contact BPA's FOIA Public Liaison, Sarah Westenberg, at the address on this letter header for any further assistance and to discuss any aspect of your request. Additionally, you may contact the Office of Government Information Services (OGIS) at the National Archives and Records Administration to inquire about the FOIA mediation services they offer. The contact information for OGIS is as follows:

Office of Government Information Services
National Archives and Records Administration
8601 Adelphi Road-OGIS
College Park, Maryland 20740-6001
E-mail:ogis@nara.gov
Phone: 202-741-5770; Toll-free: 1-877-684-6448; Fax: 202-741-5769

If you have questions about this communication, you may contact James King (CorSource Technology Group, Inc.), assigned to the BPA FOIA office, at 503-230-7621.

Sincerely,

C. M. Frost
Freedom of Information/Privacy Act Officer

Responsive Records Provided via Internet Links

BONNEVILLE POWER ADMINISTRATION
SYSTEM DISPATCHERS'
STANDING ORDER NO. 350

Mitigating the Effects of Geomagnetic Disturbances

Approved: *Chris Sanford* — *July 15, 2015*
Dittmer Dispatch Process Manager — Date

I. Purpose

Related Standing Orders - No. 135 was superseded by DSO 350
Related Standard: EOP-010-1, Geomagnetic Disturbance Operations

The purpose of this Dispatchers' Standing Order (DSO) is to provide operational procedures to identify and mitigate the effects of Geomagnetic Disturbances (GMDs) and the resulting Geomagnetically Induced Currents (GICs) on BPA's electric system.

II. Procedure

A. Normal Operating Procedure: The GIC monitor display on SCADA (at Overviews\Geo Mag Current, see Attachment 5) shows GIC currents at selected transformers, along with other background information about the monitors. GIC monitors will alarm when current exceeds 20 A for greater than 20 seconds

B. Contingency Operations Section
   1. **GIC Alarm:**
      a. Determine the validity of the alarm by trending the alarmed GIC reading over the last 20 minutes. Fluctuations or increases in current are indicative of GIC activity. A momentary spike in current is indicative of some other type of problem.
      b. Check for current space weather alerts from one of the following sources:
         1.) WECCnet from Peak Reliability, the Reliability Coordinator (RC)
         2.) http://www.swpc.noaa.gov
      c. Monitor that transformer for abnormal temperature rise that is inconsistent with loading or ambient temperature.
      d. Note locations reported to have abnormal transformer noise or vibration.
      e. Log the conditions.

2. **GMD K-index of 7 or greater**: Upon receiving notification from the RC of a GMD with a K-index of 7 or greater, the BPA Dispatchers at both Dittmer and Munro Control Centers will make an entry in the Dispatch Log. See Attachments 1, 2 and 3 for examples of RC notifications.

   The Dispatch Log Entry should include:
   a. The K-index as reported
   b. The anticipated duration of the GMD
   c. A request that unusual operating conditions attributed to the GMD be reported to the RC.

      NOTE: Examples of problems that may be detected during a GMD:
      - Real and Reactive power swings
      - Frequency excursions or voltage fluctuations
      - Tripping of capacitor banks by neutral ground current
      - Communication system problems
      - Unusual Noises and heating in transformers.
      - Elevated neutral currents in transformers
      - Oscillograph or Digital Fault Recorder (DFR) operations
      - Harmonic currents

3. **GMD K-index of 8 or greater.** Upon receiving notification from the RC of a GMD with a K-index of 8 or greater, the Dispatcher will evaluate the situation and implement the following actions as appropriate for the power system.
   a. Declare a Restricted Maintenance Operation (RMO; see DSO 150) for shunt and series capacitors, and static var compensators.
   b. Delay planned outages of 500 kV lines and 500 kV transformers until the K-index goes below 7 as per a WECCnet from RC.
   c. Turn Reactive Reserve zeroing off (go to Overviews\Reactive\Reactive Reserve, select the "Details" button for COI/PDCI Support, and select the "Turn Zeroing OFF" button).
   d. Log actions

4. **Extreme GMD - K index of 9**.
   Note that at this level, while strong, the K index of 9 can vary from relatively moderate impacts to voltage collapse or long term equipment damage.
   a. Continue or implement practices for a K-index of 8 or greater
   b. Reduce or curtail transfers across the BPA grid that do not directly feed BPA Balancing Authority load.
   c. Add as much reactive support as possible that can be absorbed
   d. If the GIC of any transformer bank 345 kV or above exceeds 90 Amps, give strong consideration to isolating the bank.

5. **Restoring the system to normal** Begin the process of returning the system to the pre-event status once a WECCnet is received from the RC declaring that the conditions for the alert no longer exist.

III. Background Information

A. The National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center (SWPC) issues space weather alerts using scales for three types of space weather: Solar Radiation Storms, Radio Blackouts and Geomagnetic Storms. (See Attachment 4) Solar Radiation Storms can arrive in as little as 10 minutes, and can affect persons in high altitude aircraft, as well as astronauts. Radio blackouts, also called X-ray emissions, can arrive in as little as 8 minutes, and can affect high frequency radio communications and low frequency navigation signals on the day side of the earth. Geomagnetic Storms take 14 hours to 4 days to arrive from the sun, can last for a day or two, and can affect power systems, spacecraft operations, and satellite navigation.

B. The two major potential effects on power systems are:
   1. Induced DC currents in transformers, resulting in excessive heating and VAR consumption.
   2. Loss of reactive power support, which could lead to voltage instability and power system collapse

C. Modeling the effects of GMD on power systems is still being developed, and the power industry is still working on the best way to mitigate the effects of GMDs on transformers. However, a major GMD event could occur at any time, and FERC issued a Notice of Proposed Rulemaking in 2013, requiring that operators of the bulk power system develop operating procedures to mitigate the effects of GMDs.

D. The locations of the GIC monitors and the GIC currents are displayed on SCADA/IPS screen Overviews\Geo Mag Current. The display, based on the information in Attachment 5, also shows the Geomagnetic latitude, because the WECC NOAA GMD Report (see Attachment 1) includes a statement in the "Potential Impacts" section about where the impacts are located. Geomagnetic latitude is different than geographic latitude, in that it depends on the location of the earth's magnetic pole. For example, the northeast corner of Washington is 49 degrees geographic latitude but is 55 degrees geomagnetic latitude.

VI. History

July 8, 2014: The purpose of this Dispatchers' Standing Order (DSO) is to mitigate the effects of Geomagnetic Disturbances (GMDs) and the resulting Geomagnetically Induced Currents (GICs) on BPA's electric system. This DSO supersedes DSO 135, Notification Procedure for Geomagnetic Storm Warnings, which was cancelled with the distribution of DSO 350.

July 15, 2015: Reviewed and added new attachments for a Peak RC GMD Warning, Alert, and Alert Cancellation (*D. Goodrich*).

Technical Approval: *John Anasis* John G. Anasis — *July 15, 2015*
Technical Operations Process Manager — Date

SRenne:smr:2912:07/15/15: (DFTP01)Z:\DSO's Official\300 series\DSO350.doc

BPA1

From: PEAK1
Sent: Tuesday, March 17, 2015 5:38 AM
To: ALL WECC
Subject: GMD WARNING: K-index of 7 (G3)

SWPC GMD WARNING K7 (G3)

SWPC Message Code: WARK07

Issue Time: 03/17/15 at 0616 MST

WARNING: Geomagnetic K-index of 7 or greater expected

Valid From: 2015 MAR 17 0615 MST

Valid To: 2015 MAR 17 1300 MST

Warning Condition: Onset

Potential Impacts: Primarily poleward of 50 degrees Geomagnetic Latitude

Induced Current Effects: Power system voltage irregularities possible, false alarms may be triggered on some protection devices.

Please report all unusual operating conditions in real-time attributed to the GMD to Peak RC (voltage fluctuations, communication system disruptions, etc.).

PEAKRELIABILITY

Area A	Area B	Area C
360.713.9097	970.776.5747	360.713.9093

BPA1

From: PEAK1
Sent: Tuesday, March 17, 2015 1:46 PM
To: ALL WECC
Subject: GMD ALERT: K-index of 7

SWPC GMD ALERT K7 (G3)

SWPC Message Code: ALTK07

Issue Time: 3/17/15 at 1334 PDT

ALERT: Geomagnetic K-index of 7

Active Warning: Yes

Threshold Reached: 2015 March 17 1330 PDT

Potential Impacts: Primarily poleward of 50 degrees Geomagnetic Latitude

Comments: Space Weather Operations (SWO) observed a K7 GMD at 1330 PDT.

PEAKRELIABILITY

Area A	Area B	Area C
360.713.9097	970.776.5747	360.713.9093

BPA1

From:	PEAK1
Sent:	Wednesday, March 18, 2015 1:19 AM
To:	ALL WECC
Subject:	EXPIRED: GMD (WARNING/WATCH/ALERT): K-index of 7 (G3)

SWPC GMD (WARNING/WATCH/ALERT) HAS EXPIRED

The Geomagnetic Disturbance (GMD) of K-index 7 and G-3 warning posted on WECCnet on 3/17 at 0521 PDT terminated at 0600 UTC 3/18(3/17 2300 PDT). PeakRC will continue to monitor and post any changes in GMD status.

The latest Alert of K-index 6 and G-2 was posted at 0119 UTC(1819 PDT).

PEAKRELIABILITY

Area A	Area B	Area C
360.713.9097	970.776.5747	360.713.9093

NOAA Space Weather Scales

Category		Effect	Physical measure	Average Frequency (1 cycle = 11 years)
Scale	Descriptor	Duration of event will influence severity of effects		
Geomagnetic Storms			Kp values* determined every 3 hours	Number of storm events when Kp level was met; (number of storm days)
G 5	Extreme	Power systems: widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. Spacecraft operations: may experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. Other systems: pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).**	Kp=9	4 per cycle (4 days per cycle)
G 4	Severe	Power systems: possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. Spacecraft operations: may experience surface charging and tracking problems, corrections may be needed for orientation problems. Other systems: induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.).**	Kp=8	100 per cycle (60 days per cycle)
G 3	Strong	Power systems: voltage corrections may be required, false alarms triggered on some protection devices. Spacecraft operations: surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. Other systems: intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.).**	Kp=7	200 per cycle (130 days per cycle)
G 2	Moderate	Power systems: high-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. Spacecraft operations: corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. Other systems: HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.).**	Kp=6	600 per cycle (360 days per cycle)
G 1	Minor	Power systems: weak power grid fluctuations can occur. Spacecraft operations: minor impact on satellite operations possible. Other systems: migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine).**	Kp=5	1700 per cycle (900 days per cycle)

* Based on this measure, but other physical measures are also considered.

** For specific locations around the globe, use geomagnetic latitude to determine likely sightings (see www.swpc.noaa.gov/Aurora)

Solar Radiation Storms			Flux level of ≥ 10 MeV particles (ions)*	Number of events when flux level was met**
S 5	Extreme	Biological: unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. *** Satellite operations: satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. Other systems: complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^5	Fewer than 1 per cycle
S 4	Severe	Biological: unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** Satellite operations: may experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. Other systems: blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle
S 3	Strong	Biological: radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** Satellite operations: single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. Other systems: degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
S 2	Moderate	Biological: passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk.*** Satellite operations: infrequent single-event upsets possible. Other systems: effects on HF propagation through the polar regions, and navigation at polar cap locations possibly affected.	10^2	25 per cycle
S1	Minor	Biological: none. Satellite operations: none. Other systems: minor impacts on HF radio in the polar regions.	10	50 per cycle

* Flux levels are 5 minute averages. Flux in particles·s^{-1}·$ster^{-1}$·cm^{-2} Based on this measure, but other physical measures are also considered.
** These events can last more than one day.
*** High energy particle (>100 MeV) are a better indicator of radiation risk to passenger and crews. Pregnant women are particularly susceptible.

Radio Blackouts			GOES X-ray peak brightness by class and by flux*	Number of events when flux level was met; (number of storm days)
R 5	Extreme	HF Radio: Complete HF (high frequency**) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. This results in no HF radio contact with mariners and en route aviators in this sector. Navigation: Low-frequency navigation signals used by maritime and general aviation systems experience outages on the sunlit side of the Earth for many hours, causing loss in positioning. Increased satellite navigation errors in positioning for several hours on the sunlit side of Earth, which may spread into the night side.	X20 ($2x10^{-3}$)	Fewer than 1 per cycle
R 4	Severe	HF Radio: HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time. Navigation: Outages of low-frequency navigation signals cause increased error in positioning for one to two hours. Minor disruptions of satellite navigation possible on the sunlit side of Earth.	X10 (10^{-3})	8 per cycle (8 days per cycle)
R 3	Strong	HF Radio: Wide area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth. Navigation: Low-frequency navigation signals degraded for about an hour.	X1 (10^{-4})	175 per cycle (140 days per cycle)
R 2	Moderate	HF Radio: Limited blackout of HF radio communication on sunlit side of the Earth, loss of radio contact for tens of minutes. Navigation: Degradation of low-frequency navigation signals for tens of minutes.	M5 ($5x10^{-5}$)	350 per cycle (300 days per cycle)
R 1	Minor	HF Radio: Weak or minor degradation of HF radio communication on sunlit side of the Earth, occasional loss of radio contact. Navigation: Low-frequency navigation signals degraded for brief intervals.	M1 (10^{-5})	2000 per cycle (950 days per cycle)

* Flux, measured in the 0.1-0.8 nm range, in $W \cdot m^{-2}$. Based on this measure, but other physical measures are also considered.

** Other frequencies may also be affected by these conditions.

This information is dated April 7, 2011 from the NOAA Space Weather Scales site located at http://www.swpc.noaa.gov/NOAAscales/.

Screenshot of the GIC display

10:08:14
02-Jul-2014

Geomagnetically Induced Current (GIC)

DSO 350

STATION	INDUCED CURRENT/AMP	GEOMAGNETIC LATITUDE *
ALVEY	** 1.20	50
BELL	0.10	54
BIG_EDDY	** 5.30	51
HATWAI	** 0.10	53
HOT_SPRG	** 7.80	54
KEELER	** 62.30	51
MONROE	** 1.10	54
PEARL	** 153.70	51
ROSS	** 6.80	51
SACAJWEA	-0.20	52
SICKLER	** 0.00	53
SNO_KING	** 0.00	53
	** 0.00	53
	** 0.00	53
	** 0.00	53
TILLAMOK	0.00	51
VANTAGE	0.00	53
	-0.20	53

* Approximate Geomagnetic latitude based on Space Weather web site: http://www.swpc.noaa.gov/Aurora/globeNW.html
** Older bank induced currents that are less accurate, for information only and will not alarm

BPA GMD Impact Assessment
TIP 264 GIC R&D

Author:	PowerWorld Corporation Scott Dahman
Client:	Bonneville Power Administration
Date:	August 26, 2013
Revised:	September 30, 2013

Purpose

The study seeks to characterize the impact of geomagnetic disturbances (GMD) on the BPA high voltage transmission grid. The focus is on transmission line and transformer geomagnetic-induced currents (GIC), GIC reactive power losses due to transformer half-cycle saturation, and the resulting AC voltage profile of the power system. Several options for mitigating GIC flow, reactive power losses, and AC voltage drop are also examined.

Study Methodology

This study incorporates models of the physical operation of the Western Interconnect power grid (WECC) under summer 2013 peak conditions, with different transfer levels on the Summer Lake-Hemingway (HMSL) interface. One model features 550 MW from Summer Lake to Hemingway (HMSL +550) and the other features 400 MW of flow from Hemingway to Summer Lake (HMSL -400).

A set of baseline GIC calculations and power flow simulations are performed, using PowerWorld Simulator GIC software. Network mitigation measures, including opening transmission lines and installing transformer capacitive neutral blocking, are considered in the next study phase.

Uniform Field Scenarios

The uniform field scenarios assume electric fields of 1 volt/km at orientations varying from south-north (zero degrees) and at 15 degree increments through 165 degrees as illustrated in Figure 1.

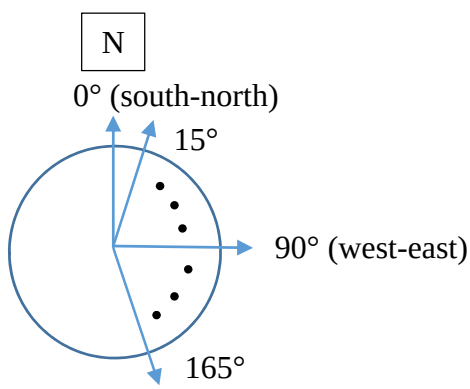


Figure 1 - Electric Field Orientation

Electric fields of identical magnitude separated by 180 degrees have identical effects, except the sign of the GICs is reversed. Thus it is only necessary to simulate half of the spectrum of field orientations. The quasi-DC GIC quantities scale linearly with field strength, so a 2 volt/km field would produce twice the GIC and transformer reactive power losses as a 1 volt/km field.

Full power flow simulation is also performed under each GMD storm scenario to quantify the extent of transformer reactive power losses, voltage drop, and risk of large-scale voltage

collapse. Geomagnetic-induced current (GIC) is calculated for the BPA network, and the control areas that comprise BPA's first-tier neighbors (areas with at least one tie-line connection to a BPA area). The uniform field strength that causes operating voltage limit violations and large scale voltage collapse is also identified for each field orientation.

GIC Network Modeling

Quasi-DC GICs flow through circuits formed by grounded transformer coils, transmission lines, and the earth. The effects are modeled as DC voltage sources in transmission lines as illustrated in Figure 2 with a simple example with two generators connected to a common transmission line through step-up transformers.

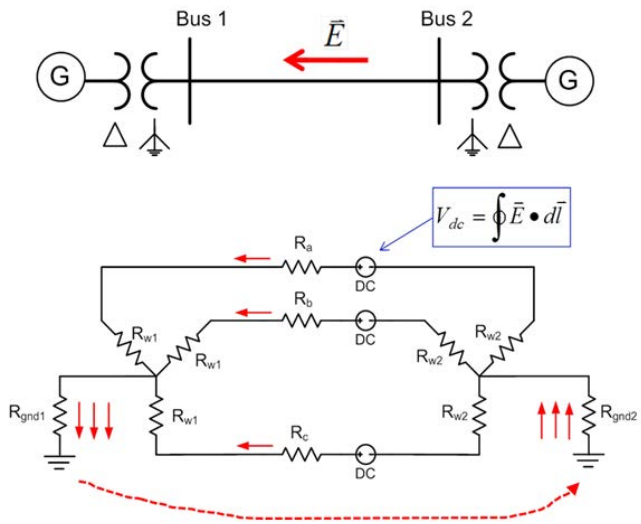


Figure 2 - Simple GIC Flow in a Two Generator Example

For purposes of this study, GIC equivalent DC voltage sources are modeled in transmission lines at operated at nominal voltages of 115 kV and above, in areas in which contain at least one transformer identified as BPA-owned in the FERC 715 power flow models, and in neighboring areas that have a connection to the zones within these areas and zones to which such BPA-owned transformers belong. The areas that contain BPA-owned transformers are shown in Table 1. Transformer GIC reactive power losses are also modeled in these areas.

Table 1 – Areas with BPA-owned Transformers at 115 kV and above

FERC 715 Name	FERC 715 Number
Northwest	40
Idaho	60
PACE	65

First-tier neighboring areas with high-voltage connections to the areas and zones that contain BPA-owned transformers are shown in Table 2.

Table 2 – First-Tier Neighboring Areas

FERC 715 Name	FERC 715 Number
PG and E	30
B.C. Hydro	50
Montana	62
Sierra	64

GIC equivalent DC voltage sources are modeled in transmission lines at operated at nominal voltages of 115 kV and above in these areas to capture the effect of GIC currents flowing into the BPA network from neighbors. Transformer GIC Mvar losses are not considered in these external areas. The study thus focuses on AC voltage issues only within the BPA system.

The study footprint is shown graphically in Figure 3, with the emphasized transmission representing the areas and zones containing BPA transformers at 115 kV and above. This includes all of area 40 and zones within areas 60 and 65 that contain such transformers. The arrows depict GIC flow through the transmission network during a 1 V/km, 0 degree uniform field GIC event.

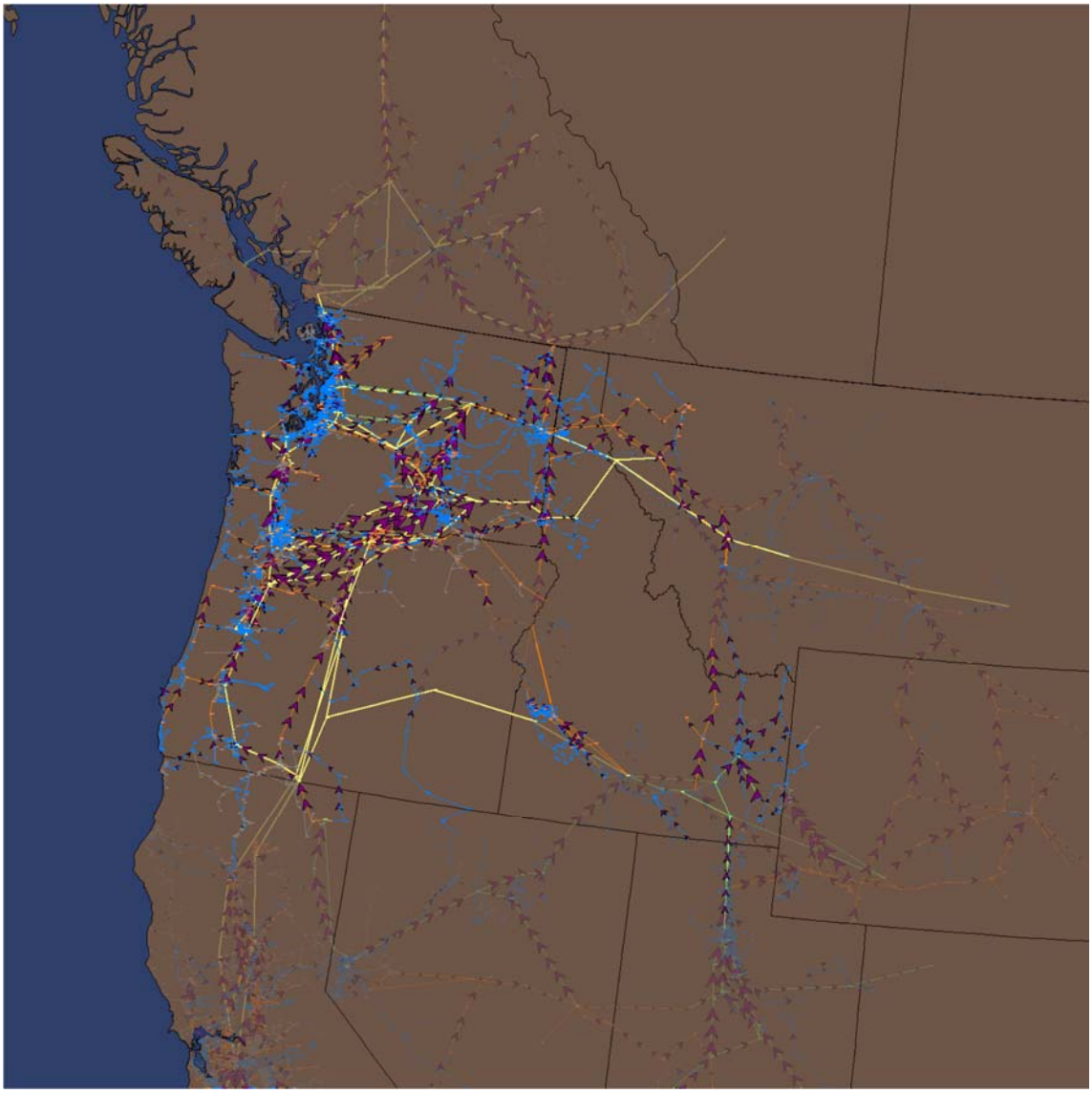


Figure 3 - Study System

Transformer Modeling

Key transformer parameters for GIC modeling include grounding configuration, coil resistance, whether the transformer is an autotransformer, and core type. PowerWorld requested these transformer parameters, as well as substation grounding resistance, from BPA and several foreign utilities. Data were provided by Avista Corporation, Chelan PUD, Clark PUD, Cowlitz PUD, Douglas PUD, Eugene Water and Electric Board, Idaho Power Company, PacifiCorp, Portland General Electric, Puget Sound Energy, Seattle City Light, Snohomish PUD, Tacoma Power, and the US Army Corps of Engineers, in addition to BPA.

There are a total of 842 transformers in the study footprint with primary voltages of 115 kV and above. Known parameter coverage rates are shown in Table 3.

Table 3 - Coverage Rates of Known Transformer Parameters, Primary Voltage of 115 kV and above (842 units total)

Parameter	Number of Units
Grounding Configuration	545 (65%)
Coil Resistance	249 (30%)
Is an Autotransformer?	557 (66%)
Core Type	289 (34%)

PowerWorld Simulator software applies a set of assumptions as follows to transformers when owner-provided data is not available:

1. Configuration: All windings are assumed to be either delta or grounded wye. If the high voltage side is greater than 100 kV and the low voltage is less than 100 kV, it is assumed the high side is grounded wye and the low side is delta. GSUs are generally subsets of this class, where the generator is connected to the low side, which is assumed delta. If the high and low voltage sides are both less than or both greater than 100 kV, both sides are assumed to be grounded wye.
2. Coil resistance is derived from the positive-sequence AC per-unit series resistance in the power flow model. The value in the power flow model contains the total series resistance for both high and low voltage windings. Simulator estimates the split between each winding as:

$$\frac{R_{pu}}{R_{Base,HighSide}} = R_{HighSide} + a_t^2 R_{LowSide} \quad (1)$$

$$R_{HighSide} = a_t^2 R_{LowSide} \quad (2)$$

3. Units are assumed to be autotransformers if all of the following criteria are met:
    a. the unit is not a phase-shifting transformer,
    b. the high side and low side are at different nominal voltages,
    c. the high side nominal voltage is at least 100 kV, and
    d. the turns ratio is less than or equal to 4.

4. K-Factor: The K-Factor relates the transformer's effective GIC current to its reactive power losses caused by GIC half-cycle saturation at nominal voltage (1.0 pu). [1] The total three-phase GIC reactive power loss, or Q_{Loss}, is computed as:

$$Q_{Loss} = V_{pu} K \left(\frac{V_{NomkV}}{500kV}\right) I_{GIC} \qquad (3)$$

where I_{GIC} is per-phase effective GIC amps. (500 kV is the assumed K-Factor base in PowerWorld Simulator software.) I_{GIC} is computed from the current flowing in the primary and secondary windings as:

$$I_{GIC} = \left| \frac{a_t I_H + I_L}{a_t} \right| \qquad (4)$$

where a_i is the turns ratio, I_H is the primary (high-side) per-phase current and I_L is the secondary (medium-side in a 3-winding transformer) per-phase current.

Simulator applies the K-Factor assumptions shown in Table 4 to compute GIC Mvar losses from GIC effective current.

Table 4 - PowerWorld Simulator K-Factor Assumptions

Core Type	Primary (Highest) Voltage	K-Factor for 500 kV Primary
Single Phase (3 separate cores)	All	1.10
Three Phase, Shell Form	All	0.82
Three Phase, Core Form Generic	All	0.50
Three Phase, 3-Legged	All	0.29
Three Phase, 5-Legged	All	0.66
Three Phase, 7-Legged	All	0.66
Unknown (not owner-specified)	>400	1.10
Unknown (not owner-specified)	<=400	0.60

GIC Mvar Losses are modeled only in BPA control areas (identified in Table 1).

[1] T. J. Overbye, T. R. Hutchins, K. Shetye, J. Weber, S. Dahman, "Integration of Geomagnetic Disturbance Modeling into the Power Flow: A Methodology for Large-Scale System Studies", *IEEE North American Power Symposium*, September 9-11, 2012.

Substation Modeling

Key substation parameters are geographic coordinates and grounding resistance. PowerWorld maintains a database of substation geographic coordinates which are applied to the study footprint. The grounding resistance is defined as the resistance, in ohms, between the substation neutral and earth ground. The best method of determining grounding resistance is from an actual measurement, such as taken during a fall of potential test. There are a total of 398 substations in the study area with at least one transformer with a primary of 115 kV or above. BPA and foreign utilities provided grounding resistance for 148 substations, or 37% of these. Simulator software applies an assumed grounding resistance to substations for which no data is provided, based on the size of the substation. The values assigned range from 0.1Ω to 2.0Ω. Substations with more buses and higher nominal voltages are assumed to have lower values.

Study Limitations

The analytic methods used in this study are highly dependent and sensitive to the transmission models and transformer and substation parameter inputs collected for the study. In particular, recent research has shown that substation grounding resistance has a significant impact on GIC network modeling and that estimated substation grounding resistance is subject to a significant standard error.[2] Furthermore, the characteristics of transformer half-cycle saturation characteristics are not well understood and are also the subject of ongoing research.

[2] U. Bui, T. J. Overbye, K. Shetye, H. Zhu, J. Weber, "Geomagnetically Induced Current Sensitivity to Assumed Substation Grounding Resistance", submitted for *IEEE North American Power Symposium*, Sept 22-24 2013.

Uniform Field Modeling Results

Uniform field simulations were performed across all orientations and for both the HMSL -400 and HMSL 500 transfer levels. Table 5 shows the total GIC transformer neutral current and GIC Mvar losses for each orientation at 1 V/km. All quantities are 3-phase, for transformers in the study footprint with high side nominal voltages of at least 115 kV.

Table 5 - GIC Transformer Neutral Current and Mvar Losses at 1 V/km Uniform Electric Field, by Orientation

	GIC 3-phase transformer neutral current (Amps)		GIC 3-phase transformer Mvar Losses (Q_{Loss})	
Orientation	HMSL -400	HMSL +550	HMSL -400	HMSL +550
0	4,789	4,800	912	911
15	5,050	5,062	1,011	1,010
30	5,506	5,502	1,131	1,130
45	6,037	6,014	1,245	1,243
60	6,431	6,403	1,325	1,323
75	6,572	6,553	1,335	1,334
90	6,499	6,484	1,284	1,283
105	6,191	6,184	1,185	1,186
120	5,739	5,741	1,051	1,053
135	5,367	5,380	960	962
150	5,019	5,034	884	887
165	4,822	4,830	863	864

The highest GIC currents and highest GIC Mvar losses tend to occur in GSUs connected to EHV transmission on the high-side. Long transmission lines have relatively high GIC DC equivalent voltages (Figure 2) and relatively low series resistance and thus can induce high GIC currents. Table 6 below shows the 20 transformers with the highest average per-unit neutral GICs[3], averaged across all simulated electric field orientations from 0 to 165 degrees. All quantities are 3-phase, except as noted.

[3] Per-unitization is applied only to rank the GIC current with consideration of the nominal voltage level and size of each transformer. As GIC is quasi-DC, there is no transformation of current or voltage in the GIC circuit model.

Table 6 – Transformers with highest GIC neutral amps under uniform field simulation at 1 V/km, averaged across all orientations and HMSL loading cases

Transformer Description	Neutral Current, pu	Neutral Amps	I_{GIC} (per phase)	Mvar Losses
Ashe 500/25 #1	0.648	74.782	24.927	29.614
Dworshak 500/13.8/13.8 #1	0.567	65.495	21.832	25.744
Lane 500/230 #1	0.524	60.458	26.479	31.960
McNary 345/230 #1	0.359	60.019	18.140	14.502
Santiam 500/230 #1	0.482	55.689	35.722	42.961
Lower Granite 500/13.8/13.8 #1	0.456	52.694	17.565	20.838
South Bremerton 230/115 #1	0.208	52.269	11.543	3.262
Aberdeen 230/115 #5	0.203	50.862	13.139	3.138
Novelty 230/115 #1	0.195	48.824	10.926	3.109
Ostrander 500/230 #1	0.410	47.380	21.906	26.186
Lower Monumental 500/13.8/13.8 #1	0.373	43.122	14.374	17.075
Slatt 500/230 #1	0.359	41.445	17.466	20.838
East Omak 230/115 #1	0.160	40.091	11.005	2.630
Bell 500/230 #1	0.343	39.581	25.165	30.090
Boardman (PGE) 500/24 #1	0.342	39.518	13.173	14.218
Aberdeen 115/13.8 #1	0.078	39.290	13.097	1.850
Salem 230/115 #1	0.152	38.062	9.921	2.847
Shelton 230/115 #1	0.150	37.553	9.698	2.327
Tacoma 500/230 #1	0.316	36.479	13.596	16.232
Snohomish 345/230 #1	0.215	35.941	12.152	9.540

Figure 4 graphically depicts concentrations of transformer neutral GIC current averaged across all simulated orientations. The flow arrows on the transmission network (de-emphasized to better reveal the contour) depict GIC flows during a 75 degree uniform field event, under which the maximum transformer neutral GIC occurs. The red contouring depicts the highest GIC currents.

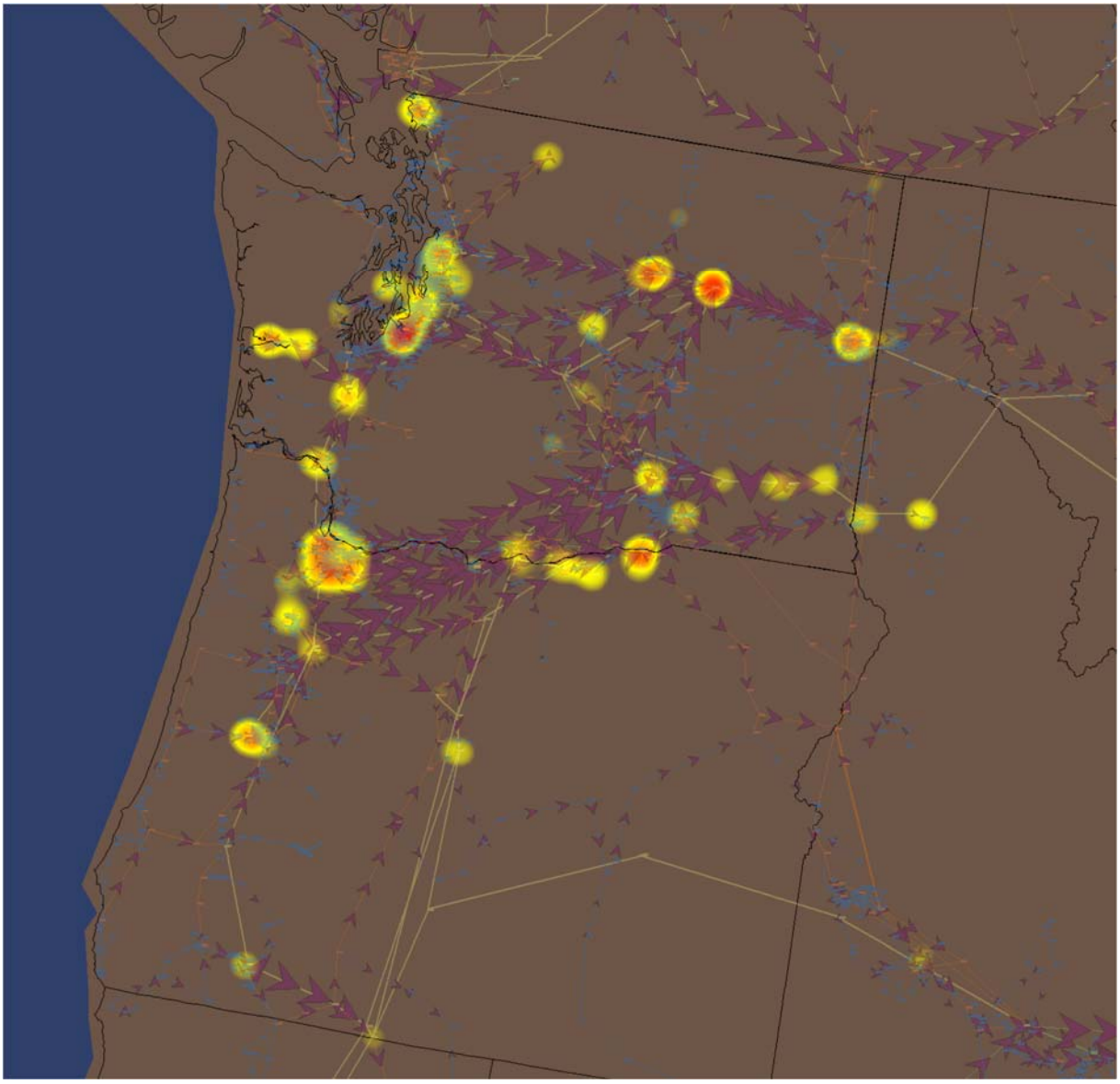


Figure 4 - Contour of Per-Unit Transformer Neutral GIC Density, Averaged Over All Simulated Orientations

Table 7 shows the same quantities for the 20 transformers with the highest GIC Mvar losses.

Table 7 – Transformers with highest GIC Mvar losses under uniform field simulation at 1 V/km

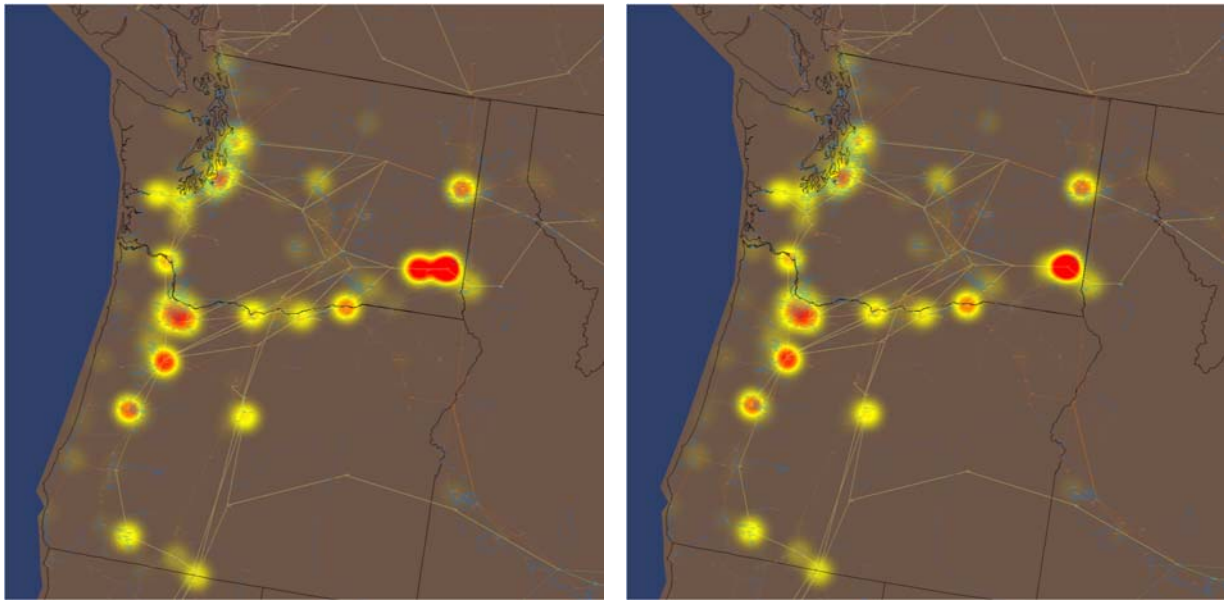
Transformer Description	Neutral Current, pu	Neutral Amps	I_{GIC} (per phase)	Mvar Losses
Santiam 500/230 #1	0.482	55.689	35.722	42.961
Lane 500/230 #1	0.524	60.458	26.479	31.960
Bell 500/230 #1	0.343	39.581	25.165	30.090
Ashe 500/25 #1	0.648	74.782	24.927	29.614
Ostrander 500/230 #1	0.410	47.380	21.906	26.186
Dworshak 500/13.8/13.8 #1	0.567	65.495	21.832	25.744
Satsop 500/230 #1	0.210	24.198	19.175	22.880
Lower Granite 500/13.8/13.8 #1	0.456	52.694	17.565	20.838
Slatt 500/230 #1	0.359	41.445	17.466	20.838
Malin 500/230 #1	0.281	32.466	15.369	17.544
Olympia 500/230 #1	0.026	3.047	14.351	17.094
Lower Monumental 500/13.8/13.8 #1	0.373	43.122	14.374	17.075
Tacoma 500/230 #1	0.316	36.479	13.596	16.232
Pearl 500/230 #1	0.240	27.753	13.273	15.949
Big Eddy 500/230 #2	0.054	6.209	12.835	15.293
McNary 345/230 #1	0.359	60.019	18.140	14.502
Boardman (PGE) 500/24 #1	0.342	39.518	13.173	14.218
Chief Joseph 500/230 #3	0.074	8.503	11.610	13.793
Ponderosa 500/230 #1	0.208	24.053	10.986	13.179
Central Ferry 500/230 #1	0.231	26.667	11.109	13.165

Some locations with high simulated GIC reactive losses have generator reactive power reserves under normal operating conditions to compensate for losses. Table 8 shows the substations with the lowest simulated difference between generation reactive reserves and average GIC reactive losses at 1 V/km across all simulated orientations. This difference is termed “Net Mvar Reserves” in the table.

Table 8 – Substations with lowest average net GIC Mvar reserves under uniform field simulation at 1 V/km

	Average Net Mvar Reserves	
Station and Voltage (kV)	HMSL -400	HMSL 550
Lower Granite 500	-77.386	-77.009
Little Goose Ph 500	-48.576	
Santiam 500	-43.305	-43.369
McNary 500	-35.185	-35.161
Lane 500	-34.344	-34.395
Bell 500	-30.666	-30.757
Big Eddy 500	-26.778	-26.790
Ostrander 500	-26.184	-26.189
Ponderosa 500	-25.085	-25.103
Allston 500	-24.696	-24.695
Satsop 500	-22.880	-22.879
Slatt 500	-20.840	-20.835
Meridian 500	-20.389	-20.411
Olympia 500	-19.951	-19.949
Pearl 500	-19.560	-19.564
Malin 500	-18.641	-18.638
Tacoma 500	-17.689	-17.696
Maple Valley 500	-13.337	-13.346
Central Ferry 500	-13.187	-13.142
Snohomish 345	-12.107	-12.124
Hatwai 500	-11.470	-11.425

Figure 5 depicts locations with negative net Mvar reserves with a geospatial contour. The red contouring depicts the most negative reserves.



(a) HMSL -400 **(b) HMSL 550**

Figure 5 - Contour of Net Mvar Reserve Density (HMSL -400), Averaged Over All Simulated Orientations

Full AC power flow solutions were also performed at each orientation with increasing electric field strength until voltage collapse. Field strengths were recorded where 0.95 pu and 0.90 pu thresholds were first crossed and where voltage collapse occurred. A summary of the results is shown in Table 9.

Table 9 – Field Strength (V/km) resulting in voltage limit violation and voltage collapse

HMSL	Voltage Level (pu)	Field Orientation (degrees)											
		0	15	30	45	60	75	90	105	120	135	150	165
-400	0.95	2.4	2.4	2.1	2.0	1.8	1.8	1.8	2.0	2.1	2.0	2.1	2.2
	0.90	4.5	4.3	4.0	3.7	3.4	3.4	3.6	3.7	3.9	4.0	4.1	4.3
	Collapse	5.6	5.2	4.7	4.2	3.9	3.9	4.0	4.4	5.1	5.7	6.0	6.1
+550	0.95	2.4	2.4	2.2	2.0	2.0	1.8	2.0	2.0	2.0	2.0	2.1	2.2
	0.90	4.6	4.3	4.0	3.7	3.6	3.6	3.6	3.7	4.0	4.0	4.0	4.3
	Collapse	5.6	5.0	4.5	4.2	3.9	3.9	4.0	4.3	5.0	5.6	6.0	6.0

A trace of the lowest per-unit voltage buses at each simulated electric field magnitude and orientation for HMSL -400 and HMSL +550 are shown in Figure 6 and Figure 7, respectively.

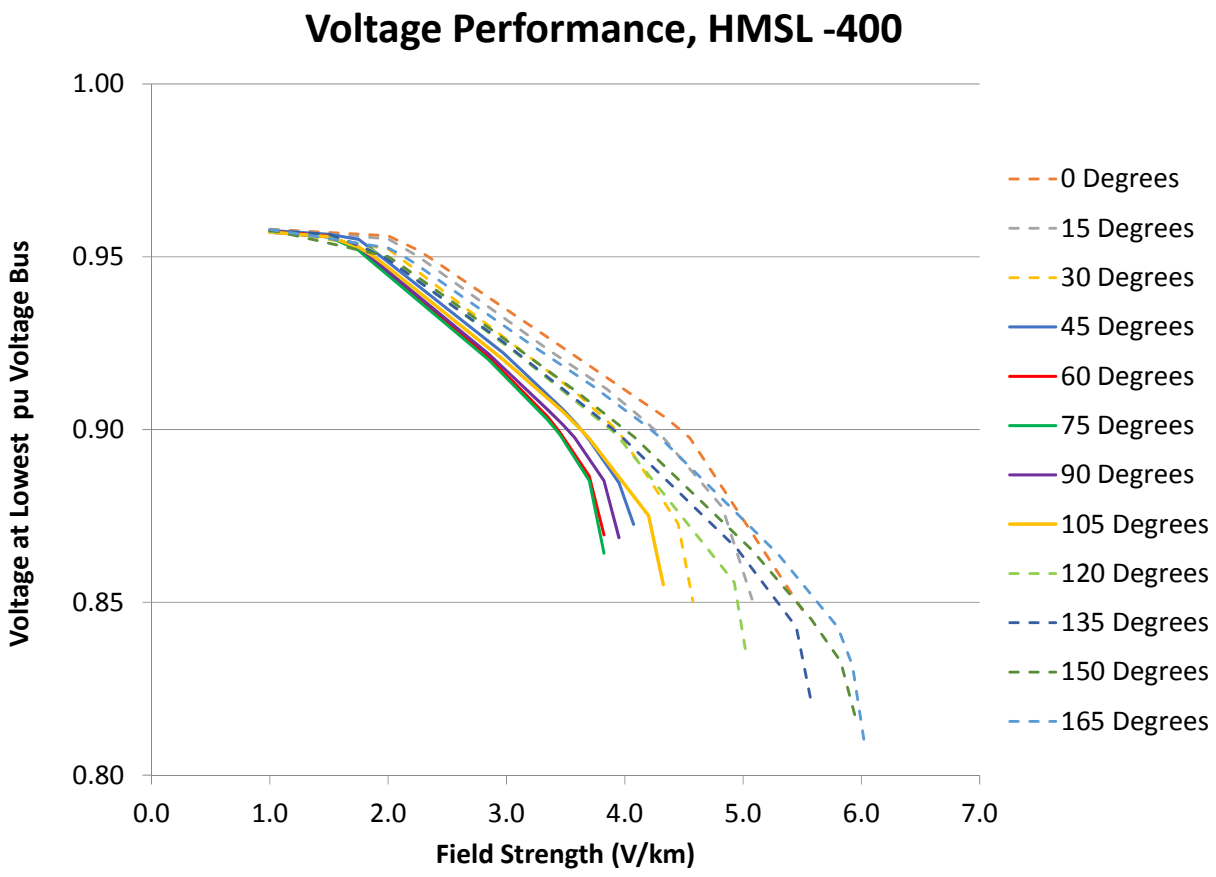

Voltage Performance, HMSL -400
1.00
0.95
0.90
0.85
0.80
Voltage at Lowest pu Voltage Bus
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
Field Strength (V/km)
0 Degrees
15 Degrees
30 Degrees
45 Degrees
60 Degrees
75 Degrees
90 Degrees
105 Degrees
120 Degrees
135 Degrees
150 Degrees
165 Degrees

Figure 6

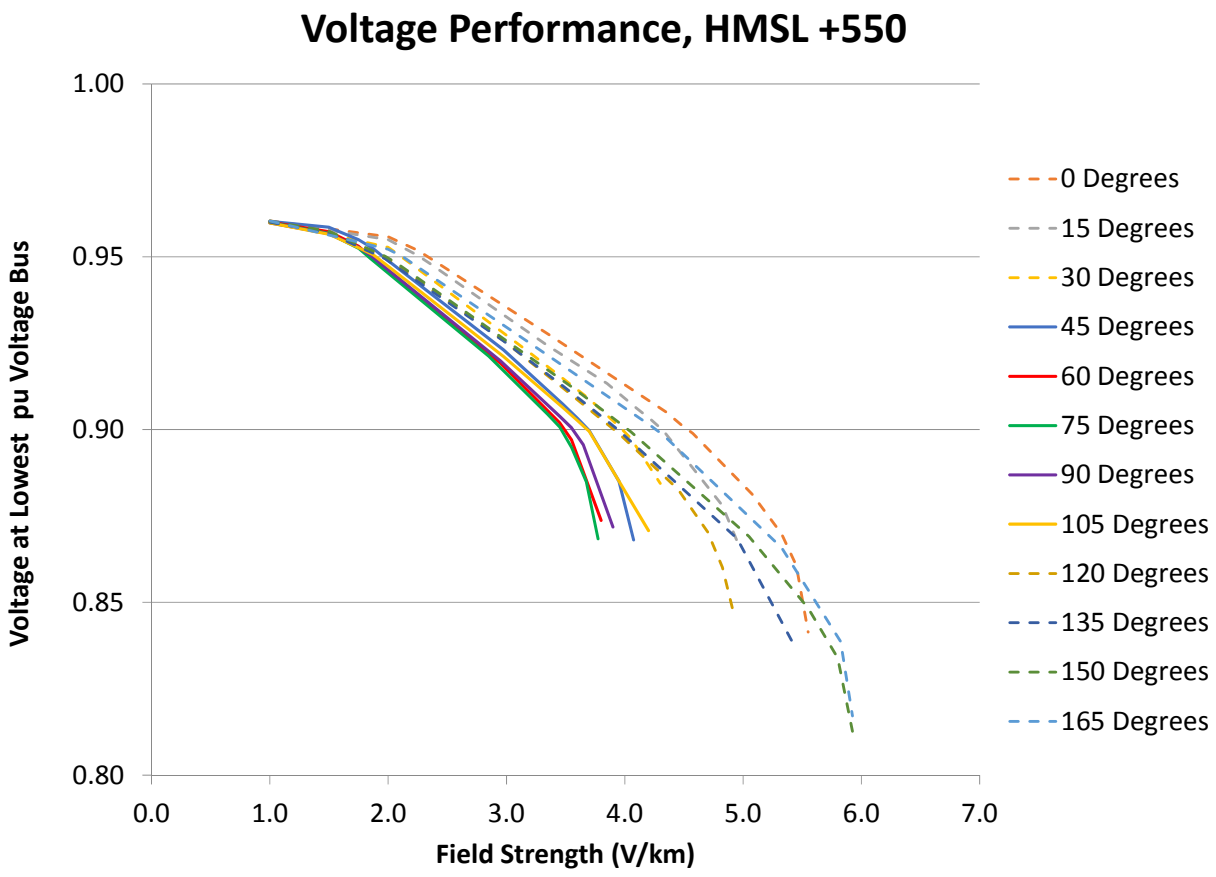
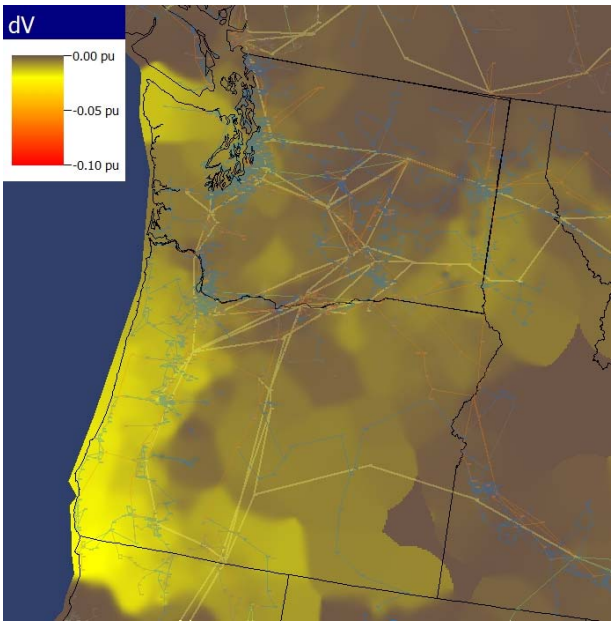
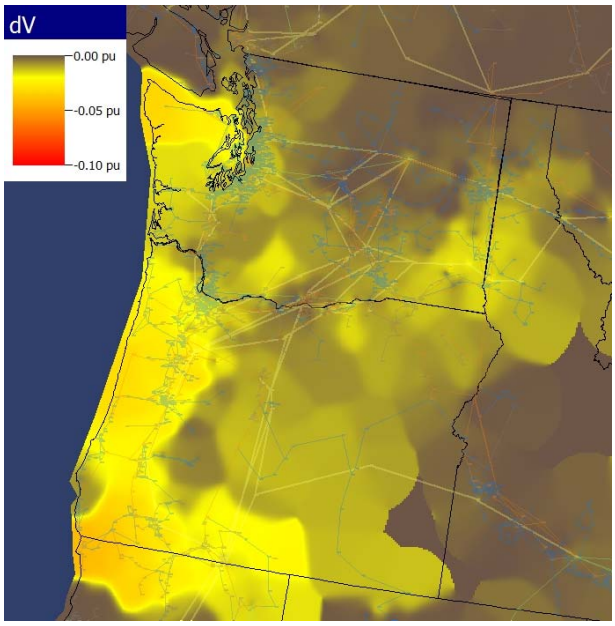


Figure 7

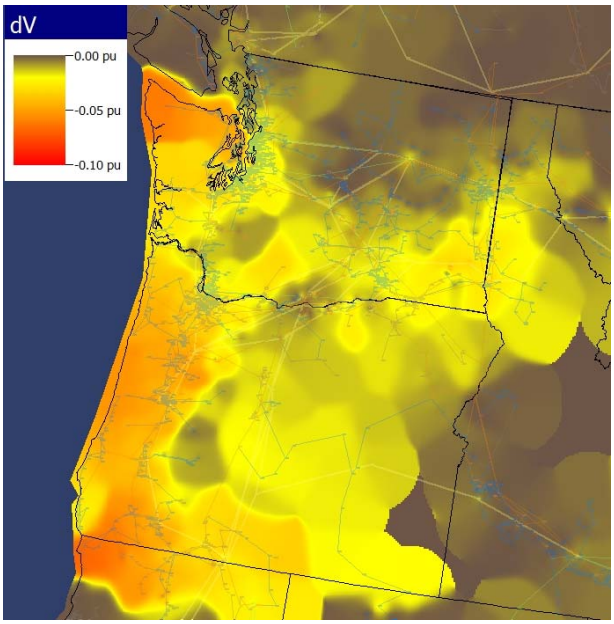
The simulations show that 60-90 degrees is the most stressful field orientation for voltage performance, with similar results for 45-105 degrees. The contours in the following figures illustrate voltage drop for the 75 degree orientation at increasing field strengths in each case.



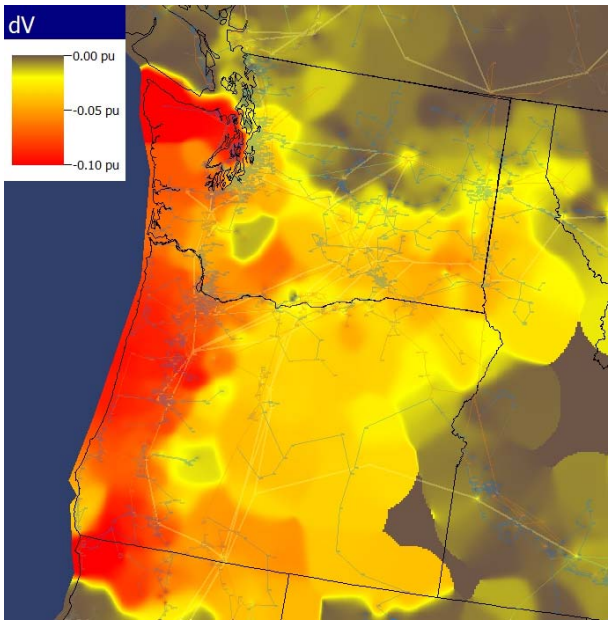
(a) 1 V/km



(b) 2 V/km

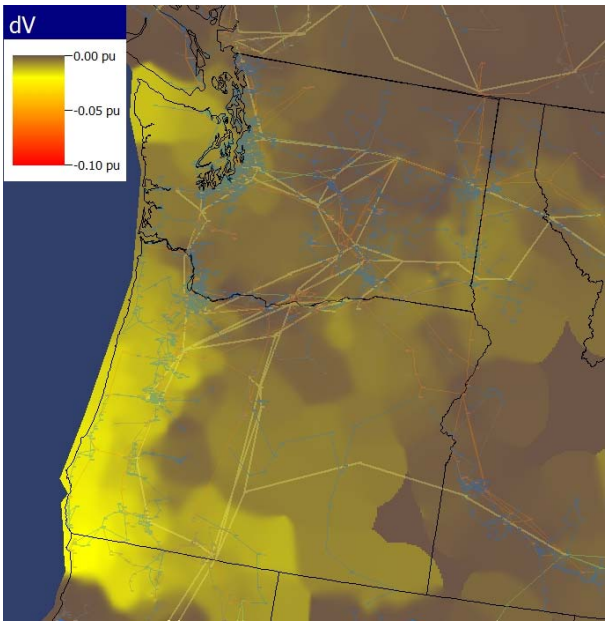


(c) 3 V/km

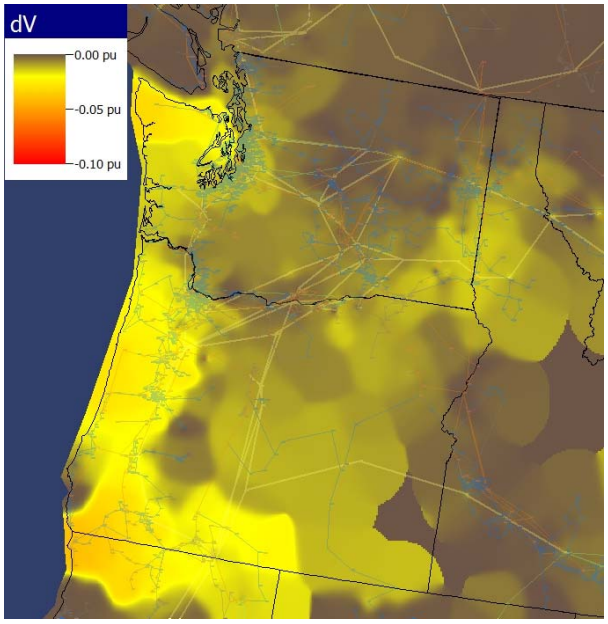


(d) 3.85 V/km - last valid solution

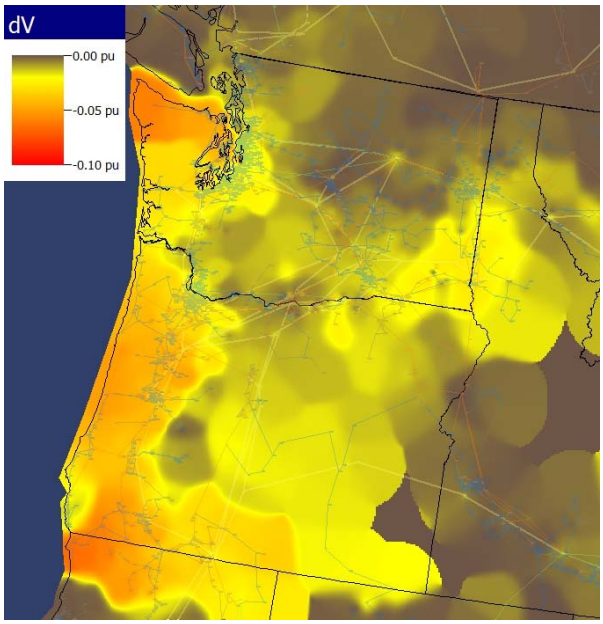
Figure 8 - Voltage Change Contours, HMSL -400, 75 degrees Electric Field Orientation



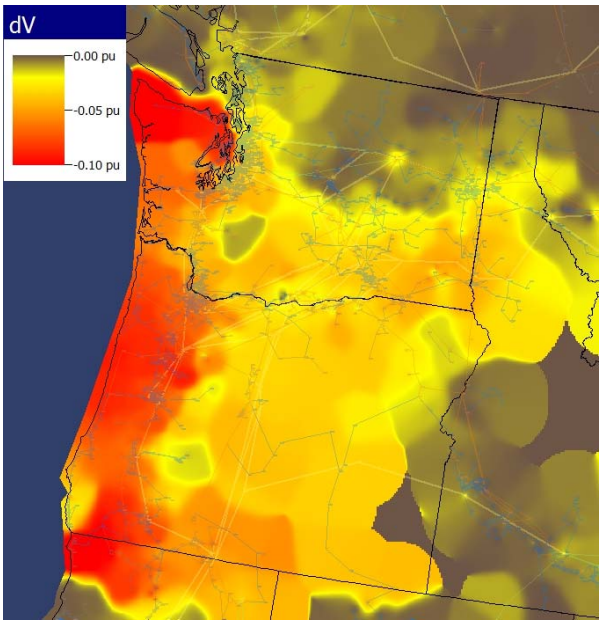
(a) 1 V/km



(b) 2 V/km



(c) 3 V/km



(d) 3.78 V/km - last valid solution

Figure 9 - Voltage Change Contours, HMSL +550, 75 degrees Electric Field Orientation

Uniform Field Analysis Conclusions

The uniform field analysis reveals some vulnerability of the Pacific Northwest power grid due to GIC transformer reactive power losses. The Olympic peninsula and coastal 115 kV networks are especially susceptible to voltage drop. The HMSL +550 scenario performs slightly better than the HMSL -400 scenario, likely a result of it having more spinning generator reactive power reserves. GMD electric field orientations of 60-90 degrees pose the greatest threat in both scenarios. The next phase of analysis will examine methods to increase the ability of the network to withstand GMD events.

Mitigation

Several mitigation strategies were examined for reducing GIC flow, GIC transformer Mvar losses, and voltage drop due to GIC during extreme events. These strategies fell into 2 broad classes: install capacitive transformer neutral blocking at select substations and open or de-energize select transmission lines. With each mitigation measure, the objective is to reduce stress on equipment by reducing GIC flow through the power system and to improve voltage performance during GMD. Voltage performance is evaluated by AC voltage drop caused by GIC transformer reactive power losses and the GIC electric field magnitude that causes widespread voltage collapse at each field orientation. Effective mitigation measures would reduce voltage drop and increase margins to voltage collapse.

Capacitive Neutral Blocking

Capacitive devices in series with grounded transformer neutrals can effectively block flow of quasi-DC GIC. For transformers that are not autotransformers, blocking the neutral effectively eliminates all GIC flow in the transformer, as the windings are electrically isolated. For autotransformers, blocking neutral usually reduces the effective GIC flow, but GIC can still flow through the series winding. Blocking GIC flow through one substation neutral causes GIC to re-distribute through the network and may even cause an increase in GIC flow and GIC reactive power losses in other substations, making it challenging to identify a globally optimum neutral blocking scheme.

Method 1: Iterative selection based on neutral current

Substations are selected one at a time, through an iterative process as follows:

```
Do until all BPA 115 kV+ transformers are protected
   Calculate average neutral current at 1 V/km, for each
   simulated storm orientation (0 to 165 degrees, in 15 degree
   increments)
   Place capacitive neutral protection in the substation(s)
   with the 5 transformers with highest average neutral
   current
Repeat
```

Only transformers with high-side voltages of 115 kV and higher are considered for capacitive neutral DC protection. Though the iterative selection is made based on the highest currents in

each transformer, it is assumed that neutral protection would be applied to all transformers in a substation, as the incremental cost is small relative to that of protecting a single transformer. Also, if a transformer with high neutral current is blocked, but other transformers in the same substation are not blocked, those other transformers would experience an increase in GIC current in many circumstances. Thus it makes sense to apply neutral blocking to entire substations.

This method, hereafter referred to as "Neutral Current Iterative Selection" seeks to identify where a transmission owner might place the first several capacitive neutral protection devices for maximum improvement in reactive power margin. This process is performed repeated on each HMSL scenario.

The iterative simulation is run on each HMSL loading case independently, though the results show a lot of common transformers and substations across the cases. Table 10 shows the selection set for each and the neutral current observed in the prior iteration (prior to blocking). The order of transformer selection and most numbers in the table are taken from a simulation on the HMSL -400 case. The first column, “Iter.” gives the iteration number in the algorithm described above. The “Station and Transformer” column lists the selected transformer (up to 5 per iteration). The GIC neutral amps, averaged across all simulated orientations at 1 V/km, are shown for each selected transformer, in the iteration prior to its selection (prior to neutral blocking). The next 2 columns show the total GIC neutral amps and GIC transformer reactive power losses in all BPA-owned transformers with primary nominal voltages of 115 kV and higher, after the neutral protection is applied in that iteration. (These numbers are given once per iteration, on the line of the first station and transformer.) The last column shows the iteration that the transformer was selected in the same simulation using the HMSL +550 case, if different from the HMSL -400 case. In most instances, they are the same.

Table 10 – Iterative Selection and GIC Neutral Current in Iteration Prior to Selection

		HMSL -400			HMSL +550
		This unit, prior iter.	All BPA xfrs, this iteration		
Iter.	Station and Transformer	GIC Neutral Amps	GIC Neutral Amps	GIC Q Losses	Iter. (if different)
0			2,106	601	
1	Lane 500/230 #1	60.46	1,856	547	
1	McNary 345/230 #1	60.09			
1	Santiam 500/230 #1	55.69			
1	Aberdeen 230/115 #5	50.86			

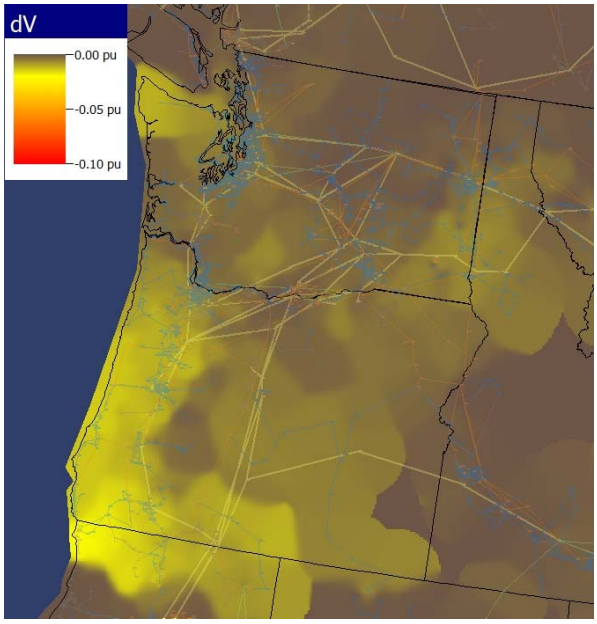
		HMSL -400			HMSL +550
		This unit, prior iter.	All BPA xfrs, this iteration		
Iter.	Station and Transformer	GIC Neutral Amps	GIC Neutral Amps	GIC Q Losses	Iter. (if different)
1	Ostrander 500/230 #1	47.38			
2	Satsop 500/230 #1	63.59	1,661	517	
2	Slatt 500/230 #1	41.57			
2	Salem 230/115 #1	41.50			
2	Shelton 230/115 #1	41.20			
2	East Omak 230/115 #1	40.08			
3	Bell 500/230 #1	39.39	1,479	478	
3	Tacoma 500/230 #1	37.05			
3	Carlton 230/115 #1	36.86			
3	Snohomish 345/230 #1	35.78			
3	Maple Valley 345/230 #1	34.12			4
4	Tillamook 230/115 #1	35.19	1,312	457	
4	Chief Joseph 345/230 #1	35.14			
4	Pearl 500/230 #1	35.06			
4	Rogue 230/115 #1	33.76			
4	Clatsop 230/115 #1	32.82			5
5	Hatwai 500/230 #1	32.40	1,153	431	3
5	Fairview 230/115 #1	31.37			
5	Sacajawea 500/115 #1	28.75			
5	Chemawa 115/59.8 #1	27.66			

Table 11 compares the voltage collapse margin for each capacitive neutral blocking set for each simulation model. Performance generally improves as transformers in more substations are blocked, though marginal improvement is generally reduced with successive iterations.

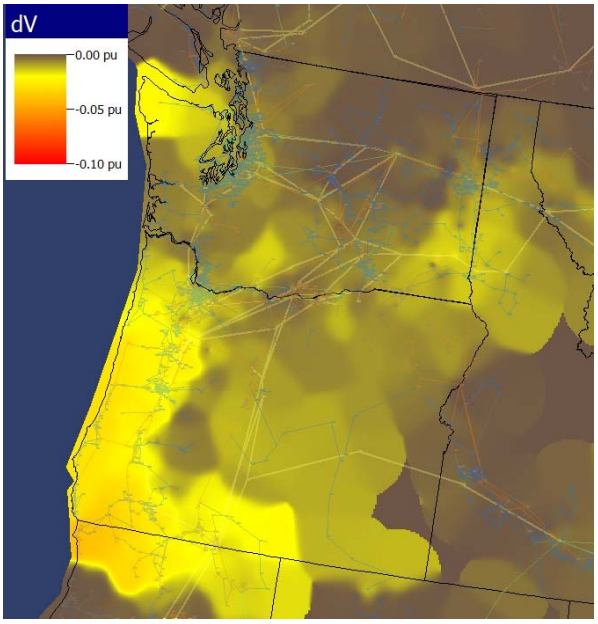
Table 11 - Field strength that causes voltage collapse with each iteration, with selection based on transformer neutral current

HMSL and substations blocked		Field Orientation (degrees)													
		0	15	30	45	60	75	90	105	120	135	150	165	Min	Avg
-400	Base	5.6	5.2	4.7	4.2	3.9	3.9	4.0	4.4	5.1	5.7	6.0	6.1	3.9	4.9
	5	6.1	5.6	5.1	4.6	4.3	4.2	4.4	4.7	5.4	6.0	6.6	6.5	4.2	5.3
	10	6.2	5.7	5.1	4.7	4.5	4.4	4.6	5.1	5.7	6.2	7.0	6.7	4.4	5.5
	15	6.3	5.7	5.2	4.8	4.6	4.5	4.7	5.1	5.8	6.4	7.1	6.8	4.5	5.6
	20	6.4	5.8	5.3	4.9	4.6	4.6	4.8	5.2	5.8	6.6	7.1	6.8	4.6	5.7
	25	6.4	5.8	5.4	5.0	4.7	4.7	4.9	5.4	6.1	6.7	7.2	7.0	4.7	5.8
	50	6.8	6.4	5.7	5.2	5.1	5.1	5.4	5.8	6.6	7.4	8.1	7.8	5.1	6.3
	75	7.4	6.6	5.8	5.4	5.1	5.1	5.4	6.0	6.8	7.6	8.5	8.2	5.1	6.5
	100	7.7	7.0	6.2	5.7	5.5	5.4	5.7	6.2	7.1	7.8	8.5	8.4	5.4	6.8
	125	7.7	7.0	6.2	5.7	5.5	5.5	5.7	6.2	7.1	7.8	8.5	8.4	5.5	6.8
	all	7.7	7.0	6.2	5.7	5.5	5.5	5.7	6.2	7.1	7.8	8.5	8.4	5.5	6.8
+550	Base	5.6	5.0	4.5	4.2	3.9	3.9	4.0	4.3	5.0	5.6	6.0	6.0	3.9	4.8
	5	6.0	5.6	5.0	4.6	4.2	4.2	4.4	4.7	5.4	5.8	6.5	6.4	4.2	5.2
	10	6.2	5.6	5.1	4.7	4.4	4.4	4.6	5.0	5.6	6.1	6.7	6.6	4.4	5.4
	15	6.2	5.7	5.1	4.7	4.5	4.4	4.6	5.0	5.6	6.2	6.8	6.7	4.4	5.5
	20	6.3	5.7	5.2	4.8	4.5	4.5	4.7	5.1	5.7	6.4	6.8	6.7	4.5	5.5
	25	6.4	5.8	5.3	4.9	4.6	4.6	4.8	5.2	5.8	6.5	7.1	6.8	4.6	5.7
	50	6.7	6.4	5.6	5.2	5.0	5.0	5.2	5.7	6.5	7.2	7.8	7.7	5.0	6.2
	75	7.3	6.5	5.8	5.2	5.1	5.1	5.3	5.8	6.7	7.4	8.2	8.1	5.1	6.4
	100	7.6	6.8	6.1	5.6	5.4	5.4	5.6	6.1	6.8	7.6	8.2	8.2	5.4	6.6
	125	7.6	6.8	6.1	5.6	5.4	5.4	5.6	6.1	6.8	7.6	8.2	8.2	5.4	6.6
	all	7.6	6.8	6.1	5.6	5.4	5.4	5.6	6.1	6.8	7.6	8.2	8.2	5.4	6.6

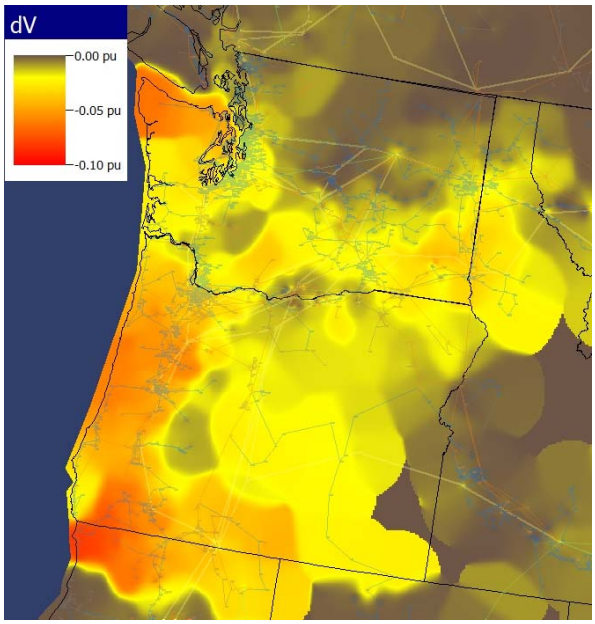
The contours in the following figures illustrate voltage drop at the 5th selection iteration (25 stations blocked) for the 75 degree orientation at increasing field strengths.



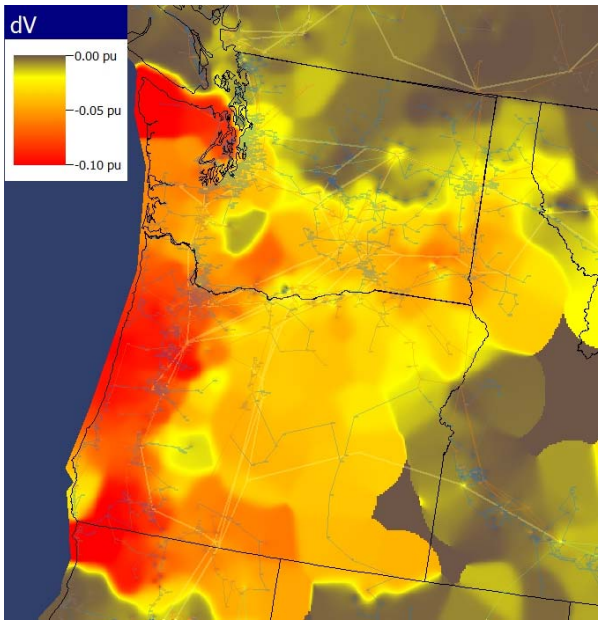
(a) 1 V/km



(b) 2 V/km

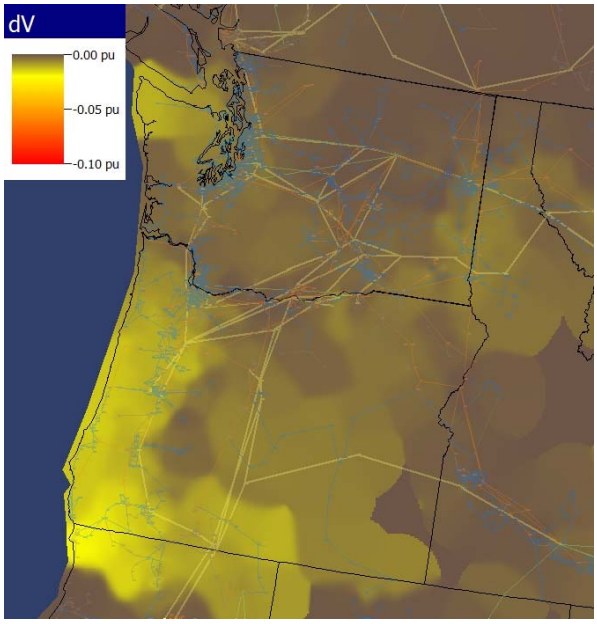


(c) 3.85 V/km – last valid solution without neutral protection

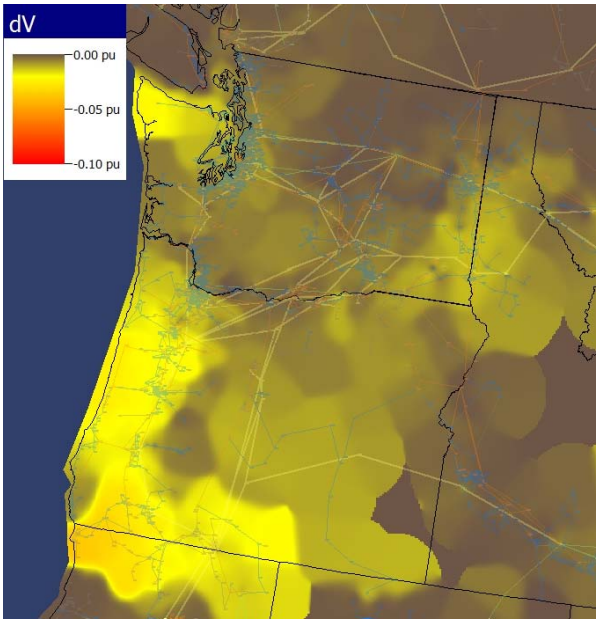


(d) 4.6 V/km - last valid solution

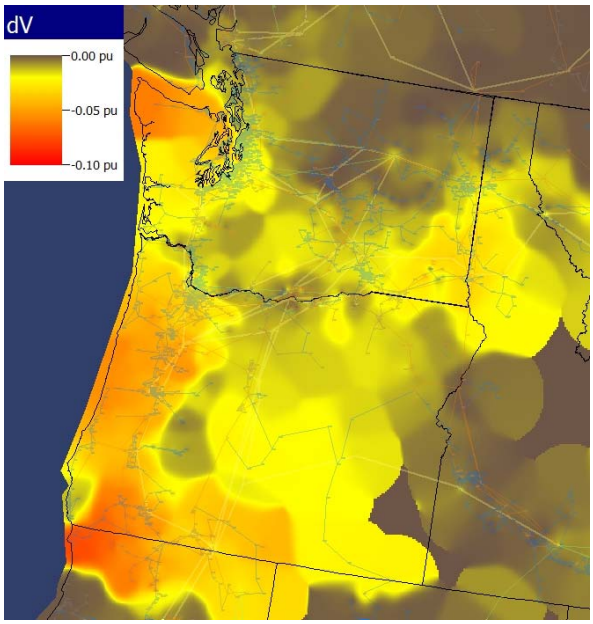
Figure 10 - Voltage Change Contours, HMSL -400, 75 degrees Electric Field Orientation, iteration with selection based on neutral current, 25 stations blocked



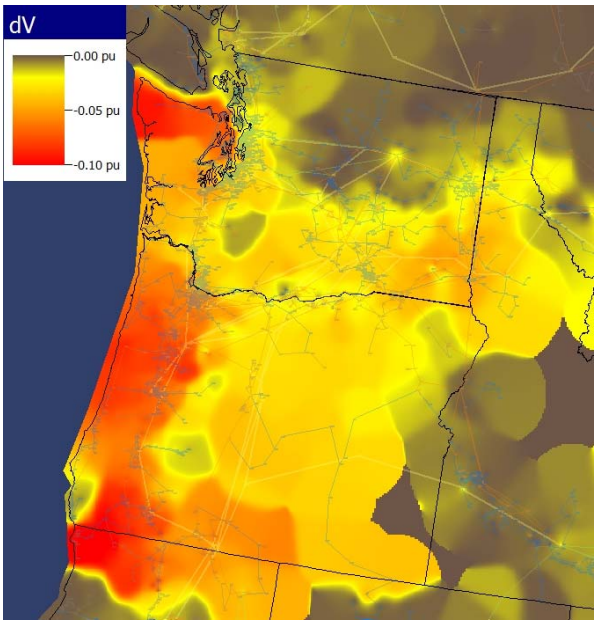
(a) 1 V/km



(b) 2 V/km



(c) 3.78 V/km – last valid solution without neutral protection



(d) 4.5 V/km - last valid solution

Figure 11 - Voltage Change Contours, HMSL +550, 75 degrees Electric Field Orientation, iteration with selection based on neutral current, 25 stations blocked

Method 2: Iterative selection by substation Mvar reserve margin

Substations are selected one at a time, through an iterative process as follows:

```
Do until 35 substations with BPA transformers protected
   Estimate the change in average net reactive power margin
   (generator reserves less GIC Mvar losses) that would be
   achieved with blocked transformer neutrals at 1 V/km,
   averaged across all uniform field orientations
   Place capacitive neutral protection on all transformers in
   the substation with the greatest estimated change in
   average reactive power margin
Repeat
```

This method, hereafter referred to as "iterative Mvar reserve" seeks to identify where a transmission owner might place the first several capacitive neutral protection devices for maximum improvement in reactive power margin. This process is repeated on each HMSL base power flow model independently, though the results show a lot of common substations across seasonal cases. Table 12 shows the selection set for each. “EAMB” refers to the estimated average margin benefit provided by blocking the neutrals of transformers in that substation at the next iteration.

Table 12 – Iterative Mvar Reserve Selection Substations and Estimated Average Reactive Power Margin Benefits

Station	Zone	HMSL -400	HMSL +550
McNary 500	Lower Columbia Basin	13.93	13.87
Lane 500	Western Oregon	12.44	12.46
Santiam 500	Western Oregon	11.17	11.19
Ostrander 500	Portland Area	8.16	8.16
Ponderosa 500	Southern Oregon	8.13	8.13
Tacoma 500	Seattle Area, Olympic Peninsula	7.78	7.78
Maple Valley 500	Seattle Area, Olympic Peninsula	7.79	7.79
Pearl 500	Portland Area	7.66	7.66
Slatt 500	Lower Columbia Basin	7.44	7.44
Bell 500	Spokane Area, N Idaho, W Montana	6.51	6.53
Alvey 500	Western Oregon	5.98	5.99
Snohomish 345	Seattle Area, Olympic Peninsula	5.85	5.86

Hatwai 500	AVA: Lewiston/Clarkston	5.72	6.29
Central Ferry 500	Southeast Washington	4.81	4.77
Keeler 500	Portland Area	4.41	4.41
Satsop 500	Seattle Area, Olympic Peninsula	4.41	4.41
Sno-king 500	Seattle Area, Olympic Peninsula	4.27	4.27
Anaconda Mill Creek 230	BUTTE_MT	4.14	4.13
Allston 500	Portland Area	3.93	3.93
Troutdale 500	PAC:PTLD	3.18	3.18
Garrison 500	Western Montana	3.05	3.07
Walla Walla 230	PAC:WALA	3.04	-
Clatsop 230	Portland Area	2.73	2.73
Intalco 230	Seattle Area, Olympic Peninsula	2.71	2.71
Sacajawea 500	Lower Columbia Basin	2.67	2.64
Longview 230	Cowlitz County, WA	2.49	2.49
Chehalis 230	Seattle Area, Olympic Peninsula	2.54	2.54
Big Eddy 500	Lower Columbia Basin	2.49	2.49
Aberdeen 230	Seattle Area, Olympic Peninsula	2.29	2.41
Sickler 500	Central Washington	2.20	2.22
Olympia 500	Seattle Area, Olympic Peninsula	2.09	2.09
Shelton 230	Seattle Area, Olympic Peninsula	2.08	2.08
Chemawa 230	Portland Area	2.06	2.06
Salem 230	Portland Area	2.59	2.60
Hot Springs 500	Western Montana	2.04	2.05
Carlton 230	Portland Area	-	1.73

Table 13 compares the voltage collapse margin for each capacitive neutral blocking set for each simulation model. Performance generally improves as transformers in more substations are blocked.

Table 13 - Field strength that causes voltage collapse, iterative Mvar reserve selection

HMSL and stations blocked		Field Orientation (degrees)													
		0	15	30	45	60	75	90	105	120	135	150	165	Min	Avg
-400	Base	5.6	5.2	4.7	4.2	3.9	3.9	4.0	4.4	5.1	5.7	6.0	6.1	3.9	4.9
	5	6.2	5.7	5.1	4.6	4.3	4.2	4.4	4.8	5.6	6.1	6.8	6.7	4.2	5.4
	10	6.4	5.8	5.2	4.7	4.5	4.4	4.6	5.0	5.6	6.2	6.8	6.7	4.4	5.5
	15	6.6	6.0	5.4	4.8	4.6	4.5	4.6	5.1	5.7	6.2	7.0	6.8	4.5	5.6
	20	6.8	6.1	5.5	5.0	4.7	4.6	4.7	5.1	5.8	6.4	7.1	7.1	4.6	5.7
	25	6.8	6.2	5.5	5.0	4.7	4.7	4.8	5.2	5.8	6.5	7.2	7.2	4.7	5.8
	30	7.0	6.2	5.6	5.1	4.8	4.8	5.1	5.5	6.2	6.8	7.6	7.5	4.8	6.0
	35	7.0	6.2	5.6	5.1	4.8	4.8	5.1	5.7	6.4	7.2	7.8	7.6	4.8	6.1
+550	Base	5.6	5.0	4.5	4.2	3.9	3.9	4.0	4.3	5.0	5.6	6.0	6.0	3.9	4.8
	5	6.1	5.6	5.0	4.5	4.2	4.2	4.4	4.7	5.4	6.0	6.6	6.6	4.2	5.3
	10	6.4	5.8	5.2	4.7	4.4	4.4	4.5	4.8	5.5	6.1	6.7	6.7	4.4	5.4
	15	6.5	6.0	5.4	4.8	4.5	4.4	4.6	5.0	5.6	6.1	6.8	6.8	4.4	5.5
	20	6.7	6.1	5.4	4.8	4.6	4.6	4.7	5.1	5.7	6.3	7.1	7.1	4.6	5.7
	25	6.7	6.2	5.5	5.0	4.7	4.6	4.7	5.1	5.7	6.4	7.1	7.1	4.6	5.7
	30	6.8	6.2	5.5	5.0	4.7	4.7	5.0	5.4	6.1	6.7	7.5	7.4	4.7	5.9
	35	6.8	6.2	5.5	5.1	4.8	4.8	5.0	5.5	6.3	7.0	7.6	7.5	4.8	6.0

Method 3: Iterative selection by voltage drop at maximum E-field

Substations are selected one at a time, through an iterative process as follows:

```
Do until 35 substations with BPA transformers protected

    Compute the per-unit voltage drop at the highest nominal
    voltage level in each substation, from the base case (no
    GMD) to the GIC electric field strength at the last valid
    power flow solution (just prior to voltage collapse)

    Place capacitive neutral protection on all transformers in
    the substation with the greatest voltage drop, averaged
    across all orientations

Repeat
```

This method, hereafter referred to as "iterative voltage drop", is repeated on each HMSL base power flow model independently, as with the other selection methods. Table 16 shows the selection set for each. The “dV” column shows the voltage drop just prior to voltage collapse and “dV/dQ mult.” shows the maximum bus dV/dQ multiple within each substation (the dV/dQ sensitivity taken just prior to voltage collapse, divided by that taken in the base case, with no GMD.)

Table 14 – Iterative Voltage Drop Selection Substations, Voltage Drop, and dV/dQ multiple

		HMSL -400		HMSL +550	
Station	Zone	dV	dV/dQ mult.	dV	dV/dQ mult.
Sappho 115	Seattle Area, Olympic Peninsula	-0.132	1.406	-0.120	1.394
Port Angeles 230	Seattle Area, Olympic Peninsula	-0.115	1.820	-0.102	2.034
Happy Valley 230	Seattle Area, Olympic Peninsula	-0.103	1.977	-0.095	1.940
Fairmount 230	Seattle Area, Olympic Peninsula	-0.096	2.209	-0.085	1.828
Toledo 230	Western Oregon	-0.095	1.656	-0.088	1.646
Kitsap 230	Seattle Area, Olympic Peninsula	-0.091	2.421	-0.086	2.383
Lane 500	Western Oregon	-0.091	3.351	-0.085	3.519
Tahkenitch 230	Western Oregon	-0.087	1.571	-0.081	1.603
Wendson 230	Western Oregon	-0.086	1.730	-0.080	1.761
Tillamook 230	Portland Area	-0.083	1.888	-0.073	1.970
Shelton 230	Seattle Area, Olympic Peninsula	-0.083	3.442	-0.075	3.976
Albany 230	Western Oregon	-0.080	2.162	-0.073	2.415
Salem 230	Portland Area	-0.079	2.165	-0.071	2.757
Aberdeen 230	Seattle Area, Olympic Peninsula	-0.076	3.662	-0.070	3.794
Drain 115	Western Oregon	-0.078	1.267	-0.071	1.315
Carlton 230	Portland Area	-0.078	2.800	-0.068	2.683
Green Valley 230	Western Oregon	-0.077	1.578	-0.069	1.628
Chemawa 230	Portland Area	-0.076	2.515	-0.072	2.406
Parker 115	Western Oregon	-0.076	1.678	-0.071	1.778
Oregon City 115	Portland Area	-0.077	1.589	-0.065	1.697
Martin Creek 230	Western Oregon	-0.074	1.984	-0.069	2.063
Satsop 500	Seattle Area, Olympic Peninsula	-0.077	6.112	-0.067	7.122

Alvey 500	Western Oregon	-0.072	4.021	-0.069	4.068
Fairview 230	Western Oregon	-0.073	1.611	-0.065	1.758
Pearl 500	Portland Area	-0.071	8.467	-0.063	9.640
Santiam 500	Western Oregon	-0.069	6.222	-0.064	8.732
Keeler 500	Portland Area	-0.069	7.854	-0.061	8.926
Troutdale 500	PAC:PTLD	-0.067	5.890	-0.062	6.229
Ostrander 500	Portland Area	-0.064	7.982	-0.060	7.796
Olympia 500	Seattle Area, Olympic Peninsula	-0.064	10.577	-0.057	7.740
Allston 500	Portland Area	-0.058	13.812	-0.048	13.521
Clatsop 230	Portland Area	-0.055	2.204	-0.051	1.816
St. Johns 230	Portland Area	-0.056	4.313	-	-
Bald Mountain 115	Portland Area	-0.056	1.254	-	-
Sifton 230	Portland Area	-0.056	4.749	-	-
Hatwai 500	AVA: Lewiston/Clarkston	-	-	-0.048	2.079
Canby 2 230	Southern Oregon	-	-	-0.046	1.143
La Pine 230	Southern Oregon	-	-	-0.046	1.254

Table 15 compares the voltage collapse margin for each capacitive neutral blocking set for each simulation model. Performance improves as transformers in more substations are blocked, though the method is less effective per blocked substation than the other iterative methods. One shortcoming of the method is that it does not incorporate an estimate of the improvement that blocking could provide for each substation. Some stations that experience the lowest voltage drop are not good candidates for blocking because they still experience voltage drop due to GIC reactive power losses in autotransformers even when the neutrals are blocked.

Table 15 - Field strength that causes voltage collapse, iterative voltage drop selection

HMSL and stations blocked		Field Orientation (degrees)													
		0	15	30	45	60	75	90	105	120	135	150	165	Min	Avg
-400	Base	5.6	5.2	4.7	4.2	3.9	3.9	4.0	4.4	5.1	5.7	6.0	6.1	3.9	4.9
	5	5.7	5.2	4.7	4.2	4.0	4.0	4.1	4.5	5.1	5.7	6.2	6.2	4.0	5.0
	10	5.8	5.4	4.7	4.4	4.1	4.0	4.2	4.6	5.3	5.7	6.3	6.4	4.0	5.1
	15	5.9	5.4	4.8	4.4	4.1	4.1	4.2	4.6	5.4	6.0	6.5	6.4	4.1	5.2
	20	6.0	5.4	4.8	4.4	4.1	4.1	4.2	4.7	5.4	6.1	6.6	6.5	4.1	5.2
	25	6.1	5.5	4.8	4.5	4.2	4.2	4.4	4.8	5.7	6.5	6.8	6.7	4.2	5.4
	30	6.7	6.0	5.2	4.7	4.4	4.4	4.6	5.2	5.8	6.7	7.5	7.4	4.4	5.7
	35	6.8	6.1	5.4	4.8	4.5	4.5	4.7	5.2	6.1	6.7	7.6	7.6	4.5	5.8
+550	Base	5.6	5.0	4.5	4.2	3.9	3.9	4.0	4.3	5.0	5.6	6.0	6.0	3.9	4.8
	5	5.7	5.2	4.6	4.2	4.0	3.8	4.1	4.4	5.1	5.6	6.1	6.1	3.8	4.9
	10	5.8	5.2	4.7	4.2	4.0	4.0	4.1	4.5	5.1	5.7	6.2	6.2	4.0	5.0
	15	5.8	5.3	4.7	4.2	4.1	4.0	4.2	4.6	5.2	5.8	6.4	6.4	4.0	5.1
	20	5.9	5.4	4.7	4.4	4.1	4.1	4.2	4.6	5.4	6.0	6.5	6.5	4.1	5.2
	25	6.2	5.6	5.0	4.6	4.3	4.2	4.5	4.8	5.6	6.4	6.7	6.7	4.2	5.4
	30	6.6	5.8	5.1	4.6	4.4	4.4	4.5	5.0	5.7	6.5	7.2	7.2	4.4	5.6
	35	6.7	6.0	5.2	4.7	4.4	4.4	4.6	5.1	5.8	6.5	7.4	7.4	4.4	5.7

De-energize Transmission Lines

The linear nature of the DC GIC network allows fast computation of sensitivities of transformer effective GIC with respect to GIC electric field across transmission lines (dI_{GIC}/dE_{field}). Sensitivities were computed for transformers in the substations that experienced the largest voltage drops prior to voltage collapse. Table 16 shows the 15 stations with the largest voltage drops system-wide, grouped into 3 general geographic zones.

Table 16 - Voltage Drop at Maximum E-field Prior to Voltage Collapse (average for all orientations)

Zone	Station	HMSL -400	HMSL +550
Seattle, Olympic Peninsula	Sappho 115	-0.1301	-0.1224
	Port Angeles 230	-0.1143	-0.1070
	Happy Valley 230	-0.1099	-0.1028
	Fairmount 230	-0.1060	-0.0990
	Kitsap 230	-0.0969	-0.0901
	South Bremerton 230	-0.0957	-0.0891
Pacificorp/Grants Pass, Crescent City	Del Norte 115	-0.1057	-0.1026
	Cave Junction 115	-0.0970	-0.0941
	Applegate Dam 115	-0.0896	-0.0869
Western Oregon	Toledo 230	-0.0917	-0.0870
	Green Peter 115	-0.0915	-0.0861
	Foster 115	-0.0905	-0.0852
	Tahkenitch 230	-0.0895	-0.0854
	Wendson 230	-0.0886	-0.0845
	Lane 500	-0.0885	-0.0847

Table 17 shows the transmission lines with the highest dI_{GIC}/dE_{field} sensitivities for transformers in these substations. Methods of GIC sensitivity are described in recent research.[4] Sensitivities are identical in both HMSL scenarios. These lines are considered as candidates for opening during a GMD event.

[4] T. J. Overbye, K. S. Shetye, T. R. Hutchins, Q. Qiu, J. D. Weber, "Power Grid Sensitivity Analysis of Geomagnetically Induced Currents", *IEEE Transactions on Power Systems*, March 2013.

Table 17 – dI_{GIC}/dE_{field} Sensitivities for transformer GIC flow in high voltage-drop substations

Zone	Line	dI_{GIC}/dE_{field}
Seattle, Olympic Peninsula	Fairmount-Shelton 230 #3	9.444
	Fairmount-Shelton 230 #4	9.444
	South Bremerton-Shelton 230 #1	8.521
	Kitsap-Shelton 230 #4	8.490
	Shelton-Kitsap 230 #3	8.141
	Fairmount-Port Angeles 230 #1	4.535
Pacificorp/ Grants Pass, Crescent City	Applegate Dam-Grants Pass 115 #1	7.908
	Meridian-Grants Pass 230 #1	1.715
	Applegate Dam-Cave Junction 115 #1	1.621
	Jerome Prairie-Selma 115 #1	1.210
	Glendale-Grants Pass 230 #1	1.166
	Grants Pass-Jerome Prairie 115 #1	1.130
Western Oregon	Lane-Marion 500 #1	36.84
	Ashe-Marion 500 #2	8.787
	Alvey-Lane 230 #1	7.456
	Santiam-Wren 230 #1	6.986

Opening too many lines causes thermal overloads and voltage drop, especially at times of peak demand. Compromises are needed to balance the base case network performance with the potential reduction in GIC flow through critical transformers. Several alternate topologies were tested on each simulation case with different sets of opened lines. The tested topologies are shown in Table 18.

Table 18 – Set of opened transmission lines for alternate topologies

Line	L1	L2	L3	L4
Fairmount-Shelton 230 #4		x	x	x
South Bremerton-Shelton 230 #1			x	x
Kitsap-Shelton 230 #4				x
Applegate Dam-Grants Pass 115 #1		x	x	x
Lane-Marion 500 #1	x	x	x	x

Simulations revealed that opening lines in the heavy summer scenarios is counter-productive. While it reduces GIC flows, especially in transformers that experience the greatest voltage change during simulated GMD events, it also weakens voltage support in zones that are already vulnerable to low voltage. It is possible that such schemes could be effective during light load periods. Table 19 compares the voltage collapse margin for each alternate to the base topology for each simulation model.

Table 19 – Field strength that causes voltage collapse for each alternate topology, system model, and electric field orientation

		Field Orientation (degrees)													
HMSL		0	15	30	45	60	75	90	105	120	135	150	165	Min	Avg
-440	Base	5.6	5.2	4.7	4.2	3.9	3.9	4.0	4.4	5.1	5.7	6.0	6.1	3.9	4.9
	L1	5.4	5.0	4.4	4.0	3.7	3.7	3.8	4.1	4.7	5.4	5.7	5.8	3.7	4.6
	L2	5.4	4.8	4.4	4.0	3.7	3.6	3.7	4.1	4.7	5.3	5.6	5.6	3.6	4.6
	L3	5.2	4.7	4.3	3.8	3.6	3.6	3.7	4.0	4.6	5.2	5.6	5.6	3.6	4.5
	L4	4.8	4.5	4.1	3.7	3.5	3.4	3.6	3.8	4.4	4.8	5.1	5.1	3.4	4.2
+550	Base	5.6	5.0	4.5	4.2	3.9	3.9	4.0	4.3	5.0	5.6	6.0	6.0	3.9	4.8
	L1	5.4	4.8	4.4	4.0	3.7	3.6	3.7	4.1	4.7	5.3	5.7	5.7	3.6	4.6
	L2	5.2	4.7	4.2	3.8	3.6	3.6	3.7	4.0	4.6	5.2	5.6	5.6	3.6	4.5
	L3	5.1	4.7	4.2	3.8	3.6	3.5	3.6	4.0	4.5	5.1	5.5	5.5	3.5	4.4
	L4	4.8	4.5	4.1	3.7	3.5	3.4	3.5	3.7	4.2	4.8	5.1	5.1	3.4	4.2

Mitigation Summary and Conclusions

Several mitigation strategies were examined for reducing GIC flow, GIC transformer Mvar losses, and voltage drop due to GIC during extreme events. These strategies fell into two broad classes: install capacitive transformer neutral blocking at select substations and open or de-energize select transmission lines. With each mitigation measure, the objective is to reduce stress on equipment by reducing GIC flow through the power system and to improve voltage performance during GMD. Voltage performance is evaluated by AC voltage drop caused by GIC transformer reactive power losses and the GIC electric field magnitude that causes widespread voltage collapse at each field orientation. Effective mitigation measures would reduce voltage drop and increase margins to voltage collapse. GIC flow through the power system is examined primarily as the current in transformer neutrals.

Capacitive neutral blocking enhances the margins to voltage collapse across all field orientations. Three different iterative methods of prioritizing substations for installation of capacitive neutral blocking were examined. Selection by neutral current and estimated improvement to Mvar reserve margin produced similar results. Selection by substation voltage drop just prior to voltage collapse did not perform as well as the other methods, but still increased margins to voltage collapse.

The capacitive neutral blocking schemes were initially examined considering only substations with BPA-owned transformers. The simulations were re-run considering all substations in the study footprint. The following figures summarize the voltage and transformer neutral current performance for each method by number of protected substations. Voltage performance generally improves if all regional substations are considered for blocking. The total current in the neutrals of BPA-owned transformers is generally reduced more if only BPA transformers are blocked, as blocking a transformer’s neutral often diverts GIC to other nearby transformers.

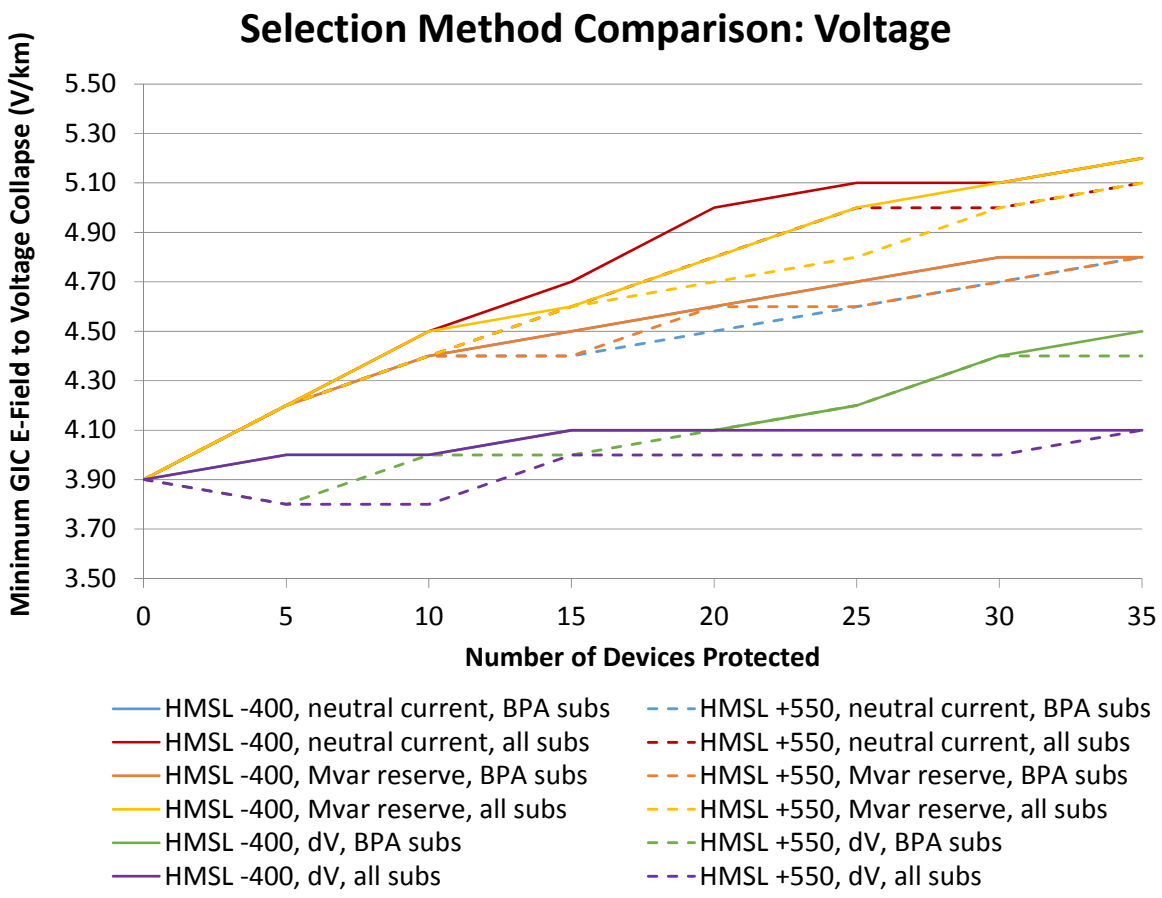

Selection Method Comparison: Voltage
Minimum GIC E-Field to Voltage Collapse (V/km)
5.50
5.30
5.10
4.90
4.70
4.50
4.30
4.10
3.90
3.70
3.50
0
5
10
15
20
25
30
35
Number of Devices Protected
HMSL -400, neutral current, BPA subs
HMSL -400, neutral current, all subs
HMSL -400, Mvar reserve, BPA subs
HMSL -400, Mvar reserve, all subs
HMSL -400, dV, BPA subs
HMSL -400, dV, all subs
HMSL +550, neutral current, BPA subs
HMSL +550, neutral current, all subs
HMSL +550, Mvar reserve, BPA subs
HMSL +550, Mvar reserve, all subs
HMSL +550, dV, BPA subs
HMSL +550, dV, all subs

Figure 12

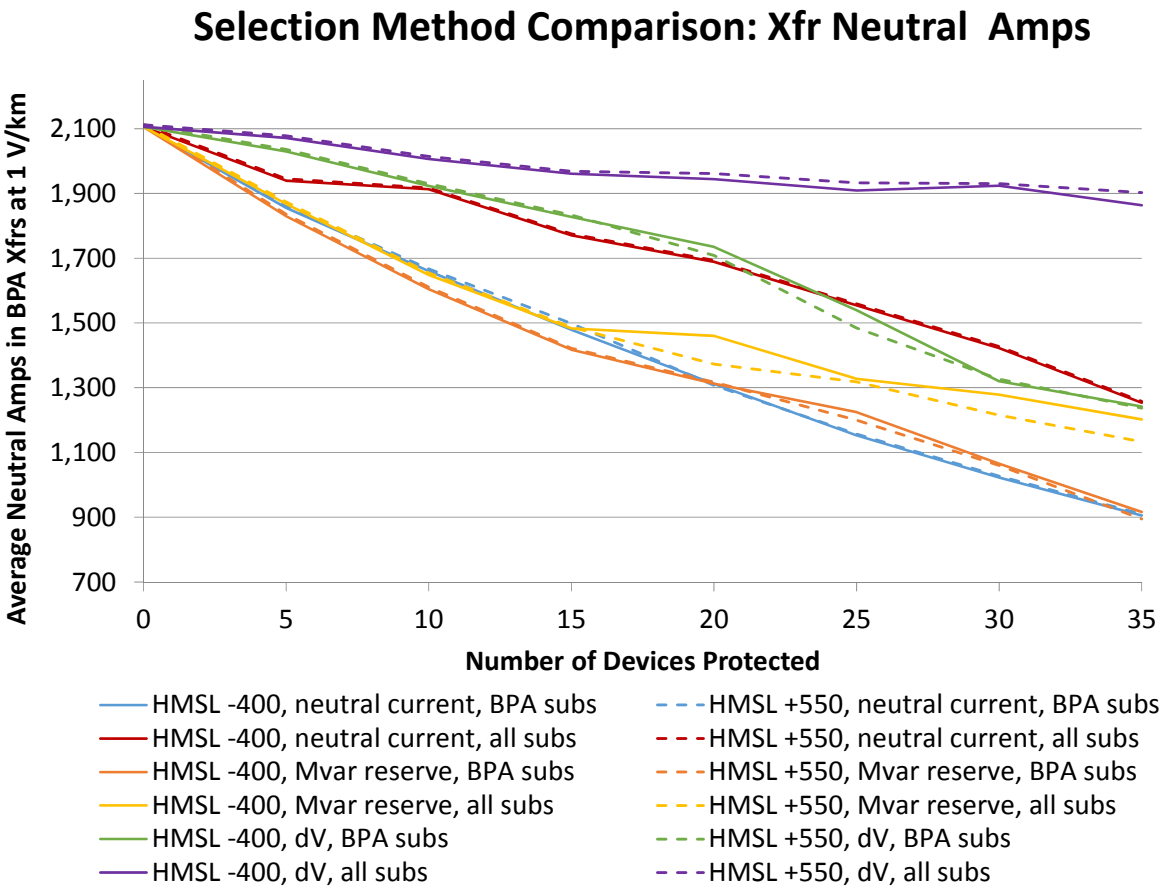


Figure 13

Several operational schemes to open transmission lines with high sensitivities to GIC currents in vulnerable transformers were tested, but none performed well under the simulated conditions. Most such lines with high sensitivities are also important to providing reactive power support. Other methods might also be considered in future work, such as the effects of adding series compensation to lines with high sensitivities to transformer GIC currents.

Appendix

The following tables show variations on Table 5 with different assumptions about GIC DC input voltages or monitored transformers. All tables are based on a 1 V/km uniform electric field.

Table 20 - GIC Transformer Neutral Current and Mvar Losses:
GIC DC voltage inputs applied to transmission lines with nominal voltage of 115 kV and higher; quantities summed on transformers with primary nominal voltage of 200 kV and higher

	GIC 3-phase transformer neutral current (Amps)		GIC 3-phase transformer Mvar Losses (Q_{Loss})	
Orientation	HMSL -400	HMSL +550	HMSL -400	HMSL +550
0	3,802	3,803	860	858
15	4,044	4,053	959	958
30	4,445	4,443	1,076	1,075
45	4,904	4,886	1,188	1,186
60	5,236	5,212	1,265	1,263
75	5,359	5,336	1,274	1,272
90	5,257	5,232	1,220	1,219
105	4,911	4,888	1,119	1,119
120	4,478	4,462	986	987
135	4,173	4,168	897	898
150	3,908	3,910	825	827
165	3,792	3,791	809	809

Table 21 - GIC Transformer Neutral Current and Mvar Losses:
GIC DC voltage inputs applied to transmission lines with nominal voltage of 200 kV and higher; quantities summed on transformers with primary nominal voltage of 200 kV and higher

	GIC 3-phase transformer neutral current (Amps)		GIC 3-phase transformer Mvar Losses (Q_{Loss})	
Orientation	HMSL -400	HMSL +550	HMSL -400	HMSL +550
0	3,539	3,544	855	855

Orientation	GIC 3-phase transformer neutral current (Amps)		GIC 3-phase transformer Mvar Losses (Q_{Loss})	
	HMSL -400	HMSL +550	HMSL -400	HMSL +550
15	3,763	3,774	954	953
30	4,075	4,075	1,060	1,059
45	4,438	4,427	1,171	1,169
60	4,717	4,692	1,249	1,247
75	4,812	4,784	1,265	1,263
90	4,689	4,659	1,216	1,214
105	4,342	4,320	1,116	1,115
120	3,886	3,869	979	978
135	3,603	3,594	888	889
150	3,453	3,452	818	820
165	3,420	3,420	804	804

Voltage Summary	Voltage Detail	Sub Reactive Margin	Xfr Average	Xfr by configuration	Xfr Detail by itr	Xfr Detail by itr BPA only	Itr Select by Neutral Amps	Itr Select by Mvar Reserve	Sub voltage drop		Itr Select by dV		Comparison
StudyID		StudyID											
												Composite (BPA Stations only)	
Case		Description		StudyID	CaseDescription	Record	Composite Key	StudyID	SubNum				StudyID
Notes	StudyID	Notes	Iteration	Description	Iteration	Line (Study and Itr)	StudyID	Case	SubName	**Line Records**	Case		Order
Description	Iteration	SubNum	Transformer Description	Notes	Transformer Description	StudyID	Description	Description	BusNomkV		Description		Xfr/Itr
Iteration	Orientation	Station and Voltage	Area	Iteration	Area	CaseDescription	Notes	Iteration	AreaName	From Number	Iteration	SubNum	Case
Threshold	FieldStrength	AvgNetMvarReserves	Avg Neutral Current, pu (3 phase)	Orientation	Avg Neutral Current, pu (3 phase)	Iteration	Iteration	SubNum	ZoneName	From Name	SubNum	Station	Description
VThreshold	BusNum	CountOfMvarReservesNet	Avg Neutral Amps (3 phase)	TotXfrNeutralAmps	Avg Neutral Amps (3 phase)	Transformer Description	NextTransformerProtected	SubName	AvgOfMinPUHighestNomkV	To Number	SubName	Zone	Desc Short
0	SubName		Avg Effective Amps (per phase)	TotGICQLosses	Avg Effective Amps (per phase)	Area	AvgNeutralAmps	AreaName		To Name	BusNomkV	dV	SelectionMethod
15	BusName	Summary	Avg Mvar Losses (3 phase)	TotXfrIEff	Avg Mvar Losses (3 phase)	Avg Neutral Current, pu (3 phase)	GICNeutralAmps	BusNomkV	SubNum	From Sub Name	AreaName	dVdQMult	
30	BusNomVolt	Sub Num	Avg High-Side Current, pu (per phase)		Avg High-Side Current, pu (per phase)	Avg Neutral Amps (3 phase)	GICQLosses		SubName	From Nom kV	Station	dV	
45	BusPUVolt	Station and kV	Avg High-Side Amps (per phase)		Avg High-Side Amps (per phase)	Avg Effective Amps (per phase)	BusNum3W	ZoneName	BusNomkV	To Sub Name	ZoneName	dVdQMult	
60	VThreshold	HMSL -400	Avg Med-Side Current, pu (per phase)		Avg Med-Side Current, pu (per phase)	Avg Mvar Losses (3 phase)	BusNum3W1	AvgMarginBenefit	AreaName	To Nom kV	dVMaxNomKV		
75	VTCross	HMSL +550	Avg Med-Side Amps (per phase)		Avg Med-Side Amps (per phase)	Avg High-Side Current, pu (per phase)	BusNum3W2	AvgNeutralAmps	ZoneName	Circuit	dVdQMultMax		
90	PFFail	include	High Bus Number		High Bus Number	Avg High-Side Amps (per phase)	BusNum3W3	AvgQLosses	AvgOfMinPUHighestNomkV	Status	dVAvg		
105	Case		Med Bus Number		Med Bus Number	Avg Med-Side Current, pu (per phase)	LineCircuit			dIeffective/dEField	dVdQMultAvg		
120	Notes		Ter Bus Number		Ter Bus Number	Avg Med-Side Amps (per phase)	Iteration		SubNum	Line	AvgMarginBenefit		
135			Star Bus Number		Star Bus Number	High Bus Number	AvgNeutralAmps		selected?	Selected?	AvgNeutralAmps		
150			Circuit		Circuit	Med Bus Number	GICNeutralAmps		SubName		AvgQLosses		
165			High-Side Config		High-Side Config	Ter Bus Number	GICQLosses		AreaName		From Name		
Min			Med-Side Config		Med-Side Config	Star Bus Number			ZoneName		To Number		
Avg			Core Type		Core Type	Circuit			HMSL -400		To Name		
			K Factor		K Factor	High-Side Config			HMSL +550		Circuit		
					Max Amps	Med-Side Config					From Sub Name		
					Amps in Top 10	Core Type					From Nom kV		
					Amps in Top 20	K Factor					To Sub Name		
						Max Amps					To Nom kV		
						Amps in Top 10					dIeffective/dEField		
						Amps in Top 20							
						Record							
						Line (Study and Itr)							
						StudyID							
						CaseDescription							
						Iteration							
						Transformer Description							
						Area							
						Avg Neutral Current, pu (3 phase)							
						Avg Neutral Amps (3 phase)							
						Avg Effective Amps (per phase)							
						Avg Mvar Losses (3 phase)							
						Avg High-Side Current, pu (per phase)							
						Avg High-Side Amps (per phase)							
						Avg Med-Side Current, pu (per phase)							
						Avg Med-Side Amps (per phase)							
						High Bus Number							
						Med Bus Number							
						Ter Bus Number							
						Star Bus Number							
						Circuit							
						High-Side Config							
						Med-Side Config							
						Core Type							
						K Factor							
						Max Amps							
						Amps in Top 10							
						Amps in Top 20							

Averaged over all orientations and HMSL -400 and HMSL +550, with all available transformer/substation data

Iteration	Transformer Description	Area	Avg Neutral Current, pu (3 phase)	Avg Neutral Amps (3 phase)	Avg Effective Amps (per phase)	Avg Mvar Losses (3 phase)	Avg High-Side Current, pu (per phase)	Avg High-Side Amps (per phase)	Avg Med-Side Current, pu (per phase)	Avg Med-Side Amps (per phase)	High Bus Number	Med Bus Number	Ter Bus Number	Star Bus Number	Circuit	High-Side Config.	Med-Side Config.	Core Type	K Factor
0	Ashe 500/2NORTHWE		0.648	74.782	24.927	29.614	0.216	24.927	0.000	0.000	40061	40063	0	0:1	1	Unknown	Unknown	Single Phai	1.10
0	Dworshak 7NORTHWE		0.567	65.495	21.832	25.744	0.189	21.832	0.000	0.000	40369	40363	40365	41201:1	1	Gwye	Delta	Single Phai	1.10
0	Lane 500/2NORTHWE		0.524	60.458	26.479	31.960	0.276	31.926	0.052	13.146	40629	40627	0	0:1	1	Gwye	Gwye	Single Phai	1.10
0	Santiam 50NORTHWE		0.482	55.689	35.722	42.961	0.436	50.339	0.127	32.879	40941	40939	0	0:1	1	Gwye	Gwye	Single Phai	1.10
0	Lower Grar7NORTHWE		0.456	52.694	17.565	20.838	0.152	17.565	0.000	0.000	44237	44231	44232	44235:1	1	Gwye	Delta	Single Phai	1.10
0	Ostrander 7NORTHWE		0.410	47.380	21.906	26.186	0.244	28.132	0.065	16.267	40808	40810	0	0:1	1	Gwye	Delta	Single Phai	1.10
0	Lower Mor7NORTHWE		0.373	43.122	14.374	17.075	0.124	14.374	0.000	0.000	44257	44251	44252	44255:1	1	Gwye	Delta	Single Phai	1.10
0	McNary 34NORTHWE		0.359	60.019	18.140	14.502	0.086	14.408	0.023	5.659	40721	41353	0	0:1	1	Gwye	Gwye	Single Phai	0.76
0	Slatt 500/2NORTHWE		0.359	41.445	17.466	20.838	0.181	20.850	0.030	7.486	40989	40986	0	0:1	1	Gwye	Gwye	Single Phai	1.10
0	Bell 500/2NORTHWE		0.343	39.581	25.165	30.090	0.318	36.664	0.105	26.309	40091	40092	0	0:1	1	Gwye	Gwye	Single Phai	1.10
0	Boardman 7NORTHWE		0.342	39.518	13.173	14.218	0.114	13.173	0.000	0.000	43049	43047	0	0:1	1	Gwye	Delta	Unknown	1.10
0	Tacoma 50NORTHWE		0.316	36.479	13.596	16.232	0.128	14.819	0.012	3.107	41051	41049	0	0:1	1	Gwye	Gwye	Single Phai	1.10
0	Hatwai 50NORTHWE		0.291	33.584	9.720	11.447	0.074	8.565	0.014	3.550	40521	40519	0	0:1	1	Gwye	Gwye	Single Phai	1.10
0	Little Goos7NORTHWE		0.286	33.076	11.025	13.094	0.095	11.025	0.000	0.000	44217	44211	44212	44215:1	1	Gwye	Delta	Single Phai	1.10
0	Malin 500/7NORTHWE		0.281	32.466	15.369	17.544	0.140	19.272	0.035	8.877	40687	40689	0	0:1	1	Gwye	Gwye	Single Phai	1.10
0	Sacajawea 7NORTHWE		0.248	28.667	4.382	5.189	0.025	2.837	0.014	6.781	40913	40911	0	0:1	1	Gwye	Delta	Unknown	1.10
0	Pearl 500/2NORTHWE		0.240	27.753	13.273	15.949	0.155	17.899	0.047	11.891	40827	40824	0	0:1	1	Gwye	Gwye	Single Phai	1.10
0	Central Fer7NORTHWE		0.231	26.667	11.109	13.165	0.114	13.184	0.020	4.999	40666	40664	0	0:1	1	Gwye	Gwye	Single Phai	1.10
0	Snohomish7NORTHWE		0.226	35.941	12.152	13.540	0.076	12.670	0.026	9.313	40994	41328	0	0:1	1	Gwye	Gwye	Single Phai	0.76
0	Pearl 500/7NORTHWE		0.214	24.726	6.616	3.613	0.052	5.949	0.021	5.202	40827	40826	0	0:2	1	Unknown	Unknown	Core, Thre	0.50
0	Satsop 500NORTHWE		0.210	24.198	19.175	22.880	0.249	28.705	0.085	21.217	40949	40947	0	0:1	1	Gwye	Gwye	Single Phai	1.10
0	South Bren7NORTHWE		0.208	52.259	11.543	13.262	0.023	5.663	0.027	11.760	42900	42901	0	0:1	1	Gwye	Gwye	Single Phai	0.28
0	Ponderosa 7NORTHWE		0.208	24.053	10.986	13.179	0.120	13.816	0.026	6.637	40837	40838	0	0:1	1	Gwye	Gwye	Single Phai	1.10
0	Aberdeen 2NORTHWE		0.203	50.862	11.139	3.138	0.037	9.324	0.015	7.630	40011	40007	0	0:5	1	Gwye	Gwye	Core, Thre	0.23
0	Maple Vall7NORTHWE		0.200	23.146	11.153	12.829	0.067	7.711	0.009	2.229	40691	40692	0	0:1	1	Gwye	Gwye	Single Phai	0.76
0	Novelty 23NORTHWE		0.195	48.824	10.926	3.109	0.040	10.104	0.032	16.100	42304	42305	0	0:1	1	Gwye	Gwye	Unknown	0.28
0	Sno-king 5NORTHWE		0.188	21.705	6.156	7.321	0.048	5.547	0.014	3.432	41007	41006	0	0:1	1	Gwye	Gwye	Single Phai	1.10
0	Chief Jose7NORTHWE		0.187	21.578	10.768	12.544	0.075	12.565	0.017	3.925	40723	40724	0	0:1	1	Gwye	Gwye	Single Phai	0.76
0	Keeler 500/7NORTHWE		0.177	20.390	7.684	9.187	0.083	9.546	0.027	7.746	40601	40599	0	0:1	1	Gwye	Gwye	Single Phai	1.10
0	Grand Coul7NORTHWE		0.170	19.579	5.788	6.877	0.045	5.160	0.006	1.383	40287	41357	0	0:1	1	Unknown	Unknown	Unknown	1.10
0	Chief Jose7NORTHWE		0.166	19.212	9.997	11.932	0.076	12.670	0.022	8.775	40724	40723	0	0:2	1	Gwye	Gwye	Single Phai	0.76
0	East Omak 7NORTHWE		0.160	40.091	11.005	2.630	0.036	9.049	0.011	5.594	40373	40371	0	0:1	1	Gwye	Gwye	Core, Thre	0.23
0	Ponderosa 7NORTHWE		0.157	18.082	8.526	10.214	0.094	10.894	0.022	5.493	40834	40836	0	0:1	1	Unknown	Unknown	Unknown	1.10
0	Troutdale 7NORTHWE		0.155	17.996	6.603	7.869	0.062	7.126	0.005	1.161	41095	41094	0	0:1	1	Gwye	Gwye	Single Phai	1.10
0	Salem 230/1NORTHWE		0.152	38.062	9.921	2.847	0.030	7.494	0.012	5.882	40921	40921	0	0:1	1	Unknown	Unknown	Unknown	0.28
0	Shelton 23NORTHWE		0.150	37.553	6.698	2.327	0.028	7.023	0.012	5.947	40971	40969	0	0:1	1	Gwye	Gwye	Core, Thre	0.23
0	Carlton 23NORTHWE		0.141	35.316	10.329	2.460	0.035	8.886	0.007	3.395	40181	40179	0	0:2	1	Gwye	Gwye	Core, Thre	0.23
0	McLoughl7NORTHWE		0.137	34.486	11.277	3.796	0.040	10.046	0.006	1.540	41014	41309	0	0:1	1	Unknown	Unknown	Unknown	0.28
0	Rogue 230/7NORTHWE		0.134	33.722	8.132	1.951	0.020	5.023	0.012	6.218	40895	40893	0	0:1	1	Gwye	Gwye	Core, Thre	0.23
0	Clatsop 23NORTHWE		0.127	31.960	9.892	5.089	0.037	9.326	0.005	2.382	40243	45314	0	0:1	1	Gwye	Gwye	Single Phai	0.51
0	Meridian 5NORTHWE		0.127	25.152	14.680	9.012	0.200	39.508	0.032	6.296	41101	45197	45195	0:1	1	Gwye	Gwye	Single Phai	1.10
0	Meridian 5NORTHWE		0.127	14.680	9.012	10.200	0.108	12.521	0.032	7.923	45197	45195	0	0:1	1	Gwye	Gwye	Unknown	1.10
0	Tillamook 2NORTHWE		0.122	30.660	8.303	1.988	0.026	6.480	0.009	4.511	41075	41073	0	0:1	1	Gwye	Gwye	Core, Thre	0.23
0	Alvey 500/2NORTHWE		0.120	13.491	2.068	2.661	0.000	0.000	0.038	8.467	40051	40049	0	0:1	1	Unknown	Unknown	Unknown	1.10
0	Boardman 7NORTHWE		0.116	29.033	10.680	2.997	0.047	11.683	0.004	2.110	40129	40127	0	0:1	1	Unknown	Unknown	Unknown	0.28
0	Hermiston 7NORTHWE		0.111	12.871	4.290	5.097	0.037	4.290	0.000	0.000	47638	47639	0	0:1	1	Unknown	Unknown	Unknown	1.10
0	Hermiston 7NORTHWE		0.111	12.871	4.290	5.097	0.037	4.290	0.000	0.000	47638	47641	0	0:1	1	Unknown	Unknown	Unknown	1.10
0	Hermiston 7NORTHWE		0.111	12.871	4.290	5.097	0.037	4.290	0.000	0.000	47638	47640	0	0:1	1	Unknown	Unknown	Unknown	1.10
0	Cowlitz 23NORTHWE		0.107	26.907	9.486	1.316	0.040	10.004	0.004	2.138	46609	46607	0	0:8	1	Gwye	Gwye	3-Legged C	0.13
0	Lower Grar7NORTHWE		0.107	12.377	4.126	4.894	0.036	4.126	0.000	0.000	44237	44233	44234	44236:1	1	Gwye	Delta	Single Phai	1.10
0	Custer 500/1NORTHWE		0.107	12.341	1.467	0.657	0.037	4.257	0.032	8.017	40323	40321	0	0:2	1	Gwye	Gwye	Single Phai	1.10
0	Cowlitz 23NORTHWE		0.106	26.553	9.391	1.242	0.040	9.931	0.004	2.144	46609	46607	0	0:9	1	Gwye	Gwye	3-Legged C	0.13
0	Custer 500NORTHWE		0.106	12.241	1.273	1.468	0.037	4.307	0.032	8.040	40323	40322	0	0:1	1	Gwye	Gwye	Single Phai	1.10
0	Allston 500NORTHWE		0.104	25.000	11.042	13.176	0.149	17.150	0.011	1.042	40403	40404	0	0:1	1	Gwye	Gwye	Single Phai	1.10
0	Rocky Reac7NORTHWE		0.101	16.927	7.056	5.660	0.067	11.153	0.031	7.717	40891	40892	0	0:1	1	Gwye	Gwye	Single Phai	1.10
0	Sickler 500NORTHWE		0.099	11.382	4.707	5.606	0.048	5.548	0.009	2.310	40973	47031	0	0:1	1	Gwye	Gwye	Single Phai	1.10
0	Anaconda 7NORTHWE		0.099	23.777	7.923	4.216	0.032	7.923	0.000	0.000	40458	40456	0	0:7	1	Unknown	Unknown	Unknown	0.28
0	McNary 500NORTHWE		0.095	11.001	10.724	12.701	0.146	16.829	0.054	13.561	40723	41351	0	0:1	1	Unknown	Unknown	Unknown	1.10
0	Kittitas Val7NORTHWE		0.094	23.710	7.903	2.191	0.031	7.903	0.000	0.000	44276	44277	0	0:1	1	Unknown	Unknown	Unknown	0.28
0	John Day 7NORTHWE		0.091	10.402	2.135	2.546	0.060	6.927	0.041	10.416	40585	40584	0	0:1	1	Gwye	Gwye	Single Phai	1.10
0	Tahkenitch7NORTHWE		0.089	22.457	7.412	1.772	0.029	7.338	0.003	1.321	41061	41059	0	0:1	1	Gwye	Gwye	Core, Thre	0.23
0	Hot Spring)IDAHO		0.089	22.219	7.406	1.012	0.030	7.406	0.000	0.000	60396	60397	0	0:1	1	Gwye	Delta	3-Legged C	0.13
0	Lower Mor7NORTHWE		0.088	10.118	3.373	4.006	0.029	3.373	0.000	0.000	44257	44253	44254	44256:1	1	Gwye	Delta	Single Phai	1.10
0	Grand Coul7NORTHWE		0.087	10.031	3.344	3.973	0.029	3.344	0.000	0.000	41743	40297	0	0:1	1	Unknown	Unknown	Unknown	1.10
0	Grand Coul7NORTHWE		0.087	10.031	3.344	3.973	0.029	3.344	0.000	0.000	41742	40296	0	0:1	1	Unknown	Unknown	Unknown	1.10
0	Grand Coul7NORTHWE		0.087	10.031	3.344	3.973	0.029	3.344	0.000	0.000	41744	40298	0	0:1	1	Unknown	Unknown	Unknown	1.10
0	Round But7NORTHWE		0.086	9.978	6.313	7.538	0.079	9.162	0.026	7.508	43485	43483	0	0:1	1	Gwye	Gwye	Unknown	1.10
0	Garrison 5NORTHWE		0.086	9.950	1.526	1.807	0.000	0.000	0.013	3.317	40459	40457	0	0:1	1	Gwye	Gwye	Single Phai	1.10
0	Alcoa 230/7NORTHWE		0.083	20.799	4.956	1.164	0.013	3.163	0.009	4.274	40033	40031	0	0:1	1	Gwye	Gwye	Core, Thre	0.23
0	Maple Vall7NORTHWE		0.083	9.636	4.978	4.412	0.061	6.992	0.021	5.192	40693	40689	0	0:1	1	Unknown	Unknown	Three Phai	0.83
0	Albany 230NORTHWE		0.081	20.295	6.786	1.541	0.028	6.934	0.004	1.823	40027	40025	0	0:1	1	Gwye	Gwye	Core, Thre	0.23
0	Black Creek7NORTHWE		0.079	9.153	6.242	0.288	0.026	2.170	0.029	7.790	41402	41402	0	0:1	1	Unknown	Unknown	Unknown	0.28
0	Aberdeen 1NORTHWE		0.078	39.290	13.097	1.850	0.026	13.097	0.000	0.000	40007	46792	0	0:1	1	Gwye	Delta	Unknown	0.14
0	Allston 500NORTHWE		0.078	8.984	9.404	11.135	0.130	14.975	0.048	12.112	40045	40043	0	0:2	1	Gwye	Gwye	Single Phai	1.10
0	Napavine 5NORTHWE		0.077	8.569	2.990	1.357	0.013	2.990	0.000	0.000	40774	47582	0	0:1	1	Unknown	Unknown	Unknown	1.10
0	Andrew Yo7NORTHWE		0.075	18.775	3.572	0.492	0.007	1.763	0.011	5.740	46860	46862	0	0:1	1	Gwye	Gwye	3-Legged C	0.13
0	Grand Coul7NORTHWE		0.075	8.627	2.876	3.417	0.025	2.876	0.000	0.000	41739	40291	0	0:1	1	Unknown	Unknown	Unknown	1.10
0	Grand Coul7NORTHWE		0.075	8.627	2.876	3.417	0.025	2.876	0.000	0.000	41741	40295	0	0:1	1	Unknown	Unknown	Unknown	1.10
0	Grand Coul7NORTHWE		0.075	8.627	2.876	3.417	0.025	2.876	0.000	0.000	41740	40293	0	0:1	1	Unknown	Unknown	Unknown	1.10
0	Grays Harb7NORTHWE		0.074	18.658	6.219	1.789	0.025	6.219	0.000	0.000	47595	47596	0	0:1	1	Unknown	Unknown	Unknown	0.28
0	Grays Harb7NORTHWE		0.074	18.658	6.219	1.789	0.025	6.219	0.000	0.000	47595	47598	0	0:1	1	Unknown	Unknown	Unknown	0.28
0	Grays Harb7NORTHWE		0.074	18.658	6.219	1.789	0.025	6.219	0.000	0.000	47595	47597	0	0:1	1	Unknown	Unknown	Unknown	0.28
0	Chief Jose)NORTHWE		0.074	8.503	11.610	13.793	0.177	20.425	0.076	19.178	40233	40232	0	0:3	1	Gwye	Gwye	Single Phai	1.10
0	Centralia 5NORTHWE		0.073	8.215	2.738	3.252	0.024	2.738	0.000	0.000	47745	47744	0	0:1	1	Unknown	Unknown	Unknown	0.28
0	Shawnee 2NORTHWE		0.070	17.580	3.880	1.097	0.008	2.093	0.008	4.145	48385	48383	0	0:1	1	Unknown	Unknown	Unknown	0.28
0	Vantage 5CNORTHWE		0.070	8.138	6.241	7.331	0.080	9.246	0.026	6.533	41113	41111	0	0:2	1	Gwye	Gwye	Single Phai	1.10
0	Happy Vall7NORTHWE		0.069	17.410	4.250	1.201	0.012	3.116	0.008	3.841	40505	47561	0	0:1	1	Unknown	Unknown	Unknown	0.28
0	Ross Dam 7NORTHWE		0.069	17.374	5.791	3.067	0.023	5.791	0.000	0.000	46461	46459	0	0:1	1	Gwye	Delta	Single Phai	0.51
0	Ross Dam 2NORTHWE		0.069	17.298	5.766	3.053	0.023	5.766	0.000	0.000	46460	46441	0	0:1	1	Gwye	Delta	Single Phai	0.51
0	Fairmount 7NORTHWE		0.067	17.286	4.740	1.114	0.015	3.718	0.004	2.093	40403	40401	0	0:1	1	Gwye	Gwye	Core, Thre	0.23
0	Centralia 5NORTHWE		0.067	8.071	1.758	2.588	0.018	1.758	0.000	0.000	47747	47740	0	0:1	1	Unknown	Unknown	Unknown	0.28
0	Fairview 2NORTHWE		0.067	16.779	2.295	3.309	0.030	7.438	0.008	1.825	40409	40407	0	0:1	1	Gwye	Gwye	Single Phai	0.51
0	Little Goos7NORTHWE		0.067	7.769	5.590	3.075	0.022	2.590	0.000	0.000	44217	44213	44214	44216:1	1	Gwye	Delta	Single Phai	1.10
0	Wind Ridge7NORTHWE		0.065	16.192	5.451	1.565	0.022	5.451	0.000	0.000	43464	43362	0	0:1	1	Unknown	Unknown	Unknown	0.28
0	Hot Spring)NORTHWE		0.065	7.539	1.155	1.376	0.006	0.002	0.010	2.515	40553	40551	0	0:1	1	Gwye	Gwye	Single Phai	1.10
0	Napavine 5NORTHWE		0.063	7.526	2.509	2.783	0.022	2.509	0.000	0.000	40774	47582	0	0:1	1	Gwye	Gwye	Unknown	1.10
0	Napavine 5NORTHWE		0.063	7.526	2.509	2.783	0.022	2.509	0.000	0.000	40774	47583	0	0:1	1	Gwye	Gwye	Unknown	1.10
0	Paul 500/1NORTHWE		0.065	7.454	4.409	5.169	0.043	4.984	0.005	2.499	40821	42806	0	0:1	1	Gwye	Gwye	Unknown	1.10
0	Beacon (Sg)NORTHWE		0.063	15.909	5.073	1.430	0.019	4.844	0.002	0.839	48031	48029	0	0:1	1	Unknown	Unknown	Unknown	0.28
0	Alvey 230/7NORTHWE		0.063	15.797	4.178	0.994	0.011	3.127	0.006	2.280	40049	40047	0	0:1	1	Unknown	Unknown	Unknown	0.28
0	Beacon (Sg)NORTHWE		0.062	15.523	4.948	1.395	0.019	4.722	0.002	0.836	48025	48023	0	0:1	1	Unknown	Unknown	Unknown	0.28
0	Monroe 50NORTHWE		0.062	7.193	5.395	6.413	0.082	9.434	0.037	9.289	40749	40747	0	0:1	1	Gwye	Gwye	Single Phai	1.10
0	Sedro Woo7NORTHWE		0.061	15.397	4.099	1.174	0.022	5.077	0.015	7.728	42100	42119	0	0:1	1	Gwye	Gwye	Single Phai	0.51
0	Beaver 23NORTHWE		0.061	15.309	5.103	1.407	0.020	5.103	0.000	0.000	43021	43017	0	0:1	1	Gwye	Delta	Unknown	0.28
0	Aberdeen 2NORTHWE		0.061	15.307	5.440	1.298	0.023	5.778	0.001	0.698	40009	40007	0	0:4	1	Gwye	Gwye	Core, Thre	0.23
0	Lane 230/1NORTHWE		0.060	15.072	3.656	1.451	0.012	2.910	0.007	3.716	40627	40625	0	0:1	1	Gwye	Gwye	Three Phai	0.38
0	Toledo 230NORTHWE		0.060	15.052	5.017	1.423	0.020	5.017	0.000	0.000	41083	41081	0	0:1	1	Unknown	Unknown	Unknown	0.28
0	Pelton 5NORTHWE		0.059	29.731	9.910	1.457	0.005	2.499	0.025	12.407	42806	42807	0	0:1	1	Gwye	Gwye	Unknown	0.14
0	J.D. Ross 3NORTHWE		0.058	9.630	6.943	5.374	0.086	14.408	0.045	11.198	40901	40899	0	0:1	1	Gwye	Gwye	Single Phai	0.76
0	COB Energ7NORTHWE		0.058	6.730	2.243	2.686	0.019	2.243	0.000	0.000	45262	45452	0	0:1	1	Unknown	Unknown	Unknown	1.10
0	Big Eddy 5(NORTHWE		0.057	6.600	9.420	11.224	0.135	15.571	0.053	13.371	40111	41343	0	0:5	1	Gwye	Gwye	Single Phai	1.10
0	Danskin W)IDAHO		0.056	14.057	4.686	0.640	0.019	4.686	0.000	0.000	60394	60391	0	0:1	1	Gwye	Delta	3-Legged C	0.13
0	Franklin 23NORTHWE		0.056	13.961	5.446	0.757	0.016	3.961	0.015	8.818	41125	41124	0	0:1	1	Gwye	Gwye	Single Phai	0.51
0	Blue Lake 2NORTHWE		0.055	13.618	5.631	1.617	0.032	7.928	0.013	7.297	43685	43684	0	0:1	1	Unknown	Unknown	Unknown	0.28
0	Sammamis7NORTHWE		0.054	13.462	3.440	0.982	0.024	5.973	0.016	8.059	42319	42323	0	0:1	1	Gwye	Gwye	Unknown	0.28
0	Southwest 5NORTHWE		0.054	13.443	4.764	0.660	0.020	5.048	0.000	0.000	46645	46643	0	0:1	1	Unknown	Unknown	Unknown	0.28
0	Big Eddy 5(NORTHWE		0.054	6.209	12.835	15.293	0.191	22.005	0.079	19.936	40111	41341	0	0:2	1	Gwye	Gwye	Single Phai	1.10
0	Drummond PACE		0.053	18.881	6.234	1.012	0.017	6.084	0.001	0.562	66843	65470	0	0:1	1	Gwye	Gwye	Core, Thre	0.16
0	Sherwood 7NORTHWE		0.053	15.802	1.836	0.225	0.006	1.465	0.011	5.542	43527	43523	0	0:1	1	Unknown	Unknown	Unknown	0.28
0	Chehalis 2NORTHWE		0.053	13.225	4.789	1.366	0.020	4.953	0.001	0.543	40207	40203	0	0:1	1	Unknown	Unknown	Unknown	0.28
0	Box Canyo7NORTHWE		0.052	25.868	8.623	1.223	0.005	2.646	0.014	6.860	47126	47009	0	0:1	1	Unknown	Unknown	Unknown	0.14
0	Vantage 5CNORTHWE		0.052	6.044	3.422	4.020	0.040	6.621	0.010	2.606	41113	41112	0	0:1	1	Gwye	Gwye	Single Phai	1.10
0	Port Angel7NORTHWE		0.051	12.918	4.860	1.373	0.020	5.098	0.001	0.792	40839	40841	0	0:1	1	Unknown	Unknown	Unknown	0.28
0	Lane 230/1NORTHWE		0.051	12.703	3.987	0.959	0.018	4.408	0.007	3.449	40627	40625	0	0:2	1	Gwye	Gwye	Core, Thre	0.23
0	Hungry Ho7NORTHWE		0.050	12.503	4.168	1.146	0.017	4.168	0.000	0.000	40557	40555	0	0:12	1	Unknown	Unknown	Unknown	0.28
0	Hungry Ho7NORTHWE		0.050	12.503	4.168	1.137	0.017	4.168	0.000	0.000	40557	40556	0	0:34	1	Unknown	Unknown	Unknown	0.28
0	Bethel (PG)NORTHWE		0.050	12.496	7.545	2.172	0.044	10.924	0.013	6.759	43039	43037	0	0:2	1	Gwye	Gwye	Unknown	0.28
0	Chemawa 7NORTHWE		0.050	12.450	7.941	1.910	0.047	11.731	0.016	7.788	40213	40211	0	0:1	1	Gwye	Gwye	Core, Thre	0.23
0	Malin 230/1NORTHWE		0.050	12.268	4.090	1.086	0.016	4.090	0.000	0.000	45189	45187	0	0:1	1	Unknown	Unknown	Unknown	0.28
0	Sno-king 2NORTHWE		0.049	12.264	2.213	0.632	0.011	2.731	0.011	5.347	41004	41002	0	0:3	1	Unknown	Unknown	Unknown	0.28
0	COB Energ7NORTHWE		0.049	5.645	1.882	2.253	0.016	1.882	0.000	0.000	44276	44277	0	0:1	1	Unknown	Unknown	Unknown	0.28
0	COB Energ7NORTHWE		0.049	5.645	1.882	2.253	0.016	1.882	0.000	0.000	45262	45451	0	0:1	1	Unknown	Unknown	Unknown	0.28
0	Toledo 230NORTHWE		0.048	12.093	4.031	1.143	0.016	4.031	0.000	0.000	41083	41081	0	0:2	1	Unknown	Unknown	Unknown	0.28
0	N. Lewisto7NORTHWE		0.048	12.082	4.857	1.381	0.028	7.134	0.013	6.361	48255	48253	0	0:1	1	Gwye	Gwye	Single Phai	0.51
0	Sunset 230NORTHWE		0.047	11.723	3.261	0.937	0.023	5.713	0.008	7.330	43740	43739	0	0:1	1	Unknown	Unknown	Unknown	0.28
0	Caldwell 2)IDAHO		0.046	11.430	3.670	0.492	0.014	3.460	0.001	0.359	60110	60105	0	0:1	1	Gwye	Delta	3-Legged C	0.13
0	Lolo 230/1NORTHWE		0.045	11.399	3.249	0.919	0.011	2.806	0.003	1.358	48197	48195	0	0:2	1	Unknown	Unknown	Unknown	0.28
0	Mur

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FY15 TI QUARTERLY STATUS REPORT

TIP number and Project Name: TIP 359: Improved System Modeling for GMD and EMP Assessments

FY16 Quarter: Quarter 1
Overall Status: Green

Activities and Accomplishments *(include information to substantiate* **overall status assessment; what happened since the last report?***):*

- The cooperative agreement with the University of Illinois (UIUC) was fully executed on November 20th, 2015. They are sub-contracting with one of the other PIs at Computational Physics Inc (CPI). As of January 1, 2016 this agreement was still being negotiated. Assuming the subcontract is signed by early January, this should not have any project impact.

Stage Gate 1: Complete

- UIUC has verified that the power system modeling data set to be used with this project is sufficiently detailed and accurate enough to represent the GIC resistance model of generation sites within the study area and boundary areas. Figure 1 shows calculated transmission line GICs using this model for a uniform 2 V/km eastward field; the size of the yellow arrows on each transmission line are proportional to the GIC flow. Figure 2 shows substation neutral flows for the same model ; the size of the substation is proportional to its GIC neutral flow, with red used to indicate substations with flows out of the ground into the system and green substations with flows into the ground.

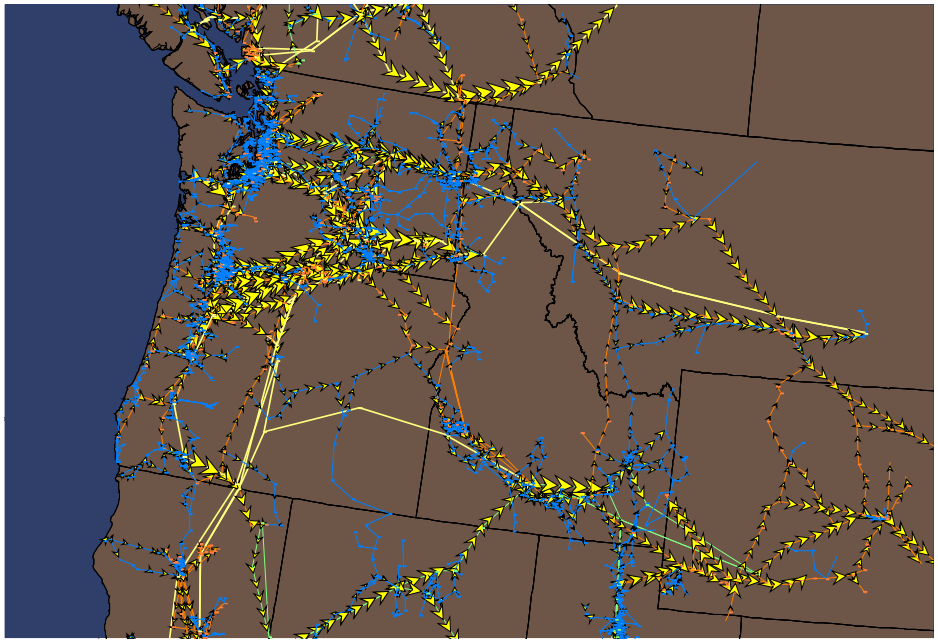

Figure 1: Transmission Line GICs in Study Footprint

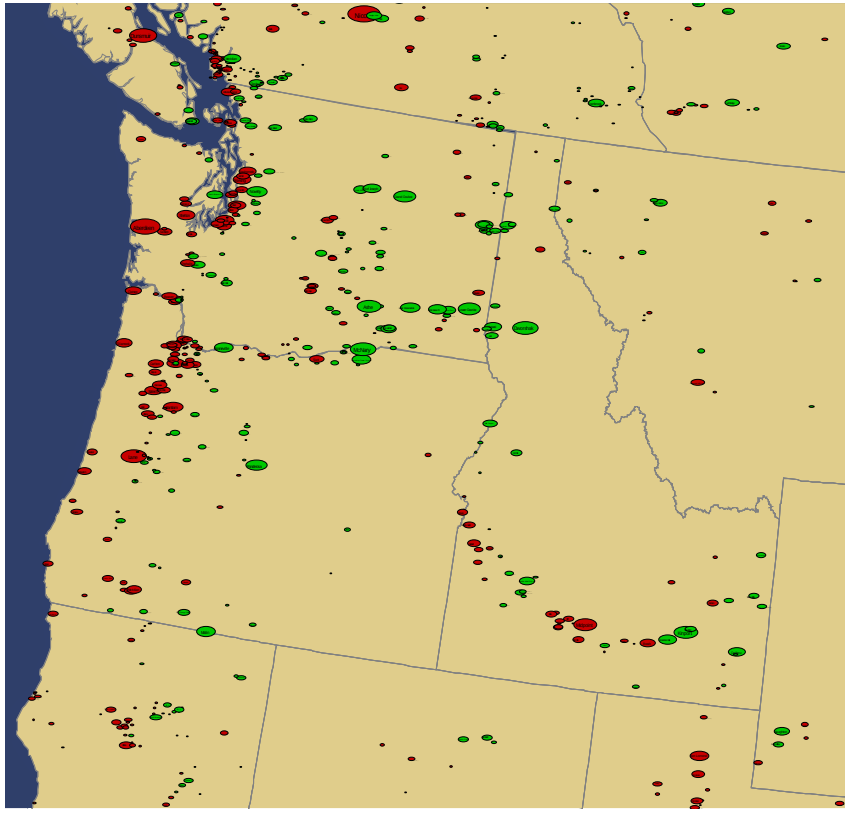

Figure 2: Substation GICs in Study Footprint

- During the January to March quarter UIUC researchers will be working on Task 1 and 2, and CPI on Task 2. In particular, for Task 1 UIUC researchers will be doing sensitivity analysis on the model to determine the most important parameters and working on mapping the planning models to the EMS models, and will be working with BPA to get the BPA transformer neutral flow GICs mapped to the models. For Task 2 UIUC will begin work on the tool that will be used to validate the system-wide GIC model. For Task 2 CPI will be working on developing an improved conductivity model for the BPA footprint based on published papers and available NSF Earthscope data.

Project Expenses: Green

FY	Total Project Budget	BPA Budget	Cost Share	BPA YTD Actual	YTD Cost Share Actual	BPA FTE	BPA FTE Actual
2016	264,330	132,165	132,165	3633	0	0	0

Schedule *(Identify major tasks and **stage gate(s)** scheduled for next reporting period)*: Green

Task	Planned Completion	Actual Completion

Setting Up System Model	April 2016	
GIC Ground Conductivity Model	August 2016	
Benchmark E-field Model	October 2016	
Grounding Resistance Model	December 2016	
Transformer Reactive Power Models	September 2017	
Transformer Harmonic Analysis	September 2017	
EMP Assessment	September 2017	

Risk Management: Green

Risk Event	Cause and Effect	Risk Response Plan	Monitoring and Control

General Concerns: None

Approvals

Project Manager: No
Project Sponsor: No
TI PMO: No

TIP 359: Improved System Modeling for GMD and EMP Assessments

Context

The potential for geomagnetic disturbances (GMDs) and electromagnetic pulse (EMP) to cause significant impacts on the power grid is now a well-recognized issue. Recently, NERC has been directed by FERC to develop reliability standards to address GMD assessments*, with the GMD operational/reliability standards already in effect (NERC standard EOP-010-1). GMDs induce very low frequency (much less than 1 Hz) electric fields at the earth's surface and consequently drive quasi-dc geomagnetically induced current (GIC) in the grid. GICs can cause half-cycle saturation of transformers, giving rise to harmonics and increased reactive power absorption in transformers. This transformer reactive power loss could severely impact the system voltage stability, while harmonics currents can cause misoperation of protection devices. Unintended isolation of needed components such as capacitor banks and transformers during GMDs further increase the vulnerability of the network to voltage collapse, as seen in the March 1989 collapse of Hydro-Quebec.

Description

This work builds upon the recent successful GMD modeling and validation works by the University of Illinois and other industrial partners. These efforts include an EPRI project on GIC flow modeling and the collaboration with AEP to assess their system.

The project will provide BPA engineers with a methodology for a validated GMD flow model and benchmark GMD scenarios, as required to be available per the upcoming FERC standards.

The first goal of this project is to establish an integrated system-data model to validate the GIC flow model. This can be used by BPA to construct a benchmark GMD storm scenario as required by standards, and to improve the accuracy of the GIC flow modeling. The second goal is to develop and validate the modeling of transformer response to the GIC flow using BPA system power flow data, as an extension to the GIC flow validation to improve the quantitative understanding of the negative GMD impacts in planning studies. The third goal of this project is to build on the GMD modeling to develop models and tools for EMP assessment of power systems, in the necessary power system dynamics time frame.

Why It Matters

Better GMD/EMP model results by validating the source of uncertainty using real data provide a higher probability of mitigating the potential impacts at both system level (higher reactive power losses) or asset level (transformer/capacitor misoperation). And better GMD/EMP assessment models would provide operators with the tools needed to mitigate system voltage collapse and transformer heating, which would help prevent wide-area power outages.

The research activities on GMD assessment and benchmark electric field construction directly fulfills the requirements per the recently released NERC reliability/ operational standard EOP-010-1.

Goals and Objectives

The overall objective of this work is to contribute to geomagnetic disturbance (GMD) and electromagnetic pulse (EMP) assessments for the BPA system, with various-level models of improved accuracy. This ultimate benefit includes enhanced decision-making regarding planning, operations and mitigation strategies in the presence of GMDs. This will be achieved by validating several GMD-related system parameters and modeling approaches for the BPA system, thanks to available data measurement during GMD storms.

Deliverables

All the validation results and methods developed in each of the tasks described earlier will be provided to BPA. Discussion on the accuracy of the GIC flow model will be offered to guide future placement of GIC monitoring devices. Documentation on the usage of those methods will also be provided.

The validation studies performed using these methods and the results of those will be delivered through reports, including the discrepancies found and the following analysis. Deliverables will include the development of the benchmark Electric field model for the BPA footprint, as required by the NERC standards. At each stage gate, all required and applicable reports, documents and tools will be submitted to BPA for evaluation of sufficient progress.

A final report will be provided, describing the execution and achievements of the entire project in detail, as well as charting out the future directions.

TIP 359: Improved System Modeling for GMD and EMP Assessments

Project Start Date: October 1, 2015

Project End Date: September 30, 2017

Reports & References

* "Reliability Standards for Geomagnetic Disturbances," FERC Final Rule, Docket No. RM12-22-000; Order No. 779, May 16 2013

Links

Participating Organizations

University of Illinois at Urbana-Champaign (UIUC)
Computational Physics, Inc. (CPI), Boulder, CO

Funding

Total Project Cost:	$503,000
BPA Share:	$251,000
BPA FY2016 Budget:	~~$132,000~~ $125,000

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Volume II: Project Description: Technical Proposal for Evaluation Purposes by or on behalf of the Bonneville Power Administration

BPA Technology Innovation Opportunity for Fiscal Year 2016

Improved System Modeling for GMD and EMP Assessments

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1 Goal and Scope of the Agreement

The general goal of this proposed work is to enhance the geomagnetic disturbance (GMD) assessment for the BPA system by developing a methodology for validating various types of GMD models. The first objective is to develop an integrated system-data model in order to validate the GIC flow model. This can be used by BPA to improve the accuracy of the GIC flow modeling within its footprint. The second objective is to develop and validate the modeling of transformer response to the GIC flow using BPA system SCADA data, as an extension to the GIC flow validation to improve the quantitative understanding of the negative GMD impacts for planning studies. The final objective is to develop models and tools that enable the assessment of electromagnetic pulse (EMP) impacts on power systems.

The proposed work directly addresses a key R&D gap (RD18: Tools for GMD/EMP assessment), mentioned in the *BPA Transmission Technology Roadmap,* published in March 2014. The major technology developments of this project will be to provide better models and benchmark GMD scenarios for the BPA footprint, validate the GIC flow model parameter accuracy, as well as the provide better quantitative models to characterize the transformer behavior due to GIC flows. A measurement-driven validation framework will be developed that could compliment or partially replace direct testing of transformers, while ensuring the results accurately reflect the actual system response.

We identify this proposed work as an important driver in helping achieve BPA's goal of improving its risk-based study tools, as mentioned in the Technology Roadmap. This work will provide BPA engineers with a methodology for a validated GMD flow model and benchmark GMD scenarios, as required to be available per the upcoming FERC standards.

2 Background

The potential for geomagnetic disturbances (GMDs) to cause significant impacts on the power grid is now a well-recognized issue. Recently, NERC has been directed by FERC to develop reliability standards to address GMD assessments [1], with the GMD operational/reliability standards already in effect (NERC standard EOP-010-1). GMDs induce very low frequency (much less than 1 Hz) electric fields at the earth's surface and consequently drive quasi-dc GICs in the grid. GICs can cause half-cycle saturation of transformers, giving rise to harmonics and increased reactive power absorption in transformers. This transformer reactive power loss could severely impact the system voltage stability, while harmonics currents can cause misoperation of protection devices. Unintended isolation of needed components such as capacitor banks and transformers during GMDs further increase the vulnerability of the network to voltage collapse, as seen in the March 1989 collapse of Hydro-Quebec.

While the models used to perform GMD assessments have come a long way, many sources of uncertainty still exist in these models. Such uncertainty lies within the geo-electric field scenario, the local accuracy of wide area conductivity models, the GIC system model, as well as within the transformer models. These uncertainties are acknowledged in the proposed standards by the directive to use locally-accurate models, where they are available. In light of these serious modeling concerns, recent efforts have been made towards validating the assessment of GMD impact in the planning cases, by using field transformer neutral GIC measurements. This proposal is aimed at solving this two-fold problem.

The proposed work builds upon the recent successful GMD modeling and validation works by the University of Illinois and other industrial partners. These efforts include an EPRI project on GIC flow modeling and the collaboration with AEP to assess their system. This previous experience laid the groundwork for the GMD

model validation tasks that we are proposing. Furthermore, the team has an ongoing BPA project on transient simulation tool verification and validation. This project familiarized us significantly with the BPA system. It was also instrumental in helping build expertise in the software packages utilized by BPA. All of these past efforts invariably make us confident in succeeding with the proposed project.

Motivated by the potential negative impacts of GMDs, utilities such as BPA are deploying advanced GIC monitors that measure a variety of useful data such as transformer neutral currents, reactive power losses, harmonics, and tank wall vibrations. These measurements present a great opportunity to help validate existing GMD models for the BPA system. The proposed validation efforts will directly address the challenges encountered by most utilities in the GMD assessment, including the ground conductivity models used in determining the induced electric fields for the benchmark GMD scenario, insufficient SCADA data on GIC flow model parameters, as well as inadequate transformer behavior understanding.

In contrast to GMDs which are naturally occurring disturbances, EMPs are man-made nuclear disturbances that can have significant impacts on power system operations. There are 3 different types of EMP waves (E1, E2, and E3) that can affect the power grid, of which the E3 wave is somewhat similar to a GMD, in the sense that they both induce electric fields at the earth's surface and induce dc currents (i.e. GICs) in the power grid. Hence, GMD modeling can be leveraged to study EMP impacts. However, the key differences in EMPs as compared to GMDs, such as the higher magnitudes of electric fields as well as their much faster rise times puts this problem in a much faster time-scale than GMDs. In the proposed project, EMPs will be modeled in the appropriate power system dynamics (i.e. transient stability) time frame to enable sound EMP assessments.

3 Location of the Project

This project will be performed at University of Illinois at Urbana-Champaign in Urbana, Illinois, and at Computational Physics, Inc in Boulder, CO.

4 BPA-Furnished Property of Services

BPA will provide no property for this project. Initially, BPA will provide UIUC with the GIC related measurement data and the associated GIC system model such as state-estimator cases. The project team has an ongoing Technology Innovation Project (TIP 268), with experiences in handling BPA's EMS data. The necessary NDAs for such cases are already in place. Additional system information such as substation geo-location and network resistance values is needed for the GIC flow analysis. The best measurement data sets would be those associated with GMD events at higher intensity. While a strong GMD event is unlikely to project timeframe, most modest GMDs occur with sufficient regularity that we believe there should be sufficient historical and new events over the project timeframe to achieve the validation goals. Any recent historical data would be needed preferably as soon as possible, no later than approximately six months from the start of the project.

All the data will be transferred to the primary applicant, in any suitable electronic format as found fit by BPA to the following address:

Professor Thomas J. Overbye
4054 ECE Building, MC 702
306 N. Wright Street
Urbana, IL 61801

Email: overbye@illinois.edu

5 Recipient-Furnished Property or Services

The applicants will provide no property for this project. The applicants will provide all services in support on this project except those mentioned under section 4 above.

6 Definitions and Acronyms

UIUC – University of Illinois at Urbana-Champaign

CPI – Computational Physics Inc

GMD – Geomagnetic disturbance

GIC – Geomagnetically induced current

EMP – Electromagnetic Pulse

7 Documentation

None.

8 General Requirements

In order to meet the objectives of this proposed project, three main tasks must be performed. The last two tasks have been divided into three subtasks for clarity and better management. The tasks and subtasks are listed below:

1. Setting up an integrated system-data model for validating GMD impacts
2. Validating the system-wide GIC flow model
   a. Improving the accuracy of the ground conductivity model at BPA footprint
   b. Determining a realistic benchmark electric field model
   c. Verifying the substation grounding resistance data from the system model
3. Validating the GIC-induced transformer behavior
   a. Validating the effect of GIC-induced transformer reactive power losses
   b. Developing a validated transformer harmonics analysis model
4. Developing models to study the impact of EMPs (E3 type) on the power grid

9 Specific Requirements

A. Objectives / Technical Problem

The overall objective of this proposed work is to contribute to GMD and EMP assessments for the BPA system, with various-level models of improved accuracy. This ultimate benefit includes enhanced decision-making regarding planning, operations and mitigation strategies in the presence of GMDs and EMPs. This will be achieved by validating related system parameters and modeling approaches for the BPA system, using available data measured during GMD storms. The first goal of this project is to

establish an integrated system-data model to validate the GIC flow model. This can be used by BPA to construct a benchmark GMD storm scenario allowed by standards to more accurately assess GMD affects than the default benchmark events, and to improve the accuracy of the GIC flow modeling. The second goal is to develop and validate the modeling of transformer response to the GIC flow using BPA system power flow data, as an extension to the GIC flow validation to improve the quantitative understanding of the negative GMD impacts in planning studies.

B. Description of tasks to be performed

Four major tasks will be accomplished in this project. Tasks 2 and 3 have been divided into three subtasks for clarity and better management. Some aspects of each task will be co-dependent on other tasks. Hence, the tasks will be executed in a logical order, and there will be parallel performance of some aspects of the tasks. The task interactions have been included in each task description.

Task 1. Setting up an integrated system-data model for validating GMD impacts

A major task while performing any type of validation in power systems is to re-create a system model as it was during a disturbance or an event, in this case for a GMD storm. To this end, real-time or EMS models provided by BPA corresponding to the GMD event(s) will be utilized. The project team has experience in handling BPA's EMS models and mapping them to planning cases to extract dynamic models, in an ongoing Technology Innovation Project (TIP 268). The necessary NDAs for such cases are already in place.

To model electric fields and their induction effects, additional system information is needed, such as the geo-locations for each substation and the bus-substation mapping. Thanks to our previous WECC footprint studies, we already have access to a majority part of this data.

Calculating GICs needs additional dc network resistance values such as those of transformer windings, and substation grounding (including the effect of shield wires). These values are not available in standard planning cases or EMS models. To enable a more accurate analysis, these values will need to be provided by BPA, from transformer test reports for instance, for as many system elements as possible. However, if these values are not available, the transformer resistance can be estimated using the series ac resistances of the transformers in the power flow case. For substation grounding resistances actual values are certainly preferred for accuracy. If these are not available, heuristics can be used (such as either considering the grounding values to be zero ohms, which usually overestimates the GICs) or rough estimates can be made based on the highest nominal voltage level of the substation. In cases where these parameter values are available from BPA, it will enable the validation of these parameter estimation algorithms used in GIC tools, leading to better default parameter values.

Different types of measurement data will be used in this project, each of which will require some pre-processing techniques, as observed in our previous works. In addition to transformer neutral current meters to monitor the GIC flow, measurements on transformer reactive power losses and (if available) harmonics would greatly benefit the validation of transformer models in Task 3. The transformer reactive power losses can be determined from standard SCADA data. Moreover, magnetometer measurements from relevant observatories (i.e. in or near the BPA footprint) can be leveraged to estimate the electric field from the real geomagnetic field data, during the GMD storms when GICs and transformer quantities are measured.

The duration of this task will be 7 months, with the first two aspects, i.e. system modeling requirements for calculating electrical field and GICs to be completed in 4 months. Collecting and incorporating various meter measurements during the GMD storms will be finished by the end of the 7-month duration.

Task 2. Validating the system-wide GIC flow model

The system-wide GIC flow analysis is essential for understanding the impacts of GMD events. However, there exist a variety of sources of uncertainty throughout the GIC calculation due to insufficient information regarding input parameters within or even outside of power systems. The lack of accuracy in the GIC parameters calls for validating the real measurement data during GMD events as collected in Task 1.

The GICs in transformer neutrals are related to the input electric (E-) field through a linear flow model. Such linear transformation solely depends on system information, including transmission line topology, substation geo-locations, as well as the winding resistance values, all of which need to be modeled in Task 1. In addition, although the induced geo-electric field is driven by changes in the geomagnetic field, the earth ground conductivity at a range of depths determines the magnitude of the electric field response. Therefore, we have developed a systematic approach to validating the GIC flow model based on measurements of transformer neutral currents and geomagnetic field. The electric field can be estimated based on two approaches, one by filtering the geomagnetic field based on the earth conductivity model, and one by data fitting the transformer neutral GIC data. Results from the two approaches can be compared with each other, in order to validate the accuracy of the assumed models on ground conductivity and GIC network flows.

Nonetheless, as widely recognized in latest NERC GMD Taskforce meetings, there is potentially a high degree of uncertainty in the ground models published by U.S. Geological Survey (USGS). Figure 1 illustrates the USGS earth ground conductivity models for different physiographic regions of the U.S., with a detailed model showing the range of uncertainties. This range of uncertainty from the USGS earth ground conductivity models has been further identified to lead to a factor of 3-4 difference in the Electric field intensity. More recently at the NERC meeting in March 2014, a location-dependent Electric field model as required by the standards, was proposed to calculate the peak Electric field relative to the reference location benchmark as given by $E_{peak} = E_{benchmark} \times \alpha \times \beta$ in Volts/km. Specifically, α is a scaling factor according to local geomagnetic latitude, while the β factor accounts for regional earth conductivity. This task will contribute to investigate the uncertainties in the ground conductivity, develop a benchmark Electric field, and validate the system model at the BPA footprint, as listed in the following three subtasks.

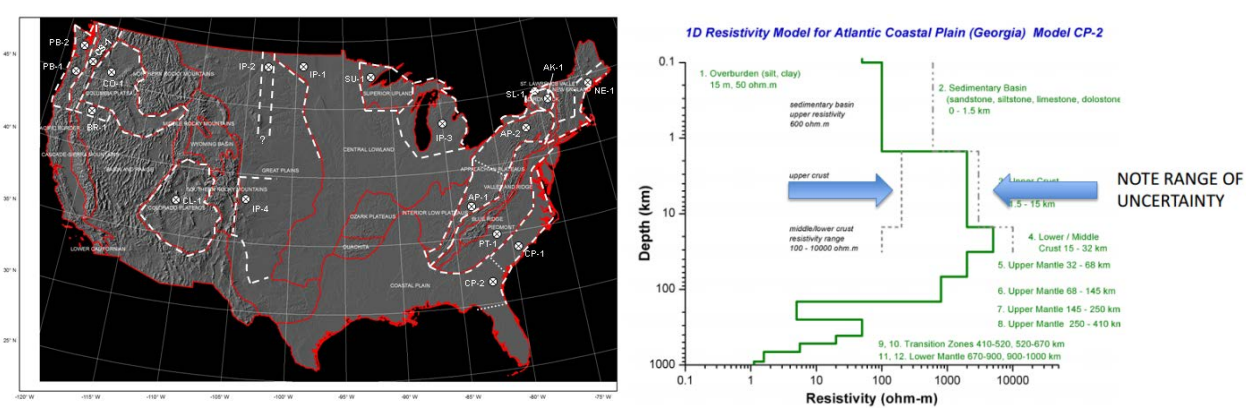


Figure 1. Location of 1D earth resistivity models with respect to physiographic regions of the U.S., with a detailed model shown to highlight uncertainties (Sources: http://geomag.usgs.gov/conductivity/)

a. Improving the accuracy of the ground conductivity model at BPA footprint: As mentioned earlier, a linear estimation approach can be used to obtain the electric field from the field GIC measurements during the disturbances. Since this estimate is obtained from real data, it offers a better representation of the actual peak electric field intensity, and thus has the potential to be used to validate the ground conductivity model for BPA footprint provided by USGS. As an example, Figure 2 illustrates the proposed electric field estimates after normalization using both GIC measurements and geomagnetic field data. It corresponds to a GMD event on March 9th, 2012, impacting a major electric utility at the U.S. Midwest region. A strong correlation between the two estimates has been observed, corroborating the validity of our proposed approach to improving the ground conductivity model by investigating the electric field intensity as estimated from the GIC measurements.

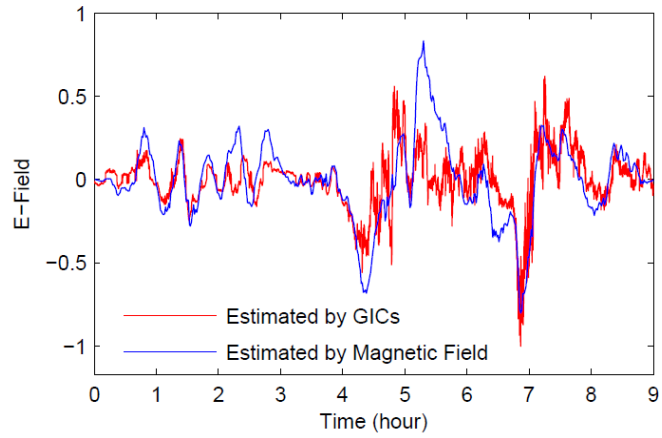


Figure 2. Comparison of northward electric fields estimated by using transformer GIC measurements and the observed magnetic field data, for a GMD storm in 2012

After the completion of the accuracy assessment of the regional USGS 1-D conductivity profiles, improvements to the local conductivity models will be made. We will first analyze the range of impact of the specified uncertainty of the existing 1-D models, using default models to identify the range of induced electric field that can occur within the error range of the regional USGS 1-D conductivity models. To narrow these uncertainties, we will improve the models over the BPA footprint by the following by adding local and lateral variations in conductivity. To achieve this goal, the following steps will be performed: a) comparison of the default 1-D models with published 3-D results from Earthscope, b) supplementation of 1-D models by adding local variations or subregions, where necessary, and c) supplementation of 1-D with lateral conductivity variation, where needed. These will produce a set of improved conductivity maps, allowing us to analyze local variations and improve the electric field estimates for a GMD event across the BPA footprint.

b. Determining a realistic benchmark electric field model: The ultimate goal of this step is to determine a range of realistic and extreme GMD storm scenarios for BPA, in order to benefit the system vulnerability analysis in the GMD mitigation programs. It is not enough to characterize a single electric field maximum over an entire region. Instead we will model the time and spatially-varying electric field over the BPA footprint. Using the improved ground conductivity model developed in the steps described above, a much more locally-accurate electric field GIC-driver than the default NERC event will be produced.

First, the improved conductivity information will be used to provide a more accurate estimate of the alpha and beta parameters used in the proposed standards for determining the maximum electric field value used in vulnerability analyses. This is the information required in the first step (GMD vulnerability analysis) of the proposed FERC regulations, and can be used as a broad-scale quantification of GIC risk across a regional area.

However, to fully understand the local impacts of an induced electric field for a given GMD event (and the impact of lateral variations in deep earth conductivity), knowledge of the evolution of the electric field over time and location must be developed. To quantify these location-specific and temporal variations, several maps of electric field magnitudes over the BPA footprint will be made (see the US example in Figure 3). These include: a) a map of the largest values, by geographic location, of induced electric field modeled over the BPA footprint, b) the variation in spectral characteristics of the induced electric field over the BPA foot print, which are used in transformer heating analyses, and c) a series of maps showing the electric field variation over time for the improved benchmark event over the BPA footprint. These can be used to understand and analyze the impact of "hotspots" in GIC evolution over a GMD event, and identify the most vulnerable assets within a broader system.

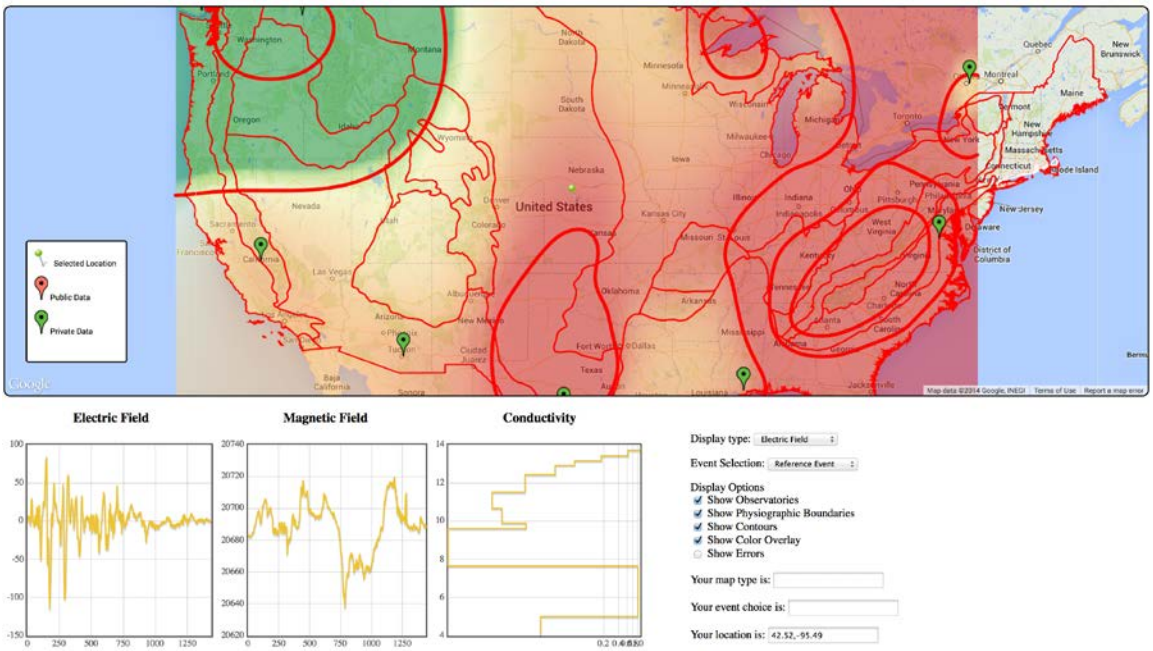


Figure 3. The US map including the evolution of electric field over space and time.

c. <u>Verifying the substation grounding resistance data from the system model:</u> This is another important aspect for GIC flow model validation. Previous works of the project team have identified that GIC values can be highly sensitive to several network parameters, such as the assumed substation grounding resistance. Based on our experiences with other utilities' systems, it is highly likely that the substation grounding resistances and/or transformer winding resistances are not accurately available from the EMS database. Hence, it is of crucial importance to study the GIC sensitivity to various network parameters of the BPA system, and accordingly to identify those can most significantly improve the accuracy of GIC flow model. The research team has worked with PowerWorld software platform to incorporate such sensitivity analysis for line resistance values, but substation grounding resistances have been recently identified to be more influential. One key pay-off of this research effort is to determine the substation locations where higher priority is needed to finding the grounding resistance values. Lastly, the aforementioned validation method based on field GIC measurements will be leveraged similarly to improve the accuracy of the grounding information at the high-priority substations. An algorithm for better estimating grounding resistances using GIC measurements has been developed and successfully implemented by the

research team. Figure 4 illustrates the performance of this estimation algorithm for a 20-bus test case, which iteratively improves the accuracy of grounding resistance values to a much more acceptable level.

The overall objective of this task is to use actual measurements to identify several crucial sources of inaccuracy in the input electric field and system model, and to eventually eliminate them for achieving a better GIC flow model for the BPA system. Task 2 will be performed as early as possible for 12 months, to make sure the success of the following Tasks 3 and 4.

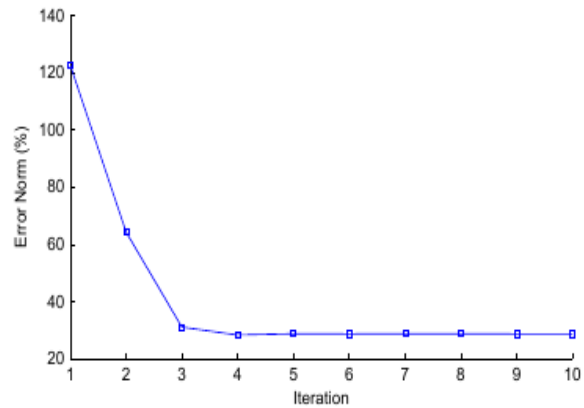


Figure 4. Error percentage in estimating grounding resistance decreases within just a few iterations for a 20-bus test case.

Task 3. Validating the GIC-induced transformer behavior

This task furthers the understanding of GMD impacts on the BPA system by improving the modeling of transformer response to the GIC flow. The flow of GICs in transformer windings causes half-cycle saturation of the transformer cores which leads to increased transformer hotspot heating, harmonic generation, and reactive power (var) absorption. Each of these effects can strongly impact large-scale power system reliability. Nonetheless, it is widely recognized that assessments of such effects at the system level are lacking, which motivates us to validate the BPA system power flow measurements during GMD storms, as collected in Task 1.

The 2012 NERC Interim GMD report concludes a major risk of system due to increased var absorption in the transformers and the resultant system-wide low voltages. NERC GMDTF recently (in March 2014) stated that planners will need to develop validated var loss models for transformers in their system, in order to perform voltage stability assessment studies. A widely-used methodology to calculate GIC-saturated var loss assumes that it scales linearly with the product of the effective GIC and bus terminal voltage. However, the linear scaling factor is generally missing for existing transformers, and could only be vaguely inferred from experiences. Due to the significant variation in transformers' scaling factors, actively validating these values for existing transformers in the BPA system is truly valuable for system voltage stability analysis.

Another equally important aspect of transformer validation is the harmonics analysis. The dc offset caused by GIC flow injects harmonic currents to the grid, and consequently affects operations of protection systems. This is exactly the case for the 1989 Hydro-Quebec blackout, where equipment protection relays were trigged within seconds leading to system voltage collapse. In addition, harmonic currents are also the culprit for transformer hot-spot heating, which could cause significant equipment damage. Albeit its potential financial effects, the harmonics analysis due to GIC is generally lacking in the literature, especially when integrated with the impact on system power flows. Clearly, it is extremely important to develop a GIC harmonics model validated by the BPA system power flow analysis.

Therefore, the task will be divided into the following subtasks.

a. Validating the effect of GIC-induced transformer reactive power losses: Compliment and partially replace in-depth transformer testing, we propose to validate the transformer var loss model using measurements from GIC monitoring devices and the SCADA system. Our prior work with BPA for estimating transmission line parameters has benefited us invaluable experience to handle challenges involved in utilizing SCADA data for parameter estimation, such as measurement noise and the lack of a known distribution of measurement errors. A finding of this work was also that the performance for reactance estimation (which is derived from measured var losses) is substantially better than that of resistance (which was an expected result given that the reactive power losses are substantially greater than the real power losses). Hence, it is very promising to leverage the same methodology to estimate the GIC var loss model, and satisfactory outcomes are expected. As an example, Figure 5 illustrates the model fitting results based on the var consumption measurements obtained by PMU devices. The PMU data are generated by the PowerWorld transient stability toolbox for a 20-bus test case. The strong agreement between the measurements and their values based on given var loss model ensures the feasibility of this approach. This method can be directly performed to validate the var loss scaling parameters for all transformers with GIC and corresponding SCADA data available. For transformers without such data, we will consider an inference framework by analyzing how the estimated scaling factors depend on transformer characteristics.

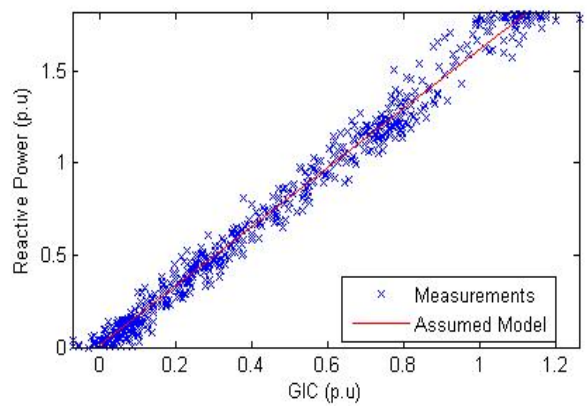


Figure 5. A measurement-based approach for validating the transformer var loss model that scales linearly with GIC values.

b. Developing a validated transformer harmonics analysis model: Thanks to the installed GIC monitoring devices in the BPA system, it is also feasible to investigate how the harmonics measurements vary with the GIC values. Similar to the var loss validation, a statistical learning framework can be adopted to develop an analytical characterization of the transformer harmonics model. Specifically, the transformer characteristics and neutral GIC measurements will be used as the input to infer how harmonics currents depend on these variables. Using the SCADA data on the harmonics level at other transformers, we can further improve and validate the accuracy of the developed harmonics model. Last, we will be interested to integrate the GIC-induced harmonics model with the power flow analysis using e.g., shooting method, in order to evaluate the negative impact on and hence the vulnerability of all system components including protection systems and distribution transformers.

The system-level GIC validation tool developed in Task 2 will be utilized to provide an accurate GIC input for validating the transformer models in the subtasks delineated under Task 3. Hence, Task 3 will start immediately once sufficient progress has made on Task2, and will last for 12 months.

Task 4. Developing models to study the impact of EMPs (E3 type) on the power grid

A high-altitude electromagnetic pulse (EMP) is a high-altitude nuclear detonation, which has a potential to blanket a large portion of the country with damaging electromagnetic radiation. An EMP wave emits three types of waves of energy, depending on their frequencies, as shown in Figure 6.

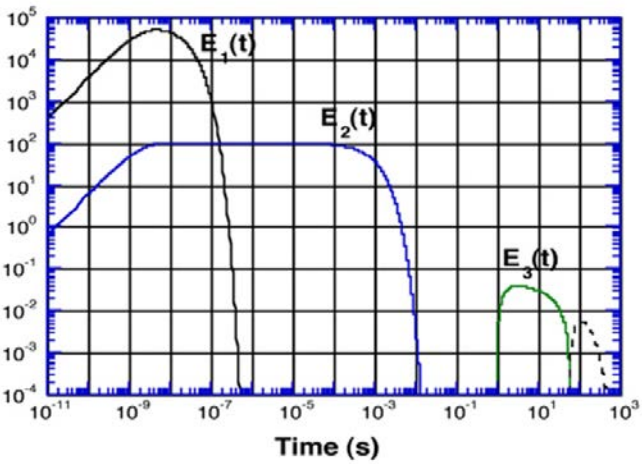


Figure 6. Waveforms of electric fields generated by the HEMP in Volts/m from IEC 61000-2-9

Of these waves, the E3 wave interacts with the power grid in a manner similar to GMDs, in that they induce geoelectric fields at the earth's surface, giving rise to GICs. A key difference, however, between the electric fields induced by EMPs and GMDs is the faster rise times (on the order of seconds), with much higher peak magnitudes caused by EMPs. For instance, the E3 wave in Figure 5 has a peak value of around 40 Volts/km, with a rise time of a few seconds. Thus, an E3 EMP operates on the same time frame as of power system dynamics, making it important to study their impacts in the transient stability domain.

This task will first involve developing the methodology to integrate EMP impacts into power system transient stability tools, and provide these tools to BPA for performing EMP assessments. In particular, the EMP disturbance will be translated into time-varying electric fields, GICs, and then the transformer reactive losses, which will be included in the transient stability solution. Such tools can be used for voltage stability studies in the presence of EMPs. Once this has been modeled, next since the underlying power system network model and transformer models are the same as that used for GMDs, this task will build on the achievements of Tasks 1 and 2 to further improve the EMP modeling to achieve more reliable simulation results, and it will last for 12 months.

The project team's expertise in both GMD and transient stability modeling will help in the successful execution of this task.

C. Project Management Protocols

UIUC will be responsible for the project management tasks related to this project.

i. Communications plan:

The UIUC team will work closely on this project, through (bi-)weekly meetings and discussions. Work progress will be reported timely to BPA through quarterly reports. At each stage gate, all applicable documents and reports will be submitted to BPA for evaluation of sufficient progress. Presentations will be delivered as a part of reporting, wherever required. The validation methods and tools developed in this work will also be provided to BPA in a timely manner. A final report of all the research results and tools developed will be submitted.

The CPI team will coordinate closely under the direction of the UIUC team, participating in meetings and discussions where deemed necessary by the UIUC lead. The CPI team will provide documentation and reports to UIUC in a timely manner to support all deliverables to BPA.

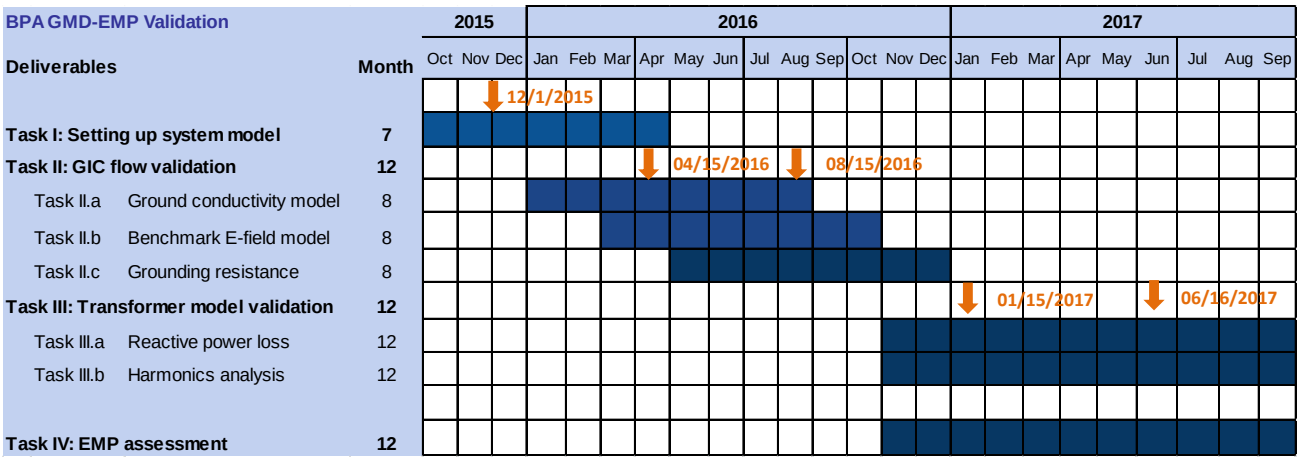
ii. Contingency plan:

The progress of the project will be evaluated at the two stage gates that have been designed for this project. This project undertakes broad and challenging tasks, which may take longer than planned for. Hence, it is somewhat possible that some tasks may not have anticipated progress at the stage gates. In case this contingency occurs, a natural remedy would be to devote the remaining hours to completing as many aspects of the tasks, charted out in the description, as possible.

iii. Stage Gates:

There will be five~~two~~ stage gates in this two-year project. The first-year stage gates will be on 12/1/2015, 04/15/2016 and 08/15/2016. The second-year ones will be on 01/15/2017 and 06/16/2017. The criteria for determining success at each stage gate have been mentioned in the Process Flow Chart in Part v.

iv. Gantt chart of all the stage gates, tasks and subtasks:

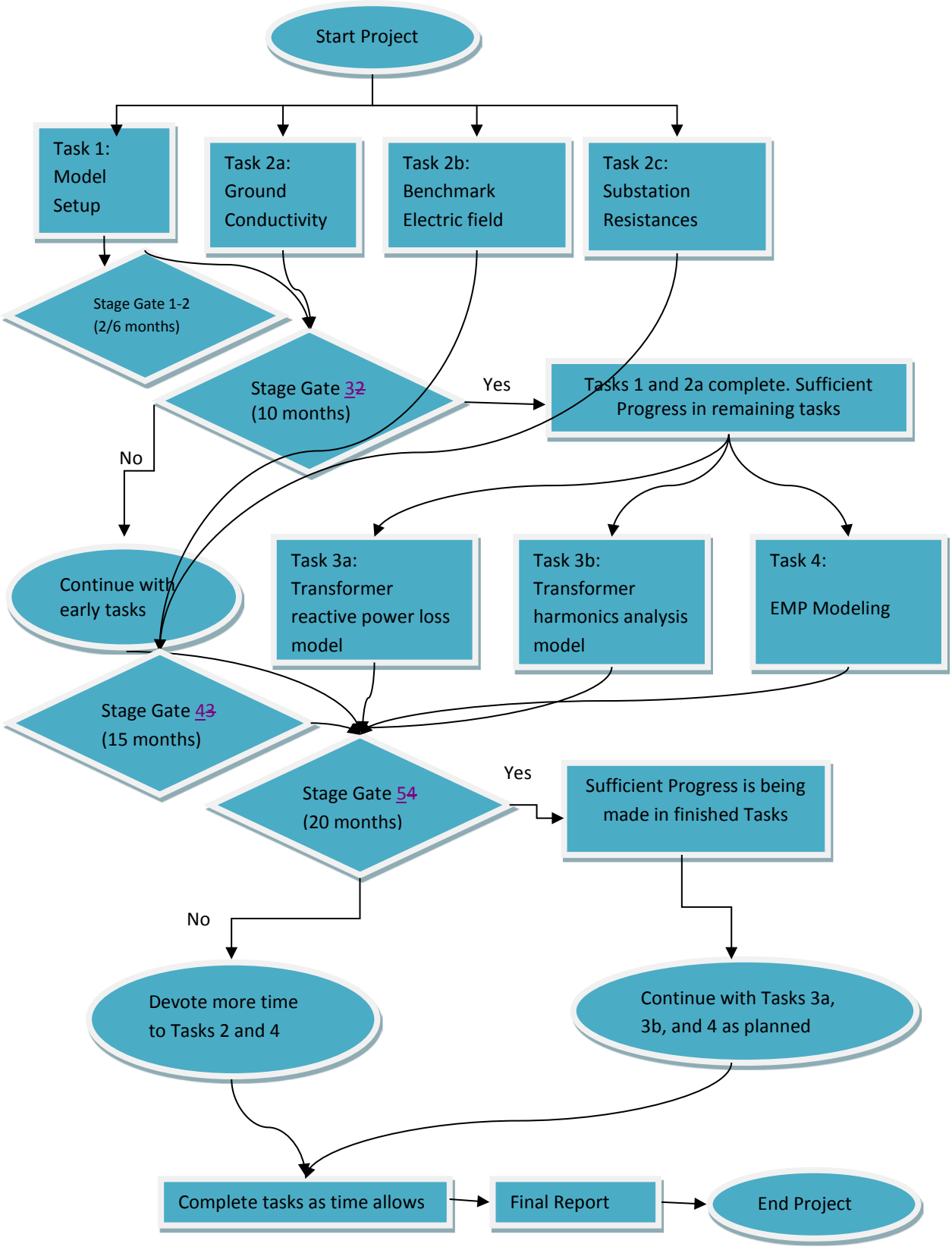


The deliverables and evaluation points at each stage gate are listed here.

Stage Gate 1	Demonstrate modeling data set to be used is sufficiently detailed and accurate enough to represent the GIC resistance model of generation sites within the study area; and boundary equivalent GIC models are sufficient to provide reasonable representation of GIC flow from/to transmission networks beyond the study area.
Stage Gate 2	An improved conductivity model for the BPA footprint will be available, based on published papers and available Earthscope data. It will be compared with the USGS 1D conductivity model for the region.
Stage Gate 3	Initial benchmark electric field maps of the BPA footprint will be created from USGS 1D conductivity models and magnetic field data. These maps include: a) a map of the largest values, by geographic location, of induced electric field b) the variation in spectral characteristics of the induced electric field, and c) a series of maps showing the electric field variation over time. BPA system GIC studies will be performed under the initial non-uniform electric field and the findings will be documented.
Stage Gate 4	Documented report on the algorithms for validating substation grounding resistance and transformer reactive power flow model. Assuming real GIC measurement data are provided to

	us, validation results on the BPA system will be discussed and potential model discrepancies will be pointed out in the report.
Stage Gate 5	Improved benchmark electric field maps will be created by incoporating the BPA conductivity model developed in Stage Gate 2. An improved benchmark electric field time series can be produced based on the validation results derived from GIC measurements. Documented report on the methodology developed to integrate EMP studies into power system transient stability tools. Details on how to use this methodology to perform EMP assessments will be provided.

v. Process Flow Chart:


Start Project
Task 1: Model Setup
Task 2a: Ground Conductivity
Task 2b: Benchmark Electric field
Task 2c: Substation Resistances
Stage Gate 1-2 (2/6 months)
Stage Gate 3~~2~~ (10 months)
Yes
Tasks 1 and 2a complete. Sufficient Progress in remaining tasks
No
Continue with early tasks
Task 3a: Transformer reactive power loss model
Task 3b: Transformer harmonics analysis model
Task 4: EMP Modeling
Stage Gate 4~~3~~ (15 months)
Stage Gate 5~~4~~ (20 months)
Yes
Sufficient Progress is being made in finished Tasks
No
Devote more time to Tasks 2 and 4
Continue with Tasks 3a, 3b, and 4 as planned
Complete tasks as time allows
Final Report
End Project

vi. Technology Transfer

The results of this research project have the potential to move into the application zone, through tests and demonstrations in order to integrate them with existing related tools. The methodology to validate ground conductivity model and substation grounding resistances will be beneficial for BPA to perform routine check-up, with more data during GMD events becoming available. The data-driven validation framework for transformer modeling that will be developed in this work can be used by BPA to regularly test the transformer behavior in their system. Both will also be particularly be useful as newer system components, such as more transmission lines and transformers, are added to the existing planning models. This framework and the underlying procedures developed in this project can be used to assess the vulnerability of the BPA system to extreme GMD scenarios, and to further design blocking device placement or other protection schemes against the negative impacts. The model validation tool can potentially be integrated into BPA's existing model validation framework. New techniques such as GIC-induced transformer harmonics analysis can be integrated to system power flow analysis, which will be a particularly unique contribution in such a framework.

D. Deliverables

All the validation results and methods developed in each of the tasks described earlier will be provided to BPA. Discussion on the accuracy of the GIC flow model will be offered to guide future placement of GIC monitoring devices. Documentation on the usage of those methods will also be provided. The quarterly and stage gate reports will also document the research process behind the development of these tools. The validation studies performed using these methods and the results of those will be delivered through reports, including the discrepancies found and the following analysis. Deliverables will include the development of the benchmark Electric field model for the BPA footprint, as required by the NERC standards. At each stage gate, all required and applicable reports, documents and tools will be submitted to BPA for evaluation of sufficient progress. A final report will be provided, describing the execution and achievements of the entire project in detail, as well as charting out the future directions.

E. Time Schedule

The project will be performed over 24 months from start to completion.

	Duration (number of days)	**Fixed**	**Start** (number of days since award)	**Finish** (number of days since award)
Task 1	210		0	210
Stage Gate 1		12/01/2015		
Stage Gate 2~~1~~		04/15/2016		
Task 2a	240		91	331
Stage Gate 3~~2~~		08/15/2016		
Task 2b	240		151	391
Task 2c	240		211	451
Stage Gate 4~~3~~		01/15/2017		
Task 3a	365		366	730
Task 3b	365		366	730
Task 4	365		366	730

Stage Gate 54		06/16/2017		

10 Technical Exhibits

None.

Technology Innovation

TIP #359: Improved System Modeling for GMD and EMP Assessments

Prof. Tom Overbye, Prof. Hao Zhu,
Komal Shetye
University of Illinois at Urbana-Champaign

Dr. Jennifer Gannon
Computational Physics Inc. (CPI)

Project Background

- Geomagnetically induced currents (GICs) have the potential to severely disrupt electric power grids around the world by causing either a rapid voltage collapse or long term high voltage transformer damage
- GICs are caused by solar events causing geomagnetic disturbances (GMDs)
  - Storm in 1989 took out the Quebec electric grid, much larger storms occurred in 1921 and 1859
  - Storm size can be continental
  - According to NASA Earth had a “near miss” in July 2012 for a storm that would have matched 1859

Project Background

- Impact on the power grid is caused by a changing magnetic field causing an electric field along the lines that induces the quasi-dc GICs
  - Magnitudes of the electric field depend upon size of magnetic field change and deep earth (hundreds of km) conductivities
- The ability to do power flow integrated GIC studies is now in commercial software
  - PowerWorld also allows GIC in transient stability
  - Initially just uniform electric fields, but now non-uniform
- PowerWorld did a uniform electric field study for the BPA in 2013

Project Participants

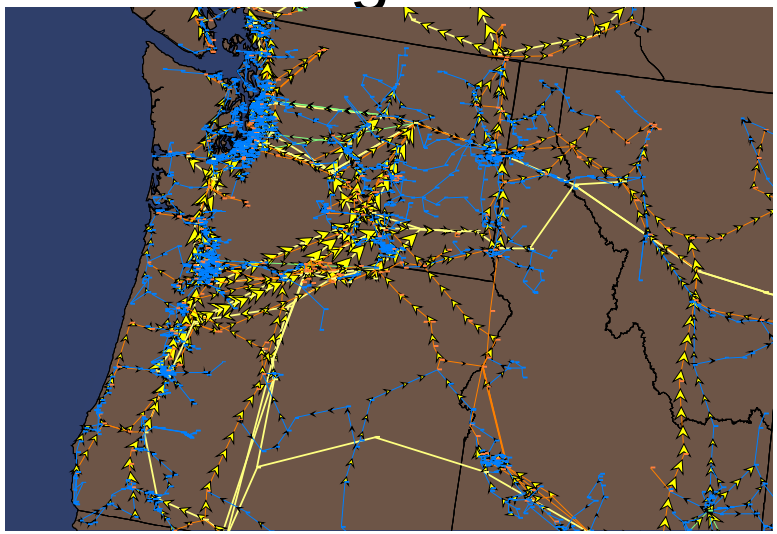
- Project involves collaboration between University of Illinois at Urbana-Champaign (UIUC) and Computational Physics Inc. (CPI) researchers
- The UIUC team is
  - Prof. Tom Overbye: Project lead, model development
  - Prof. Hao Zhu: New validation algorithms
  - Research Engineer Komal Shetye, system studies
  - Graduate Student Adam Birchfield
- The CPI participant is Jennifer Gannon, who will do ground model development and validation
- BPA Project Manager is Alexander L. Stewart

Financial Information FY16

Total FY16 Budget	BPA FY16 Budget	Cost Share FY16 Budget	BPA Actual as of (date)	Cost Share Actual as of (date)	BPA FTE Budget	BPA FTE Actual as of (date)
$256,816	$132,165	$124,651	$3,633	$13,805	0.8	0.2

Project Synopsis

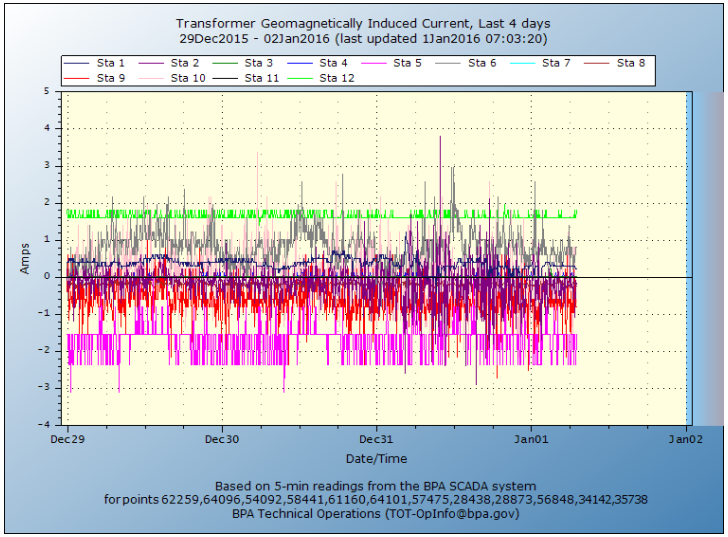
- The overall goal is to enhance the BPA geomagnetic disturbance (GMD) assessment by developing a methodology for validating the models used for GMD analysis

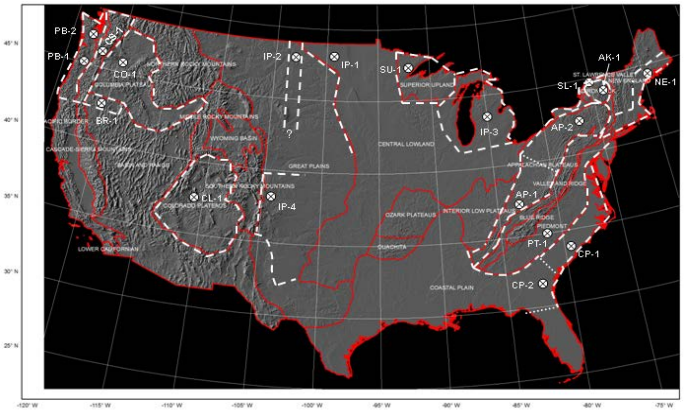


- Task 1 of the project setups the system models. From the previous PowerWorld study we already have most of the needed electrical parameters. These have been reviewed; we will be doing sensitivity analysis on the parameters.

Project Synopsis

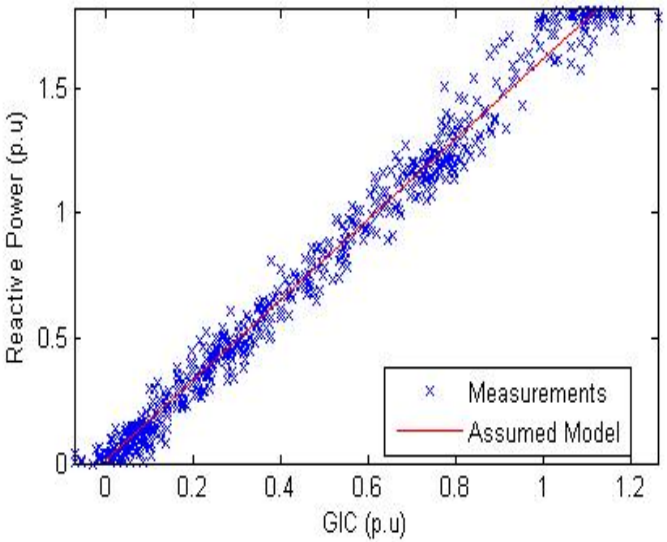
- Task 2 involves validating the model using actual data from BPA transformer neutrals during GMD events
  - There is public BPA data from twelve stations at five minute intervals
  - Validation involves coupling this data with a BPA EMS model and information on the estimated geoelectric field; the geoelectric field depends on the ground conductivity going down 100's of miles





Project Synopsis

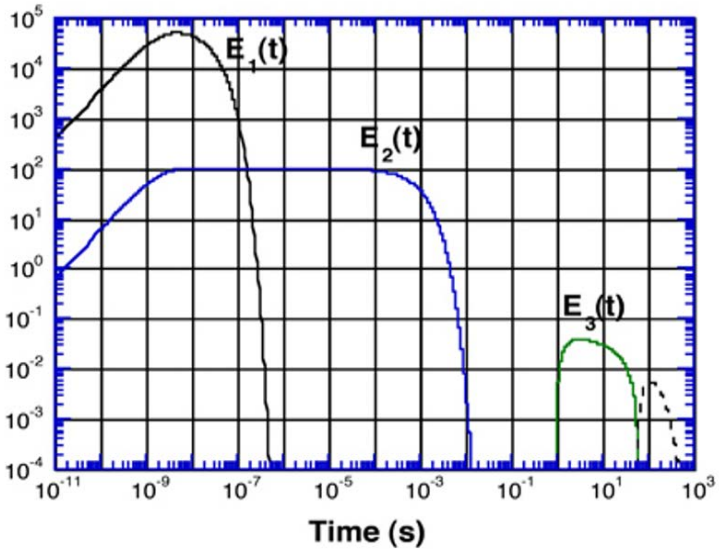
- Task 3 is validation of the GIC induced transformer reactive power behavior
  - Reactive power losses are usually assumed to vary with the effective GICs in the transformer (a is different from the neutral flow)



  - Using SCADA data, coupled with the task 2 results, we will develop a methodology and tools for doing this validation, allowing for non-linear models

Project Synopsis

- Task 4 is to develop models and perform high altitude electromagnetic pulse (EMP) analysis of E3 waveforms impact on the BPA system
  - As shown in the figure (IEC 61000-2-9) EMPs cause three different time varying electric fields: E1, E2, E3; of these E3 is quite similar to GMDs, except larger but shorter in time



  - Leveraging the models developed in the previous tasks, we will setup example EMP waveforms and do the analysis on the BPA system

Expected Benefits

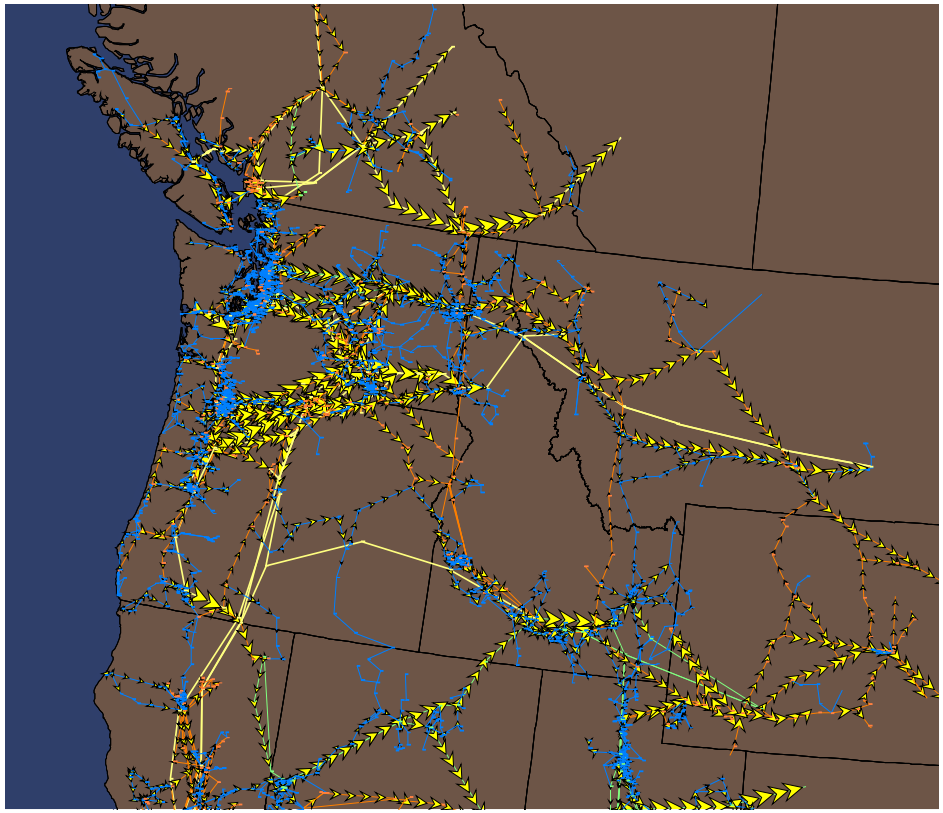
- The key benefit to BPA is to allow a better determination of GMD and EMP risk, allowing for consideration of cost effective risk reduction
- The risk can only be adequately assessed by having accurate models including the underlying ground conductivity
- Expected benefit is at least as medium, perhaps high since it will provide between models and tools for decision making associated with GMD and EMP risk

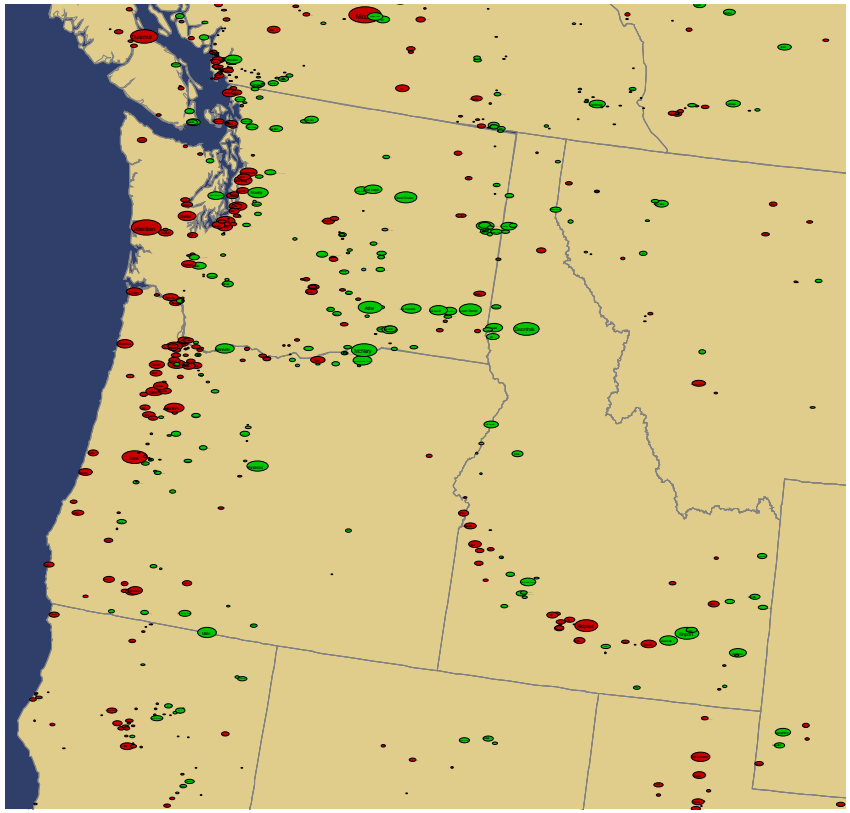
Accomplishments

- UIUC project contract was signed in November 2015, with subcontract set with CPI in January
  - Included FISMA to allow access to EMS models
- We met the requirements of Stage Gate 1. That is, we have received the 2013 GIC models and have verified that the models are sufficiently detailed for this project
  - Detailed GIC models for BPA footprint, approximate models for the rest of WECC
- The project is on schedule

Accomplishments: Stage Gate 1 Results

Images show GICs in BPA footprint and surrounding areas assuming a uniform 2 V/km eastward field. Left image shows the line flows and the right image the substation neutral flows.





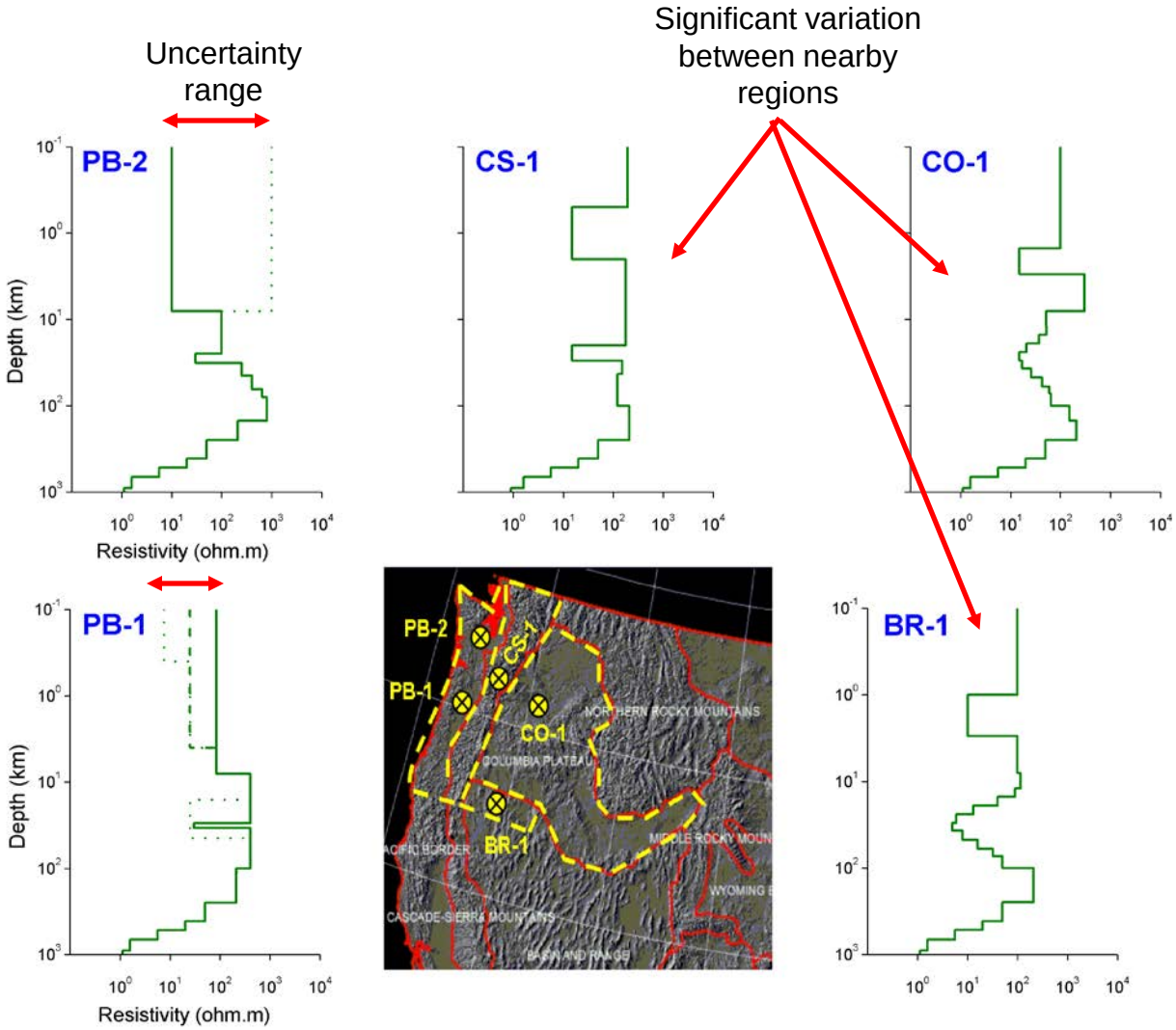
Project Direction/Next Steps

- Task 1 work will involve mapping the existing GIC models to the EMS models and to the actual GIC transformer neutral measurements
  - We will also be doing parameter sensitivity studies
- Task 2 work will involve setting up the ground conductivity model, the benchmark electric field model, and development of the validation tools
- Next stage gate (4/15/16) is an improved conductivity model for the BPA footprint
- Tasks 3 and 4 will start in November 2016
- We are planning on giving a talk on GMDs to the Portland IEEE PES Section in Spring

Technology Transfer/Application to BPA

- Technology readiness levels range from TRL 2 to TRL 6
- Tools, including documented methodologies, will be provided to BPA, for updating GIC models based on transformer neutral measurements
- We will work with software vendors such as PowerWorld Simulator to implement improved ground conductivity models in GIC analysis
- A tool for data driven transformer GIC validation will be provided
- Final project report, publications

Project Direction/Next Steps – Task 2



From Fernberg et al., EPRI, 2012

The 5 existing 1-D (EPRI/USGS) conductivity models that cover the BPA footprint are shown here.

There is a high level of uncertainty in these particular models, as well as considerable lateral variation.

Studies of induced electric field in the region have shown that these simplified models may not adequately reflect local variation.

Project Direction/Next Steps – Task 2

Because of localized conductivity variations throughout the BPA footprint, improvements need to be made to accurately calculate the induced electric field that drives GICs.

There are existing data sources that provide more highly refined local information, including:

1. **Published scientific results**: Numerous published results contributed to the USGS/NERC 1-D conductivity models. These are reflected in the uncertainty ranges given for each model. We will use these data to further refine local and lateral variation.
2. **Earthscope Data**: The NSF Earthscope project has completed 3D conductivity measurements in the BPA region. These data are publicly available and will be incorporated into the improved conductivity model, where possible.
3. **Coastal effects**: Coastal proximity (<100 miles) has been shown to increase induced electric field and GIC hazard. The 1-D models do not include this effect. An estimate will be added to the improved conductivity maps.

Project Direction/Next Steps – Task 2

We will first evaluate the gaps in existing conductivity models and assess the areas where conductivity model improvements are needed by:

1. Comparing USGS/EPRI 1-D models to published 3-D results from Earthscope.
2. Comparing modeled GICs to measured currents.

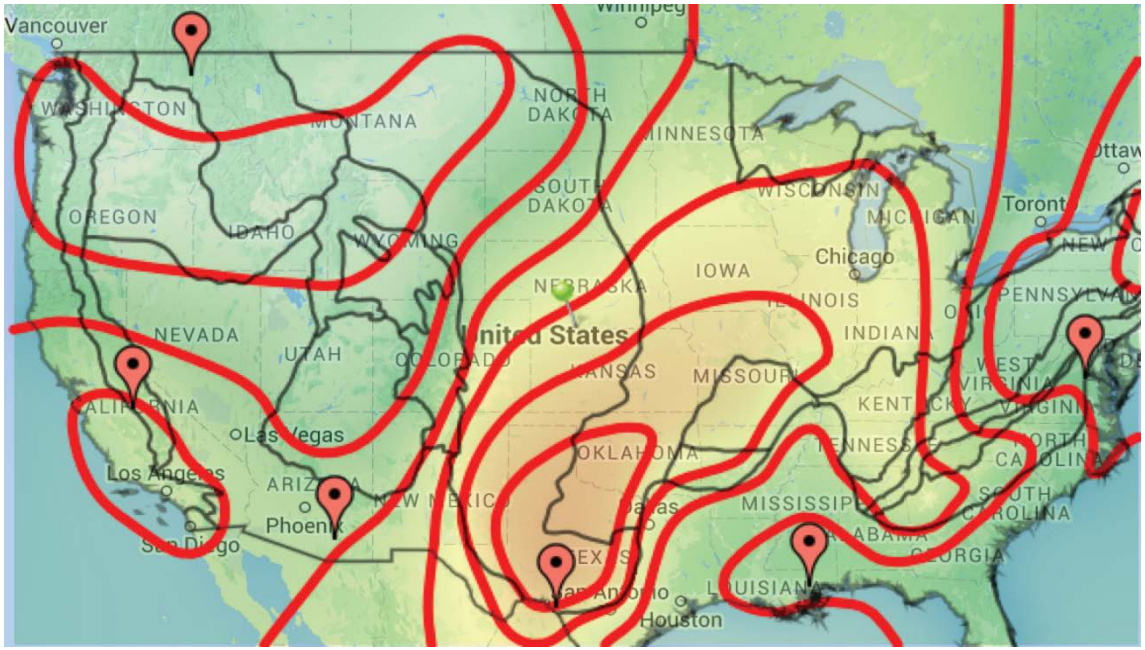
Using results from these comparisons, we will then iteratively improve conductivity maps in the BPA footprint by:

1. Identifying/adding subregions within existing maps.
2. Adding lateral variations and local conductivity features, where needed.
3. Estimating a coastal effect within 100 miles of the coast line.

These will produce a set of improved conductivity maps, allowing us to analyze local variations and improve the electric field estimates for a GMD event across the BPA footprint.

Technology Transfer/Application to BPA

Improved conductivity maps will allow us to produce a realistic spatially-varying electric field map (US example below) and a more accurate reference event electric field for the BPA footprint.



The reference event can be used with available software, such as PowerWorld Simulator, to understand and analyze the impact of “hotspots” in GIC evolution over a GMD event, and identify the most vulnerable assets within a broader system.

Q&A