Modeling Geomagnetically Induced Currents in PowerWorld Simulator

Introduction

The purpose of this document is to explain how the impact of geomagnetically induced currents (GICs) can be modeled in PowerWorld Simulator, with their impacts directly included in the power flow equations.   The document assumes a basic familiarly with PowerWorld Simulator including the power flow, one-lines and case information displays. PowerWorld on-line training, including videos and slides, is available at [1].

As is described in [2], GICs are induced in the electric power grid when coronal mass ejections (CMEs) on the sun send charged particles towards the earth. These particles interact with the Earth's magnetic field causing what is known as a geomagnetic disturbance (GMD). So changes in the earth's magnetic field, usually expressed in nT/minute variation, produce electric field variations. These in turn give rise to quasi-dc (frequencies much below 1 Hz) currents in long conducting paths such as pipelines, railways and the high voltage transmission grid.

Two main methods have been proposed for modeling the impact of this electric field variation in the power grid; either as dc voltage sources in the ground or as dc voltage sources in series with the transmission lines [3], [4]. In [4] it was shown that while the two methods are equivalent for uniform electric fields, only the transmission line approach can handle the non-uniform electric fields that would be expected in a real GMD event. Therefore in PowerWorld Simulator the impact of the magnetic field variation is represented by series dc voltage sources in series with each of the transmission lines. The details of the determination of these voltages in PowerWorld Simulator is discussed later.

How the GICs flow in the electric transmission system depends upon the induced dc voltage in the transmission lines and the resistance of the various system elements. Since the GICs are essentially dc, device reactance plays no role in there determination.   Values that impact the GICs include the resistance of the transmission lines, the resistance of the coils of grounded transformers, the resistance of the series windings of auto-transformers (and their common winding if grounded), and the substation grounding resistance.   This is illustrated for a simple two bus network in **Figure 1**. Note that from a GIC perspective the three phases are in parallel. Since the concept of per unit plays no role in GIC determination, resistance values are expressed in Ohms (Ω), conductance in Siemens (S), current is in amps (A), and the dc voltages are given in volts (V).
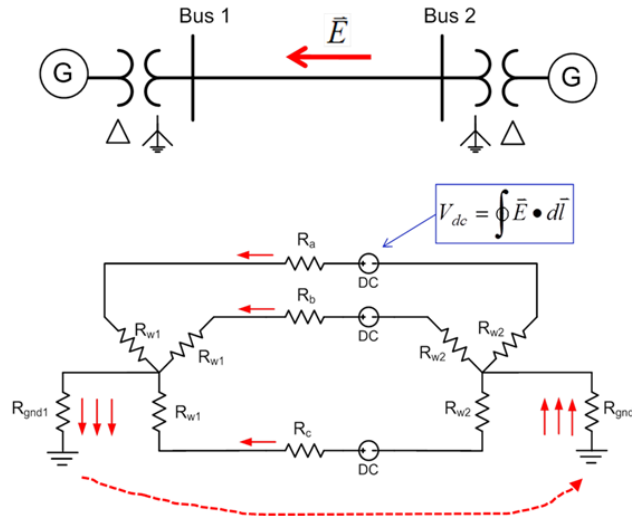
$$V_{dc} = \oint \bar{E} \bullet d\bar{l}$$

Figure 1: Simple GIC Flow in a Two Generator Example

Figure 2 shows an example of such a system modeled in PowerWorld Simulator with Bus 1 and its generator (Bus 3) in Substation A, and Bus 2 with its generator (Bus 4) in Substation B. Assume Buses 1 and 2 are joined by a 765 kV line that has a per phase resistance of 3Ω, the per phase resistance of the high side (grounded side) coil of each of the two transformers is 0.3Ω, and the grounding resistance for each of the substations is 0.2 Ω. Let the magnitude of the GMD induced voltage in the 765 kV line be 150 volts, with a positive polarity on the Bus 1 side.
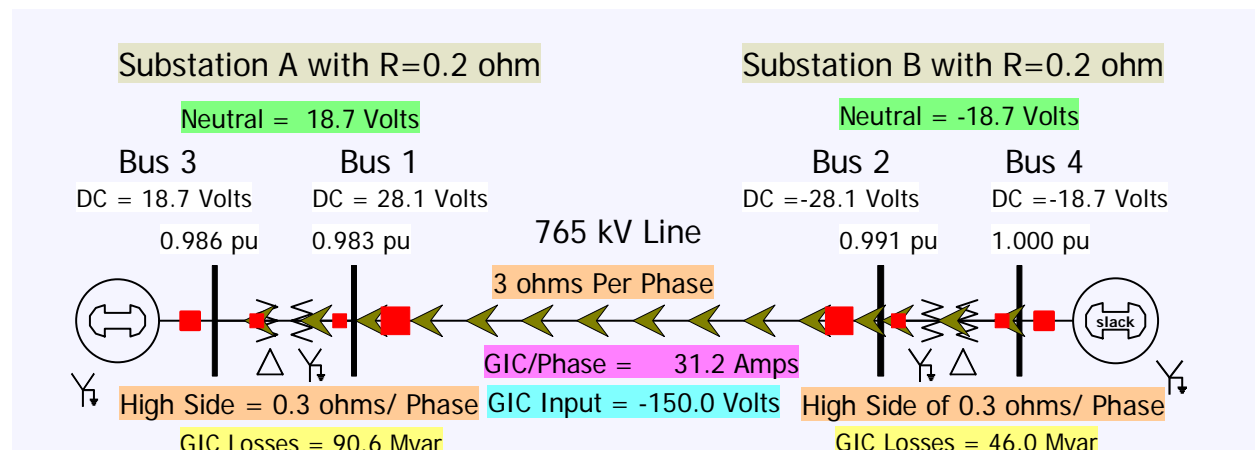

Figure 2: Two Generator GIC Example in PowerWorld Simulator

The GICs can then be determined by solving a simple dc circuit. From a GIC perspective the three phases for the transmission line and transformers are in parallel, so the total three phase resistance for the 765 kV line is (3/3)Ω = 1Ω, and (0.3/3) Ω = 0.1 Ω for each of the transformers. These resistance are then in series with the Substation A and B grounding resistance giving

$$I_{GIC,3Phase} = \frac{150\,\text{volts}}{(1+0.1+0.1+0.2+0.2)\Omega} = 93.75\,\text{amps} \qquad (1)$$

with the flow from the grounding into the high side coil of the Substation B transformer, down the 765 kV line into the high voltage coil in Substation A and back into the ground. In the figure the direction and size of the brown arrows superimposed on the transmission line and transformers are used to visualize the direction and magnitude of the GIC flow[1].

The substation neutral and bus dc voltages can then be calculated by a straightforward application of Ohm's law. For example, the Substation B neutral voltage is (0.2Ω)*(-93.75A) = -18.75V, while the Bus 2 voltage is (-18.75V) + (0.1Ω)*(-93.75A) = -28.1V. Because of the delta connection on the low side of the transformers, no GIC passes through the transformers. However, since the generators are assumed to be grounded through a low resistance into the substation neutral, their dc bus voltage is the same as their respective substation neutral.

A potential point of confusion in interpreting the results of the GIC calculations is to differentiate between the per GIC phase currents in transmission lines and transformers, and the total GIC three phase current in these devices. From a results display perspective either the per phase current or the total current could be shown. Of course since the three phases are in parallel, the conversion between the two is straightforward since the total current is just three times the per phase current.

In PowerWorld Simulator the convention is to show the per phase current for transmission lines and transformer coil flows. The reasoning is since the resistance of transmission lines and transformer coils is always specified on a per phase basis, the voltage drop across a device can then be easily calculated by multiplying the per phase resistance by the per phase current. Since there is just a single neutral flow wire, the neutral flow is always the sum of the phase flows for the incident devices.

The impact of the GICs on the operation of the power grid is primarily due to the half-cycle saturation they cause in the transformers. For interested readers these impacts are well described in [2], particularly Chapter 8. The gist is this transformer saturation can create large amounts of harmonics, including even harmonics, which can cause transformer heating issues, relay misoperation, and capacitor/SVC/generator tripping.

However, most germane to the power flow analysis considered here, the half-cycle saturation causes an increased transformer reactive power loading [5], with widespread agreement that the increased reactive power loading varies linearly with the GIC flowing through the transformer (a slightly more detailed handling for auto-transformer flows is considered later). Hence a simple scaling constant is used to couple the transformer GIC flow to the transformer's increased reactive power losses. In PowerWorld this is implemented by adding an additional reactance in parallel with the existing shunt magnetizing reactance, with the magnitude of this new reactance determined dynamically from the GIC flows and the scaling constant.

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[1] For transformer flows currently PowerWorld Simulator cannot currectly display that the GIC flow is actually only in the grounded coil of the transformer; this issue will probably be addressed in future software releases.

Since the scaling constant is transformer specific, ideally a value would be entered for each transformer. However, since these values are often not known, defaults are provided, with more details provided later. Referring back to **Figure 2**, the GIC reactive power losses for each transformer are shown in the yellow fields underneath the transformer, with a scaling value of 1.0 used for the left transformer and 0.5 for the one on the right. Hence the additional Mvar loading at unity voltage for the left transformer would be (1.0*93.75) = 93.75 Mvars, with the actual value varying with the square of the terminal voltage.

PowerWorld Simulator GIC Analysis Form Overview

In PowerWorld Simulator the primary means for setting the GIC specific fields and viewing the results is through the GIC Analysis Form. This form can be displayed by selecting the **Tools** ribbon, then clicking on **Other** (located towards the right side of the ribbon), and on **GIC Calculations**. Note, for quicker access to this form right click on the **GIC Calculations** and select **Add to Quick Access Toolbar** to place it in the Quick Access Toolbar. The form is shown in Figure 3.

Figure 3: GIC Analysis Form

PowerWorld Simulator allows the GIC calculations to be either directly integrated into the power flow solution, or done separately without solving the power flow (the reason for this will be explained later in the large system analysis section). When the **Include GIC in Power Flow** box is checked, anytime the standard PowerWorld Simulator power flow is solved (for example by clicking on the **Single Solution** button in the Quick Access Toolbar), the GIC values are recalculated, with their impact then included in the power flow solution. If this box is not checked then any existing GIC solution results are cleared before the power flow is solved.

The GIC values can be calculated separately from the power flow by selecting the **Update GIC Values** button. Since this just requires the solution of a linear system, it is quite fast even for large systems. Clicking the **Clear GIC Values** button clears out all the GIC specific results.

The **Specified Time Point (Seconds)** is used to determine which set of GMD-induced transmission dc voltage values should be used in the GIC calculations. PowerWorld Simulator models these values for each transmission line using a piecewise linear model, with each point assigned a time value (in seconds). The reason time was chosen as the parameter is for future inclusion of GIC modeling in transient stability calculations. For the power flow the units of time are irrelevant. These piecewise linear time points are managed on the **Create GMD Electric Field Input** page, which will be discussed

later. When the **Update on Time Change** box is checked, the GICs are automatically recalculated anytime the **Specified Time Point** value is changed.

Most of the other page tabs (**Areas**, **Buses**, **Generators**, **Lines**, **Substations**, **Transformers**) are used for both specifying the GIC input parameters and viewing the results. Details on the specific fields are given in the next section. The **GMatrix** page provides access to the conductance matrix used in the calculation of the GICs, and is primarily intended for advanced users.

As an example of using this form, open the GIC_FourBus case, which contains the four bus system considered previously and open the **GIC Analysis Form**. The case models the GMD-induced voltage on the line between Buses 1 and 2 using two time points. The first point (at zero seconds) has zero voltage, while the second point (at 30 seconds) has -150 volts (positive numbers indicate a positive dc polarity towards the To bus [Bus 2 for this line], while negative numbers mean a positive polarity towards the From bus [Bus 1]).   Then, making sure that the **Update on Time Change** box is checked, gradually decrease the time by clicking on the down arrow next to the **Specified Time Point (Seconds)** field (the default is to change 5 seconds per click). Notice that this updates the GIC fields on the one-line (shown in Figure 4 for ten seconds = -50 volts) but does NOT change the power flow solution. To resolve the power flow, including the impact of the GIC values, make sure that the **Include GIC in Power Flow** box is checked, then solve the power flow using the standard procedure (for example by clicking on the "calculator" button in the Quick Access Toolbar). The results for ten seconds are shown in Figure 5. Notice the change in the ac per unit (pu) voltages. The GIC losses also change slightly since they are modeled as shunt reactances.
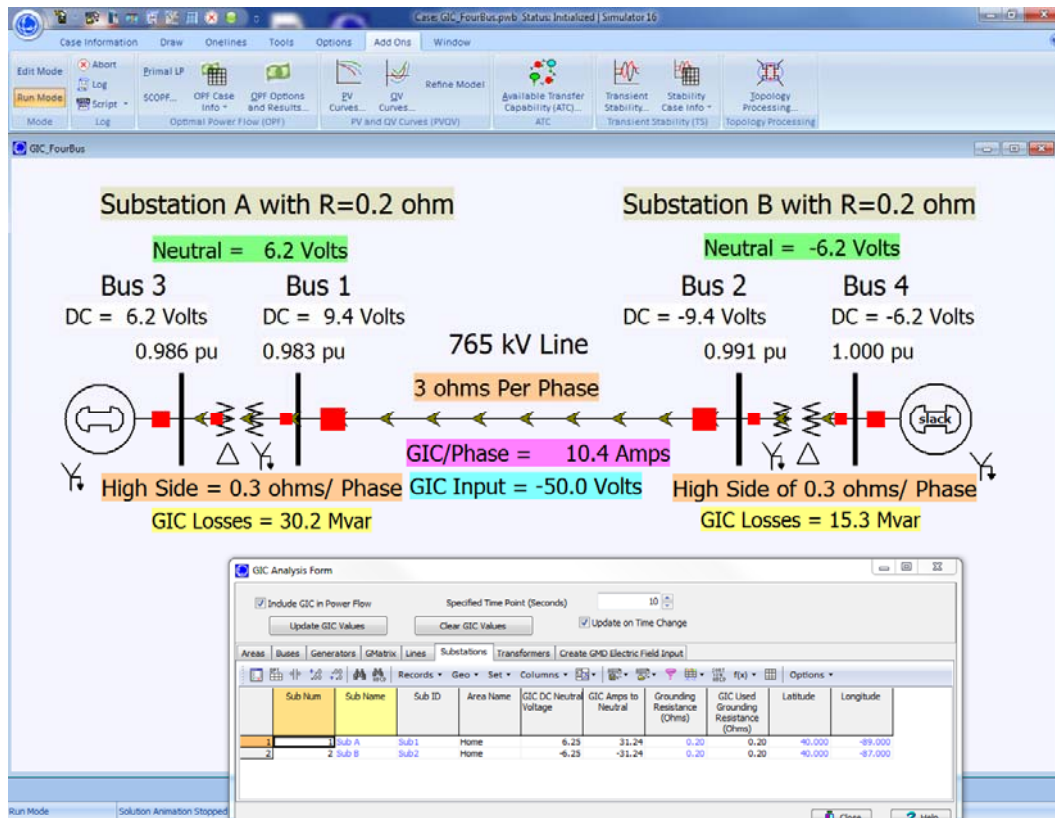
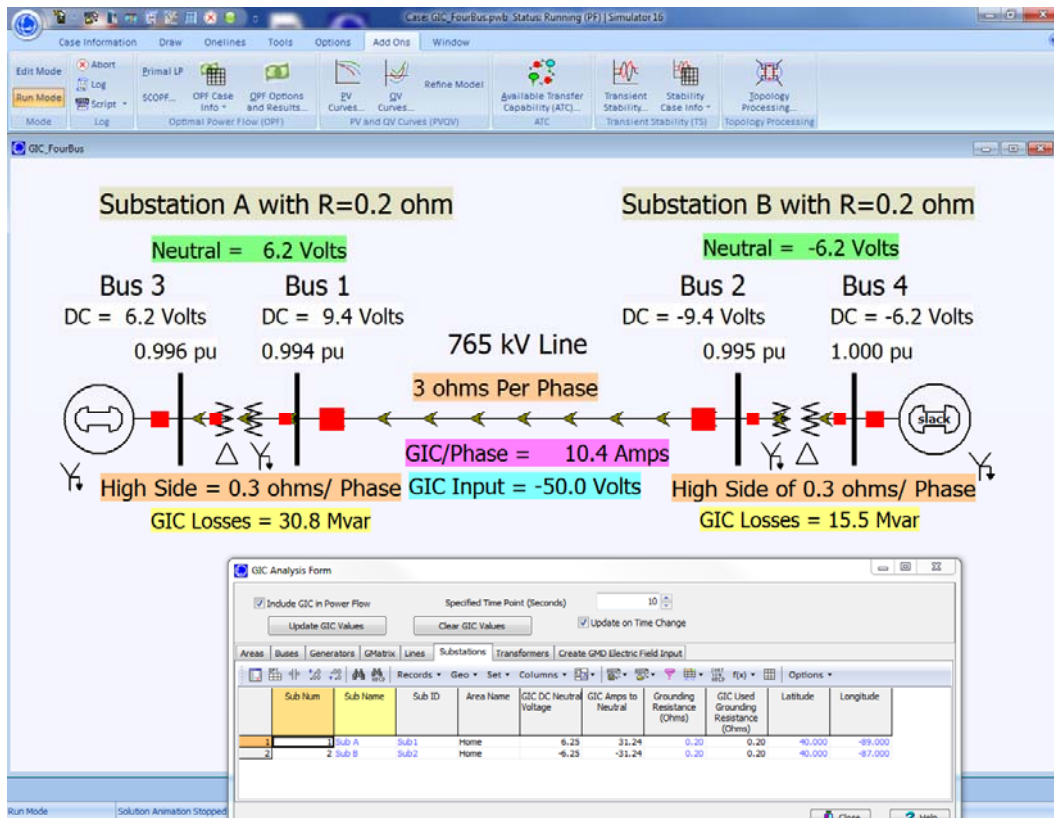Figure 4: Variation in GIC Values by Changing Specified Time Point

Figure 5: New GIC Values Included in Power Flow Solution

The animated flows on the **GIC_FourBus** one-line diagram are set to show the sum of the GIC current in all 3 phases, which is stored in the branch field **Custom Float 1**. Note that if you are using **Custom Float 1** to hold other quantities, those will be lost upon performing GIC Analysis.

New GIC-specific fields are also available on the **Power Flow List** and **Quick Power Flow List**, accessible from the **Case Information** Ribbon. The GIC current per phase is shown for each transmission line in the **Power Flow List**. The **Quick Power Flow List**, shown in **Figure 6**, also includes the GIC DC Voltage at each bus and the Substation DC Neutral Voltage.

Figure 6: Quick Power Flow List

The **Bus View One-line** may also be customized to show GIC-related quantities. Open the **Bus View...** from the Onelines ribbon and switch to the **GIC** view using the **Views** drop down at the top of the window. The **GIC** view is shown in **Figure 7**.
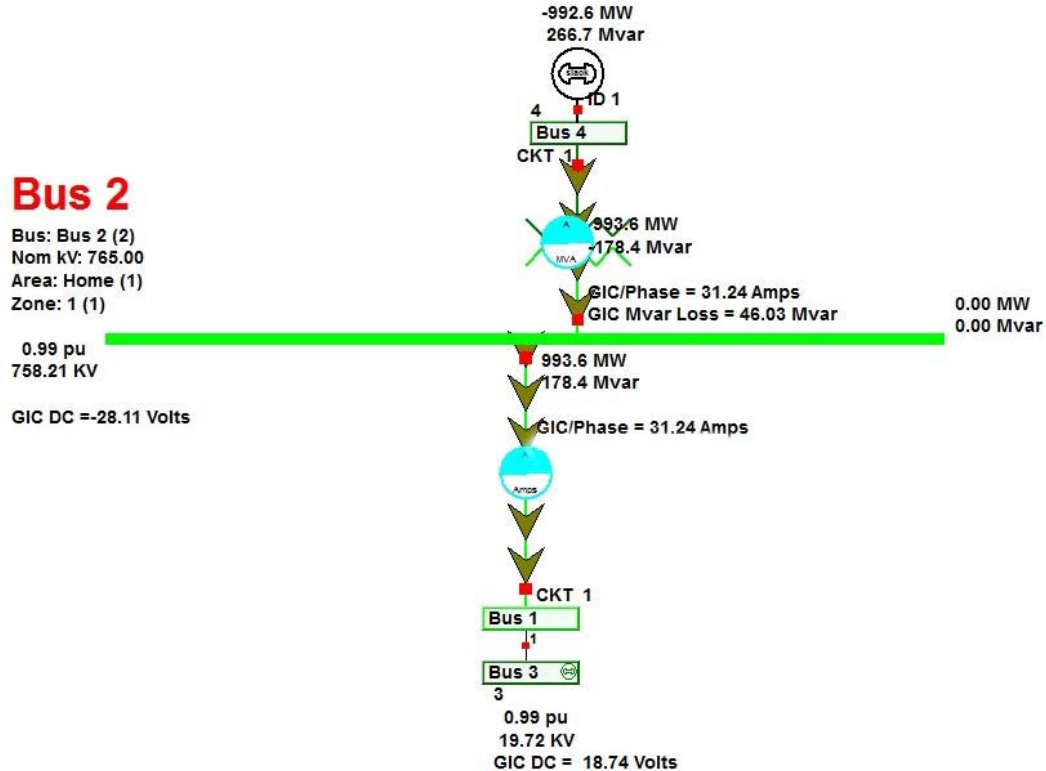

Figure 7: Bus View One-line, with GIC Custom View

Next, to see an example of changing system parameters, with the time still set at 10 seconds, select the Substation tab. This page displays GIC related information for each of the substations in the case. As shown in the lower portion of Figure 5 the page shows the substation dc neutral voltage, the total three phase amps flowing into the substation neutral, the inputted substation ground resistance, the grounding   actually used, and the substation latitude and longitude.   If the inputted substation grounding resistance is not zero then that value is used; otherwise the value is estimated.   For this example, change the inputted value for both substations from 0.2Ω to 0.5Ω, and then click **Update GIC Values**. The anticipated three phase flow is given (2), while the per phase flow is shown in **Figure 8**.

$$I_{GIC,3Phase} = \frac{50\,\text{volts}}{(1+0.1+0.1+0.5+0.5)\Omega} = 22.73\,\text{amps} \qquad (2)$$
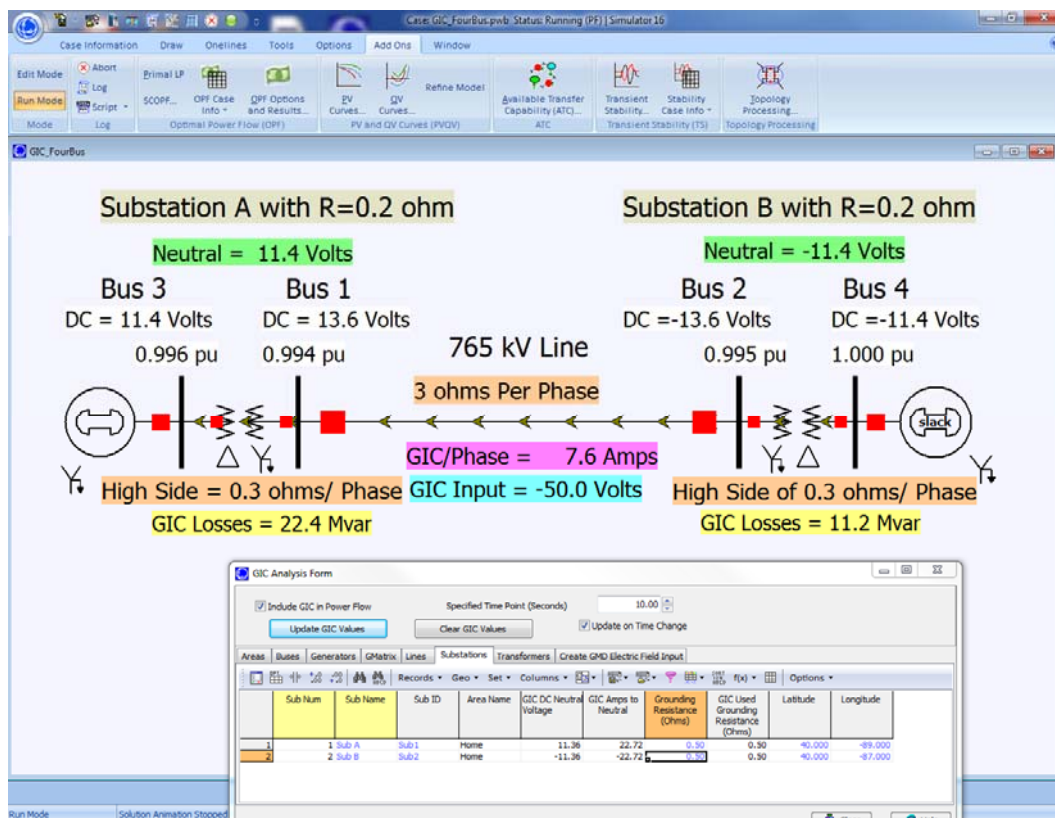

Figure 8: GIC Values with Modified Substation Grounding Resistance

Entering GMD Electric Field Inputs

PowerWorld Simulator provides easy mechanisms both for setting up GMD induced line voltages for quick studies and for importing line voltages when a more detailed model is appropriate. As mentioned in Section 8.3 of [2] (coming from [4]), "…the voltages induced on transmission circuits at any one point in time depend upon the interaction between the solar wind, the electrojet and the Earth's magnetic field. The geology of the area and geographical location of the transmission circuits also have a strong

influence on the induced-earth potentials." So determining these values can be quite involved. However, [2] goes on to say that for planning studies a simpler approach of assuming a uniform electric field can be used. This section shows how both the simple approach, and the more detailed approach can be used.

The GMD included transmission line voltages are setup using the Create GMD Electric Field Input tab. The top portion of this page is associated with the creation of new inputs, whereas the bottom portion of the page, in the AC Line Input Voltages, lists the existing time point inputs. As was mentioned previously, PowerWorld Simulator models these values for each transmission line using a piecewise linear model, with each point assigned a time value (in seconds). As example of this page for the four bus case is shown in Figure 9, with the two time point values shown in the last two columns of the AC **Line Input Voltages** tab. The first row is always the **Time in Seconds** for the timepoint, with the remaining rows corresponding to the transmission lines and transformers in the case. Hence the number of rows is fixed. The first several columns are used to identify the line, including the latitude and longitude of its terminal buses; the remaining columns are the time points.

Figure 9: Create GMD Electric Field Input

New time points are inserted by entering a time in the **Input at Time (Seconds)** field on the top-left side of the page, and then clicking on the **Add New Input Values** at Time button on the right. If a time point already exists for this time its entries are overwritten. Existing time points can be deleted by either selecting some cells in the timepoint column(s) and clicking on **Delete Selected Time Values** or clicking on **Delete All Input Time** Values to delete all the time points.

When a new timepoint is added, the magnitude of the associated voltage is determined based upon the geographic coordinates of the line and the assumed electric field. PowerWorld currently supports two different electric field models, with the type determined by the entry in the **Electric Field Model Type** radio group. The simplest is the Uniform field approach, in which a constant electric field is assumed,

with the magnitude given in the **Maximum Electric Field** field in units of either volts/mile or volts/km (selectable in the **Units of Distance** field). The direction of the field is then specified in a compass angle in degrees, with 0 degrees being north, 90 degree east, etc.

The dc line voltage is then calculated using the approach from [4] (also described in Attachment 8 of [2]) of integrating the dot product of the electric field vector over the length of the line. With a constant electric field just the end points of the transmission line are important. Written in rectangular coordinates the voltage equation for a line is

$$V_{line} = \overline{E} \bullet \overline{L} = E_x L_x + E_y L_y \tag{3}$$

where E_x is the northward component of the electric field, L_x is the north transmission line distance, E_y is the eastward electric field component and L_y the eastward transmission line distance. In PowerWorld Simulator transmission lines are assumed to go from the From bus to the To bus, with a positive voltage having polarity towards the To bus.

In determining latitude and longitude distances, PowerWorld Simulator uses a slight approximation to the WGS84 standard [6] (the same as used for GPS systems), which recognizes that the earth is not a true sphere, so there is a slight variation (up to 1 km)in the distance of one degree of latitude. The values used for the distance of one degree of latitude and longitude at latitude ϕ are [7],

$$\text{One degree latitude} = 111.133 \text{ - } 0.560\cos(2\phi) \text{ km}$$

$$\text{One degree longitude } = \frac{111.320\cos(\phi)}{\sqrt{(1-0.00669\sin^2\phi)}} \text{ km} \tag{4}$$

In the case of a uniform electric field, the distance per degree is evaluated at the average of the latitude and longitude of the end points of the line.

As an example, consider a transmission line going from 44N, 88W to 45N, 87W in a 2.0 V/km uniform electric field with a direction of 30 degrees (NNE). Then

$$E_x = 2\cos(30°) = 1.732 \text{ V/km}, \ E_y = 2\sin(30) = 1.0 \text{ V/km}$$
$$L_x = (45-44)(111.123) = 111.123 \text{ km}$$
$$L_y = (88-87)(79.661) = 79.661 \text{ km} \tag{5}$$
$$V_{line} = 1.732 \times 111.123 + 1.0 \times 79.661 = 272.1 \text{ V}$$

The second electric field type is a simple non-uniform model with the associated parameters shown in Figure 10. For this option the electric field magnitude is assumed to be at the maximum for a band of width **Storm Width Max Field**, centered at the **Storm Center Latitude and Longitude**, and going in the **Storm Direction**. The key difference is the magnitude of the electric field tampers linearly down to zero over **Storm Total Width**. A contour of the electric field magnitude for a large system model is shown later in this document **in** Figure 14**.** While certainly still an approximation, this model does recognize that a storm is unlikely to have a uniform electric field over an entire large scale interconnected grid.

The transmission line's voltage is calculated by adding up the voltage obtained by sequentially applying the previous procedure for small sections of the transmission line, with the assumption that the field is constant over each small segment (with the current segmentation equal to one mile).

Figure 10: Non-uniform Electric Field Input

The last approach for entering line voltages is to used PowerWorld Simulator's copy and paste functionality to create the ac line input voltages using an external program, loading these results into a spreadsheet and then pasting in the results. The easiest way to see the required format is to first copy existing timepoint results into a spreadsheet. This is done by right-clicking somewhere in the **AC Line Input Voltages** grid that already has at least one time point column to display the local menu. Then select **Copy/Paste/Send, Copy All** to place all the results in the Window Clipboard. Then paste into a spreadsheet such as Excel. This is shown in Figure 11. For convenience the latitude and longitude of the line's From and To buses are also included. Results can then be modified in the spreadsheet or by an external program. To paste them back into PowerWorld Simulator, select all in the spreadsheet, copy into the Clipboard, right click on the AC Line Input Voltages grid and select **Copy/Paste/Send, Paste** to update the timepoints.

Figure 11: AC Line Input Voltages Pasted into Excel

GIC Analysis Form Object Fields

This section provides a reference explanation for each of the GIC specific fields on the GIC Analysis Form Pages.

Areas Page

The Areas page contains the following fields:

Area Num, Area Name: Give the standard identifiers for each area.

Ignore GIC Losses: Indicates whether or not GIC related losses are calculated for the transformers in the area. In large cases when solving the power flow it may be helpful to avoid calculating the GIC related losses for transformers in distant areas.

Mvar Losses: Gives the total GIC related transformer Mvar losses for the area.

Buses Page

The Buses page contains the following fields:

Number, Name, Area Name and Nom kV: Give the standard identifiers for each bus.

PU Volt: The AC solution per unit voltage.

GIC DC Volt: The GIC DC voltage for the bus.

GIC Neutral DC Volt: The bus's substation neutral bus voltage.

GIC Gen Step-up Conductance Per Phase: Total of the per phase conductance for all the implicitly modeled generator step-up transformers at the bus. See the Generator Page for details.

GIC Gen Step-up Amps to Neutral: Total of the amps flowing into the neutral for all the implicitly modeled generator step-up transformers at the bus. See the Generator Page for details.

Generators Page

The Generators page contains the following fields:

Number of Bus, Name of Bus, ID: Give the standard identifiers for each generator.

Status, Gen MW: Status and real power output of the generator.

Include Implicit GSU: Often the generator step-up transformer (GSU) is modeled explicitly in the power flow. For this situation the transformer would appear on the Transformers page and this field should be **No**. However, sometimes the transformer is not explicitly modeled. This may be indicated by the generator being directly connected to a high voltage bus, or it may be indicated by non-

zero entries for the **R** and **X** fields in the **Generator Step-up Transformer** group on the Generator Dialog, Faults page. If this is the cause then the field should be **Yes**. If unknown then the entry should be **Default**, in which case an implicit GSU is assumed if either 1) the R or X fields are non-zero, or 2) the generator is connected to a bus with a nominal voltage greater than 30 kV. This implicit generator is assumed to be y-connected on the transmission side, delta on the generator side. If the **R** value is non-zero the associated per phase conductance is calculated from this value. Otherwise a default value is used. Currently the default value cannot be changed.

GIC Step-up Amps to Neutral: The total amps (all three phases) flowing from the implicitly modeled GSU into the substation neutral.

GIC Step-up Conductance Per Phase: Per phase conductance for the implicitly modeled GSU; zero indicates no transformer.

Implicit GSU Mvar Losses: Total of the Mvar losses associated with the implicitly modeled GSU. Currently this is not implemented, but will be added shortly.

Ignore Losses from Implicit GSU: This field is always disabled to indicate it is not set here. It tells whether the GIC related losses from the implicitly modeled GSU are ignored for the generator's area.

GMatrix Page

The GMatrix page shows the entries in the **G** (conductance) matrix. The entries are for the parallel combination of all three phases.

Lines Page

The Lines page contains entries for all the transmission lines and transformers in the model. It contains the following fields:

From Number, From Name: Standard identifiers for the From end bus.

To Number, To Name: Standard identifiers for the To end bus.

Circuit: Line two character circuit ID.

GIC DC Volt Input: **T**he GIC DC voltage modeled for the line. This comes from the data on the **Create GMD Electric Field** Input page. The polarity is the positive terminal is towards the To end.

GIC DC Amps Per Phase From: For a transmission line this is the per phase GIC current in amps flowing into the From end of the line. If this is a transformer then this is the per phase current flowing into the substation neutral unless it is an auto-transformer. For an auto-transformer it is either the series or common

winding flow, depending upon whether the From or To bus has the higher nominal voltage.

GIC DC Amps Per Phase To: For a transmission line this is the per phase GIC current in amps flowing into the To end of the line. If this is a transformer then this is the per phase current flowing into the substation neutral unless it is an auto-transformer. For an auto-transformer it is either the series or common winding flow, depending upon whether the From or To bus has the higher nominal voltage.

GIC DC Amps Per Phase Max Abs Value: This is the absolute value of the maximum current flow in the previous two fields. The field is included to make it easy to sort by the maximum current.

GIC DC Volt From: The GIC DC voltage for the From bus.

GIC DC Volt To: The GIC DC voltage for the To bus.

GIC Conductance Per Phase: The per phase conductance for all the transmission lines. The field value is determined from the per unit power flow data. This field is zero for transformers since the winding values are given/entered on the Transformers page.

GIC Mvar Losses: The GIC related reactive power losses for the transformers. Field is blank for transmission lines.

Distance Between Substations: Distance between the From and To bus substations in either km or miles, depending on the value of the **Units of Distance** field on the **Create GMD Electric Field Input** page.

Compass Angle Between Substations: Compass angle in degrees pointing from the From bus substation to the To bus substation.

Substations Page

The Substations page contains entries for all the substations in the model. It contains the following fields:

Sub Num, Sub Name, Sub ID: Standard identifiers for the substation

GIC DC Neutral Voltage: DC voltage of the substation neutral

GIC Amps to Neutral: Total amps flowing into the substation neutral; a negative number is used for current flow out of the neutral into the system.

Grounding Resistance: Substation grounding resistance in Ohms. This is a user input field and should be set if known. If the value is left zero then an approximated value will be used in the computations (see the next field).

GIC Used Grounding Resistance: This is the grounding resistance value in Ohms that was actually used in the GIC calculations. If the Grounding Resistance field is non-zero then that value is used. Otherwise the resistance is approximated, based upon the the voltage of the highest bus in the substation and the number of buses in the substation. The approximation assumes larger, higher voltage substations have a larger footprint and hence a lower resistance.

Latitude, Longitude: Latitude and longitude for the substation. Latitude values in the Northern Hemisphere are entered as positive numbers and those in the Southern Hemisphere as negative values. Longitude values in the Eastern Hemisphere are entered as positive values and those in the Western Hemisphere as negative values.

Transformers Page

The Transformers page contains entries for all the transformers in the model. It contains the following fields:

From Number, From Name: Standard identifiers for the From end bus of the transformer.

To Number, To Name: Standard identifiers for the To end bus of the transformer.

Circuit: Line two character circuit ID for the transformer.

Manually Enter Coil Resistance:Toggle to allow the transformer's coil resistance to be set manually (Yes) or estimated based upon the transformer's series resistance in the power flow (No). Ideally these values should be set manually. However, in a large case this may be impractical. A reasonable approach could be to set the values for key transformers in the area of interest. When this field is set Yes the next two fields are enterable. Otherwise the next two fields are overwritten with the resistance value actually used in the GIC solution.

From Side Ohms per Phase: If the **Manually Enter Coil Resistance** field is Yes then this field is enterable, and should be set to the per phase coil winding resistance for the From Bus winding. Otherwise the coil resistance is estimated, and this value is overwritten. The value need not be set for coils that are not connected to ground except is should be set for the series winding on an auto-transformer.

To Side Ohms per Phase: If the **Manually Enter Coil Resistance** field is Yes then this field is enterable, and should be set to the per phase coil winding resistance for the To Bus winding. Otherwise the coil resistance is estimated, and this value is overwritten. The value need not be set for coils that are not connected to ground except is should be set for the series winding on an autotransformer.

Is AutoTransformer: Indicates whether the transformer should be modeled as an autotransformer. Since this is not a standard power flow model parameter, the default value is Unknown. Set to Yes if it is an autotransformer and No if it is not. When the value is Unknown the current functionality is to assume it is an autotransformer provided 1) it is not a phase shifter, 2) the From and To bus nominal voltage values differ, 3) the turns ratio is no greater than 3 to 1, 4) the highest nominal voltage is above 100 kV.

Assumed to be an AutoTransformer: Indicates whether the GIC calculations treated the transformer as an autotransformer.

Transformer GIC Neutral Amps: Total amps flowing from the transformer into the substation neutral.

GIC Mvar Losses: Total GIC induced reactive power losses (in Mvar) for the transformer. The following fields describe how this value is calculated.

Ignore GIC Losses: Indicates whether the GIC losses for the transformer are being ignored. Since this is currently set on an area by area basis, the field is disabled here; it is just for informational purposes.

Core Type: Core type of the transformer. This value is only used if the next field, **GIC Model Type,** is Default. Available core types are 1) Unknown, 2) Single Phase, 3) Three Phase Shell, 4) 3-Legged, Three Phase, and 5) 5-Legged, Three Phase. Since the core type is not a standard power flow field the default value is Unknown.

GIC Model Type: The GIC Model Type field is used to relate the GIC currents flowing into the transformer coils into reactive power losses. Currently two values are available, either Default or Linear. When the value is set to Linear, the total GIC-related Mvar losses modeled in the power flow are this value times the GIC coil current in amps. A typical range for this field is between 0.3 to 1.5. When the value is Default, a linear model is used with the reactive power losses estimated based on the core type.

GIC Model Param: When the GIC model type is linear, this field is used to determine the transformer reactive power losses based on the GIC current flowing in the transformer coils.

GIC Blocked on From Side Winding: When set to Yes the GIC current is assumed to be blocked for the From side winding of the transformer. Physically this is implemented by setting the associated resistance from the From side winding to the substation neutral to a large value.

GIC Blocked on To Side Winding: When set to Yes the GIC current is assumed to be blocked for the To side winding of the transformer. Physically this is implemented by setting the associated resistance from the To side winding to the substation neutral to a large value.

Large System Model Starting with a Power Flow

This section provides an example of how to start a GIC study from a standard power flow case. The example considered is a Eastern Interconnect case that contains more than 62,000 buses (a 2010 series MMWG case representing summer 2012 conditions) saved in the *.raw format.

To start the process, open the *.raw file and perform an initial power flow solution. Then save the case in pwb format. Next, since the *.raw files do not contain substation/geographic information, this data needs to be provided. Currently PowerWorld has *.aux files for the North American Eastern Interconnect (MMWG) and Western Interconnect (WECC) that assign the buses to substations, and provided latitude and longitude information for the substations.   These files are provided to commercial GIC customers for use with their studies. However, please note that since bus numbers change from case to case even within the same "series" of power flow cases, the *.aux file must be customized for the case in question. For example, with the MMWG 2010 Series cases a particular bus number might correspond to a bus in Substation A in the Summer 2012 case, and a bus in Substation B in another case in the same series.

To load the substation *.aux file, click on the PowerWorld icon above the toolbar to display the File menu; select **Load Auxiliary**. For the case considered here this file mapped more than 98% of the buses into substations. For an actual system study, the remaining buses of interest would need to be manually mapped into substations (such as high voltage buses in the study area).

Next, open the **GIC Analysis Form** and click on the **Create GMD Electric Field Input** tab. As described previously page is used for quickly creating different storm scenarios. For this example, we'll just create a single storm scenario (**Input Time** = 0) using a non-uniform electric field model, with a maximum electric field of 2 volts/mile, going NE to SW (direction 45 degrees), centered over Southern Michigan (latitude of 42.0 [north], longitude of -84.5 [west]), with a maximum electric field width of 200 miles, and a total width of 600 miles. Set the fields on this page to these values, then select **Add New Input Values at Time**. This sets the assumed electric field at each substation, and then calculates the GMD induced voltage for each transmission line.   The electric field input values are shown in Figure 12.

Figure 12: Assumed Electric Field Input Values

If a substation oneline is available, the assumed electric field magnitude can be contoured. This is done by right-clicking on an open area of the one-line to display the local menu and selecting Contouring, which causes the Contour Dialog to appear. For the **Object** type selected Substation, then for the Value click on the **Find** button and selected Geomagnetically Induced Current, Assumed Electric Field. Then set the **Maximum** field to the assumed electric field in volts/mile (2.0 for this example), **Nominal** to 1.0, and Minimum to 0.0. Selected OK to display the contour, which is shown in **Figure 13**.
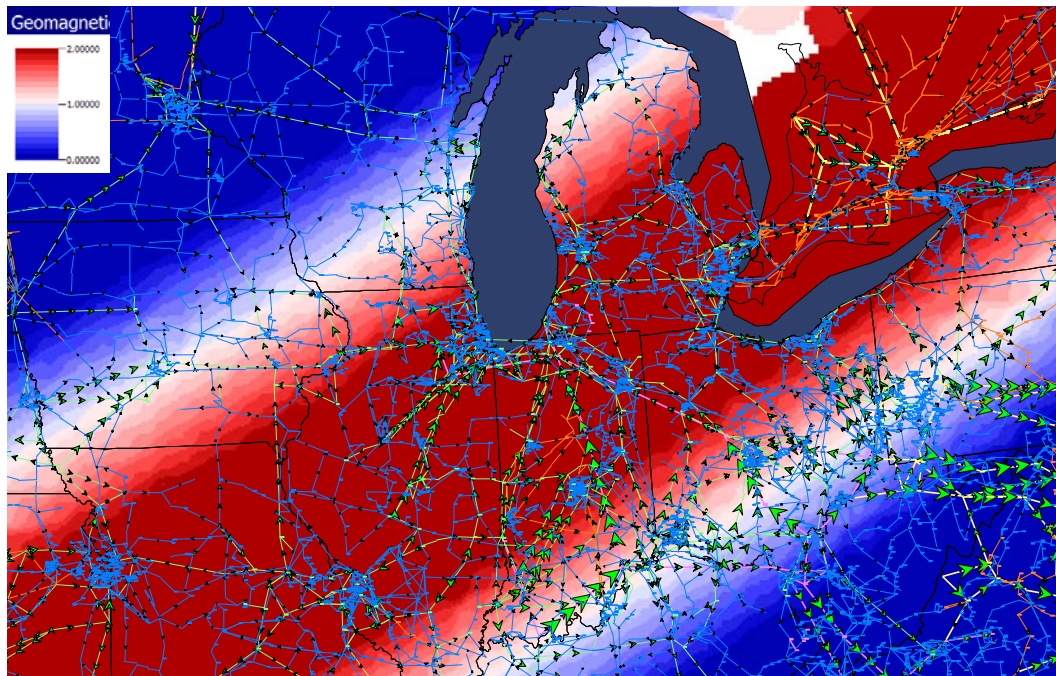
Figure 13: Contour of Assumed Electric Field Magnitude (Volts/Mile)

Next, to calculate the GIC values without performing a power flow solution, return to the GIC Analysis Form and select **Update GIC Values**. This uses default
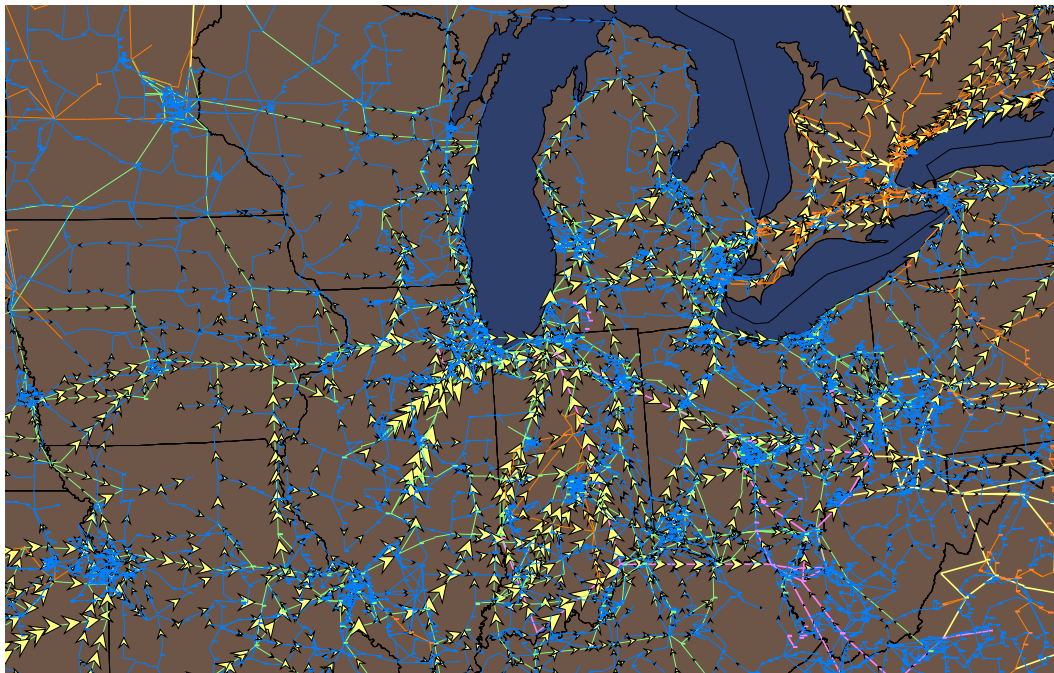

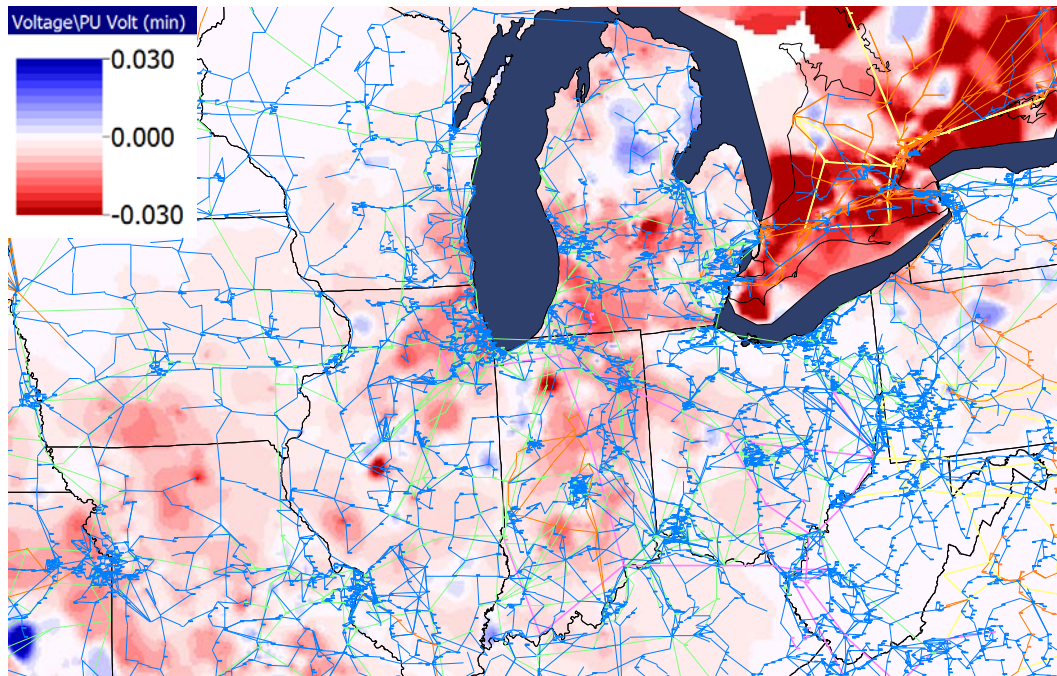Figure 14: Contour of Assumed Electric Field Magnitude (Volts/Mile)

Figure 15: Contour of Change in Bus Voltages Due to the GICs

References

[1]   http://www.powerworld.com/services/webtraining.asp

[2]   *2012 Special Reliability Assessment Interim Report: Effects of Geomagnetic Disturbances on the Bulk Power System*, NERC, February 2012.

[3]   V.D. Albertson, J.G. Kappenman, N. Mohan, and G.A. Skarbakka, "Load-Flow Studies in the Presence of Geomagnetically-Induced Currents," IEEE Trans. on Power Apparatus and Systems, vol. PAS-100, February 1981, pp. 594-606.

[4]   D.H. Boteler, R.J. Pirjola, "Modeling Geomagnetically Induced Currents Produced by Realistic and Uniform Electric Fields," *Proc. IEEE Trans. on Power Delivery*, vol. 13, October 1998, pp. 1303-1308.

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[6]   http://en.wikipedia.org/wiki/WGS84#Longitudes_on_WGS_84

[7]   http://en.wikipedia.org/wiki/Latitude