## Application Guide for Geomagnetically Induced Current (GIC) Analysis with OpenDSS

OpenDSS is an open-source program originally-designed for various advanced utility distribution planning analysis. It has been made available as open source specifically to support research into grid modernization efforts. It can presently be obtained from [www.sourceforge.net](http://www.sourceforge.net), a popular open source software sharing site.

In 2010, OpenDSS was modified to add the capability to perform geomagnetically-induced current (GIC) analysis of power systems. It has the capability to represent large networked transmission system as well as typical unbalanced radial distribution circuits. The GIC analysis can take advantage of the N-phase modeling capability of OpenDSS to perform the analysis on a three-phase basis as well as a single-phase basis as is commonly done in transmission power flow tools.

GIC are quasi-dc; thus, GIC simulations involve performing a low frequency analysis of the resulting dc network. The driving force behind the flow of GIC in the network is the voltage induced in the transmission lines[[1]](#footnote-1). The induced voltage is generated by the coupling of the transmission lines with the induced geoelectric field at the surface of the earth. Specialized quasi-dc models, which are described below, have been added to the program circuit element models for transmission lines, transformers, substation ground grids, and GIC blocking devices.

Once the dc model of the network has been constructed the following two OpenDSS commands are used to perform the solution:

Set frequency=0.1

Solve

This sets the solution frequency to 0.1 Hz and then a standard OpenDSS snapshot solution is performed. The sources in the problem at this frequency are the voltages induced along the lines. These sources are contained in the **GICLine** model. Transformers are modeled by special transformer models using the **GICTransformer** element. Descriptions of these elements follow immediately. Examples of the scripting required to execute the standard test case and produce the values to use in a transmission system power flow to represent the additional reactive power losses from transformers follow that.

## GICLine Object

The GICLine model is a key element used in the calculation of geomagnetically-induced current (GIC). Normally, one would think of a Line element as a power delivery device in OpenDSS, but in GIC analysis a transmission line is actually a source, or a power conversion device. Each phase of the transmission line is represented by a quasi-dc induced voltage (0.1 Hz) in series with the dc resistance of the line. The reactance is typically neglected but could be included if the user determines that there is some need to do so. The resulting model is depicted in Figure 1.

## 

Figure 1. GICLine Model

The induced voltage shown in Figure 1 can be computed internally by the program or supplied via the Volts property of the GICLine model.

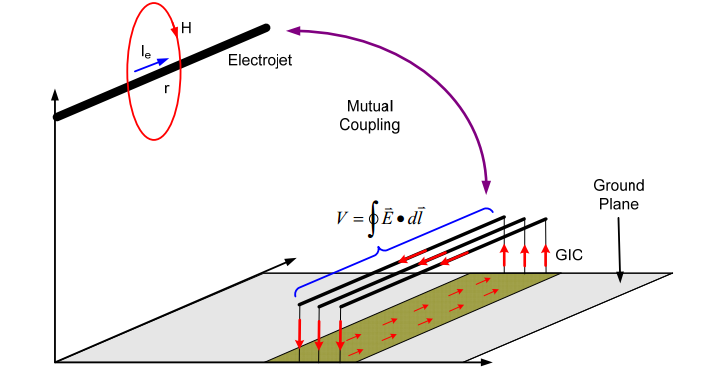


Figure 2. Coupling of Electrojet Current to Transmission Line to Produce GIC

The following describes the procedure utilized by OpenDSS to compute the induced voltage.

The induced voltage shown in Figure 17 is determined by an application of Faraday’s Law:



where is the electric field vector at the location of the transmission line, and is the incremental line segment length including direction. Because the distance between the source of the induced geoelectric field (electrojet) and the earth’s surface is generally on the order of 100-200 km, the electric field at the height of the transmission line can assumed to be the same as that of the earth’s surface. If the geoelectric field is assumed constant in the geographical area of a transmission line, then only the coordinates of the end point of the line are important, regardless of routing twists and turns. The resulting incremental length vector , becomes . The induced voltage can therefore be computed as follows:



The vector , representing the length and direction of the line between end points can be constructed using an arbitrary reference; however, such methods can introduce error. An improved method is to construct the vector , by computing the distance in the Northward and Eastward directions independently as depicted in Figure 3.



Figure 3. Substation Location Coordinates

Recall that the dot product of two vectors A and B can be computed using:



Thus, the dot product of the induced electric field and the length vector can be approximated by:



where *EN* is the northward electric field (V/km), *EE* is the eastward electric field (V/km), *LN* is the northward distance (km), and *LE* is the eastward distance (km).

The following procedure can be used to compute northward and eastward distances. Consider a transmission line between substations A and B as shown in Fig. 18. The northward distance can be computed using:



where ∆lat is the difference in latitude (degrees) between the two substations A and B. The eastward distance can be computed using:



where ∆long is the difference in longitude (degrees) between the two substations A and B, and α is defined as the average of the two latitudes:



The properties of the GICLine model, in order, are:

**Angle=** Phase angle in degrees of first phase. Default=0.0. See Voltage property

**bus1**= Name of bus for terminal 1. Node order definitions optional.

**bus2**= Name of bus for terminal 2.

**C=** Value of line blocking capacitance in microfarads. Default = 0.0, implying that there is no line blocking capacitor.

**EE=** Eastward Electric field. If specified, Voltage and Angle are computed from EN, EE, lat and lon values.

**EN=** Northward Electric field. If specified, Voltage and Angle are computed from EN, EE, lat and lon values.

**frequency=** GIC Source frequency. Defaults to 0.1 Hz.

**Lat1=** Latitude of Bus 1 (degrees)

**Lat2=** Latitude of Bus 2 (degrees)

**Lon1=** Longitude of Bus 1 (degrees)

**Lon2=** Longitude of Bus 2 (degrees)

**Phases**= No. of phases. Default = 3. A line has the same number of conductors per terminal as it has phases. Neutral wires are not explicitly modeled unless declared as a “phase”, and the impedance matrices must be augmented accordingly. For example, a three-phase line has a 3x3 Z matrix with the neutral reduced, or a 4x4 Z matrix with the neutral retained.

**R=** Resistance of line, ohms of impedance in series with GIC voltage source.

**Volts=** Voltage magnitude, in volts, of the GIC voltage induced across this line. When spedified, voltage source is assumed defined by Voltage and Angle properties. Specify this value OR EN, EE, lat1, lon1, lat2, lon2. Not both!! Last one entered will take precedence. Assumed identical in each phase of the Line object.

**X=** Reactance at base frequency, ohms. Default = 0.0. This value is generally not important for GIC studies but may be used if desired.

The following properties are common to all Power Conversion elements and inherited by GICLine.

**like=** Make like another GICLine object

**Basefreq=** Inherited Property for all PCElements. Base frequency for specification of the reactance value, X, if defined.

**enabled=** {Yes|No or True|False} Indicates whether this element is enabled. Inherited Property for all PCElements.

**Spectrum=** Inherited Property for all PCElements. Name of harmonic spectrum for this source. Default is "defaultvsource", which is defined when the DSS starts. Not used for GIC analysis.

## GICTransformer Object

The GICTransformer model is used in combination with the GICLine model for the calculation of geomagnetically induced current (GIC). The GICLine model contains the source representing the induced voltage. Transformers with a connection to ground provide a return path for the resulting current.

Power transformers are represented by their dc equivalent circuits, and only windings with connection to ground are included in the analysis. The model is a resistor network for the purposes of computing GIC in transformers. Only frequency domain models are necessary.

### Generator Step-Up Banks

A common transformer connection in large networked power systems is the grounded-wye delta connected generator step-up transformer (GSU). A three-phase model of a GSU used in GIC calculations is shown in Figure 4.



Figure 4. Three-phase Model of a Generator Step-Up Transformer

Note that the delta winding does not have any connection to the external network since it is not physically connected to ground and is open to the zero sequence. Thus, it is not included in the OpenDSS model. The HO terminal refers to the neutral point, and is modeled explicitly. Rw1 and Rw2 are defined as the dc winding resistance values of the high voltage or extra-high voltage and medium voltage windings, respectively.

Transformer windings are modeled with resistive branch circuits as shown in Figure 5.

[[2]](#footnote-2)

Figure 5. GSU Model in OpenDSS

The winding terminals designated as NH.1, NH.2, and NH.3 in Fig. 23 must be connected together to construct the wye winding. The bus number is arbitrary, but typically the name of the high side bus is used with the next available terminal number. An example OpenDSS script with high voltage bus named ‘Bus1’ and dc winding resistance of 0.1 Ω/phase is as follows:

New GICTransformer.T1 busH=Bus1.1.2.3 busNH=Bus1.4.4.4 R1=0.1 type=GSU

To illustrate the previous comment of utilizing the next available terminal value for the neutral bus, two identical GSUs in parallel can be described by the following:

New GICTransformer.T1 busH=Bus1.1.2.3 busNH=Bus1.4.4.4 R1=0.1 type=GSU

New GICTransformer.T2 busH=Bus1.1.2.3 busNH=Bus1.5.5.5 R1=0.1 type=GSU

Naming the neutral buses in this manner allows for the creation of individual neutral buses for each GSU which is necessary when modeling GIC blocking devices.

### Three-Winding Transformers

A three-phase model of a three-winding transformer used in the calculation of GIC is shown in Figure 6. Note that the delta tertiary winding is not included in the model since it does not have any physical connection to ground. Thus, the same model can be used for both two winding and three winding transformers. The neutral nodes of both of the wye windings (i.e. X0 and H0) are modeled explicitly. In some cases, either the X0 or H0 bushing may be ungrounded. In the GIC model, the node can be grounded through a large resistance, e.g. 1 MΩ to represent such connections.



Figure 6. Three-phase Model of a Three-Winding Transformer (Grounded-Wye, Grounded-Wye, Delta)

Rw1 and Rw2 are defined as the dc winding resistance values of the high voltage or extra-high voltage and medium voltage windings, respectively. Rw3 is defined as the dc winding resistance values of the low voltage tertiary winding; however, it is not included in the DSS model since it has no physical connection to ground.

Transformer windings are modeled in DSS with resistive branch circuits as shown in Figure 7.



Figure 7. Two-winding and Three-winding Transformer model in DSS

The winding terminals designated as NH.1, NH.2, NH.3 and NX.1, NX.2, NX.3 in Figure 7 must be connected together to construct each of the wye windings. The bus numbers are arbitrary, but typically the name of the high side bus is used with the next available terminal number. An example OpenDSS script with high voltage bus named ‘Bus1’, low voltage bus named ‘Bus2’, dc winding resistance of 0.2 Ω/phase for the H winding and 0.1 Ω/phase for the X winding is as follows:

New GICTransformer.T1 busH=Bus1.1.2.3 busNH=Bus1.4.4.4 busX=Bus2.1.2.3 busNX=Bus1.5.5.5 R1=0.2 R2=0.1 type=YY

### Autotransformers

A three-phase model of an autotransformer used in determining GIC flow is shown in Figure 8. Note that the delta tertiary winding (if applicable) is not included in the DSS model since it does not have any physical connection to ground. The common autotransformer neutral (H0/X0) is modeled explicitly.

Rw1 and Rw2 are defined as the dc resistance values of the series and common windings, respectively. Transformer windings are modeled in DSS with resistive branch circuits as shown in Figure 9.



Figure Three-phase Model of a Three-Winding Autotransformer



Figure 9. Two-winding and Three-winding Autotransformer model in DSS

The winding terminals designated as NX.1, NX.2, and NX.3 in Figure 9 must be connected together to construct the neutral connection. The bus numbers are arbitrary, but typically the name of the high side bus with the next available terminal number is used to designate the neutral bus. An example OpenDSS script with high voltage bus named ‘Bus1’, low voltage bus named ‘Bus2’, dc winding resistance of 0.1 Ω/phase for the series winding and 0.2 Ω/phase for the common winding is as follows:

New GICTransformer.T1 busH=Bus1.1.2.3 busX=Bus2.1.2.3 busNX=Bus1.4.4.4 R1=0.1 R2=0.2 type=auto

The properties of the GICTransformer model, in order, are:

**Basefreq=** Inherited Property for all PCElements. Base frequency for specification of reactance value.

**busH**= Name of bus High-side (H) bus. Node order definitions optional.

**busNH**= Name of Neutral bus for H, or first, winding. Defaults to all phases connected to H-side bus, node 0, if not specified and transformer type is either GSU or YY. (Shunt Wye Connection to ground reference)For Auto, this is automatically set to the X bus.

**busNX**= Name of Neutral bus for X, or Second, winding. Defaults to all phases connected to X-side bus, node 0, if not specified. (Shunt Wye Connection to ground reference).

**busX**= Name of bus Low-side (X) bus. Node order definitions optional.

**enabled=** {Yes|No or True|False} Indicates whether this element is enabled. Default is Yes/True.

**faultrate=** Number of failures per year. Typically not specified in GIC calculations.

**phases=** Number of phases. Default is 3.

**R1=** Resistance, each phase, ohms for H winding, (Series winding, if Auto). Default is 0.0001.

**R2=** Resistance, each phase, ohms for X winding, (Common winding, if Auto). Default is 0.0001.

**Type=** Type of transformer: {GSU\* | Auto | YY}. Default is GSU.

**MVA=** Optional. MVA Rating assumed Transformer. Default is 100. Used for computing vars due to GIC and winding resistances if kV and MVA ratings are specified.

**KVLL1=** Optional. kV LL rating for H winding (winding 1). Default is 500. Required if you are going to export vars for power flow analysis or enter winding resistances in percent.

**KVLL2=** Optional. kV LL rating for X winding (winding 2). Default is 138. Required if you are going to export vars for power flow analysis or enter winding resistances in percent..

**%R1=** Optional. Percent Resistance, each phase, for H winding (1), (Series winding, if Auto). Default is 0.2. Alternative way to enter R1 value. It is the actual resistances in ohmns that matter. MVA and kV should be specified.

**%R2=** Optional. Percent Resistance, each phase, for X winding (2), (Common winding, if Auto). Default is 0.2. Alternative way to enter R2 value. It is the actual resistances in ohms that matter. MVA and kV should be specified.

**K=** Mvar K factor. Default way to convert GIC Amps in H winding (winding 1) to Mvar. Default is 2.2. Commonly-used simple multiplier for estimating Mvar losses for power flow analysis.

Mvar = K \* kvLL \* GIC per phase / 1000

Mutually exclusive with using the VarCurve property and pu curves. If you specify this (default), VarCurve is ignored.

**VarCurve=** Optional. *XYCurve* object name. Curve is expected as TOTAL pu vars vs pu GIC amps/phase. Vars are in pu of the MVA property. No Default value. Required only if you are going to export vars for power flow analysis using curves. See K property.

**like=** Make like another object, e.g. New GICTransformer.T2 like=T1 ...

The following properties are inherited from the Power Delivery elemen class, but are ignored for GIC calculations

**normamps=** Normal rated current. Typically not specified in GIC calculations.

**emergamps=** Maximum current. Typically not specified in GIC calculations.

**pctperm=** Percent of failures that become permanent. Typically not specified in GIC calculations.

**repair=** Hours to repair. Typically not specified in GIC calculations.

## Example: GIC Test Case

The example system represents a hypothetical 20 bus EHV network consisting of 500 kV and 345 kV lines and transformers[[3]](#footnote-3). Figure 10 shows a single-line diagram of the network. The network includes single transmission lines as well as some that occupy the same transmission corridor as another. The substations feature both conventional transformers and autotransformers. Also included are series (series capacitors) and neutral connected GIC blocking devices.



Figure 10. One Line Diagram of Example GIC System

Data for the system described in Figure 10 are provided in Tables 1-3.

Table 1.  
GIC Example Substation Location and Grid Resistance

|  |  |  |  |
| --- | --- | --- | --- |
| Name | Latitude | Longitude | Grounding Resistance (Ohm) |
| Sub 1 | 33.613499 | -87.373673 | 0.2 |
| Sub 2 | 34.310437 | -86.365765 | 0.2 |
| Sub 3 | 33.955058 | -84.679354 | 0.2 |
| Sub 4 | 33.547885 | -86.074605 | 1.0 |
| Sub 5 | 32.705087 | -84.663397 | 0.1 |
| Sub 6 | 33.377327 | -82.618777 | 0.1 |
| Sub 7 | 34.252248 | -82.836301 | N/A |
| Sub 8 | 34.195574 | -81.098002 | 0.1 |

Table 2.  
 GIC Example Transmission Line Data

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Line | From Bus | To Bus | Voltage  (kV-LL) | Length (miles) | Resistance (ohm/phase) |
| 1 | 2 | 3 | 345 | 77.18 | 3.512 |
| 2 | 2 | 17 | 345 | 77.47 | 3.525 |
| 3 | 15 | 4 | 500 | 87.51 | 1.986 |
| 4 | 17 | 16 | 345 | 102.54 | 4.665 |
| 5 | 4 | 5 | 500 | 103.31 | 2.345 |
| 6 | 4 | 5 | 500 | 103.31 | 2.345 |
| 7 | 5 | 6 | 500 | 131.05 | 2.975 |
| 8 | 5 | 11 | 500 | 154.57 | 3.509 |
| 9 | 6 | 11 | 500 | 63.59 | 1.444 |
| 10 | 4 | 6 | 500 | 205.57 | 4.666 |
| 11 | 15 | 6 | 500 | 128.81 | 2.924 |
| 12 | 15 | 6 | 500 | 128.81 | 2.924 |
| 13 | 11 | 12 | 500 | 102.39 | 2.324 |
| 14 | 16 | 20 | 345 | 88.98 | 4.049 |
| 15 | 17 | 20 | 345 | 152.53 | 6.940 |

Table 3.  
 GIC Example Transformer Data

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Name | Type | Resistance W1  (Ohms/phase) | Bus No. | Resistance W2  (Ohms/phase) | Bus No. |
| T1 | GSU w/ GIC BD | 0.1 | 2 | N/A | 1 |
| T2 | GY-GY-D | 0.2 | 4 | 0.1 | 3 |
| T3 | GSU | 0.1 | 17 | N/A | 18 |
| T4 | GSU | 0.1 | 17 | N/A | 19 |
| T5 | Auto | 0.04 | 16 | 0.06 | 15 |
| T6 | GSU | 0.15 | 6 | N/A | 7 |
| T7 | GSU | 0.15 | 6 | N/A | 8 |
| T8 | GY-GY | 0.04 | 5 | 0.06 | 20 |
| T9 | GY-GY | 0.04 | 5 | 0.06 | 20 |
| T10 | GSU | 0.1 | 12 | N/A | 13 |
| T11 | GSU | 0.1 | 12 | N/A | 14 |
| T12 | Auto | 0.04 | 4 | 0.06 | 3 |
| T13 | GY-GY-D | 0.2 | 4 | 0.1 | 3 |
| T14 | Auto | 0.04 | 4 | 0.06 | 3 |
| T15 | Auto | 0.04 | 15 | 0.06 | 16 |

### OpenDSS Script for Example System

The following scripts can be used to model the example system in OpenDSS with an Eastward electric field of 1 V/km. The scripts are provided with the OpenDSS download and on the OpenDSS website. See Distrib\Examples\GICExample folder on the OpenDSS website. The file containing a complete run script is *GIC\_Example.DSS*.

**Transmission Lines**

Note: Text lines appear wrapped in this document due to Word limitations, but are all one OpenDSS statement in the actual OpenDSS script file.

!GIC Line Data

New GICLine.1-Bus2-Bus3 bus1=2 bus2=3 R=3.512 Lat1=33.613499 Lon1=-87.373673 Lat2=33.547885 Lon2=-86.074605 EE=1.00 EN=0.00

New GICLine.2-Bus2-Bus17 bus1=2 bus2=17 R=3.525 Lat1=33.613499 Lon1=-87.373673 Lat2=34.310437 Lon2=-86.365765 EE=1.00 EN=0.00

New GICLine.3-Bus15-Bus4 bus1=15 bus2=4 R=1.986 Lat1=33.955058 Lon1=-84.679354 Lat2=33.547885 Lon2=-86.074605 EE=1.00 EN=0.00

New GICLine.4-Bus17-Bus16 bus1=17 bus2=16 R=4.665 Lat1=34.310437 Lon1=-86.365765 Lat2=33.955058 Lon2=-84.679354 EE=1.00 EN=0.00

New GICLine.5-Bus4-Bus5 bus1=4 bus2=5 R=2.345 Lat1=33.547885 Lon1=-86.074605 Lat2=32.705087 Lon2=-84.663397 EE=1.00 EN=0.00

New GICLine.6-Bus4-Bus5 bus1=4 bus2=5 R=2.345 Lat1=33.547885 Lon1=-86.074605 Lat2=32.705087 Lon2=-84.663397 EE=1.00 EN=0.00

New GICLine.7-Bus5-Bus6 bus1=5 bus2=6 R=2.975 Lat1=32.705087 Lon1=-84.663397 Lat2=33.377327 Lon2=-82.618777 EE=1.00 EN=0.00

New GICLine.8-Bus5-Bus11 bus1=5 bus2=11 C=32.0 R=3.509 Lat1=32.705087 Lon1=-84.663397 Lat2=34.252248 Lon2=-82.836301 EE=1.00 EN=0.00

New GICLine.9-Bus6-Bus11 bus1=6 bus2=11 R=1.444 Lat1=33.377327 Lon1=-82.618777 Lat2=34.252248 Lon2=-82.836301 EE=1.00 EN=0.00

New GICLine.10-Bus4-Bus6 bus1=4 bus2=6 R=4.666 Lat1=33.547885 Lon1=-86.074605 Lat2=33.377327 Lon2=-82.618777 EE=1.00 EN=0.00

New GICLine.11-Bus15-Bus6 bus1=15 bus2=6 R=2.924 Lat1=33.955058 Lon1=-84.679354 Lat2=33.377327 Lon2=-82.618777 EE=1.00 EN=0.00

New GICLine.12-Bus15-Bus6 bus1=15 bus2=6 R=2.924 Lat1=33.955058 Lon1=-84.679354 Lat2=33.377327 Lon2=-82.618777 EE=1.00 EN=0.00

New GICLine.13-Bus11-Bus12 bus1=11 bus2=12 R=2.324 Lat1=34.252248 Lon1=-82.836301 Lat2=34.195574 Lon2=-81.098002 EE=1.00 EN=0.00

New GICLine.14-Bus16-Bus20 bus1=16 bus2=20 R=4.049 Lat1=33.955058 Lon1=-84.679354 Lat2=32.705087 Lon2=-84.663397 EE=1.00 EN=0.00

New GICLine.15-Bus17-Bus20 bus1=17 bus2=20 R=6.940 Lat1=34.310437 Lon1=-86.365765 Lat2=32.705087 Lon2=-84.663397 EE=1.00 EN=0.00

**Changing the E Field Values**

This example shows a constant E field of EE=1.0 and EN = 0.0. It is a simple matter to generate a script to change these values. The OpenDSS does not have to be restarted. Savvy programmers could script OpenDSS behavior via its COM interface but one could also simply produce a script with a powerful text editor. For example, to change the values for GICLine.9 and export the results, one possible script sequence would be:

...

(Script to Define circuit)

...

Solve

Export GIC Case\_1.CSV

GICLine.9.EE=0.86 EN=0.12

Solve

Export GIC Case\_2.CSV

...

Etc.

...

You only need to set the property values that will change. All others remain the same.

**Transformers**

Note: Text lines appear wrapped in this document due to Word limitations, but are all one OpenDSS statement in the actual OpenDSS script file.

New GICTransformer.T1 busH=2 busNH=2.4.4.4 R1=0.1 type=GSU\_

New GICTransformer.T2 busH=4 busNH=4.4.4.4 busX=3 busNX=4.4.4.4 R1=0.2 R2=0.1 type=YY

New GICTransformer.T3 busH=17 busNH=17.4.4.4 R1=0.1 type=GSU

New GICTransformer.T4 busH=17 busNH=17.4.4.4 R1=0.1 type=GSU

New GICTransformer.T5 busH=15 busX=16 busNX=15.4.4.4 R1=0.04 R2=0.06 type=Auto

New GICTransformer.T6 busH=6 busNH=6.4.4.4 R1=0.15 type=GSU

New GICTransformer.T7 busH=6 busNH=6.4.4.4 R1=0.15 type=GSU

New GICTransformer.T8 busH=5 busNH=5.4.4.4 busX=20 busNX=5.4.4.4 R1=0.04 R2=0.06 type=YY

New GICTransformer.T9 busH=5 busNH=5.4.4.4 busX=20 busNX=5.4.4.4 R1=0.04 R2=0.06 type=YY

New GICTransformer.T10 busH=12 busNH=12.4.4.4 R1=0.10 type=GSU

New GICTransformer.T11 busH=12 busNH=12.4.4.4 R1=0.10 type=GSU

New GICTransformer.T12 busH=4 busX=3 busNX=4.4.4.4 R1=0.04 R2=0.06 type=Auto

New GICTransformer.T13 busH=4 busNH=4.4.4.4 busX=3 busNX=4.4.4.4 R1=0.2 R2=0.1 type=YY

New GICTransformer.T14 busH=4 busX=3 busNX=4.4.4.4 R1=0.04 R2=0.06 type=Auto

New GICTransformer.T15 busH=15 busX=16 busNX=15.4.4.4 R1=0.04 R2=0.06 type=Auto

**Substation Ground Grid Model**

The Line elements and Transformer elements in the example case are all defined as 3-phase elements, which is the OpenDSS default for most devices. The substation grounding system is represented in this model as a resistance to remote earth. This is modeled in OpenDSS using the Reactor model, which in its simplest form is a series R-L branch. The L part is ignored and only the resistance is non-zero. The single-phase resistances are connected from the neutral points to ground at the transformers. The three phase conductors are connected to nodes 1, 2, and 3 at a bus while the neutrals are connected to node 4. The Reactor elements representing the ground resistance are therefore connected between nodes 4 and 0 at a bus (the Bus2= property of a reactor defaults to node 0 at the same bus). The exception is the ground connection in Sub1, which has a neutral blocking capacitor (see next section).

!Substation Ground Grid Data

New Reactor.SUB2gnd phases=1 bus1=17.4 R=0.200 X=0

New Reactor.SUB3gnd phases=1 bus1=15.4 R=0.200 X=0

New Reactor.SUB4gnd phases=1 bus1=4.4 R=1.0 X=0

New Reactor.SUB5gnd phases=1 bus1=5.4 R=0.100 X=0

New Reactor.SUB6gnd phases=1 bus1=6.4 R=0.100 X=0

New Reactor.SUB8gnd phases=1 bus1=12.4 R=0.100 X=0

**Neutral Blocking Capacitor**

One way of blocking GIC is to place a neutral in series with a transformer neutral as shown for Sub1. This is represented in OpenDSS by a single-phase Capacitor element in series with a single-phase Reactor element.

New Capacitor.T1 bus1=2.4 bus2=2.5 phases=1 cuf=10

New Reactor.SUB1gnd phases=1 bus1=2.5 R=0.200 X=0

**Solving for GIC**

The remainder of the OpenDSS script to execute the basic GIC example is:

!Perform analysis

Set frequency=0.1

Solve

!Load file with bus coordinates, used for plotting

LatLongCoords LatLonFile.csv

Show Current Elements

plot circuit Current Max=70 dots=y labels=y subs=n C1=$00FF0000

This sets the solution frequency to 0.1 Hz and solves for the currents. The script following the Solve command loads in latitude and longitude coordinates for the buses so that the OpenDSS can create a circuit diagram. The coordinates for the test case are shown in Figure 11.

11 34.252248 -82.836301

12 34.195574 -81.098002

15 33.955058 -84.679354

16 33.955058 -84.679354

17 34.310437 -86.365765

2 33.613499 -87.373673

20 32.705087 -84.663397

3 33.547885 -86.074605

4 33.547885 -86.074605

5 32.705087 -84.663397

6 33.377327 -82.618777

Figure 11. Bus Coordinates in Latitude and Longitude

The resulting OpenDSS circuit plot is shown in Figure 12.

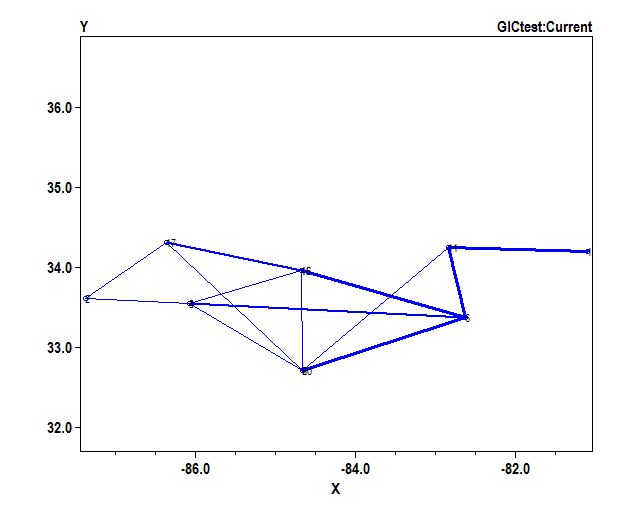


Figure 12. OpenDSS Depiction of the Test Circuit with Line Thickness Proportional to GIC.

## Estimating Transformer Reactive Power Losses from GIC

A major impact of a GMD event is the excess reactive power demand imposed by transformers saturated by GIC. To study the impact of this increased demand with respect to the system voltage profiles and reactive-source biasing, the reactive power produced from the fundamental-frequency positive-sequence exciting current component is of interest.

These reactive power demands vary for different transformer types. Figure 13 illustrates the reactive power consumption versus GIC for three-phase transformer configurations.



Figure . Reactive power consumption versus GIC for three-phase transformer configurations [1]

Due to the predominantly linear relationship, an approximate equation is sometimes used for studying system impact. A common expression in terms of volts and amperes is:

*Qexc* is total three-phase reactive power “loss” in Mvar

*k* is a transformer specific constant (default in OpenDSS is 2.2)

*IGIC* is the dc amperes per phase

*kVll* is the line-line rms voltage

## Example: Transformer Mvar Loss Calculation for GIC with OpenDSS

The OpenDSS does not perform a transmission system power flow, but can export a Mvar loss estimation from GIC saturation for use in a transmission power flow program. The estimation can be made by a simple “K factor” based on the GIC or, if the user has specific data for a transformer, curve representing per unit Mvar vs per unit phase current can be used. To do the latter, the transformer MVA must be define (note that this is not defined in the GIC test case).

#### K-Factor Approximation

The var demand in OpenDSS can be calculated using the relationship:

*Qexc* is total three-phase in Mvar

*k* is a transformer specific constant

*IGIC* is the dc amperes per phase

*kVll* is the line-line rms voltage

This will convert the GIC Amps in H winding (winding 1) in the program to Mvar. The default is K=2.2, a commonly-used simple multiplier for estimating Mvar losses for power flow [1].

Using the values above with the default of K=2.2, the Mvars values for this example can be extracted by simply using the exporting GIC command:

Export GIC

The results for the transformers’ Mvar losses and the GIC are as follows:

Table 4.  
 Mvar example results, K=2.2

|  |  |  |
| --- | --- | --- |
| Bus | Mvar | GIC Amps per phase |
| 2 | 1.75E-05 | 0.000398 |
| 4 | 5.268 | 6.941 |
| 4 | 16.506 | 21.747 |
| 4 | 5.268 | 6.941 |
| 4 | 16.506 | 21.747 |
| 5 | 13.581 | 17.893 |
| 5 | 13.581 | 17.893 |
| 6 | 64.996 | 59.087 |
| 6 | 64.996 | 59.087 |
| 12 | 24.621 | 22.383 |
| 12 | 24.621 | 22.383 |
| 15 | 26.481 | 34.889 |
| 15 | 26.481 | 34.889 |
| 17 | 1.388 | 31.548 |
| 17 | 1.388 | 31.548 |

The Mvars can then be imported to another program for a power flow analysis.

#### Piecewise linear Approxiation

Another option for specifying the var relationship to the GIC is to use an XYCurve object available in OpenDSS. The var curve is expected in pu TOTAL vars vs pu GIC amps/phase as shown in Figure 13. Vars are in pu of the MVA property of the corresponding GICTransformer element.

Using the values shown in Figure 13 for 3-single phase transformers, the XYCurve is defined as:

New XYCurve.GIC npts=2 xarray=[0 0.3] yarray=[0 0.54]

This is a simple linear relationship consisting of just 2 points, but could be more detailed if data were available. This var curve may be assigned to each transformer as follows:

GICTransformer.T1.Varcurve=GIC

GICTransformer.T2.Varcurve=GIC

GICTransformer.T3.Varcurve=GIC

GICTransformer.T4.Varcurve=GIC

GICTransformer.T5.Varcurve=GIC

GICTransformer.T6.Varcurve=GIC

GICTransformer.T7.Varcurve=GIC

GICTransformer.T8.Varcurve=GIC

GICTransformer.T9.Varcurve=GIC

GICTransformer.T10.Varcurve=GIC

GICTransformer.T11.Varcurve=GIC

GICTransformer.T12.Varcurve=GIC

GICTransformer.T13.Varcurve=GIC

GICTransformer.T14.Varcurve=GIC

GICTransformer.T15.Varcurve=GIC

After the GIC solution, the results can be written to a CSV file and viewed by the command:

Export GIC

The results for the transformers’ Mvar losses and the GIC for the test case are shown in Table 5.

Table 5.  
 Mvar example results, var curve

|  |  |  |
| --- | --- | --- |
| Bus | Mvar | GIC Amps per phase |
| 2 | 1.75E-05 | 0.000398 |
| 4 | 5.279 | 6.941 |
| 4 | 16.54 | 21.747 |
| 4 | 5.279 | 6.941 |
| 4 | 16.54 | 21.747 |
| 5 | 13.609 | 17.893 |
| 5 | 13.609 | 17.893 |
| 6 | 65.13 | 59.087 |
| 6 | 65.13 | 59.087 |
| 12 | 24.672 | 22.383 |
| 12 | 24.672 | 22.383 |
| 15 | 26.536 | 34.889 |
| 15 | 26.536 | 34.889 |
| 17 | 1.391 | 31.548 |
| 17 | 1.391 | 31.548 |

The Mvar values can then be imported into a power flow program for a power flow analysis. The Mvar losses are lumped at the first bus to which the transformer is connected.

[1] EPRI Proceedings: Geomagnetically Induced Currents Conference, TR-100450

1. D.H. Boteler, R.J. Pirjola, “Modeling Geomagnetically Induced Currents Produced by Realistic and Uniform Electric Fields”, *IEEE Transactions on Power Delivery*, Vol. 13, No. 4, pp. 1303-1308, October 1998. [↑](#footnote-ref-1)
2. [↑](#footnote-ref-2)
3. R. Horton, D.H. Boteler, T.J. Overbye, R.J. Pirjola, R.Dugan, “A Test Case for the Calculation of Geomagnetically Induced Currents,” Submitted to IEEE Transactions on Power

   Systems, March 2012. [↑](#footnote-ref-3)