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# A Case Study of the Geomagnetic Induced Current (GIC) Level from the Neighboring System

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# 1.0 ABSTRACT

During a Geomagnetic Disturbance (GMD) event, Geomagnetic Induced Current (GIC) will enter into the transmission system through the ground wire of the Wye-grounded transformer. Since the GICs will occur across the utilities, including the GICs entering from the neighboring system is necessary in the analysis. The size of the neighboring system (boundary of the neighboring system) included in the study model may change the GIC level in the study area significantly. A case study was performed to evaluate the GIC levels from the neighboring system by changing the size of the neighboring system included in the study model. The study cases were developed with the different sizes of the neighboring system with a study utility (Lubbock Power & Light) and its neighboring system data. GIC module of Siemens PTI's Power System Simulator for Engineers (PSS®E) software was used in the analysis. This paper discusses the observed GIC levels coming into a study utility and its correlation to the size of the neighboring system included in the model. The modeling portion of this case study satisfied Requirement R2 of the NERC TPL-007-1 standard.

# 2.0 INTRODUCTION

## 2.1 Background

When corona mass ejections out of the Sun come towards the Earth, a Geomagnetic Disturbance (GMD) event occurs on the Earth. Rapidly changing electromagnetic fields over large regions on the Earth induce voltage potentials on the Earth's surface. Different voltage potentials on the ground level induce Geomagnetically Induced Current (GIC) and will enter into the transmission system through the ground wire of a Wye-grounded transformer. The GIC in the transmission system can have a wide impact from transformer loading to system harmonics interference [1][2].

Federal Energy Regulatory Commission (FERC) directed North American Electric Reliability Corporation (NERC) to develop a reliability standard that addresses the impact of GMD on the bulk electric system under FERC Order No.779. (Reliability Standards for Geomagnetic Disturbances) [3]. NERC issued a draft transmission planning standard TPL-007-1, "Transmission System Planned Performance During Geomagnetic Disturbances" as a response to the FERC Order No.779. The draft standard passed the final ballot and NERC filed a petition seeking FERC approval on January 21, 2015 [4]. The NERC TPL-007-1 standard includes seven different requirements that Transmission Planners or Planning Coordinators must meet at different deadlines. Since GIC is quasi-DC current, one of the requirements involves developing and maintaining DC equivalent models of the system to effectively study GIC impact.

## 2.2 Problem Description

This technical paper discusses one important modeling issue, the impact of the neighboring system, which Transmission Planners or Planning Coordinators may encounter as they develop their equivalent DC model. While it is not clear how much of the neighboring system has to be included in the equivalent DC model for compliance with the NERC TPL-007-1 standard, the impact of the neighboring system on the GIC level is significant. The impact of the neighboring system was investigated through a case study utilizing information from Lubbock Power and Light (LP&L)'s 230 kV transmission system and assumed data on their neighboring system. This paper also discusses different considerations when determining the boundary of the neighboring system. The GIC module of Siemens PTI's Power System Simulator for Engineers (PSS®E) software was used to perform the analysis in the case study.

# 3.0 STUDY ASSUMPTIONS

The study was completed using the GIC Module in PSS®E version 34. System data specific to the LP&L system was provided by LP&L. The pertinent considerations in the development of the study models are summarized below.

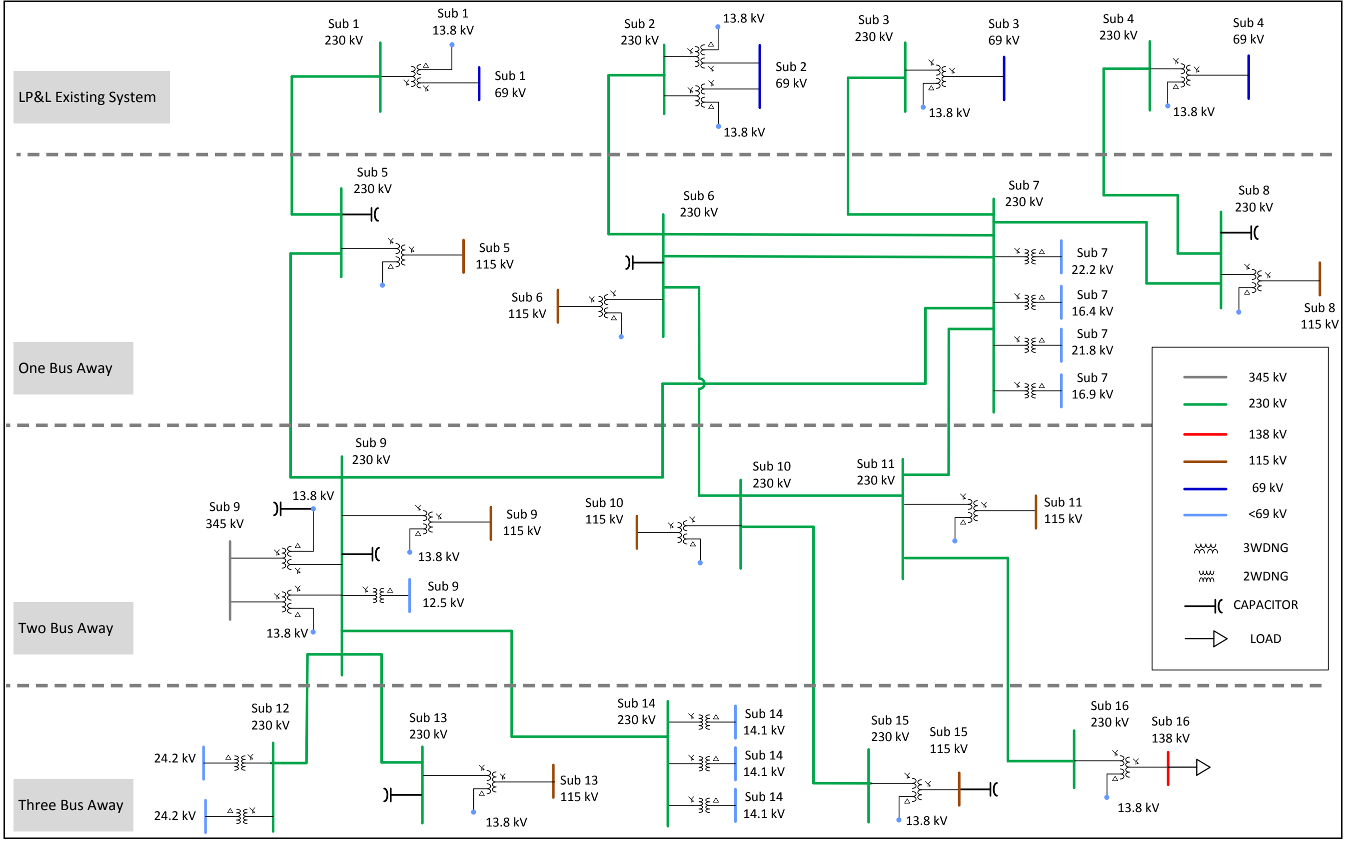
## 3.1 Neighboring System

Collecting the necessary information required to develop an equivalent DC model for the area outside a utility's system can be challenging. Thus, a discussion about how to set the neighboring system boundary pertains to the issue of accuracy but also to the issue of availability and efficiency. The NERC Application Guide for Computing Geomagnetically-Induced Current in the Bulk- Power System [5] describes three different options to model the neighboring system:

1. Leave the neighboring system connection as an open circuit and only develop the utility's own system.
2. Represent the neighboring system as a line to the first substation of the neighboring system and its resistance to ground.
3. Represent the neighboring system as a very long line. The resistance of the first line and the induced voltage are included in the model, but not the resistance to ground.

PSS®E GIC Module provides a way of including the neighboring system into the GIC calculation. The user can assign Intertie Levels to include specified neighboring system levels. However, at the edges of the Intertie Level, an open circuit is assumed and ignored in GIC calculation. In the case study, the Intertie Level was varied from 1 to 3 and the GIC was evaluated within the study area. The study area and neighboring configuration used in the case study is shown in Figure 3-1. The diagram does not reflect substation geographical information but rather is arranged with respect to their Intertie Level.

**Figure 3-1 Study Area and Neighboring System***



* The diagram only includes details of the 200 kV and above network.

## 3.2 Transformer Configuration

In typical load flow modeling, transformer configurations are often not completely captured and the data within the load flow models do not reflect actual configurations, however, in equivalent DC modeling the configuration of the transformers is of utmost importance. There are two reasons for this. The first reason is that the transformers in the system provide most of the physical connections to Earth (grounding). This physical connection to Earth provides the path for GIC to travel from the Earth into the electrical system. Shunt devices also provide such a ground path but are far fewer in number. Furthermore, the configuration of the transformer ground connection is important. If the transformer has a delta connection and it does not have a ground path from the transformer to the ground, then there is no path for the GIC to enter the system. GIC only enters the system through Wye-grounded connections. This concept is codified within the NERC TPL-007-1 standard in that it requires developing equivalent DC models for transformers higher than 200 kV voltage on its high side with Wye-grounded connections [4]. The GIC coming through the below 200 kV system has a comparatively smaller impact on the 200 kV and above system because of the relatively higher impedance associated with the transmission lines on the lower voltage system. The second reason transformer configurations are important is that the configurations can produce different heating effects within the transformers.

The transformer configuration parameters in the PSS®E load flow case in the study area was updated to match the transformer data listed in the transformer test data provided by LP&L. The configuration in the PSS®E load flow case for the neighboring system transformers was assumed to be correct and the vector code associated with this configuration was applied and saved in the study case.

## 3.3 Transformer Data

The transformer DC resistance values and configurations for the study area and Intertie Levels used within this case study are discussed in this section. There are 5 transformers with high sides greater than 200 kV within LP&L's selected study area. Some of the transformer parameters are shown in Table 3-1.

**Table 3-1: Study Area Transformer Data**

| Transformer | Configuration | 3 phase Winding Resistance (Ohms/phase) | | Converted DC Resistance (Ohms/phase) | |
|---|---|---|---|---|---|
| | | Series | Common | Series | Common |
| 1 | 3 winding, grounded wye, auto | 0.3884 | 0.0473 | 0.1295 | 0.0158 |
| 2 | 3 winding, grounded wye, auto | 0.5444 | 0.1889 | 0.1815 | 0.0630 |
| 3 | 3 winding, grounded wye, auto | 0.5444 | 0.1889 | 0.1815 | 0.0630 |
| 4 | 3 winding, grounded wye, auto | 0.3872 | 0.0471 | 0.1291 | 0.0157 |
| 5 | 3 winding, grounded wye, auto | 0.3884 | 0.0473 | 0.1295 | 0.0158 |

As described in the NERC Application Guide for Computing Geomagnetically-Induced Current in the Bulk- Power System [5] (GIC Application Guide), the best source for transformer information is the transformer test reports. Test reports for the study area were analyzed and the values for winding resistance at the reference temperature (75 degrees) for each winding were found. This value was converted from the three phase value to the DC resistance value in the manner described in Table 2 of the GIC Application Guide.

Intertie Level 0 is defined as the study area. Intertie levels are defined by the number of buses away from the study area. The Level 1 intertie represents 1 bus away from the study area. In this study, Intertie Level 1 includes 4 substations and 7 transformers in addition to the network modeled explicitly in Level 0. The data for the additional transformers is presented in Table 3-2.

**Table 3-2: Intertie Level 1 Transformer Data**

| Transformer | Configuration | Converted DC Resistance | | Unit |
|---|---|---|---|---|
| | | Series | Common | |
| 5 | 3 winding, wye grounded | 0.5870 | 0.1470 | Ohm/Phase |
| 6 | 3 winding, wye grounded | 0.2330 | 0.0580 | Ohm/Phase |
| 7 | 2 winding, wye grounded | 0.1815 | 0.0630 | Ohm/Phase |
| 8 | 2 winding, wye grounded | - | 0.2700 | Ohm/Phase |
| 9 | 2 winding, wye grounded | - | 0.2430 | Ohm/Phase |
| 10 | 2 winding, wye grounded | - | 0.2670 | Ohm/Phase |
| 11 | 3 winding, wye grounded | 0.2330 | 0.0580 | Ohm/Phase |

Intertie Level 2 represents 2 buses away from the study area. In this study, Intertie Level 2 includes 3 substations and 7 transformers in addition to the network modeled explicitly in Level 1 for a total of 11 substations. Table 3-3 presents the additional transformer data for Level 2 substations.

**Table 3-3: Intertie Level 2 Transformer Data**

| Transformer | Configuration | Converted DC Resistance (Ohms/Phase) | |
|---|---|---|---|
| | | Series | Common |
| 12 | 2 winding, wye grounded | - | 0.5770 |
| 13 | 3 winding, wye grounded | 0.2300 | 0.0580 |
| 14 | 3 winding, wye grounded | 0.2490 | 0.0620 |
| 15 | 3 winding, wye grounded | 0.1520 | 0.0670 |
| 16 | 3 winding, wye grounded | 0.1470 | 0.0650 |
| 17 | 3 winding, wye grounded | 0.4730 | 0.1180 |
| 18 | 3 winding, wye grounded | 0.4810 | 0.1200 |

Intertie Level 3 represents 3 buses away from the study area. This Intertie Level adds 5 substations and 8 transformers in addition to the network modeled explicitly in Level 2 for a total of 16 substations. Table 3-4 presents transformer data for the additional transformers at these substations.

**Table 3-4: Intertie Level 3 Transformer Data**

| Transformer | Configuration | Converted DC Resistance (Ohms/phase) | |
|---|---|---|---|
| | | Series | Common |
| 19 | 3 winding, wye grounded | 0.4810 | 0.1200 |
| 20 | 2 winding, wye grounded | 0.0640 | 0.0010 |
| 21 | 2 winding, wye grounded | 0.0660 | 0.0010 |
| 22 | 2 winding, wye grounded | 0.4420 | 0.0020 |
| 23 | 2 winding, wye grounded | 0.4420 | 0.0020 |
| 24 | 2 winding, wye grounded | 0.4420 | 0.0020 |
| 25 | 3 winding, wye grounded | 0.6430 | 0.1690 |
| 26 | 3 winding, wye grounded | 0.4070 | 0.1470 |

## 3.4 Substation Grounding Grid Resistance and Earth Model

Substation grounding DC resistance in Ohms is necessary for the GIC calculation. Test data on the grounding resistance of the Level 0 substations was not available at the time of the study, so a value was calculated using design modeling. This is the best alternative as outlined in the GIC Application Guide. For the grounding resistance calculation, a soil resistivity assumption of 60 Ohm-m was used. The ground grid depth assumed for all Level 0 sites was 18”. Where ground grid drawings were available, the grounding information from the drawing was used. For substations without clear information from the ground grid drawings, a 20’ mesh grid with 2/0, 7 strand copper conductor was assumed. Also, the geographical location of the substations was used for the earth model of the area. IP4 represents the Interior Plains (Great Plains) physiographic region of the US. Table 3-5 provides a summary of the study area substation information.

**Table 3-5 Substation Ground Grid Information**

| Substation | Grounding Resistance | Earth Model |
|---|---|---|
| 1 | 0.257 | IP4 |
| 2 | 0.177 | IP4 |
| 3 | 0.151 | IP4 |
| 4 | 0.254 | IP4 |

Information on grounding resistance for non-Level 0 substations was not available for this study. In this case, the lowest ground grid value found in the Level 0 substations was used as the assumed grounding resistance for all non-Level 0 substations. This assumption was used because the lower ground grid resistance creates a worst case scenario by decreasing the overall resistance in the equivalent GIC DC circuit. For all substations outside the explicitly modeled levels, the assumed substation grounding DC resistance was 0.1 ohm.

# 4.0 GIC CALCULATION STUDY

The study was performed with GIC Module in PSS®E version 34 for different Intertie Levels. Since the orientation of the GMD event created different GIC levels within the system, GMD orientation was fixed at 90 degrees for the simulation while Intertie Levels were varied from Level 0 to Level 3.

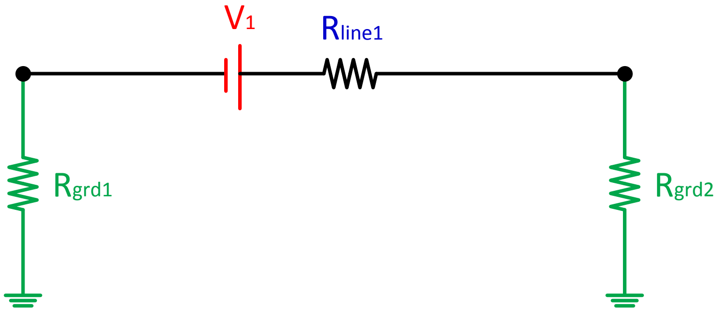
## 4.1 GIC Calculation Results

GIC calculation results are presented by Intertie Level in the following sections.

### 4.1.1 Analysis with Intertie Level 0

There were 4 ground connections on the high side of the transformers but there were no transmission lines between substations in the study area. The 4 ground connections would provide a path for GIC to flow if the high side non-transformer connections existed. PSS®E GIC Module uses the GIC calculation method that applies induced voltage on the transmission line. This is the latest recommended methodology by NERC [6]. The illustration of the GIC calculation method is shown in Figure 4-1. Since there is no transmission line within the case study Level 0, GIC cannot be calculated.

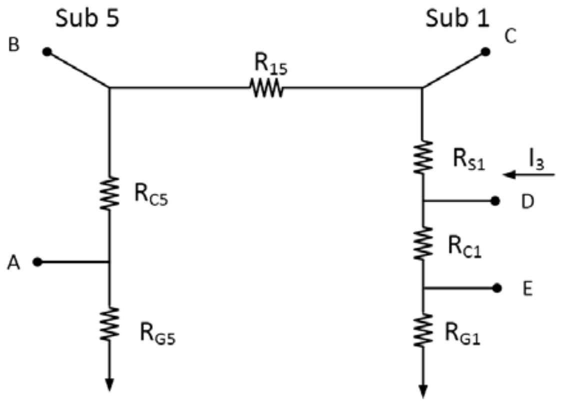
**Figure 4-1 GIC Calculation Illustration**



### 4.1.2 Analysis with Intertie Level 1

Intertie Level 1 model included 4 additional substations, 4 of 230 kV transmission lines and 8 new grounding connections on the high side of transformers. To illustrate the results of the GIC calculations, one DC circuit created with the additional Level 1 substations is isolated in this section. It is important to do this isolation now because as Intertie Levels increase the resultant DC circuits will become more interconnected and complex. This will make nodal analysis much more difficult. Figure 4-2 shows the DC circuit created from the addition of the Level 1 intertie for Sub 1.

**Figure 4-2 DC Circuit Representation of Sub 1 for GIC Calculations**



Sub 1 is in the Level 0 study area while Sub 5 is in Intertie Level 1. There were two connections to ground on the high side of the transformers in this circuit. The two substations were connected on the high side with a transmission line. The high side winding of the 3 winding wye-grounded transformer in

Sub 5 and the common and series winding of the 3 winding auto transformer in Sub 1 complete the DC circuit. The substation grounding resistances were also modeled in the DC circuit. All voltages, currents, and resistances in Figure 4-2 are presented in Table 4-1.

**Table 4-1 Intertie Level 1 Voltages, Currents, and Resistances**

| Node | DC V | Branch | Current (A) | Element | R (Ohms/Phase) |
|---|---|---|---|---|---|
| A | 0.06429 | A-B | 0.14192 | G1 | 0.257 |
| B | 0.14763 | B-C | 0.14192 | C1 | 0.016 |
| C | -0.12983 | C-D | 0.14192 | S1 | 0.130 |
| D | -0.11138 | D-E | 0.14192 | 12 | 0.159 |
| E | -0.10921 | E-G1 | 0.14192 | G2 | 0.151 |
|  |  |  |  | C2 | 0.587 |

In Table 4-2, it shows that current in the common winding is the same as the current in the series winding. The current is the same because the Intertie Level 1 did not include low voltage transmission lines (69 kV line) and the current $I_3$ in Figure 4-2 is 0. This is the case for Intertie Level 1, but it will not be the case in further Intertie Levels as the study area grows for Sub 1. However, for Sub 2, Sub 3 and Sub 4, Intertie Level 1 includes the low voltage transmission lines connecting one another, the current flows through the low voltage transmission lines and the flow through the common winding and series winding are not same. The GIC values for the transformers for Sub 1, Sub 2, Sub 3 and Sub 4 are shown in Table 4-2.

**Table 4-2 Intertie Level 1 Study Area Winding Currents**

| Substation | Common Winding GIC (A) | Series Winding GIC (A) |
|---|---|---|
| 1 | -0.14192 | 0.14192 |
| 2 | 1.3809 | -0.58657 |
| 3 | -1.50725 | 0.39824 |
| 4 | -0.35733 | -0.12231 |

The table shows that the GIC for the common winding and series winding for Sub 1 are the same while for the other substations they are different.

Another important observation in Table 4-1 is that the currents in branch A-B equal those of branches B-C, C-D and D-E. This is because GIC can only go through the DC path shown in Table 4-2. There are no other connections for the current to go through. The Intertie Level 1 for Sub 1 shows a radial network characteristic. The magnitude of the GIC is dependent on two transformers and one transmission line.

The rest of the substations (Sub 2, Sub 3 and Sub 4) have DC circuits connecting one another. Thus, all of these substations in Intertie Level 1 model already have a meshed network characteristic. The magnitude of the GIC is calculated out of all the transformers and transmission lines (both high voltage and low voltage). Since it was calculated all together (Sub 2, Sub3, Sub 4, Sub 6 and Sub 7), the summation of all substation GICs on the high side show 0. The GIC for all the substations is summarized in Table 4-3.

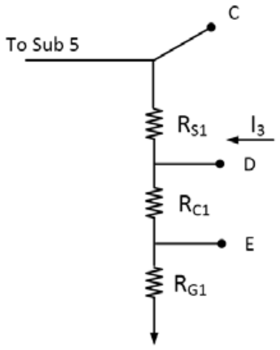
**Table 4-3 Intertie Level 1 Substation GIC**

| Substation | Current (A) |
|---|---|
| 2 | 8.28538 |
| 3 | -4.52174 |
| 4 | -1.07200 |
| 6 | -0.45293 |
| 7 | 0.00000 |
| 8 | -2.23869 |

### 4.1.3 Analysis with Intertie Level 2

The addition of Intertie Level 2 results in a total of 11 substations and 16 high side ground connections. At this level the DC circuit is meshed for all substations and includes all ground connections. Figure 4-3 focuses on the connection to ground at substation 1.

**Figure 4-3 Substation 1 Grounding Connection Diagram**



The currents in the study area transformer windings are presented in Table 4-4.

**Table 4-4 Intertie Level 2 Study Area Winding Currents**

| Substation | Common Winding Current (A) | Series Winding Current (A) |
|---|---|---|
| 1 | 5.12754 | 2.93729 |
| 2 | 2.94748 | 0.76033 |
| 3 | 0.81456 | 0.85368 |
| 4 | 0.88801 | 0.94328 |

Because of the additional connections in Intertie Level 2, $I_3$ is no longer 0, therefore the currents in the series and common windings at Sub 1 are no longer equal. Effective GIC is a function of all three currents, so the addition of Intertie Level 2 will subsequently affect the resulting effective GIC at Sub 1.

To analyze Intertie Level 2 as a whole we can look at the substation GIC through the grounding connections. These currents are presented in Table 4-5.

**Table 4-5 Intertie Level 2 Substation GIC**

| Substation | GIC (A) | Substation | GIC (A) | Substation | GIC (A) |
|---|---|---|---|---|---|
| 1 | -2.93729 | 5 | 3.34559 | 5 | 3.34559 |
| 2 | -0.76033 | 6 | 0.46452 | 6 | 0.46452 |
| 2 | -0.76033 | 7 | 0.56268 | 7 | 0.56268 |
| 3 | -0.85368 | 9 | 0.01834 | 9 | 0.01834 |
| 4 | -0.94328 | 9 | 0.01698 | 9 | 0.01698 |

It can be seen in Table 4-5 that the currents in the study area (Sub 1 through Sub 4) have increased. One might conclude that a pattern is developing but this is not necessarily the case. The current values will be determined by the resulting DC circuit. As Intertie Levels change so does the DC circuit configuration. This may result in an increase or a decrease in current values. The sum of the GICs for all substations is 0.

### 4.1.4 Analysis with Intertie Level 3

The addition of Intertie Level 3 results in a total of 16 substations with a total of 20 high side transformer ground connections. All the connections are meshed into one DC circuit. The currents through the transformers in the study area are presented in Table 4-6.

**Table 4-6 Intertie Level 3 Study Area Winding Currents**

| Substation | Common Winding Current (A) | Series Winding Current (A) |
|---|---|---|
| 1 | 4.49339 | -0.65357 |
| 2 | 1.95853 | 0.30678 |
| 3 | -1.05275 | 0.37706 |
| 4 | -0.12717 | 0.19074 |

With the addition of Intertie Level 3 a new DC circuit is created such that the current levels in the common and series windings have decreased. Also notable is that the common and series winding current values are not the same as was seen in the results in Intertie Level 2. The currents for all the high side ground connections in Intertie Level 3 are presented in Table 4-7.

**Table 4-7 Intertie Level 3 Substation GIC**

| Substation | GIC (A) | Substation | GIC (A) | Substation | GIC (A) | Substation | GIC (A) |
|---|---|---|---|---|---|---|---|
| 1 | 0.65357 | 5 | -0.35135 | 9 | 0.11946 | 11 | -2.15599 |
| 2 | -0.30678 | 6 | -0.69464 | 9 | 0.1233 | 12 | -0.28151 |
| 2 | -0.30678 | 7 | -0.24537 | 9 | 0.00125 | 15 | 3.92974 |
| 3 | -0.37706 | 9 | 0.03499 | 9 | 0.01396 | 16 | -1.47013 |
| 4 | -0.19074 | 9 | 0.03239 | 10 | 1.47168 |  |  |

Comparing the current values in Table 4-7 to those in Table 4-5, it can be seen that some values have increased, some have decreased and some have switched direction altogether. This is because the equivalent DC circuit changes as the equivalent DC model grows and because newer loops can be created by the increased equivalent DC model.

## 4.2 Effects of Intertie Levels on GIC Values

The impact of Intertie Levels (neighboring substations) on the substation GIC values was analyzed. Since the effective GIC value is dependent on the transformer's own characteristics, the substation GIC flow was used for the Intertie Level impact comparison. The GMD event angle was changed from 0 to 360 degree and the GIC through each substation is summarized in Figure 4-4 to Figure 4-6 for Intertie Levels 1-3.

**Figure 4-4 Substation GIC Flow – Intertie Level 1**

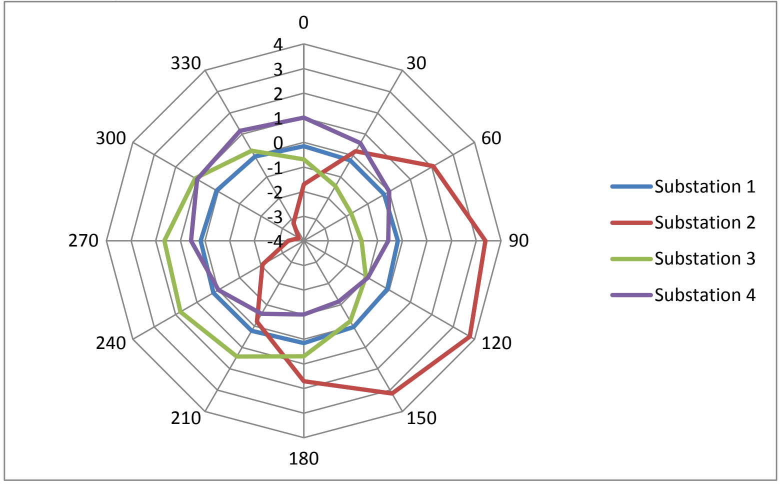


**Figure 4-5 Substation GIC Flow – Intertie Level 2**

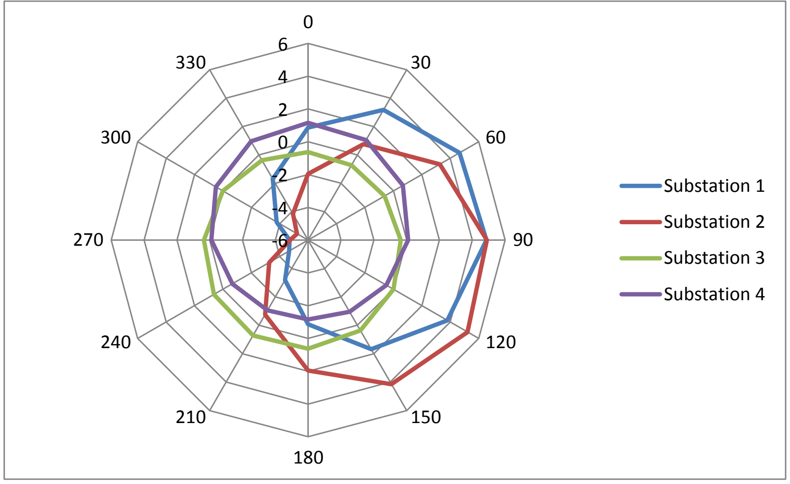
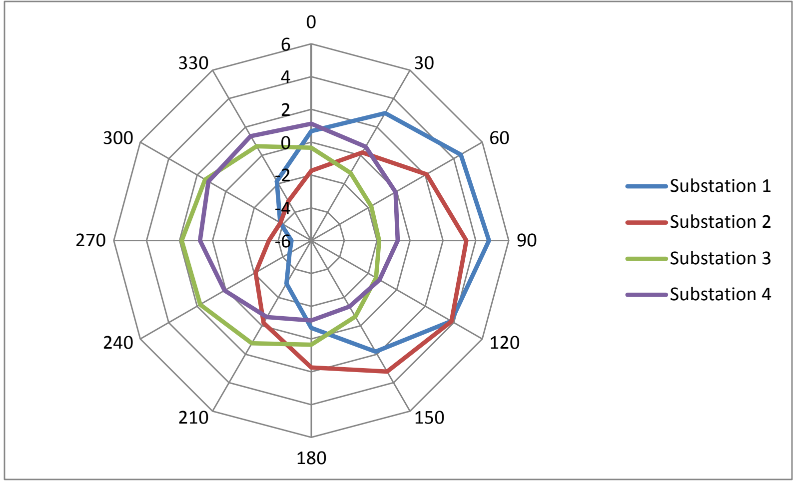


**Figure 4-6 Substation GIC Flow – Intertie Level 3**



The diagrams show the changes in the GIC magnitude (intensity of GIC) and shape (dependency to the GMD event angle). The substation GIC flow for Sub 1 (blue color) changed significantly from Intertie Level 1 to Intertie Level 2 while the GIC of other substations showed similar magnitude and shape. The reason why Substation 1 changed significantly was because the characteristic of the system changed from radial network to mesh network. As more substations were included in the model from Intertie Level 2 to Intertie Level 3, the GIC flow magnitude and shape became less sensitive. When the system is radially connected to the neighboring substation, the impact of GIC will be highly dependent on the transmission line orientation and the GIC flow from the neighboring substation. However, if the system is connected to a mesh network, the sensitivity to each neighboring substation decreases.

## 5.0 CONCLUSIONS

The main goal of this case study was to evaluate the impact of the neighboring system on GIC levels. The size of the neighboring system for the equivalent DC model was changed from Level 0 to Level 3 representing the complexity of the study area. The results of the analysis showed that the GIC will change significantly where the equivalent DC model's characteristic changes from radial network to mesh network. When the system was radially connected to the neighboring substation, the impact of GIC was highly dependent on the transmission line orientation and the GIC flow from the neighboring substation. However, if the system was connected to a mesh network, the sensitivity to each neighboring substation decreases. Thus, when a system planner develops the equivalent DC model and sets the boundary of the neighboring system, considering the characteristics of the neighboring system (radial network or mesh network) is recommended instead of setting a fixed boundary assumption applicable to all the connections. The modeling portion of this case study satisfied Requirement R2 of the NERC TPL-007-1 standard. While the maximum effective GIC is not presented in this paper, it was also a product of the case study and satisfied Requirement R5 of the NERC TPL-007-1 standard.

## ACKNOWLEDGEMENTS

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