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**Measuring Geomagnetically-Induced Currents
in each Phase of an Auto Transformer Bank**

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SUMMARY

Geomagnetic Disturbances (GMD) are a result of the interaction of the earth's magnetic field and the particles discharged from the sun during a solar storm. Changes in the earth's magnetic field will induce a quasi-dc voltage, which will send Geomagnetically Induced Currents (GIC) through grounded transformers and high voltage transmission lines.

Measuring and understanding GIC magnitude, direction, and distribution is important to assess the possible impact on large transformers and on the bulk electric power system. American Electric Power (AEP) commissioned a line GIC measurement system on one of its 765/345 kV transformers to evaluate the GIC distribution.

This paper describes AEP's experience and lessons learned on the design and commissioning of a line GIC measurement system. The GIC data is being collected to better understand the GIC direction and distribution during a GMD event, and to validate existing transformer GIC models.

KEYWORDS

Geomagnetic Disturbances (GMD), Geomagnetically Induced Currents (GIC), Fiber Optic current Sensor (FOCS)

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INTRODUCTION

The electric utility industry is focusing to assess the impact of Geomagnetic Disturbances (GMD) on bulk electric power system reliability. GMDs result when the earth’s magnetic field interacts with particles discharged from the sun during a solar storm. Changes in the earth’s magnetic field induce a quasi-dc voltage, which will send Geomagnetically Induced Currents (GIC) through grounded transformer windings and high voltage transmission lines.

To assess the impacts on large transformers and bulk electric power system reliability, it’s important to measure and evaluate GIC flow direction and distribution. AEP commissioned a line GIC measurement system on one of its 765/345 kV transformers to measure GIC distribution.

This paper discusses AEP’s previous efforts on GIC evaluation and research, and highlights the motivation behind the project development, design, commissioning efforts and capturing of GIC data.

AEP EFFORTS IN MONITORING GIC

AEP has been a pioneer in addressing the impact of GMD to ensure continued reliable operation of the nation’s largest transmission grid. AEP has been working with transformer manufacturers and research institutions to study the impact of GIC on large Extra High Voltage (EHV) power transformers [1]. In addition, AEP has installed permanent GIC sensors on large transformer neutrals across its system to detect and evaluate GMD impacts on large transformers [2]. AEP has also designed and commissioned an off-station magnetometer system [3] to measure earth magnetic field changes, in order to more accurately correlate measured transformer-neutral GIC currents with simulated GIC currents.

WHY MEASURE LINE GIC

Given all of the previous research efforts, AEP had an overall idea on how the GIC would flow, based on the transmission topology and the geographic location of its transmission assets. However, AEP needed to find out the exact GIC distribution, measurement of GIC flow through the transmission lines connected to grounded transformer banks. To elaborate on this concept, consider an auto-transformer consisting of series and common winding, as shown in Figure 1.

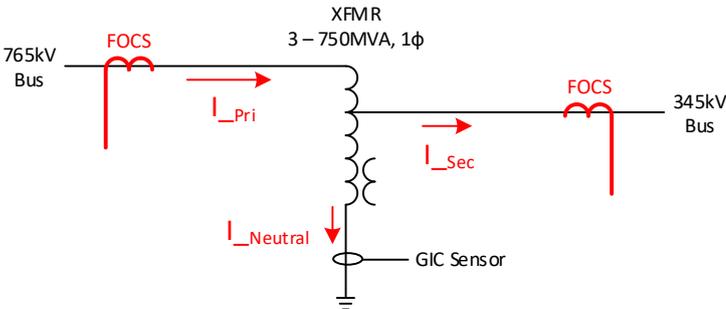


Figure 1 : GIC distribution in an auto-transformer bank

During a GMD event, GIC flowing towards the transformer could split between the neutral and secondary sides. By measuring at least two out of the three current components, the third current component can be calculated:

$$I_{Pri} = I_{Sec} + I_{Neutral}$$

Existing GIC neutral sensors will only measure the GIC components flowing through the neutral (towards the ground or from the ground), which will not provide the complete picture of the GIC distribution. This project will provide the actual GIC direction and distribution by measuring the GIC components on the primary and secondary side of the transformer. Analysis of measured data demonstrates that GIC will not equally distribute among three phases. Actual GIC distribution within each phase will be discussed in a later section.

LINE GIC SYSTEM DESIGN

The line GIC measurement system is designed with four main components, as listed below and shown in Figure 2.

- a. Fiber Optic Current Sensor (FOCS)
- b. Merging Unit
- c. Measuring Unit
- d. GIC Data Access

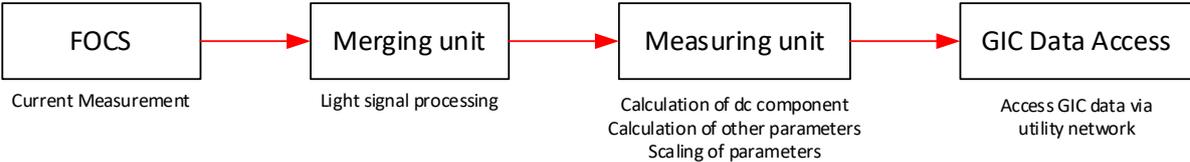


Figure 2 : GIC Measurement System Design

The Fiber Optic Current Sensor (FOCS) is installed with the optical cables wrapped around the primary conductor (similar to a connection of a regular induction current transformer). The FOCS is positioned on top of a freestanding insulator structure, which is fixed to a steel structure with a concrete foundation, as shown in Figure 3. Each phase has individual FOCS units measuring phase currents.



Figure 3 : FOCS installed on free standing structure

The merging unit and measuring unit are located in a kiosk in the yard near the FOCS freestanding structures. The measuring device is configured to communicate with the AEP network, to transfer the GIC measurement and other parameter data values via DNP3 communication. The GIC measurement system design is shown in Figure 4.

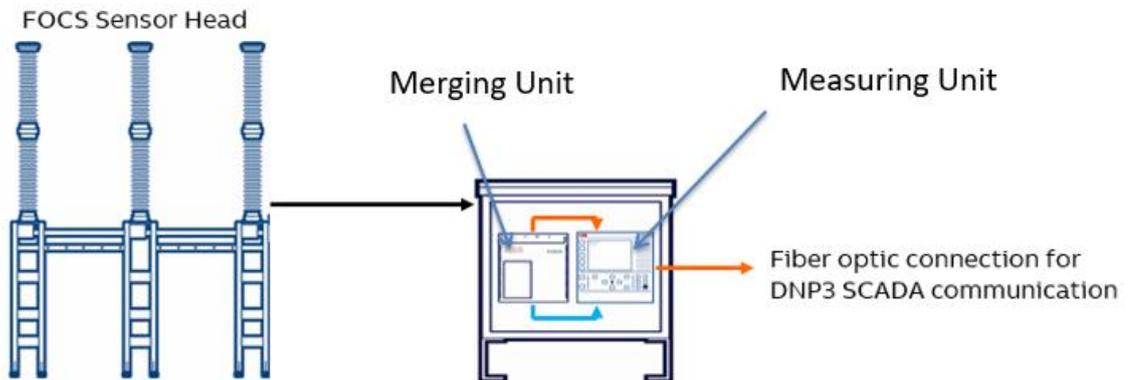


Figure 4 : GIC Measurement System Design Installation [4]

FOCS SYSTEM

In order to measure the GIC flow on a transmission line, it is required to calculate the direct current (dc) component of the individual phase currents. Regular wire-wound current transformers with magnetic induction are not capable of providing the dc component. Therefore, an alternative solution is needed to calculate the dc current component. The FOCS is capable of measuring the phase current and, together with a merging and measuring units, it is possible to calculate the directional dc component.

Within the FOCS, sending and receiving light signals will travel through the fiber optic cables at the same speed when there is no magnetic field present. When the current flows in the primary conductor, sending and receiving light signals will travel at different speeds and will induce a phase shift, as shown in Figure 5. This optical phase shift is proportional to the instantaneous primary current.

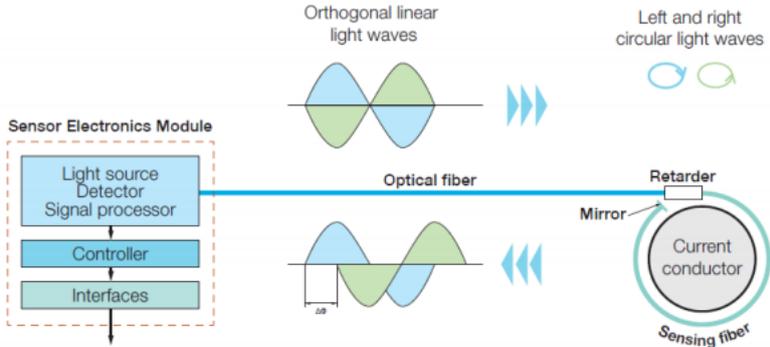


Figure 5 : Optical phase-shift in the sending and receiving light signal [5]

MERGING UNIT

The merging unit is designed to control the sending and receiving light signals to and from FOCS units, using closed loop detection circuits with integrated optic phase modulators. One merging unit will process the optoelectronics data from each FOCS for all three phases. Measured and scaled optical phase shift data will be transferred to the measuring unit which is installed in the same kiosk. Figure 6 depicts the merging unit components and functions.

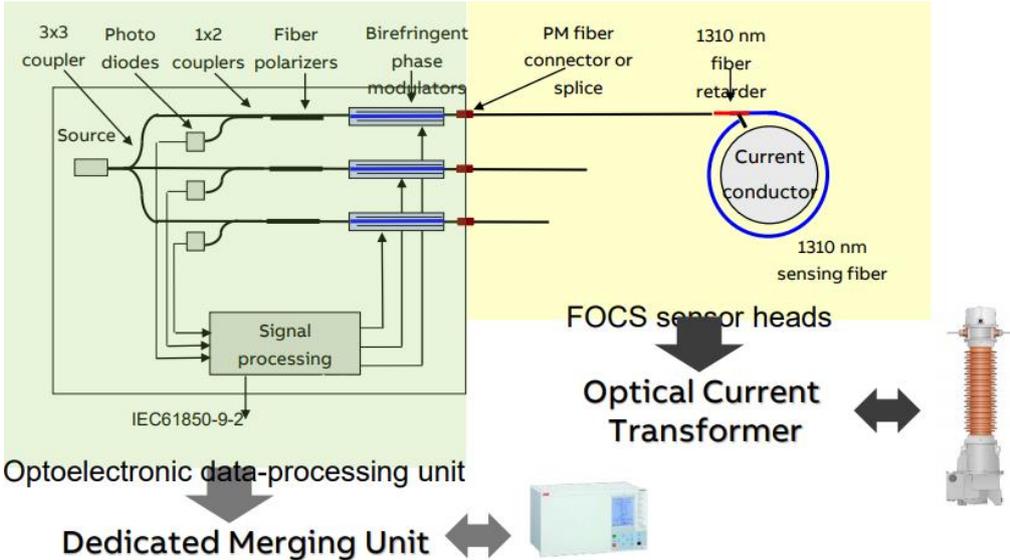


Figure 6: Merging Unit Components [5]

MEASURING UNIT

The measuring unit is a protection relay platform which will receive three-phase currents from the merging unit. In addition, the measuring unit is wired to receive secondary voltages from the line capacitive coupled voltage transformers (CCVT) as shown in the Figure 7.

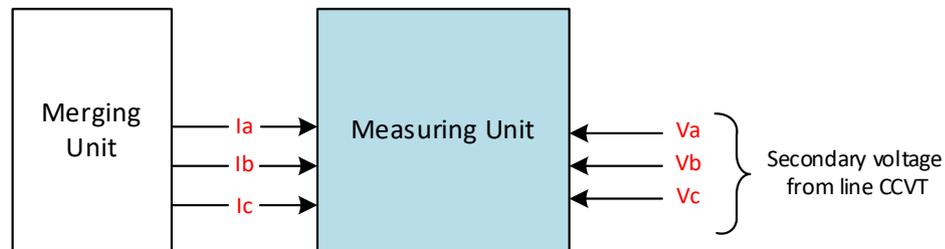


Figure 7: Measuring unit input signals

The dc components of the received current signals are calculated by performing a Fast Fourier Transform (FFT) to the input current signals, utilizing a customized harmonic measurement module in the protection relay. Utilizing the three-phase current and voltage inputs, the measuring unit will provide the following parameters for each phase, which will then be scaled to proper engineering units.

- DC current magnitude with polarity (Amperes)
- AC current magnitude (Amperes)
- AC current angle (degrees)
- Line voltage (Kilo Volts, kV)
- Line voltage angle (degrees)
- Active power (Mega Watts, MW)
- Reactive power (Mega Vars, MVar)
- Apparent power (Kilo Volts Amps, kVA)

DATA TRANSFER

As mentioned above, measured and calculated quantities were configured with DNP3 to transfer to the AEP Supervisory Control And Data Acquisition (SCADA) network for remote access and long term archiving. In addition, watch dog (faulty device) alarms were hard wired to monitor the status of merging unit and the measuring unit. Two sets of data streams were configured for the high and low voltage of the transformer.

LABORATORY TESTING

Detailed lab testing was performed with a secondary current injection test set, simulated FOCS unit, actual optoelectronics and merging unit and a measurement unit. In addition, data transfer was verified on the AEP network prior to deployment in the field.

COMMISSIONING EXPERIENCE - INSTALLATION AND CALIBRATION

To optimize the usage of the existing installations of a transformer neutral GIC sensor and the off-station magnetometer, the project was located in an EHV substation transformer. This will allow for measurement of the GIC flow through the line, GIC flow through the transformer neutral, and changes in earth magnetic field in the same area, leading to more accurately correlated data. FOCS ratings were selected to exceed the maximum transformer seasonal loading levels and minimum power limiting device in the circuit.

During the commissioning period, merging units were calibrated by using a primary current injection test set to inject primary current to the FOCS, then comparing the measured current magnitude and angle values through merging units and injected values from the test set. Measurement unit (protection relay) settings were configured to match the Current Transformer (CT) ratio, CCVT ratios and transformer ratings. Output current, voltage and power values were compared against SCADA values to verify the accuracy.

DATA VALIDATION

Transformer low side and high side calculated dc components with direction are shown for an entire day without any significant geomagnetic activity (below in Figures 8 and 9). The sign convention indicates positive numbers for current flow into the transformer on both windings.

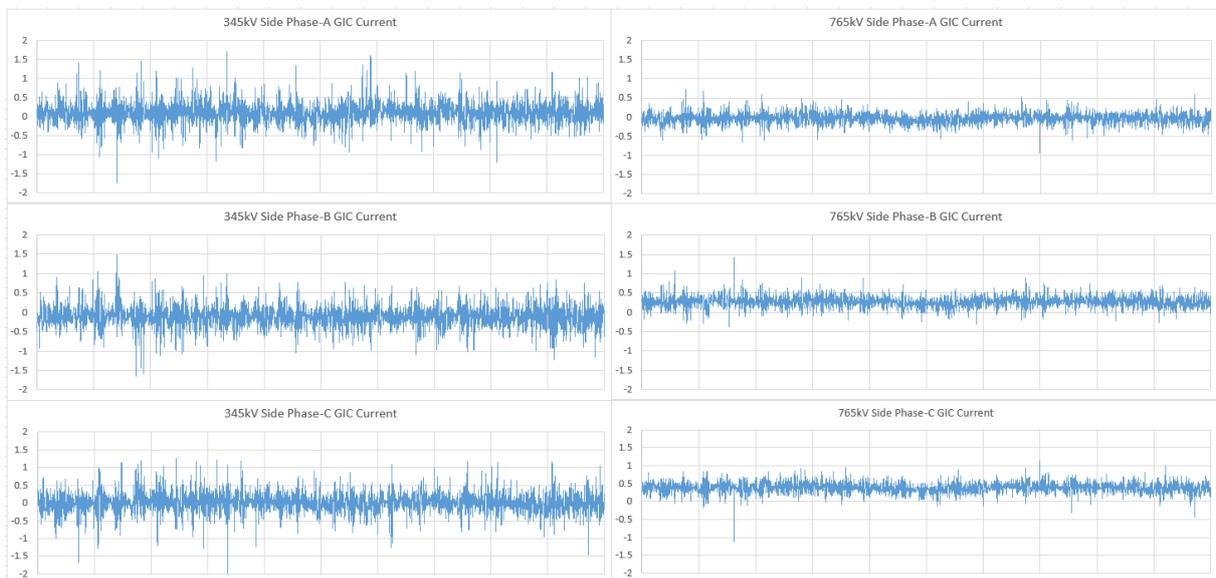


Figure 8 : Low side and high side measured GIC

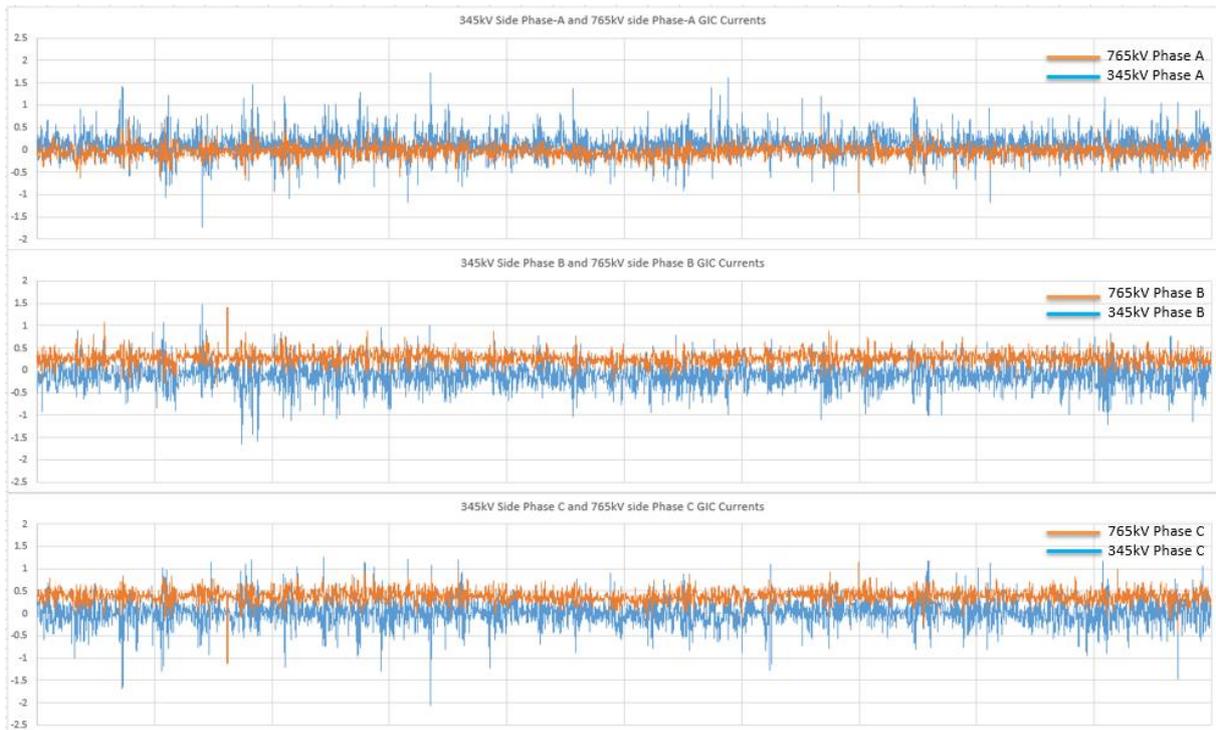


Figure 9 : Low side and high side measured GIC – per phase

Utilizing the measured GIC from high and low side of the transformer, GIC flow through the neutral could be calculated from subtracting the low side GIC from high side GIC for each phase, and then adding the components together, as shown below:

$$I_{a_Calculated} = (I_{a_765kV}) - (I_{a_345kV})$$

$$I_{b_Calculated} = (I_{b_765kV}) - (I_{b_345kV})$$

$$I_{c_Calculated} = (I_{c_765kV}) - (I_{c_345kV})$$

$$I_{_Calculated} = I_{a_Calculated} + I_{b_Calculated} + I_{c_Calculated}$$

The above calculated GIC component could be compared against the measured GIC from the neutral sensor. In Figure 10, calculated and measured neutral GIC components are compared for fifteen days, where the blue plot is the calculated GIC component and the orange plot is the measured GIC from the neutral sensor.

Calculated GIC data for the transformer neutral is consistent with the measured neutral GIC from the sensor. The outlier toward the end of the plot is related to a station line reactor switching event.

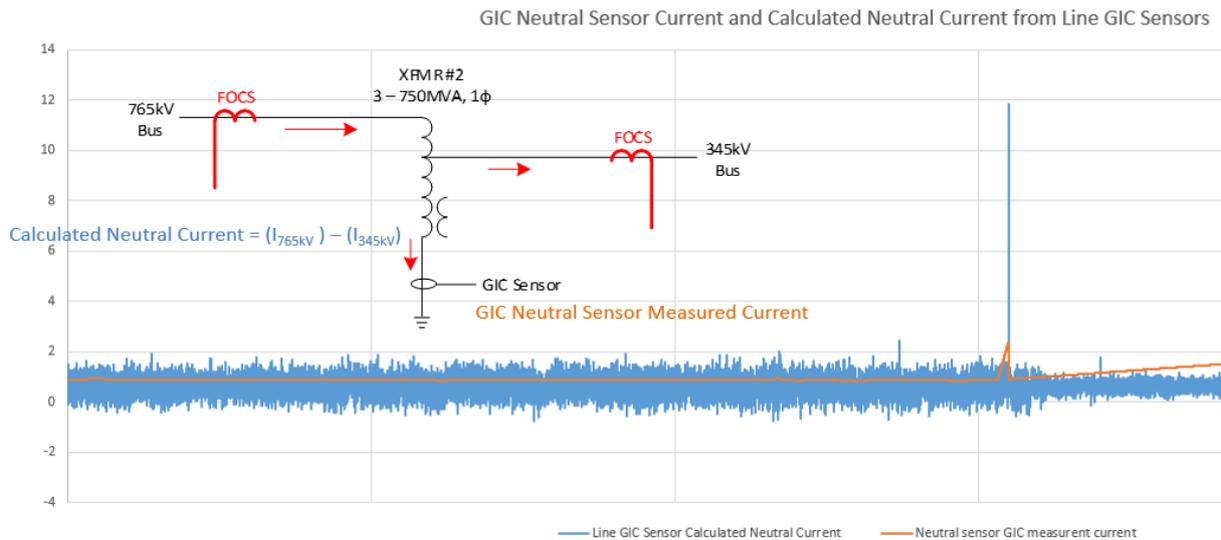


Figure 10: Comparison of calculated GIC current through the neutral and measured GIC from the neutral sensor

GIC DATA OBSERVATIONS

Measured data demonstrates that GIC will not equally distribute among three phases. Figure 11 and 12 show the histograms of GIC data for a fifteen day period, which depicts the dispersion of GIC among phases. This time period did not have any significant geomagnetic activity.

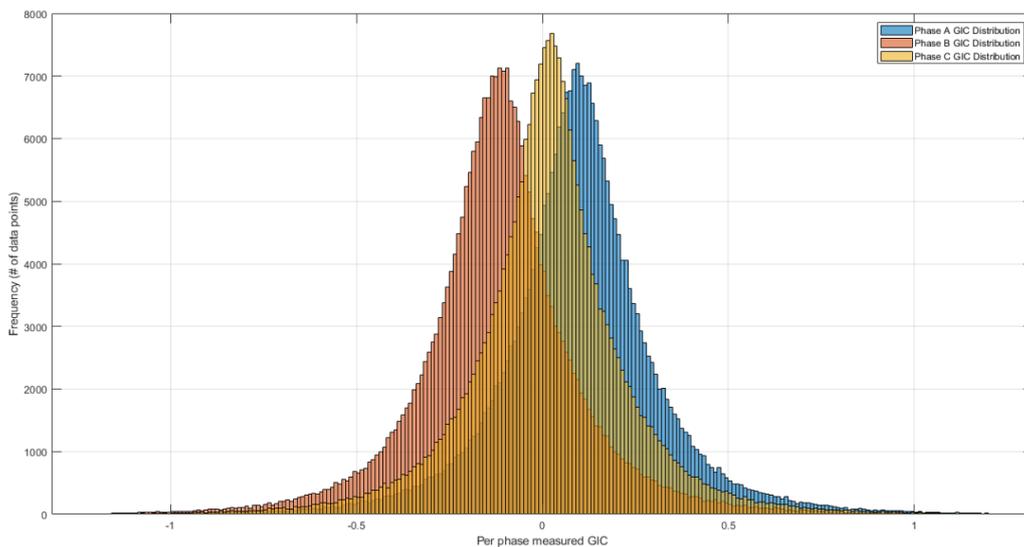


Figure 11 : Transformer low side measured GIC dispersion

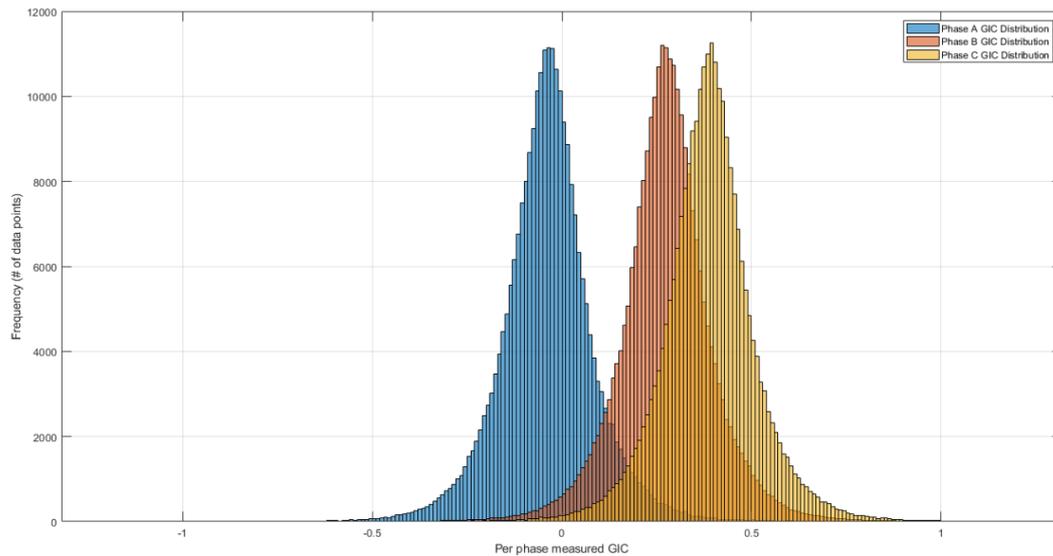


Figure 12 : Transformer high side measured GIC dispersion

CONCLUDING REMARKS

This paper documents AEP’s experience in designing and commissioning a line GIC system to measure the direction and distribution of the GIC within an EHV transformer’s windings during a GMD event. AEP will be using this data, along with transformer neutral GIC measurements, to help validate its GIC system models, and also to gain a better understanding of the impacts of GMD events on its system. This will enable AEP to prepare for and better understand the impacts of GIC on its system and to take possible mitigating actions in the future.

Future work for this project includes further analysis of the GIC data for significant GMD events and correlation with magnetometer data, to evaluate the possible impact on the EHV transformers.

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