Contract No:

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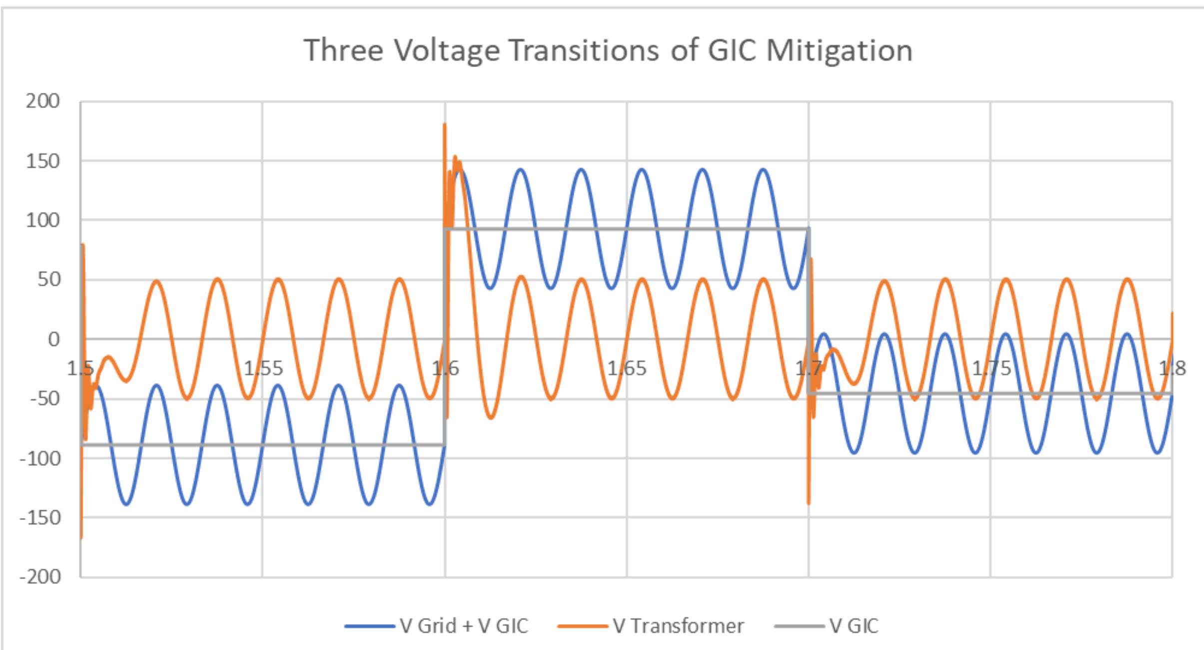
Disclaimer:

HEMP Transformer Defense Through Power Electronics

High altitude electromagnetic pulse (HEMP) generated by exoatmospheric nuclear burst has the ability to affect the electric power grid. The main power grid components, cables and transformers, act as large antennas that have current induced in them from the HEMP. These currents are called geomagnetically-induced currents (GIC), and they can occur during geomagnetic disturbances from HEMP or solar flares. HEMPs produce pulses with high electric field strengths that breakdown the dielectric of most electronics and, it is broken into three stages: E1 pulse with a microsecond width, E2 the falling trail of the pulse, and E3 a constant DC component. Oak Ridge National Laboratory has proven that transformers fitted with lightning arrestors do not receive damage from E1 and E2 pulses. However, the DC component of the E3 causes the transformer's core to saturate and induce rapid heating that damages the transformer. SRNL is developing a power electronic system that is connected to the neutral of the high voltage side of large power transformers (LPT). This system will inject the inverse of the DC effect from the HEMP into the primary side of the transformer canceling out the E3 waveform and protecting the transformer from half-cycle-saturation. This year SRNL successfully simulated removing the DC injected and accurately simulated saturation on the transformer.



Intellectual Property Review

This report has been reviewed by SRNL Legal Counsel for intellectual property considerations and is approved to be publically published in its current form.

SRNL Legal Signature

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Signature Date

HEMP Transformer Defense through Power Electronics

Project Team: Klaehn Burkes (Primary), Vincent Cessyens

Subcontractor: Clemson University

Thrust Area: Secure Energy Manufacturing

Project Start Date: October 1, 2018

Project End Date: September 30, 2020

High altitude electromagnetic pulse (HEMP) generated by exoatmospheric nuclear burst has the ability to affect the electric power grid. The main power grid components, cables and transformers, act as large antennas that have current induced in them from the HEMP. These currents are called geomagnetically-induced currents (GIC), and they can occur during geomagnetic disturbances from HEMP or solar flares. HEMPs produce pulses with high electric field strengths that breakdown the dielectric of most electronics and, it is broken into three stages: E1 pulse with a microsecond width, E2 the falling trail of the pulse, and E3 a constant DC component. Oak Ridge National Laboratory has proven that transformers fitted with lightning arrestors do not receive damage from E1 and E2 pulses. However, the DC component of the E3 causes the transformer's core to saturate and induce rapid heating that damages the transformer. SRNL is developing a power electronic system that is connected to the neutral of the high voltage side of large power transformers (LPT). This system will inject the inverse of the DC effect from the HEMP into the primary side of the transformer canceling out the E3 waveform and protecting the transformer from half-cycle-saturation. This year SRNL successfully simulated removing the DC injected and accurately simulated saturation on the transformer.

FY2019 Objectives

- Issue Clemson contract for developing grid support control function (2/7/2019)
- Receive Typhoon CHIL hardware (1/7/2019)
- Simulate Power Electronic System in Typhoon (7/31/2019)
- Write Paper on Power Electronic Design and Simulation (9/31/2019)

Introduction

A high altitude electromagnetic pulse (HEMP) is generated from exoatmospheric nuclear busts that consist of three stages: E1 pulse with a microsecond width and a nanosecond rise time, E2 the falling edge of the initial pulse, and an E3 a constant DC component. This waveform is represented by Figure 1. The high electric field of the E1 pulse train is responsible for causing dielectric breakdown in traditional electronic components by causing arcing because of the high strength of the electric field. This E1 strength is not relative to the yield of the nuclear device, but from the air conductivity, the height of the burst and the line of sight to the observer on the ground [1]. Oak Ridge National Laboratory has studied the effects of E1 on distribution transformers as well as large power transformers and have dictated that using lightning arrestors transformers can be protected from this high electric field [2]. This protection comes from the E1 waveform being a double exponential pulse that is the same as a lighting pulse with just a higher electric field. Figure

1 shows the intermediate-time, E2, waveform is a much lower electric field and has the same mathematical representation as E1. E2 is not as damaging as E1 because of the lower electric field.

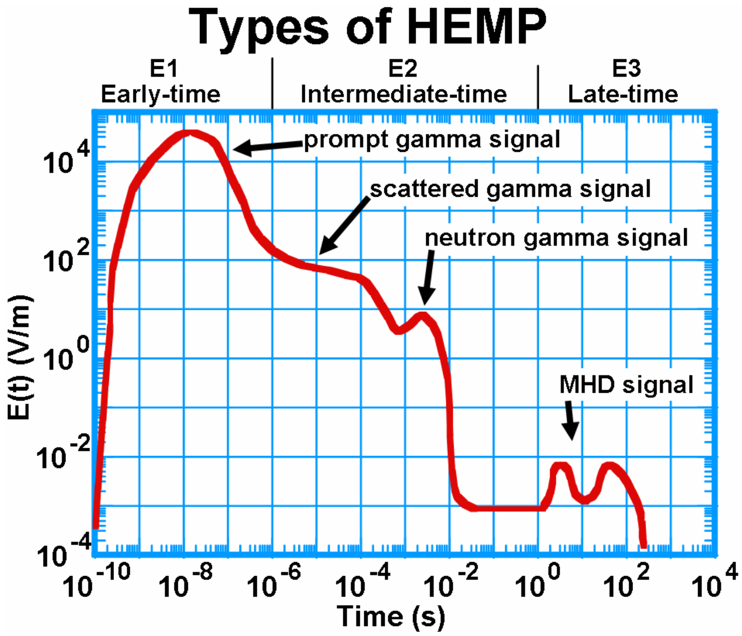

Figure 1: Electric Field Produced from High Altitude Electromagnetic Pulse

The late-time, E3, portion of the waveform is the longest portion of the HEMP waveform and is produced mainly from the generation of X-Rays from the nuclear explosion. It consists of two components, the blast and the heave, and is attributed to the driving factor to damaging electric grid components [3]. The blast heave changes the earth's magnetic field and causes large currents to be produced in the ionosphere that are millions of amperes in magnitude. These large currents have a resulting magnetic field that is very large and can couple with conducting paths throughout the earth surface such as transmission lines, metallic pipes, telephone cable, and railways [4]. In the power system the transmission network is grounded throughout by design for paths for fault current to flow. However, this causes a circuit between the ground and the transmission network. Therefore, the mutual coupling between the transmission lines and the electrojets causes voltage differentials throughout the transmission system, which causes current to flow between the transmission lines and ground Figure 2.

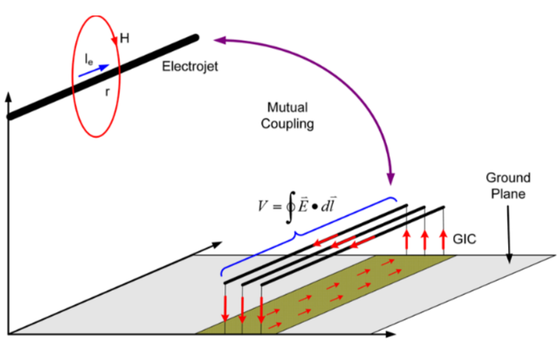

Figure 2: Method for E3 Coupling on Transmission Lines [3]

The E3 of a HEMP creates GICs from the motion of the ionized bomb debris and is broken into two parts the Blast Wave and the Heave. The blast wave is created by the fire ball expansion of the explosion which expels magnetic field. This bubble of magnetic field distorts the magnetic field lines of the earth. The heave is when the blast wave causes the upper atmosphere to heat and rise. The rising creates a conductive patch that produces currents and magnetic fields on the earth's surface [3]. The result of both these are magnetic fields on the earth's surface and thus occurs electric fields in the earth's surface and long conducing paths as discussed before with GMD. These electric fields now cause voltage differentials and circulating currents or GICs. And the result as with GMD is GICs circulating through the ground and the transmission system but with a different amplitude and duration than GMDs.

Impacts of GIC from GMD/E3 on Power Grid

The electric power grid was built to operate with 60 Hz AC power in the United States. There are mechanisms for handling harmonic currents and conversions from AC to DC, but the system was not built to handle AC and DC coupled together. This is especially true for magnetic transfer of power. Therefore, because GICs are quasi-DC meaning they are injected constant currents at different magnitudes for a small duration of time. They can cause transformers, reactors, voltage regulators, and other components to saturate and operate in a non-linear condition. This quasi-DC causes magnetic systems to undergo half-cycle saturation from the DC shift in the AC waveform and draw large amounts of magnetic current as shown in Figure 3.

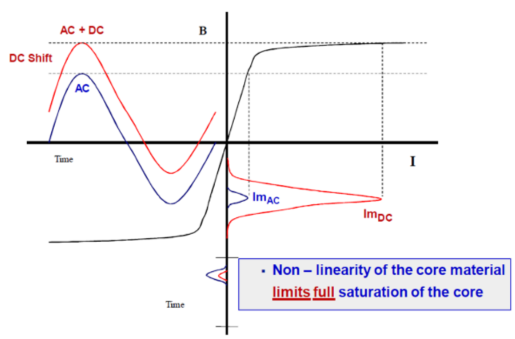

Figure 3: Effect of Half-Cycle Saturation [5]

The quasi-DC currents cause the core of transformers to saturate and cause internal heating. The magnetic current drawn from saturation requires massive amounts of reactive power draws which effects power system stability and power quality. There is the capability of miss operation of protective relays due to the reactive power and harmonics produced. There is also a greater chance of damage to shunt capacitors, static var compensators, and harmonic filters. Generators can experience rotor heating from saturation [6].

As discussed GICs flow through the power system through long transmission lines and back through ground by grounded neutrals on the transformers. These GICs will not flow if there is no return path to ground. The electric field magnitudes form E3 can be on the amplitude of up to 35 V/km [7] which can affect shorter length transmission and distribution. However, GMD are in the range from 1 to 6 V/km [4]. Therefore, high voltage potential difference can only be built up on longer lines, and for the power system these will be mainly be extra high voltage (EHV) transmission lines. This is because of the larger line length and lower average resistance. Therefore, the transmission lines have more DC current induced and the transformers in the EHV system will experience higher and longer saturation levels. This is critical to the power grid because the EHV system is critical in bulk power transformer [8].

The LPT in the EHV system will experience high and longer saturation levels. This means they will produce more harmonics causing miss operation of protective relays and overloading of capacitor banks. The longer saturation will allow for more heating from the magnetic flux extending beyond the core. This causes eddy currents to flow, and the transformer will experience high magnetization losses with more heating in the core. Finally, it will draw massive amounts of current from the electric power grid causing instability and blackouts. These currents can be on the magnitude of 10 times the traditional peak as seen in Figure 4.

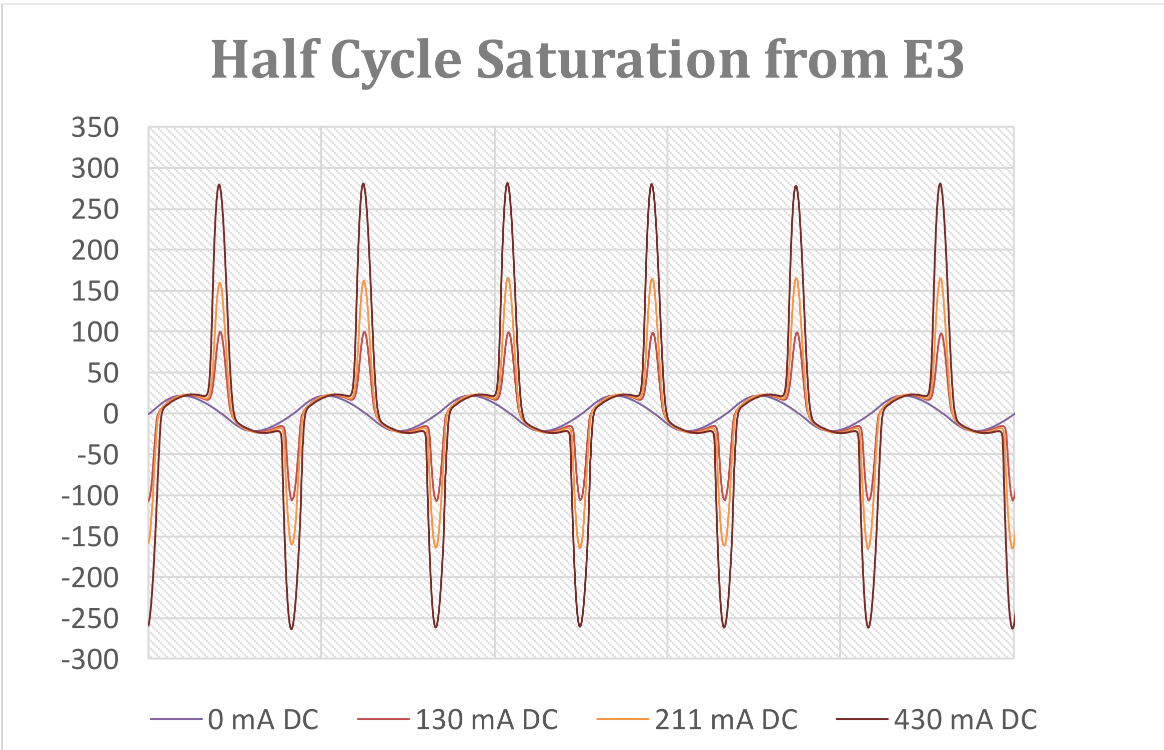

Figure 4: Half Cycle Saturation from E3 on Distribution Transformers [9]

Approach

A passive method for protecting devices from HEMP would be to just filter the waveform out. However, when dealing with distribution or transmission components this is not possible because of the high voltage requirement of capacitors and high current requirements of reactors needed. Therefore, a series power electronic compensator was used as the design for developing the prototype. The architecture of the power electronics will be similar to an inverter on connected to the neutral of the transformer. This design will be used because it can actively regulate the voltage going into the transformer without having to control high voltages or currents. A simplified architecture is presented in Figure 5, and it operates in the following manner. A H-Bridge Converter is used as the foundation of the power electronic components and converts AC to DC and vice versus. A capacitor is placed across the DC side of the H-bridge, and a reactor is used to connect the converter to the electric grid. The H-bridge will charge up and discharge the capacitor based on the voltage difference across the reactor. By monitoring the input voltage to the transformer, the converter can change its output in order to draw current through the reactor as to control the voltage going into the transformer. This is how the compensator will be able to regulate the voltage going into the transformer and absorb the HEMP waveform.

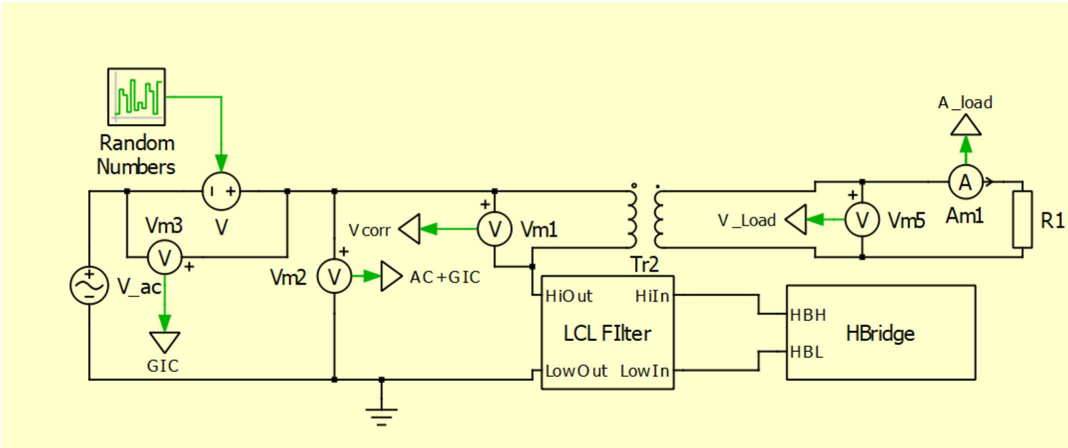

Figure 5: PLECS Simulation Block Diagram of GIC Mitigation

Understanding how the HEMP saturation effects the transformer is important for simulation purposes. Also, when developing a model for testing the controller hardware in the loop, accurate representation of the effect of DC on transformers is required before implementing in the laboratory. Therefore, Typhoon HIL will be used to perform controller hardware in the loop testing. The following simulation, Figure 6 was set up in Typhoon to simulate the GIC. Two transformers are placed high voltage to high voltage windings with being energized and loaded by the low voltage windings. This is because in the laboratory setting this is the safest and most accurate way of determining what is the direct effect of GIC on a transmission system.

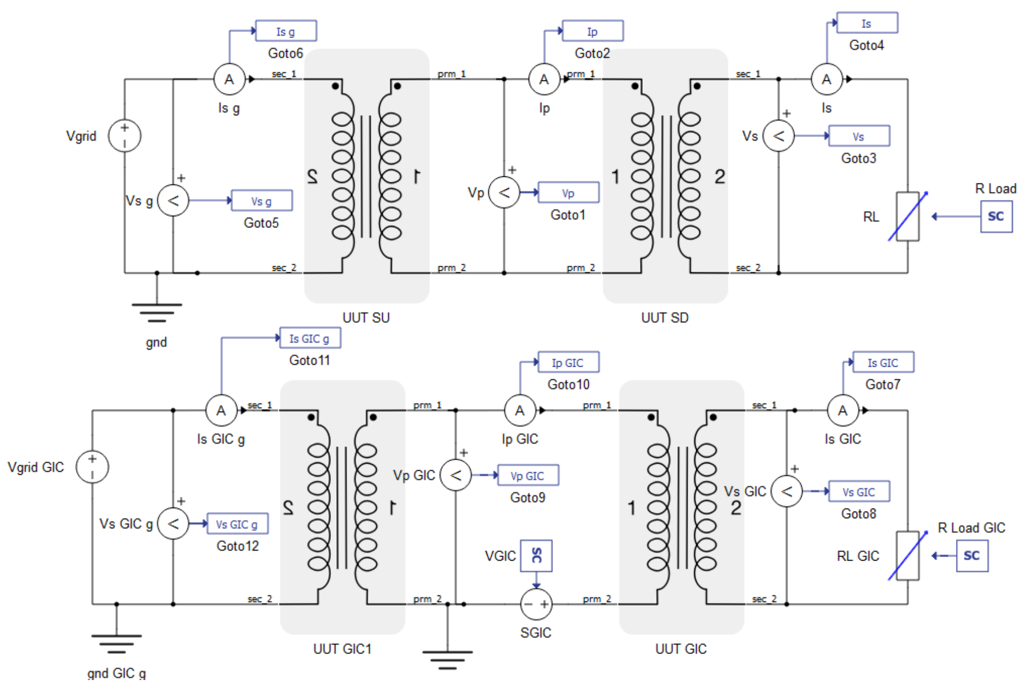

Figure 6: Typhoon Simulation of Test Setup for Distribution Transformers

Results/Discussion

The simulated H-Bridge converter successfully was able to compensate and remove the DC injected from GIC to the transformer. This is shown in Figure 7. A random DC amplitude was injected into the circuit and changed every 0.1 seconds. This emulated how GMD would effect a transformer more the E3 because E3 would not vary randomly but have a defined DC. Never the less, the system would remove both GMD and E3 from a transformer. The grey plot is the amount of GIC voltage induced on the system. In simulation the amplitude of DC was much larger that what is seen in real life. This was done to make sure that the converter system could handle large amounts of DC with very large swings in amplitude. The Blue plot is what would be the voltage to the transformer without having any DC compensation. The orange plot is what is seen by the transformer. It can be seen that there are transient spikes when the DC changes. However, it dampends out very quickly.

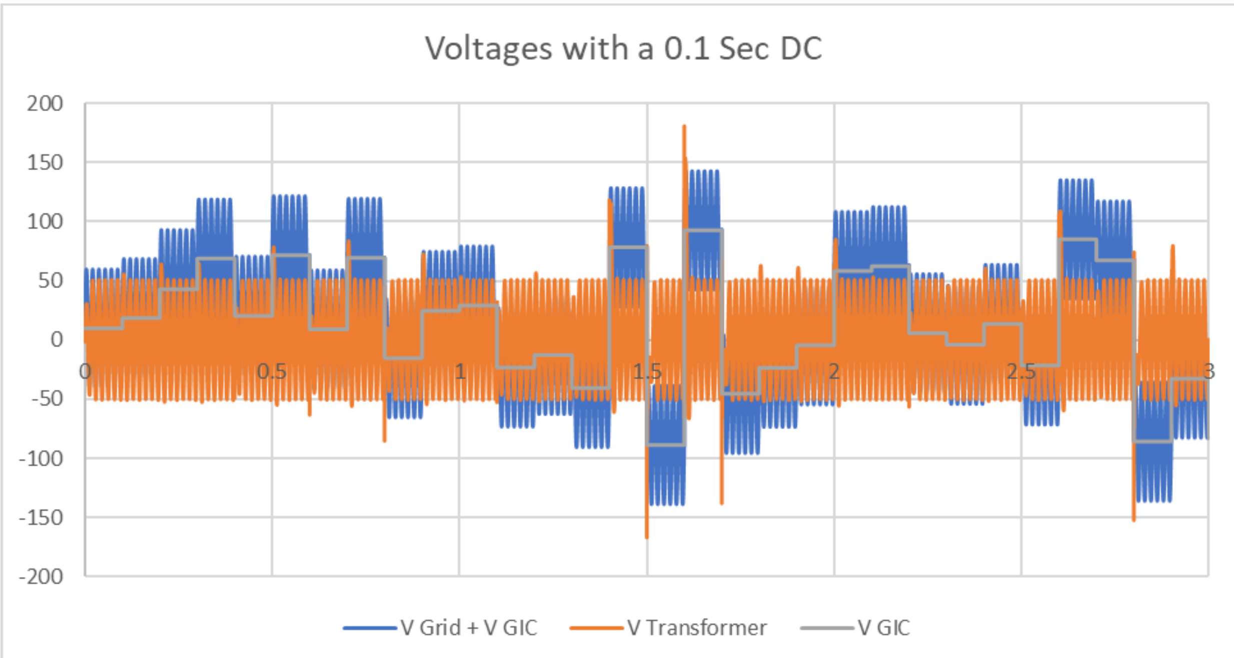

Figure 7: GIC Removal to Transformer

The reaction of the control algorithm for injecting DC to compensate for GIC is shown in Figure 8. When the DC jumps the input to the converter follows and then within about a cycle the voltage to the transformer stabilizes. This will be acceptable for the GIC compensation system because the quasi-static transients from E3 EMP/GMD are not fast transitions. Also, they will not be step changes but more exponential rises and decays. This system shows that large amounts of DC can be removed from the voltage going into the transformer by changing the reference position of the ground on the transformer. With this work now moving to testing the compensation when the transformer is capable of being saturated is the next step and then performing controller hardware in the loop testing.

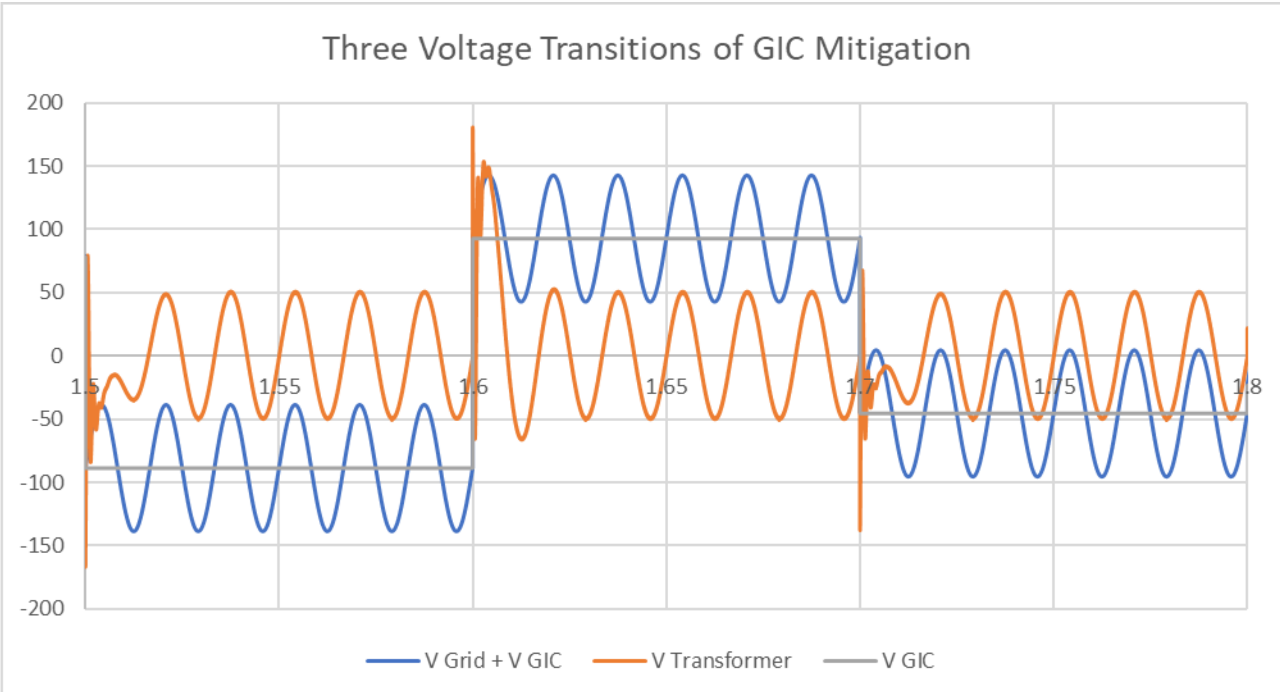

Figure 8: Three Transisitons of Voltage waveforms

FY2019 Accomplishments

- ✓ Submit three conference paper on failure mechanisms from GMD and HEMP of transformers and previous research on testing GICs
- ✓ Working with Clemson professor, 2 post docs, and PhD students for developing the topology for protecting transformers
- ✓ Purchased and programming a controller hardware in the loop (Typhoon) for increasing the capability for simulation and development of power electronic systems.
- ✓ Simulated GIC effect on transformers
- ✓ Simulated DC compensation on transformer

Future Directions

- Build Power Electronic System to test at eGRID
- Integrate PES with distribution transformers for testing
- Put DC on distribution transformers neutral and monitor results
- Research detection methods to responding to GIC and E3

FY 2019 Publications

- M. Nazir, K. Burkes, M. Babakmehr, F. Harirchi and J. H. Enslin, “Transformerless Converter-based GMD Protection for Utility Transformers,” Submitted to APEC 2020.

- M. Nazir, K. Burkes and J. H. Enslin, “Enhanced Grid Stability through GIC elimination and Grid Support,” Submitted to ISGT 2020.
- K. Burkes, J. Cordaro, T. Keister, J. Keister, B. Schafer, J. Enslin, “E3/GMD Effect and Testing of Quasi-DC Currents on Distribution Transformers,” Will be submitted to PES GM 2020.

Acronyms

- Alternating Current (AC)
- Direct Current (DC)
- Electromagnetic Pulse (EMP)
- Extra High Voltage (EHV)
- Geomagnetic Disturbance (GMD)
- Geomagnetically Induced Currents (GIC)
- High Altitude Electromagnetic Pulse (HEMP)
- Large Power Transformer (LPT)

Intellectual Property

Invention disclosure is being submitted and then a JIPA with Clemson

Total Number of Post-Doctoral Researchers

Two post-doctoral researches and two PhD students worked on the project through Clemson University

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