Contract No:

This document was prepared in conjunction with work accomplished under Contract No. DE-AC09-08SR22470 with the U.S. Department of Energy (DOE) Office of Environmental Management (EM).

Disclaimer:

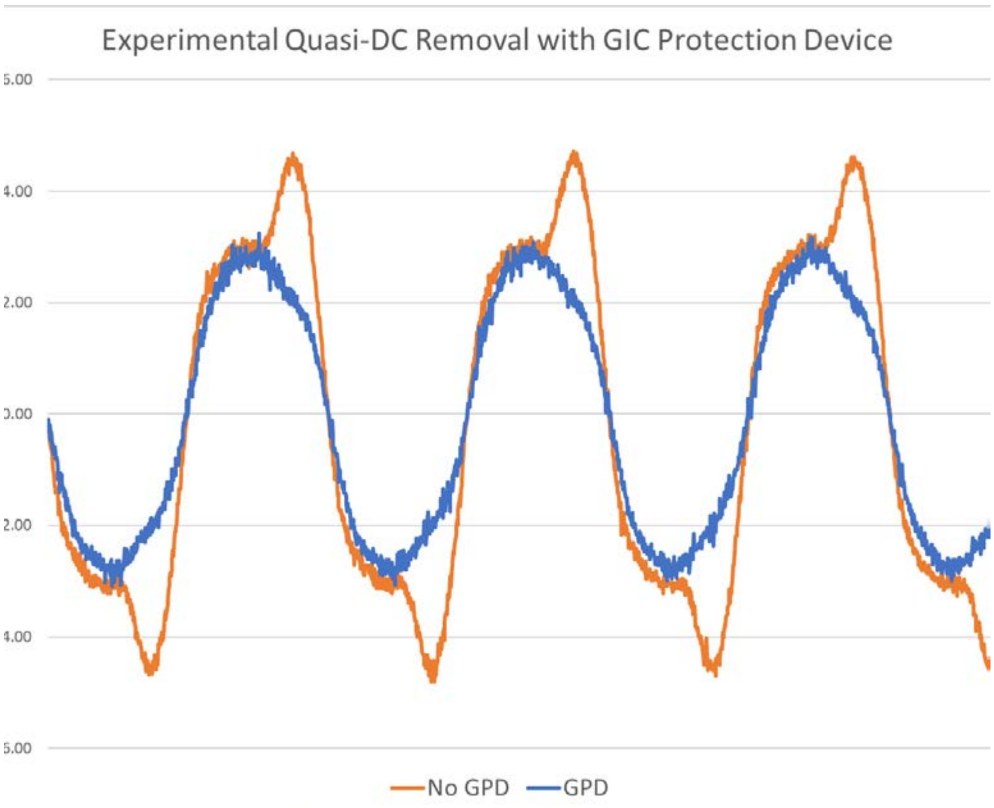
This work was prepared under an agreement with and funded by the U.S. Government. Neither the U. S. Government or its employees, nor any of its contractors, subcontractors or their employees, makes any express or implied:

1) warranty or assumes any legal liability for the accuracy, completeness, or for the use or results of such use of any information, product, or process disclosed; or
2) representation that such use or results of such use would not infringe privately owned rights; or
3) endorsement or recommendation of any specifically identified commercial product, process, or service.

Any views and opinions of authors expressed in this work do not necessarily state or reflect those of the United States Government, or its contractors, or subcontractors.

HEMP Transformer Defense through Power Electronics

Half cycle saturation was successfully remediated from a pair of transformers with power electronics connected on the neutral. This proves that power electronics can protect large power transformers from saturation from high altitude electromagnetic pulses.



Intellectual Property Review

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

SRNL Legal Signature

______________________________ ______________

Signature **Date**

HEMP Transformer Defense through Power Electronics

Project Team: Klaehn Burkes (Primary) and Vincent Cyssens

Subcontractor: Clemson University

Project Type: Standard

Project Start Date: October 1, 2018
Project End Date: September 30, 2020

High altitude electromagnetic pulses and geo-magnetic disturbances have the potential to severely impact the electric power grid by damaging large power transformers and causing severe power quality issues. This impact comes as a result of a quasi-static bias induced on transmission lines by geomagnetically induced currents which saturate magnetic components in the electric power system. This paper introduces the concept of utilizing a h-bridge inverter on the neutral of a LPT to inject a DC bias equivalent voltage onto the neutral side of the transformer windings. This biasing floats the transformer windings, eliminating the effect of the DC current and keeping the transformer from saturating. Schematic diagrams will be presented, along with simulation model data using Typhoon and PLECS, and finally test results from a benchtop hardware test.

FY2020 Objectives

- Perform controller hardware in the loop testing of GIC compensation and validate with simulations from last FY
- Build benchtop prototype of the GIC protection device
- Test benchtop prototype and validate with controller hardware in the loop testing
- Clemson develop grid support functions for improving business case for implementation

Introduction

High altitude electromagnetic pulses (HEMPs) and geo-magnetic disturbances (GMDs) are grave concerns for the electric power grid. These two events, through different means, both produce geomagnetically induced currents (GICs) on long transmission lines [1] [2]. These GICs are quasi-DC in nature in that they do not change fast with respect to the 60Hz power system. Therefore, these quasi-DC currents pose a serious threat to large power transformers (LPT) because the amplitude of GICs from HEMP and GMDs are large enough to saturate the core of the LPT, resulting in potentially fatal damage and large amounts of reactive current consumption [3] [4] [5] [6]. This large amount of reactive power consumption takes the form of heat and due to the temperature increase can cause damage to the insulation and windings of the transformer [7].

GICs flow through the power system through long transmission lines and back to ground via grounded neutrals on the transformers. If these ground paths are removed, GICs will not flow within the transmission system. The electric field magnitudes from E3 can be on the amplitude of up to 35 V/km [8] which can affect shorter length transmission and distribution. However, GMD is typically in the range from

The research presented in this paper was funded by SRNL's Laboratory Research and Development program.

1 to 6 V/km [9]; therefore, high voltage potential difference can only be built up on longer lines, and for power systems, these will primarily be extra high voltage (EHV) transmission lines. This is because of the longer line lengths and lower average resistance. Therefore, EHV transmission lines typically have more induced DC current and transformers in the EHV system will experience higher levels and longer times of saturation. This can impact the electric power grid significantly because the EHV system is critical backbone for routing large amounts of power over long distances from large generation to large loads in the bulk power system [10].

Several different techniques have been proposed to solve or mitigate this problem [3], [11], and [12], but in this paper we put forward an alternative solution. Here, it is proposed to add a device to the neutral of the high voltage winding of LPTs which would inject a DC bias, equal to the quasi static DC bias from GICs, theoretically to float the transformer windings by the few volts removing the voltage differential in the power lines from HEMP or GMD. This research is a proof of concept from simulation to a low voltage benchtop system for testing. This design was tested in Typhoon and PLECS modeling software. Design schematics and model simulation results are presented and compared. Then, a low voltage single phase hardware benchtop system was designed, fabricated, and tested. The test setup is described, and the data gathered from this test is presented. Finally, comparison to high voltage simulation results and low voltage experimental results are presented to show the theoretical functionality of the proposed protection method.

Approach

The GIC protection device (GPD) is comprised of a h-bridge inverter with a capacitor, resistor and DC voltage source on the DC side, and a LC filter on the h-bridge output in parallel with a resistor. The GPD is attached on the neutral of the high voltage winding of LPTs, which would inject a DC bias, equal to the quasi static DC bias from GICS, see Figure 1. Theoretically, this floats the transformer windings by the amount of DC GIC volts, removing the voltage differential in the power line from HEMP. This research was proof of concept from simulation to a low voltage benchtop system for testing. Final comparison of the high voltage simulation results and low voltage experimental results show the theoretical functionality of the proposed method works.

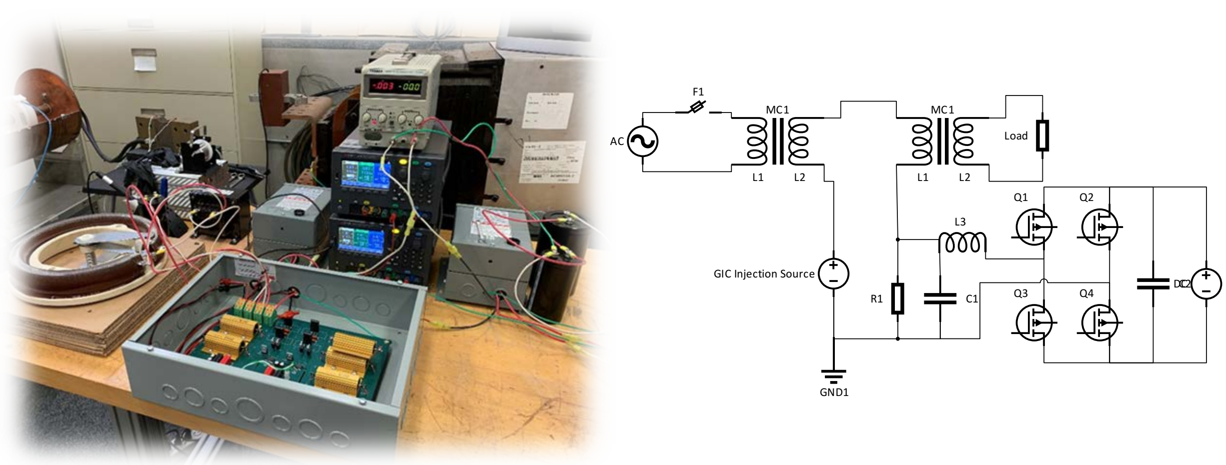


Figure 1: GPD Experimental Setup and Schematic Diagram

Results/Discussion

With most of the simulations done during the previous FY, the goal of the hardware benchtop test was to demonstrate that the results seen in the simulations are achievable in the real world. Often, simulations do not, or cannot, capture the complexities of real circuits. First, as a baseline, data was collected with the system set at 70% of its max input, with the GPD disconnected from the system, the transformer neutral connected directly into the power supply negative terminal, and no GIC. The 70% input allows for the operation of the benchtop system without getting close to its operating limits, and thus avoiding any saturation that may happen at those operating limits. The results can be seen in Figure 2. This waveform is free from saturation and provides a clean signal that can be utilized to compare future waveforms.

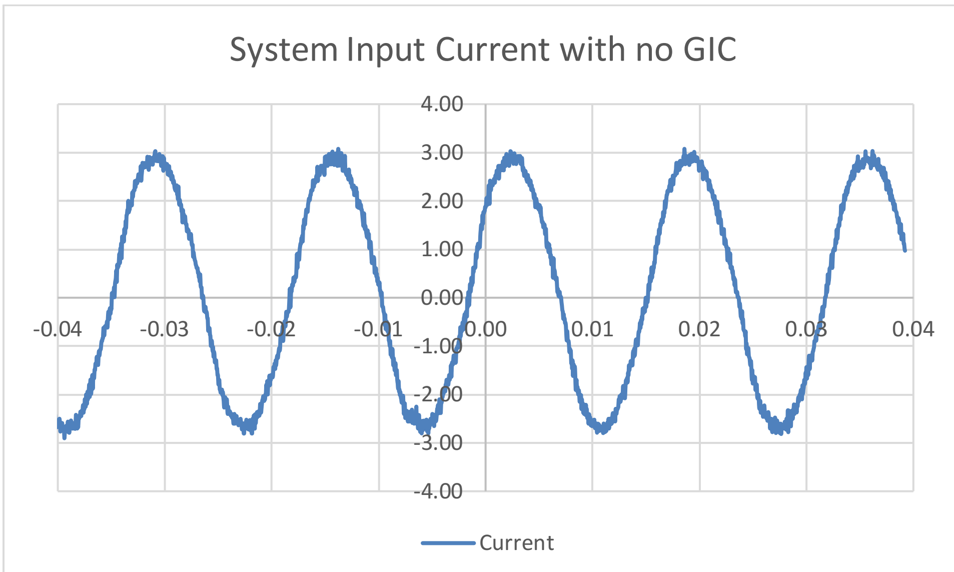


Figure 2: Input current as measured by the CT with no GIC

Next, it is important to understand how the system will respond without the GPD but under GIC. 8.7VDC was used for the GIC voltage input from the power supply. This was chosen as it is large enough to elicit a large amount of half-cycle saturation, allowing the GPD to better demonstrate its protection capabilities. The input current to the system under test with 8.7VDC GIC can be seen in Figure 3. The waveform can be seen with half-cycle saturation on both the positive and negative cycles of the current waveform. In the current testing topology, there are two transformers present. The DC is also in different polarities across the two transformers. This causes one transformer to saturate in the negative region and the other to saturate in the positive region. Therefore, the source must supply both saturation currents and sees two half cycle saturation waveforms superimposed on top of the 60Hz load current. Without the GPD connected and running, the peak-to-peak current has more than doubled. The base waveform was not affected by saturation and has remained unchanged.

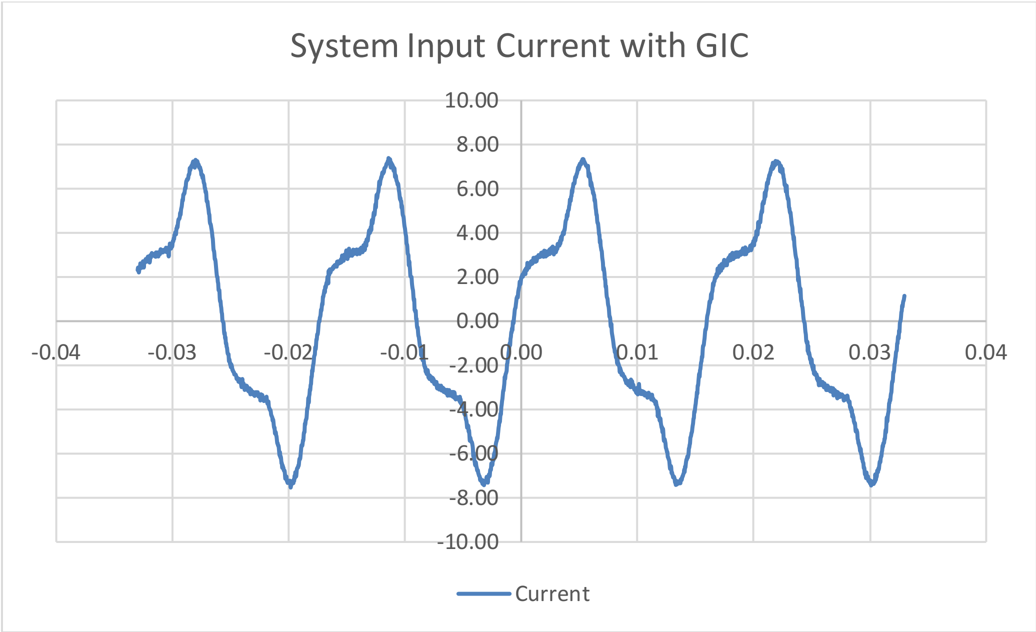


Figure 3: Current Absorbed by the Test System with 8.7VDC GIC Input

Now that the system's baseline and GIC current responses have been demonstrated, the GPD was added to the circuit, and the system's current waveform with 8.7VDC GIC and the GPD set at 80% duty cycle (for a 9.0VDC output). The GPD was set at 9V, slightly above the 8.7V GIC, because of the losses inside the GPD. The waveform can be seen in Figure 4.

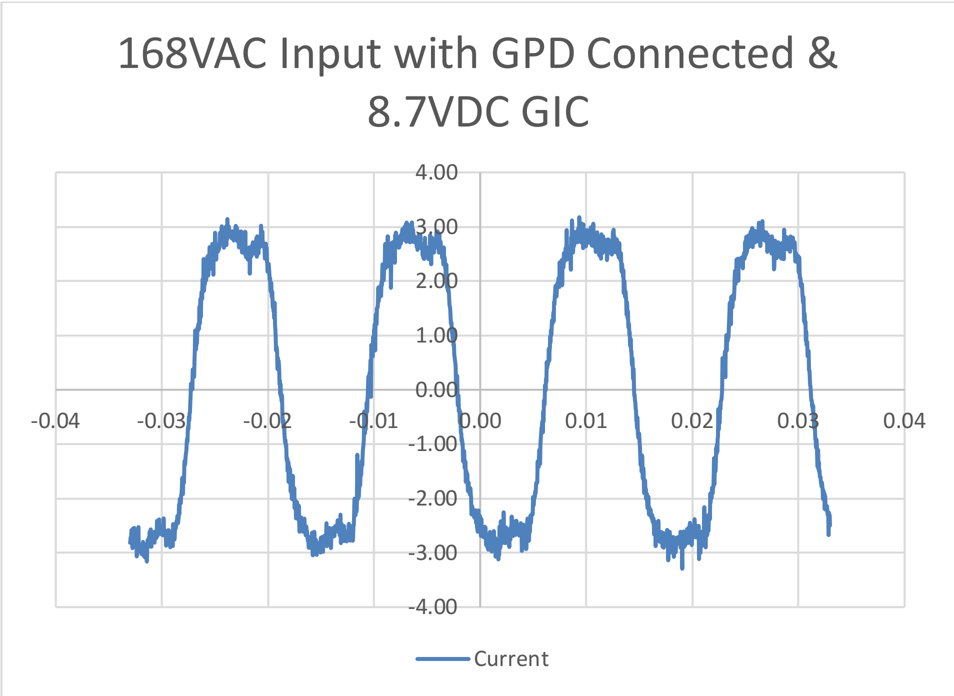


Figure 4: Current Waveform with GPD connected with 8.7VDC GIC

The half-cycle saturation humps have been drastically reduced, though not completely removed, and the peaks and troughs of the graph are noisier than before. Overall, a comparison between Figure 3 and Figure 4 demonstrates the GPD's ability to bias the transformers voltage differential from GICs and reduce the saturation effect. However, the remaining presence of saturation as evidenced by the slight half-cycle current humps indicates that the expected losses were greater than calculated. It turns out that the small accommodation made for losses was not nearly enough. To account for these losses, the GIC voltage was adjusted down to 7VDC with the GPD output held constant at 80% duty cycle. This imitates a situation where the total losses have been calculated, and the output has been biased up to account for them. The current waveform with the GIC adjusted to 7.0VDC can be seen in Figure 5. From these results it is clear the GPD benchtop system is capable of compensating for the electric potential differential across transmission lines from HEMP or GMD thus causing GIC to not flow through the transformer coils.

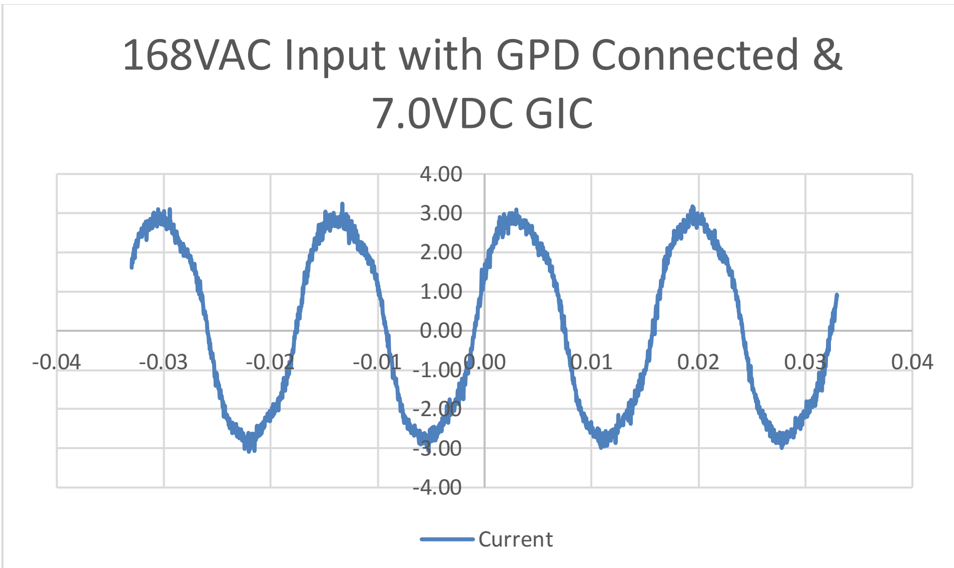


Figure 5: Current Waveform with 7VDC and GPD Connected with 80% Duty Cycle

FY2020 Accomplishments

- ✓ 1 provisional patent submitted and will be finalized this FY
- ✓ 5 peer review journals & 2 conference submissions
- ✓ Working with Clemson professor, and PhD student, developed code to perform grid support functionality
- ✓ Coded control algorithms on microcontroller and successfully testing using Typhoon CHIL
- ✓ Designed and Built prototype device and motherboard to allow for bench testing
- ✓ Built Bench Test System to check device operation
- ✓ Successfully removed half-cycle saturation current that was 200% of rated amplitude

Future Directions

SRNL will integrate this GPD into the Distribution Substation Testing Facility that SRNL is building. From there it will be tested on distribution transformers and those and these results will be presented to DOE AMO and TRAC offices for funding for technology transition and further testing.

FY 2020 Peer-reviewed/Non-peer reviewed Publications

1. M. Nazir, K. Burkes and J. Enslin, "Converter-based Power System Protection against DC currents in Transmission and Distribution Networks," in *IEEE Transactions on Power Electronics*, vol. 35, no. 7, Dec. 2019.

2. M. Nazir, K. Burkes, M. Babakmehr, F. Harirchi and J. H. Enslin, "Transformerless Converter-based GMD Protection for Utility Transformers," *2020 IEEE 35th Applied Power Electronics Conference (APEC)*, NewOrleans, LA, USA, 2020.

3. M. Nazir, J. H. Enslin and K. Burkes, "Enhanced Grid Stability through GIC elimination and Grid Support," *2020 IEEE 11th Conference on Innovative Smart Grid Technologies (ISGT)*, Washington, DC, USA, 2020.

4. M. Nazir, J. H. Enslin and K. Burkes, "Solar Farm Harmonic Analysis and Operation under DC currents," *2020 IEEE 11th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, Dubrovnik, Croatia, 2020, In press.
5. M. Nazir, K. Burkes, and J. H. Enslin, "Converter-Based Solutions: Opening New Avenues of Power System Protection Against Solar and HEMP MHD-E3 GIC," Accepted to IEEE Transactions on Power Delivery

6. M. Nazir, K. Burkes, and J. H. Enslin, "Electrical Safety Considerations of Neutral Blocker Placements for Mitigating DC Currents," Submitted to IEEE Transactions on Industry Applications.

7. M. Nazir, K. Burkes, and J. H. Enslin, "Transformation of Traditional Grid Transformers into Hybrid Smart Transformers," Submitted to IEEE Transactions on Power Electronics.

8. V. Ceyssens, K. Burkes, "Simulation and Testing of a GIC Protection Device on Transformer," Submitted to IEEE Transactions on Power Electronics.

Presentations

None

Works Cited

[1] J. Glibert, J. Kappenman, W. Radasky and E. Savage, "The Late-Time (e3) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid," Federal Energy Regulatroy Commission, Oak Ridge, 2010.

[2] J. Kappenman, "Low-Frequency Protection Concepts for the Electric Power Grid: Geomagnetically Induced Current (GIC) and E3 HEMP Mitigation," Federal Energy Regulatory Commission, Oak Ridge, 2010.

[3] T. S. Molinski, "Why utilities respect geomagnetically induced currents," *Journal of Atmospheric and Solar-Terrestial Physics ,* vol. 64, pp. 1765 - 1778, 2002.

[4] V. D. Albertson, B. Bozoki, W. E. Feero, J. G. Kappenman, E. V. Larsen, D. E. Nordell, J. Ponder, F. S. Prabjakara, K. Thompson and R. Walling, "Geomagnetic Disturbance Effects on Power Systems," *IEEE Transactions on Power Delivery,* vol. 8, no. 2, pp. 1206 - 1216, 1993.

[5] NERC, "Geo-Magnetic Disturbances (GMD): Monitoring, Mitigation, and Next Steps," in *April 2011 NERC GMD Workshop*, 2011.

[6] M. Nazir, J. H. Enslin and M. Babakmehr, "Power System Protection response under Geomagnetically Induced Currents," in *2020 Clemson University Power Systems Conference*, Clemson, SC, 2020.

[7] N. Takasu, T. Oshu, F. Miyawaki, S. Saito and Y. Fujuwara, "An Experimental Analysis of DC Excitation of Transformers by Geomagnetically Induced Currents," *IEEE Transactions on Power Delivery,* vol. 9, no. 2, pp. 1173 - 1182, 1994.

[8] R. Horton, *Perspective on Protecting the Electric Grid from an Electromagnetic Pulse or Geomagnetic Disturbance,* Washington D.C.: Hearing of the U.S. Senate Homeland Security and Governmental Affairs Committee, February 27, 2019.

[9] NERC, "Geo-Magnetic Disturbances (GMD): Monitoring, Mitigation, and Next Steps," Atlanta GA, 2011.

[10] J. Kappenman, "Geomagnetic Storms and Their Impacts on the U.S. Power Grid," Metatech Corporation, Goleta, CA, January 2010.

[11] A. Rajapakse and e. al, "Power grid stability protection against GIC using a capacitive grounding circuit," in *PES T&D 2012*, Orlando, 2012.

[12] D. T. Phillips, "Solar Shield--Protecting the North American Power Grid," NASA, 26 October 2010. [Online]. Available: https://science.nasa.gov/science-news/science-at-nasa/2010/26oct_solarshield. [Accessed 17 December 2019].

Acronyms

- LPT – Large Power Transformer
- HEMP – High-altitude Electro-magnetic Pulse
- GMD – Geo-Magnetic Disturbance

- GIC – Geo-magnetically Induced Current
- GPD – GIC Protection Device

Intellectual Property

1. K. Burkes, V. Ceyssens, J. Enslin, M. Nazir, "E3 EMP/GMD Compensation for Large Power Transformers through Neutral Current DC Injection," SRS Invention Disclosure SRS-20-004.

2. K. Burkes, V. Ceyssens, J. Enslin, M. Nazir, "DC Compensation for Power Transformer Through Neutral DC Injections," Provisional Patent Number 62/989,004

Total Number of Post-Doctoral Researchers

- Mohammad Babakmehr: off-site at Clemson
- Farnaz Harirchi: off-site at Clemson

Total Number of Student Researchers

- Septimus Boshoff: off-site Clemson Master Student
- Moazzam Nazir: off-site Clemson PhD Student

External Collaborators (Universities, etc.)

- Clemson University: Johan Enslin