Contract No:

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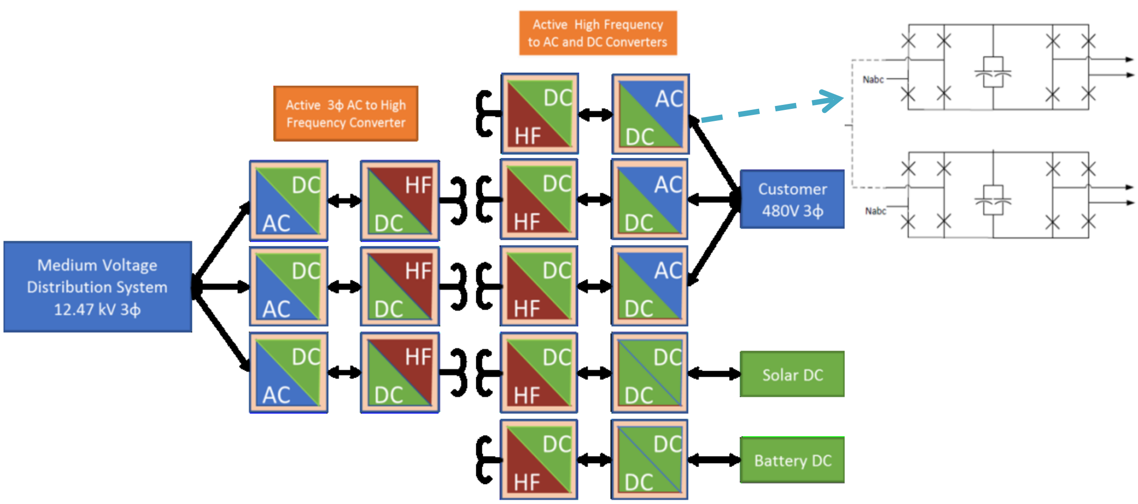
Power Hardware-in-the-Loop Testing of Distribution Solid State Transformers

Savannah River National Laboratory and Resilient Power Systems have developed a utility grade solid state transformer and are planning on deploying it for testing in January 2018. The solid state transformer is the next generation solution to implementation of distributed energy resources such as solar and batteries. They can directly connect the solar and battery systems to DC ports and rout power between these DC ports and load ports. The solid state transformer can revolutionize current grid modernization initiatives by supplying grid support and building support services at the edge of the grid. These services consist of volt-VAR optimization, power factor correction, voltage regulation, frequency regulation, fault current support, demand side management, DC bus for AC/DC capable houses, and power routing between multiple ports for transactive control. For this fiscal year a test plan for testing the SST capabilities was develop. Along with the FPGA controls for the SST output ports. These controls will allow for any waveform to be produced by each port of the SST. Finally, a hybrid distribution SST was tested at the eGRID resulting in medium voltage testing experience for SRNL engineering team. DOE is currently engaged, through the Building Technology Office and Infrastructure Security and Energy Restoration in future work building from this project.



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

Signature **Date**

Power Hardware-in-the-Loop Testing of Distribution Solid State Transformers

Project Team: John McIntosh (Primary), Klaehn Burkes

Subcontractor: Resilient Power System and Clemson University

Thrust Area: Secure Energy Manufacturing

Project Start Date: October 1, 2016

Project End Date: September 30, 2018

Savannah River National Laboratory and Resilient Power Systems have developed a utility grade solid state transformer (SST). The SST is the next generation solution to implementation of distributed energy resources such as solar and batteries. The SST can revolutionize current grid modernization initiatives by supplying grid support and building support services at the edge of the grid. This is not currently a function for traditional transformers. For this fiscal year a test plan for testing the SST capabilities was develop. Along with the FPGA controls for the SST output ports. These controls will allow for any waveform to be produced by each port of the SST. Finally, a hybrid distribution SST was tested at the eGRID resulting in medium voltage testing experience for SRNL engineering team. DOE is currently engaged in future work building from this project.

FY2018 Objectives

- Develop SST Test Bed and System
- Lease and test functionality of GridBridge Hybrid Transformer
- Receive Distribution SST at eGRID
- Develop Control Strategy for Lithium Ion Battery systems (December)
- Perform Load Profile Shaping at eGRID (February 18)
- Develop Control Strategy for Lead Acid and Lithium Ion Dual Battery Systems (July)
- Perform SST Functionality Tests (August 18)

Introduction

The electric grid is changing rapidly through the integration distributed energy resources (DER) that consists of intermittent renewable energy sources, battery energy storage systems (BESS), and other advanced technologies. DERs require higher levels of control from power electronic inverters and rectifiers to convert the DC power consumed or produced into AC power to connect to the electric grid. To fully leverage DER penetration, passive elements such as a traditional transformers and passive inverters and rectifiers need to be replaced with equivalent active elements like a solid state transformer (SST). With SSTs integrated into the electric grid more functionalities are becoming readily available at the grid edge to perform grid and building support functions such as control of power flow on multiple ports, reactive power support, power factor correction, integration of renewables and BESS on DC buses, fault isolation, advanced metering, load shaping, demand side management, and transactive control.

Renewable sources are being integrated into the electric grid at alarming amount and not only in the California region. North Carolina has the second highest integration of photovoltaic (PV) energy in the country see Figure 1. One problem seen by this large amount of PV integration is that generation peak and load peak don't occur at the same time. This is because the largest power demand is at the end of the day, when people are returning home from work. PV systems peak power supply is in the middle of the day. Since PV's supplied power is falling off when the load is increasing, high spinning reserves and fast ramp rate generators have to be committed to supply power late in the day. This is a large amount of wasted money to support the loss of PV energy. This problem can be solved by integrating a BESS controlled by a distribution scale SST to absorb the PV energy during the peak and supplying it back into the system as PV energy lessens and load is ramping up.

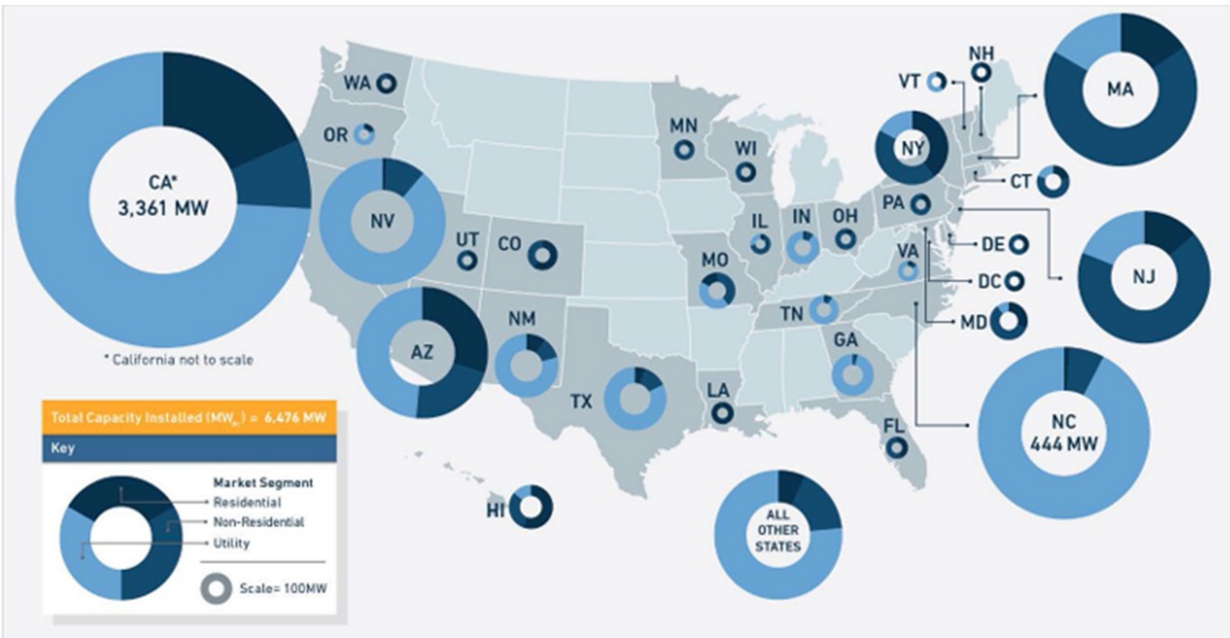


Figure 1: PV installations in the US by state in 2014 [1]

Approach

SRNL worked with Resilient Power Systems to develop the solid state transformer. Together SRNL and RPS determined the parameters for the SST, what type of functionality the SST would be capable of performing, how many ports the SST contains, and how the SST will operate above that of a traditional transformer. SRNL also worked with GridBridge a startup company developing hybrid transformers to test a utility deployed hybrid SST. GridBridge is owned by ERMCO a transformer manufacture.

The solid state transformer consists of power electronics that convert the AC power delivered by the electric grid to a high frequency AC power. This high frequency allows for a smaller transformer to be used to isolate the primary from the secondary. The high frequency transformer is a 1 to 1 transformer and only performs isolation. The power electronics on the secondary are configured in a way to which they drop the voltage down to the secondary voltage level. A block diagram of the system is shown in Figure 2. The primary and secondary power electronics are utilizing multiple modules that consist of active h-bridge architectures to control power flow bi-directionally. This allows for power to be routed through any port in the transformer in any direction. To increase power and voltage the modules are cascaded to reach desired levels, and the modules utilize silicon IGBTs and not wide band gap devise. This allows for reduced losses and costs because the power is being distributed throughout many modules, and the costs of wide band gap devises would make the system astronomically expensive and not cost competitive with current installed technologies.

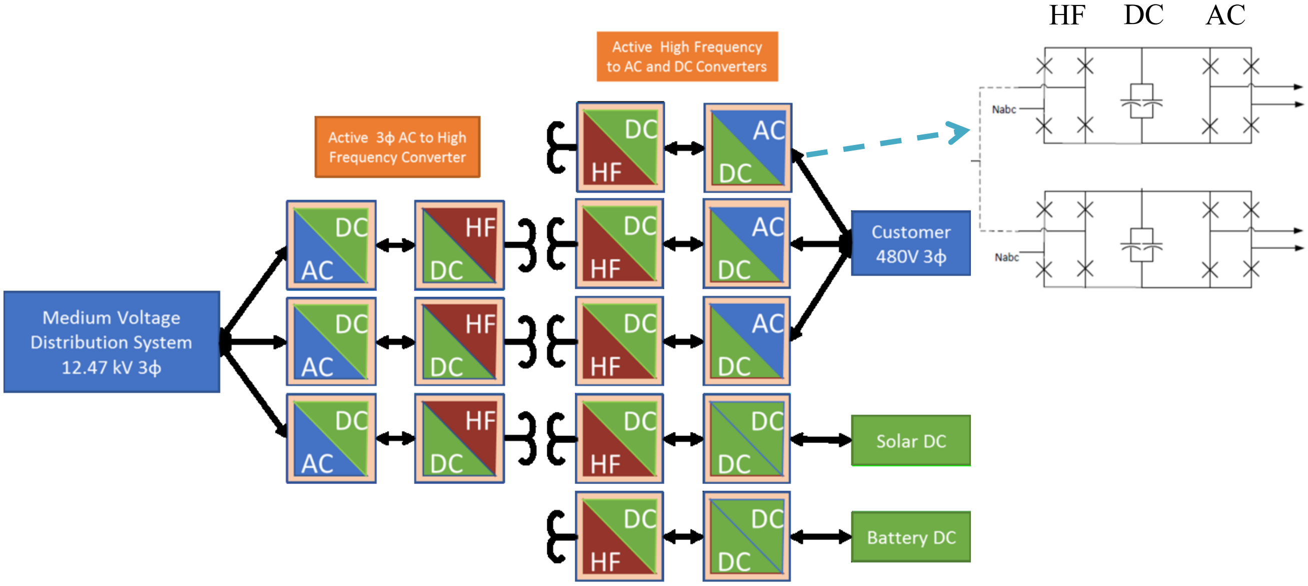


Figure 2: SST system block diagram

Results/Discussion

SRNL developed control signatures to produce any type of waveform from each port on the SST. This includes DC, 60 Hz AC, higher frequency AC, and integration of harmonics. An example of the output waveforms is shown in Figure 3. This will allow for future emulation of any type of waveform, and also allow for the improvement of power quality for both primary and secondary sides of the transformer. The control works by sending a specific voltage point at a set time step to result in any arbitrary waveform. By performing this point on wave control with a 12kHz control loop, SRNL has high accuracy and fidelity in output wave forms that traditional power electronic systems.

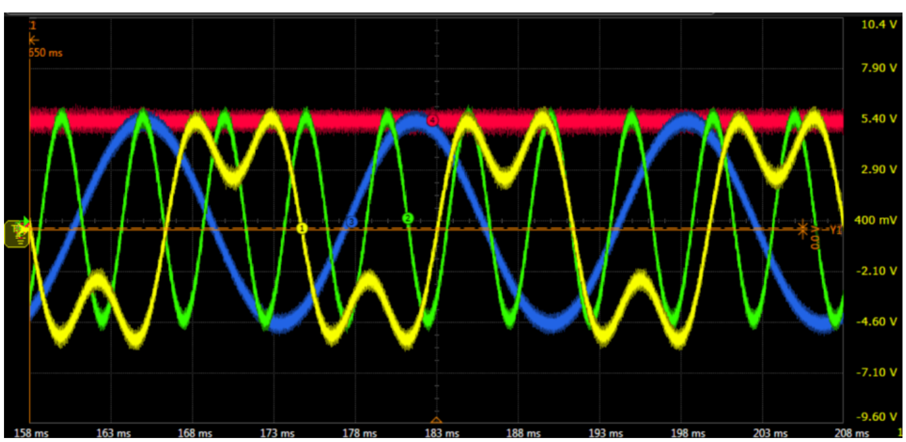


Figure 3: Waveform Output for controlling SST

SRNL also tested the hybrid distribution SST at the Clemson University eGRID. This gave SRNL experience in testing medium voltage distribution components and making accurate measurements at high voltage and low current. SRNL experimented with different types of sensors to improve the accuracy of the power measurement taken on the transformers. High voltage differential probes were required to reach the 7.2 kV voltage of the primary side of the transformer. A current shunt was ultimately used on the neutral return of the transformer to measure the primary current. This is because the voltage potential on the neutral is very low an is safe to utilze low voltage probes. The instrumentation connections are shown in Figure 4. The transformer was driven by the PAUs from the eGRID and loaded with a RLC load bank shown in Figure 5.

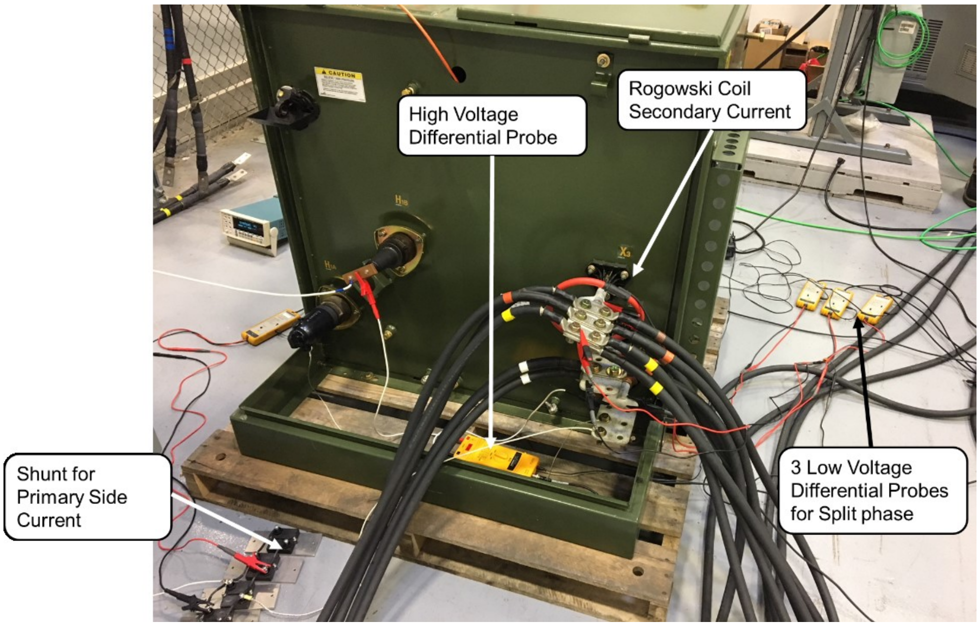


Figure 4: Instrumentation for hybrid distribution SST

Figure 5: Connection to eGRID for distribution SST

FY2018 Accomplishments

- ✓ Test procedure for function testing SST was developed in coordination with Clemson.
- ✓ FPGA control of SST was developed by SRNL to provide 12kHz control loop to provide point on wave control
  - ✓ Allows for SRNL to dictate any waveform on SST secondary
  - ✓ Includes DC, Harmonics, AC, High frequency
  - ✓ Has been tested on prototype secondary system for limited cycles
  - ✓ System will allow SRNL to perform more advanced controls than other SST developers such as HEMP mitigation
- ✓ Tested hybrid distribution SST at eGRID
  - ✓ Lessons learned in types of instrumentation
    - ✓ High voltage with high accuracy
    - ✓ High voltage with low current
- ✓ Full 500kVA 12.47kV SST delivered to eGRID for future research applications

Future Directions

SRNL is currently working with PNNL, GridBridge, ERMCO, and Clemson University to integrate distribution SSTs into transactive control of buildings and campuses. This work is being funded through Building Technology Office and scoping study is currently in process to develop a test plan for the next three years to full hardware in the loop transactive control utilizing demand response and distribution SSTs. This will lead into a new GMLC lab call proposal.

SRNL is also working with Resilient Power systems to develop solid state power substations that are hardened from high altitude electromagnetic pulses. The SST or hybrid SST can be used to reduce the amount of neutral current and core saturation caused by the E3 component of the HEMP electric field. By using the SST to remove or counter this component damage can be mitigated.

References

[1] "Solar Market Insight Report 2014 Q4" Solar Energy Industries Association, 2014. Accessed 9/20/2017) https://www.seia.org/research-resources/solar-market-insight-report-2014-q4

Acronyms

- DER – Distributed Energy Resources
- BESS – Battery Energy Storage Systems
- SST – Solid State Transformer
- AC – Alternating Current
- DC – Direct Current
- PV – Photovoltaic
- PAU – Power Amplifier Unit

Total Number of Post-Doctoral Researchers

Two post-doctoral researches worked on the project through Clemson University.