2.2 Large Scale System Simulation (LSSS) Testbed

Year 10 Projects and Participants			
Project Number	**Project Title**	**Participants**	**Institution**
Y10.LSSS.1	Dynamic simulation and validation of FREEDM systems on large scale test feeders using OpenDSS	Ayyanar Crow Baran	ASU MST NCSU

2.2.1 Intellectual Merit and Impact

The purpose of the Large Scale System Simulation (LSSS) testbed is to provide a scalable system with which to demonstrate and evaluate FREEDM capabilities and functionalities on a large scale. Through the use of extensive simulations, the LSSS allows researchers to analyze and predict how a future FREEDM system will operate across a variety of loads, devices, and renewable energy sources. The testbed has been used to compare the FREEDM system against traditional energy distribution systems and to benchmark several system-level functionalities, including control strategies, component interactions, fault dynamics, and pilot protection.

The LSSS thrust area has developed multiple control and optimization methods ranging from device/converter level control of SST to system-wide volt-VAR control for different optimization objectives used in other thrust areas. Many of the advanced dynamic simulation methods such as hybrid phasor and electromagnetic transient simulation developed in this thrust find applications in studying the dynamic impact of large, realistic distribution systems with very high penetration of distributed, intermittent renewable resources that are interfaced through high frequency power electronic converters. These methods have also been implemented in open source tools such as OpenDSS facilitating the widespread adaption of the developed techniques.

2.2.2 Role in FREEDM Strategic Plan

LSSS as a test bed was created in Y4 as part of revamping the test bed structure to create a more streamlined and better aligned flow from the sub-thrusts to the integrated test bed. The focus for the test bed was to digitally validate the FREEDM System concepts with large and realistic number of nodes and resources.

The LSSS testbed provides the capability to test and validate system-level FREEDM capabilities. The LSSS testbed complements the HIL and GEH testbeds by addressing the scalability aspect. Through large scale simulation, it is possible to analyze and ultimately predict how a future FREEDM system will operate with deployment of a wide variety of loads, SSTs, energy storage devices, and renewable energy sources. This testbed allows FREEDM researchers to benchmark new approaches against a traditional non-FREEDM distribution system. The testbed models are validated against both hardware and other modeling platforms (such as Matlab/Simulink) to assure high fidelity of results.

In the recent past, the LSSS has been used to benchmark a newly developed system-level volt-var control strategy, the pilot protection approach, a new design methodology for SST system control, and as a simulation tool for the nonlinear system complexity analysis project.

2.2.3 Technical Approach

The LSSS thrust area has developed new methods and implementation techniques to study large scale distribution systems with large number of SSTs and other FREEDM components and subsystems. In addition, the thrust has also developed several new control methods, optimization algorithms, protection methods and dynamic simulation methods. Three of these contributions to FREEDM and external research community are highlighted in this report.

2.2.4 Stability Design Criteria for Distribution Systems with Solid-State Transformers

2.2.4.1 Technological barriers and fundamental research

The inclusion of a high number of power-electronic converters in a traditional ac grid introduces a number of technical issues in control and stability that have not previously been encountered. One area of concern is the potential for instability caused by SST interactions. This instability may take the form of a harmonic resonance induced by the interaction of the input impedance and the source output impedance. We have established the potential for instability when SSTs are energized in a distribution system. We have proposed a design criterion for the SST input filter to mitigate instabilities in the system and validated the design using the IEEE 34-bus distribution system testbed.

2.2.4.2 Unique Approaches

We hypothesize that the primary reason behind instability in distribution systems with large number of SSTs is the violation of an impedance-based (similar to the Middlebrook) stability criterion. This is not a design issue that occurs with conventional transformers and is therefore seldom experienced in a distribution system. We propose a design criterion that provides guidance to size the input filter such that harmonic instability can be avoided. Specifically, we propose that system stability can be assured if the input filter is chosen such that the input impedance magnitude exceeds the source impedance. Now, using the stability criterion, it stands to reason that if the SST filters were selected such that the input impedance magnitude exceeded the source impedance, then the system would remain stable.

2.2.4.3 Technology Innovations and Results

To illustrate the impact of multiple SSTs in a distribution system, three (out of the total of 16 SSTs) are placed on the *b* phase of a modified IEEE 34-bus distribution test system shown in Fig. 1.

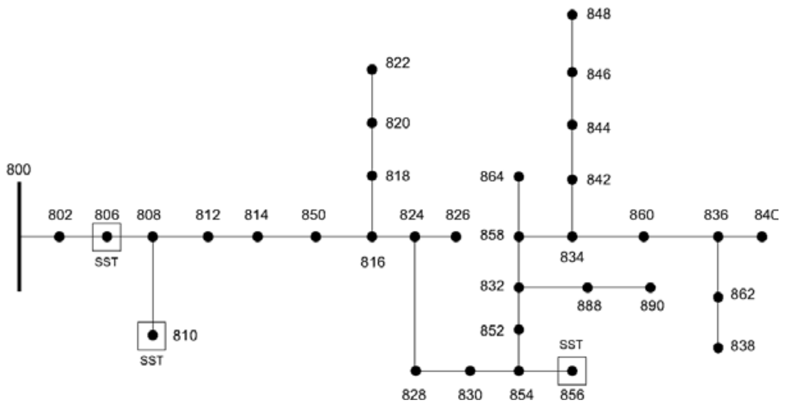
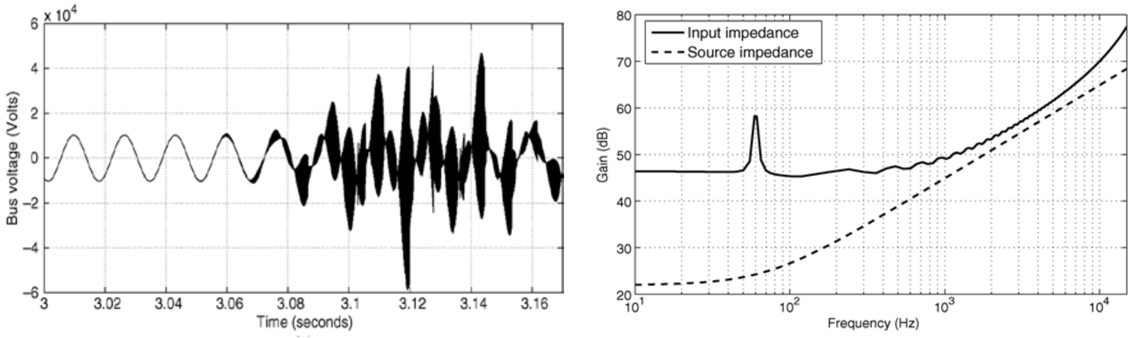


Fig. 1: IEEE 34-bus distribution test system with three SSTs

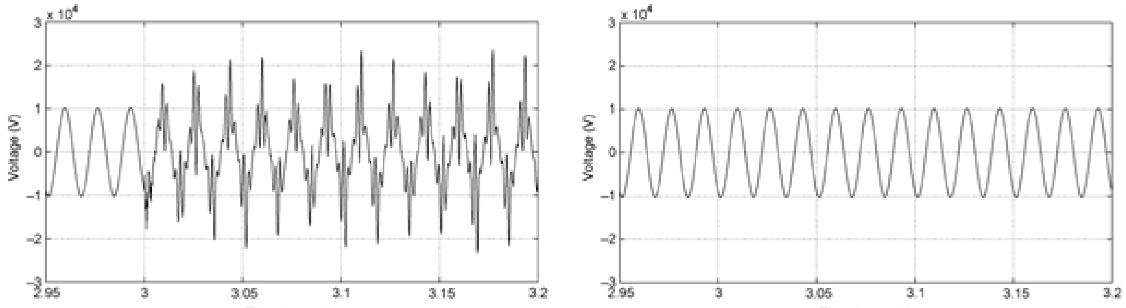
The three SSTs are connected sequentially from the substation down the feeder. The SST at bus 806 is connected at 1 s, the SST at bus 810 is connected at 2 s, and the SST at bus 856 is connected at 3 s. Fig. 2(a) shows the bus 856 ac voltages, from the time SST 856 is connected at no load. The bus voltage and SST current become increasingly erratic. We hypothesize the primary reason behind this behavior is the violation of an impedance-based (similar to the Middlebrook) stability criterion. A good design practice requires that the gain margin of 6 dB be maintained; this margin is violated as shown in Fig. 2b explaining the exhibited instability. This is not a design issue that occurs with conventional transformers and is therefore seldom experienced in a distribution system. Therefore, care must be taken with the deployment of SSTs.



(a) (b)

Fig. 2: (a) Bus voltage at bus 856 when an SST is added, (b) sources and input impedance at bus 856

We propose a design criterion that provides guidance to size the input filter such that harmonic instability can be avoided. Specifically, we propose that system stability can be assured if the input filter is chosen such that the input impedance magnitude exceeds the source impedance. Now, using the stability criterion, it stands to reason that if the SST filters were selected such that the input impedance magnitude exceeded the source impedance, then the system would remain stable as shown in Fig. 3.



original filter (a) resized filter

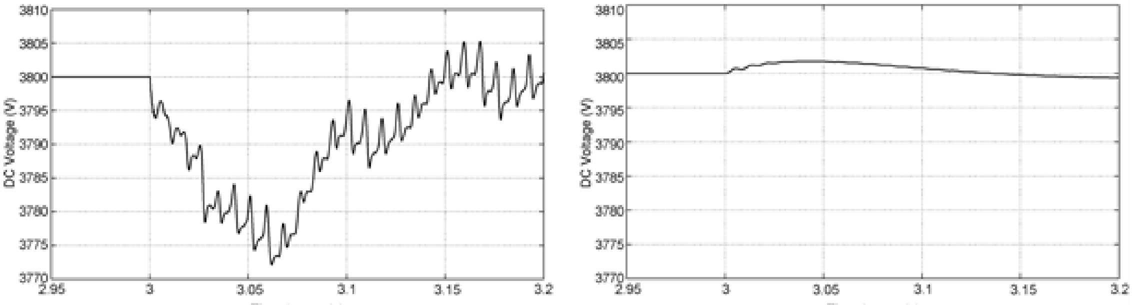


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Fig. 3: Bus 890 SST responses with all 16 SSTs on system with designed filters: (a) ac voltage (b) dc link voltage

2.2.5 Online Volt-VAR Control for Distribution Systems with Solid-State Transformers

2.2.5.1 Technological barriers and fundamental research

In distribution power systems, feeder voltages can be very sensitive to changes in load and/or distributed generation. The voltage fluctuations and the potential for violations for voltage limits are some of themain concerns of distribution system operation under very high penetration of distributed, intermittent renewable generation. This research introduces a solid-state-transformer-based local voltage-control strategy to reduce variability distribution system bus voltages. An online dynamic volt-var control (VVC) algorithm is proposed to regulate bus voltages by injecting or absorbing reactive power through a solid-state transformer (SST). The proposed algorithm does not require any communication between the SST and the substation and makes control decisions locally. The main goal of the voltage-control algorithm is to enforce strict voltage constraints on the system voltages.

2.2.5.2 Unique Approaches

SST-based volt-var control was first introduced by Baran and his students. The primary goal of their control strategy was to minimize system power losses while enforcing voltage limits across the system. The method was a centralized approach that assumed that all SSTs participate in volt-var control. Furthermore, implementation of volt-var control requires communication of all bus voltages to the central controller. The concept of local voltage control that is pursued in this LSSS task is quite different in that our proposed method does not require centralized computation nor is it applied at every SST. Only a subset of SSTs at particular “pilot” nodes participates in volt-var control, leaving remaining SSTs available for other functions.

2.2.5.3 Technology Innovations and Results

The SST can perform voltage regulation on the HV ac side as well as the LV ac side. The proposed volt-var control is used to control the voltage at the HV ac side. In this project, it is assumed that all conventional transformers in the distribution system have been replaced by SSTs. This is a generalization and, in practice, not all transformers are required to be SSTs, only the transformers at the pilot buses. In the absence of voltage control, the SSTs operate in unity power factor mode. The main goal of the algorithm is to enforce strict real-time voltage constraints for sensitive buses with the help of reactive power compensation from the SSTs. The VVC proposed in this work is accomplished in two steps. In the first step, the pilot buses are identified. In the second step, the proposed voltage-control algorithm is implemented to enforce strict voltage constraints.

The load varies throughout the day in accordance with the normalized load curve shown in Fig. 4a, which represents a typical residential load. The solar insolation at each pilot bus is shown in Fig. 4b.

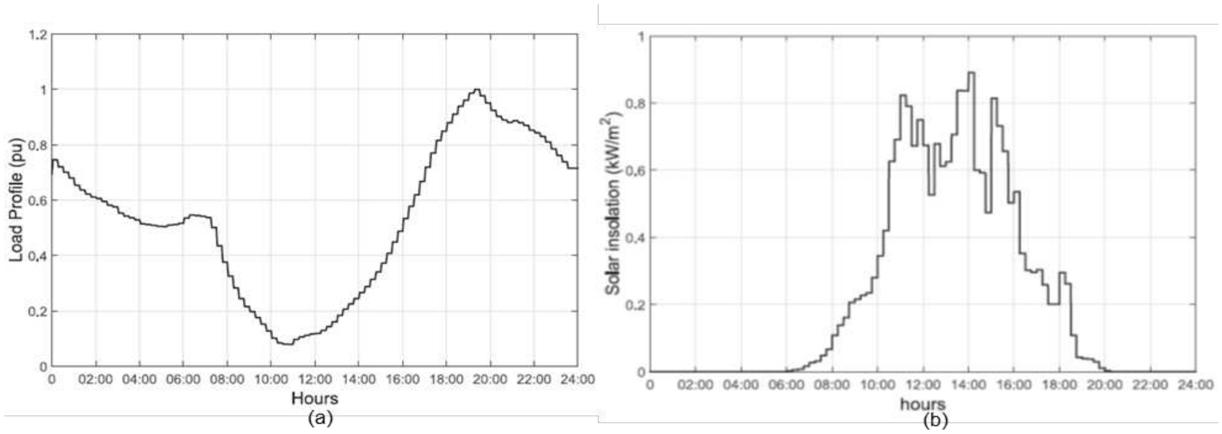


Fig. 4: (a) Daily load profile for a typical weekday (normalized) and (b) daily insolation profile for a summer day

Fig. 5a shows the results of the algorithm on the voltage magnitude at bus 890. Note that without volt-var control, the competing effects of the diurnal load and the solar insolation cause the uncontrolled voltages to violate the minimum and maximum voltage limits. However, once the VVC algorithm is implemented, the voltages are maintained within operational boundaries.

Fig. 5b shows the bus powers at bus 890. Note that during the period in which active power is injected by the PV array into the system, the bus voltages increase. Thus, reactive power is absorbed during the same period to maintain the voltages below the voltage limit. Conversely, when the active power load is high, the reactive power injection is also high to compensate for the drop in voltage. Note also that the total apparent power through the SST is always well below the kVA rating of the SST.

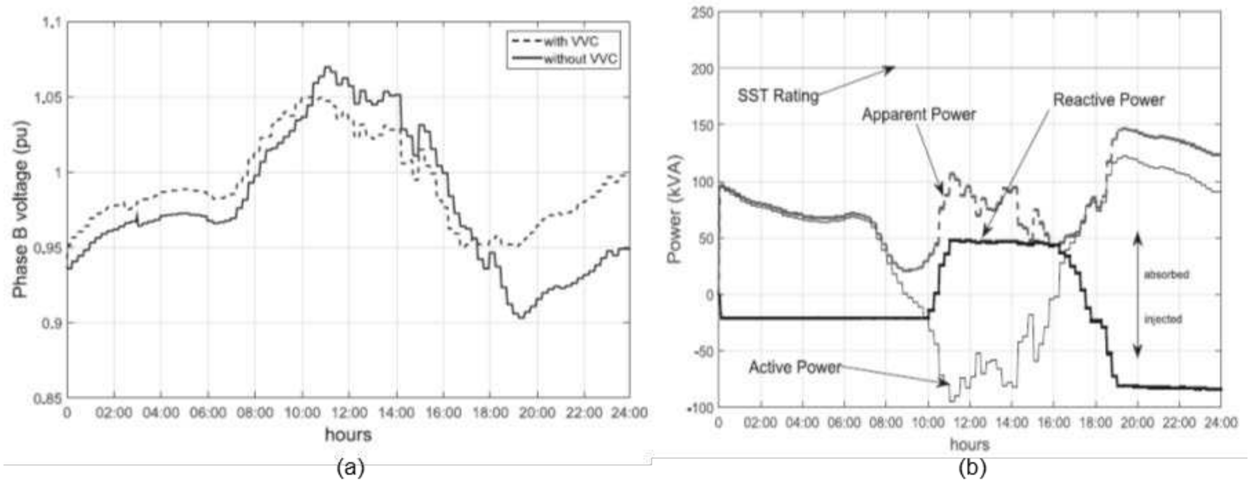


Fig. 5: (a) Bus voltage of phase B at SST 890, (b) active, reactive, and apparent SST power at bus 890

2.2.6 Dynamic simulation and validation of FREEDM systems on large scale test feeders using OpenDSS

2.2.6.1 Technological barriers and fundamental research

The *dynamic* (as opposed to quasi-static time series) simulation of multiple SSTs in a distribution system is needed to analyze and validate various SST control schemes where the SST behavior may differ from the standalone situation because of the dynamic interactions between the SST and components in the system including other SSTs. The extreme number of SSTs to be modeled in a large distribution system with several thousands of nodes, and the wide range of time scales involved in the different dynamic events make the dynamic analysis challenging. The nature of distribution system in terms of large unbalance and single-phase loads and single-phase generators (and SSTs) makes it particularly challenging to perform dynamic simulations. In this work, the differential-algebraic equations (DAE) based simulation involving a hybrid of electromagnetic transient simulation (EMT) and phasor transient stability (TS) type simulation is proposed and demonstrated for the dynamic simulation of SSTs in large-scale distribution systems.

2.2.6.2 Unique Approaches

As shown in Fig. 6a, the differential-algebraic equations (DAE) based simulation is proposed and implemented for the dynamic simulation of SSTs in large-scale distribution systems. It is a reduced order simulation where the major part of the system (mainly the passive network and loads) is simplified with static model which is governed by algebraic equations. The solution of the static system is obtained from a suitable power flow program. The remaining part which is the dynamic system (mostly SSTs and other converter interface generation and storage) is governed by differential equations and can be solved through integrations such as what is done in electromagnetic transient (EMT) simulations. As compared to the full order EMT simulation, the proposed method saves considerable computation resource while retaining the dynamic properties of the selected components.

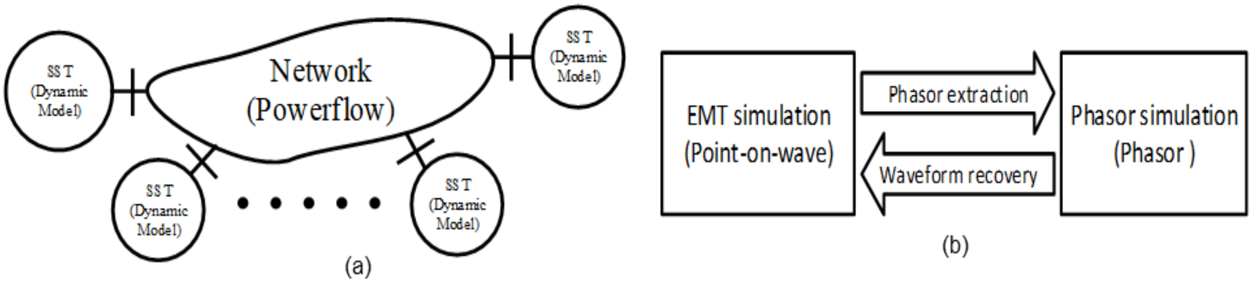


Fig. 6: (a) DAE based simulation of SSTs in large systems, (b) Data conversion between EMT and phasor simulation

As shown in Fig. 6b, the variables used in the power flow and EMT simulations are in different types, thus the data conversion is needed in the hybrid simulation. The power flow uses phasors which is the magnitude and phase angle of the line frequency components. The EMT simulation usually calculates the point-on-wave results namely the instantaneous value of the sinusoidal waveforms. Three different methods of implementing the phasor extraction shown in Fig .6b, including FFT, direct-quadrature transformation and analytical complex signal model (dynamic phasor) based methods, have been analyzed and compared. An analysis on the numerical stability of the simulation based on these phasor extraction methods has been done analytically. The result shows the *dynamic phasor* based method is more numerically stable than the other two, and hence this method is adapted for the dynamic analysis.

DAE based simulation of SSTs in OpenDSS: In order to extend the capability of OpenDSS beyond snapshot and quasi-static analysis, DAE based dynamic simulations have been implemented for SSTs by developing the Dynamic Linked Library (DLLs) of SST dynamic model. The equations based on the dynamic phasor model of the SST including both the power stage circuit and the controllers are derived for developing the DLLs. Embarcadero Delphi is used as the IDE in the DLL development.

2.2.6.3 Technology Innovations and Results

The interaction between the power flow program in OpenDSS and the DLL is shown in Fig. 7. The external system is represented as a Thevenin voltage source at the SST terminal where the voltage value is provided by the power flow result. The DLL containing the SST dynamic model calculates the SST terminal current which is used in the power flow as the current injection at the SST bus.

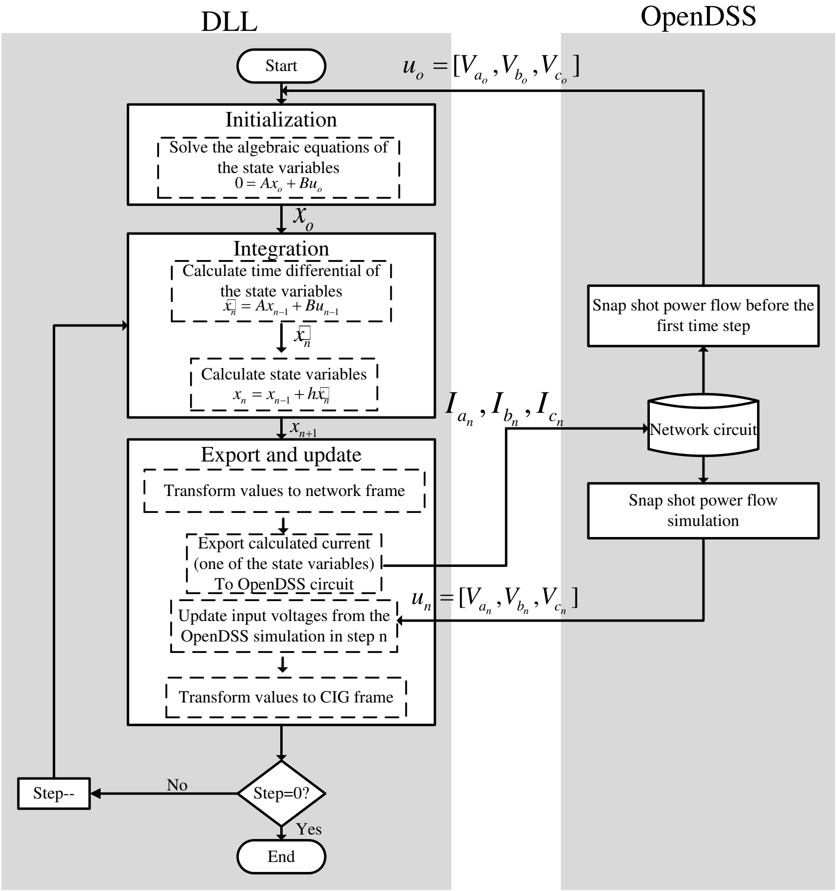


Fig. 7: Algorithm of interaction between the DLL and OpenDSS during dynamic simulation

2.2.7 Validation of the derived DLL in IEEE 13-node test system

To validate the developed DLL, a dynamic simulation is conducted by using the IEEE 13-node test system model. A SST which is connected to phase A of bus 675 through a step-down transformer is simulated. The full detailed EMT simulation is also conducted for the same system in PLECS. The simulation results are shown in Fig. 8. Fig. 8a shows the phasor result of the SST current in OpenDSS and the corresponding point-on-wave result in PLECS under a step change of the SST grid side current command. The phasor result has been used to recreate a point-on-wave result and compared with the PLECS result as shown in Fig. 8b. It shows a good agreement between the result of the DAE based simulation in OpenDSS by using the developed DLL and the full detailed EMT simulation in PLECS.

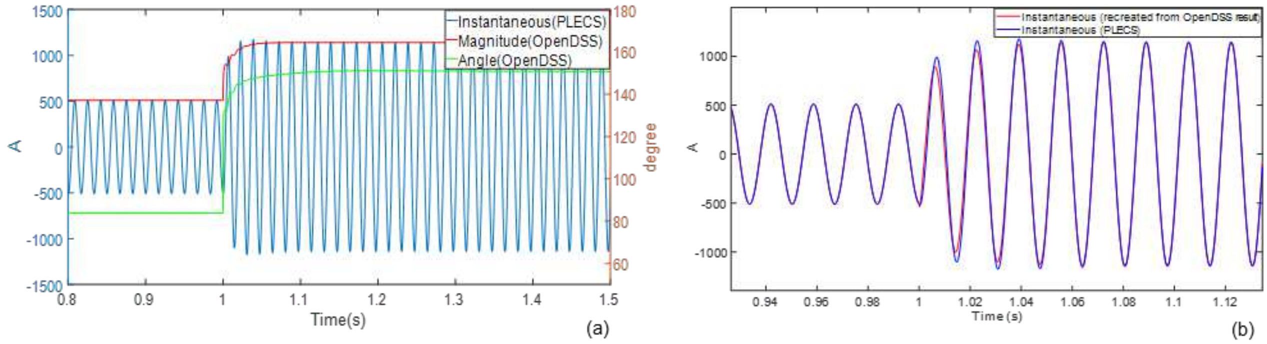
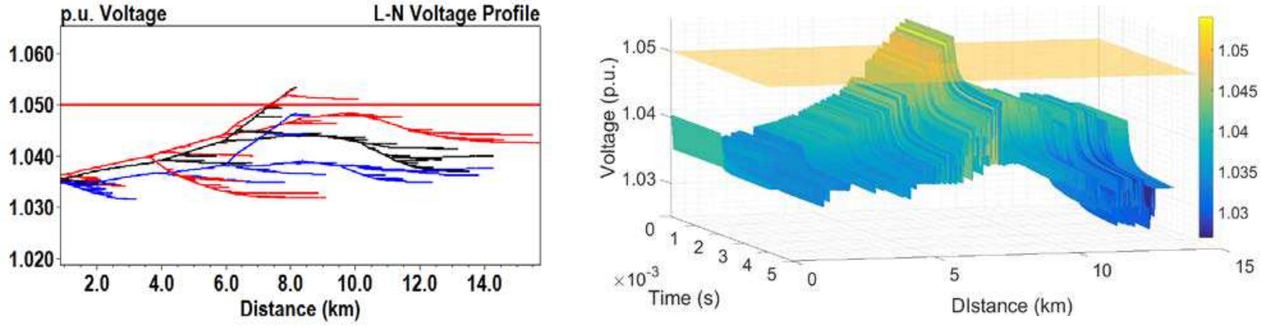


Fig. 8: Comparison of SST current under a step change of the current command: (a) phasor value in OpenDSS vs. point-on-wave value in PLECS (b) point-on-wave value comparison: OpenDSS vs. PLECS

2.2.8 Volt-VAR control implementation in a large real feeder

In another test case, the model of a real feeder located in Flagstaff, AZ is used to test the developed DLL. Two three-phase 700 kW PVs as well as over 100 residential PVs are installed on the feeder, causing a high possibility of over-voltages under the PV impact. Thus, the two three-phase 700 kW PVs are replaced by the SST DLL to test the Volt-VAR control capability of the SST. The steady state voltage profile along the feeder without Volt-VAR control of the two SSTs is given in Fig. 9a. It can be seen that over-voltage happens on certain lines under the impact of PV contribution. Fig. 9b shows the dynamic simulation result of the feeder voltages where the Volt-VAR control of the SSTs is enabled at 2 ms. It shows that the feeder voltages gradually dip after 2 ms, and no over-voltage exists after 2.4 ms.



(a) (b)

Fig. 9: Simulation result of Volt-VAR control of a large feeder: (a) feeder voltage profile without Volt-VAR control at a specific time (snapshot simulation), (b) feeder voltage profile vs. time in dynamic simulation before and after enabling Volt-VAR control

2.2.9 Fault analysis on IEEE 8500-node test feeder

The developed DLL has also been tested with large-scale system. The IEEE 8500-node distribution test feeder is used in the test case. Three SSTs, CIG 1, CIG 2 and CIG 3 are installed along the feeder, at bus M1142843, bus M1069517 and bus M1047522 respectively. The fault current contribution from the converter-interfaced generation (CIG) is limited to 1.5 times of the rated current capacity. The fault current contribution from CIG is highly dependent on the location of the fault and the CIG terminal voltage. The traditional testing results do not reflect the variation in the fault current contribution at different locations in large-scale systems. In this work, using the DAE simulation method, three-phase fault are applied at multiple locations to study the fault contribution. Fig. 10 shows the results corresponding to a fault in the middle of the feeder.

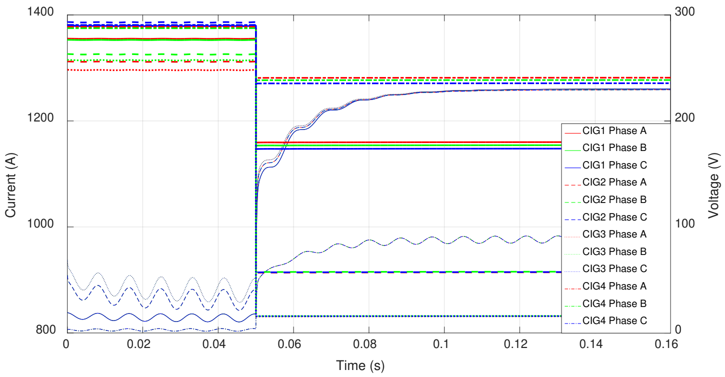


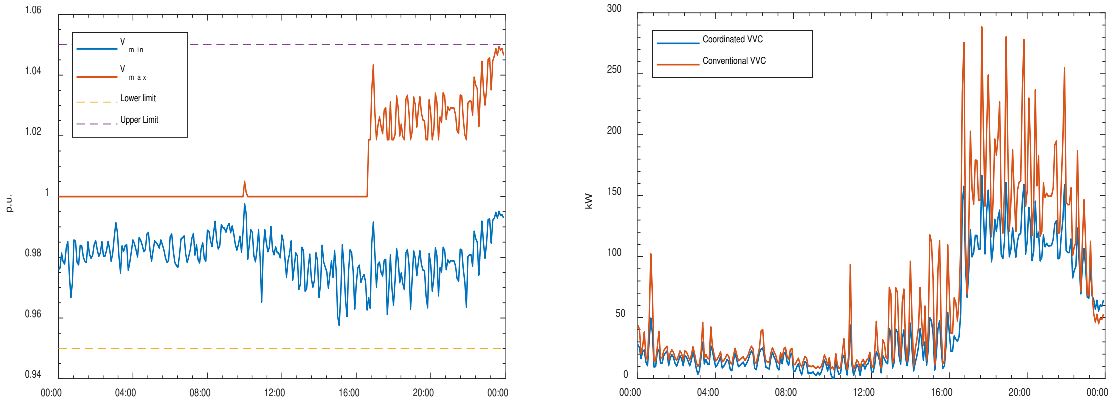
Fig. 10: SST output currents during a three-phase fault in the middle of the IEEE 8500 node test feeder

The developed dynamic simulation methods and models have also been extended real-time simulation. In order to simulate a large-scale microgrid in real-time, the DAE based simulation is used where the microgrid network is solved by the phasor solver ePHASORsim in OPAL-RT, while the components in the energy cell are modeled as a dynamic system which is solved by the EMT solver eMEGAsim in OPAL-RT. A controller-hardware-in-loop (CHIL) simulation has also been set up to test the real-time controls for the local controller. The local controller is implemented on a realistic real-time control platform (EZDSP F28335) to control the simulated SST in the real-time simulator through a customized interface board. The central microgrid controller is being developed as an independent application software which can be run on a remote PC. A Modbus based communication network has been set up for the communication between the microgrid controller and the energy cells being simulated in OPAL-RT. The microgrid controller will also be used to control a real commercial smart inverter which supports the Modbus communication.

2.2.10 Coordinated Volt/VAR Control

The main accomplishment on coordinated VVC involved extension of the VVC scheme for a practical system which employs both the traditional voltage control devices such as voltage regulators (VRs) and the new devices such as SST. In this case, the goal for VVC is to minimize voltage variations while also avoiding the excessive operation of Voltage Regulators (VRs) and Cap Banks, which may occur due to high variability in PV output. To achieve this, we make use of the fact that while the VRs are mainly designed to adjust the voltages, Cap Banks and Smart Inverters are mainly reactive power support devices for power factor correction. These features helps us to decompose the problem into two loops, a slower voltage control loop and a faster VAR compensation loop. The proposed coordinated two-level VVC scheme is computationally efficient, easy for practical implementation, and accommodates the operating constraints.

To test the method, the IEEE 123 node test feeder is used as the LSSS testbed. There are four VRs and 4 Capacitors on the system and we added PVs and SSTs at 20% of locations on the system. The PVs represents 80% of peak load. Simulations results are given here for a heavy load day. For this system, with the conventional control scheme, there are voltage violations during peak load. Figure 11.a confirms that VVO keeps the system voltages always within the range 0.95 – 1.05 p.u.



(a) Voltage profile

(b) system power loss

Fig. 11: Performance of the coordinated VVO method

Fig. 11.b shows the power loss profile under both the proposed method and the conventional VVC during the day. The results indicate that the proposed VVC provides considerable power loss reduction compared to the conventional VVC scheme: the total energy loss during the day in this case is 31.25% lower than that of the conventional VVC scheme. Test results also confirm that while conventional VR control results in excessive VR operations, the proposed coordinated VVC scheme reduces the operation of VRs significantly.

These test results show that the proposed method handles the three operational requirements for VVC effectively: maintaining the node voltages within limits while avoiding excessive device operations, and reducing power losses.

2.2.11 Validation of the Research

Intellectual Property (Licensing and Patents): None

LSSS testbed has been used to benchmark a newly developed system-level Volt-VAR control strategy, the pilot protection approach, a new design methodology for SST system control, and as a simulation tool for the nonlinear system complexity analysis projects. It has contributed to various other thrusts including SST, SMC and DGI, and other testbeds including HIL and GEH, and provided inputs to FREEDM Architecture Working Group. Some of the main outcomes in terms of technical papers and graduated students are described below.

2.2.12 Selected Key Papers (includes papers from core and related associated projects):

D. Shah, M.L. Crow, “Online Volt-VAR Control for Distribution Systems with Solid-State Transformers,” *IEEE Transactions on Power Delivery*, vol. 31, 2016, pp. 343-350

D. Shah, M.L. Crow, “Stability Design Criteria for Distribution Systems with Solid-State Transformers,” *IEEE Transactions on Power Delivery*, vol. 29, 2014.

D. Shah, M.L. Crow, “Stability Assessment Extensions for Single-Phase Distribution Solid-State Transformers,” *IEEE Transactions on Power Delivery*, vol. 30, 2015, pp. 1636-1638.

A. Nagarajan, R. Ayyanar, “Design and Strategy for the Deployment of Energy Storage Systems in a Distribution Feeder with Penetration of Renewable Resources,” *IEEE Transactions on Sustainable Energy*, vol. 6, 2015, pp. 1085-1092. (27 citations in Google Scholar)

Y. Tang, R. Ayyanar, “Methodology of Automated Protection Analysis for Large Distribution Feeders with High Penetration of Photovoltaic Systems,” *IEEE Power and Energy Technology Systems Journal*, vol. 4, 2017, pp. 1-9.

2.2.13 Key Graduate/Graduated Students (includes students of core and related associated projects):

Darshit Shah, (West Texas A&M university); Ziwei Yu (ASU), Tong Yao (Galatech Inc.), Yingying Tang (PNNL), Adarsh Nagarajan (NREL), Yue Shi (ABB)