FREEDM Industry Advisory Board Minutes
March 1, 2018
10:00 am – 11:30 am US eastern

Attendees

Company	Name	Membership Level
ABB	Sandeep Bala	Full
Duke Energy	Kevin Chen	Full
EPRI	Bruce Rogers	Associate
FPL	Jared Hobbs	Associate
Gilbarco	Sravan Narayan	Full
Schneider Electric	John Shea	Associate
Total	Wente Zeng	Full
Weidmann	Giuseppe Gatti	Associate
FREEDM	Ken Dulaney Megan Morin	

The meeting began with attendance and reading the antitrust statement. Sravan is VP of Business Development at Gilbarco and Fortive and introduced his company. Fortive is a mid-sized industrial conglomerate and includes Fluke, Tektronix and Gilbarco. Gilbarco is a large fueling company and is interested in electric vehicle charging to help them meet the challenges facing their industry.

There were several announcements. Final dates for the annual conference are June 6, 7 and 8. The IAB meeting is the afternoon of June 6. FREEDM will also be represented at several upcoming conferences including the IEEE Applied Power Electronics Conference, the Microgrid Global Innovation Summit, and the State Energy Conference for North Carolina. Ken promised to provide an update from his presentation at the Microgrid Summit.

Ken provided an update on recruiting efforts. FREEDM hosted visits from Software Controlled Motors which makes switched reluctance motors, RevoDeve which is a Taiwanese company interested in inverter development and EV charging, and from Trilliant.

Ken shared a few interesting facts from his recent conferences:

- Several FREEDM members attended the PowerAmerica conference. Key takeaway was that many manufacturers are making chips as fast as possible and are capacity constrained. Expect many more SiC devices to hit the market especially in utilities and data centers.

- At the Southeast Clean Power Summit, Ken learned that ConEd in New York uses large batteries on trucks to provide grid stability services at certain locations to offset infrastructure expenses in the short term. Kevin Chen noted that he worked on this project when he was with ConEd. The point is that the flexibility of storage has real economic value to utilities.
- The Southern Cross is a high voltage DC connection planned to link ERCOT to somewhere in the Southeast US. (Here is a link to the project website.) The goal is to move excess wind power from Texas to Mississippi.
- Customer surveys show high demand for renewable energy and utilities are responding. As an example, Xcel Energy plans to add 1500 MW of wind within the next 5 years.

Dr. Raja Ayyanar from Arizona State University presented his research on “Dynamic Simulation of Grid-connected Converters in Large-Scale Distribution Systems using OpenDSS.” His work has helped refine issues with modeling large numbers of PV inverters and SSTs on the grid. OpenDSS is open source software available from EPRI and is a convenient platform for this type of analysis. Dr. Ayyanar uses a hybrid solution approach leveraging the strengths of full transient simulation with a quicker solution technique of differential equations. Model dynamics are confirmed by comparison to PLECS simulations of known power converters. The model is then used for 3 standard test cases: Fault in IEEE 8500 node test feeder, Islanded mode control in IEEE 123 node feeder, Voltage control on model of an actual feeder with high PV penetration in Flagstaff. Dr. Ayyanar also presented some of his work on real time simulation for microgrid controller development. His setup integrates OPAL RT with SST models on the IEEE 123 node model. There was one question regarding fault simulation results and system stability. Raja noted his research was mainly to validate the model, but it could be used to evaluate various fault conditions and generation mixes.

We concluded the meeting with a discussion of the Annual Conference agenda. Ken emphasized that industry members will be asked to make some presentations at the conference. He shared the draft agenda and asked for feedback. There was a question about offering a workshop. Ken explained the Center plans to host a workshop later in the fall. There was also a suggestion to address the technical implementations of the FREEDM System through a roadmap process.

The call concluded at 11:10. Note that we will not meet in March. The next meeting is May 3.

Actions

1. Ken will share his presentation from the Microgrid Summit.

Appendix A
Presentation from Dr. Raja Ayyanar

Dynamic Simulation of Grid-Connected Converters in Large-scale Distribution Systems Using OpenDSS

Raja Ayyanar
School of Electrical, Computer and Energy Engineering
Arizona State University

March 1, 2018

FREEDM SYSTEMS CENTER

ASU IRA A. FULTON SCHOOLS OF engineering ARIZONA STATE UNIVERSITY

OpenDSS

- OpenDSS is an open source distribution system analysis tool which can runs various types of simulation for large-scale unbalanced systems
- It has the capability of modeling n-phase lines and transformers in any configurations
- OpenDSS provides the platform to run DAE based dynamic simulation on large-scale systems with the dynamic model of specific components such as SST, PV and storage converters implemented in dynamic linked libraries (DLL)

EMT-TS hybrid simulations

Electromagnetic-transient (EMT) simulation

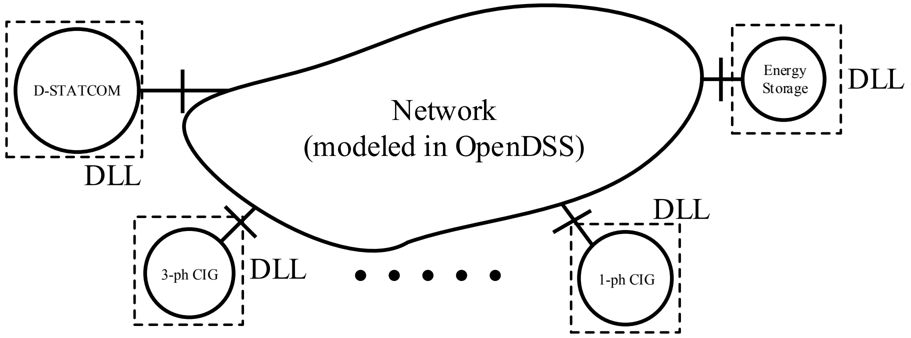
- Represented with instantaneous value of the variables (natural waveforms)
- Need to solve the state-space model representing the dynamics in the system
- Computationally intensive, suitable for simulating small systems

Phasor simulation

- Represented with magnitude and phase angle of fundamental frequency components
- Results can be solved by running power-flow program
- Suitable for simulating large-scale transmission/distribution systems

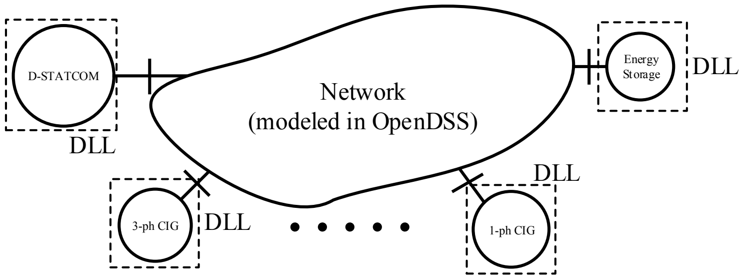
Hybrid (DAE) EMT-TS approach

- Network model is represented as algebraic equations (similar to power flow) and the converters are modeled by differential equations (EMT simulation)
- Dynamic model can be developed for user-defined components such as SST by using dynamic link library (DLL)



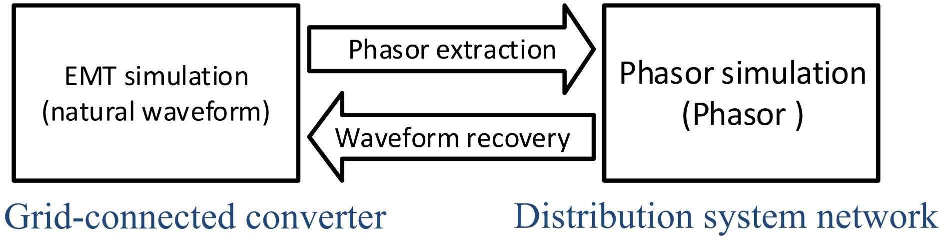
Dynamic simulation using DLL in OpenDSS

EMT-TS hybrid simulation in distribution systems

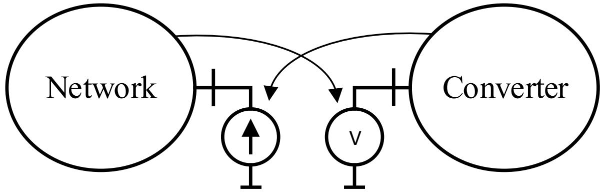


Challenge of dynamic simulation for distribution systems

- Network can be unbalanced
- Simulating single-phase dynamic systems such as single-phase inverter



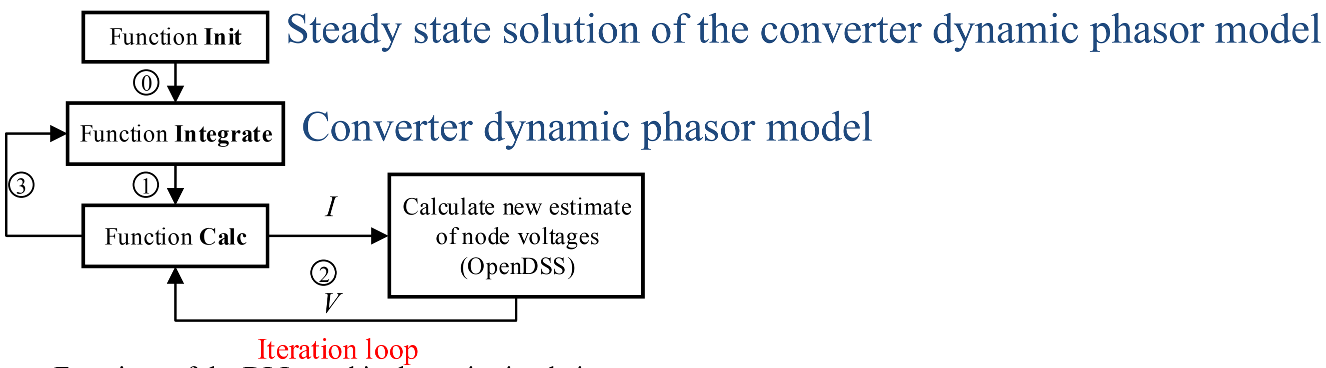
- In DAE based simulations, the dynamic model calculates the current injection to the corresponding node while the node voltage is given by the network solution.



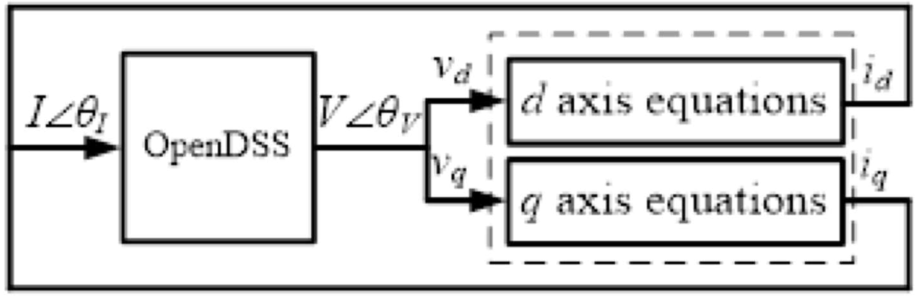
Representation of EMT and phasor systems in hybrid simulation

Dynamic modeling and simulation

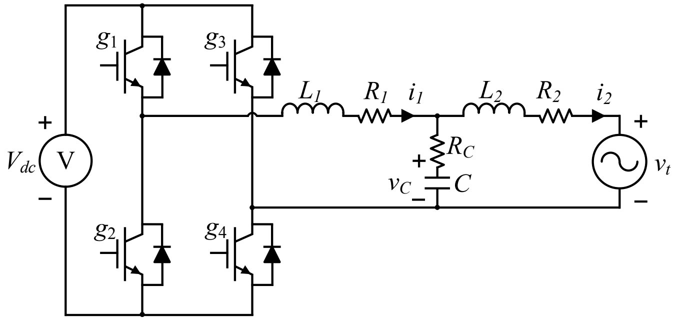
- Dynamic model can be developed for user-defined components such as SST by using DLL
- Both input and output of the dynamic model have to be phasors to be interfaced to the network model in OpenDSS
- Dynamic phasor represents the system response with time-varying Fourier coefficients
- The analytical model including algebraic and differential equations are derived for both power stage and closed-loop controls
- Three-phase instead of positive-sequence equations are used for three-phase component in order to include the unbalance effect.



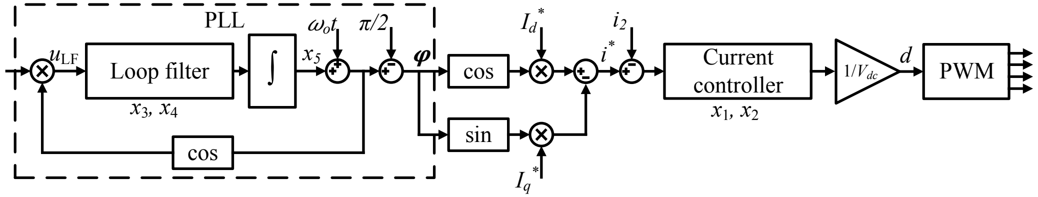
Functions of the DLL used in dynamic simulation



Dynamic phasor model of a single-phase grid connected converter



Power stage circuit



Converter controller

Power stage equations

$$\frac{d\bar{i}_1}{dt} = -j\omega_o \bar{i}_1 - \frac{R_C + R_1}{L_1}\bar{i}_1 + \frac{R_C}{L_1}\bar{i}_2 - \frac{1}{L_1}\bar{v}_C + \frac{1}{L_1}\bar{e}$$

$$\frac{d\bar{i}_2}{dt} = -j\omega_o \bar{i}_2 - \frac{R_C + R_2}{L_2}\bar{i}_2 + \frac{R_C}{L_2}\bar{i}_1 + \frac{1}{L_1}\bar{v}_C - \frac{1}{L_1}\bar{v}_t$$

$$\frac{d\bar{v}_C}{dt} = -j\omega_o \bar{v}_C + \frac{1}{C}\bar{i}_1 - \frac{1}{C}\bar{i}_2$$

Current controller equations

$$\frac{d\bar{x}_1}{dt} = -j\omega_o \bar{x}_1 - 0.6\bar{x}_1 - 277.6\bar{x}_2 + \bar{i}^* - \bar{i}_2 \qquad \frac{d\bar{x}_2}{dt} = -j\omega_o \bar{x}_2 + 512\bar{x}_1$$

$$\bar{d} = \left(K_R \bar{x}_1 + K_P\left(\bar{i}^* - \bar{i}_2\right)\right)/V_{dc} \qquad \bar{e} = V_{dc}\bar{d} = K_R \bar{x}_1 + K_P\left(\bar{i}^* - \bar{i}_2\right)$$

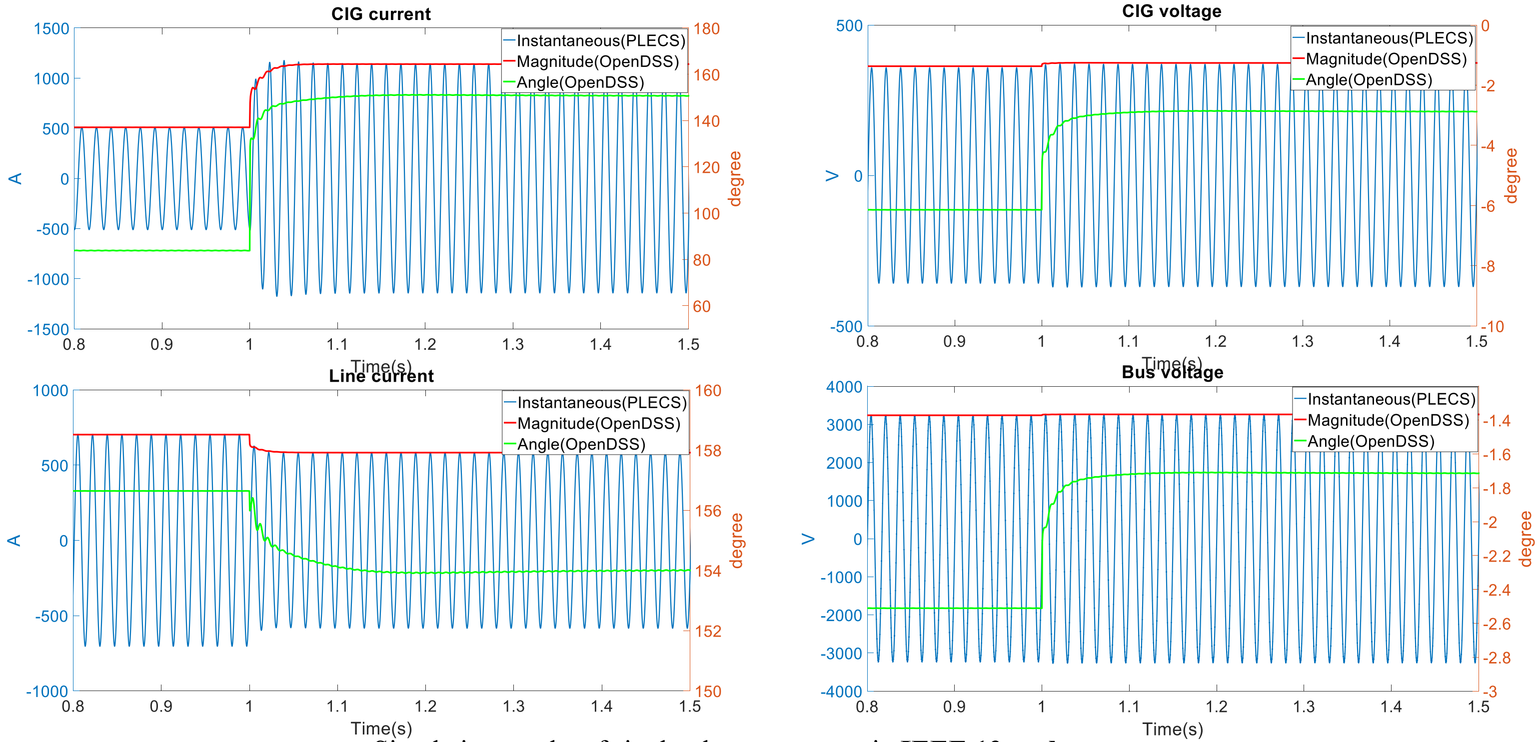
PLL equations

$$\begin{bmatrix} \dot{x}_3 \\ \dot{x}_4 \\ \dot{x}_5 \end{bmatrix} = \begin{bmatrix} -46.9 & 0 & 0 \\ 1 & 0 & 0 \\ 2.357 & 7.938 & 0 \end{bmatrix} \begin{bmatrix} x_3 \\ x_4 \\ x_5 \end{bmatrix} + \begin{bmatrix} 2u_{LF} \\ 0 \\ 0 \end{bmatrix}$$

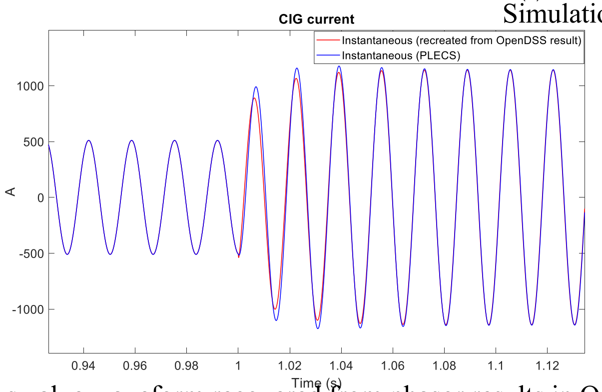
$$\bar{i}^* = \left(i^* + j\mathrm{H}(i^*)\right)e^{-j\omega_o t}$$
$$= I_d^* \cos(x_5) - I_q^* \sin(x_5) + j\left(I_d^* \sin(x_5) + I_q^* \cos(x_5)\right)$$

$$u_{LF} = v_t \cos(x_5 + \omega_o t)$$
$$= \left(\mathrm{Re}(\bar{v}_t)\cos(\omega_o t) - \mathrm{Im}(\bar{v}_t)\sin(\omega_o t)\right)\cos(x_5 + \omega_o t)$$
$$= \frac{\mathrm{Im}(\bar{v}_t)\cos(x_5) - \mathrm{Re}(\bar{v}_t)\sin(x_5)}{2} \cdots$$
$$- \frac{\mathrm{Im}(\bar{v}_t)\cos(x_5 + 2\omega_o t) + \mathrm{Re}(\bar{v}_t)\sin(x_5 + 2\omega_o t)}{2}$$
$$\approx \frac{\mathrm{Im}(\bar{v}_t)\cos(x_5) - \mathrm{Re}(\bar{v}_t)\sin(x_5)}{2}$$

Comparison between OpenDSS and PLECS simulations on a simple system



Simulation results of single-phase converter in **IEEE 13-node** test system



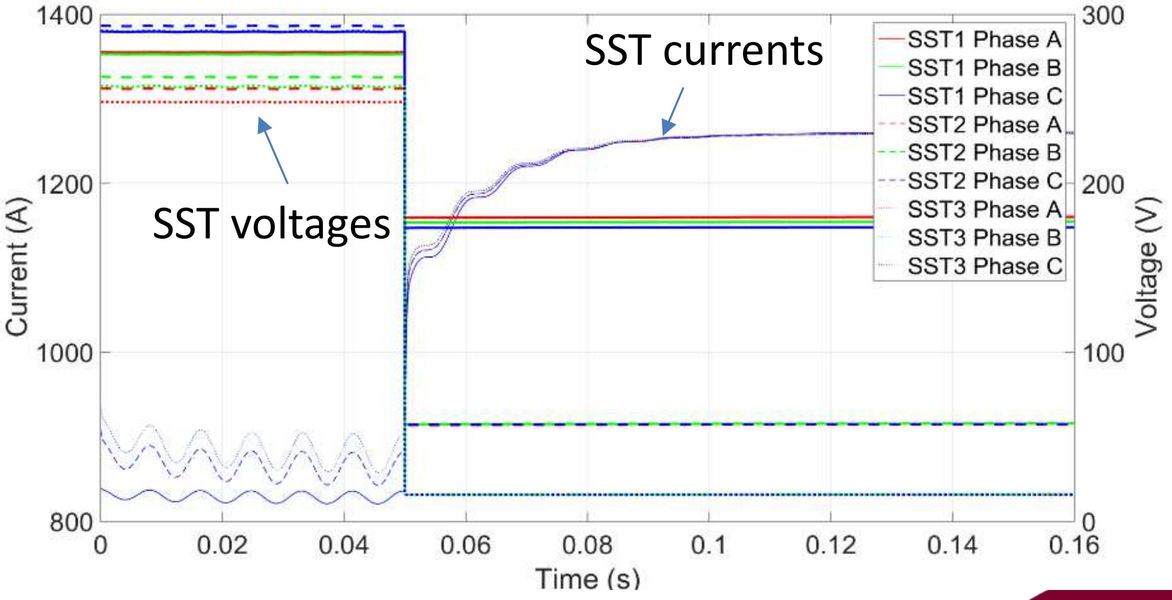
Instantaneous value waveform recovered from phasor results in OpenDSS

Simulation time comparison

CPU model: Intel Core i7-6700 @ 3.4 GHz	
Length of the simulation: 2 s	
Simulation time-step size: 5 us	
Simulation time	
Dynamic simulation by OpenDSS	EMT simulation by PLECS
28 s	67 s

Fault analysis in IEEE 8500 node test feeder

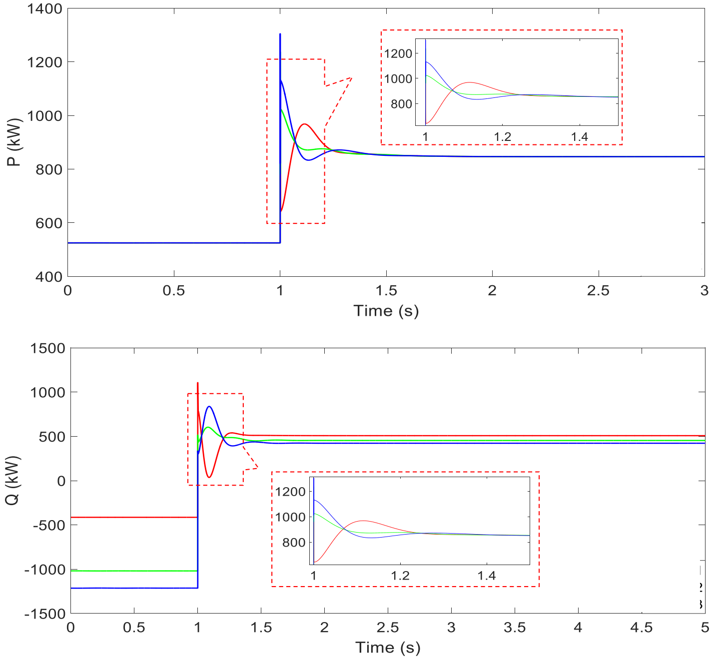
- The developed DLL has been tested in the IEEE 8500 node distribution test feeder
- Three SSTs rated at 700 kW are installed along the feeder at bus M1142843, M1069517 and M1047522 respectively. A three-phase fault is applied in the middle of the feeder
- The SST fault current contribution is limited to 1.5 times of the rated current by the current controller



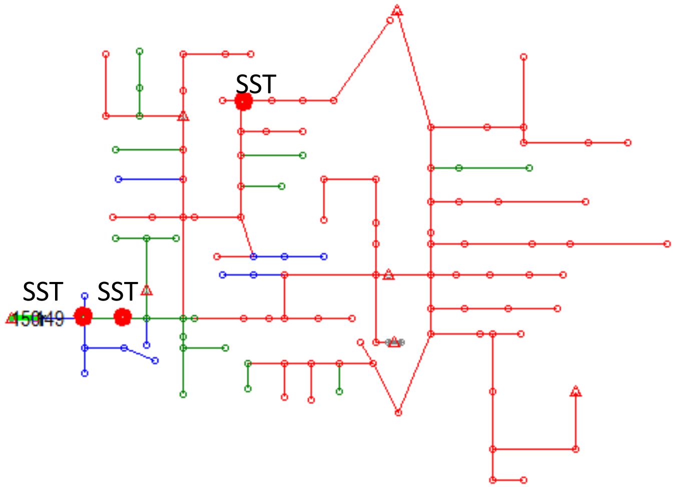
Islanded mode control in IEEE 123 node test feeder

- DLL of SST model with islanded mode control is developed for IEEE 123 node distribution test feeder
- Three SSTs connected to the system at bus 1, 7 and 47
- The breaker near the substation is opened to form an islanded system.
- The lost generation is picked up by the SSTs. Since the same droop settings are used for all of the three SSTs, the total active power is shared equally among them. The reactive power outputs are different due to different impedance seen by each SST.

Active and reactive power of SSTs, system is islanded at 1s



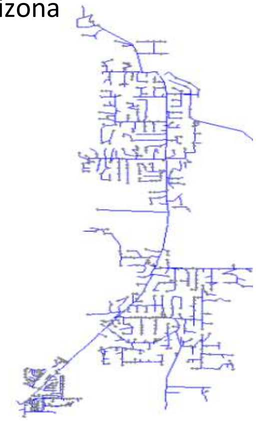
IEEE 123 node distribution test feeder



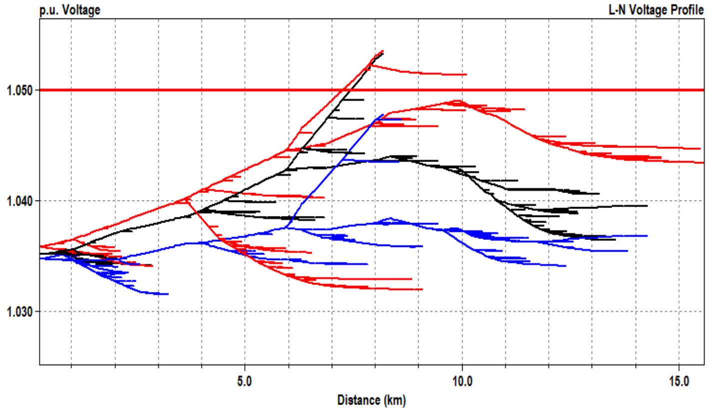
Voltage control on a model of actual distribution feeder

- DLL of PV inverter model with voltage control is developed and tested in a real distribution feeder in Arizona.
- Two three-phase 700 kW PVs as well as over 100 residential PVs are modeled in the system by using the developed DLL.

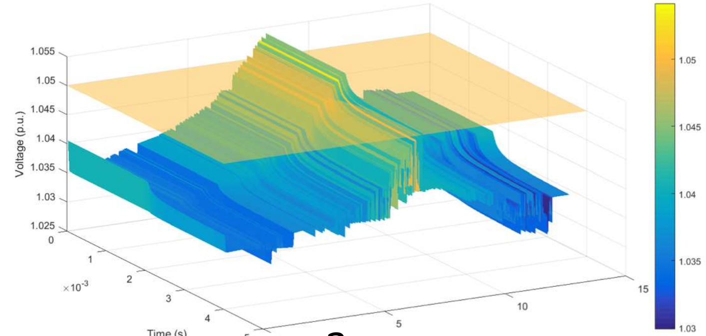
Model of a real distribution feeder in Arizona



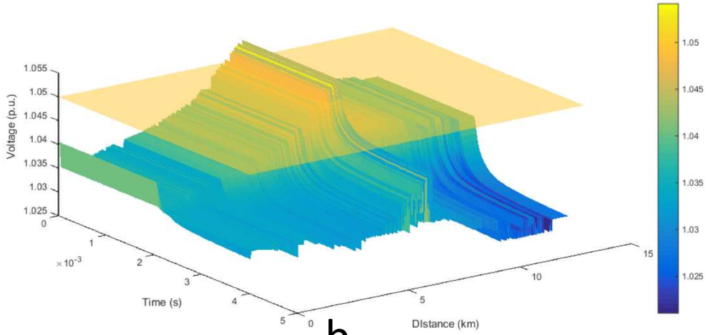
Snap shot result of voltage along the feeder overvoltage is seen due to PV generation



Dynamic simulation result of overvoltage mitigation control 1
All of the inverters are switched from unity power factor to a power factor of **a) 0.98 b) 0.9** at 2ms

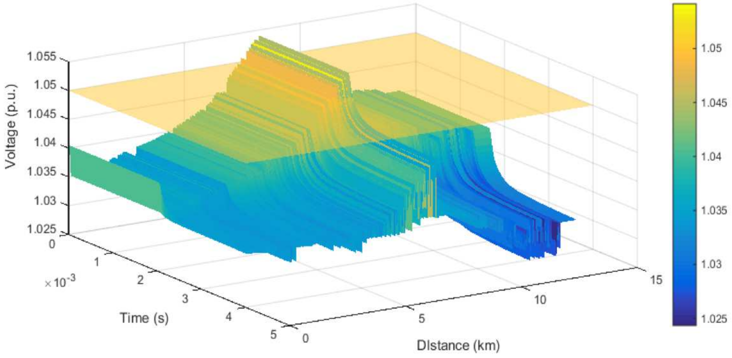


a



b

Dynamic simulation result of overvoltage mitigation control 2
All of the inverters are enabled with volt-VAr function at 2ms

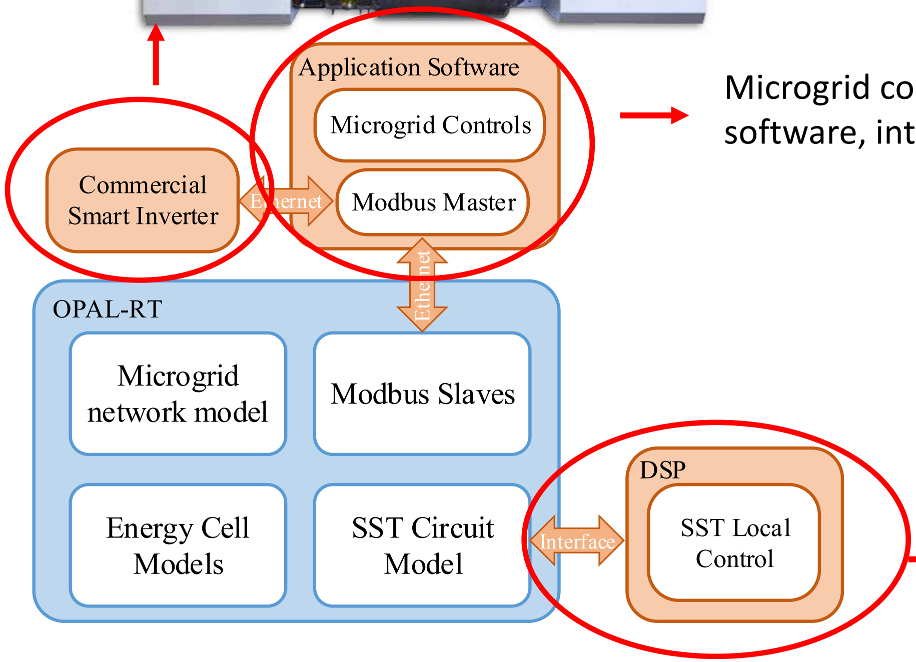


Real-time simulation test bed under development

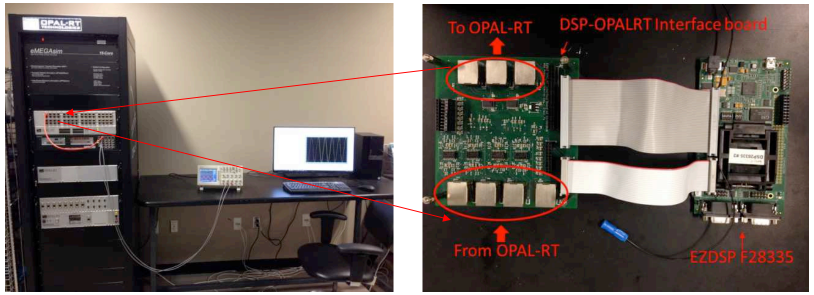
- Multi-platform simulation used to test the controllers, devices as well as the communication network outside of the simulator

Multi-platform simulation

Mircrogrid controller communicates with real commercial inverters which support Modbus communication



Microgrid controller running in an independent application software, integrated with Modbus master program

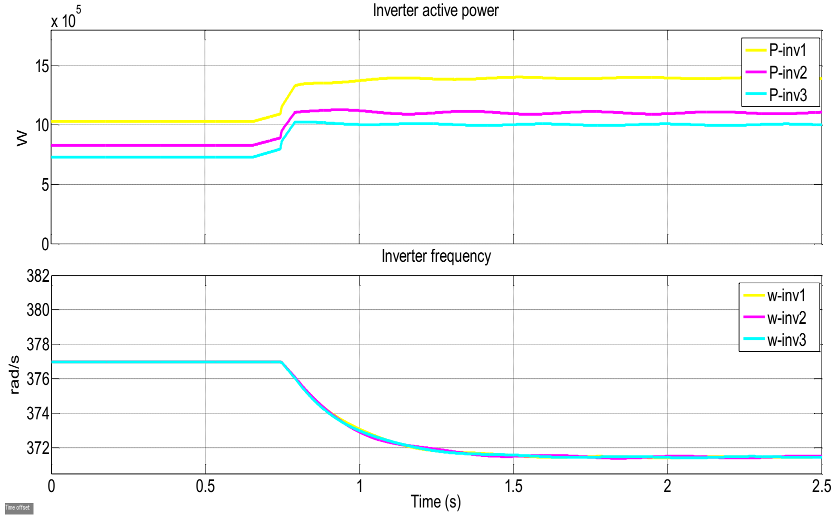


Controller-hardware-in-loop (CHIL) simulation by implementing the VSG control in realistic digital controller

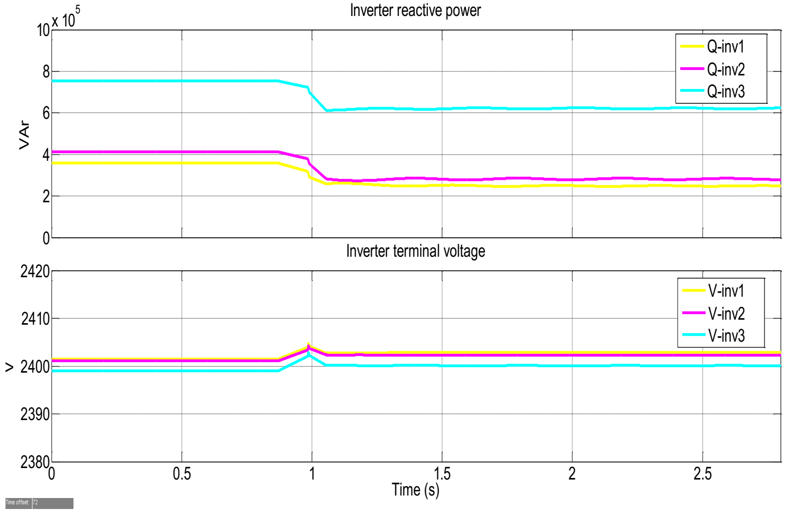
Preliminary results from real-time simulation

- IEEE 123 bus test feeder and three energy cells interfaced with the feeder through SST have been modeled in OPAL-RT
- The energy cells being simulated can be controlled on a remote PC through a Modbus based communication network
- The SST controller which can operate in islanded mode is modeled

Real-time simulation result of SSTs with islanded mode control in IEEE 123 bus test feeder



P-f before and after the disconnection of the main grid



Q-V before and after the disconnection of the main grid

Thank You !