Y9.LSSS.2 Dynamic Simulation and Analysis of FREEDM Systems on Large Scale Test Feeders Using OpenDSS

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1. **Project Goals**
   - Develop hybrid, differential-algebraic-equations (DAE) based simulation methods using OpenDSS, which enable simulation of very large-scale power systems with large number of power electronic converters.
   - Develop models (DLL) in OpenDSS for the main FREEDM components - SST, DESD and DRER including the main controllers and IEM and IPM.
   - Simulate and analyze FREEDM system performance and stability when scaled to large scale feeders with thousands of nodes.

2. **Role in Support of Strategic Plan**
   This tasks supports the validation of different concepts developed in FREEDM through dynamic simulation on large scale feeders using open source tools such as OpenDSS. This can be used to study the scalability and system level issues.

3. **Fundamental Research, Technological Barriers and Methodologies**
   - Derive analytical model of FREEDM components – SST, DESD and DRER including the main controllers and IEM and IPM, and represent in appropriate differential and algebraic equations.
   - Identify time constants of various dynamics in the full-order models, develop reduced-order models suitable for large-scale power system simulations.
   - Develop user-defined dynamic models for the corresponding FREEDM components in OpenDSS by using Dynamic Linked Libraries (DLLs).
   - Interface the dynamic models with the network powerflow solver by using single-phase *dq* frame modeling method.
   - Validate developed DLLs through comparison with detailed PLECS model in small systems. Perform dynamic simulation for large-scale systems with developed DLLs in OpenDSS.
   - Use the above hybrid method for dynamic simulations involving fault current analysis, microgrid operation with droop control, and anti-islanding tests on the large distribution system.
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4. **Achievements**

Detailed analytical model based on Gen-II SST

A detailed and accurate analytical model has been developed based on the actual Gen-II SST hardware setup and DSP controls. The physics-based equations including differential and algebraic equations have been derived based on the average model of the power stage circuit and continuous domain representation of the DSP controls. The final state-space model of the system contains 34 states and nonlinearities brought by multiplications of states and trigonometric functions. The derived state-space model is validated through time domain simulation in Simulink/MATLAB. The derived equations are used to build S-function blocks to calculate the derivative of the states under each integration step. The simulation results are then compared with a switching model of the SST with discrete controls to validate the correctness of the derived equations. To interact with the power flow solver in DAE based dynamic simulations, the SST equations are

transformed into synchronous frame. As shown in Fig. 1, a modeling method based on the single-phase dq transformation is proposed to deal with unbalanced systems and single-phase systems.
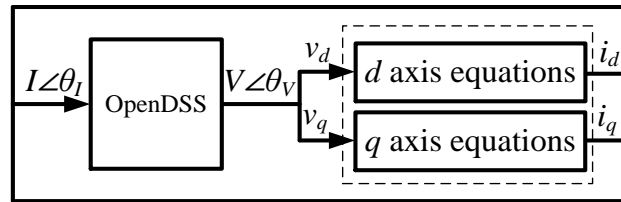

Fig. 1 Single-phase *dq* frame model for dynamic simulation in OpenDSS

Implementation of user-defined model for SSTs for dynamic study in OpenDSS
In order to extend the capability of OpenDSS that only performs snapshot analysis and quasi-static, time series analysis, Embarcadero Delphi is used to develop the Dynamic Linked Library (DLL) of user-defined model for dynamic studies. Based on the definition of dynamic phasor model, the equations of the target component, including both power stage circuit and controller equations are derived for developing the code of the DLL. Fig. 2 shows the hybrid differential-algebraic-equations (DAE) based dynamic simulation function in OpenDSS. Power flow is solved for the network in OpenDSS so that the SST terminal voltage can be provided. DLL does the calculation for the SST dynamic model based on the updated terminal voltage; the SST terminal current is provided as an output of the DLL. Fixed step (improved Euler-Cauchy method) solver is used for the DAE based simulation; the time step size is determined by the user. Each SST is modeled in its own reference frame, reference frame transformation is used to pass the value between OpenDSS powerflow solution and SST model output. Fig. 3 shows an illustration of the interactions between the user-defined model DLL and the network model during dynamic simulation.
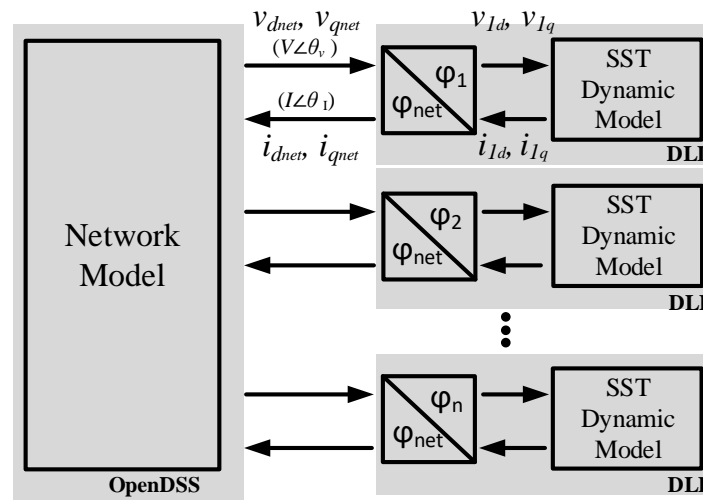

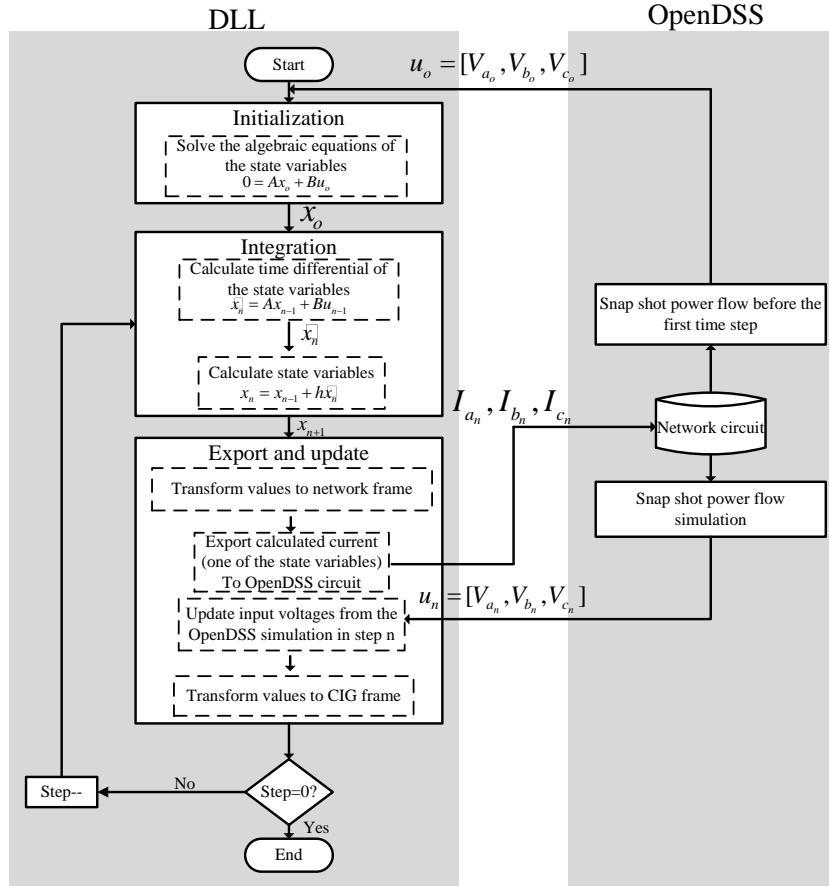**Fig. 2 OpenDSS hybrid dynamic simulation by using DLL**

Fig. 3 Algorithm of interaction between the DLL and OpenDSS during dynamic simulations

The flowchart contains the following labels:

DLL | OpenDSS

Start

$u_o = [V_{a_o}, V_{b_o}, V_{c_o}]$

Initialization
Solve the algebraic equations of the state variables
$0 = Ax_o + Bu_o$

x_o

Integration
Calculate time differential of the state variables
$\dot{x_n} = Ax_{n-1} + Bu_{n-1}$

$\dot{x_n}$

Calculate state variables
$x_n = x_{n-1} + h\dot{x_n}$

x_{n+1}

Export and update
Transform values to network frame

Export calculated current (one of the state variables) To OpenDSS circuit

Update input voltages from the OpenDSS simulation in step n

Transform values to CIG frame

Step=0?

No — Step--

Yes

End

$I_{a_n}, I_{b_n}, I_{c_n}$

$u_n = [V_{a_n}, V_{b_n}, V_{c_n}]$

Snap shot power flow before the first time step

Network circuit

Snap shot power flow simulation

Model verification by comparison with detailed PLCES simulation

The DLL of the rectifier stage of a three-phase SST has been created and verified with PLECS results in a three-bus system shown as Fig. 4. A single-phase fault is applied to phase A of the transformer primary side. Fig. 5 shows instantaneous currents from the inverter models in OpenDSS simulation, as well as those obtained from the detailed simulation in PLECS. The inverter output current obtained from the OpenDSS hybrid dynamic simulation overlaps those obtained via detailed simulation in PLECS. When showing as phasors, the magnitude of distorted sine wave has high frequency oscillation on top of the average value. In contrast, the output current waveforms are markedly different from the PLECS output when a traditional positive-sequence inverter model is used in OpenDSS, due to its requirement of balanced condition assumption. In terms of simulation execution time, the PLECS simulation requires approximately 3 s while the OpenDSS simulations by using DLL requires less than 0.5 s. It may be noted that PLECS simulations are not practical for systems much larger than the simple system shown in Fig. 4.
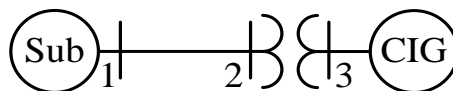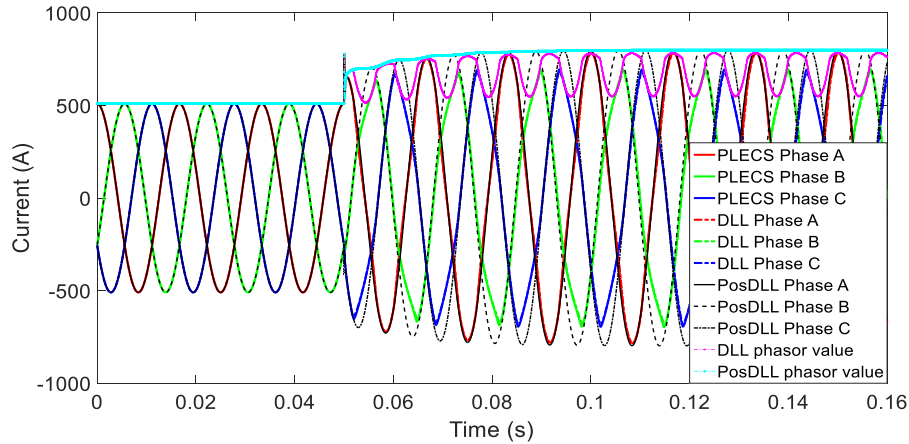

Fig. 4 Three-bus system for DLL model verification (CIG: Converter interfaced generator)

Fig. 5 Simulated SST output current for a single-phase fault in PLECS, DLL, and positive sequence DLL

Large-scale test case: fault analysis on IEEE 8500-node test feeder
The developed DLL has also been tested with a large-scale system. The IEEE 8500-node distribution test feeder [1] 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 power rating of the SSTs is set to 700 kW. The fault current contribution from the CIG is limited to 1.5 times of the rated current capacity. Traditionally, the fault current contribution from the CIGs is obtained by applying a fault at the CIG terminal and measuring the output current either through a simplified hardware testing or by simulation using EMTP solvers. However, 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. Three-phase faults are applied at two different locations to study the impact. As an example, the simulation results corresponding to a three-phase fault in the middle of the feeder are shown in Fig. 6.
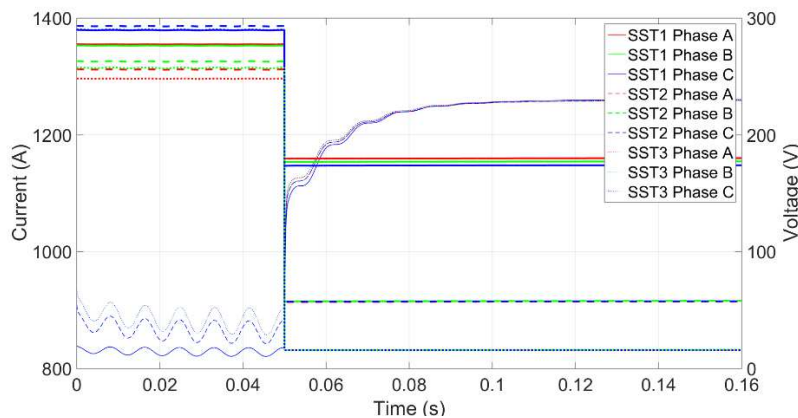

Fig. 6 SST voltage and current during a three-phase fault in the middle of the IEEE 8500 node test feeder

Large-scale test case: *Volt-Var* control on Flagstaff feeder model
In another test case, the model of a real feeder [2] with more than 900 transformers 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. The two three-phase 700 kW PVs are replaced by the SST DLL to test the Volt-VAr control capability of the SST. Fig. 7 shows the dynamic simulation result of the feeder voltages where the Volt-VAr control of the SSTs is enabled at 2 ms. It shows

over voltage conditions prior to 2 ms, and Volt-VAR control gradually bringing down the feeder over-voltage, such that no over-voltage condition exists after 2.4 ms.
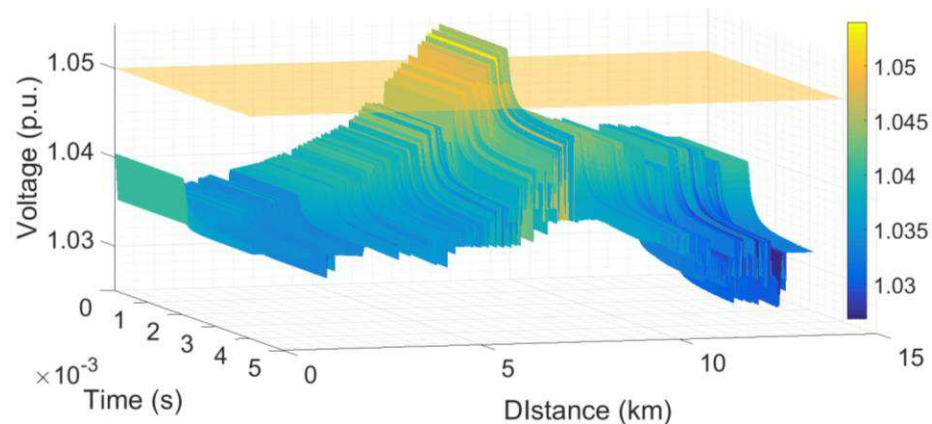
Fig. 7 Voltage profile in dynamic simulation before and after *Volt-VAr* is enabled

Large-scale test case: microgrid operation on IEEE 123-bus test feeder
The IEEE 123-bus system has also been used to test the microgrid mode controls of the SST using the proposed hybrid simulation method. SST DLL with both P/f droop and Volt-VAr controllers is used in this test case. Three SSTs are connected to the system at bus1, bus7 and bus 47 respectively, which are shown to share the total load based on the selected droop coefficients and power ratings.

5. Other Relevant Work Being Conducted Within and Outside of the ERC
Several studies on large distribution systems with high penetration of PVs rely on extensive time-series quasi-static approaches. For dynamic simulations typically only small systems and highly reduced order models of the network are used. Hybrid DAE based methods have been employed in integrated study of transmission and distribution systems.

6. Milestones and Deliverables
9/30/16 – Finalization of SST models and specific IEM and volt-VAR functions to be modeled in OpenDSS
12/31/2016 – Development of DLLs for FREEDM components and validation against switching model simulations on simple (3-SST) systems and with available HIL results
3/31/2017– IEM and volt-VAR algorithms demonstrated on very large scale test feeder
6/30/2017 – Simulation of main use cases including extensive islanded microgrid operation completed

7. Plans for Next Five Years
The plans for future work include further refining the models (DLLs) and IPM/IEM algorithms based on the continuous development of these in other thrusts in the center especially in GEH. Another direction for future work is to adapt the models and hybrid methods developed here for implementation in the real-time simulators such as Opal-RT which is available at ASU.

8. Member Company Benefits
No member companies are directly related to this project.

9. References

[1] IEEE PES Distribution System Analysis Subcommittee, Distribution Test Feeders, 2013, available at: http://ewh.ieee.org/soc/pes/dsacom/testfeeders/index.html

[2] Y. Tang, X. Mao and R. Ayyanar, "Distribution system modeling using CYMDIST for study of high penetration of distributed solar photovoltaics," North American Power Symposium (NAPS), 2012, Champaign, IL, 2012, pp. 1-6.