Smart Inverter Experiences in Southern California Edison (SCE)

APEC Industry Sessions

Md Arifujjaman, Ph.D., P.Eng.

Grid Technology Innovation
Southern California Edison

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Outline

- ❑ Introduction
- ❑ Modeling and HIL Testbed Description
- ❑ Preliminary Results and Discussions
- ❑ Concluding Remarks

Introduction

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SCE Activities and Need

- ❑ The Distributed Energy Resource (DER) technologies are emerging as one of the most prominent solutions for Southern California Edison (SCE) to augment California's Green House Gas (GHG) reduction goals.

- ❑ The adoption of such technologies in the existing grid is also encouraged by the California Public Utilities Commission (CPUC) through numerous avenues. Such as the Electric Program Investment Charge (EPIC) program.

- ❑ Rule 21 compliant Smart Inverter (SI), which is a mandatory requirement for the interconnection of inverter-based DER technologies.

- ❑ The installed Legacy Inverters (LIs) are capable of performing certain functions, but in sharp contrast, SIs offer unique and advanced control capabilities when integrated with DER technology.

Inverter Integrated Application at SCE

Field Evaluation of Solar PV

- SCE installed power quality monitors on solar PV plants to capture the performance

Utility Charging Program

- Demonstrated to industry critical elements of program
- Developed first implementation of energy management system

Smart Inverter Assessment

- Testing of smart solar inverters verified grid support functions needed for higher DER penetration
- Supported California Rule 21, UL 1741SA, IEEE 1547A, and IEEE 1547-2018

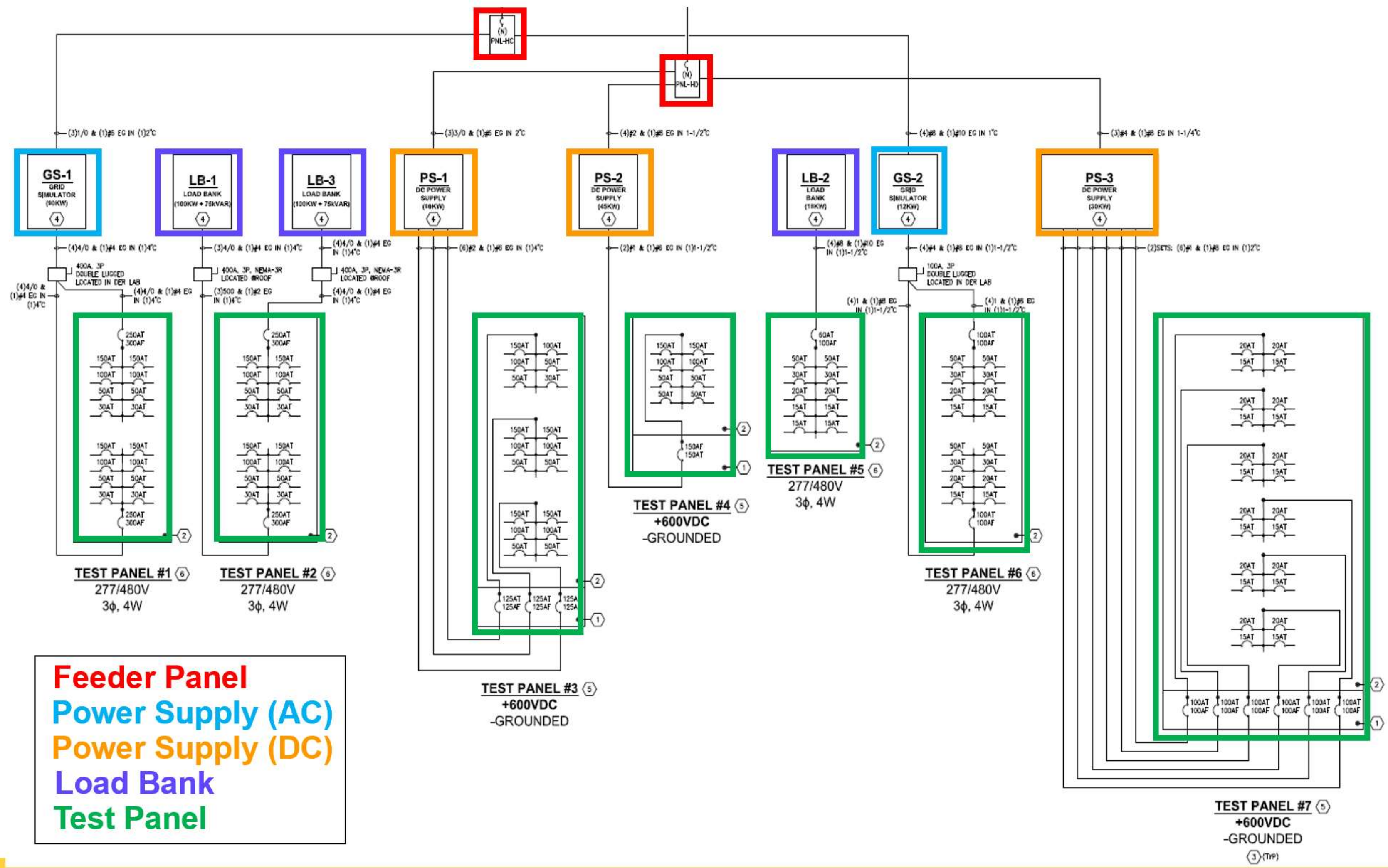
Energy Storage Construction

- Large scale grid-connected storage system participating in the wholesale market
- Know-how to deploy a storage system in six months

DER Laboratory Equipment

- Hardware-In-Loop (HIL) Test Bed
- Smart Inverters
- AC Power Supplies ~ Grid Simulators
  - 90 kVA
  - 12 kVA
- DC Power Supplies ~ PV Simulators
  - 90 kW
  - 60 kW
- Electronic Load Bank
  - 18 kW
- Roof Load Banks
  - Delta: 100kW / 75kVAR
  - Wye: 105kW / 78.75kVAR
- Data Acquisition Racks
- Short Circuit Test Box

DER Lab Wiring Diagram



Power Electronics Research at SCE

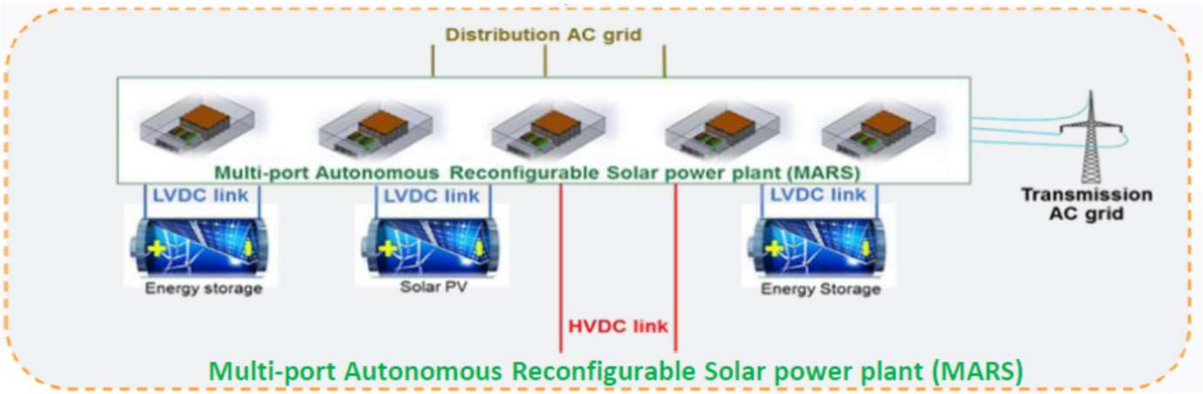
- ❑ Develop mathematical models for a smart inverter based DER system

- ❑ An organizational, vendor-agnostic HIL testbed to enhance the ease of integrating DER into the SCE grid.

- ❑ Advancing the use of inverter-based DERs dynamics integration by modeling the system based on impedance is an essence for SCE's future success.

Rule 21 advanced inverter functions include:

- Volt/VAr support
- Volt/Watt support
- Frequency/Watt support
- Fixed power factor
- Voltage ride-through
- Frequency ride-through
- Soft start



Collaboration with Oak Ridge National Laboratory to develop integrated power electronics to interface utility-scale solar power, energy storage, dc, and ac systems with grid services.

Modeling and HIL Testbed

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Use Case #1 - PV-based Power Circuit Structure

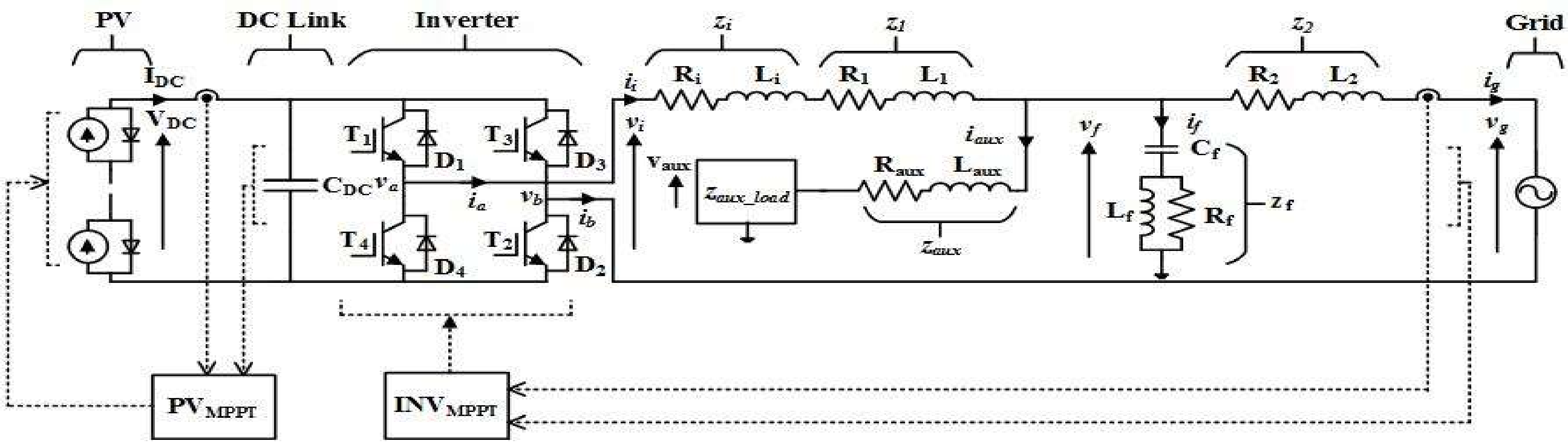

Fig. 1 Basic power circuit for an inverter-based PV system

- ❑ Photovoltaic (PV) is connected to an inverter before integrating it to the LV grid
- ❑ The inverter is connected to the grid through a filter
- ❑ Various line impedances are integrated to reflect the actual field condition

Use Case #1 - Modelling: PV and Inverter

- PV array current can be expressed as $$I_{DC1} = I_{SC} \times \left[1 - C_1 \times \left(\exp\left(\frac{V_{DC1}}{C_2 \times V_{OC}}\right) - 1\right)\right] \times \frac{G_{ref}}{G_m}$$

where, $$C_1 = \left(1 - \frac{I_m}{I_{SC}}\right) \times \exp\left(\frac{-V_m}{C_2 \times V_{OC}}\right) \qquad C_2 = \frac{\frac{V_m}{V_{OC}} - 1}{\ln\left(1 - \frac{I_m}{I_{SC}}\right)}$$

- The PV array power production is calculated as $P_{DC1} = V_{DC1} \times I_{DC1}$

- The inverter equivalent impedance can be expressed as $$z_p = \frac{1}{\frac{1}{z_{aux} + z_{aux\_load}} + \frac{1}{z_f} + \frac{1}{z_1 + z_i + z_{DC}}}$$

- The rated power of the inverter can be written as $$P_i \cong \frac{1}{n} \sum_n V_{ab} I_a$$

Use Case #1 - Proposed HIL Testbed in DER Laboratory, SCE

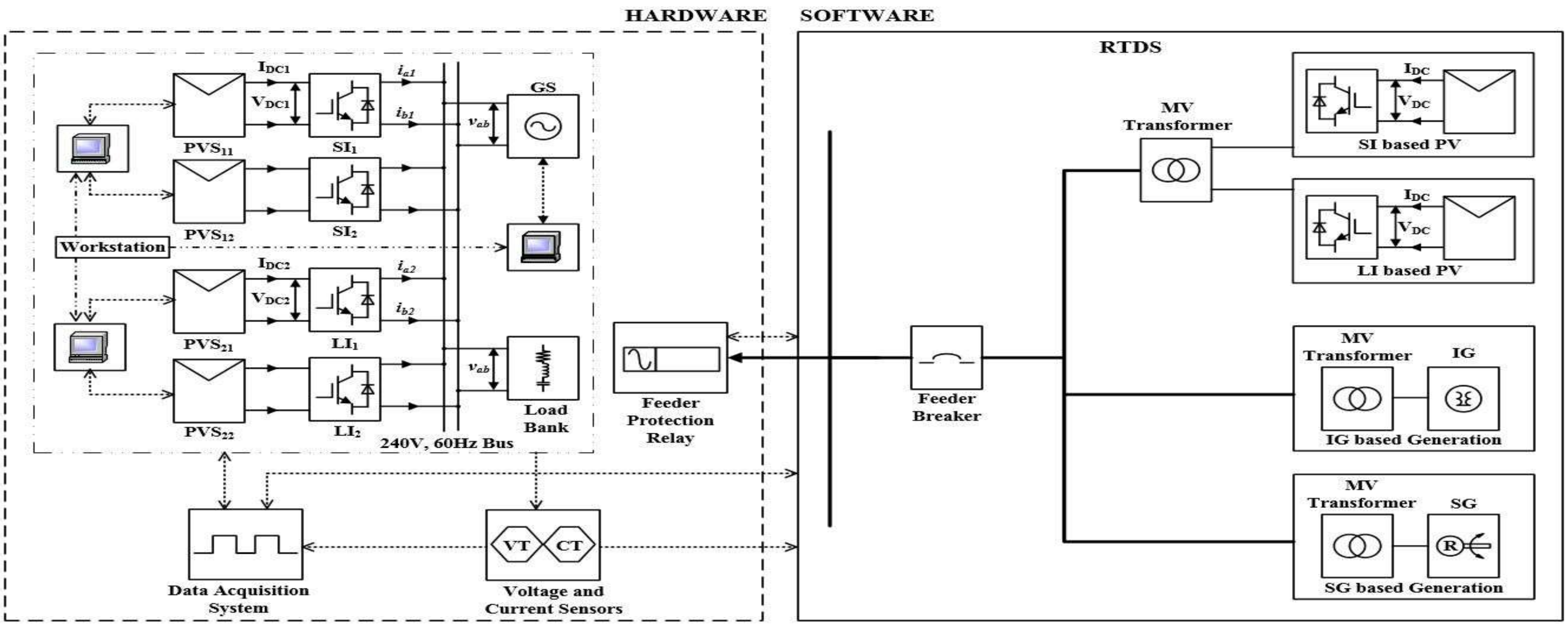

Fig. 2 HIL Testbed for DER dynamics integration demonstration

- The testbed comprised of both **hardware and software components**: smart and legacy inverters PV inverters, RTDS, sensors, DAC and computer models of: inverters, synchronous and induction machines, protective relay, and an SCE feeder.
- The MPPT control will be performed locally

Use Case #2 - Smart Inverter Testbed in DER Laboratory, SCE

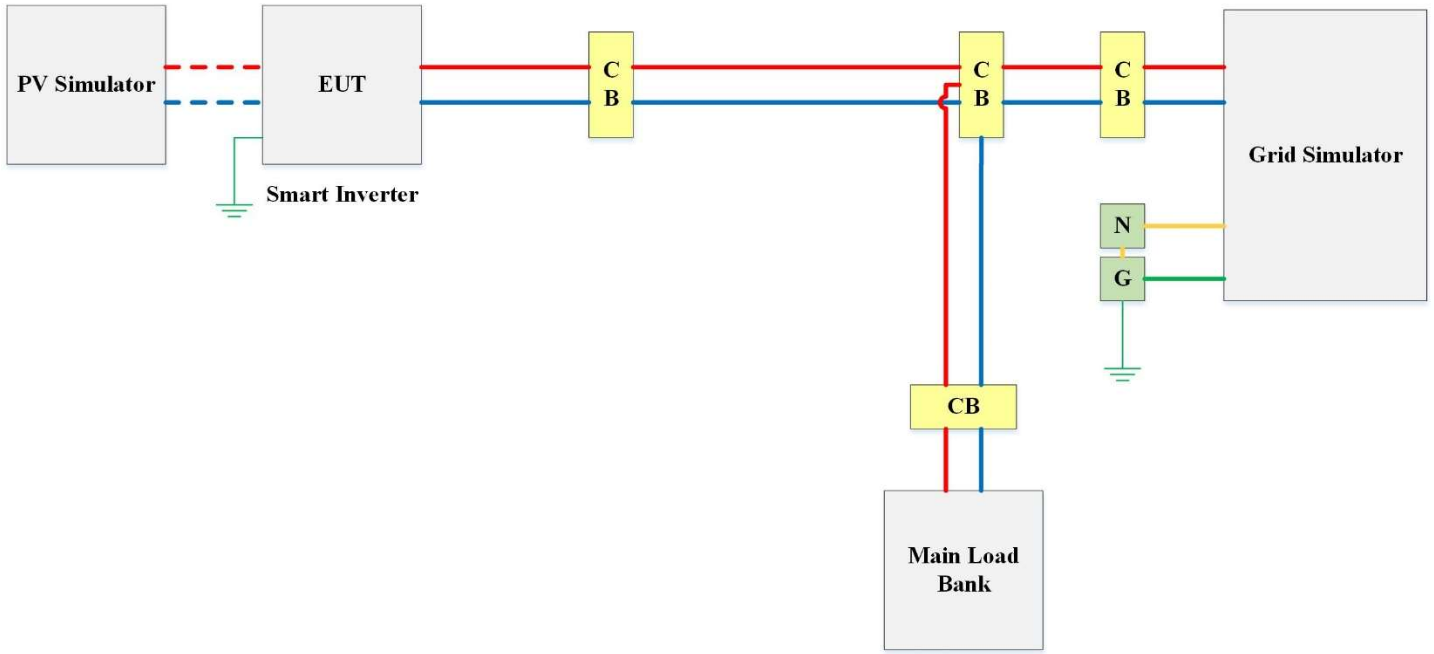

Fig. 3 Smart Inverter test set-up in the DER laboratory at SCE

- The test-bed comprised of: (1) a grid simulator; (2) a solar PV simulator; (3) a load bank; (4) equipment under test (EUT) that is Rule-21 supporting residential smart solar PV inverter; and (5) data acquisition system
- The MPPT control will be performed locally

Preliminary Results and Discussions

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Use Case #1 - PV – Simulation and Experimental

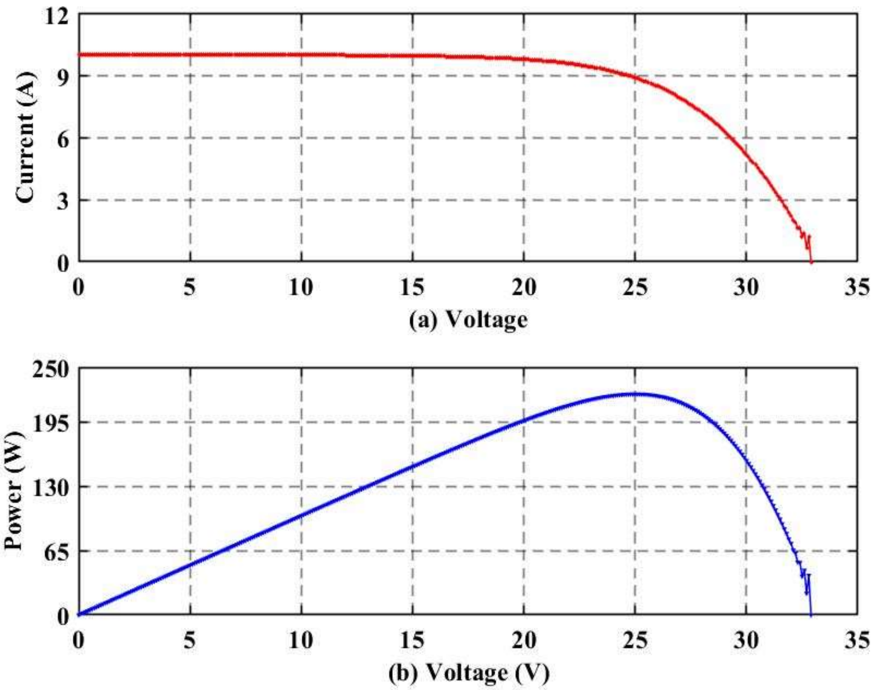

Fig. 4 Simulation results for PV module. (a) I-V curve. (b) P-V curve

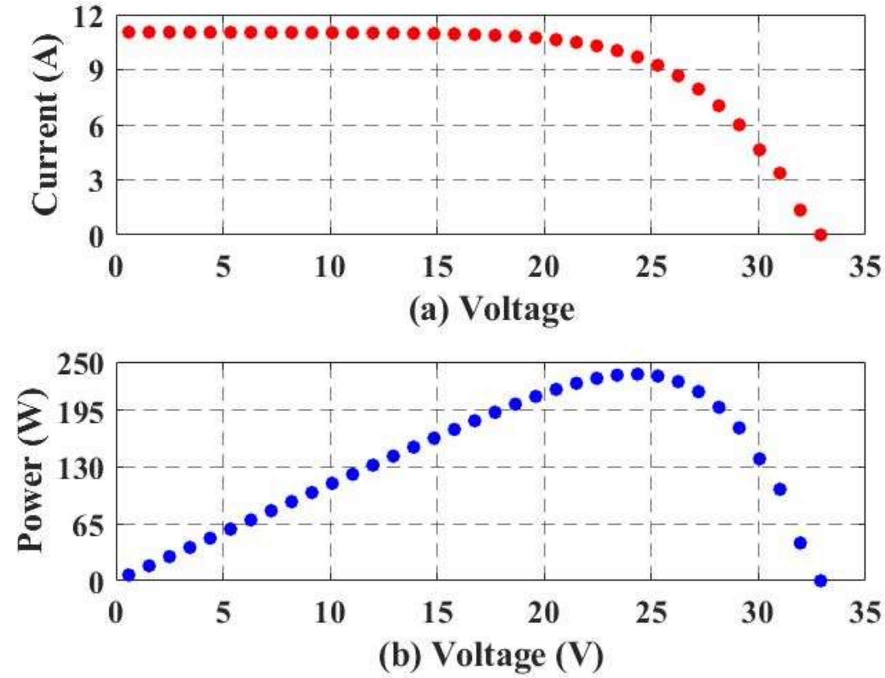

Fig. 5 Experimental results for PV module, (a) I-V curve, (b) P-V curve

- It is visible that for the simulation, the MPPT voltage and current, V_m, and I_m are 24.9V and 8.9A, while the calculated power, P_{dc} is 3,119W.

- The experimental V_m and I_m are 24.3V and 9.6A respectively, while the power production is 3,304W.

- It can be asserted that the simulated I-V curve is in ample agreement with the experimental results

Use Case #1 – Smart Inverter – Simulation and Experimental

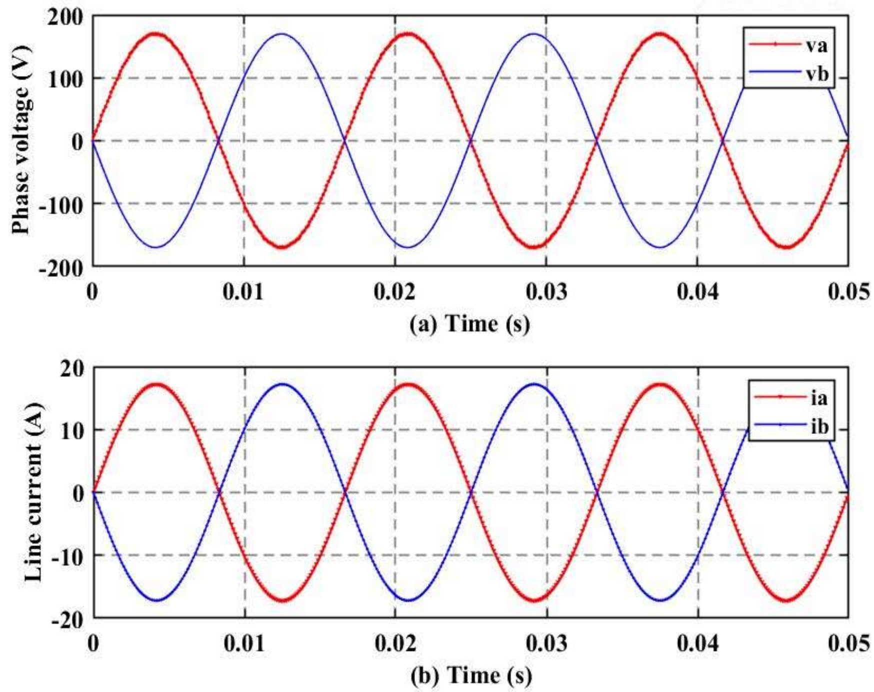

Fig. 6 Simulation results of inverter (a) Phase voltage, (b) Line current

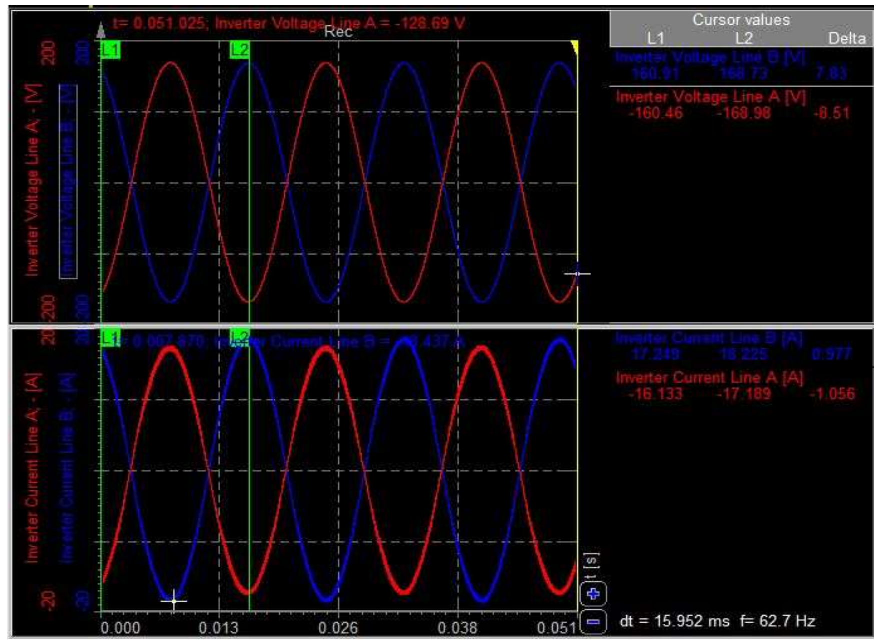

Fig. 7 Experimental results of inverter (a) Phase voltage, (b) Line current

- ❑ The simulation RMS value of v_a (or v_b) and current i_a (or i_b) are approximately 169V and 12.1A respectively and i_a (or i_b) remains in phase with v_a (or v_b) and 180^{0}, apart from i_b (or i_a)

- ❑ The experimental RMS value of v_a (or v_b) and current i_a (or i_b) are approximately 169V and 12.1A respectively

- ❑ The experimental voltage and current matches the simulated values, confirming the effectiveness of the proposed impedance-based method is developed

Use Case #1 – Smart Inverter – Simulation and Experimental

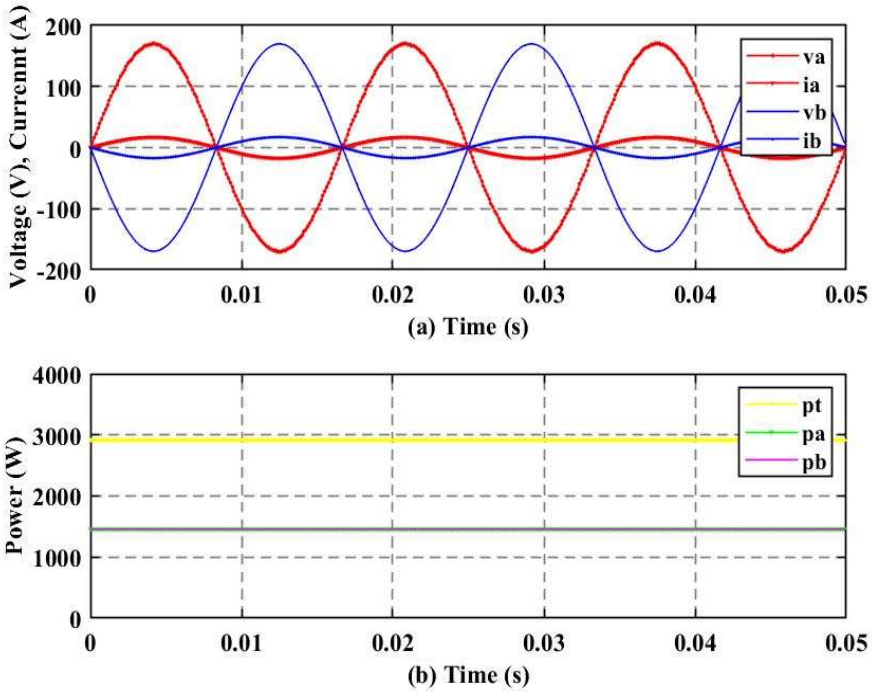

Fig. 8 Simulation results, (a) Phase voltage and line currents, (b) Total and phase power

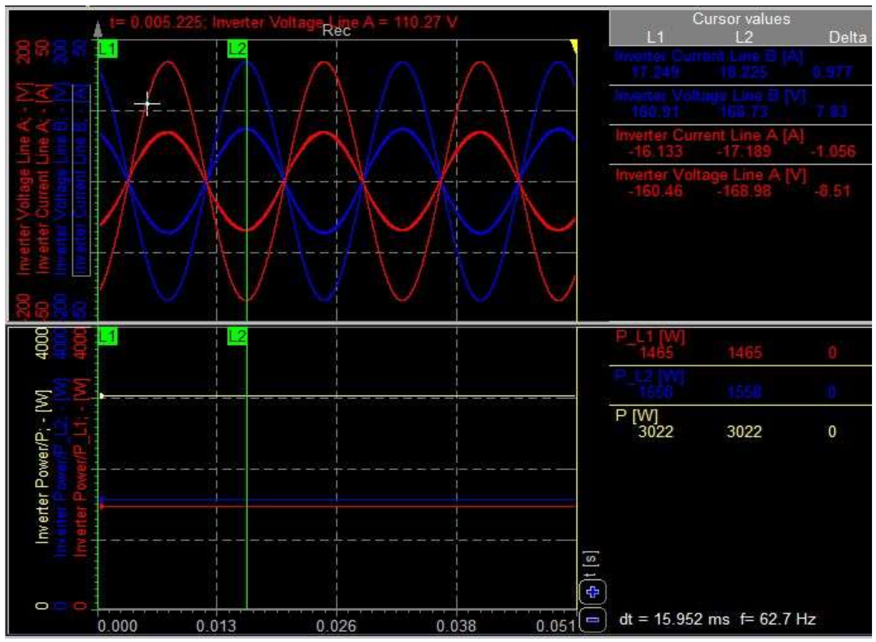

Fig. 9 Experimental results (a) Phase voltage and line currents, (b) Total and phase power

- The inverter phase voltages and currents, yields the total power, P_t is calculated over the whole cycle, yields P_a and P_b each as 1,459W, while the total power, P_t is 2,917W.
- The phase power yields P_a and P_b are 1,465W and 1,668W, while the total power, P_t is 3,022W.
- The error values for power remain less than 3%, which ensures the validity of the modeling approach is presented

Use Case #2 – Smart Inverter – Undervoltage Testing

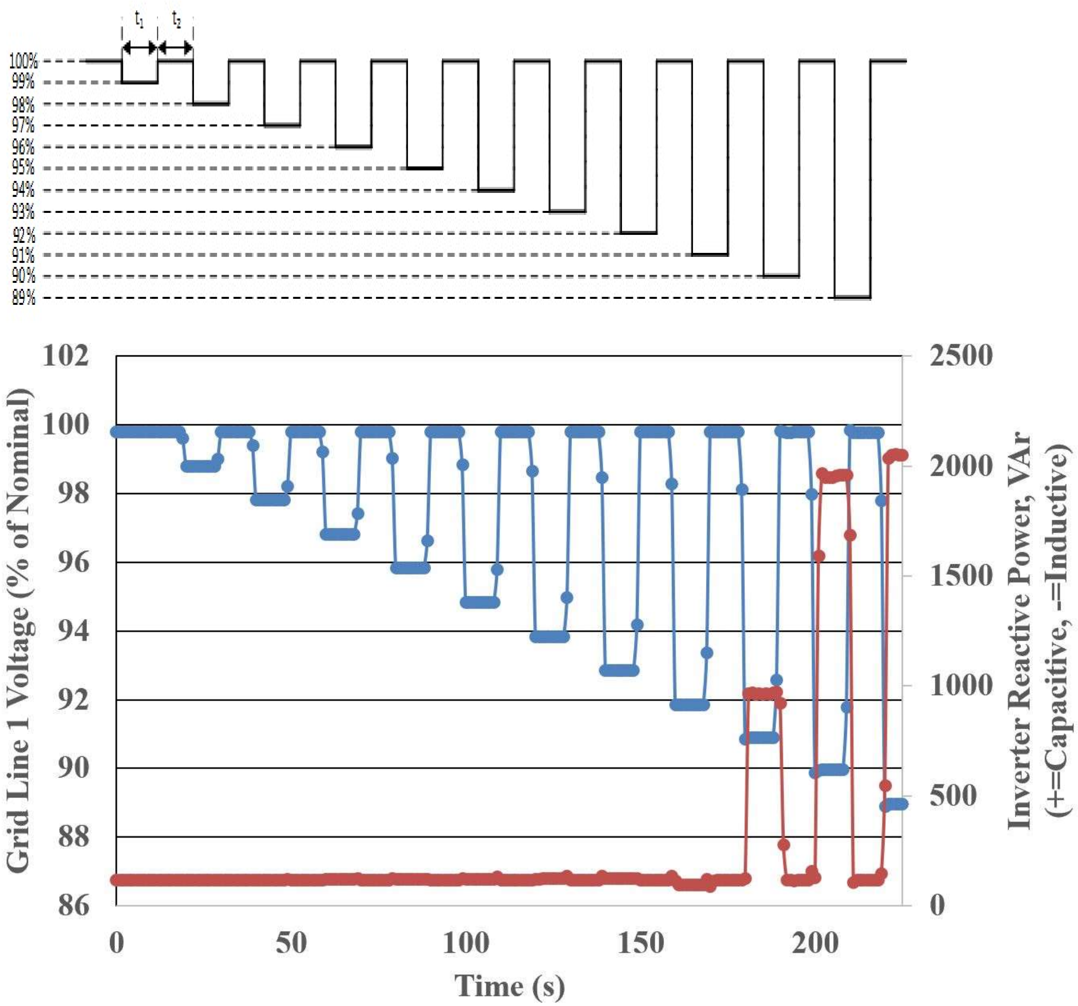

Fig. 10 Experimental results for undervoltage testing

- The tested nominal voltage have durations of t_1 = 10 seconds and delay t_2= 10 seconds.
- Grid simulator was programmed to perform various under-voltage events needed for the test.
- The inverter increases its VAR output after voltage drops below 91%

Use Case #2 – Smart Inverter – Over voltage Testing

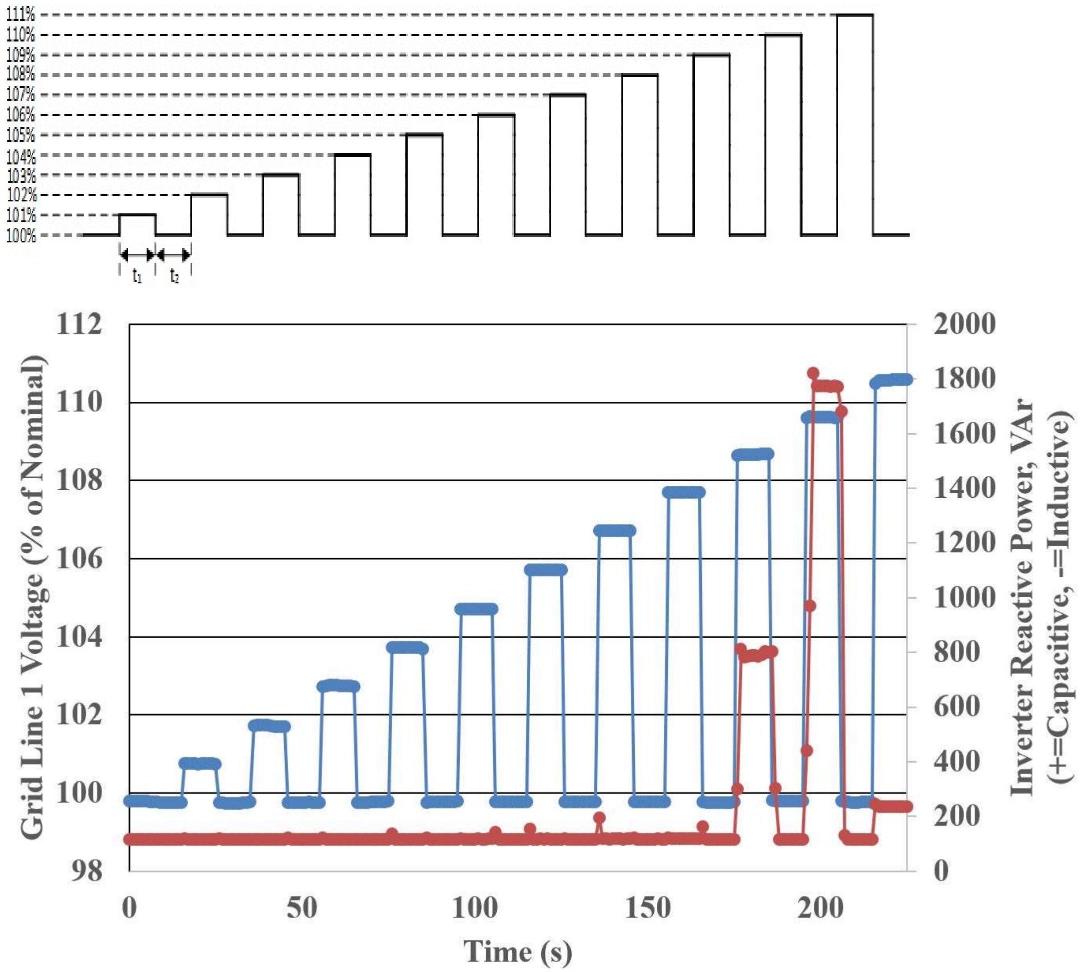

Fig. 11 Experimental results for overvoltage testing

- The tested nominal voltage have durations of t_1 = 10 seconds and delay t_2= 10 seconds.
- Grid simulator was programmed to perform various under-voltage events needed for the test.
- The inverter decreases its VAR output after voltage increases above 108%

Concluding Remarks

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Summary and Remarks

- ❑ Mathematical modeling, simulation, and development of a Hardware-in-the-Loop (HIL) testbed at Southern California Edison (SCE)'s Distributed Energy Resource (DER) Laboratory is described
- ❑ The simulation results are verified by experimentation.
- ❑ This modeling and testbed can benefit SCE to study the impacts of protection systems or emerging technologies without the need to conduct in-field trials
- ❑ Smart and Legacy inverter technological developments must be informed by a holistic understanding of the creation of the modern grid of the future
- ❑ Smart inverter will contribute to the advanced management and control systems needed to modernize the grid
- ❑ More detailed understanding of the role of smart inverter as well as power electronics in safety, standards, and system integration is needed

Q & A