SEPTEMBER 2023

SPEC
Semiconductor Power Electronics Center

TEXAS
The University of Texas at Austin

Photovoltaic Synchronous Generator (PVSG): A Grid Forming PV Inverter System with a DC Coupled Energy Storage

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Team: Houshang Salimian Rizi, Zibo Chen, and Dr. Alex Q. Huang

1. Background & Highlights

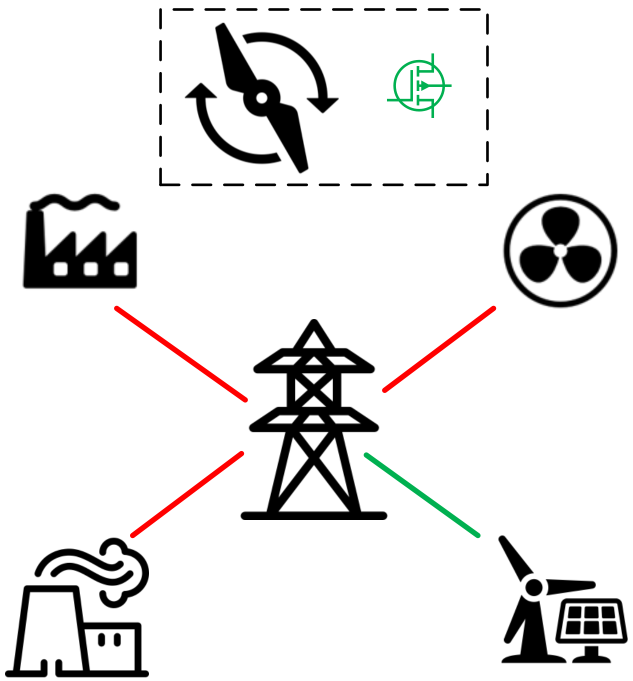
2. AC Coupled PVSG

3. DC Coupled PVSG

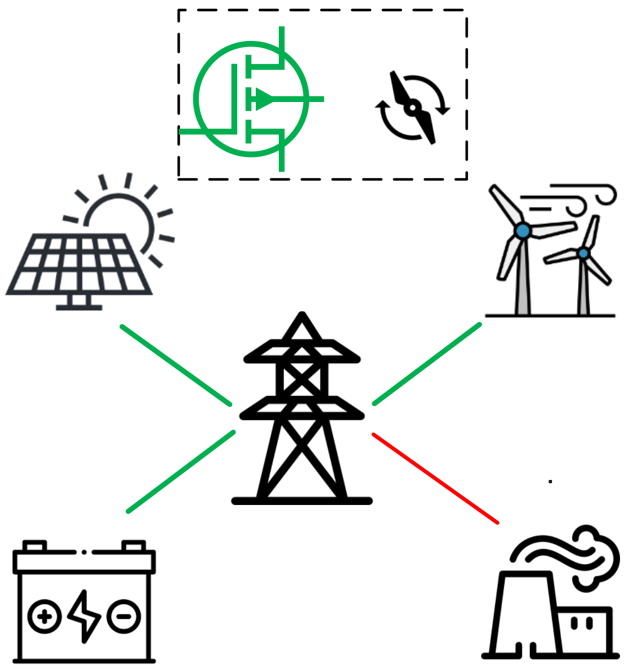
4. Single Stage Solid State Condenser (SSC)

Grid and Renewable Generation

Conventional Grid



Future Grid



How to have a stable IBR dominated grid?

Today's PV: Following the grid

Current source(Current control)

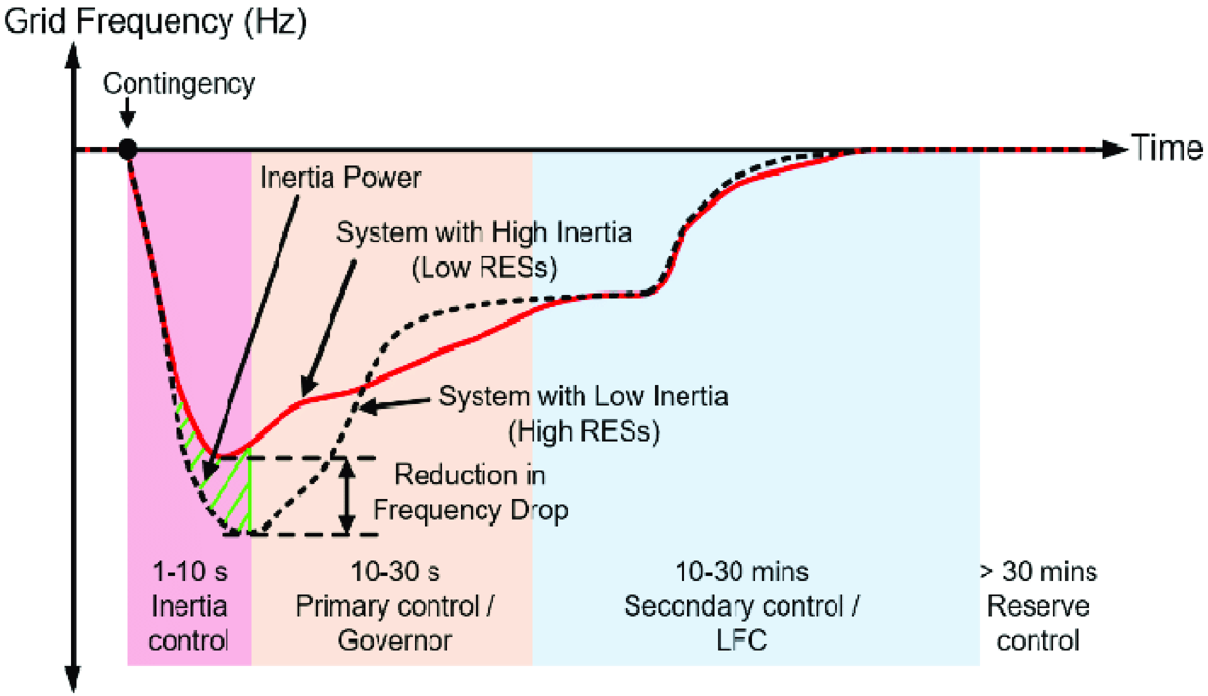
- PLL is required to follow grid voltage & frequency
- Fast response to the intermittent irradiation levels (no buffer)
- Can't work when grid fail

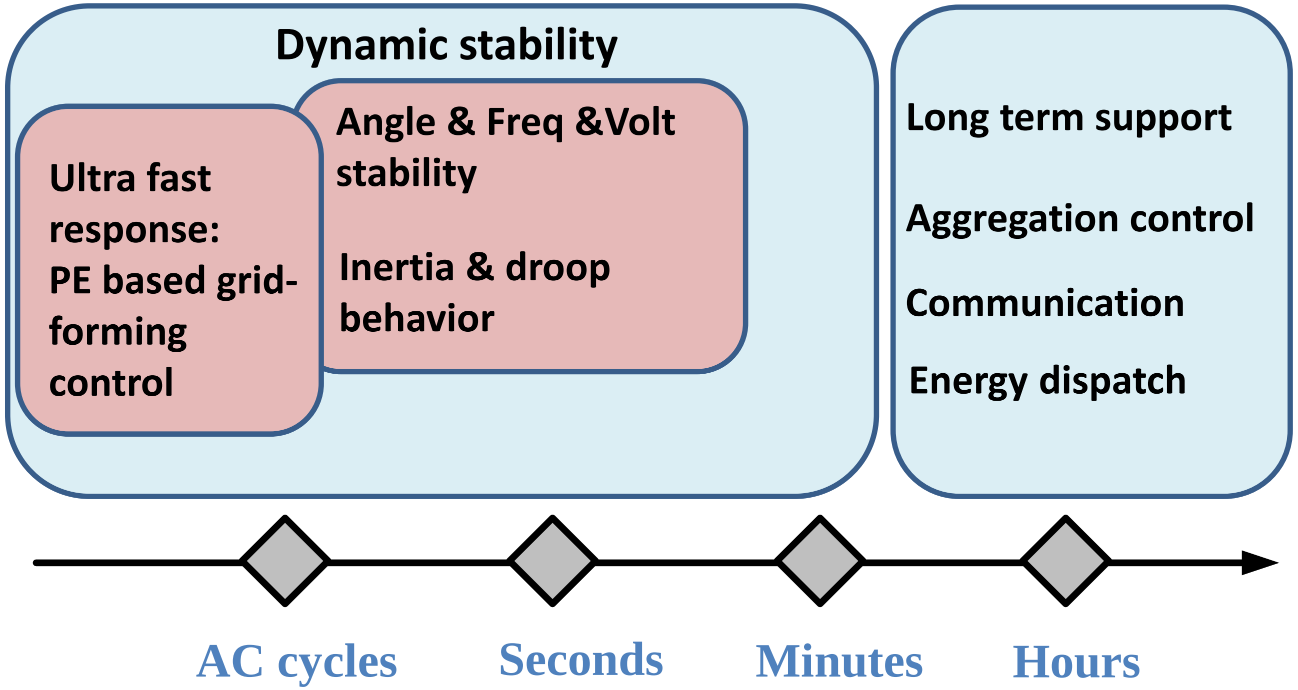
Forming the grid

Voltage source (can serve as PV bus or PQ bus)

- Has its own voltage & frequency (Swing bus)
- No PLL required
- Inertia support & primary frequency response
- Black start, islanding
- Operate as frequency estimator

Frequency Response

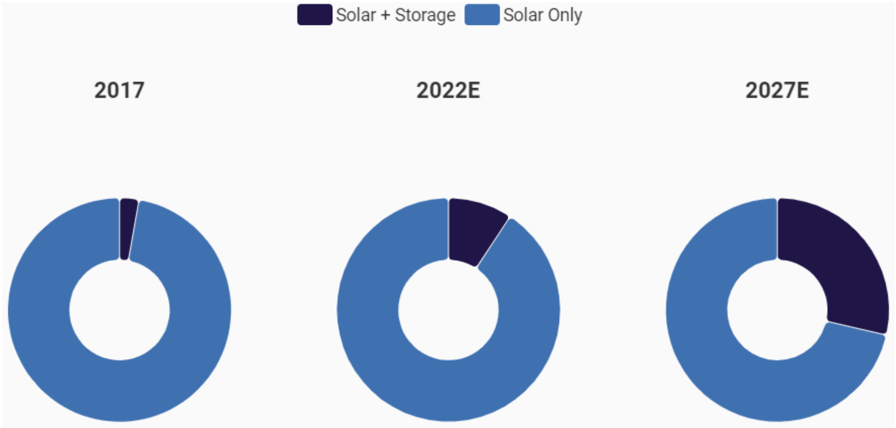




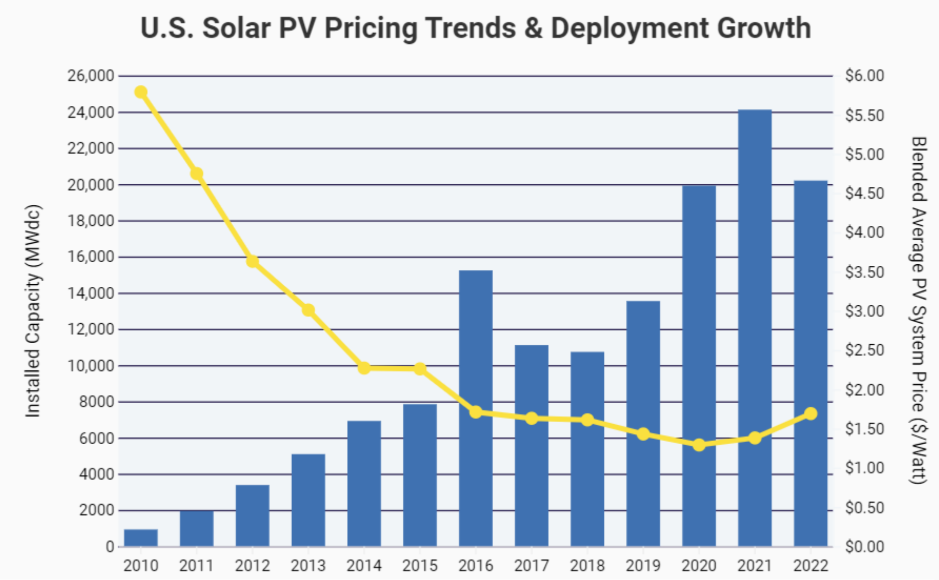
Solar Generation Growth

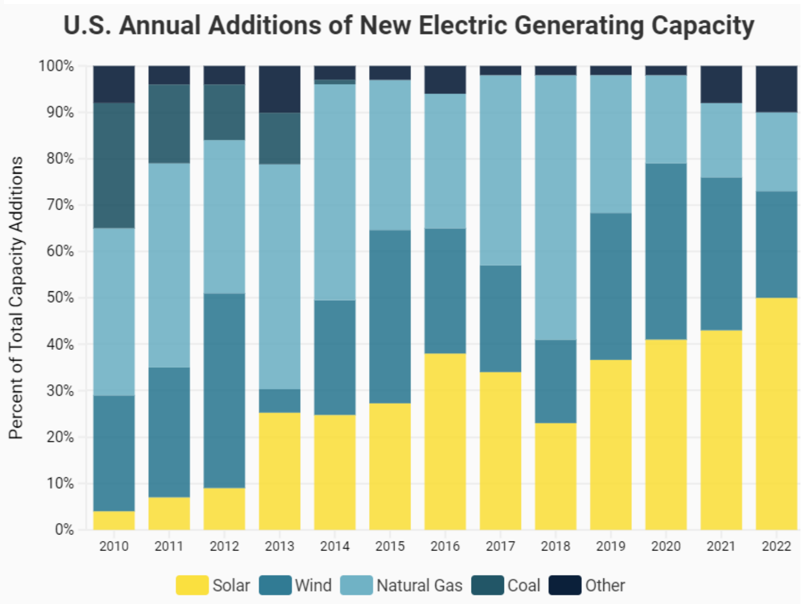
Why Solar?

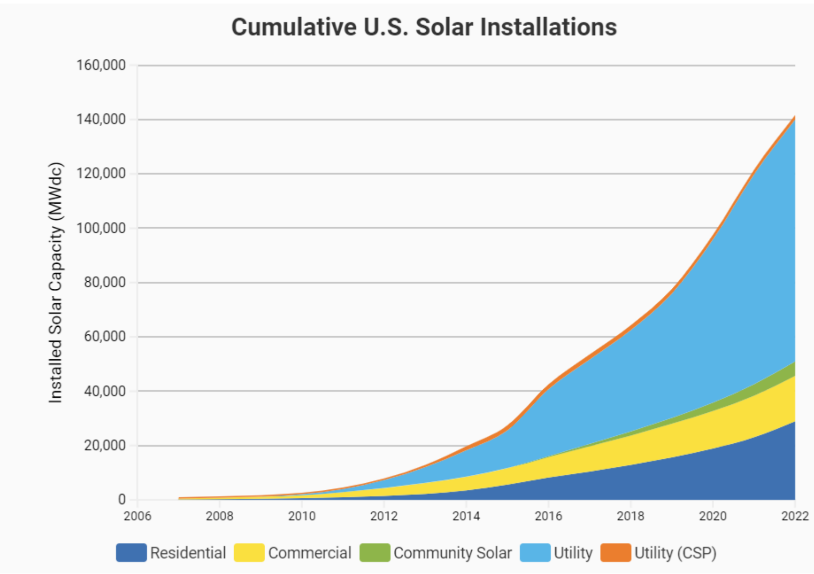
- Solar panel installation cost reduction (50% in last decade)
- Solar is growing faster than wind
- 50% of all new capacity added to grid in 2022 was by solar
- Higher penetration expected in the future
- Increasing share of PV plus energy storage
- Utility installation has the greatest solar share
- Can they displace traditional SG generator?



[1] Solar Energy Industries Association (SEIA), https://www.seia.org/







Introduction to GFM

GFM

- **Energy reserve** for filtering power intermittences
- **Power control loop** for generating voltage and phase angle references

Energy Reserve

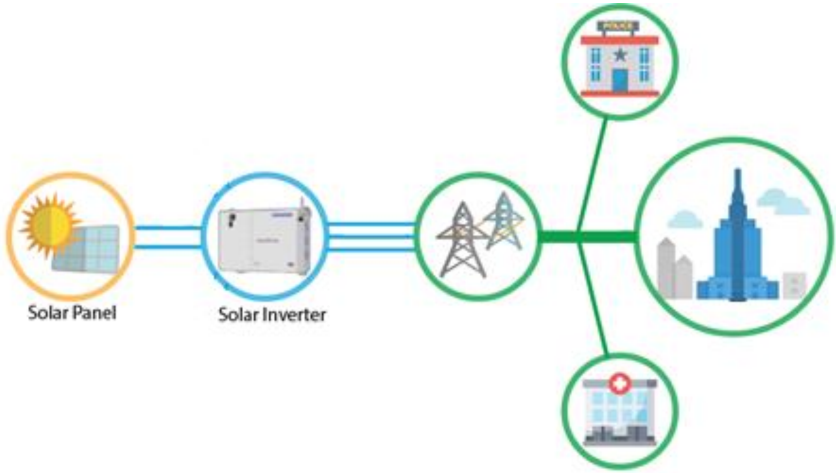
- Battery energy storage
- Super capacitor energy storage (SCES)
- Reserve in PV generation
- Load reserve

GFM Controllers

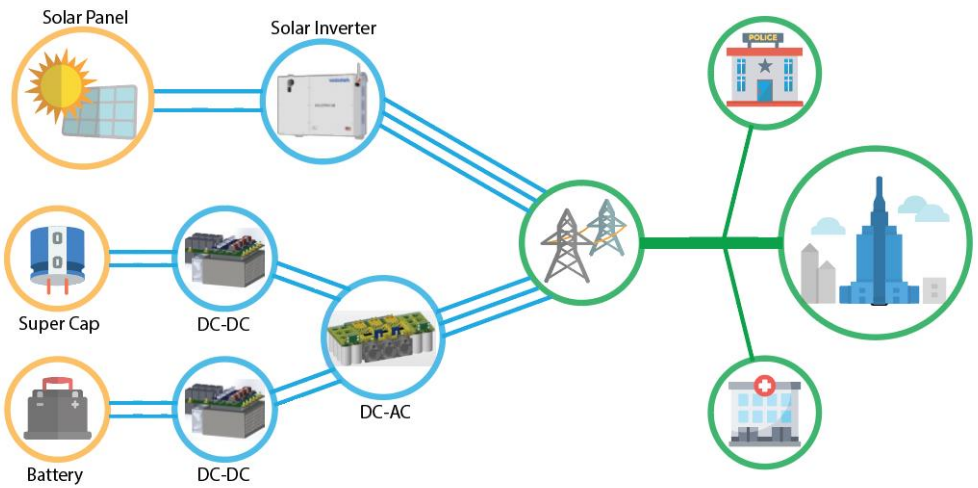
- **Droop based** Using P-f and Q-V droop equations
- **Virtual synchronous generator (VSG)** Emulating SG equations in controller
- **Virtual synchronous oscillator control (VOC)** Emulating a non-linear oscillator in inverter control

Different Solutions for PV GFM

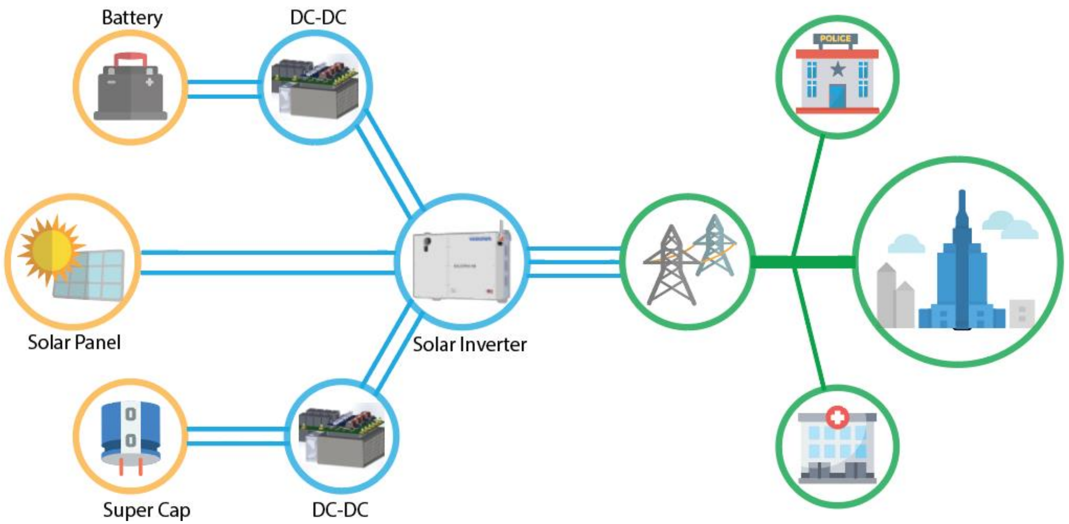
PV Inverter without Storage



AC Coupled GFM and Energy Storage

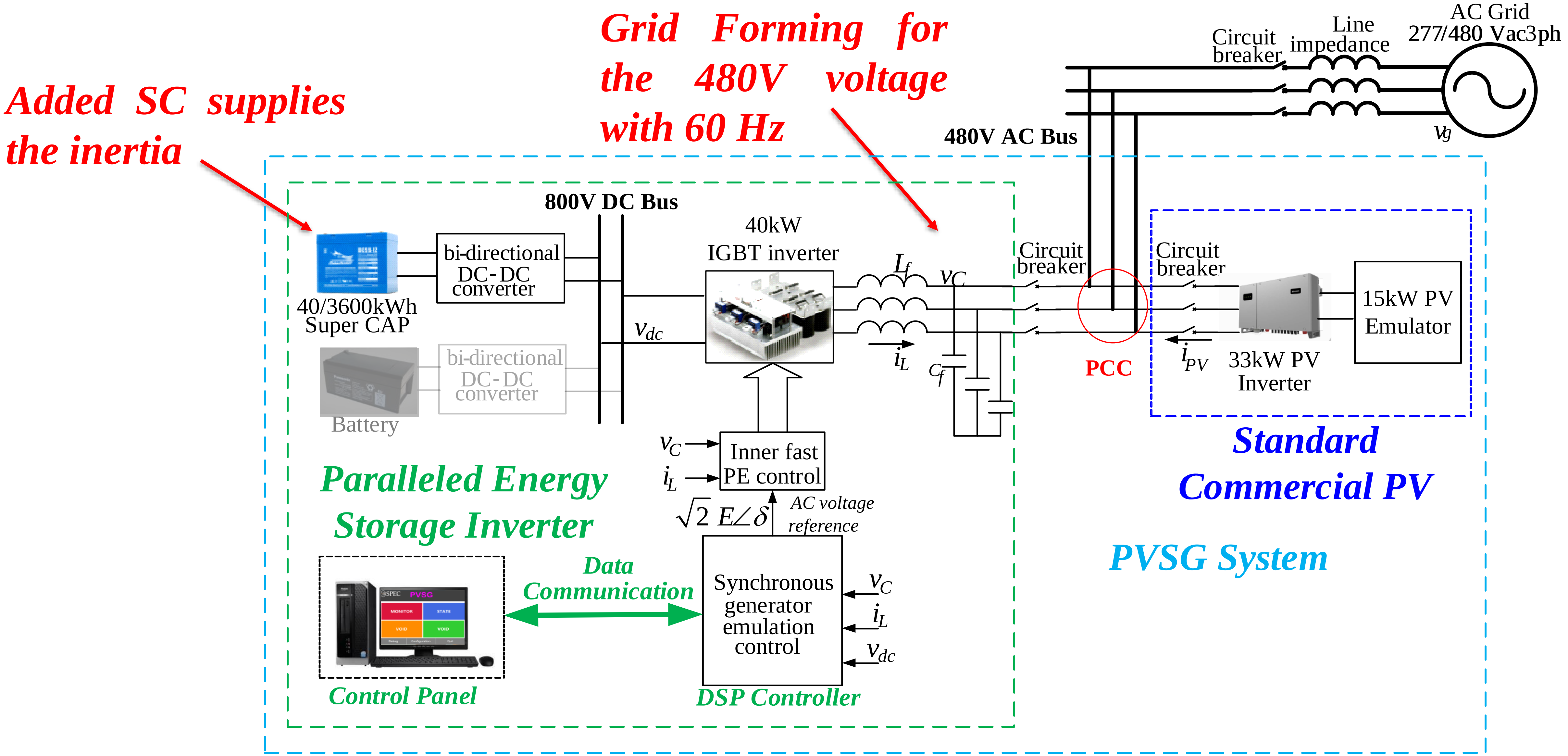


DC Coupled GFM and Energy Storage

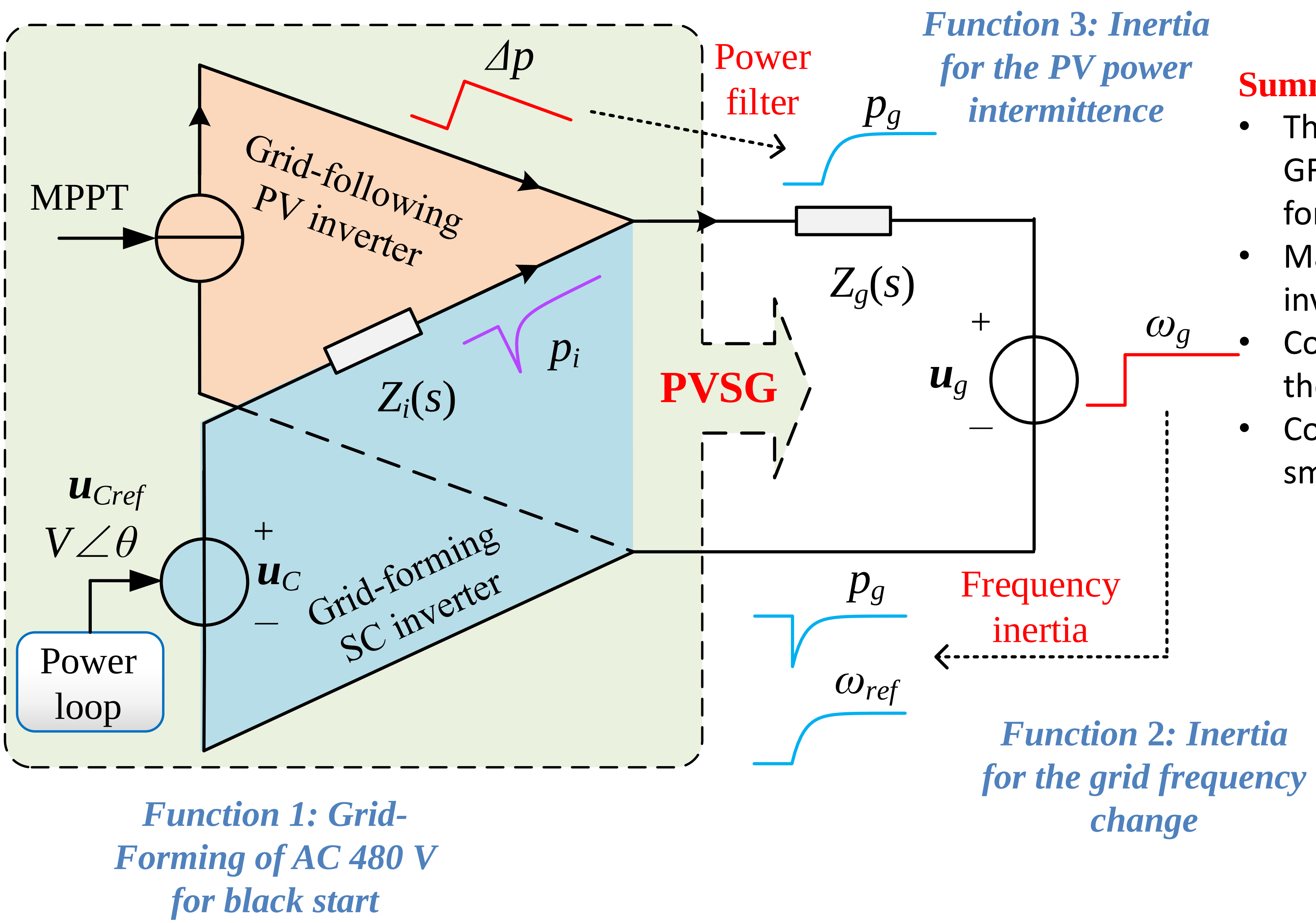


1. Background & Highlights
2. AC Coupled PVSG
3. DC Coupled PVSG
4. Single Stage Solid State Condenser (SSC)

40kW/480V AC Coupled PVSG



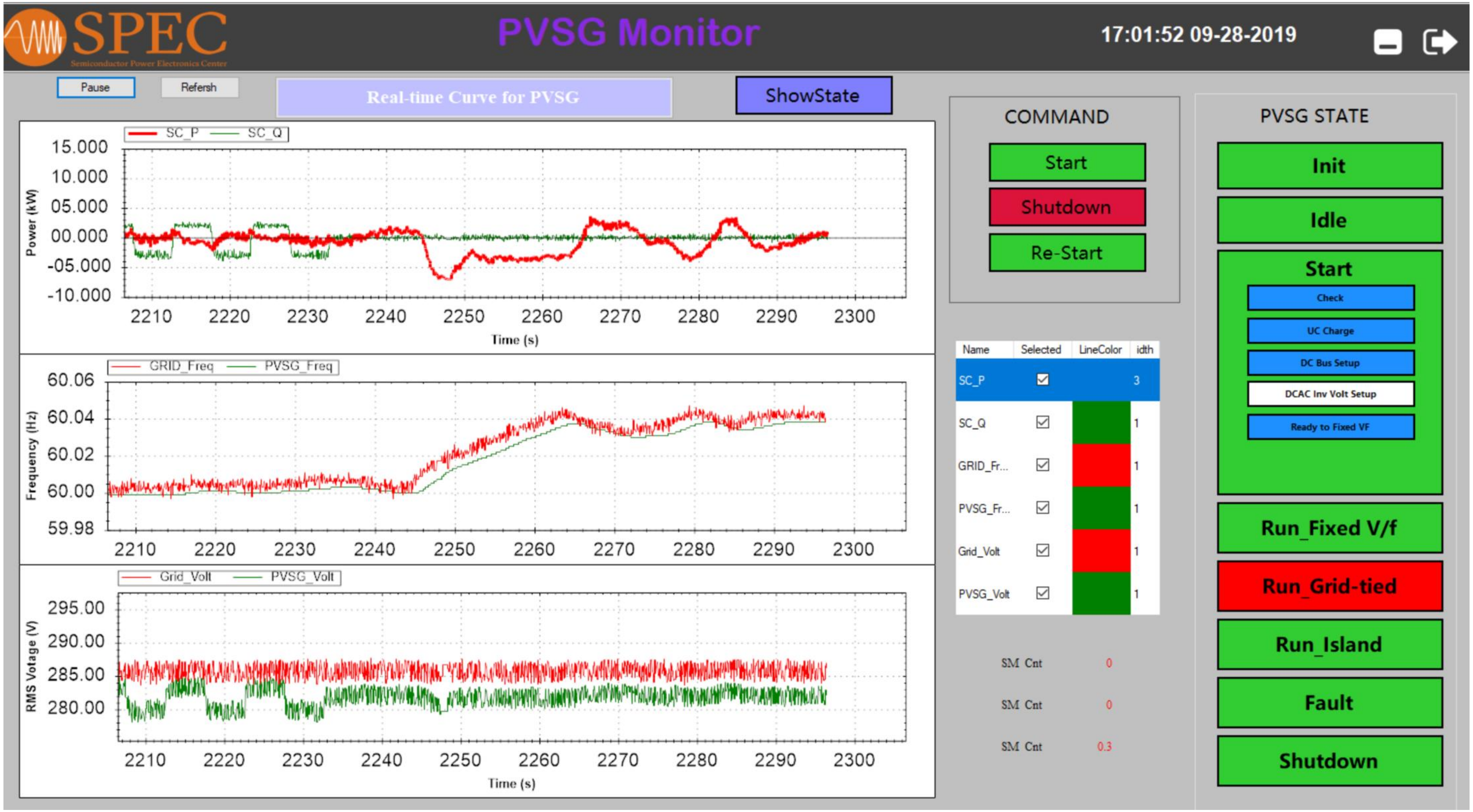
Interpretation from Phasor Circuit



Summary

- The whole system (GFL PV + GFM SCES) operates as a grid forming system
- Makes commercial GFL PV inverters a GFM setup
- Controllable inertia response in the controller
- Controllable PV power smoothing

Inertia Against the Grid Frequency Change



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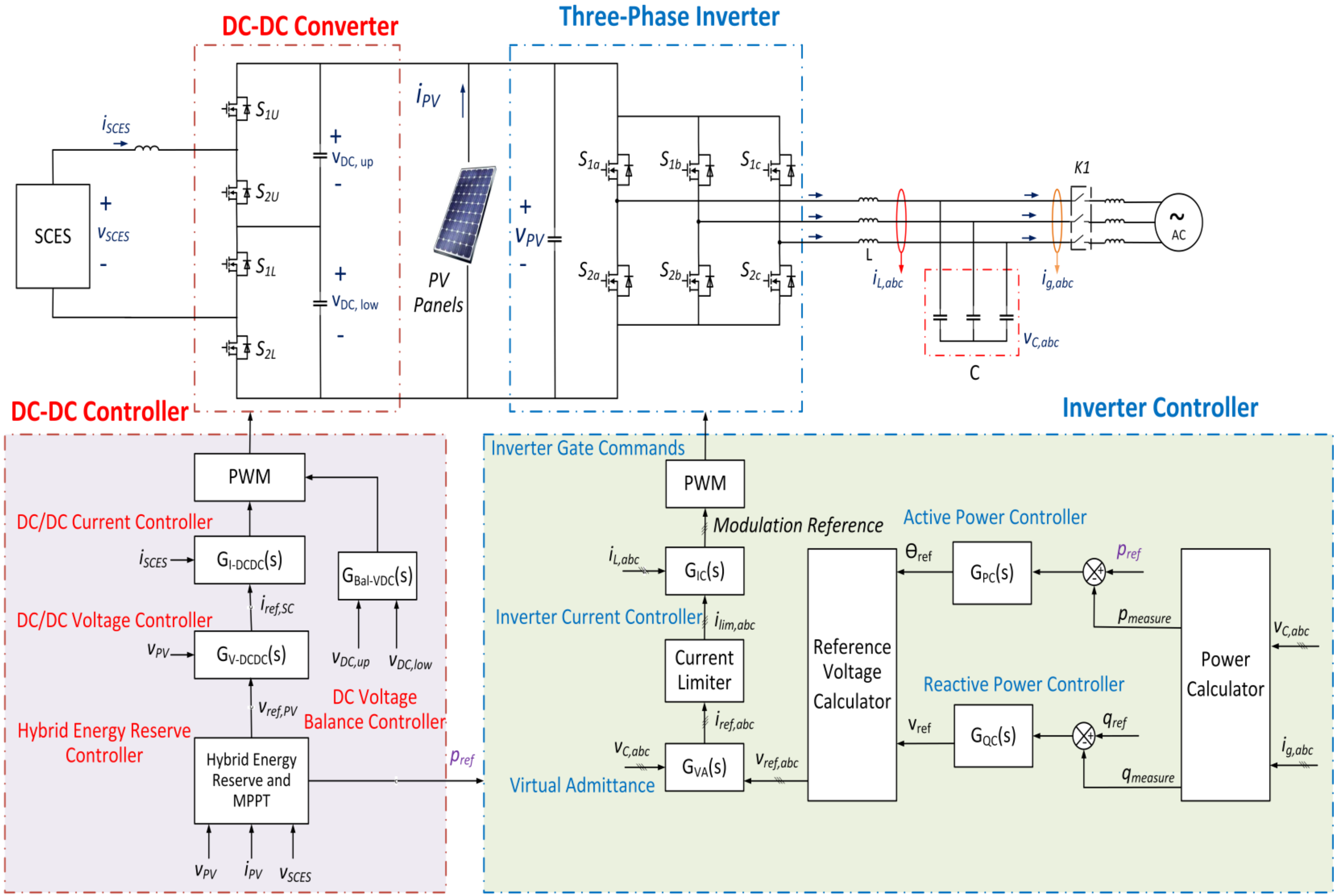
PVSG with DC Coupled SCES



PVSG Features

- Black start
- Self synchronizing
- Frequency support
- Reactive power compensation
- Current limiting
- PV MPPT
- Negative sequence current control for unbalanced loads
- Precise inductance value by virtual admittance in the control loop

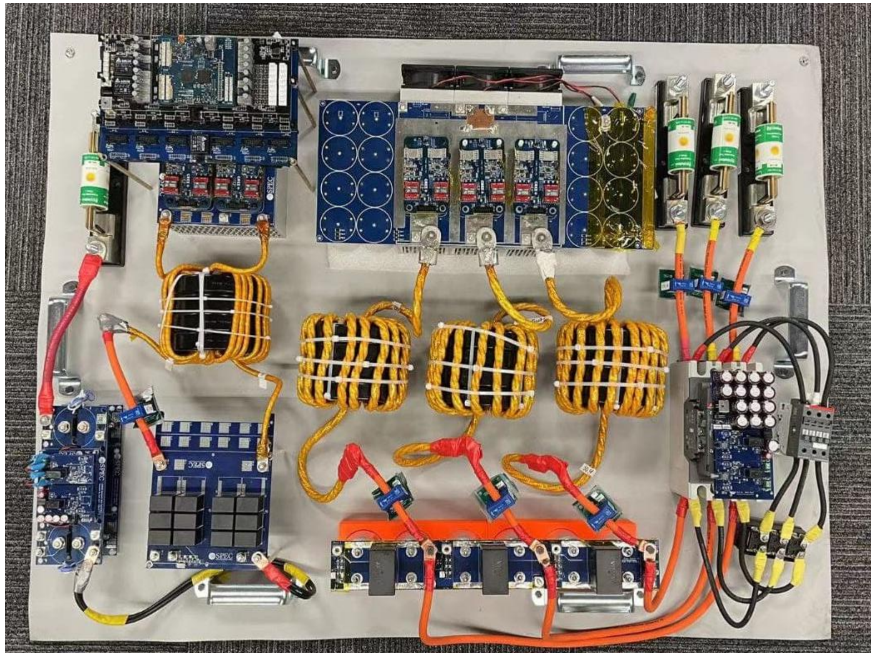
DC Coupled vs AC Coupled

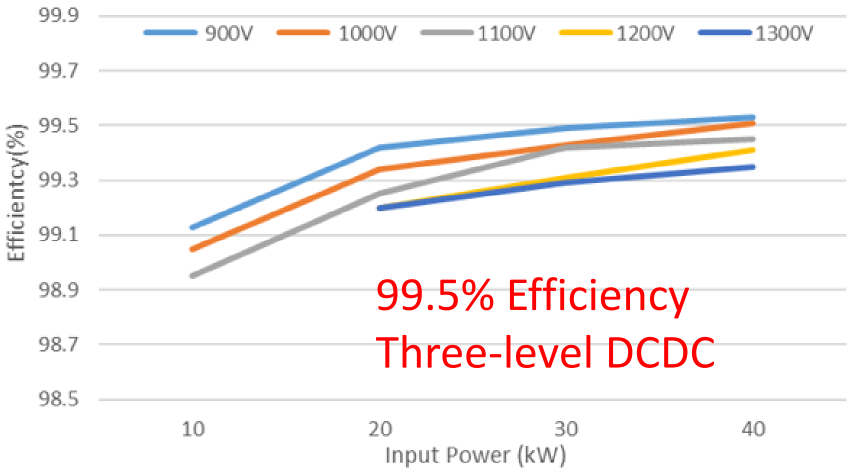
- One less power electronic stage compared to AC coupled PVSG
- Lower loss
- Integrated PV and energy storage control
- Requires change in hardware and control design

GFM Hardware Development

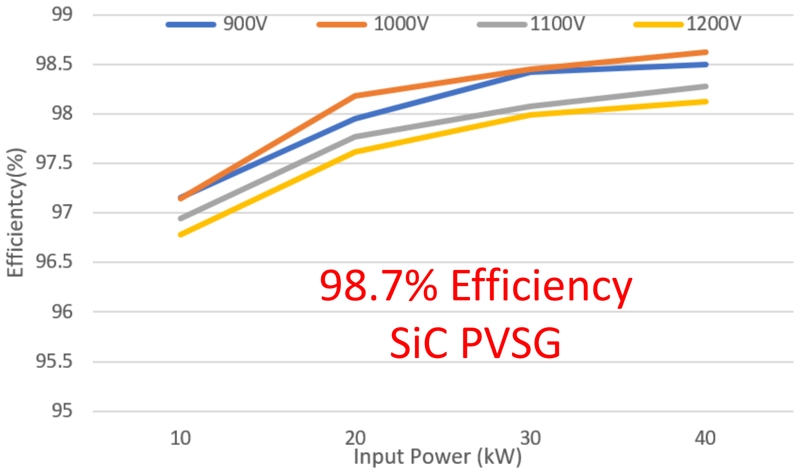
Three-level SiC DCDC Converter

150kW SiC inverter



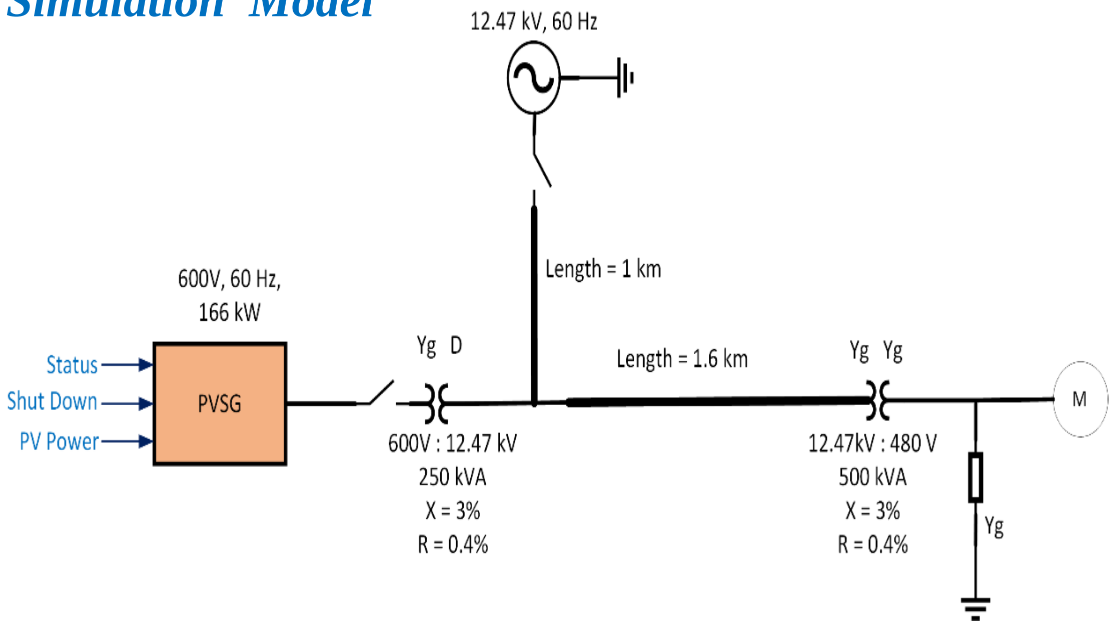


Super Capacitor Energy Storage 2.4 F 800V-max



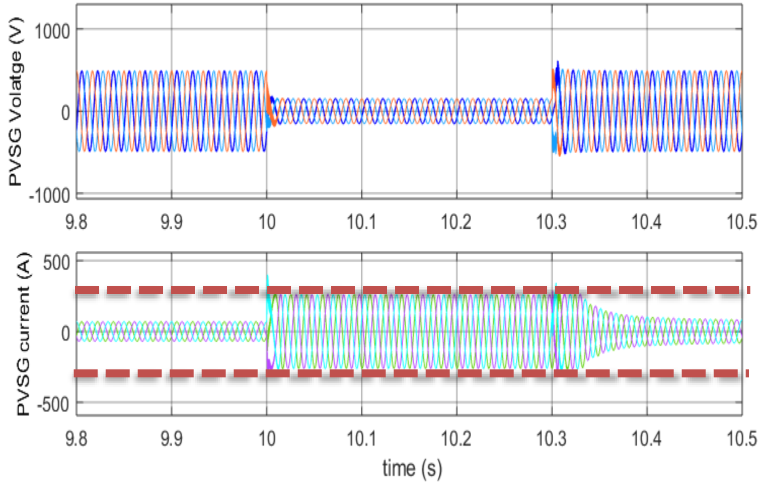
Average Model Results

Simulation Model

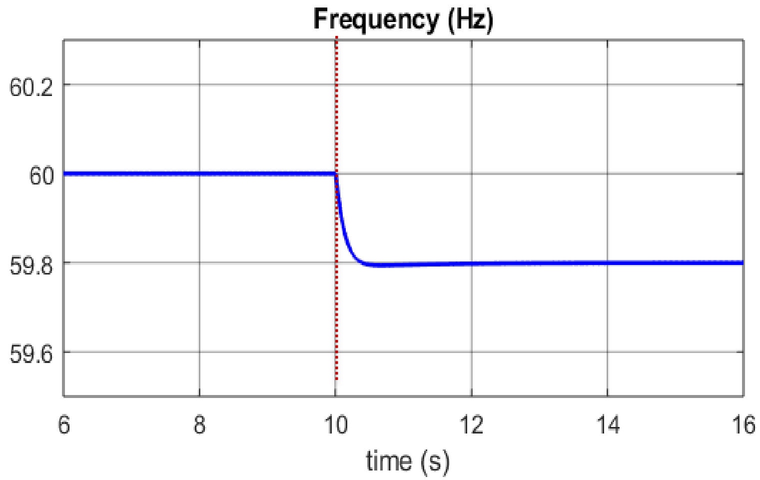


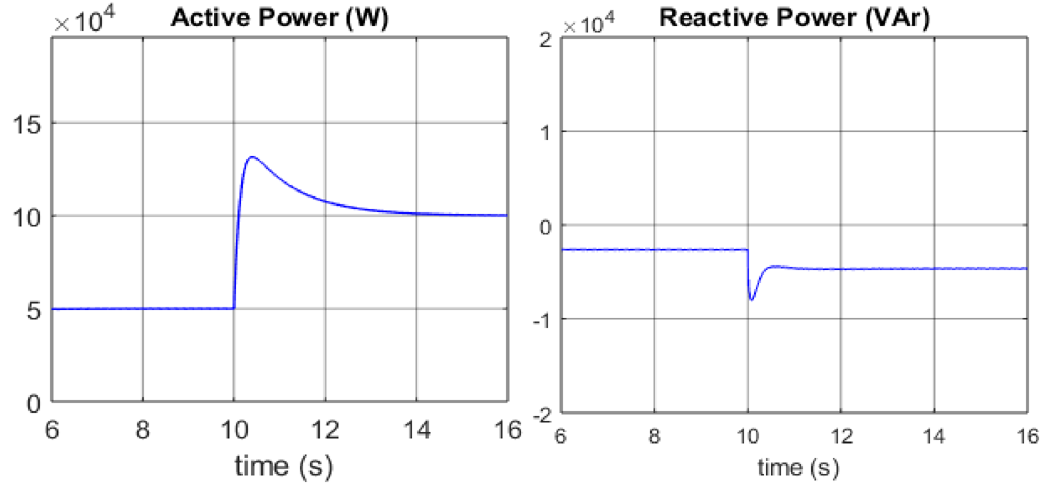
Over current protection

- Current limiting to 1.2pu after a three-phase to ground fault at t= 10s
- Fault clears at t=10.3s



Frequency support (grid connected)





Hardware Verification Results

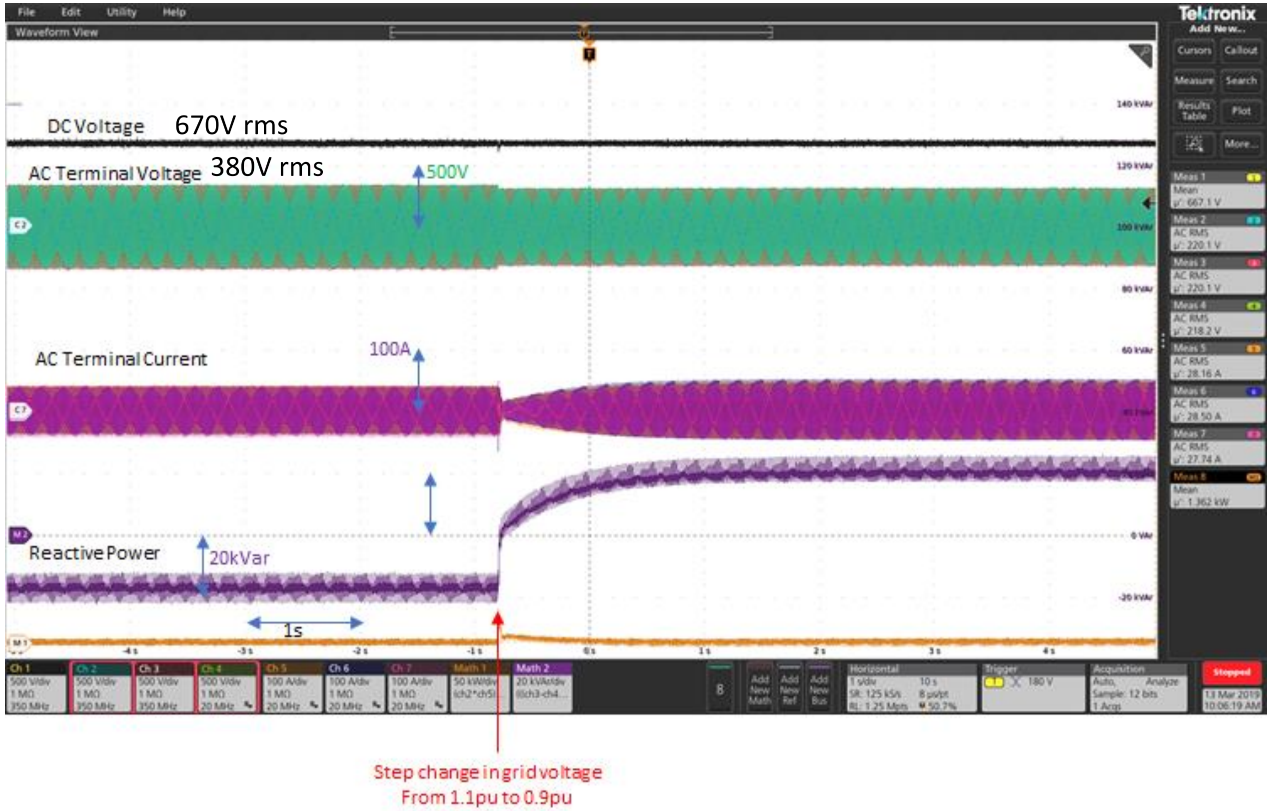
1. GFM Test Results with Droop

a) Grid Connected Test Results

PVSG Connected to 480V grid simulator with
D_p = 25000 W.s/rad and D_q= 500 Var/V
T_{set} = 5s

Frequency Support

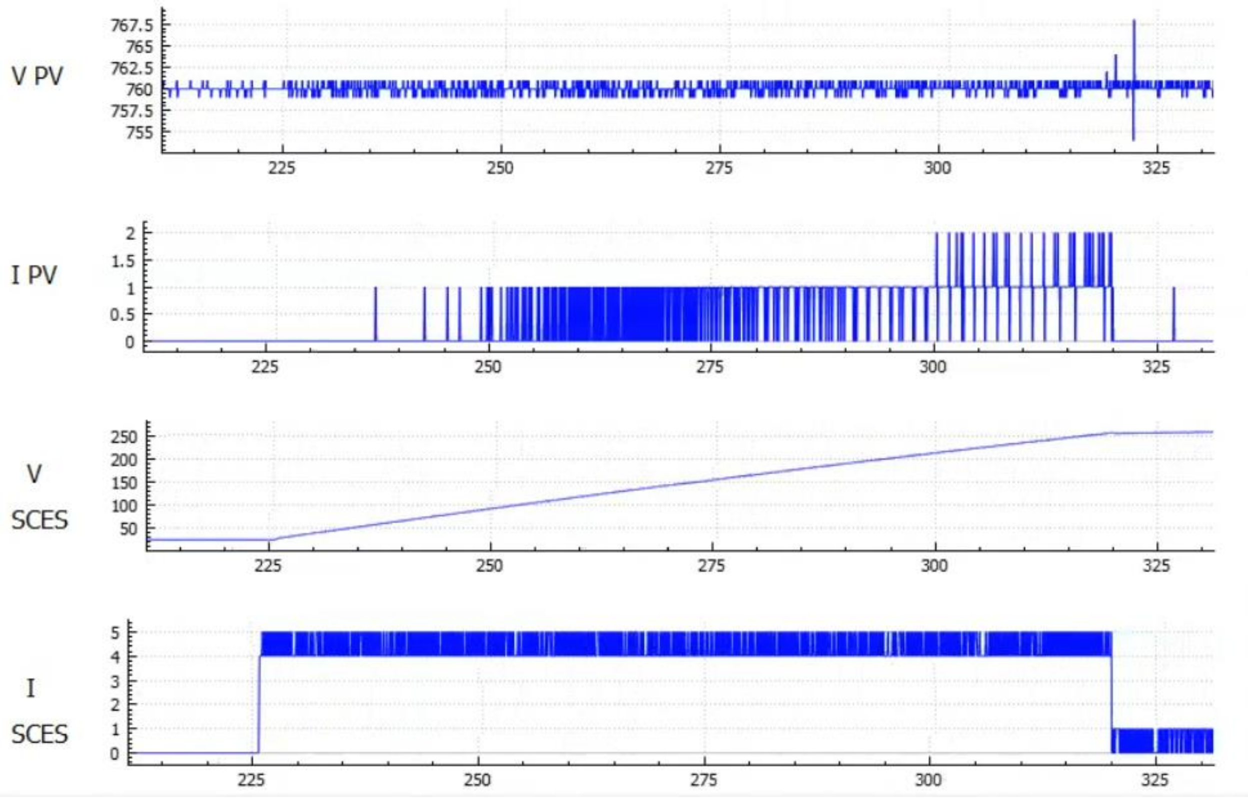
Voltage Support

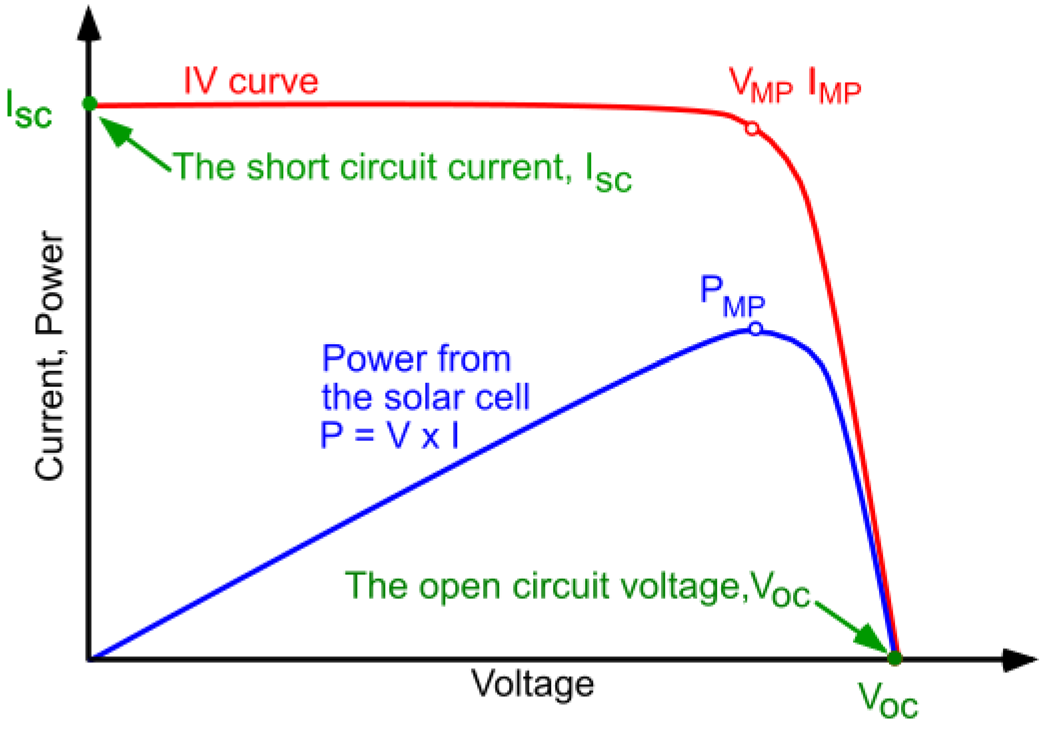


Hardware Verification Results

2. PVSG with DC coupled SCES connected to 480V Grid

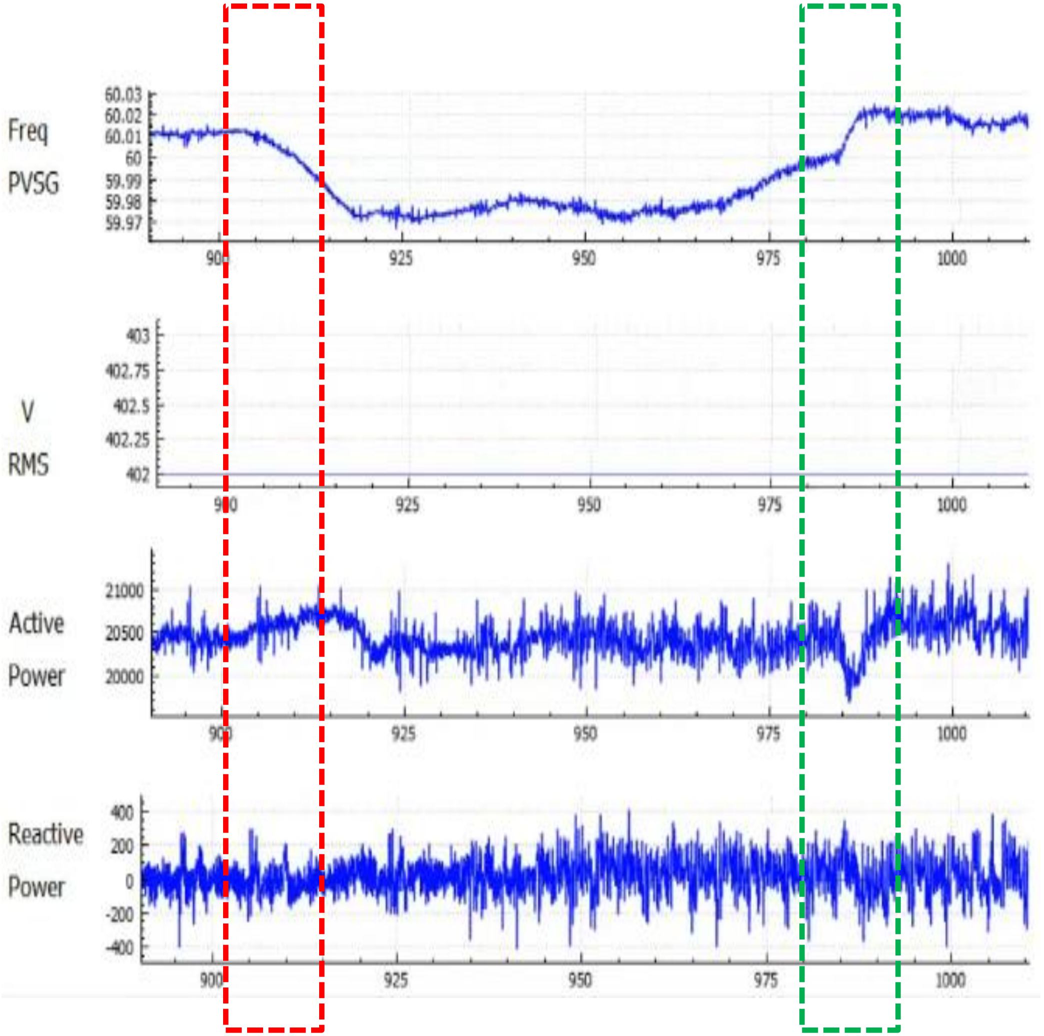
a) Charging SCES by PV Power

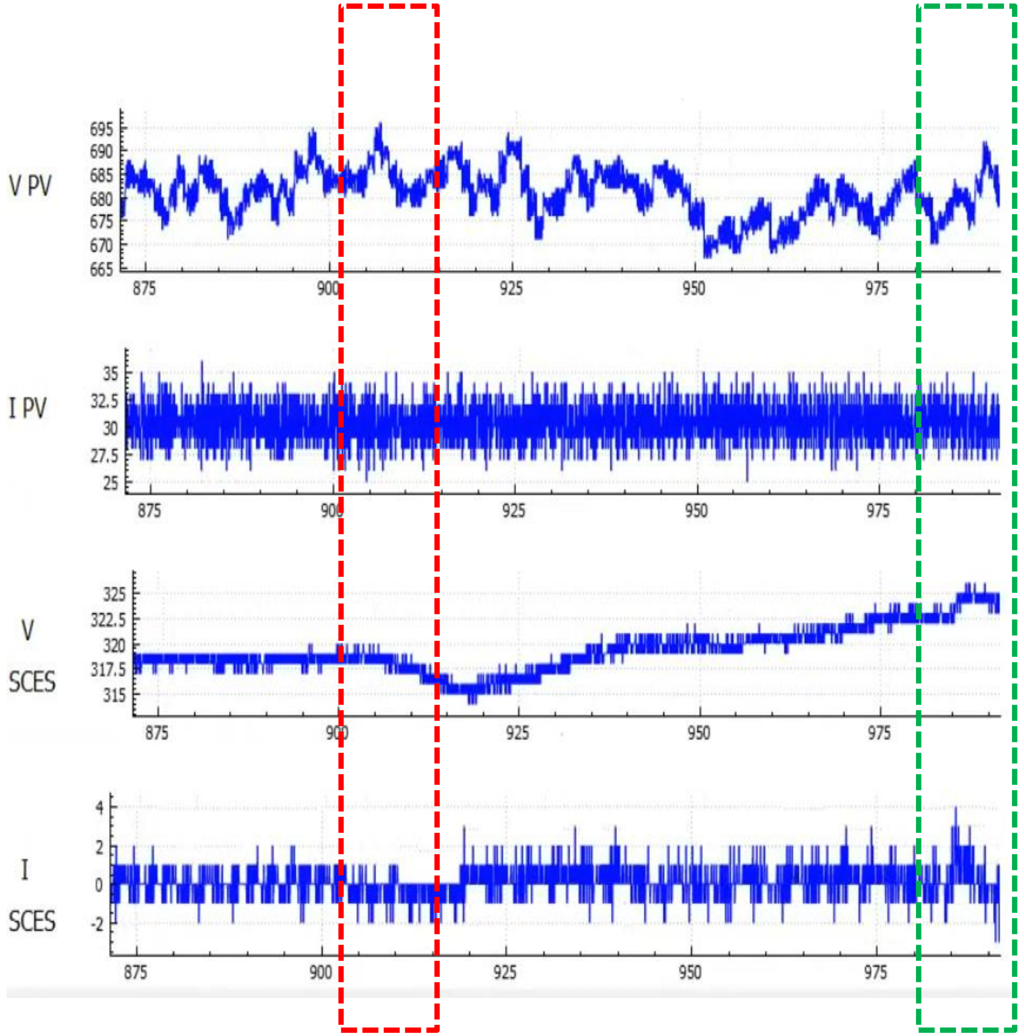




Hardware Verification Results

b) Inertia Response and MPPT



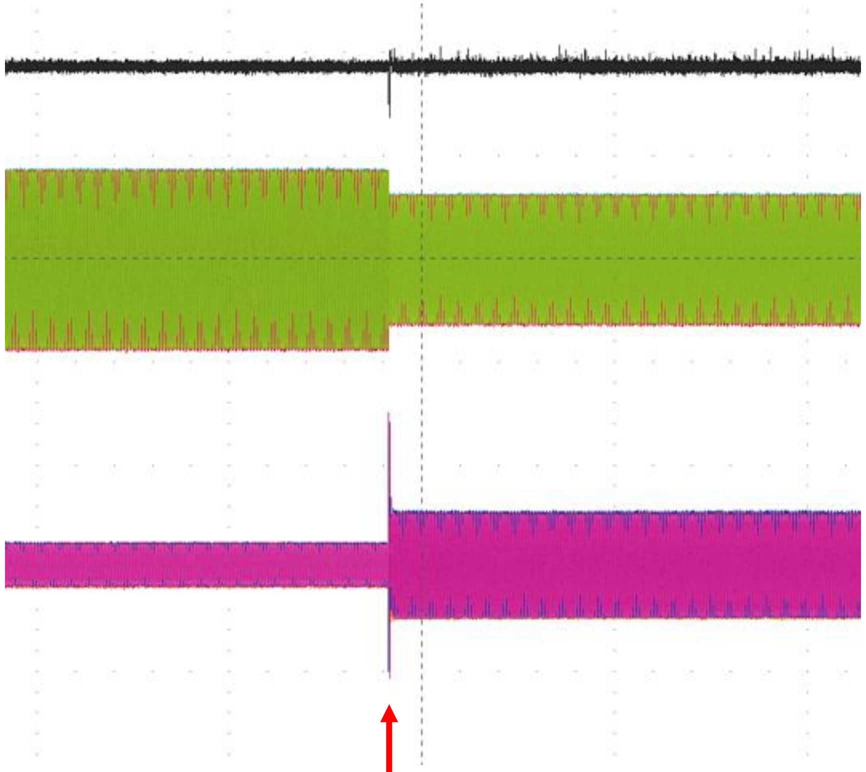


Hardware Verification Results

c) Short Circuit Current Limiting

Voltage

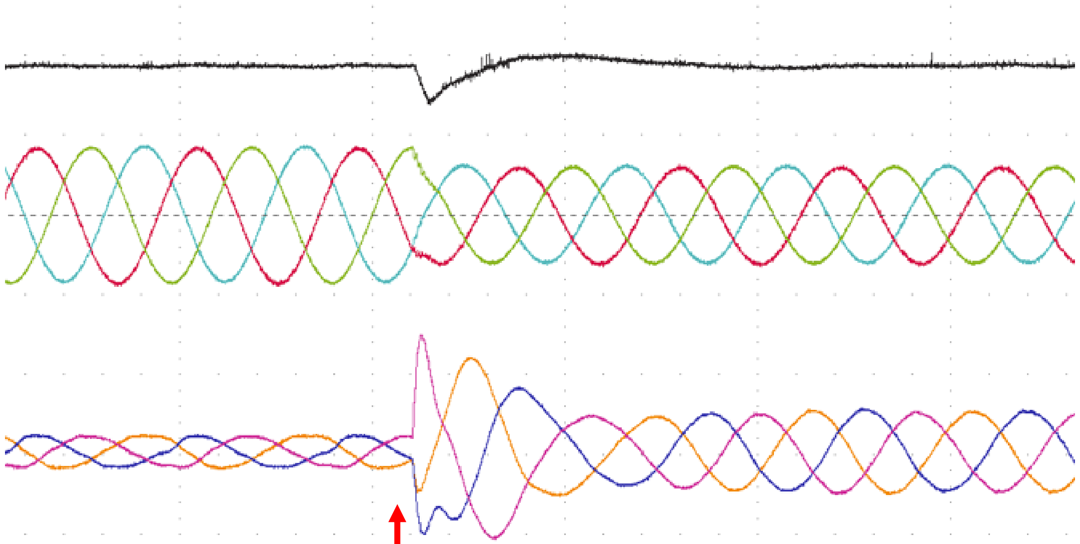
Current



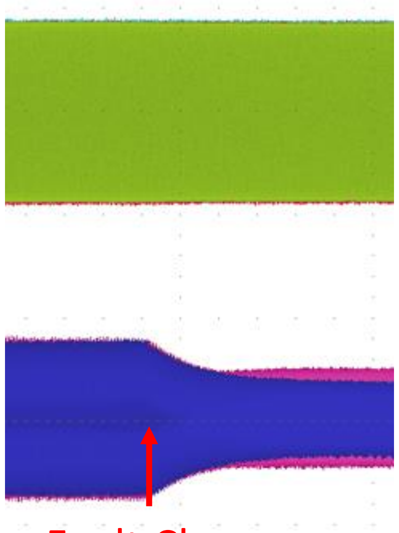
Fault Start with 30% voltage reduction

Voltage

Current



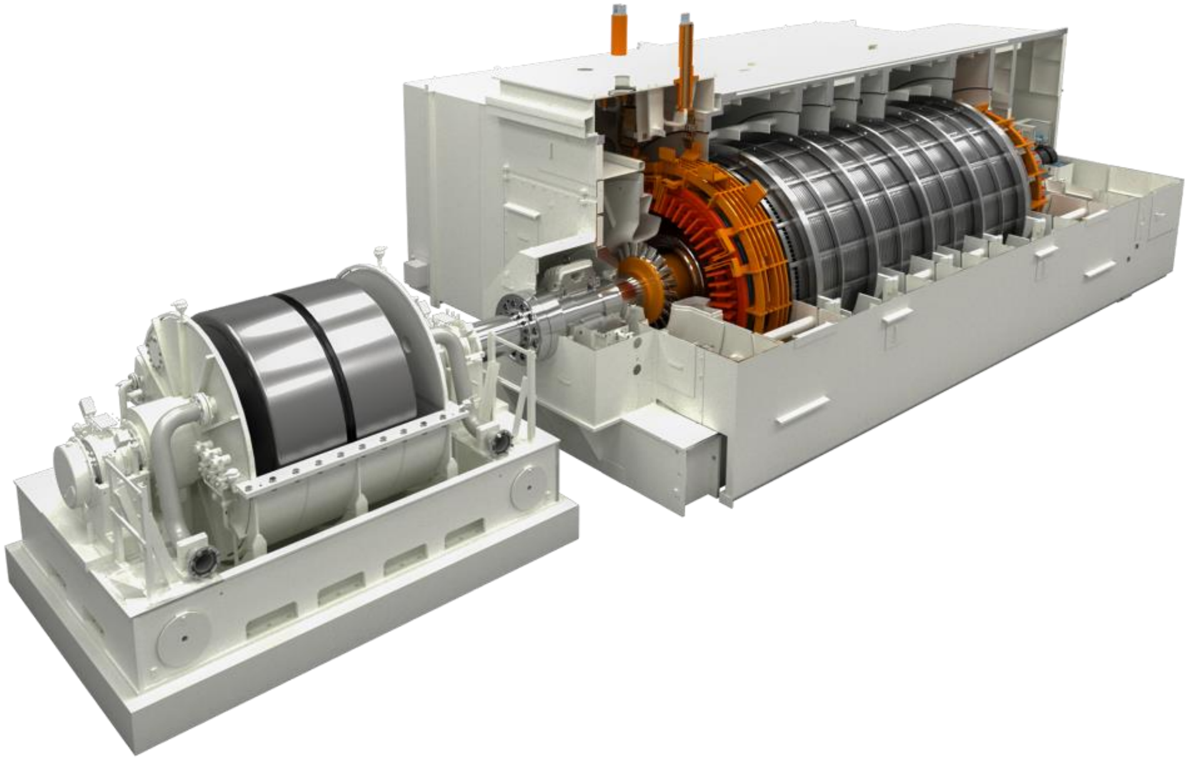
Fault Start with 30% voltage reduction



Fault Clears

Synchronous Condenser

Flying Wheel
Large rotating part



- **Short Circuit Power**
- **Voltage Support**
- **Short term overload Capability**
- **Inertia Response to the grid**

- **Replaced by FACTS for reactive power support STATCOM and SVC**

Energy Storage and Inertia

Swing Equation

$$P_m - P_e = J\omega_n \frac{d\omega}{dt} + D_f \omega_n \Delta\omega \quad (1)$$

SSC Inertia

$$P_{SCES} = C v_C \frac{dv_C}{dt} \quad (2)$$

$$\frac{d\omega}{dt} \propto \frac{dv_C}{dt} \quad (3)$$

$$J\omega_n \propto C v_C \quad (4)$$

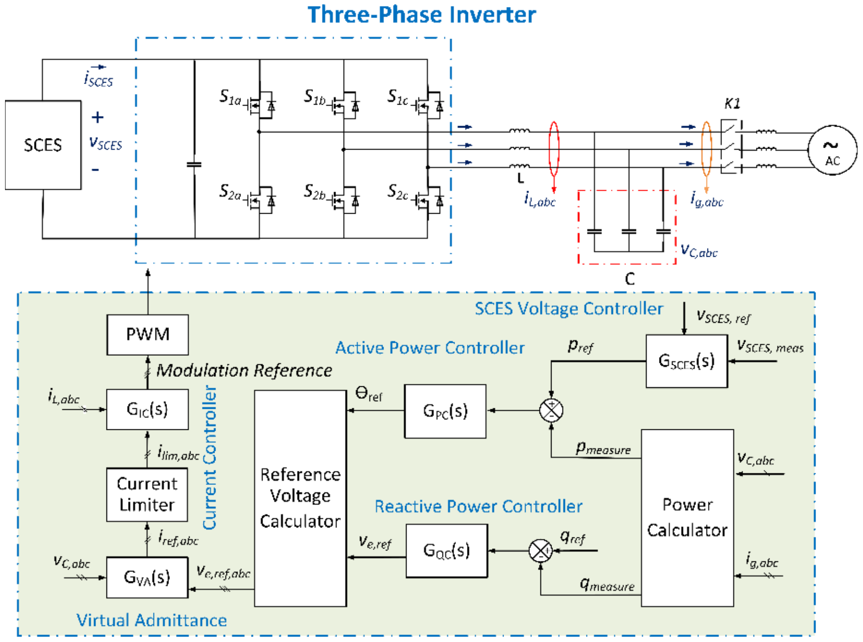
Super Capacitor provides inertia

Super Capacitor Voltage Limits

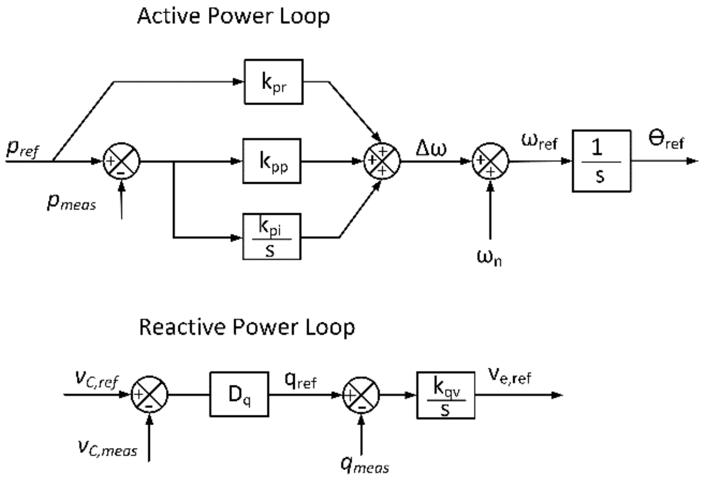
$$V_{DC,min} = 1.05\sqrt{2}V_{LL} \quad (5)$$

$V_{DC,max}$ set be inverter and SCES rating

$$V_{DC,nom} = \frac{\sqrt{2\left(V_{DC,max}^2 + V_{DC,min}^2\right)}}{2} \quad (6)$$



(a)



(b)

Energy Requirement for Inertia Support

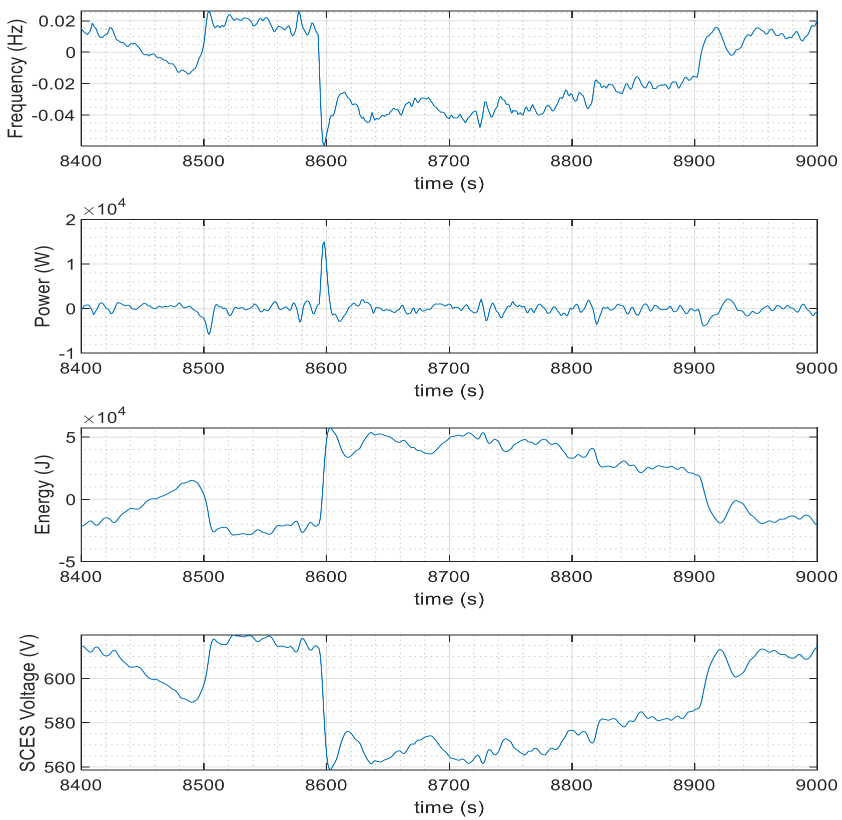
College Station Texas real time results

- ❖ Resolution 1s – f_{nom}= 60Hz
- ❖ Time 05/20/2019 Starting 7:20AM

Design 1

- Injecting 50kW to grid after 0.2Hz step change
- 5s inertia time

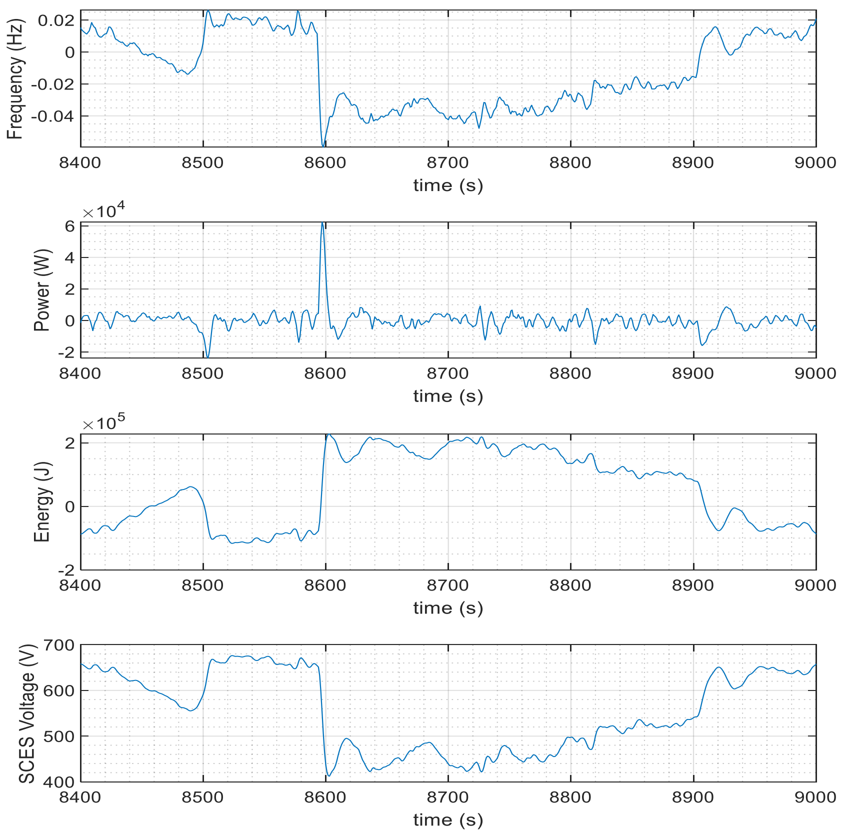
Lower Inertia Support



Design 2

- Injecting 300kW to grid after 0.2Hz step change
- 15s inertia time

Higher Inertia Support



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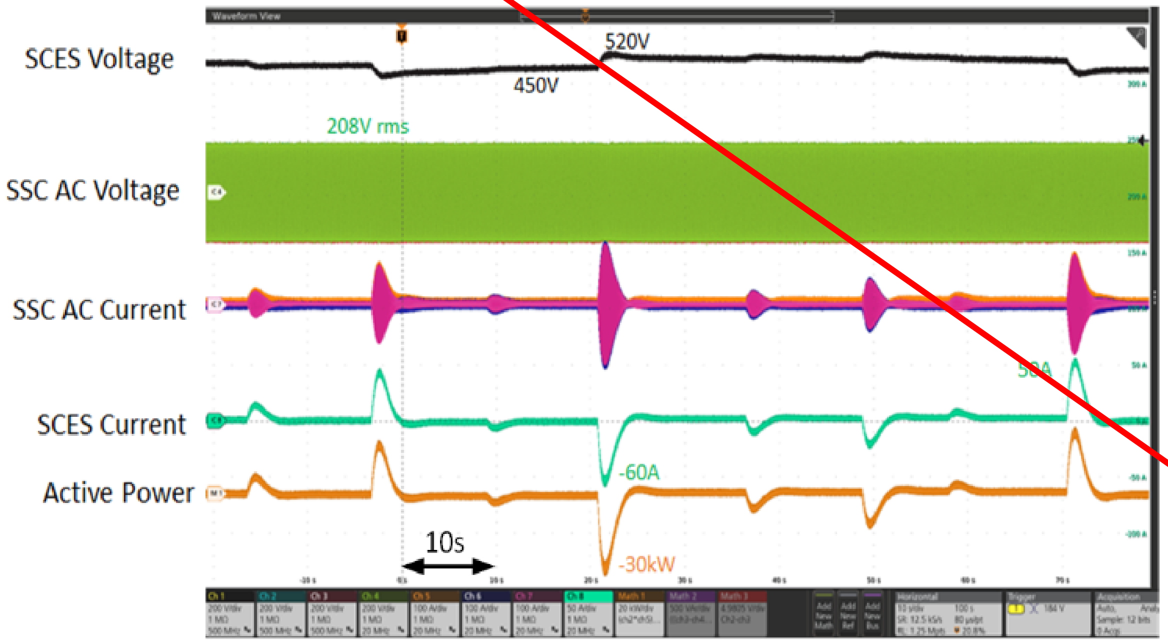
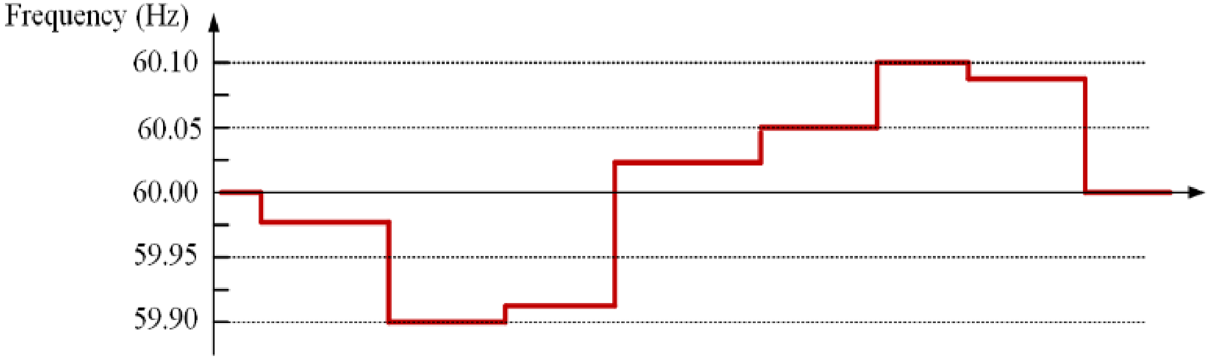
Hardware Verification Results

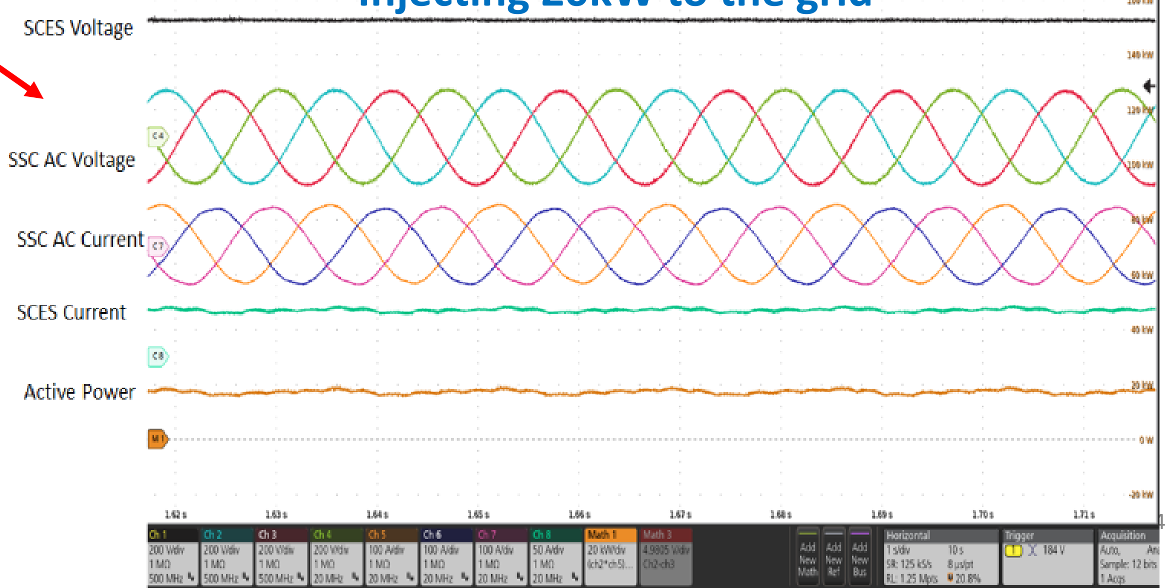
- $J = 295\ kg.m^2$
- $T_{set} = 4s$
- 30 kW at $\Delta\omega = 0.1Hz$

Parameter	Value
$V_{AC\ LL}$	208 V
f_{grid}	60 Hz
f_{sw}	20 kHz
L_{filter}	50 µH
$V_{DC,\ nom}$	450 V
$V_{DC,\ min}$	310 V
C	2.4 F





Injecting 20kW to the grid



Publications

- H. S. Rizi, Z. Chen, E. Nazerian, W. Xu and A. Q. Huang, "Solid State Condenser (SSC) - A New FACTS Device for Grid Inertia Support," *2023 IEEE Texas Power and Energy Conference (TPEC)*, College Station, TX, USA, 2023, pp. 1-6, doi: 10.1109/TPEC56611.2023.10078567.
- Z. Chen, H. S. Rizi, W. Xu, R. Yu and A. Q. Huang, "Hardware Design of a 150kW/1500V All-SiC Grid-forming Photovoltaic Synchronous Generator (PVSG)," *2022 IEEE Applied Power Electronics Conference and Exposition (APEC)*, Houston, TX, USA, 2022, pp. 1977-1984, doi: 10.1109/APEC43599.2022.9773550.
- Z. Chen, H. S. Rizi, C. Chen, P. Liu, R. Yu and A. Q. Huang, "An 800V/300 kW, 44 kW/L Air-Cooled SiC Power Electronics Building Block (PEBB)," *IECON 2021 – 47th Annual Conference of the IEEE Industrial Electronics Society*, Toronto, ON, Canada, 2021, pp. 1-6, doi: 10.1109/IECON48115.2021.9589811.
- C. Chen, Z. Chen, H. S. Rizi and A. Q. Huang, "Comparative Study of 100kW Three-Level Bidirectional DC-DC Converters for Battery Storage Integration with 1500V PV Inverter," 2023 IEEE Applied Power Electronics Conference and Exposition (APEC), Orlando, FL, USA, 2023, pp. 3061-3068, doi: 10.1109/APEC43580.2023.10131202.
- X. Quan, R. Yu, X. Zhao, Y. Lei, T. Chen, C. Li, A. Q. Huang, "Photovoltaic Synchronous Generator: Architecture and Control Strategy for a Grid-Forming PV Energy System," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 8, no. 2, pp. 936-948, June 2020, doi: 10.1109/JESTPE.2019.2953178.
- X. Quan, X. Zhao, L. Zhang, R. Xu, Y. Lei and A. Q. Huang, "Novel Power Control of Voltage-Controlled Inverters for Grid Inertia Support," 2019 IEEE Applied Power Electronics Conference and Exposition (APEC), Anaheim, CA, USA, 2019, pp. 927-931, doi: 10.1109/APEC.2019.8722003.

Thanks for your attention !

Questions?