Center for Power Electronics Systems
The Bradley Department of Electrical and Computer Engineering
College of Engineering
Virginia Tech, Blacksburg, Virginia, USA

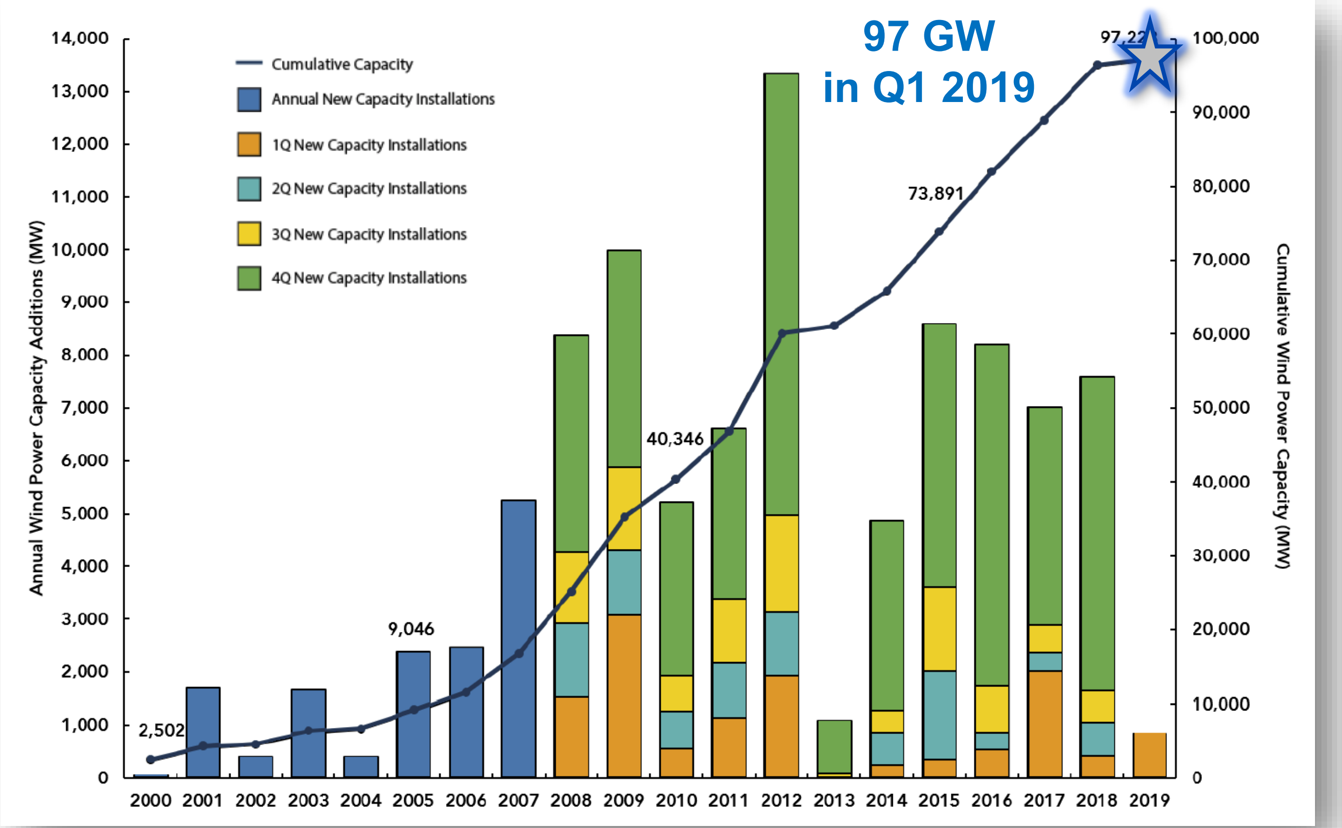
"High-Efficiency Modular SiC-based Power-Converter for Flexible-CHP Systems with Stability-Enhanced Grid-Support Functions"

Flexible CHP Portfolio Meeting

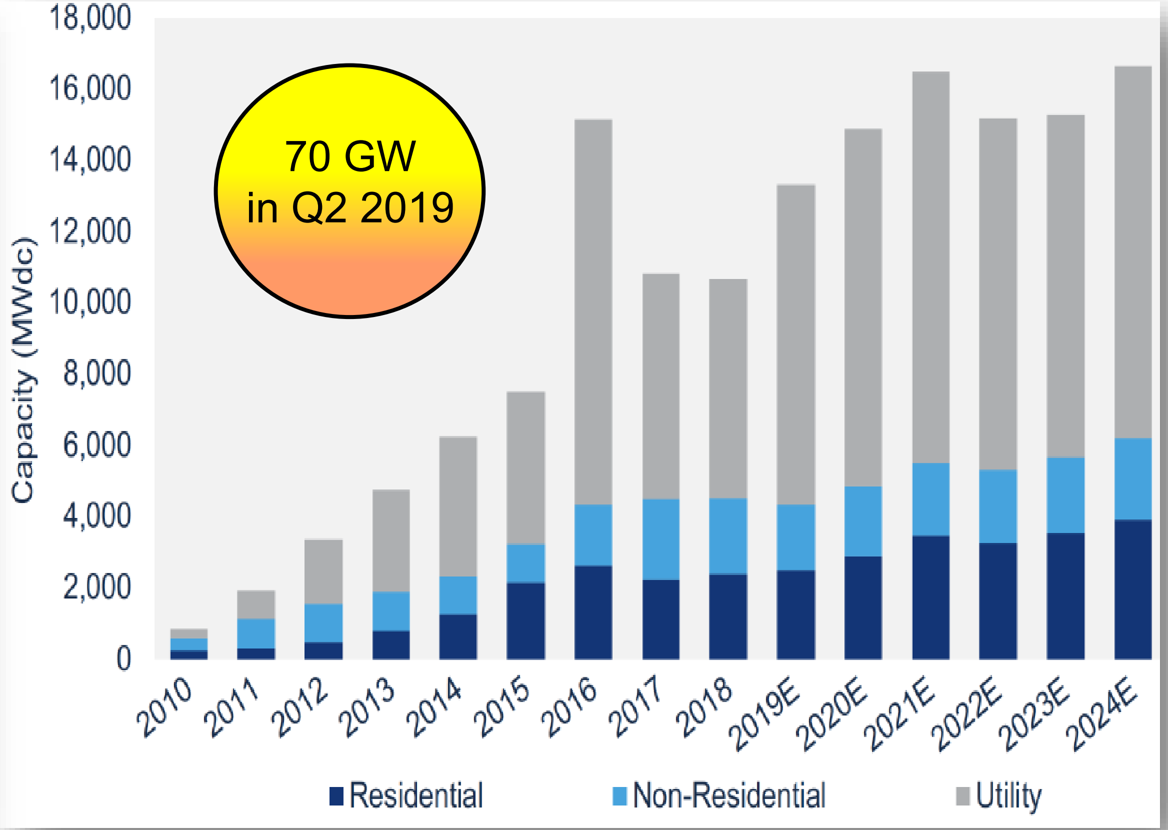
Rolando Burgos, Bo Wen, Virgilio Centeno, Dushan Boroyevich,
Tobias Ahlgrim, and Gopal Mondal

Wind and Solar Power Growth in the United States

WIND Generation Capacity

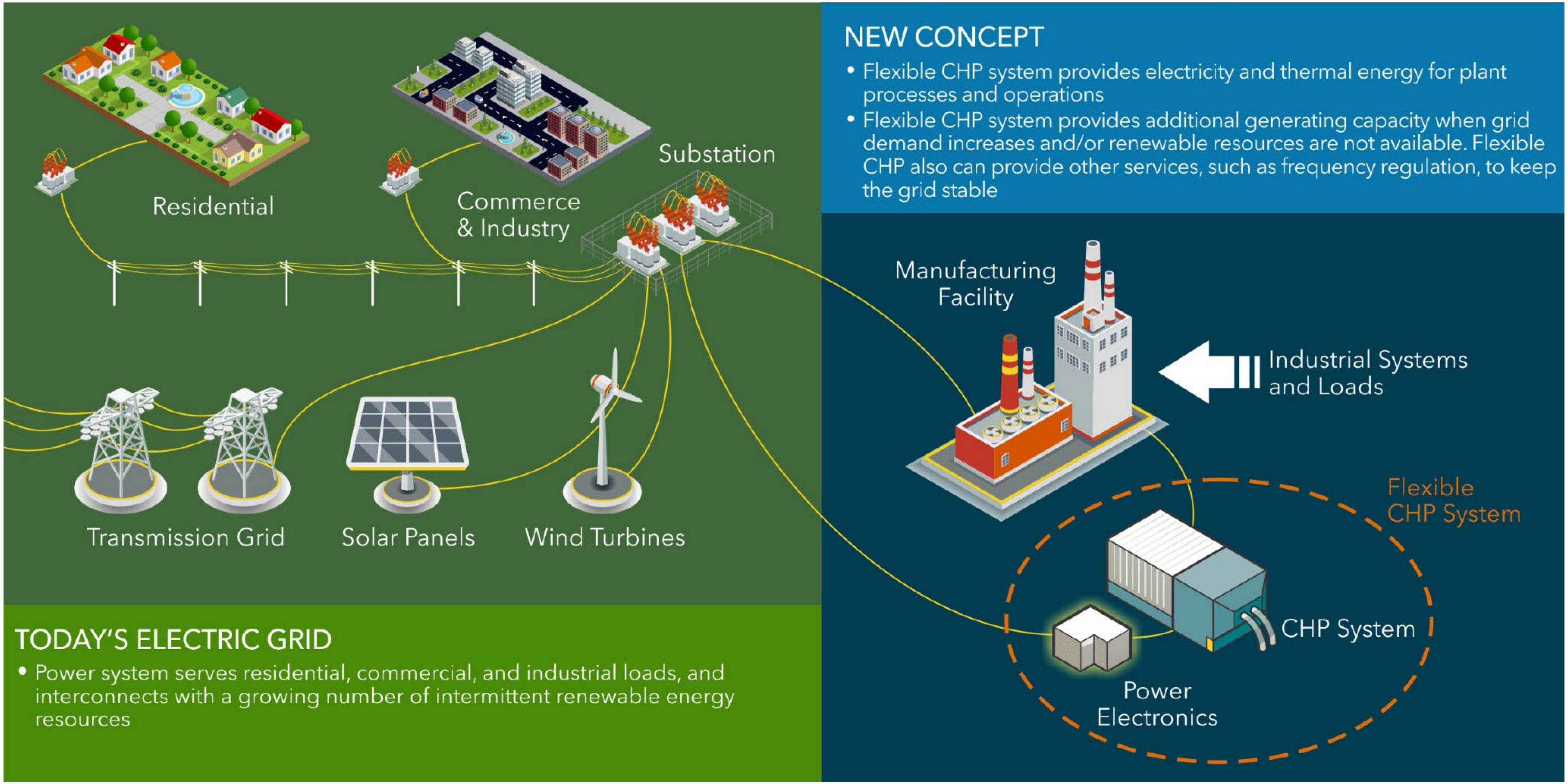


PV Generation Capacity



U.S. Generation Capacity = 1,203 GW

Flexible Combined Heat and Power (F-CHP) Vision

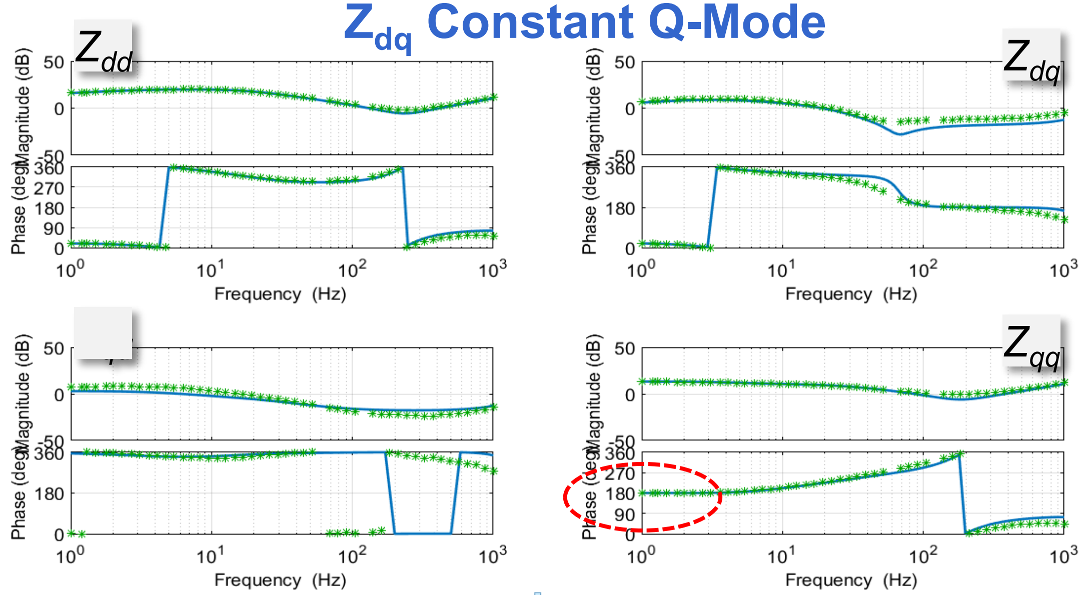


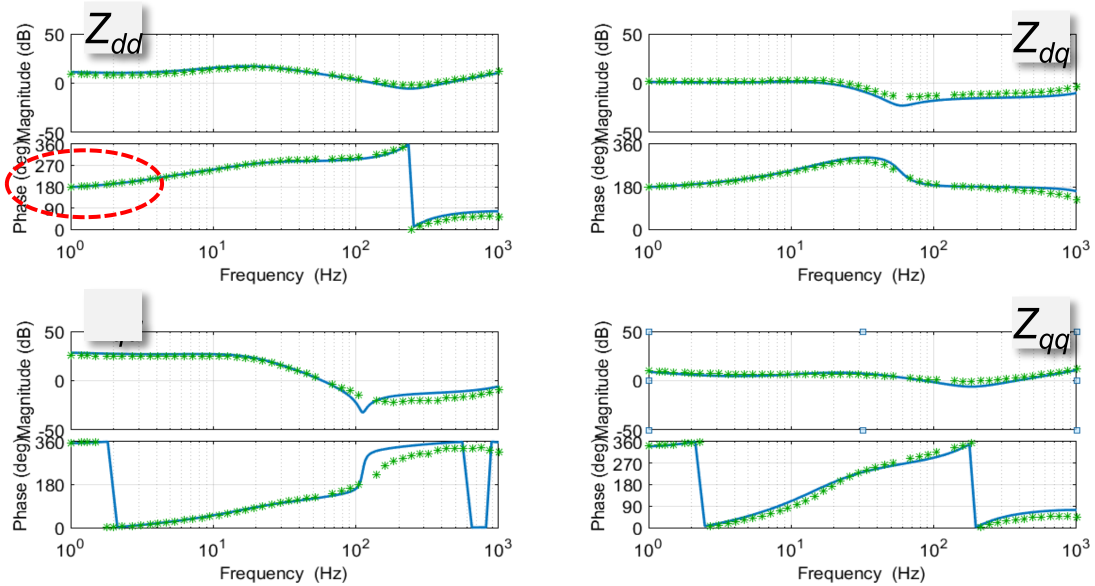
Project Goals

1. To develop an F-CHP power converter featuring:
   - Full compliance with the IEEE Standard 1547, category B, for operation in local areas with high aggregated DER penetration
   - Full compliance with the IEEE Standard 2030.7 for the specification of microgrid controllers
   - **Stability-enhanced grid-support functions** avoiding the onset of dynamic interactions with the grid and other system components
2. To enable F-CHP systems for both microgrid and standalone applications
3. To develop a **modular**, **scalable** MV power converter concept based on 10 kV SiC MOSFET devices achieving:
   - Efficiency > 99 %, and power density > 10 kW/l

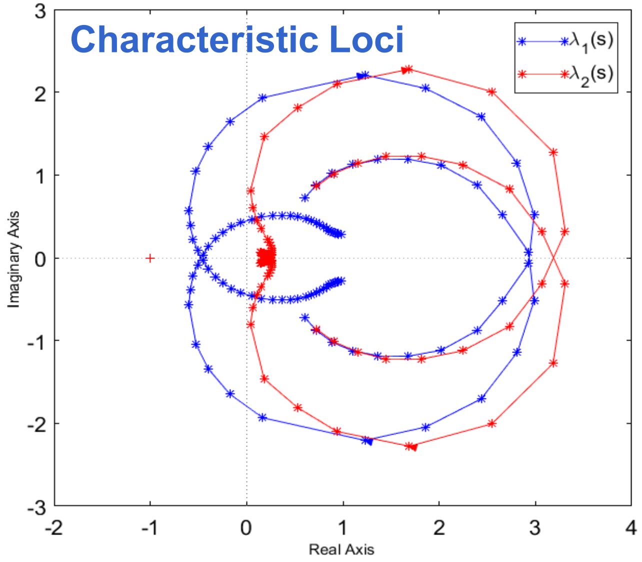
Instability Triggered by use of Droop-Mode Voltage Control

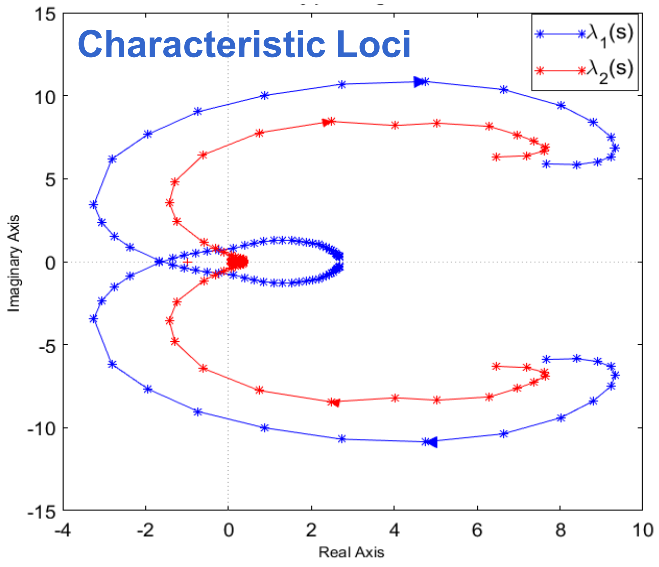
Z_{dq} Constant Q-Mode

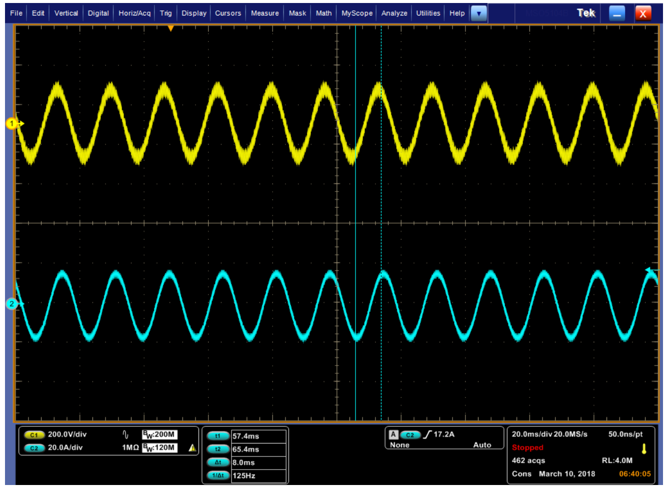




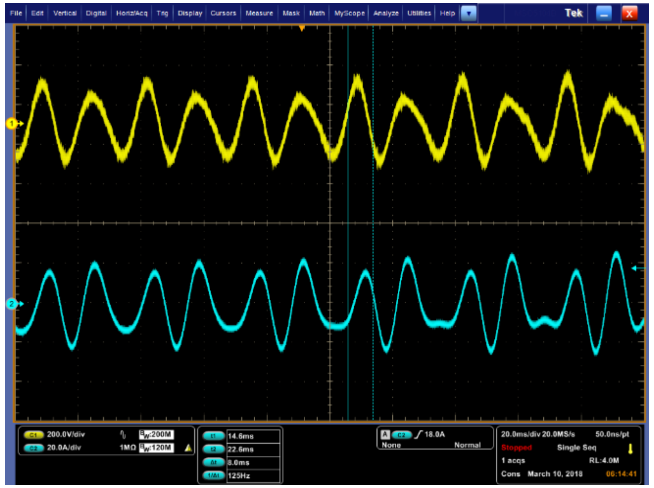
Z_{dq} Droop Q-V Mode







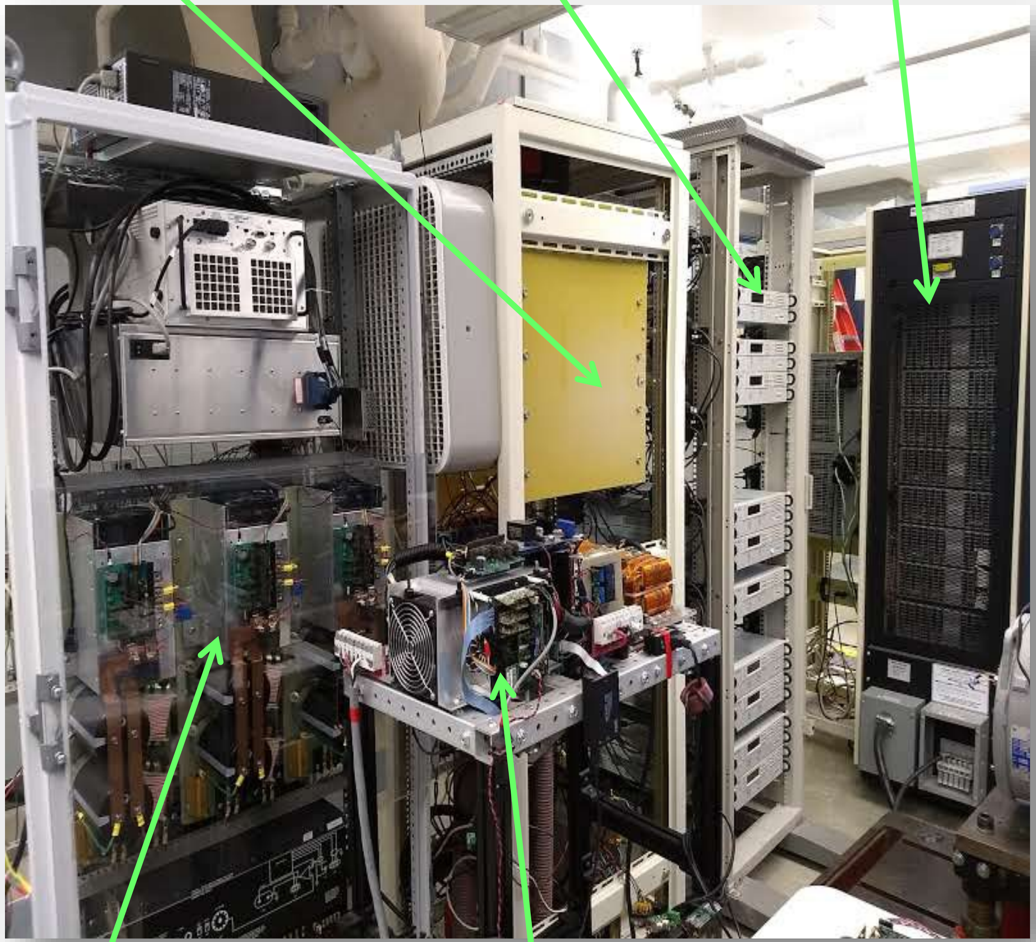
Constant Q Mode



Droop Q-V Mode

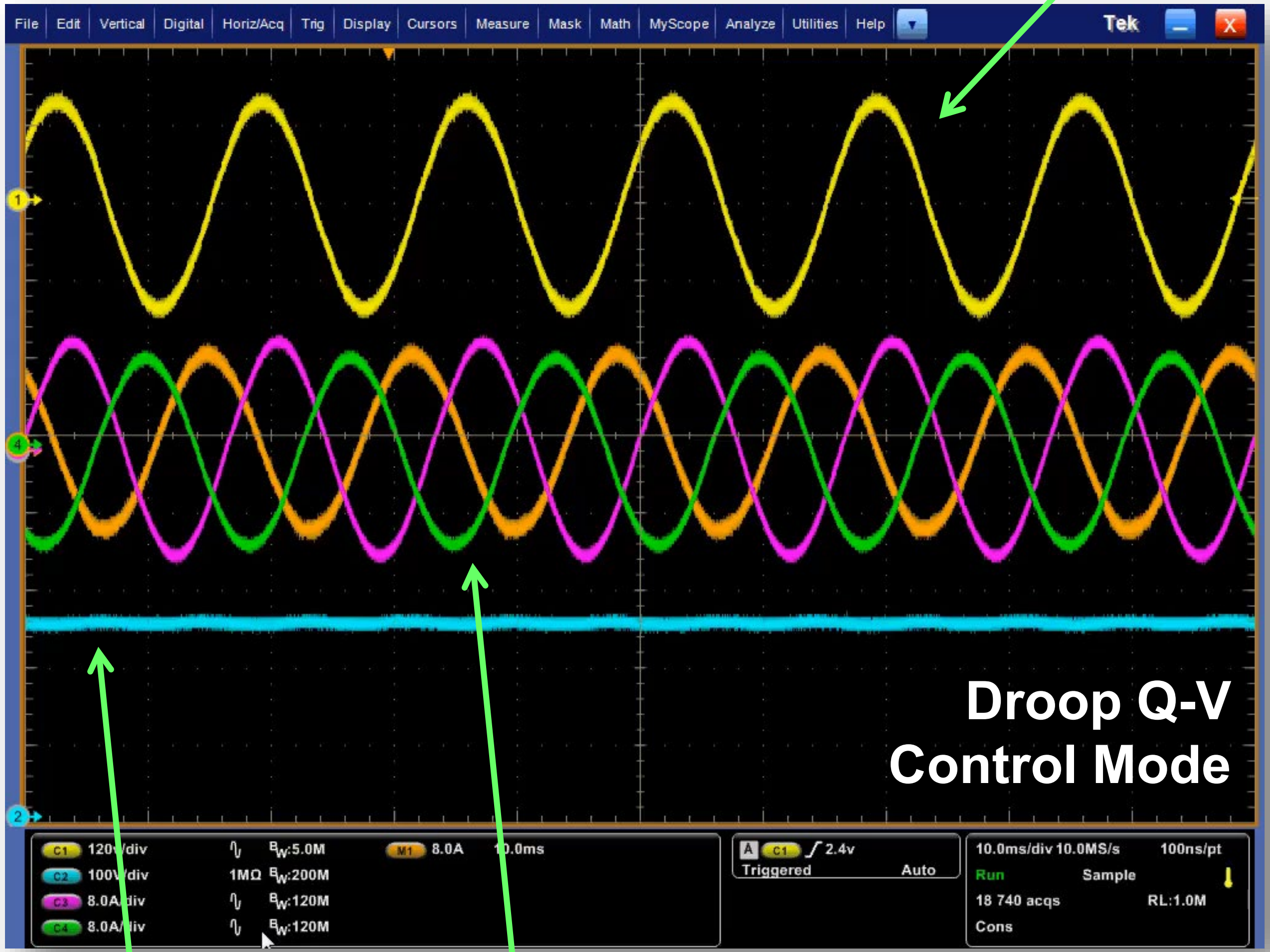
PV Inverter Tests in Droop Q-V Mode

AC Feeder PV Emulator AC Source



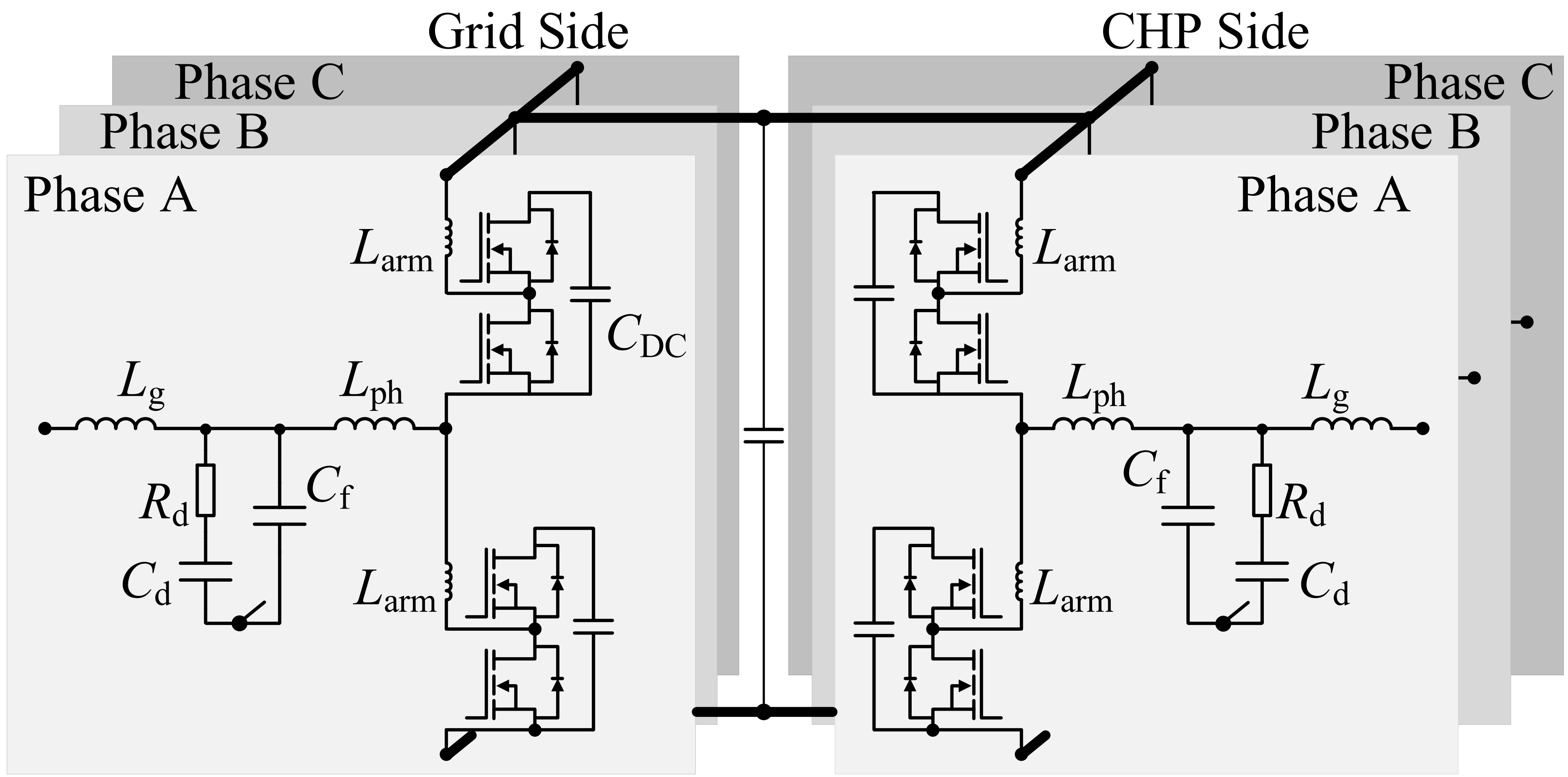
IMU PV Inverter

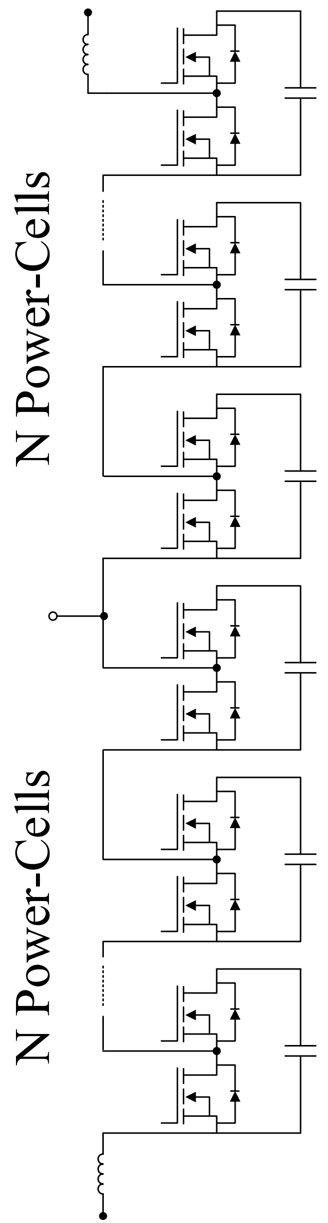
AC Voltage



DC Bus AC Currents

The Modular Scalable AC-AC Circuit





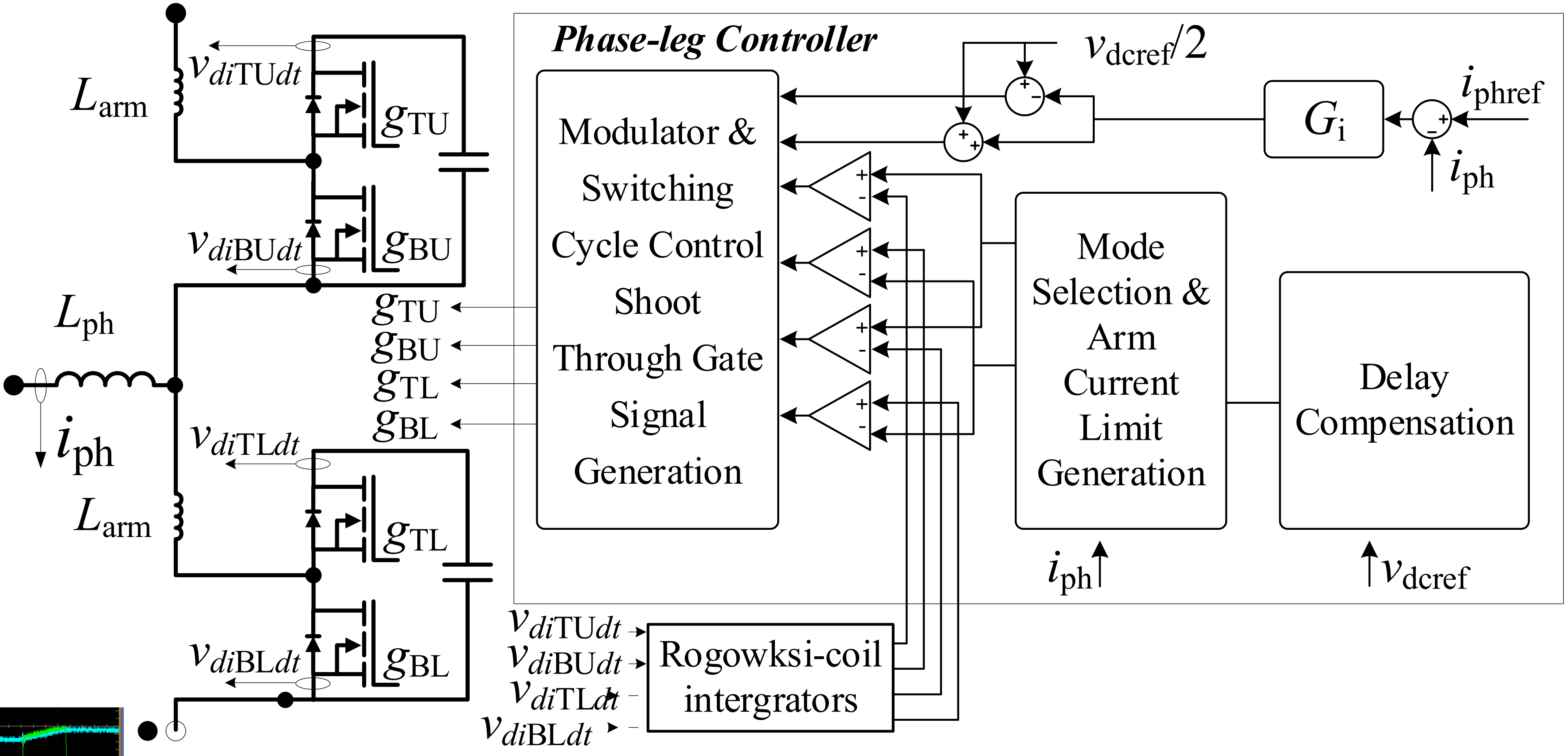
The Prototype AC-AC Circuit Constructed

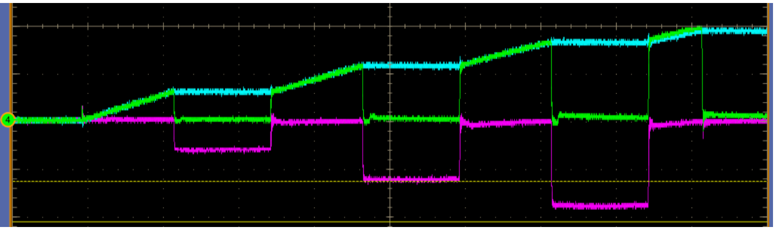
Constructed converter prototype, inverter side

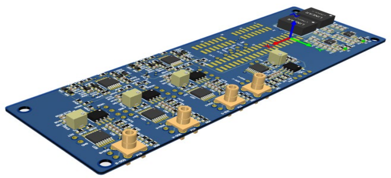
Symbol	Description	Value
V_{dc}	F-CHP converter dc-link voltage	1000 V
V_{ac}	Grid and CHP generator voltage	480 V
P	Active power rating	100 kW
Q	Reactive power rating	±75 kVar
f	Line frequency	50/60 Hz
L_g	Grid side filter inductance	4 μH
R_d	Grid side filter damping branch resistance	0.56 Ω
C_d	Grid side filter damping branch capacitance	20 μF
C_f	Grid side filter capacitance	20 μF
L_{ph}	Phase-leg output inductance	200 μH
L_{arm}	Arm inductance	10 μH
f_{sw}	Switching frequency	20 kHz
C_{dc}	Cell dc capacitance	74 μF
N	Number of cells per arm	1
device	1.7 kV SiC CAS300M17BM2	\

S. Zhou, B. Wen, J. Wang "Design and hardware implementation of the peak current mode switching cycle control for voltage balancing of modular multilevel converters", APEC 2021.

Peak Current Mode (PCM) Switching Cycle Control (SCC)

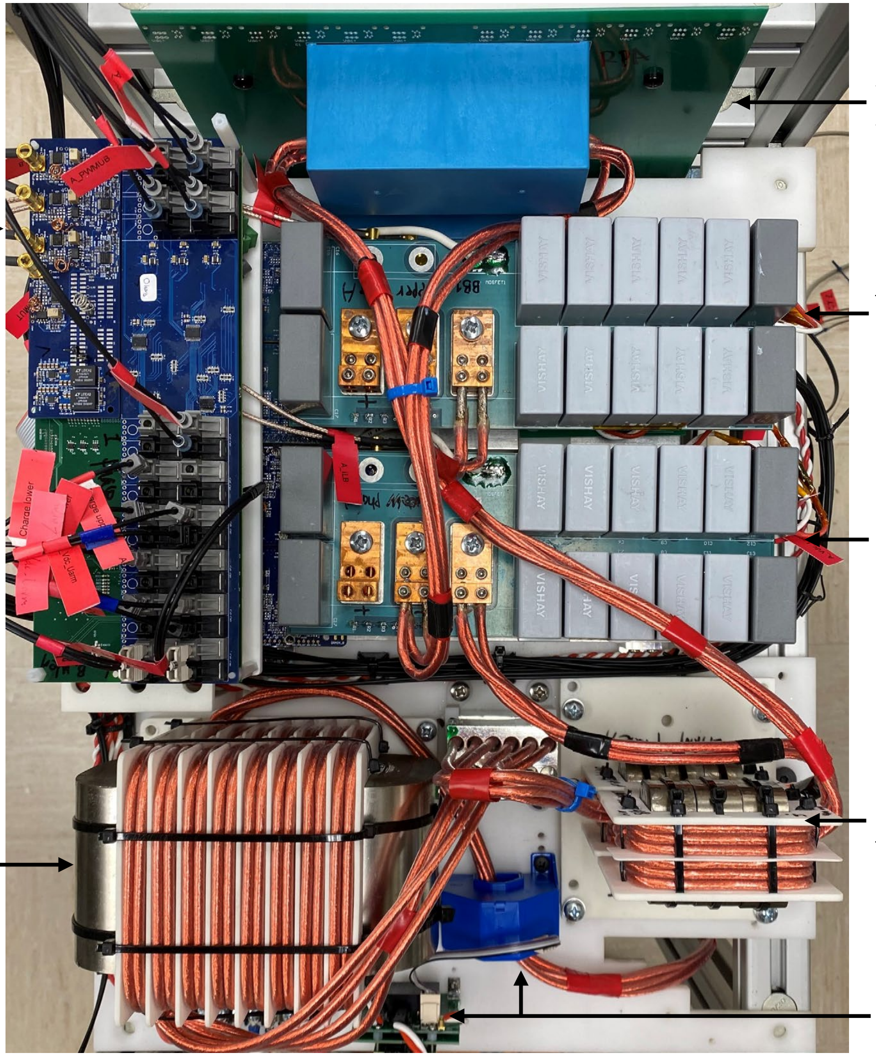


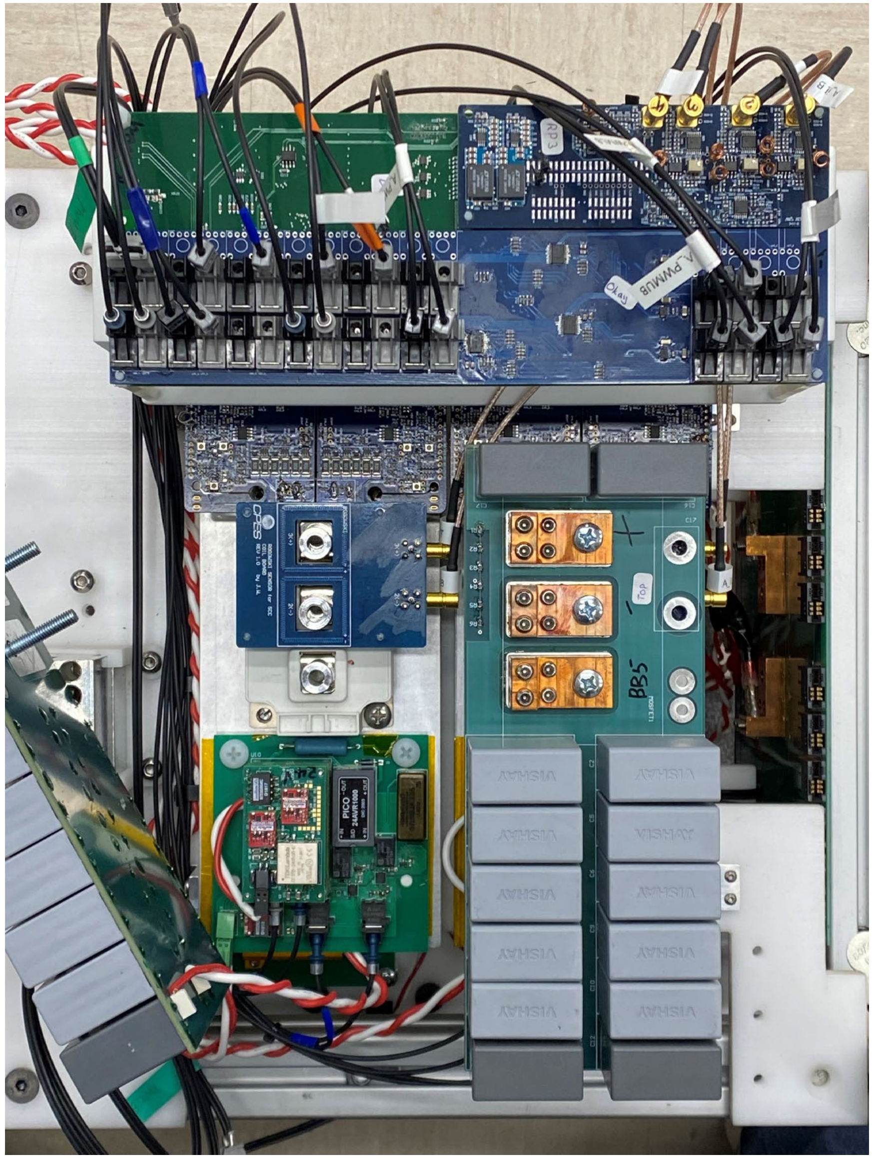




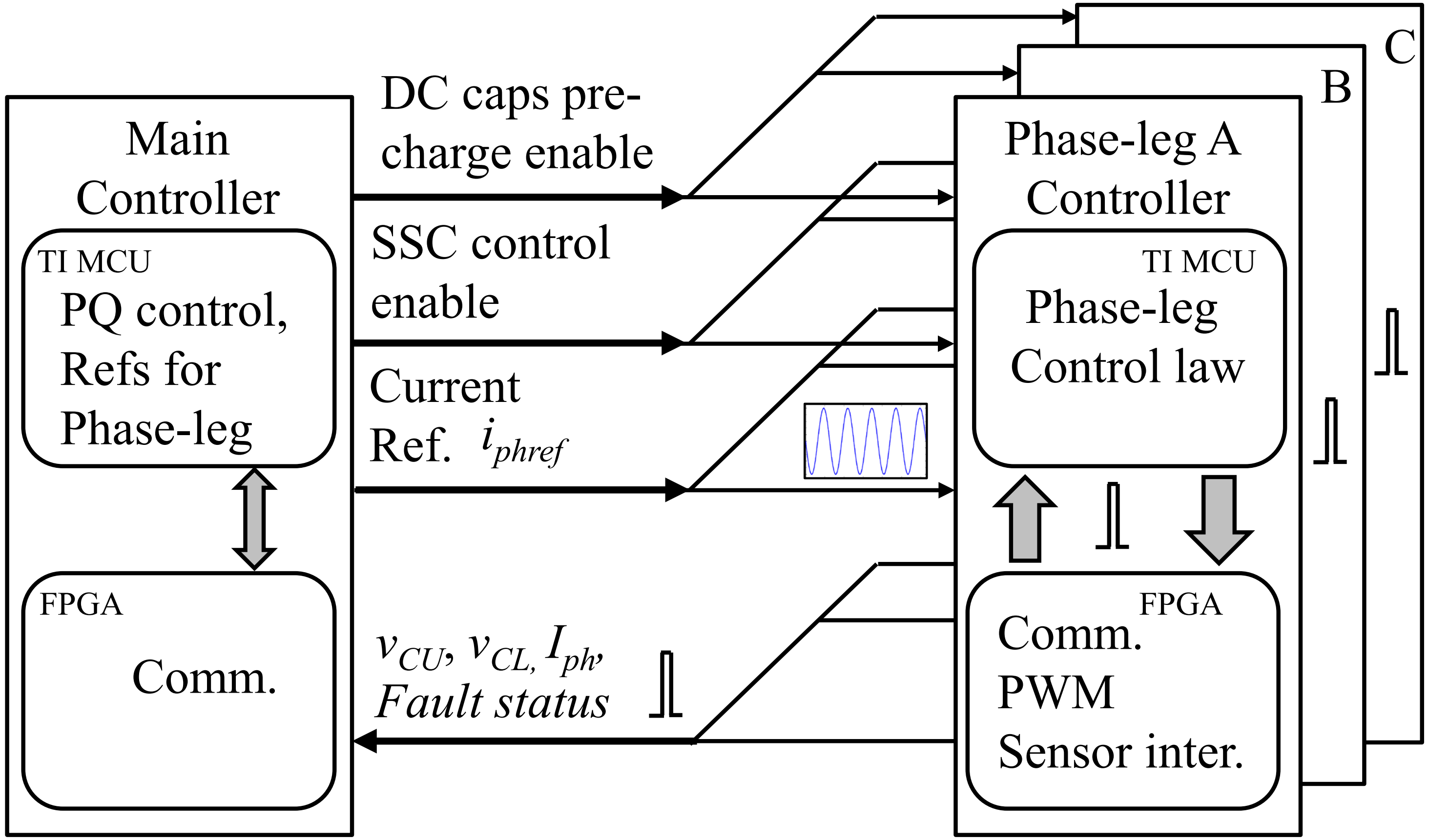
S. Zhou, B. Wen, J. Wang "Design and hardware implementation of the peak current mode switching cycle control for voltage balancing of modular multilevel converters", APEC 2021.

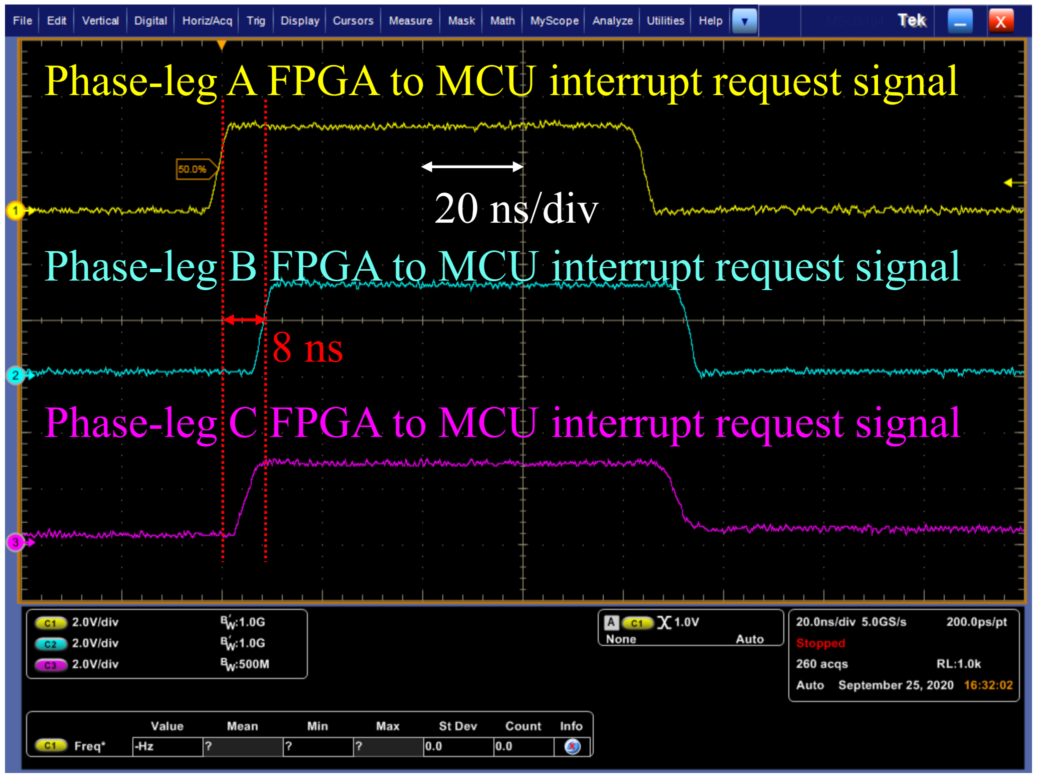
Phase-Leg with PCM and SCC





Distributed Control System





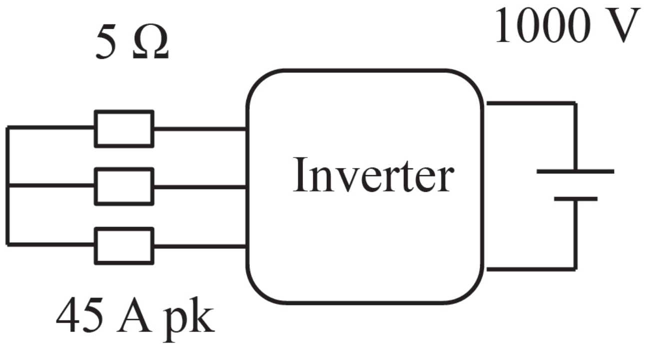
IEEE 1588 Precision Time Protocol (PTP) Synchronization Proposed in 2002 for synchronization.

Digital controller

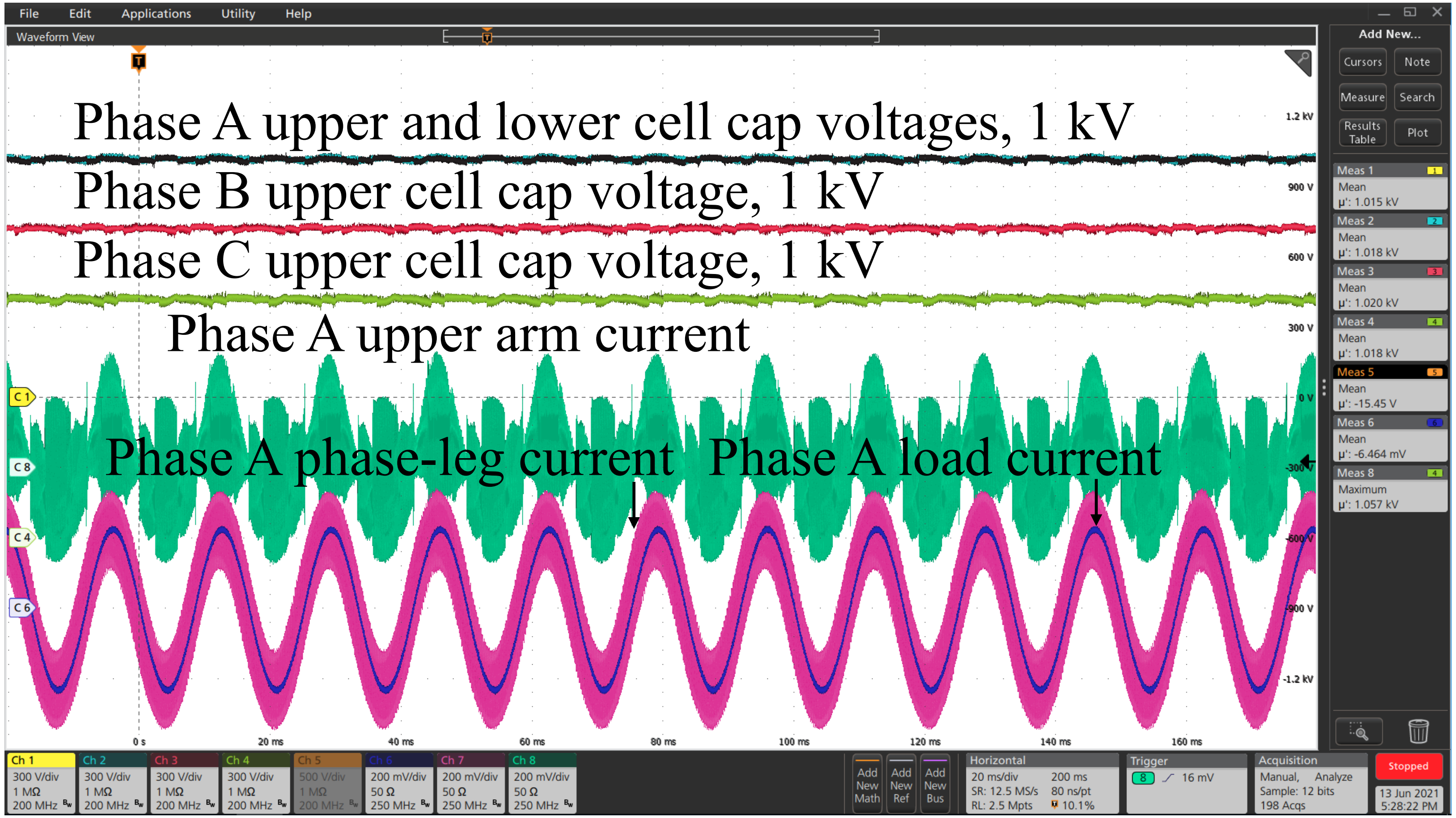
- TI TMS320 DSP (Control algorithm)
- Altera MAX 10 FPGA (Communication protocol)

Y. Rong, J. Wang, Z. Shen, S. Zhou, B. Wen "A synchronous distributed communication and control system for SiC-based modular impedance measurement units", IEEE Journal of Emerging and Selected Topics in Power Electronics, early access.

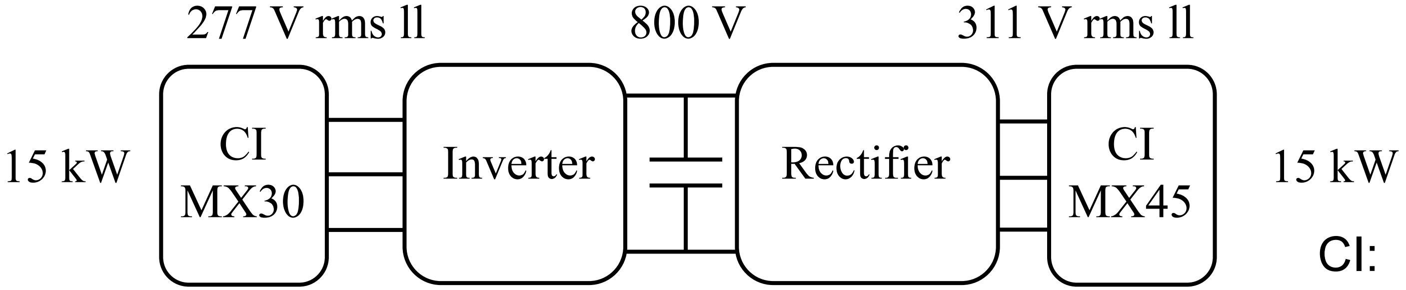
Three-phase Test Results with PCM and SCC



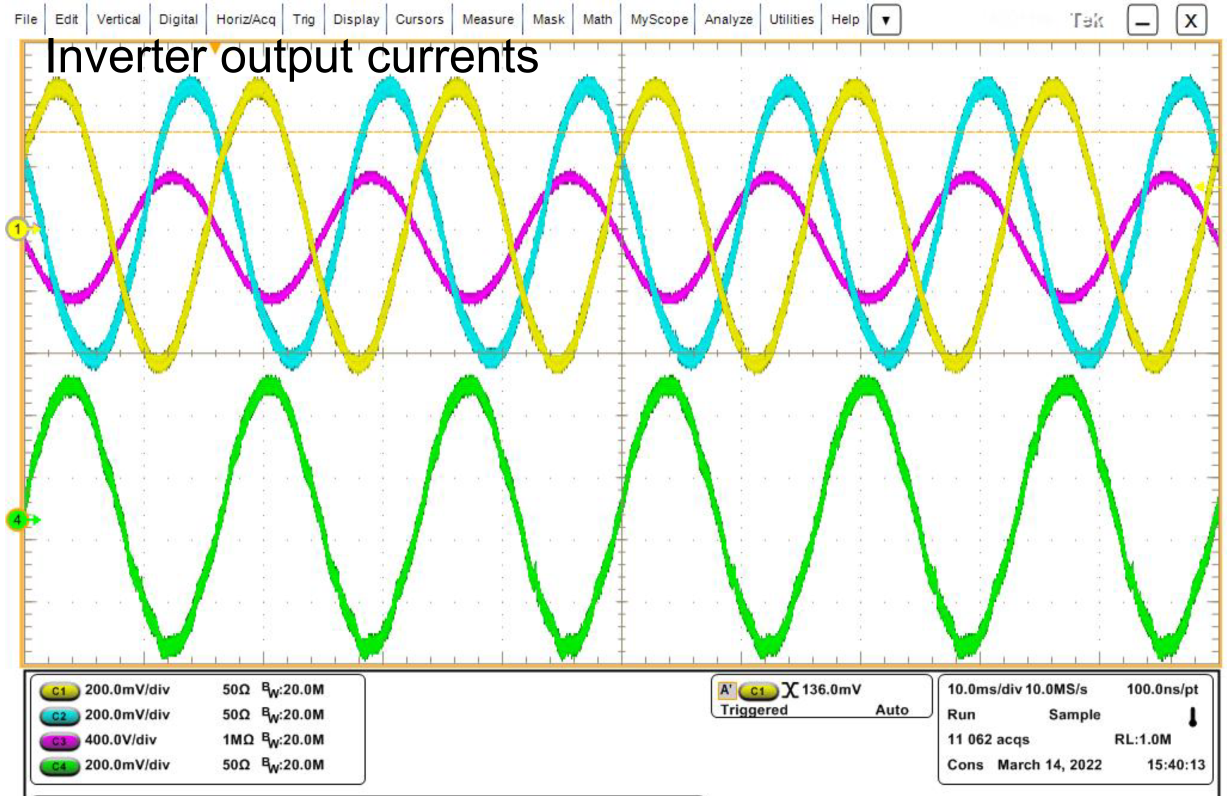
Designs	DC Cap	L_{Arm}
MMC	1 mF	100 µH
SCC	74 µF	10 µH



AC to AC Operation with Two AC Power Supplies

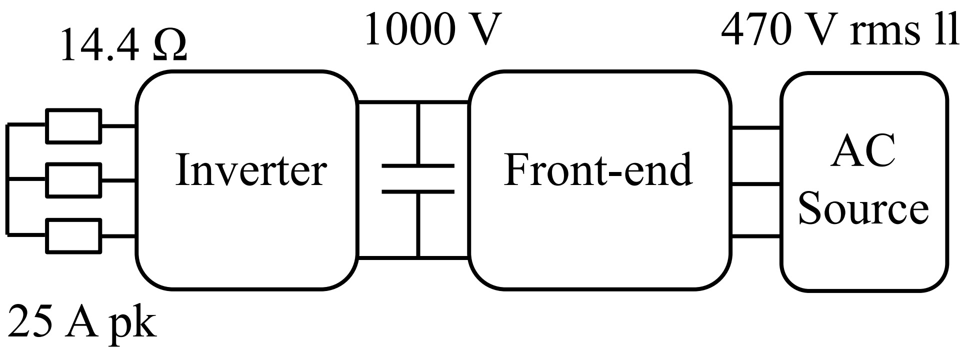


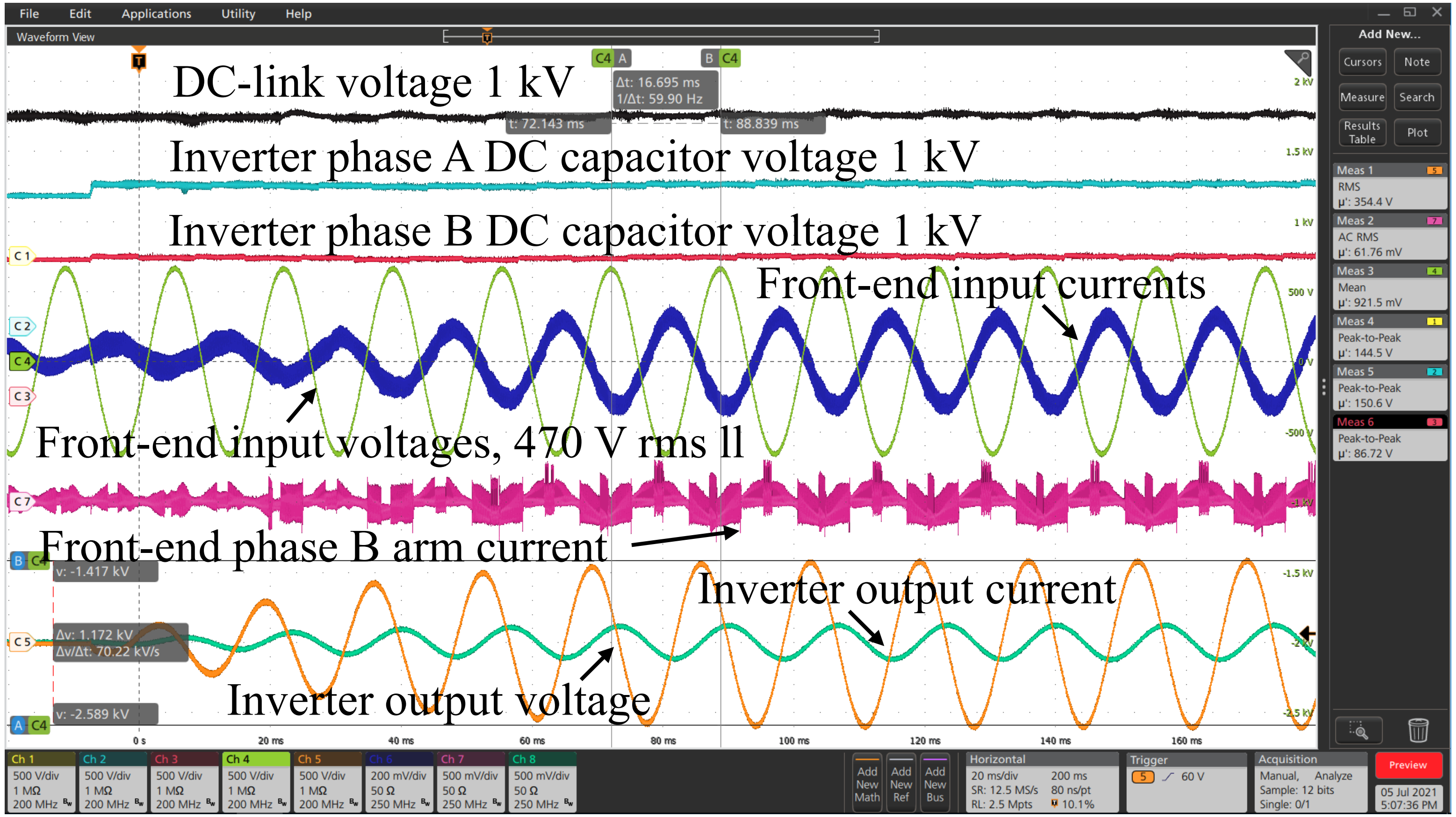
CI: California Instrument



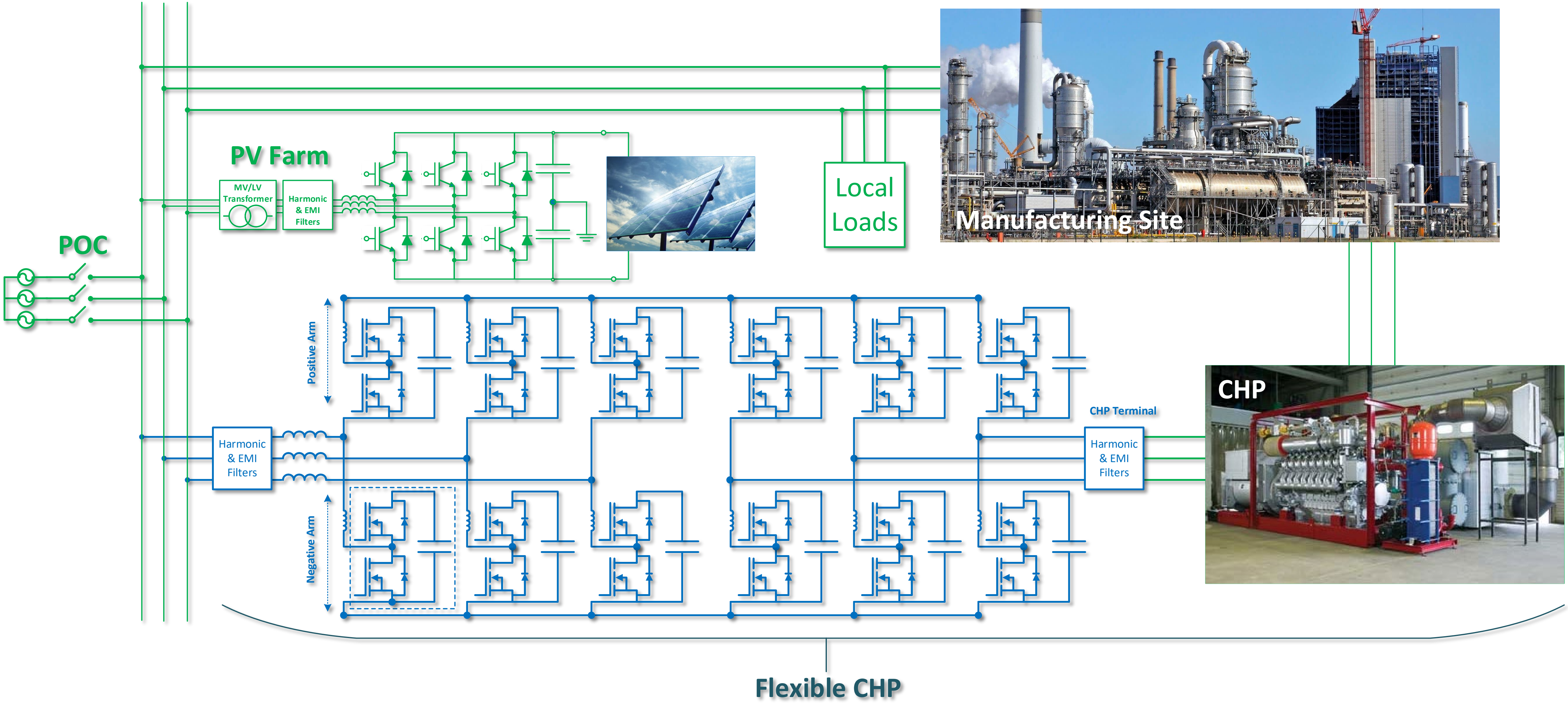
		Value	Mean	Min	Max	St Dev	Count	Info
C4	RMS	295.9mV	294.83836m	11.92m	296.0m	4.192m	11.06k	
C3	RMS	286.4V	286.21473	62.91	302.8	116.2m	11.06k	
C2	RMS*	313.0mV	312.042m	13.52m	361.1m	4.565m	11.06k	

AC to AC Operation @ 1 kV DC, 470 V rms AC

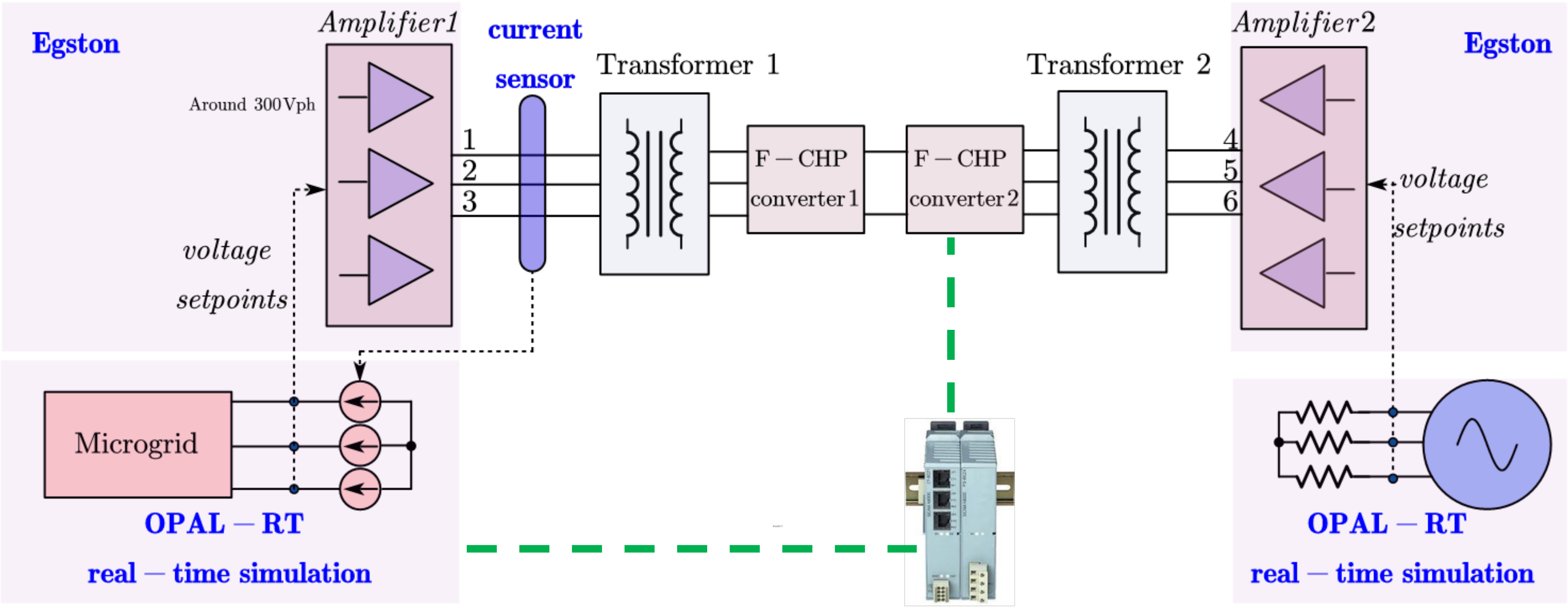




Microgrid Power Hardware-in-the-Loop (P-HIL) Test Bed



P-HIL Test Bed Implementation



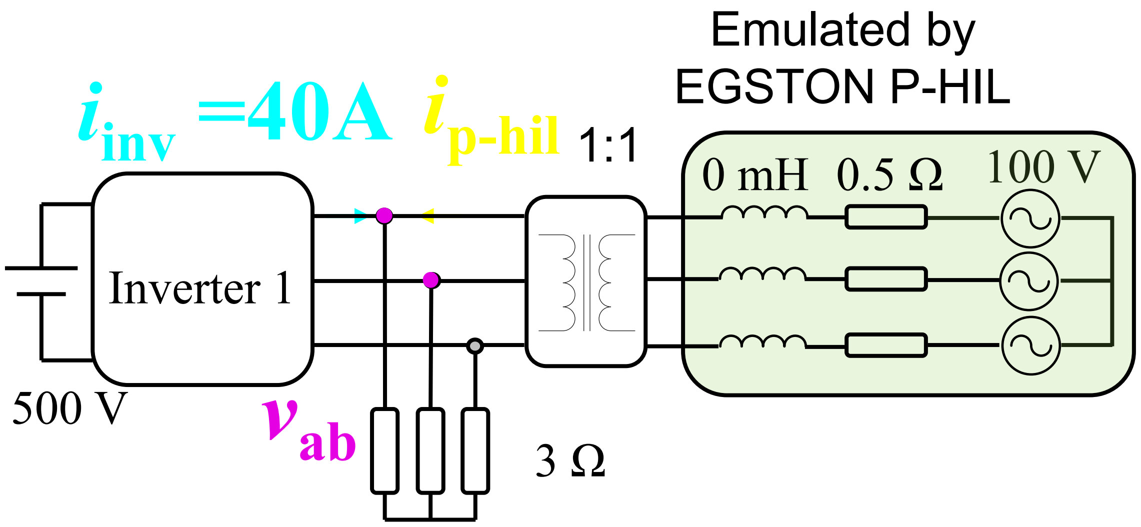
Egston Amplifier

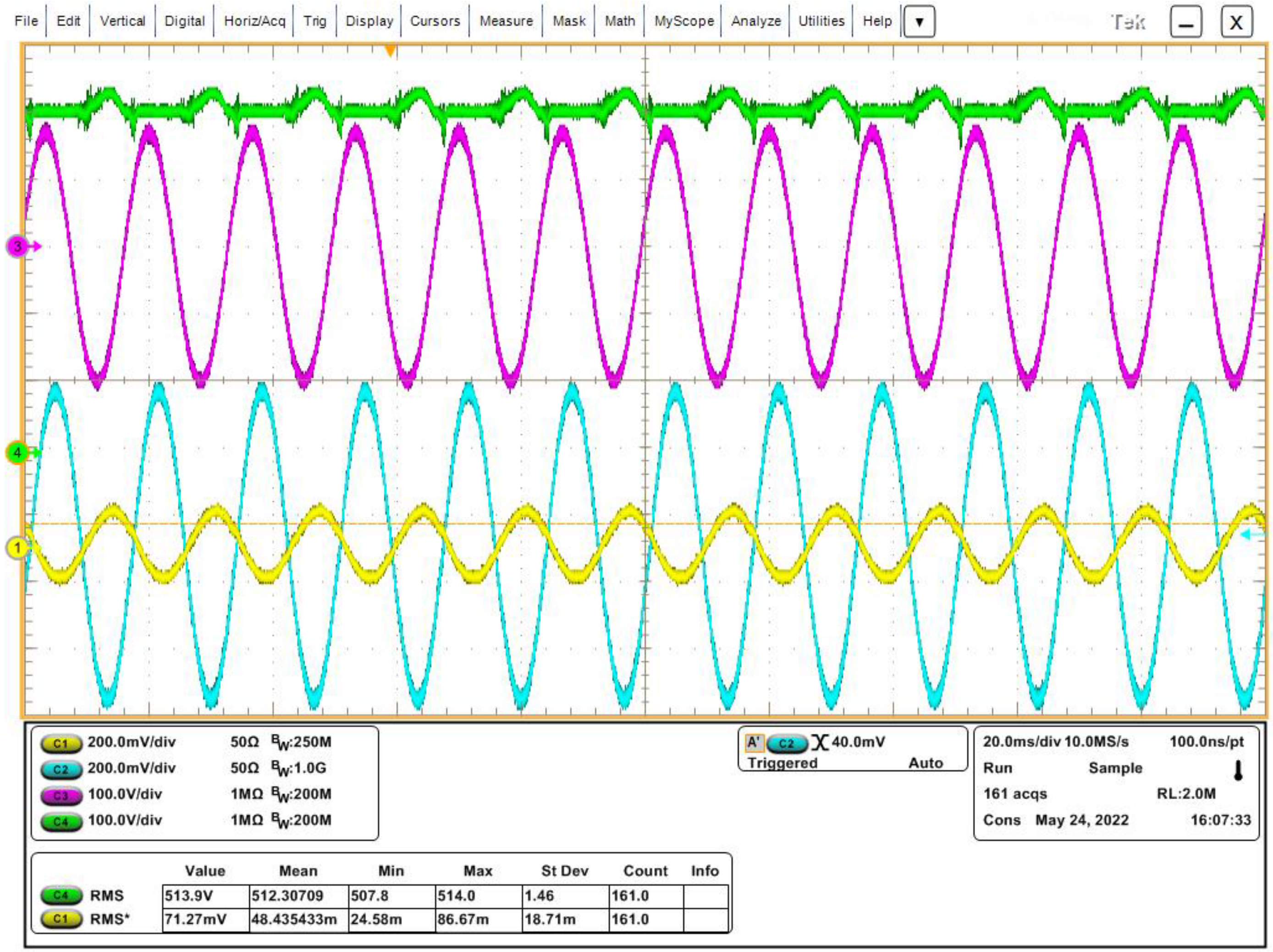
OPAL-RT & Current Sensor

Transformer

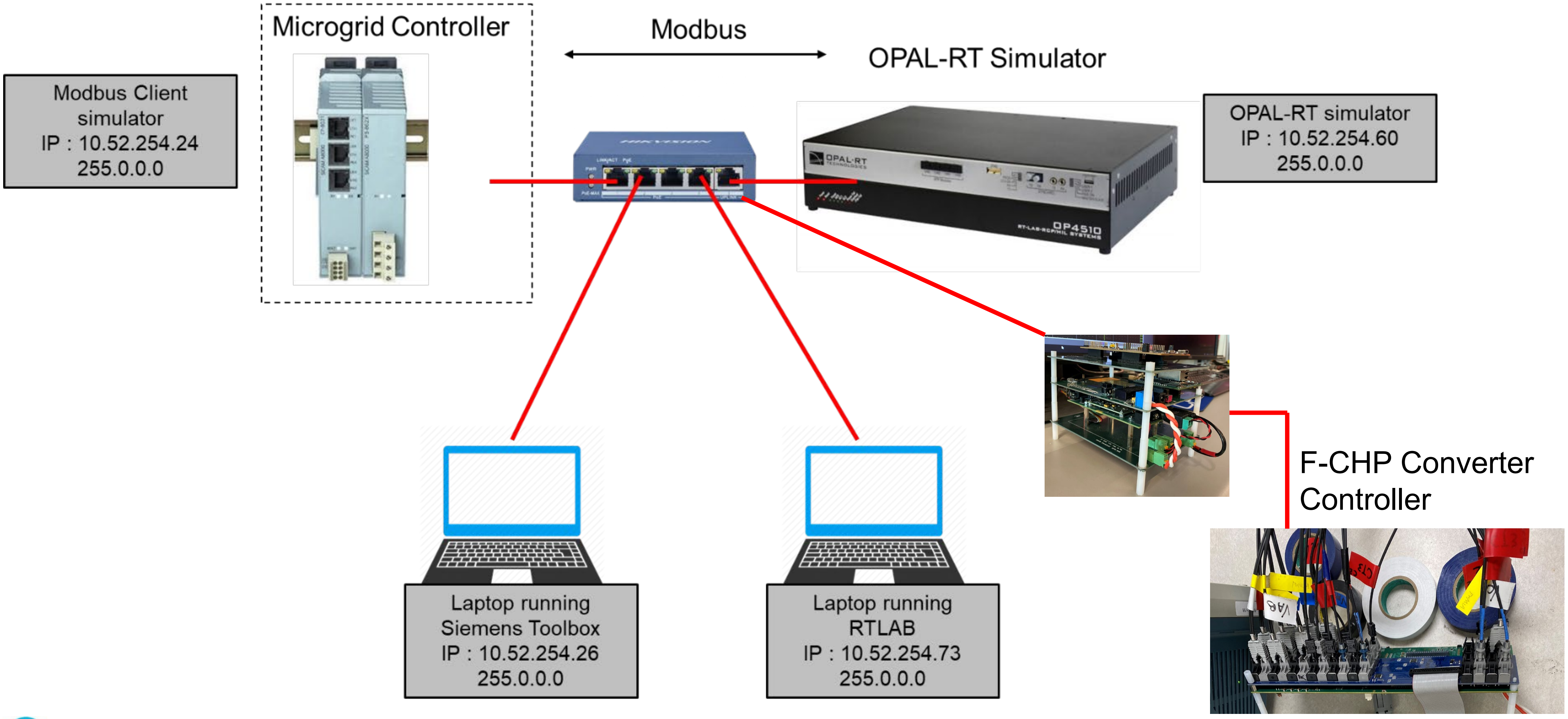
F-CHP Converter

EGSTON Working with OPAL-RT and Current Sensors

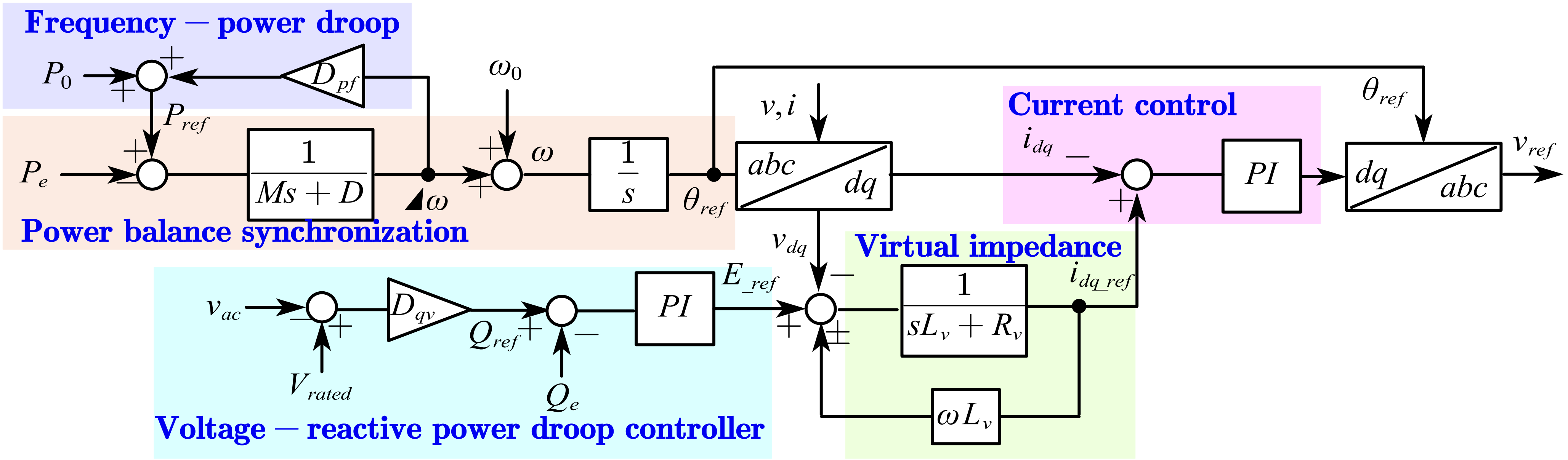




Network Configuration of Emulated Microgrid

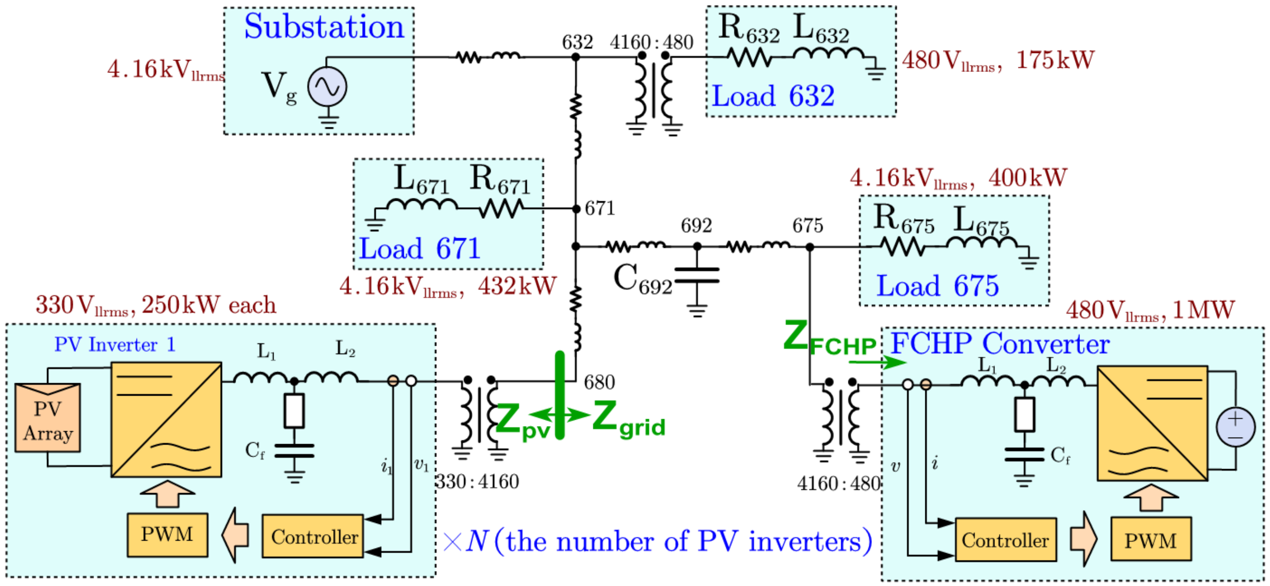


F-CHP Converter Grid-Forming Control in Grid-Connected Mode

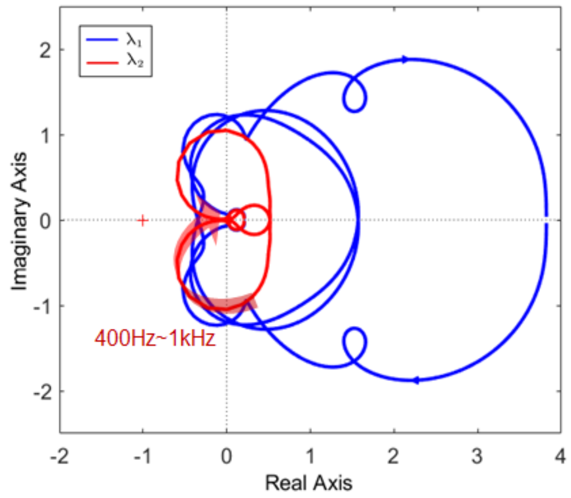


Dynamic Benefits of F-CHP Converters

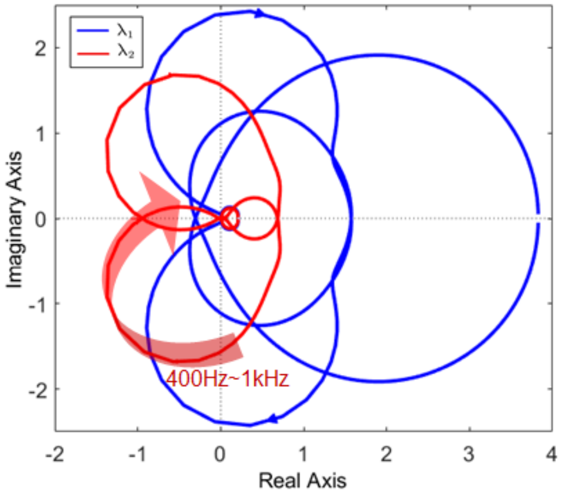
- The F-CHP converter reduces the equivalent grid impedance seen by PV inverters
- Dynamic interactions between PV inverters and the grid are avoided
- PV inverters can increase their power generation



Impedance-based Stability Analysis



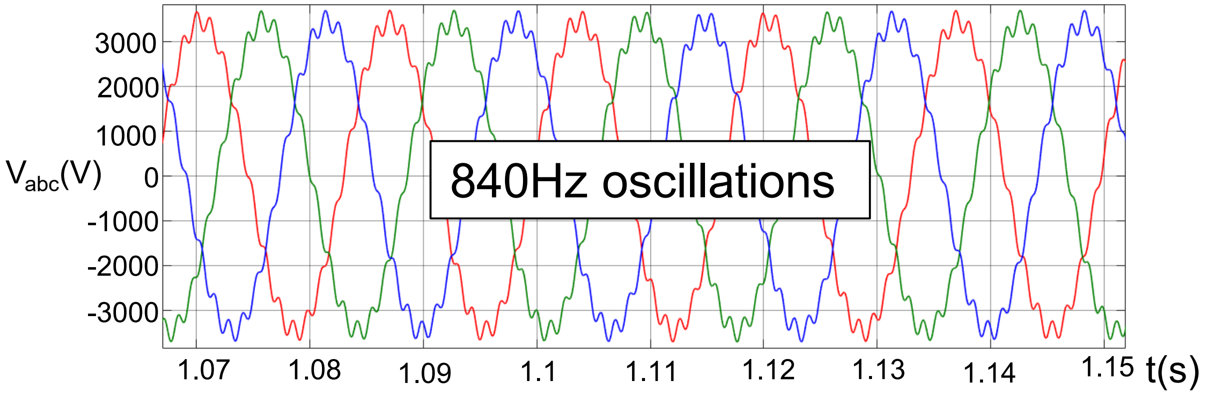
PV 4.5MW, 100% load, **with** F-CHP converter

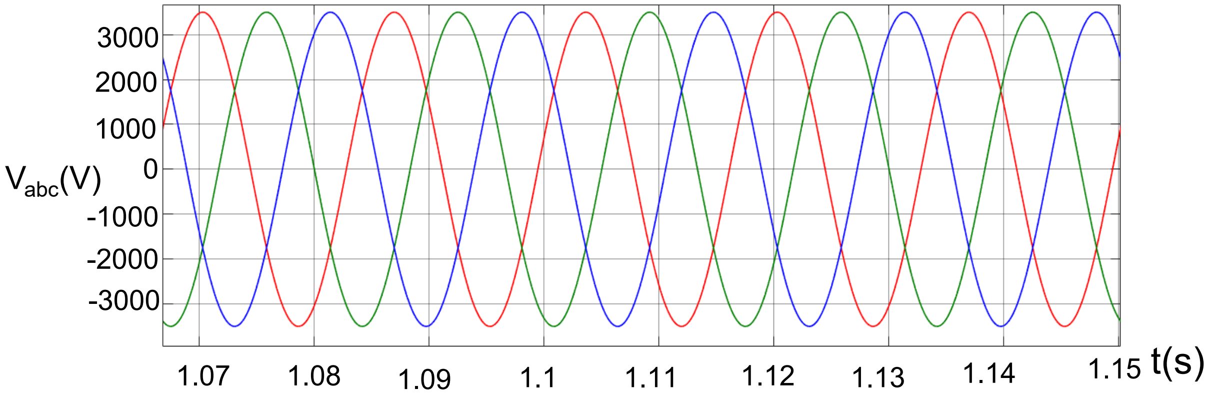


PV 4.5MW, 100% load, **without** F-CHP converter

Benefits of F-CHP Converter

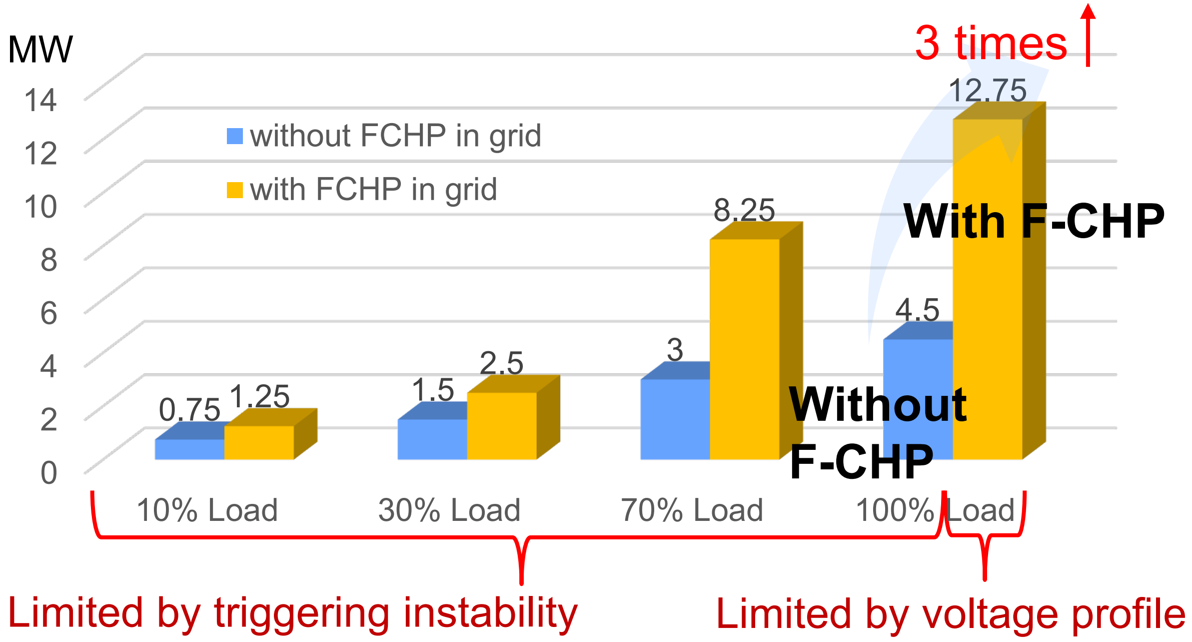
PV 6 MW, 100 % load, without F-CHP converter



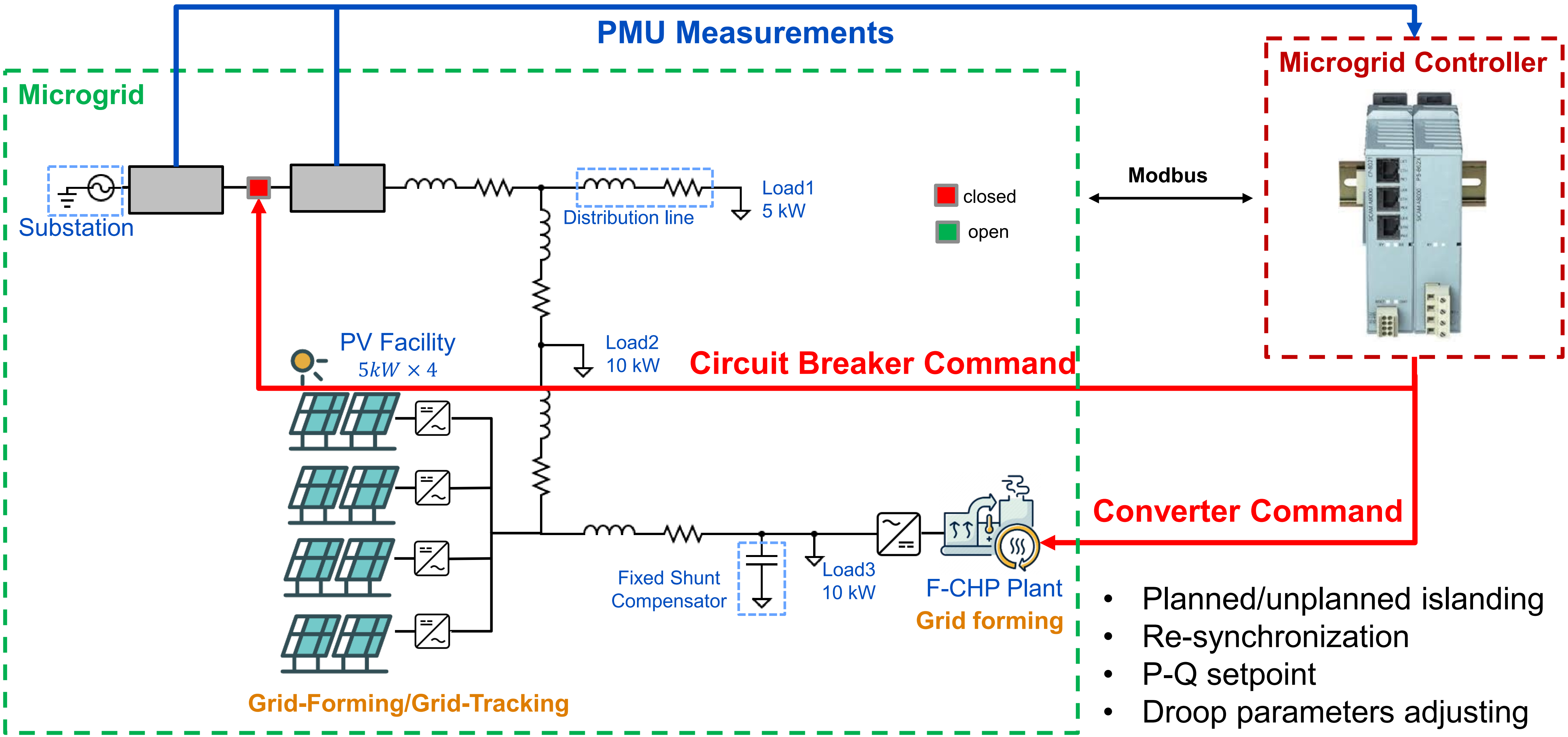


PV 6 MW, 100 % load, with F-CHP converter

PV Maximum Integration Capacity



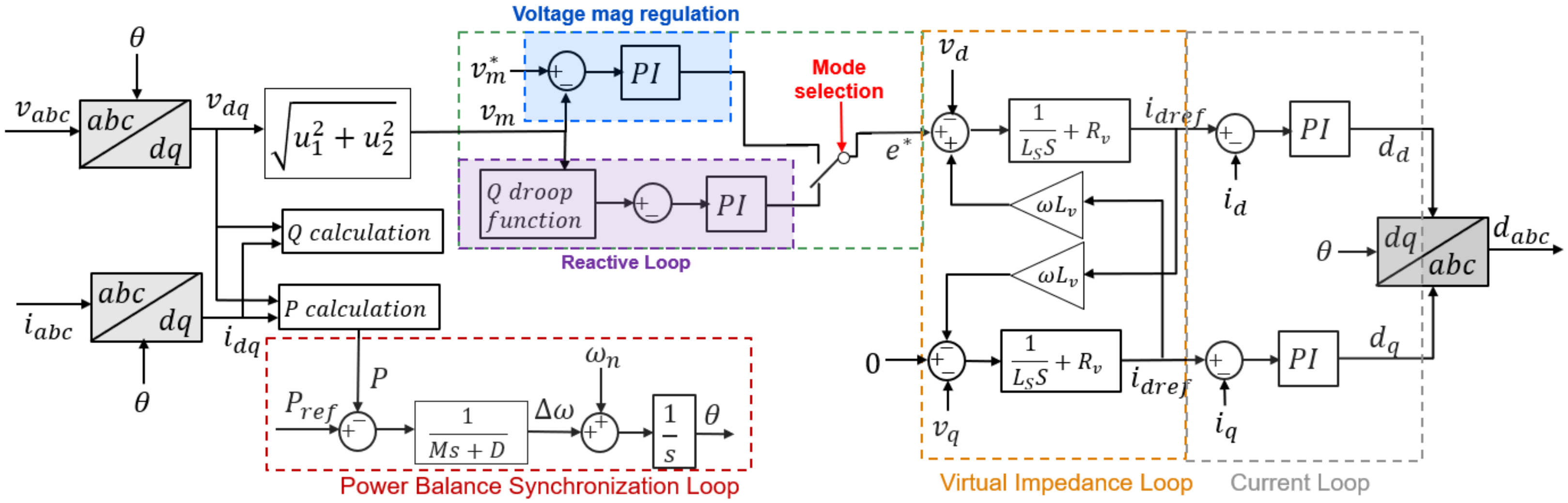
Islanding Operation in 13-bus Microgrid With Microgrid Controller

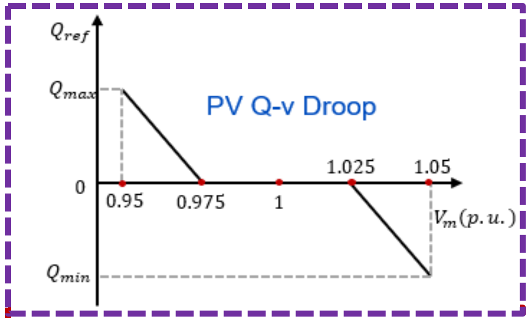


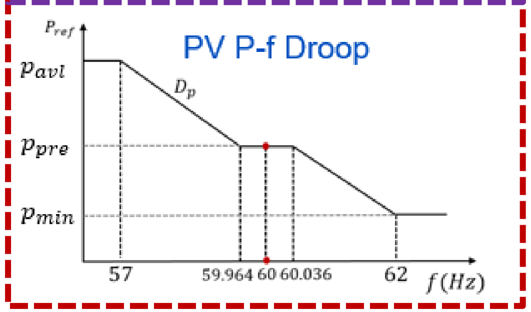
- Planned/unplanned islanding
- Re-synchronization
- P-Q setpoint
- Droop parameters adjusting
- …

Islanded Operation Control Schemes

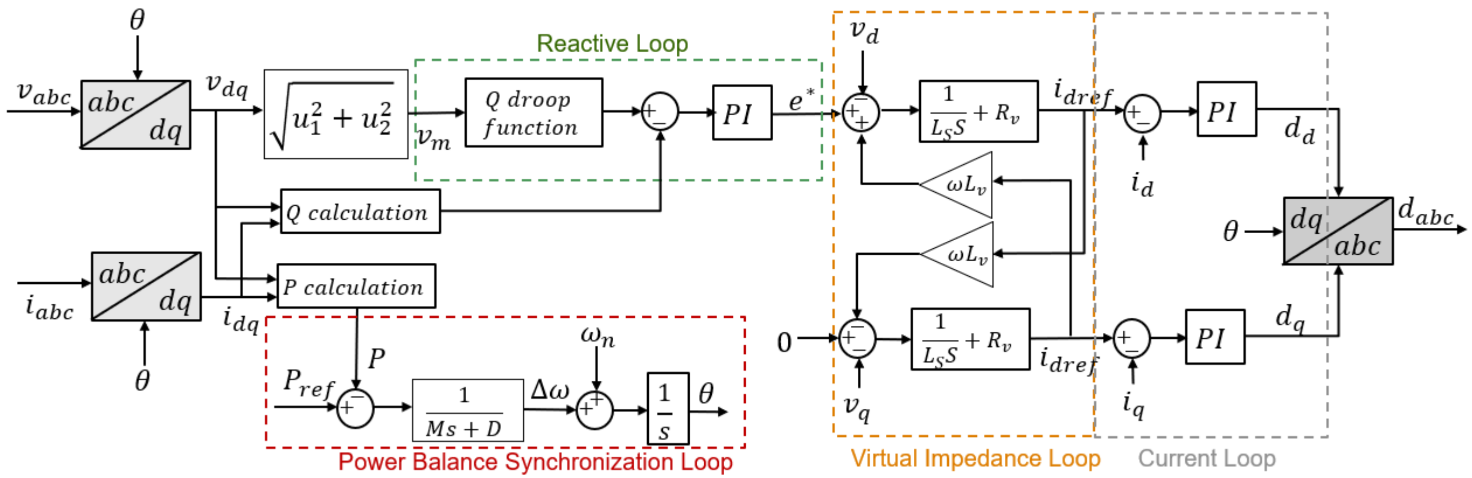
- **Scheme I**: Reactive loop replaced by voltage regulation loop when switching to IS operation mode





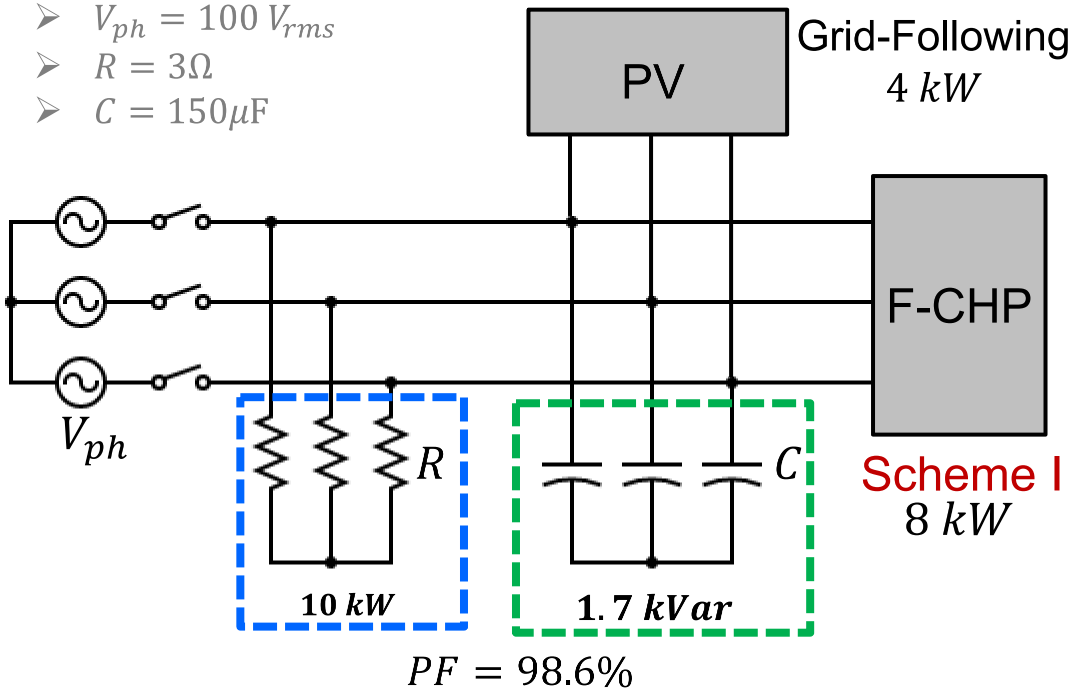


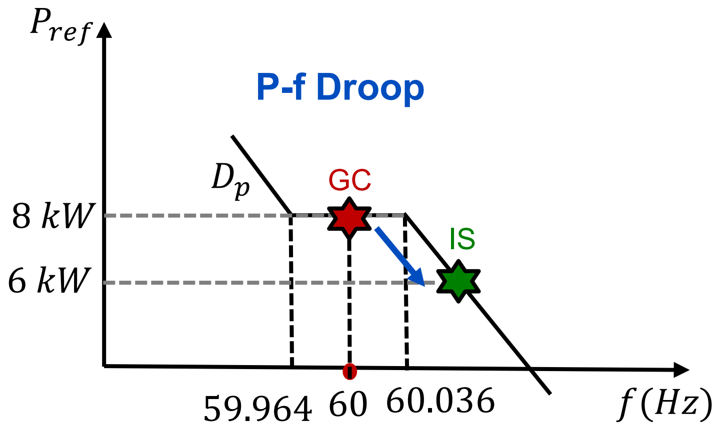
- **Scheme II**: Reactive loop works uninterruptedly

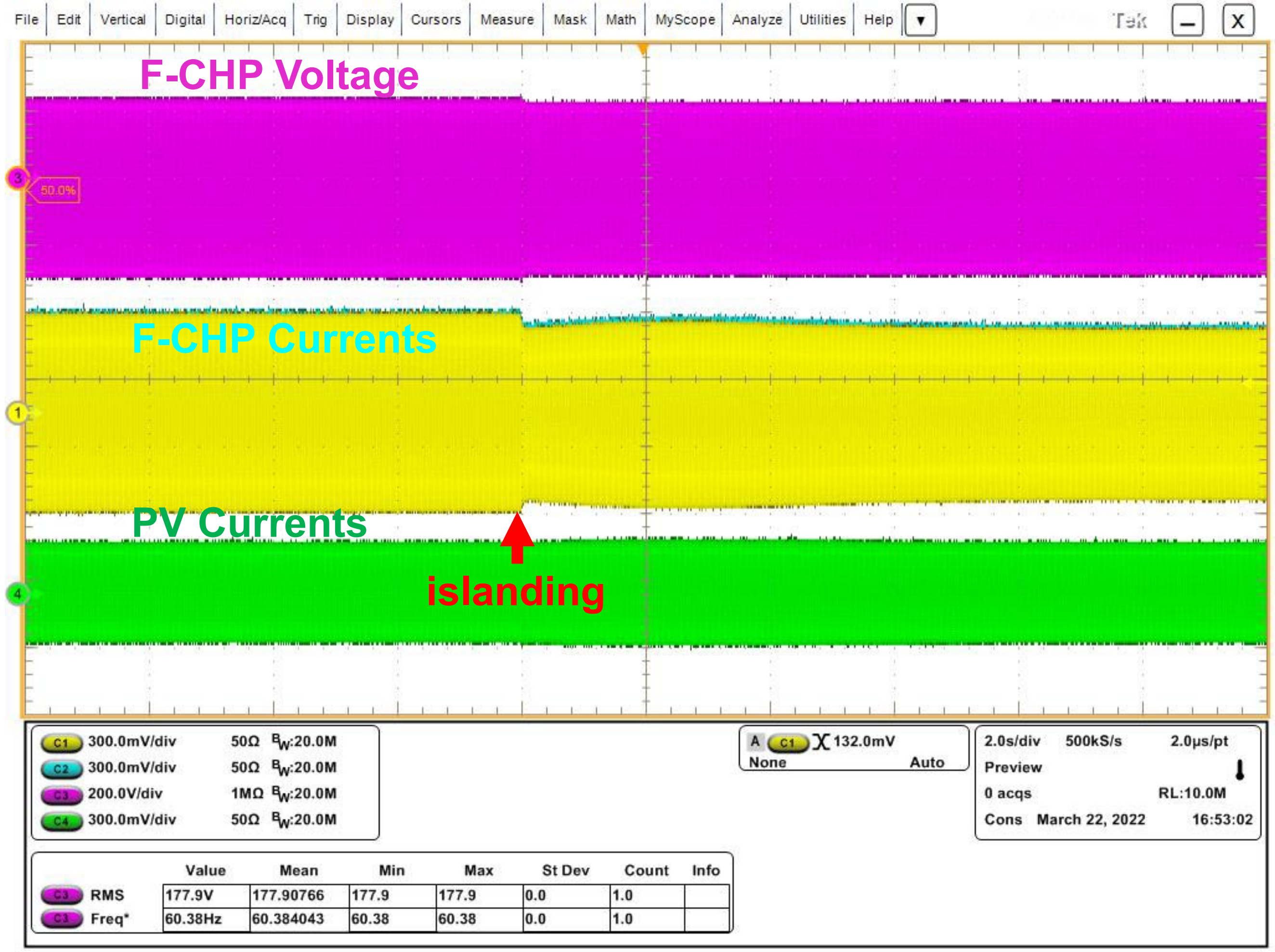


Islanded Operation Test Results—Scheme I

- $V_{ph} = 100\ V_{rms}$
- $R = 3\Omega$
- $C = 150\mu F$



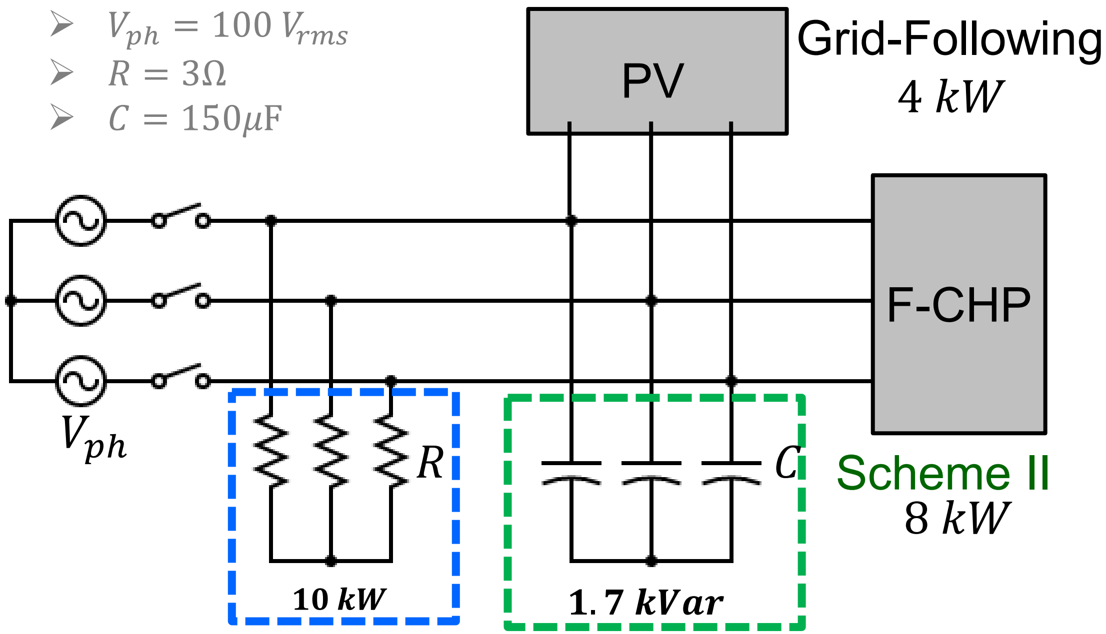




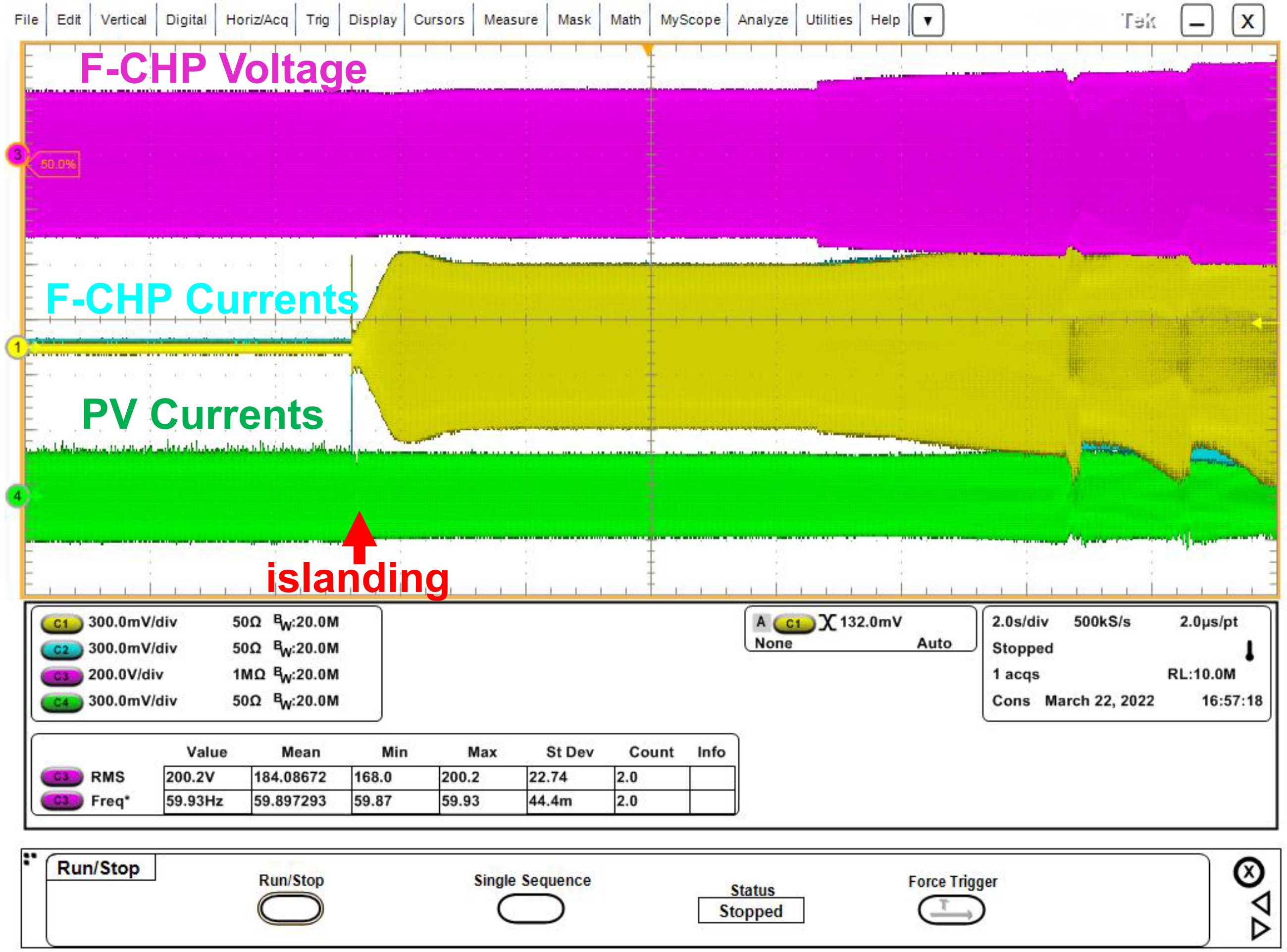
- PV power remains unchanged under grid following mode
- Under Scheme I, the F-CHP injects reactive power as needed to regulate the PCC voltage

Islanded Operation Test Results—Scheme II

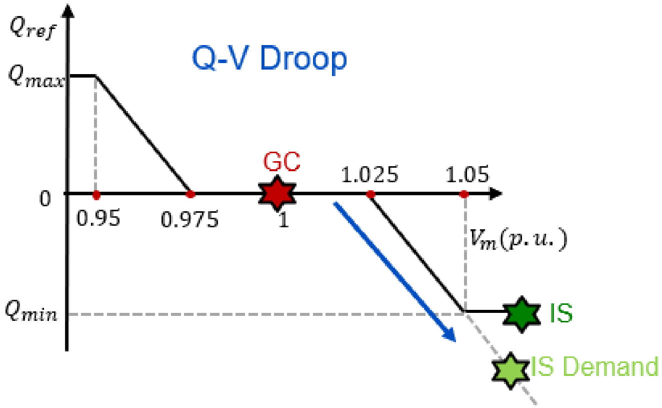
- $V_{ph} = 100\ V_{rms}$
- $R = 3\Omega$
- $C = 150\mu F$



$PF = 98.6\%$



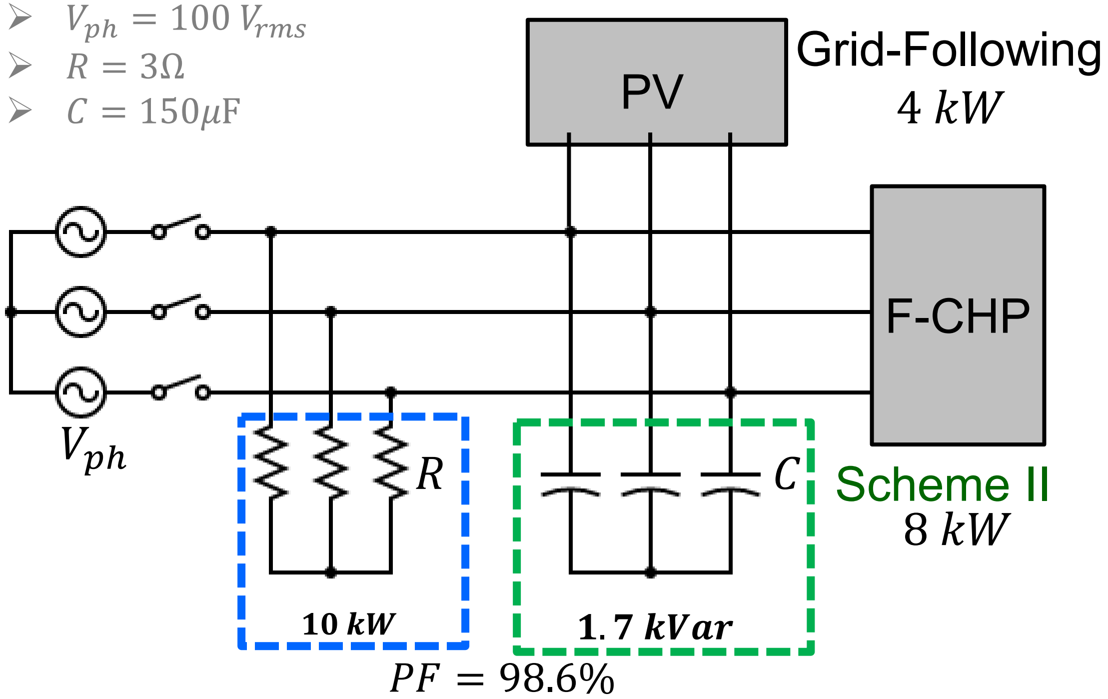
- $Q_{max} = 2\ kVar$



- DERs unable to meet the reactive power load demands in the islanded system, which caused the instabilities

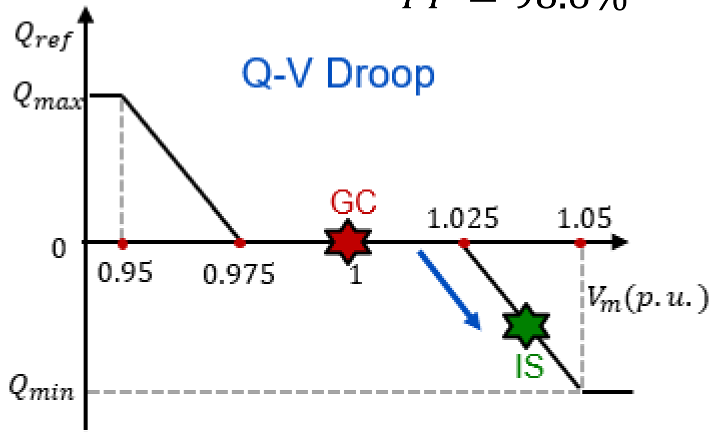
Islanded Operation Test Results—Scheme II

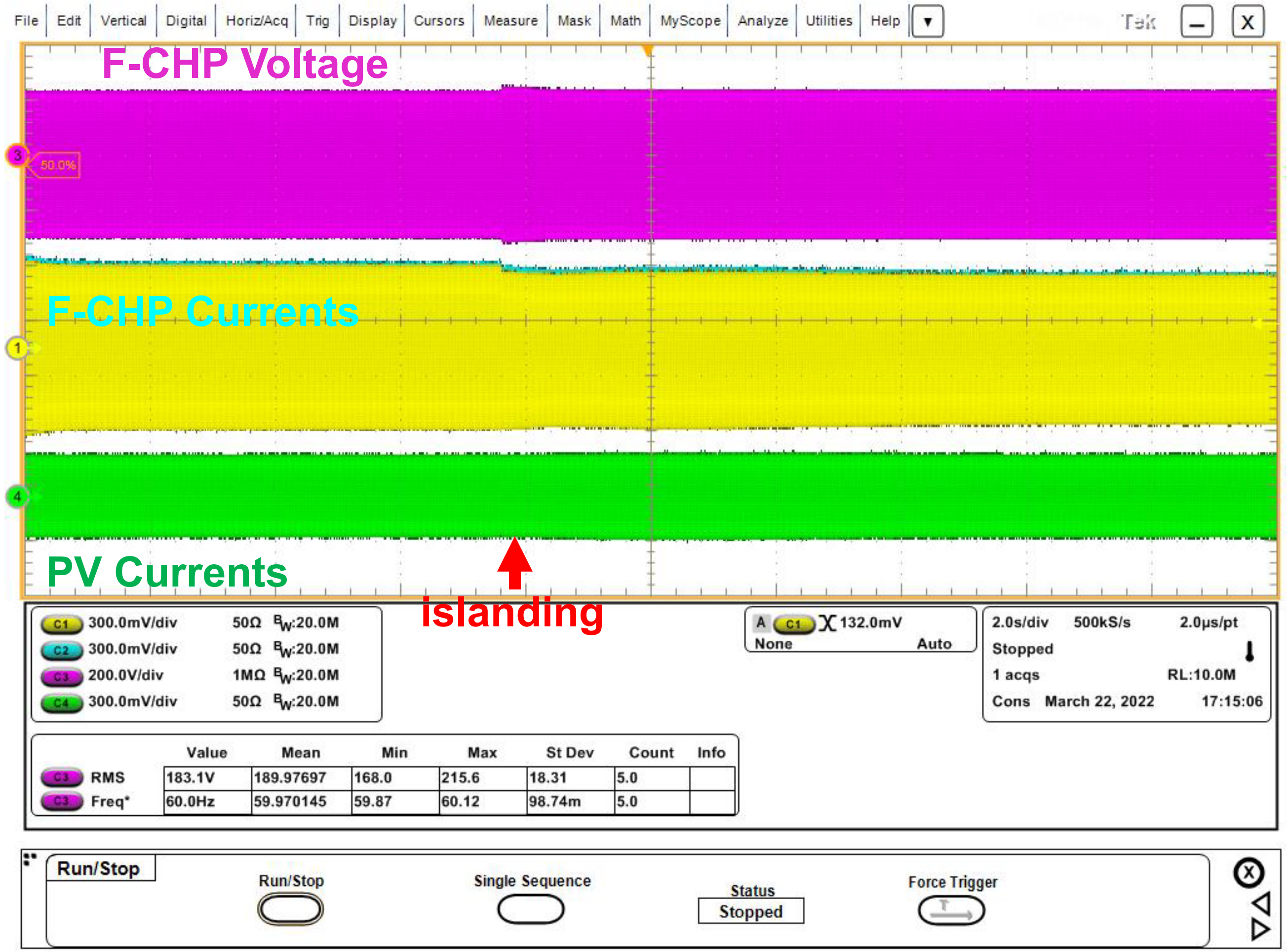
- $V_{ph} = 100\ V_{rms}$
- $R = 3\Omega$
- $C = 150\mu F$



$PF = 98.6\%$

- $Q_{max} = 4\ kVar$





- After increasing the reactive power injection capability (Q_{max}), the reactive demand was met, instabilities disappear

Concluding Remarks

- The proposed F-CHP converter has demonstrated its modularity and high efficiency attained by the adoption of SiC devices
- The F-CHP converter provides **effective static compensation** of PV inverter generation
- The F-CHP converter **enhances the electrical system dynamics** avoiding interactions between converters **AND** enabling PV inverters to increase their active power generation
- The **proposed grid-forming control** enables the F-CHP converter operation in grid-connected and islanded modes as well as under severe system faults

➢ *FINAL STEP*: full microgrid P-HIL demonstration

VIRGINIA TECH

CPES
Center for Power Electronics Systems

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U.S. DEPARTMENT OF ENERGY
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

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Flexible CHP Portfolio Meeting

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