SiC Based Modular Transformer-less MW-Scale Power Conditioning System (PCS) and Control for Flexible CHP (F-CHP) System

University of Tennessee, Knoxville (UTK) Team

PI: Fred Wang

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Outline

- Project Introduction
- Technical Progress
  - Technical Approach
  - 13.8 kV/1 MW PCS Converter Design Considering Grid Requirements
  - 13.8 kV/100 kW PCS Converter Prototype Development and Test
  - F-CHP System Controller Design, Implementation, and Test
- Summary and Future Work

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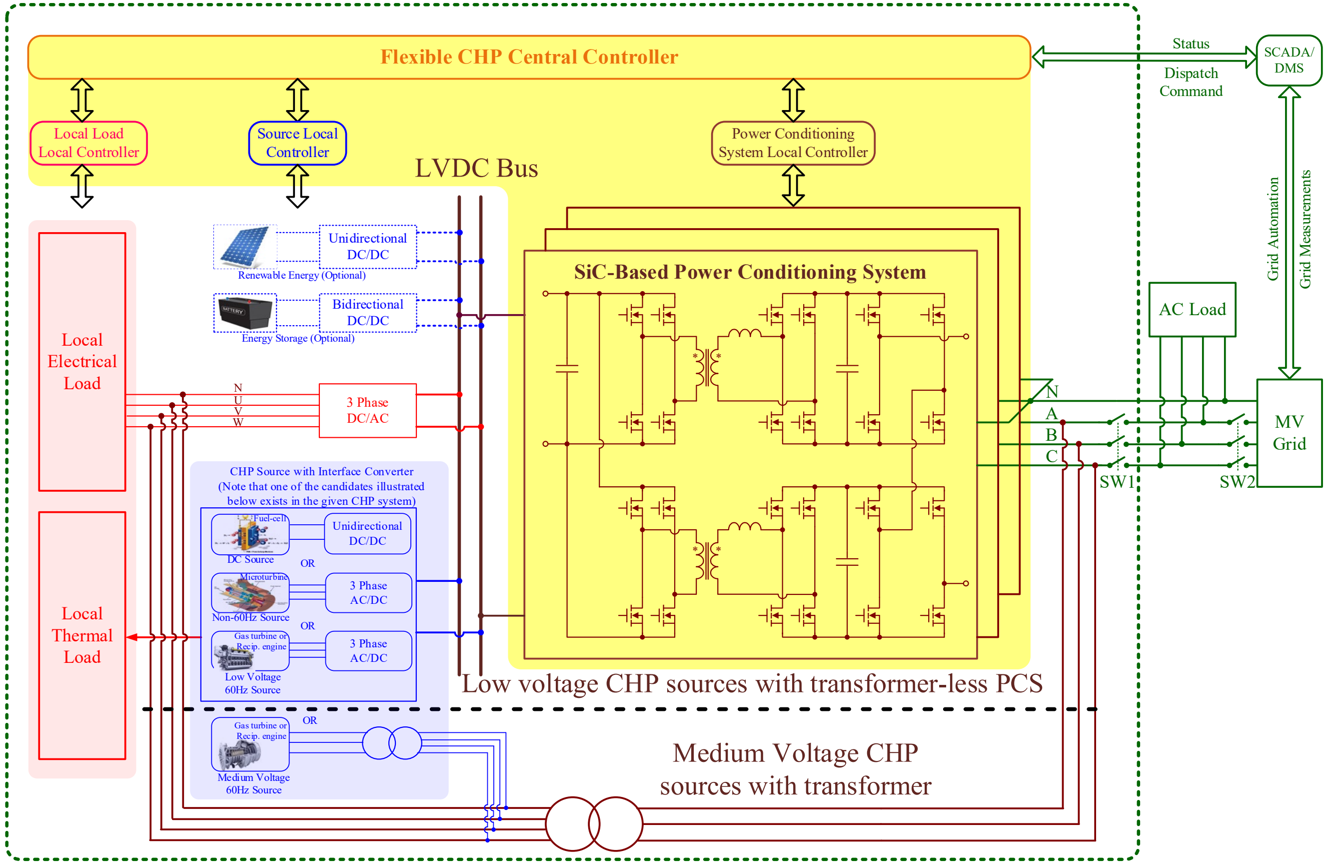
- ❑ Summary and Future Work

Project Description

❑Objectives/Summary

- Develop a SiC based, modular, transformer-less, MW-scale, power conditioning system (PCS) and a corresponding control system for flexible CHP (F-CHP) systems
- The PCS and controller are designed to meet the distributed energy resources and microgrid interconnection standards (IEEE 1547 and 2030.7), capable of grid support functions, as well as operating under other abnormal grid conditions (e.g. unbalance, faults and transient overvoltage)



Project Goals

- **Project goals are to improve the baseline technology (Si-based solution) to meet the DOE FOA and other related targets:**
  - SiC-based PCS Features
    1) integrate with different CHP sources (conventional turbines, reciprocating engines, micro turbines, fuel cells) and other energy resources (PV, energy storage) etc.
    2) modular and transformer-less for resiliency, scalability to MW level and low cost
    3) support unbalanced loads and abnormal grid-conditions, and provide extra system benefits utilizing SiC fast switching capability
    4) meet IEEE 1547 and 2030.7 standards, together with F-CHP controller
  - F-CHP Controller Features
    1) integrate with different CHP sources and other DERs, function together or independent of the PCS
    2) meet IEEE DER and microgrid standards, easily integrated with existing distribution grid controller, and provide grid-support functions
    3) automatic transfer between various operation modes
    4) general-purpose controller hardware for cost reduction

Uniqueness, Barriers and Challenges

❑Uniqueness

- A SiC-based four-wire PCS that can interface flexibly with various energy sources on CHP side, and interface directly to MV with grid support functions
- A F-CHP controller that enables automatic transfer between various operation modes, including a dynamic microgrid boundary to maximize utilization of resources and better resiliency/ reliability and meet grid requirements
- Use of modular and transformer-less PCS, general-purpose controller hardware, and existing smart-grid assets for lower cost

❑Barriers and Challenges

- Utilization of HV SiC devices in PCS to directly interface to the MV grid without low frequency transformers, considering grid requirements (var support, voltage/frequency ride through, mode transition, unbalanced load, insulation, etc.)
- F-CHP controller development to support different flexible CHP sources, and to cooperate with local renewable energy sources, storages and loads
- Cost reduction for overall CHP system including controller and PCS

Expected Outcomes & Impact

❑ Expected Outcomes:

- Scalable MW-scale DC/AC PCS converter, as an interface between LVDC (e.g. 800 V to 1 kV) and MVAC (e.g. 13.8 kV), meeting related specifications and grid requirements. A prototype with two 100 kW scaled PCS converters will be completed
- F-CHP Controller, including F-CHP central controller, local load local controller (LC), source LC, and PCS LC

❑ Project Impact

- The developed power electronics and controller technology will enable F-CHP with various types of energy sources to provide a range of services to the grid at low cost and high reliability
- It will help to increase the market acceptance of MW-scale F-CHP and accelerate the proliferation of CHP for grid applications

Overall Schedule

Budget Period	Task	Expected Goal
BP1: (Oct. 2018 - Dec. 2019)	➢ Design SiC-based, transformer-less, MW-scale, four-wire DC/AC PCS ➢ Design F-CHP Controller including F-CHP CC, Local Load LC, Source LC, and PCS LC	Design report of PCS and F-CHP controller completed
BP2: (Jan. 2020 - Sep. 2021)	➢ Build A 100 kW PCS prototype based on the design in BP1 ➢ Build MV test platform and demonstrate PCS functions ➢ F-CHP controller tested and validated in HIL and UTK's HTB platform	100 kW PCS prototype and F-CHP Controller hardware demonstrated
BP3: (Oct. 2021 - Sep. 2022)	➢ Develop PCS paralleling technology ➢ Build two 100 kW PCSs prototype and test scalability of the PCS ➢ Test F-CHP controller to handle the scaled PCS	Scalable PCS prototype (two 100 kW PCS) demonstrated with test report

CURENT :completed :ongoing

Team Members and Roles

THE UNIVERSITY OF TENNESSEE KNOXVILLE

- Overall lead and project management
- PCS design and development
- F-CHP controller algorithm development
- Controller HIL and PCS testing
- Report to DOE

OAK RIDGE National Laboratory

- Assist with control algorithm development for F-CHP system
- Provide advice on testing

GE

- Help on PCS design considering future manufacturing and commercialization

NC STATE UNIVERSITY

- Provide expertise on CHP system, data, and model
- Advise on siting and sizing
- Promote developed technology

epb

- Provide guidance on requirements of PCS and controller
- Provide data and model for projected CHP system

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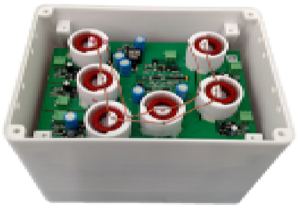
Overall Technical Approach

PCS Converter Development

- Grid requirements identification
- PCS converter design considering grid requirements
- Multiple grid support functions
- Topology, control and modulation
- SiC device application issues
- PCS converter function test



Parallel

Scalable PCS

- F-CHP controller design support scalable PCS
- Gate signal synchronization
- Circulating current limitation

Interface

SiC Based Modular Transformer-less MW-Scale Power Conditioning System and Control for Flexible CHP System

Interface

F-CHP Controller development

- F-CHP controller architecture and functionality
- F-CHP controller operation in different modes
- Transition between operating modes
- Controller design considering protection
- F-CHP controller modeling and test

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PCS Specs and Requirements

<table>
<tr><th>Parameter</th><th>Value</th><th>Parameter</th><th>Value</th></tr>
<tr><td>Power rating</td><td>1 to 20 MW</td><td rowspan="8">MVAC side functions</td><td rowspan="8">1)Low/high voltage ride through follow IEEE Std 1547
2)Low/high frequency ride through follow IEEE Std 1547
3)Active power for frequency support, reactive power/power factor for voltage support
4)Current source operation for grid-connected mode and voltage source operation for islanded mode
5)Voltage ride through in islanded mode
6)Active power filtering
7)Stability enhancement
8)Seamless mode transition between islanded/grid-connected mode
9)Start up both from LVDC and MVAC sides
10)Ground fault isolation between MVAC and local load side</td></tr>
<tr><td>MVAC voltage rating</td><td>13.8 kV (-12% ~ 10%)</td></tr>
<tr><td>LVDC voltage rating</td><td>850 V (-5% ~ 5%)</td></tr>
<tr><td>Power factor</td><td>Four-quadrant operation</td></tr>
<tr><td>TDD in MVAC</td><td>5% (IEEE Std 1547)</td></tr>
<tr><td>Efficiency</td><td>98%</td></tr>
<tr><td>Ambient temp</td><td>-25ºC ~ 55ºC</td></tr>
<tr><td>Cooling</td><td>Forced air or liquid cooling</td></tr>
<tr><td>Reliability</td><td>MTBF > 10 years</td><td>LVDC functions</td><td>±5% LVDC voltage variation</td></tr>
<tr><td>Power density</td><td>> 0.6 MW/m^3</td><td>Unbalanced load support</td><td>33% unbalance load support for AC grid side, <4% voltage variation, 120 +/- 2.8˚</td></tr>
<tr><td rowspan="2">Fault</td><td rowspan="2">1) AC side fault including three-phase and single-phase grounding, and phase-to-phase short
2) Overvoltage and overcurrent fault in LVDC bus</td><td>RF requirement</td><td>47 CFR 1.1307 (FCC standard)</td></tr>
<tr><td>EMC</td><td>1) No requirement in MVAC
2) FCC 15 CLASS B in LVDC</td></tr>
<tr><td rowspan="3">Grounding</td><td rowspan="3">1)Chassis grounded
2)Midpoint of LVDC grounded
3)MVAC side: Neutral is grounded in grid-connected and islanded modes; No impact on temporary over voltage/current level under ground faults for existing grid; No impact (or minor change) on ground fault protection for existing grid.</td><td>Control Bandwidth</td><td>voltage control bandwidth > 300 Hz,
current control bandwidth > 1 kHz</td></tr>
<tr><td>PCS protection (external)</td><td>Over-voltage protection, over-current protection, under-voltage, ground fault</td></tr>
<tr><td>Transient overvoltage</td><td>Lightning and switching overvoltage</td></tr>
</table>

PCS Converter Design Results

- Comparison Summary Between Baseline Design and Design Considering Grid Requirements

	Weight		Size		Comment
	Baseline	Grid	Baseline	Grid	
DC/AC stage	206.3 kg	314 kg	0.236 m^3	0.271 m^3	Most of weight and size increase sre due to: 1) filter inductor because of higher inrush current during grid transients; 2) transient overvoltage limitation device (e.g. arresters)
DC/DC stage	174.6 kg	203.1 kg	0.147 m^3	0.209 m^3	Most of weight and size increase are due to: 1) transformer because of increasing insulation; 2) larger DC link capacitor considering source/load change;
Total	380.9 kg	517.1 kg	0.383 m^3	0.480 m^3	Specific power: 2.62 kW/kg → 1.93 kW/kg Power density: 2.6 MW/m^3 → 2.08 MW/m^3

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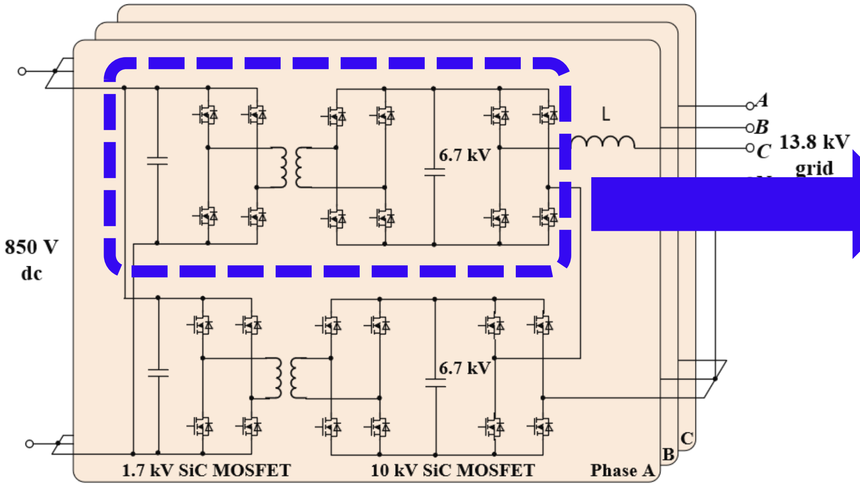
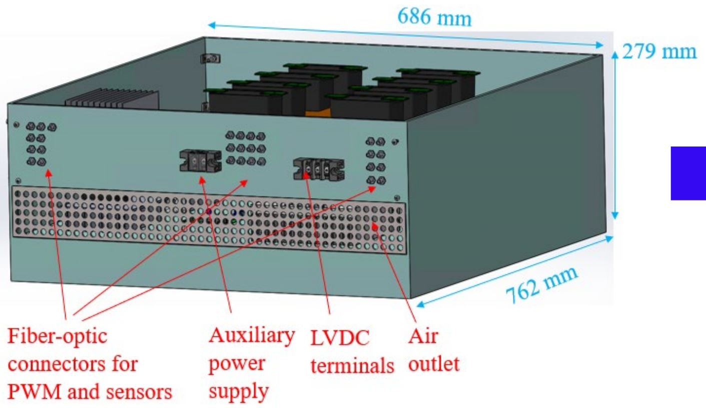
PCS Converter Prototype Development and Test

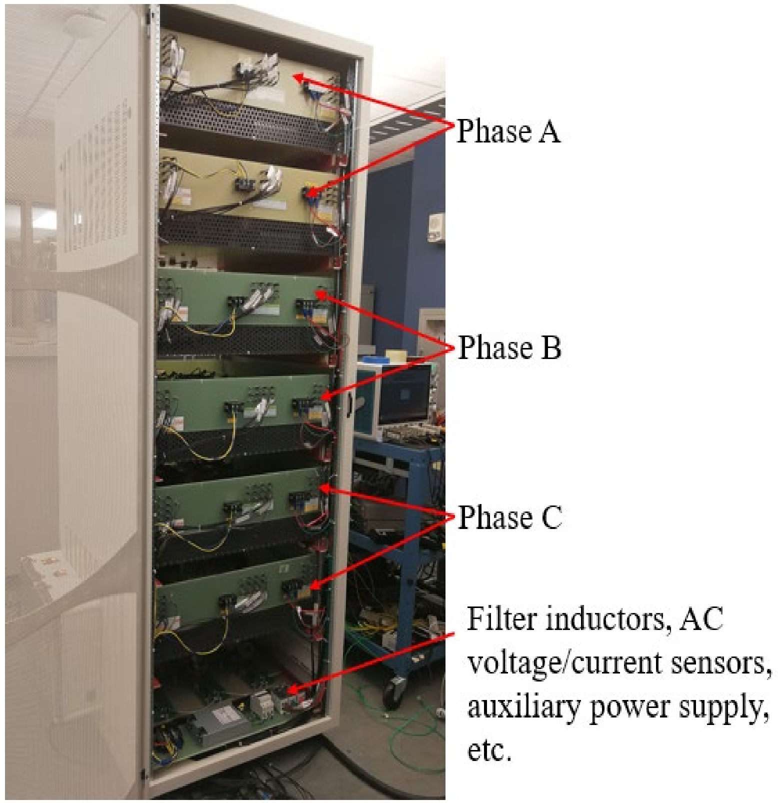
❑ Converter Hardware

- Modular design
- Separated LV and MV area and outlets





Power module front view

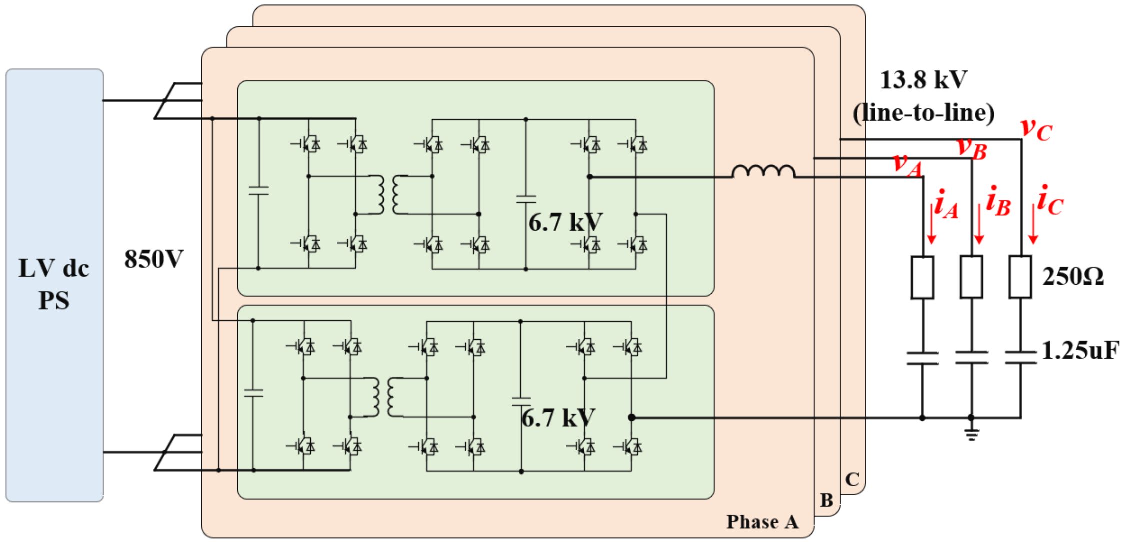


Three-phase converter hardware pictures

PCS Converter Prototype Development and Test

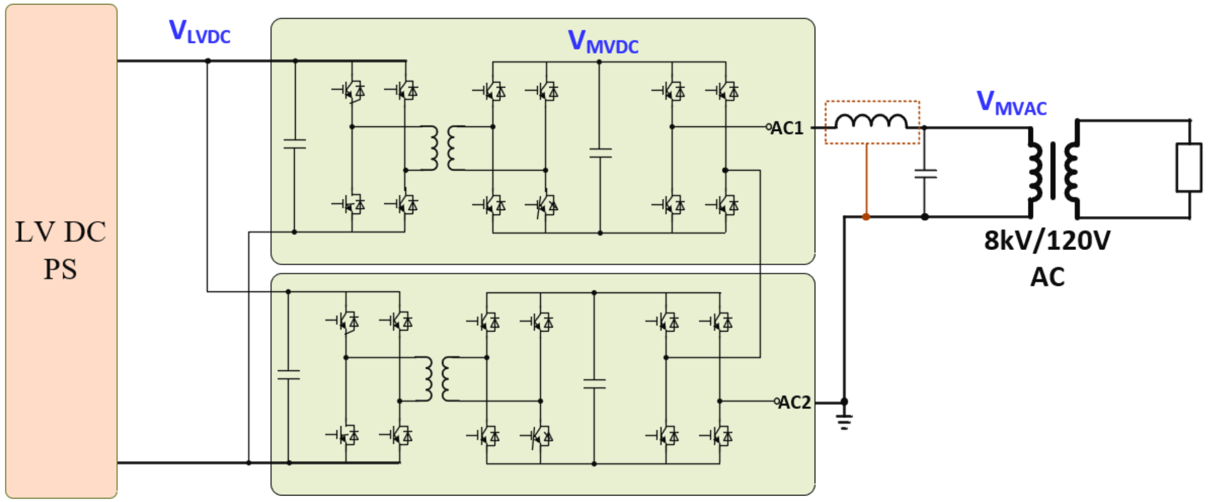
❑ Test Setup 1

- Hardware Test
  - Insulation test
  - AC side full power rating test
- Performance Test
  - Power quality test
  - Control bandwidth test



❑ Test Setup 2

- DC/DC stage (active power) full rating test
- Efficiency test
  - Power analyzer is used to measure both the LV DC side input power and the MV AC side output power



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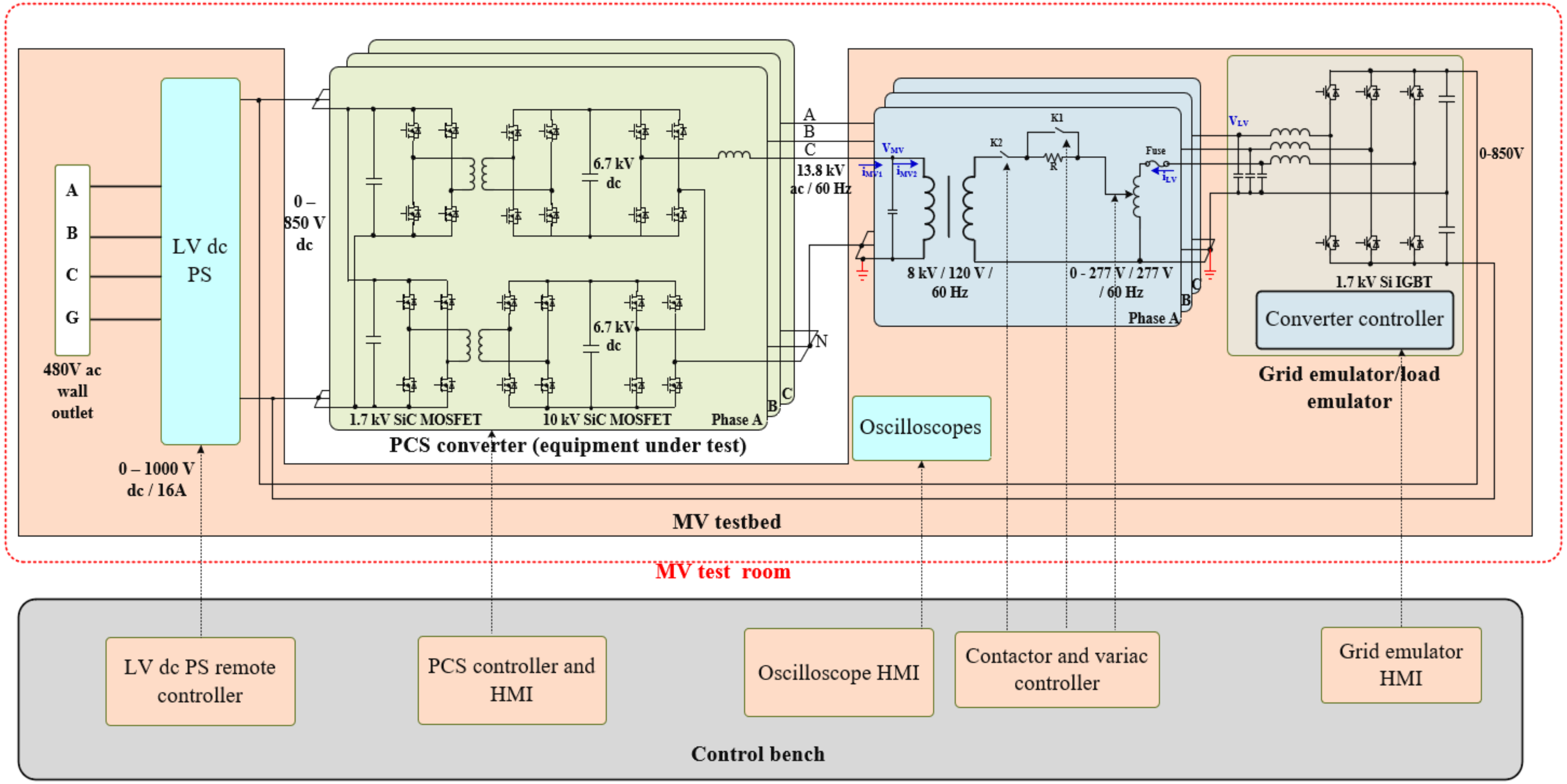
PCS Converter Prototype Development and Test

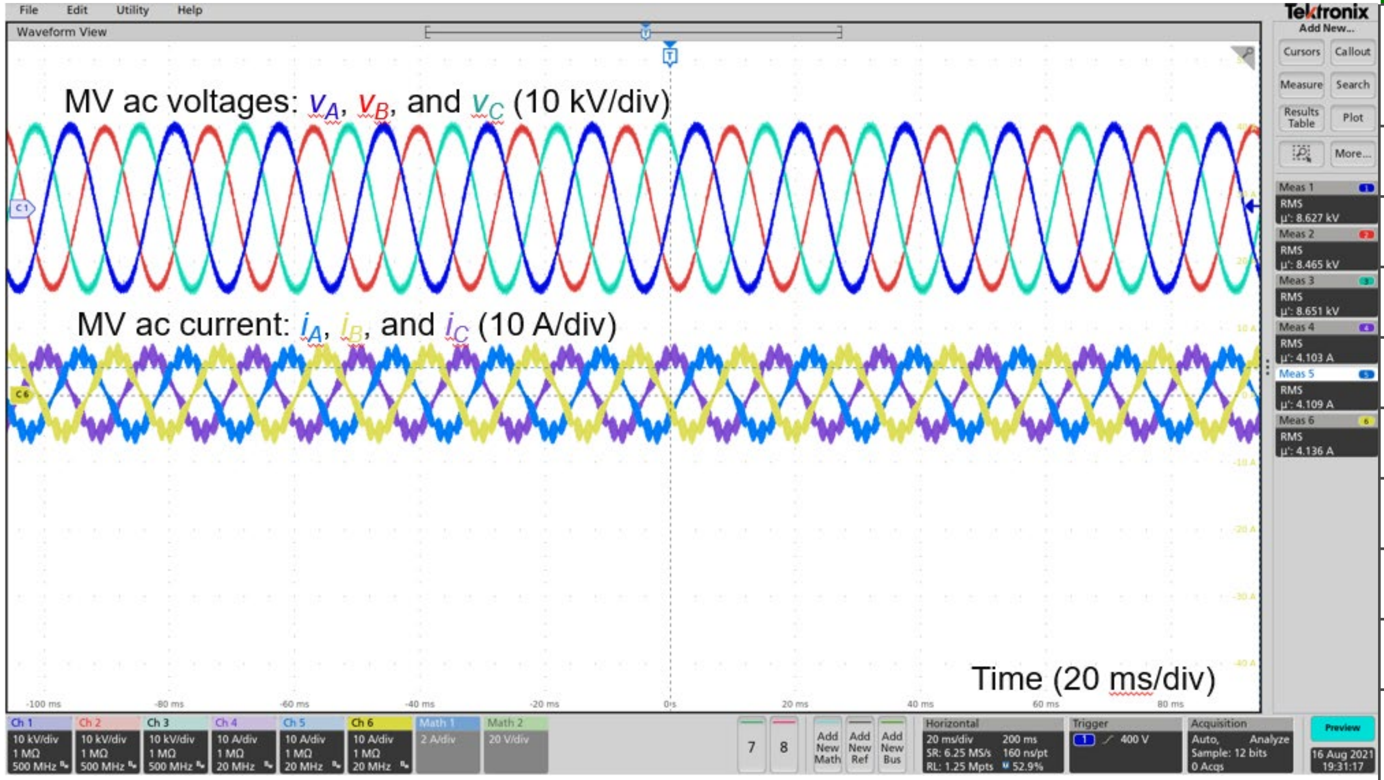
❑ Test Setup 3

- Four-quadrant operation
- Grid normal and abnormal conditions
- Grid-connected mode and islanded mode operation
- Power circulating
- Safety consideration
- Multiple protection schemes (both hardware and software)



PCS Converter Prototype Development and Test

❑ Test Results



<u>**MV AC voltage and current waveforms @ 13.8 kV/100 kVA**</u>

- Performances and functions tested

#	Category	Function
1	Converter performance	Full voltage and power rating operation (13.8 kV/100 kW)
2		Voltage THD ~ 2.72% (up to 50^{th}-order)
3		Current TDD ~ 0.8% (up to 50^{th}-order)
4		Efficiency ~ 96.4%
5		Voltage control bandwidth ~ 300 Hz
6		Current control bandwidth ~ 1.1 kHz
7	Grid requirements /functions	Var support (voltage support)
8		Frequency ride Through
9		Voltage ride through
10		Protection (over voltage, under voltage, over frequency, under frequency, etc.)
11		Balanced/unbalanced load support in the islanded mode

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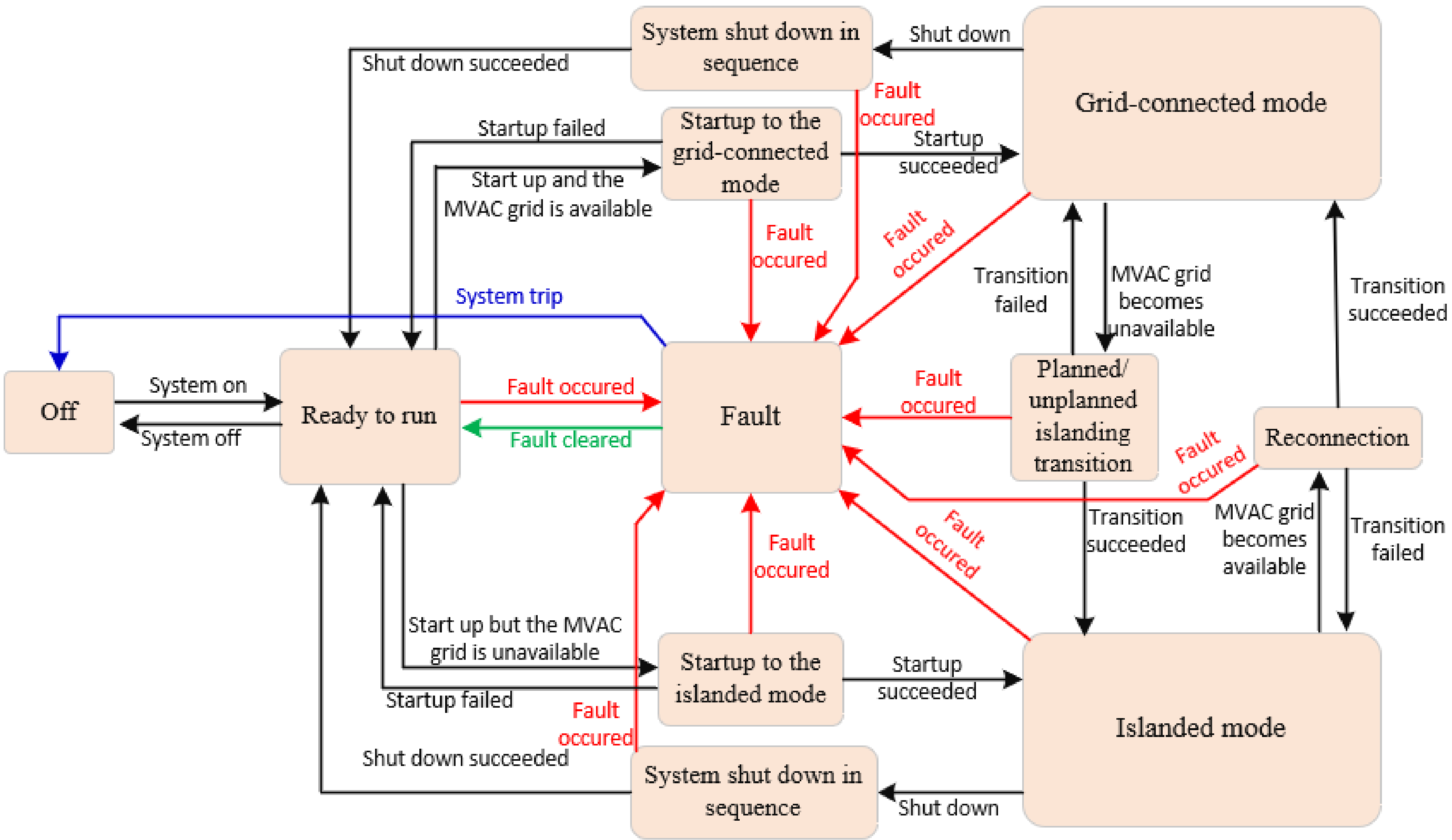
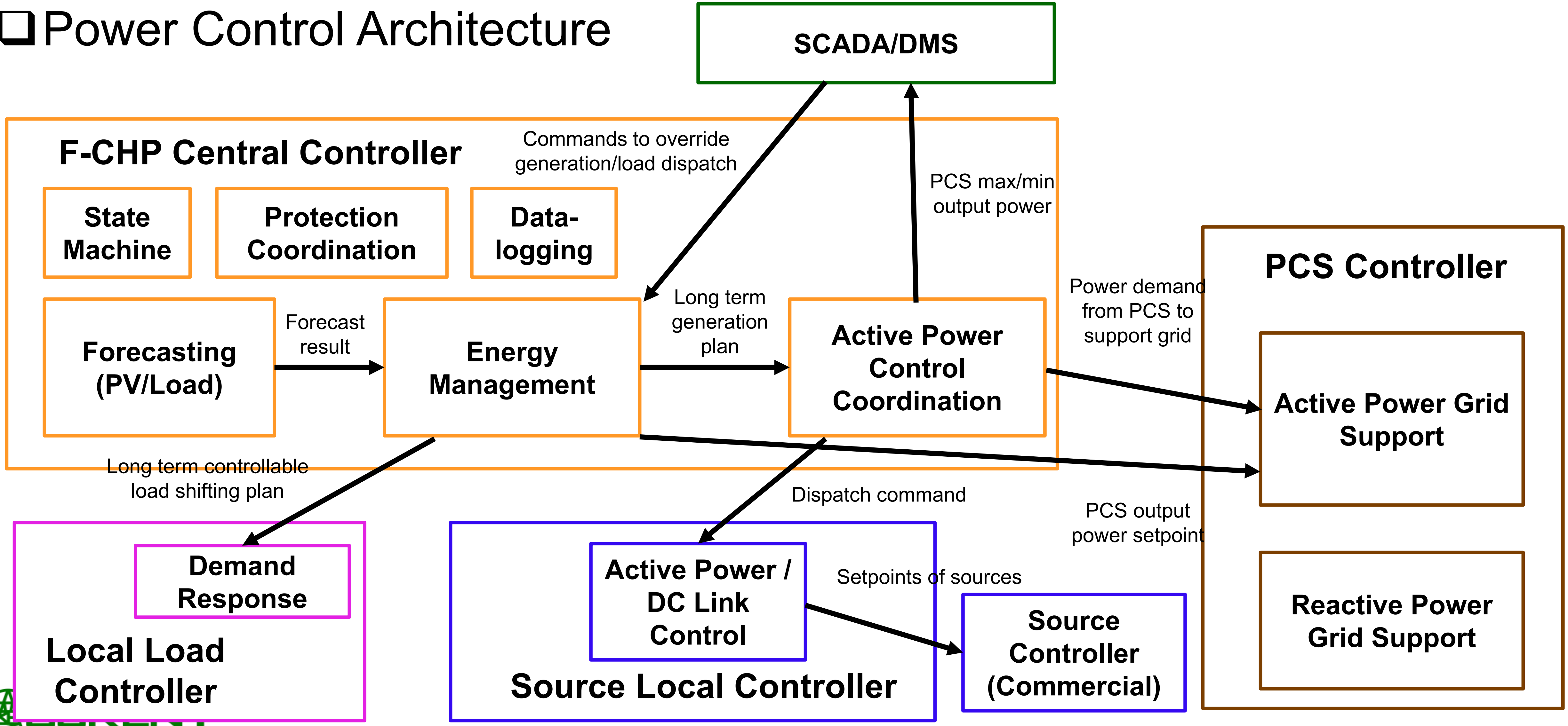
F-CHP Controller Design, Implementation, and Test

❑ Central Controller State Machine



F-CHP Controller Design, Implementation, and Test

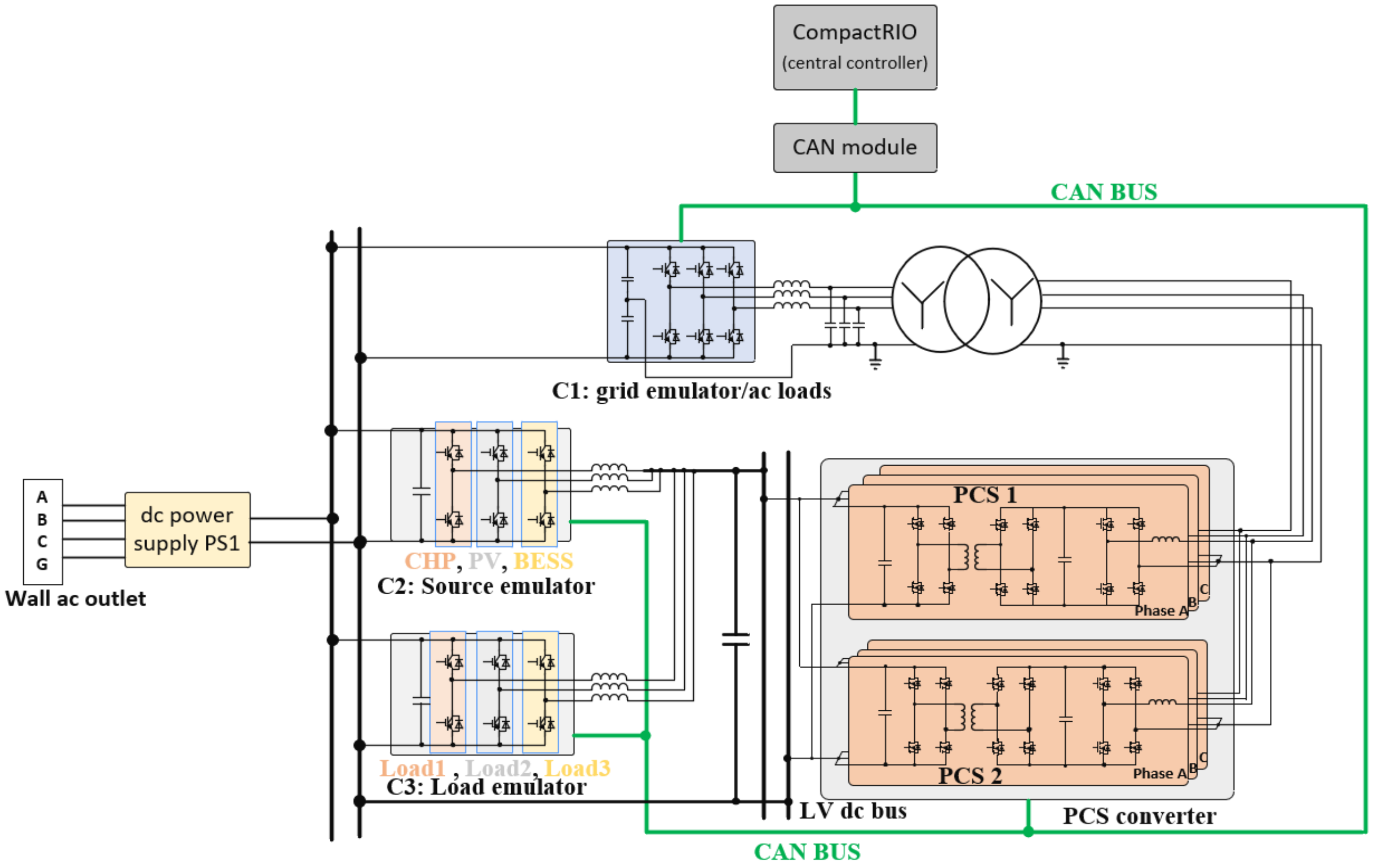
- Power Control Architecture



F-CHP Controller Design, Implementation, and Test

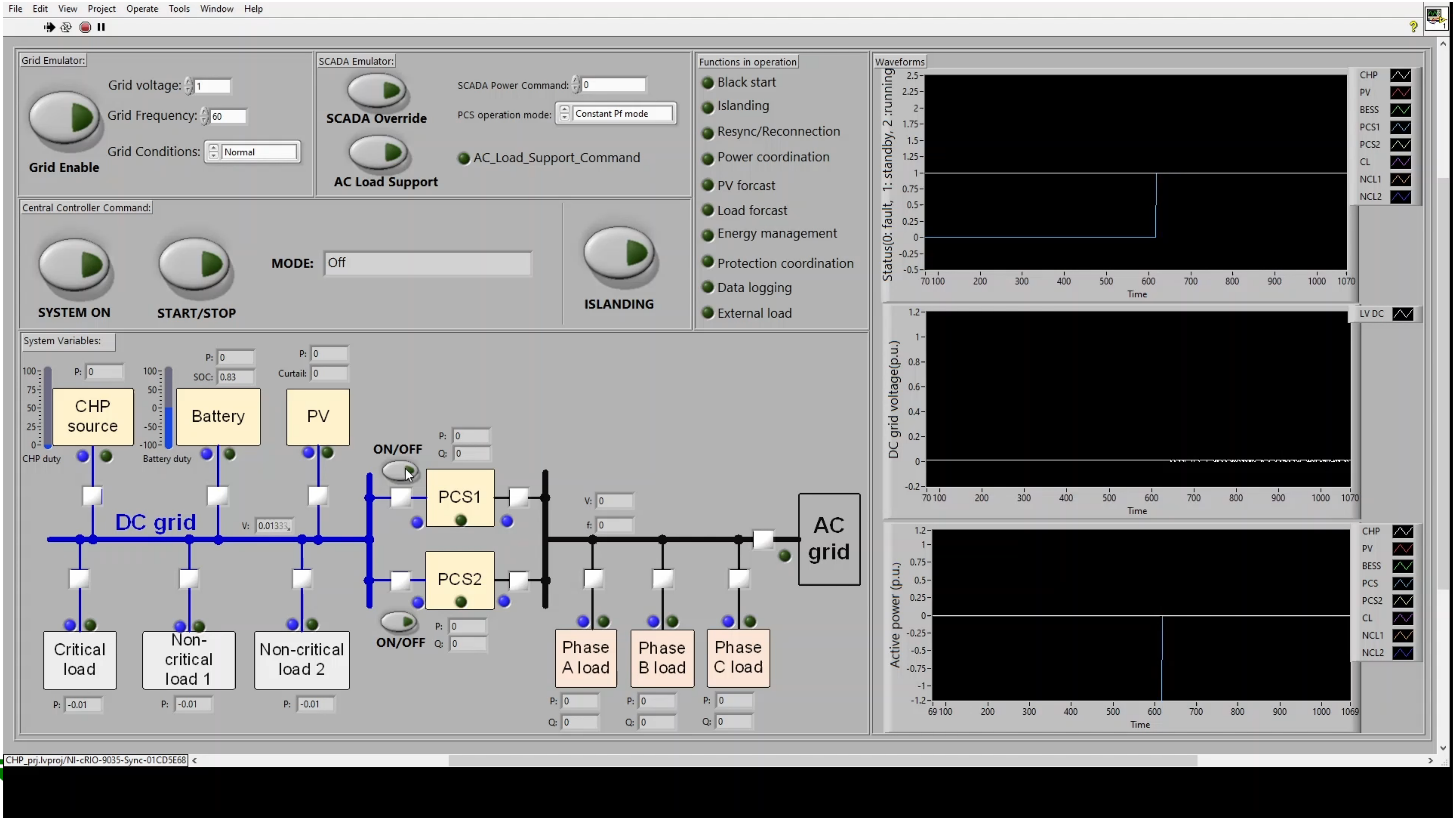
❑ The Hardware Testbed (HTB) test

- Support grid-connected mode, islanded mode, and mode transitions
- Normal and abnormal grid condition emulation
- Emulators for CHP, PV, BESS, and local loads
- PV and load profiles
- Small-scale PCS converter with the same topology and controller
- Central controller implemented in a CompactRIO
- Power circulating



Configuration of the HTB for the F-CHP controller test

F-CHP Controller Design, Implementation, and Test



F-CHP Controller Design, Implementation, and Test

❑ Tested Scenarios

#	Test	
1	F-CHP system start	From the LVDC side (to islanded mode)
2		From the MVAC side (to grid-connected mode)
3	Grid-connected mode operation(including PV and local load profiles)	
4	Islanded mode operation	Stand alone(including PV and local load profiles)
5		Support external AC loads (including AC load profiles)
6	Transitions and transient	Planned islanding
7		Unplanned islanding
8		Reconnection
9		AC grid fault transient

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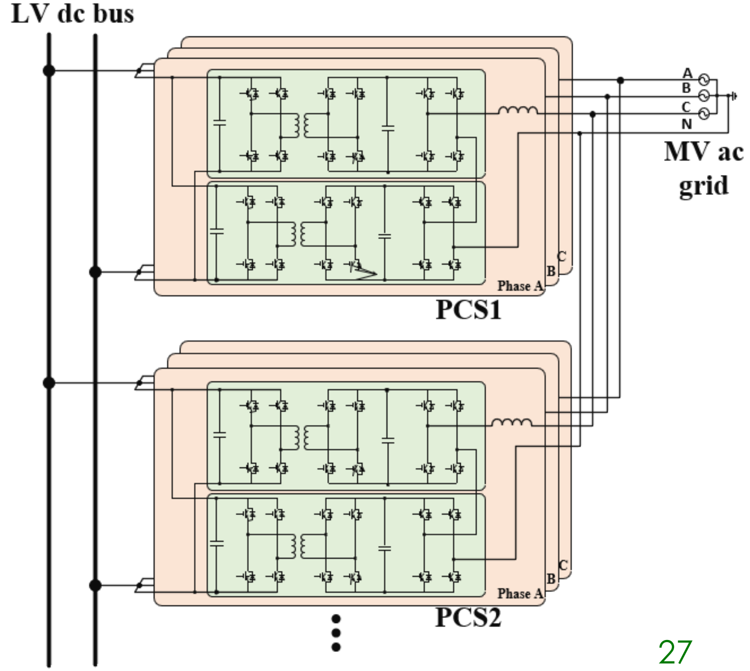
Summary and Future Work

❑ Summary

- The BP1 and BP2 are completed, and the BP3 is in progress
- The 13.8 kV/1 MW PCS converter is designed considering grid requirements
- A 13.8 kV/100 kW PCS converter prototype is developed and fully tested, which verified the converter design approaches
- The F-CHP system controller is designed, implemented, and tested in the HTB
- The F-CHP system controller is also tested for the scalable PCS operation

❑ Future Work

- A second 13.8 kV/ 100 kW PCS converter prototype, with better efficiency and power density, is under development to validate the scalability of the PCS



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