High Speed Medium Voltage CHP System with Advanced Grid Support

DE-EE0008409

(October 2018 – July 2022)

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DOE AMO CHP Workshop

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

DE-EE0008409: High Speed Medium Voltage CHP System with Advanced Grid Support

Project Partners:

Project Duration: 45 months
Project Start Date: October 1, 2018
Requested NCE for BP2 to October 31, 2022

Project Goals:

- Enable a TRL 5 demonstration of the 1 MW, 500 Hz, 15000 RPM high frequency CHP generator and electric machine system, utilizing advanced grid support functions required by IEEE Std. 1547-2018 and UL 1741 SA.
- Validate the grid tied SiC enabled high frequency CHP generator converter.
- Implement and validate the system replicating the gas turbine dynamics and high-speed generator-tied converter.
- Demonstrate island mode transitions and resynchronization for reconnection with the power grid with the fully coupled system prototype setup.

HS MV CHP with Grid Support Concept

- High Speed CHP systems operating directly at medium voltage may provide smaller footprint
- No 60 Hz power transformer with direct interface to medium voltage
- High speed machine drive may provide advanced grid support functions, i.e. reactive power support, voltage regulation, harmonic filtering and frequency regulation.
- The primary goal of this project is to be in a position to develop a medium voltage commercial grid-tied system with advanced grid support functions validated against IEEE-1545-2018 and UL 1741 SA
- Enable a TRL 5 demonstration of 1 MW, 500 Hz, 15,000 RPM machine system for advanced CHP grid integration

The demonstration system will:

- Validate the grid-tied SiC enabled high frequency CHP generator converter
- Implement and validate the system replicating the gas turbine dynamics and high speed generator-tied converter
- Demonstrate island mode transitions and resynchronization with the power grid with fully coupled system prototype setup

Demonstration System Specifications	
Generator Voltage	4.16 kV
Power Rating	1 MW
Operating Speed Range	11,000 – 15,000 RPM
Grid Voltage	480 V – 13.8 kV
Enabling Technology	WBG SiC MOSFET
Microgrid Controller	Compliant with IEEE Std. 2030.7
Interconnection and Interoperability	Compliant with IEEE Std. 1547-2018
Installed Cost Target	< $1,800 / kW rated power

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Project Scope

- Project is divided into seven tasks spanning two and a half budget periods.
- The development and hardware validation tasks are staggered to allow for incremental
- The project is capped off with a complete system demonstration with Power Hardware-In-the-Loop
- Mostly Completed Tasks 1-4
- Partially Completed 5-6
- Final Task 7 Planned for 2023

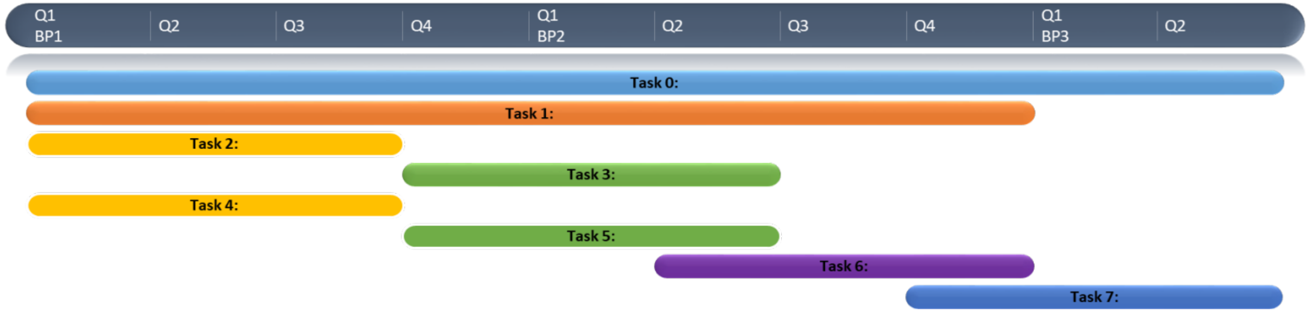
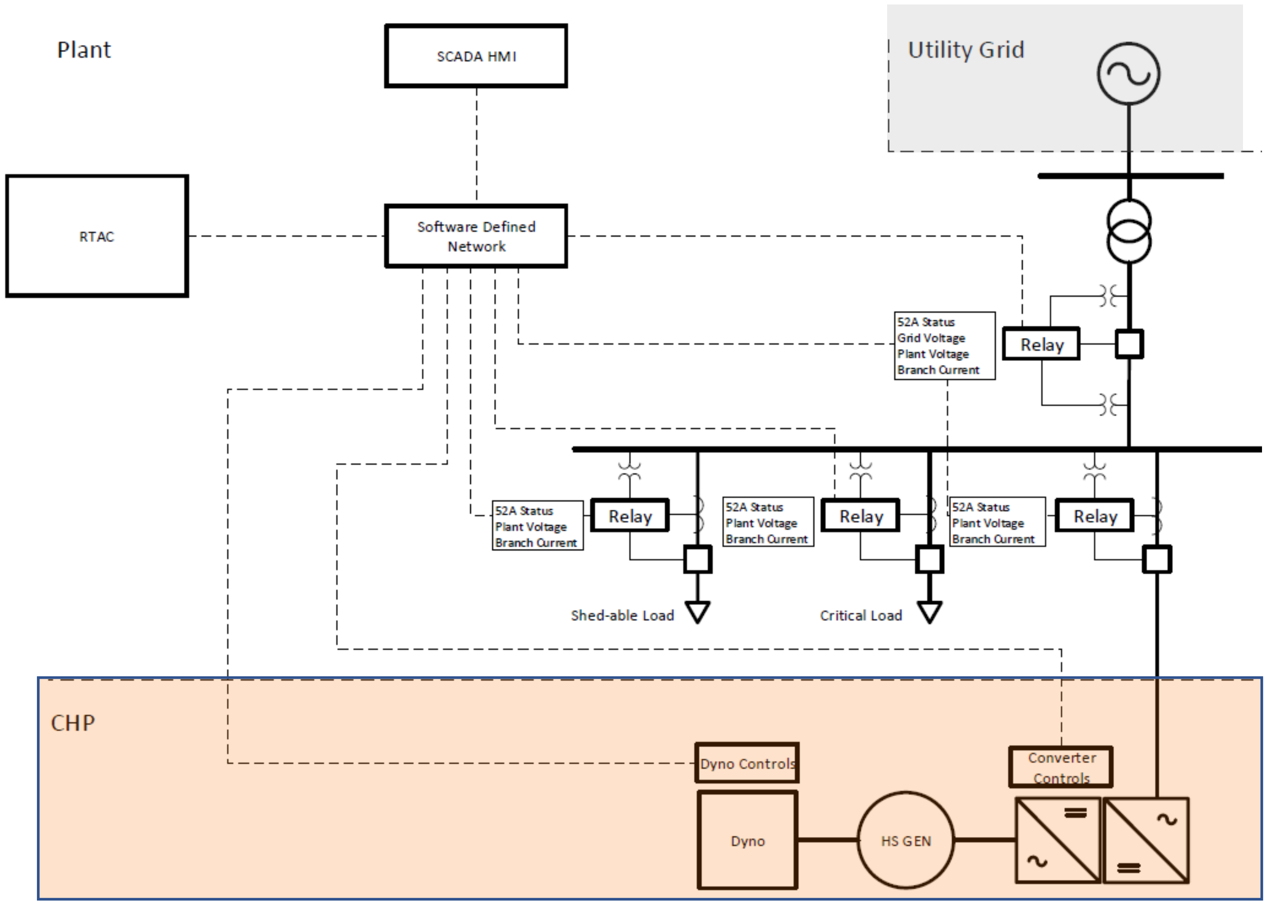


Table of Project Task Descriptions

Task	Description
1	Integration of Power Electronics Coupled CHP in Advanced Manufacturing Plants
2	Development of Advanced Grid Support Functions
3	Hardware Validation of Advanced Grid Support Functions
4	Development of Machine Controls for High Speed Gas Turbine Dynamics
5	Hardware Validation of the Coupled Gas Turbine and High Speed Generator Dynamics
6	Simulation and Controller Hardware-In-the-Loop Validation of the Fully Coupled System
7	Power Hardware-In-the-Loop Testing of the Fully Coupled System

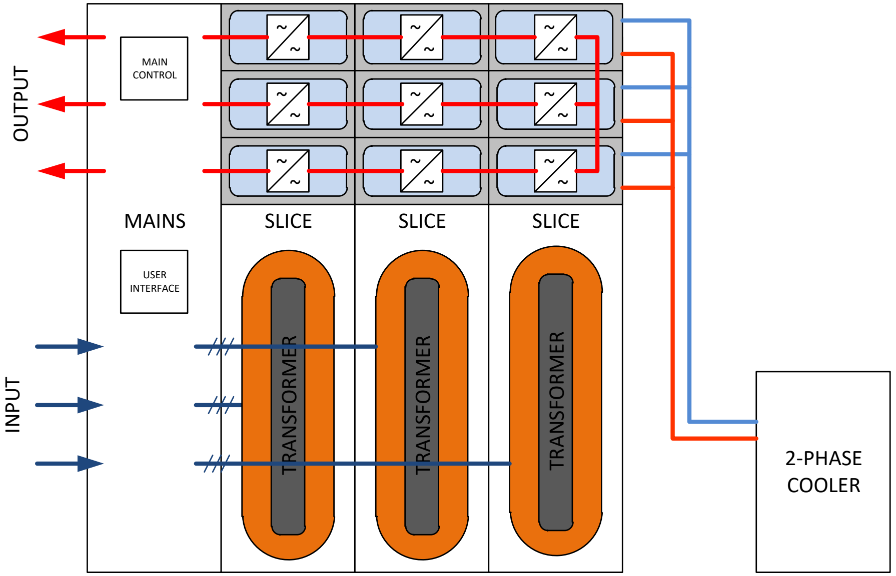
Base Line Manufacturing Plant Configuration

- CHP is the only source of distributed generation
- Islanding switch on the customer side of the utility interconnection
- Referenced at 1 MW DG and up to 2 MW plant load
- Consists of critical and shed-able plant loads
- COTS control hardware and software



WBG Power Electronics Architecture (Task 1)

- Series Connected H-Bridge (SCHB) topology with bi-directional power flow capabilities
- High frequency motor control enabled through SiC 1700 V MOSFETs
- Cascaded converters allow for direct connection up to 13.8 kV
- Integrated isolation transformers allow for a range of medium voltage grid connections from 4,160V up to 35 kV



TECO Westinghouse Schematic and actual system installation of a 1 – 2.5 MW SCHB architecture CLEMSON UNIVERSITY

Grid Interactive Converter:
Scope of Algorithm Development (Task 3)

- Five main areas of development, in order of priority

1. Phase lock loop bandwidth and stability under asymmetrical voltages
2. Measured voltage transformation(s)
3. Current regulation for asymmetrical voltages
4. Active unintentional islanding scheme with reactive power
5. Active and reactive power controller

Groupings of IEEE 1547 and UL 1741 Functional Requirements

Reactive and Active Power Control

- Constant Power Factor
- Constant Reactive Power
- Volt-VAR Reactive Power Control
- Watt-VAR Reactive Power Control
- Volt-Watt Regulation

Voltage Ride-Through

- Symmetrical and Asymmetrical

Frequency Ride-Through

- Under and over frequency

Frequency Regulation

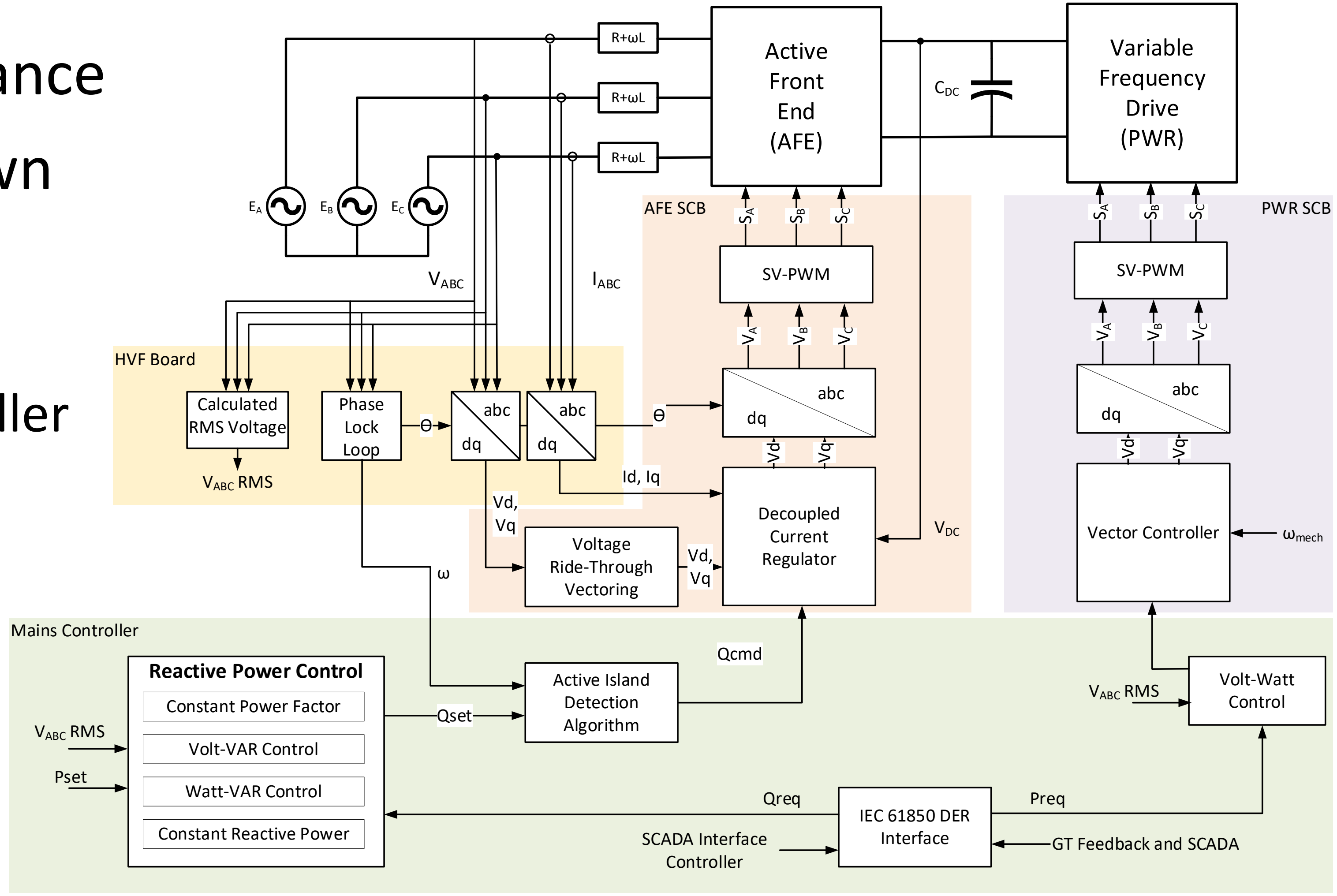
- Droop mode frequency regulation
- Inertial response

Unintentional Islanding

- Active unintentional islanding
- Passive unintentional islanding

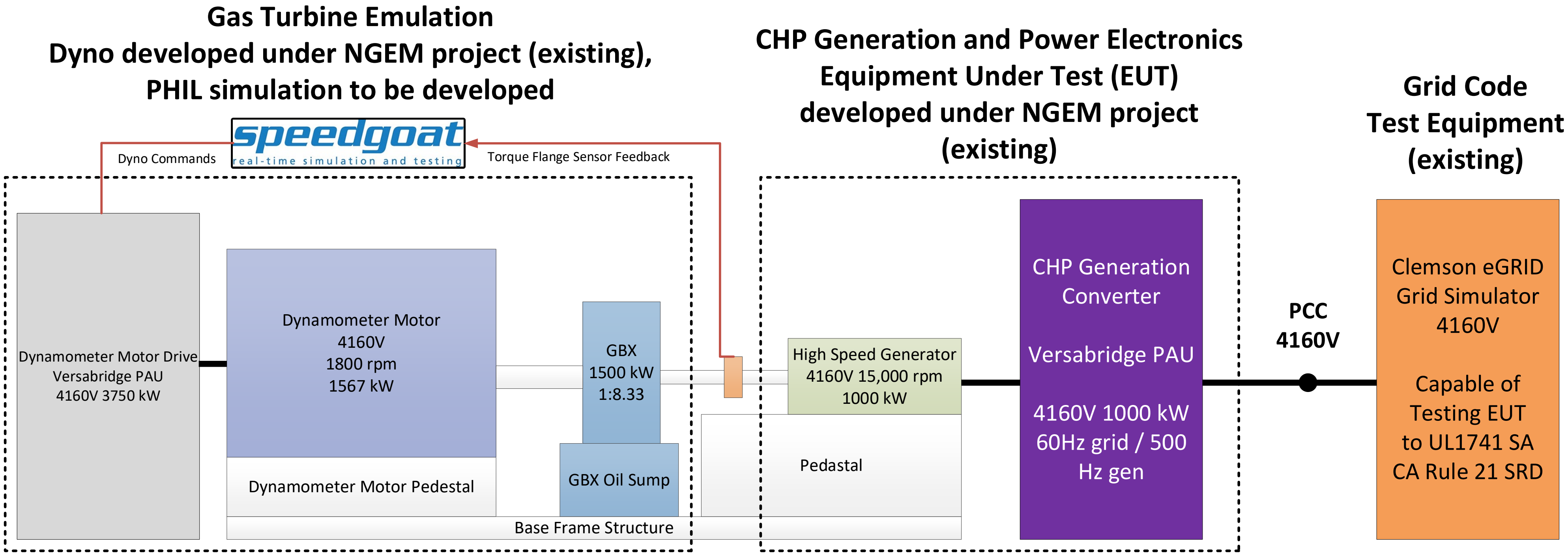
Grid Interactive Converter: Scope of Algorithm Development (Task 3 and 4)

- IEEE 1547-2018 compliance
- Trip logic units not shown
- Other possible inputs:
  - GT engine control
  - SCADA Interface Controller



System Validation in Task 7

- Power Hardware-In-the-Loop simulation of the gas turbine dynamics
- Utilizing existing eGRID capabilities for grid code compliance testing



Block diagram of the Power Hardware-In-the-Loop system validation

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SCADA Interface Controller (Task 6)

- SCADA Interface Controller
  - Function 1: Coordinate utility SCADA requests
  - Function 2: Manage islanding transitions
  - Function 3: Provide microgrid energy management functions
- Plant EPS to use IEC 61850 data framework
  - CHP plant to use a mixed definition
    - IEC 61850-7-420 for DER functions
    - Additional logic nodes for IEEE 1547 and IEEE 2030 islanding transitions
  - Provides a clear roadmap to integrate future resources

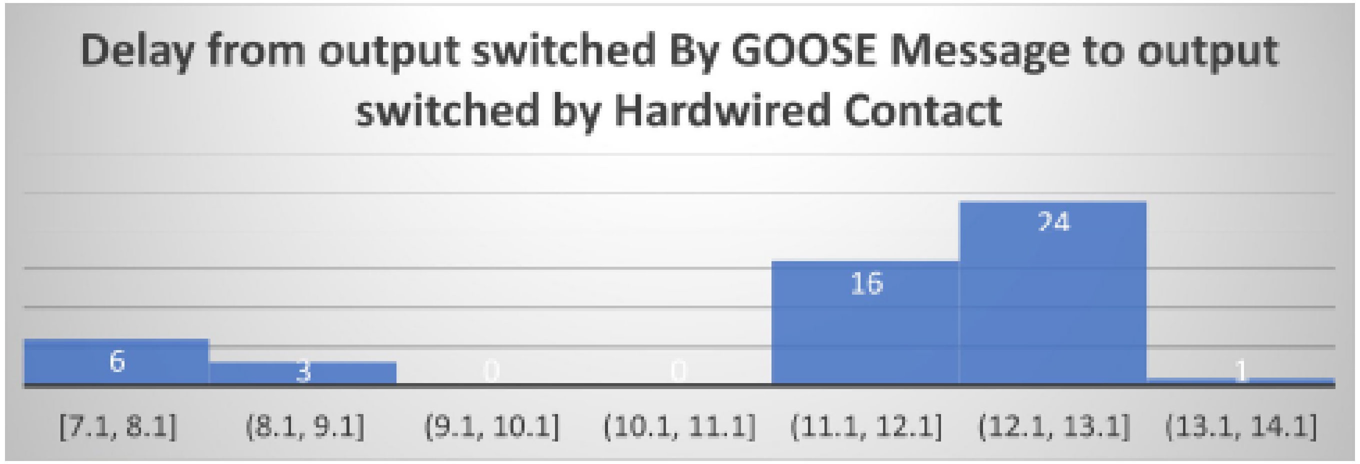
TABLE II
PARAMETERS THAT MAKE UP AN IEC 61850 PROFILE FOR ENERGY MANAGEMENT OF CHP UNITS

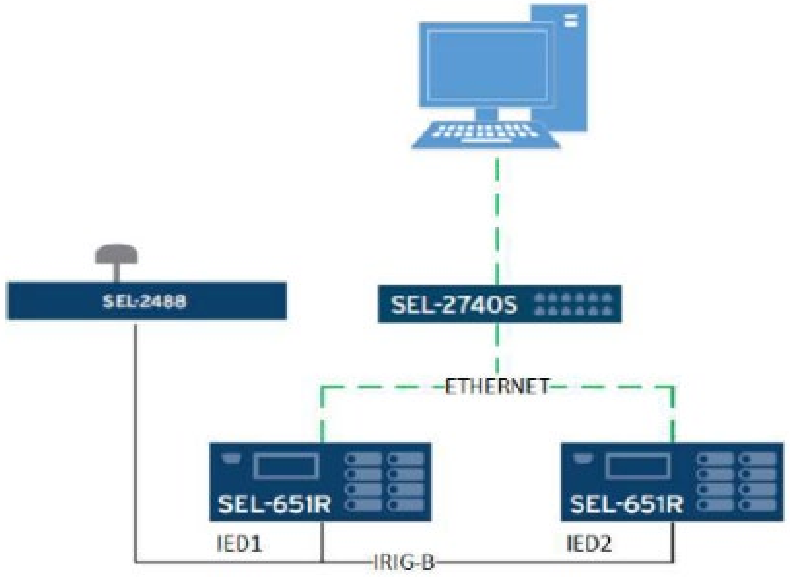
param. name	unit	description
chp-heat-power-efficiency	%	heat to electricity
chp-operation-possible	bool	flag which states whether the target power of the CHP unit(s) may be set
chp-power	W	current power of the CHP unit(s)
chp-target-power	W	to set the target power
chp-min-power	W	minimal elec. CHP power
chp-max-power	W	maximum elec. CHP power (sum of the power of available CHPs)
chp-step-size	W	the modulation step size
chp-active-control	bool	a keep alive bit - which has to be set in constant intervals to keep control
storage-max-capacity	Wh	maximum capacity of storage
storage-loss-over-time	%/h	loss of storage tank over time
storage-state-of-charge	%	state of charge of the storage tank
boiler-power	W	current power of the boilers

S. Feuerhahn, R. Hollinger, C. Do, B. Wille-Haussmann and C. Wittwer, "Modeling a vendor independent IEC 61850 profile for energy management of micro-CHP units," *2012 3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe)*, Berlin, 2012, pp. 1-5.

SCADA Interface Controller Hardware-In-the-Loop (CHIL)

- Capable of benchmarking and proving use cases with the complete
- Utilizing real-time power electronics and power system simulation tools
- Coupled simulation to real control elements and IEC 61850 enabled IEDs
- Using industry recognized hardware and software for system configuration and control





GOOSE messaging benchmark diagram

Real-Time Distributed Control system used for initial controller demonstration

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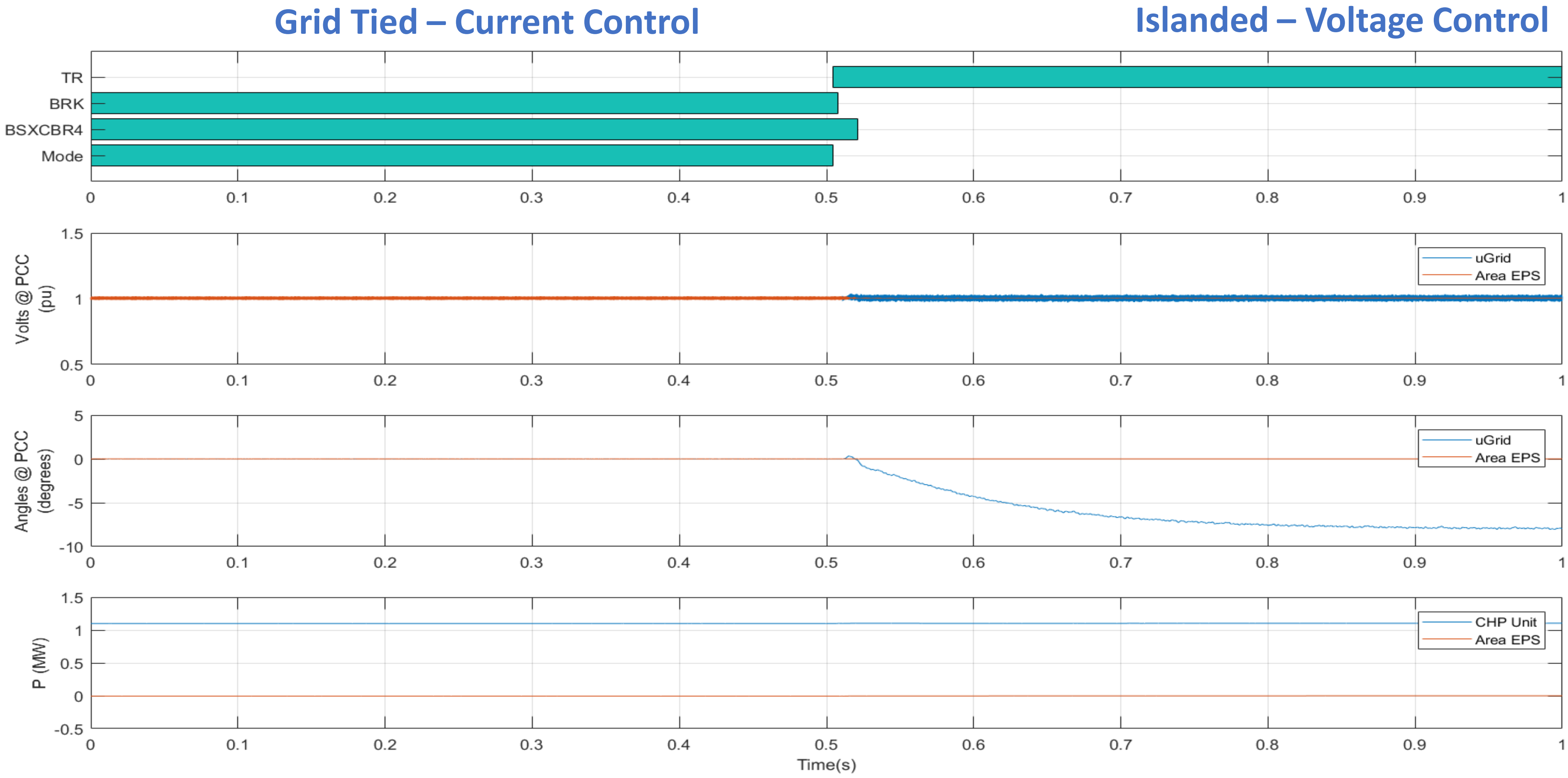
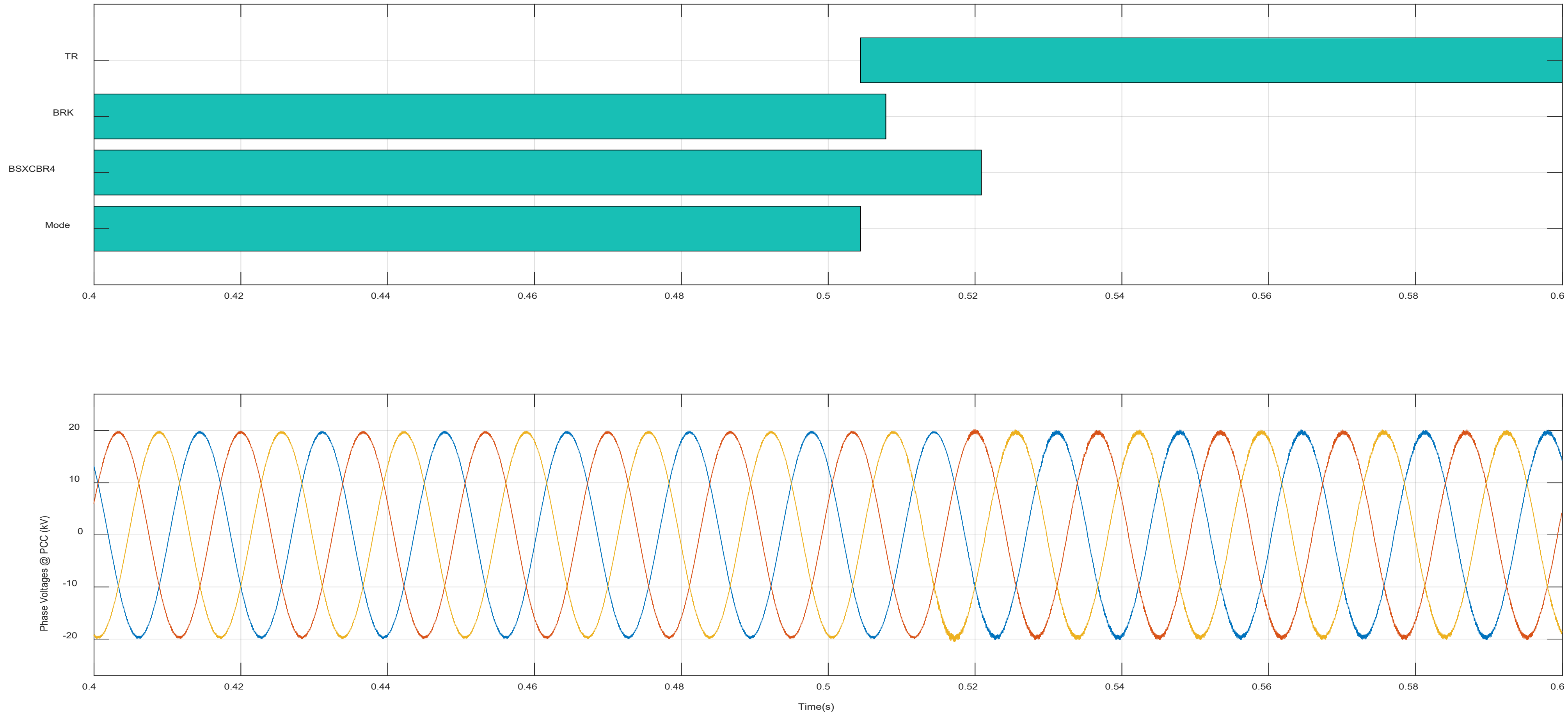
Transition to Islanding: Balanced Power



Transition to Islanding: Balanced Power

Grid Tied – Current Control

Islanded – Voltage Control



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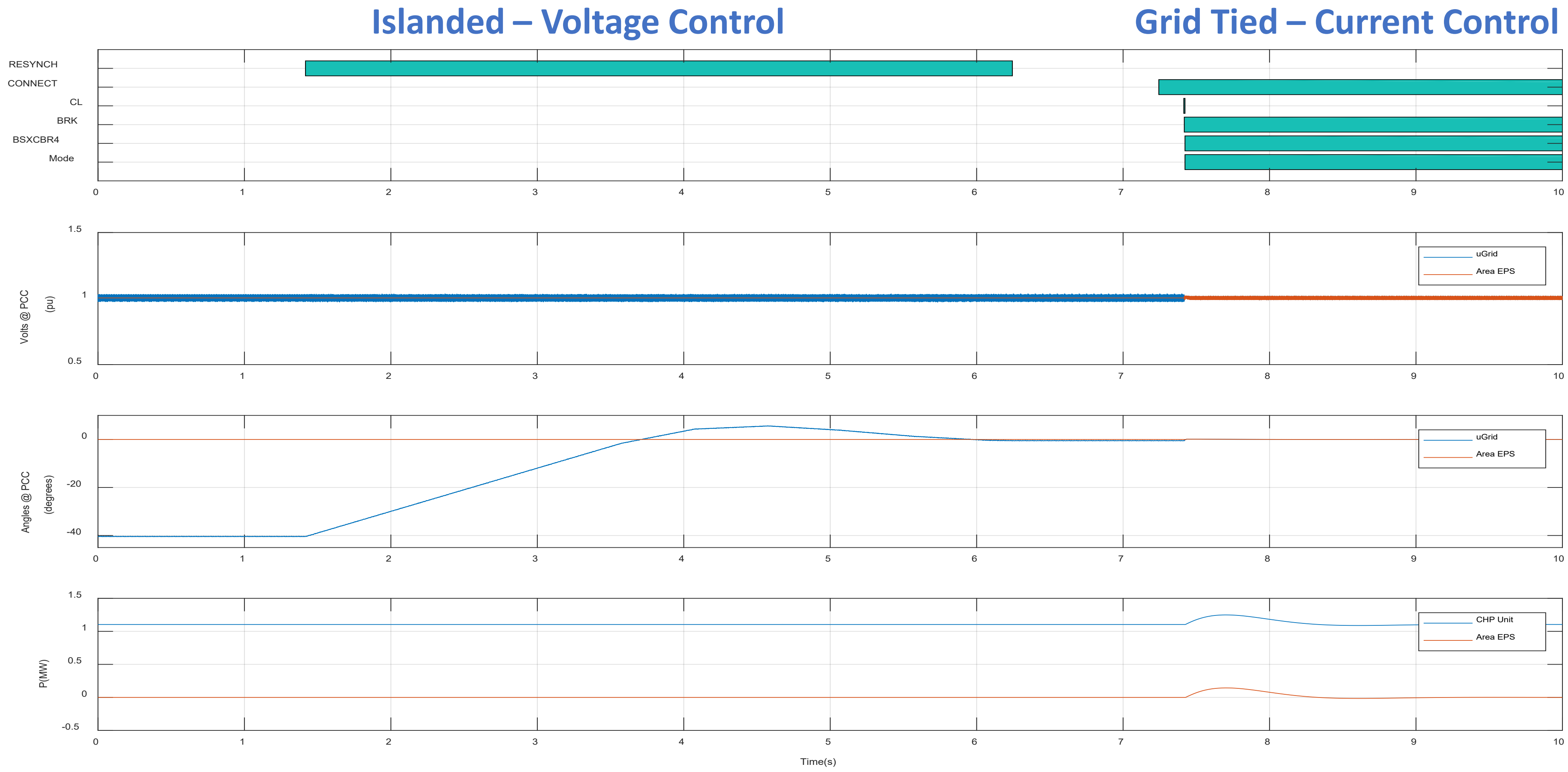
Automatic Reconnect of Islanded System



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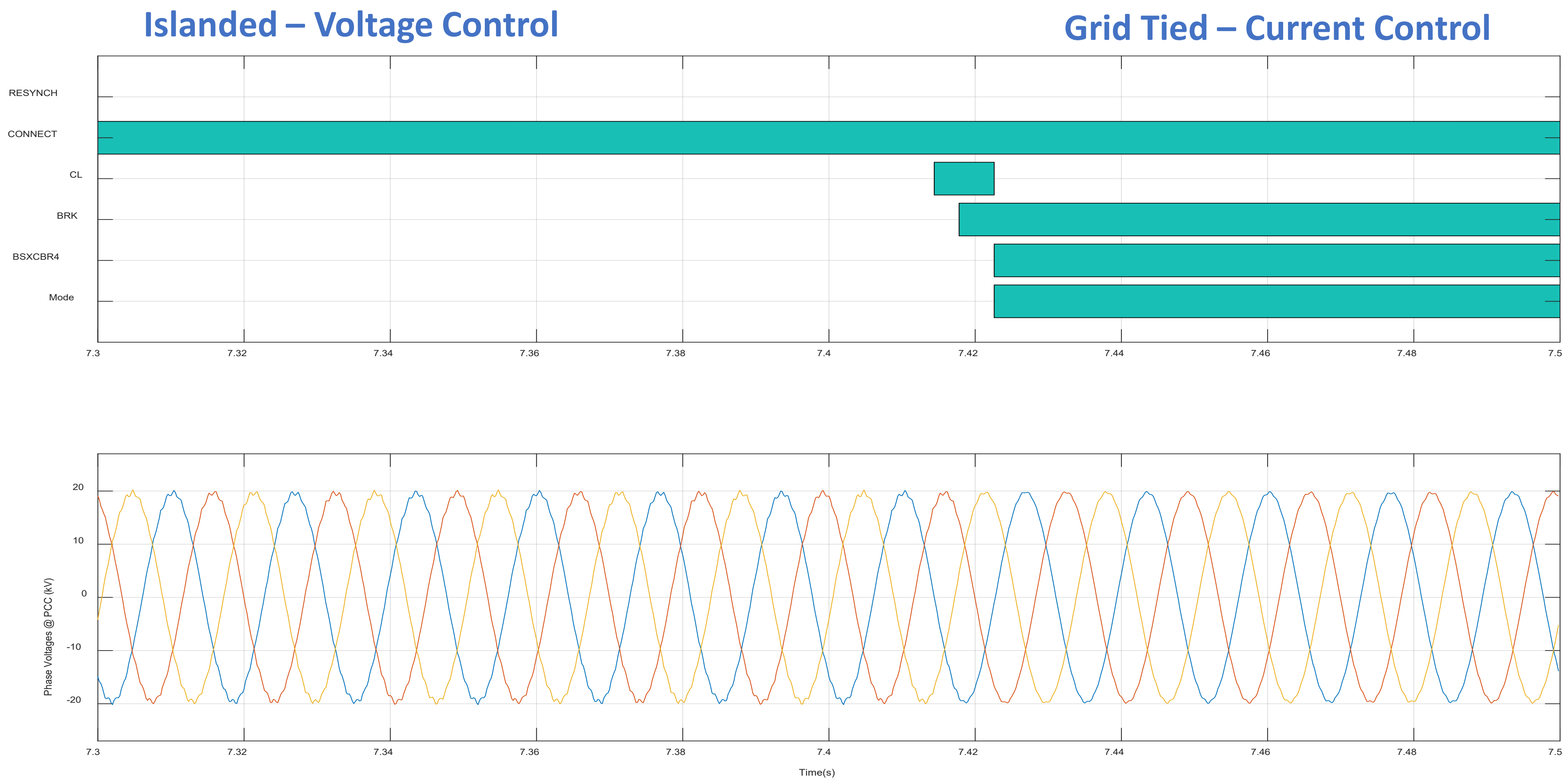
Automatic Reconnect of Islanded System



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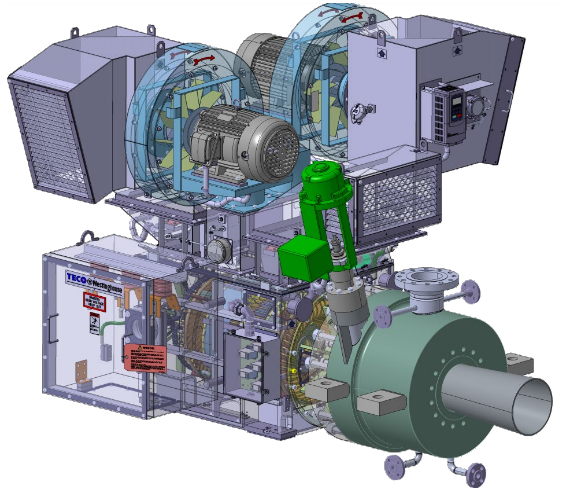
Enabling Technology

- High Frequency Medium Voltage Variable Frequency Drive
  - Multi-level design suitable for many applications
  - Modular design for simplified O&M requirements
  - Using state-of-the-art Silicon Carbide power electronics to increase efficiency

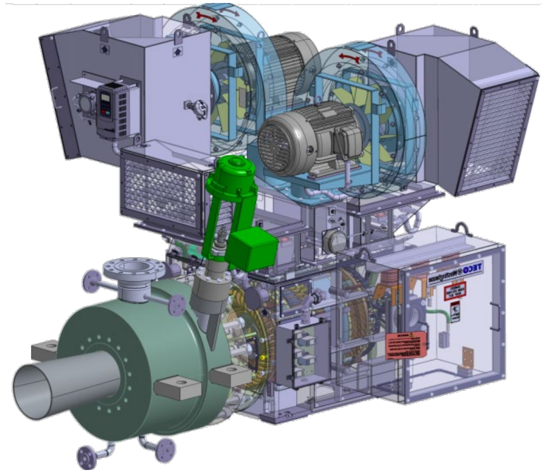


- High Speed Medium Voltage Induction Machine
  - Robust machine design building off decades of experience
  - Low maintenance squirrel cage design with no permanent magnets
  - Open or totally enclosed designs available
  - Can be designed for hazardous environments

High Speed Medium Voltage Induction Machine

- Considered a squirrel-cage induction motor topology for the high speed application because of its robustness
- Selected commercially available materials with low losses and high strengths
- Optimized the geometry for the application to achieve the required performance with lowest cost
- Designed the stator coils using type 8 Litz conductors to minimize eddy current proximity losses

Prototype 1 MW, 15,000 RPM Induction Machine



3D rendering with the turbo expander attached

1 MW Reference System Specifications

(sensitive data removed)

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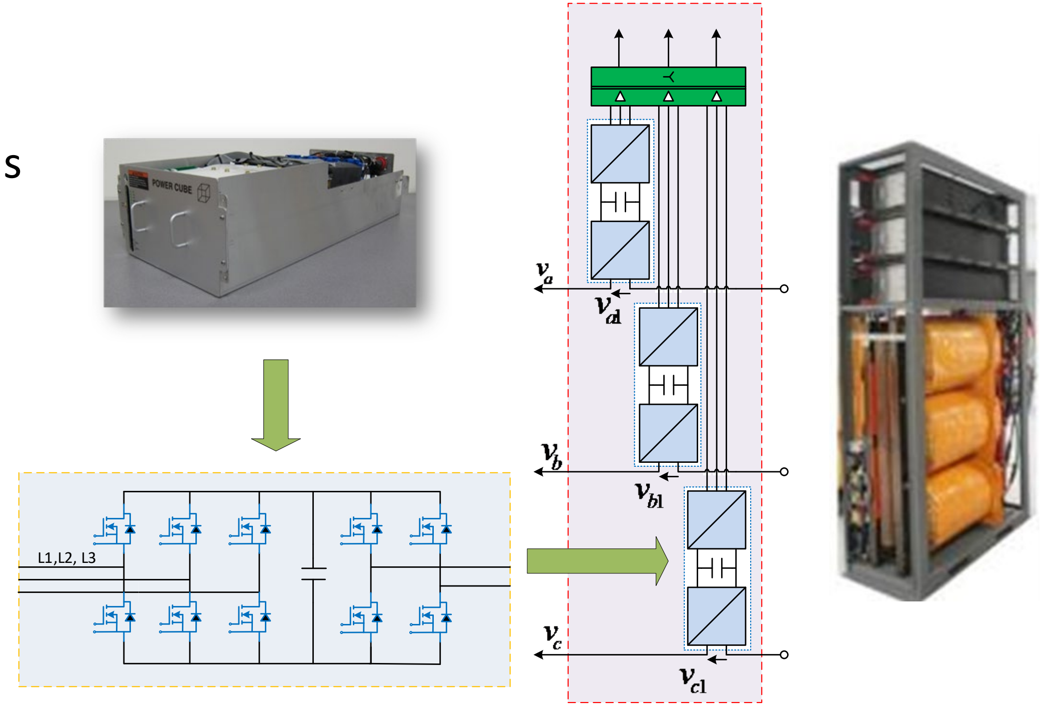
High Frequency Medium Voltage Variable Frequency Drive

- Modular, multi-level system architecture
  - Scalable in voltage by adding slices in series
  - Scalable in power by adding units in parallel
- Suitable for high speed motoring and generation applications
- Able to use low voltage SiC MOSFETs, leveraging cost reductions from other industries
- Low input and output distortion reducing grid and induction machine requirements

1 MW Reference Hybrid SiC based System Specifications

(sensitive data removed)

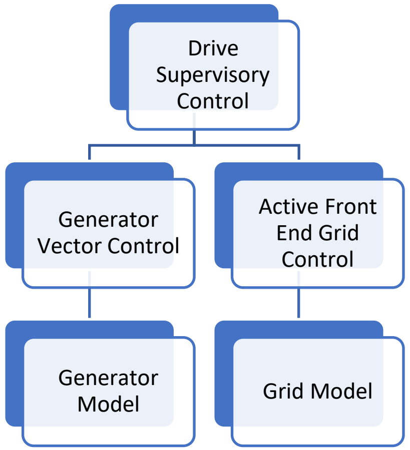


Modular, multi-level, medium voltage VFD architecture scalable in the 1 to 20 MWe range

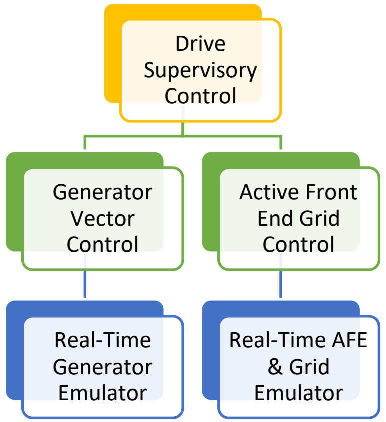
Controller HIL Approach (Task 5)

- Clemson has developed a real-time model of the complete system to investigate the Drive Supervisory Control
  - This controller contains the elements of the Generator Vector Control and the Active Front End Grid Control
  - Enables control development around the coordination of the Generator and Grid control requirements
- TWMC is working to finalize the CHIL for:
  - Generator Vector Control and Real-Time Generator Emulator – BP2 M1
  - Active Front End Grid Control and Real-Time AFE & Grid Emulator – BP2 M3
  - Development must be completed at TWMC due to the control hardware setup involved
  - Clemson has supported development of both the generator and AFE & Grid emulators

Clemson Full System Real-Time Model and Control



TWMC Controller Hardware-In-the-Loop Implementation

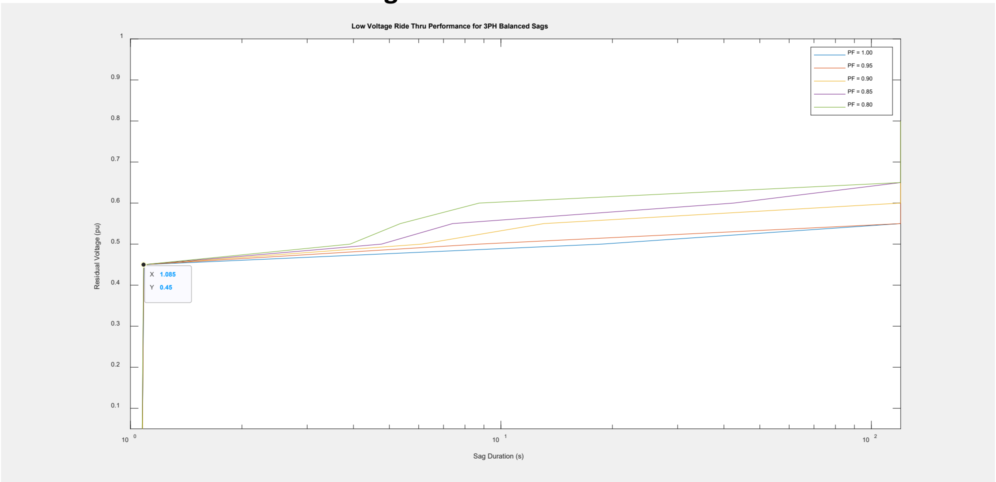


TWMC is focusing on CHIL of Vector and AFE Control to meet milestones

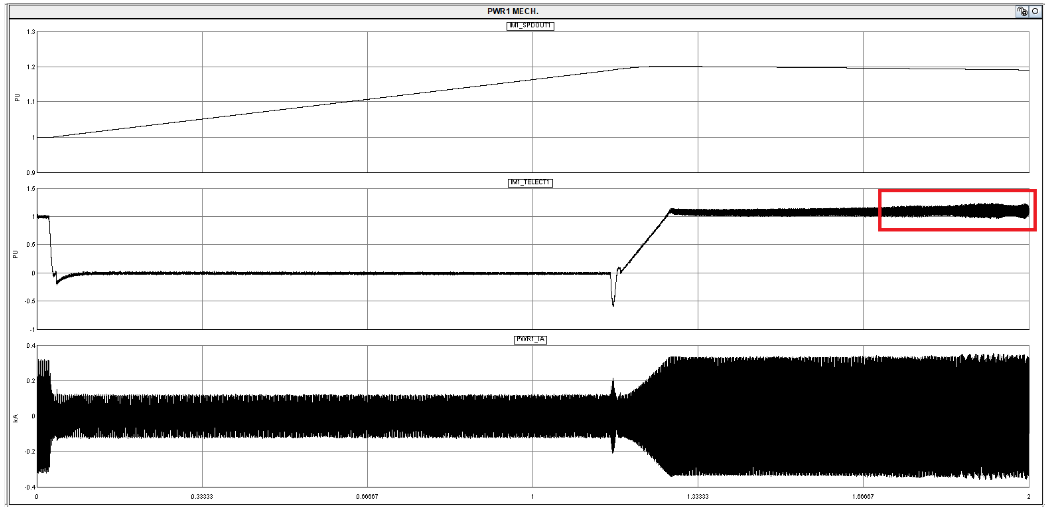
Drive Supervisory Control (Task 5)

- The AFE overcurrent limits are sufficiently large so that the system should ride through the majority of low voltage conditions in the IEEE 1547 2018 Cat. III *mandatory operation* region
  - For single phase and two phase sags, the system will ride through indefinitely regardless of the power factor setpoint
  - For three phase sags, the power factor setpoint will affect the allowable ride through duration at the combination of low power factor and large voltage sags
- The system meets the 1.0s ride through requirement in the *momentary cessation* region.

3 Phase Sag Maximum Duration Vs. Power Factor



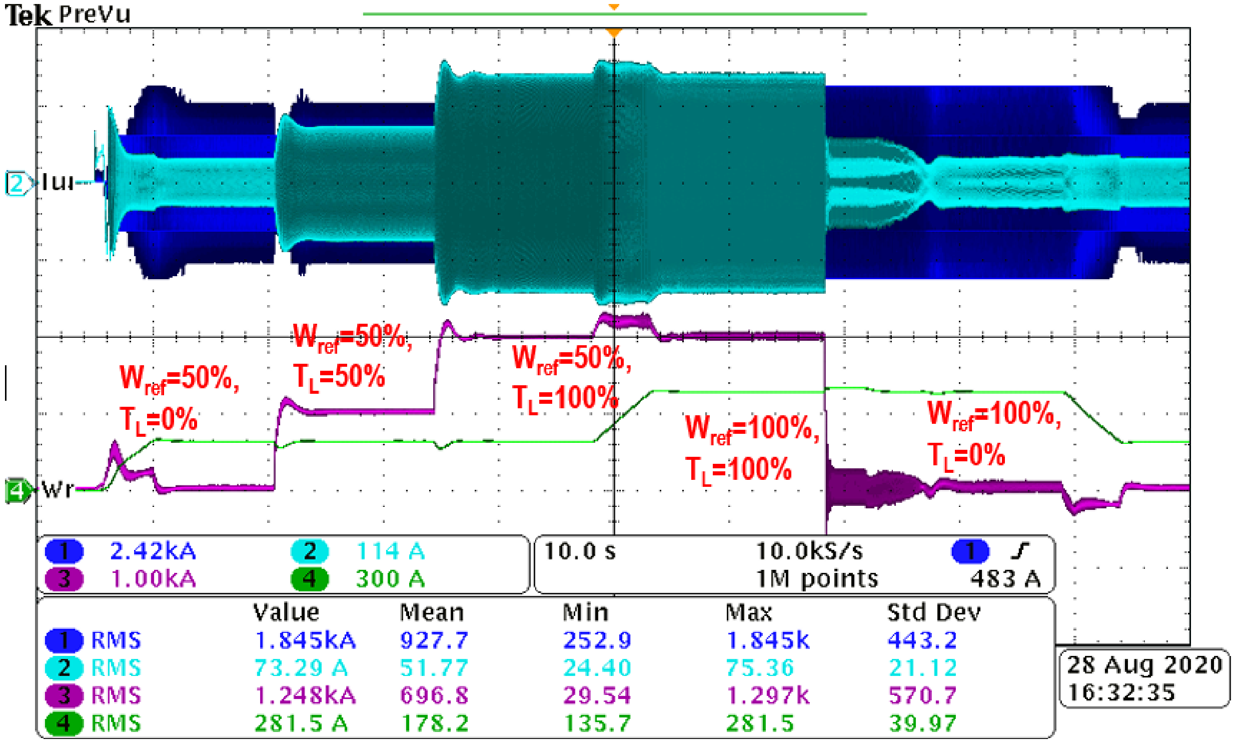
Example 1.2 s, 50% voltage sag ride-through example



TWMC Controller HIL Simulator (Task 5)

TWMC "Iron Bird" CHIL Setup

60 Hz operation of a Virtual Induction Machine Utilizing CHIL Environment



- Shown torque dynamic response as command is varied from 0%, 50%, 100% and back to 0%
- Correspondingly, speed response as command changes from 0%, 50%,100%, and back to 50%

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TWMC Controller HIL Simulator (Task 5)

NEXT CHIL Activities at TWMC to complete BP2 Tasks:

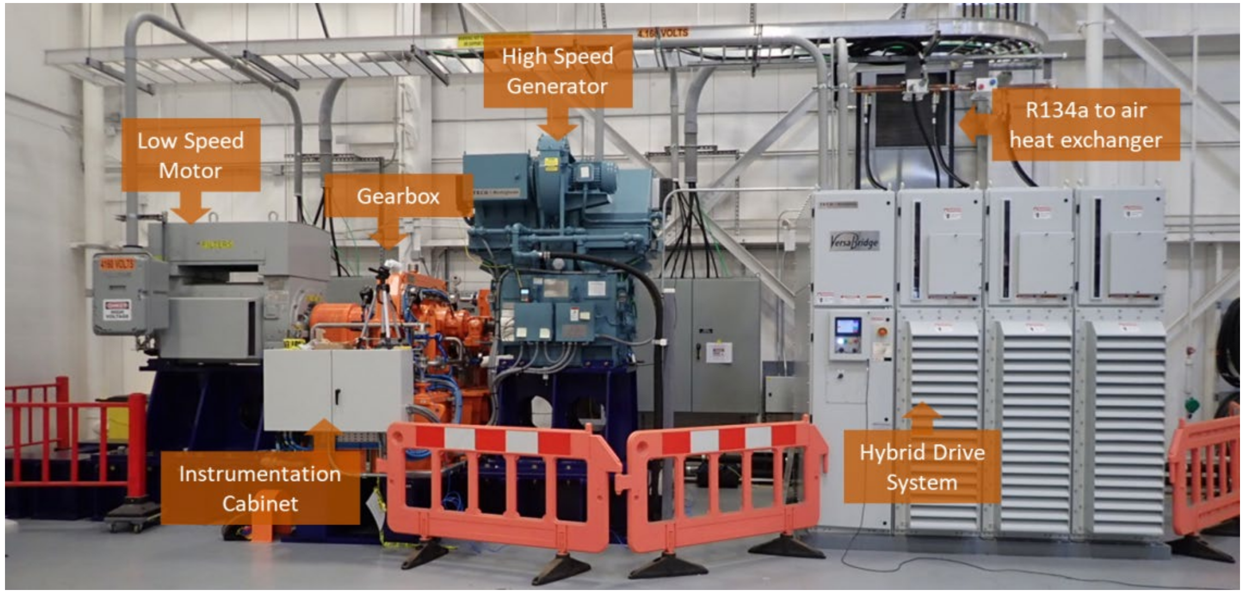
- Tune the virtual LabView FPGA encoder model to reliably emulate real motor encoder operation at 500Hz (15000 RPM)
- Test AFE Grid Control and Real-time AFE &Grid Emulator (CHIL environment)
- Transfer tested system Control Code for final PHIL prototype validation

500 Hz operation of a Virtual Induction Machine Utilizing CHIL Environment

- The figure above shows correct input voltage, output voltage, and output current at 50% speed command.
- At speed >50%, output currents (NOT shown) demonstrate some imbalances. Encoder model may require more tuning.

1 MW Prototype System Validation (Task 7)

- Initial full power runs completed demonstrating successful results
  - Total system efficiency, shaft to grid > 92%
- Comprehensive test plan developed and validation testing underway



1 MW reference design undergoing validation testing at the Clemson University eGRID Center

Protocol Reference	Title
IEEE Std 1566™-2005	IEEE standard for performance of adjustable speed ac drives rated 375 kW and larger
UL 347A-2015, 1st Ed.	Medium voltage power converter equipment, standard for safety
IEC 61800-4:2002	Adjustable speed electrical power drive systems-general requirements-rating specifications for ac power drive systems above 1000 VAC and not exceeding 35 kV
IEEE Std 519™-1992	IEEE recommended practices and requirements for harmonic control in electrical power systems
IEC 61000-3-6:2008	Harmonic Emission Limits for Customers Connected to MV, HV and EHV
IEEE Std 112™-2017	IEEE standard test procedure for polyphase induction motors and generators
NEMA MG1-2014	Motors and generators
IEEE Std 85-1973	IEEE Test Procedure for Airborne Sound Measurements on Rotating Electric Machinery
IEEE Std 1547.1-2020	IEEE Standard Conformance Test Procedures for Equipment Interconnecting Distributed Energy Resources with Electric Power Systems and Associated Interfaces
UL 1741 SA, 2nd Ed.	Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy Resources

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Questions