Consolidated Utility Base Energy (CUBE) Performance Test Report

Mariko Shirazi and Gregory Martin
National Renewable Energy Laboratory

Christopher Niebylski
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Photo by D. Schroeder, NREL

NREL is a national laboratory of the U.S. Department of Energy
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National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

Work for Others Report
NREL/TP-5B00-52768
December 2014

Contract No. DE-AC36-08GO28308

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NATIONAL RENEWABLE ENERGY LABORATORY

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There are many people without whom the Consolidated Utility Base Energy (CUBE) would just be an idea or a pile of parts. The authors would like to thank Bill Kramer for being the vision behind the CUBE and bringing the opportunity to NREL. The CUBE was initially built and tested at NREL's Distributed Energy Resources Test Facility (DERTF). The authors would like to thank Bob Hansen for building and wiring the entire CUBE at the DERTF. The authors would also like to thank Noel Dillman for helping with the mechanical design and Blake Lundstrom for helping code the algorithms. The CUBE was moved to the Energy Systems Integration Facility (ESIF) to complete performance testing. The authors would like to thank the extensive support team at the ESIF that helped make this possible. In particular, the authors would like to thank Kyle Tangler, Josh Martin, Roy Fraley, and Scott Walters for mechanically installing the tactical quiet generators (TQGs), including diesel fuel plumbing and exhaust ducting. The authors would like to give additional thanks to Kyle for pulling lonely night-shift duty during both 24-hour tests and to Josh for designing and installing cooling system upgrades for the CUBE. The authors would also like to thank Rick Ferree, Mike Corkery, and Encore Electric for electrically installing the CUBE, TQGs, and all associated power components; Lee Ann Underwood and Phil Clark for ensuring worker health and safety during the CUBE testing; Susan Bond, Greg Moyer, and Bryan Shu for providing computer support; Dan Olis and Travis Simpkins for modeling the system to determine the specific load and solar profiles; and Adam Bailey and Mike Simpson for programming the ESIF load bank and photovoltaic (PV) simulator with these profiles. Finally, the authors would like to thank Carolyn Elam for steadfastly making available the ESIF resources and personnel necessary to successfully complete the CUBE testing.

Executive Summary

This report provides performance test results for a photovoltaic (PV)-battery-diesel hybrid power system developed by the National Renewable Energy Laboratory (NREL) for the U.S. Army Rapid Equipping Force (REF) and the Expeditionary Energy and Sustainment Systems (E2S2) to provide power to Forward Operating Bases (FOBs). The cornerstone of the hybrid power system is the Consolidated Utility Base Energy (CUBE) system. The CUBE provides the power conversion, distribution, and protection necessary to integrate the various power sources and was built from the ground up to provide a flexible platform that can be modified to meet specific FOB needs. The CUBE was tested to demonstrate fuel savings as well as power quality relative to a baseline diesel-generator-only system. The fuel savings were verified by performing two 24-hour tests: one test with the complete CUBE system operating with two 30-kW diesel generators, 21.2 kW of simulated PV, and a 30-kW/40-kWh lithium-ion battery; and one test with the two diesel generators only. The tests were performed using a measured 24-hour FOB load profile and a measured 24-hour solar profile. Over the 24-hour period, the CUBE system was able to achieve a 31% reduction in fuel use and a 42% reduction in overall diesel run-time relative to the diesel-only case. These benefits were achieved with a total battery throughput of less than 1.4% of the total load energy, with only one additional generator start, and while maintaining power quality comparable with that provided by the diesel generators alone. Additional tests were performed to demonstrate CUBE power quality during load steps, mode transitions, and a black start. Results demonstrated the ability of the CUBE to provide comparable load step response as a diesel generator, to maintain high power quality during transitions from diesel generator as grid-forming unit to CUBE as grid-forming unit and vice versa, and to provide high power quality during a black start onto a load.

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Introduction

The Consolidated Utility Base Energy (CUBE) system is an integrated power electronic platform for a 60-kW photovoltaic (PV)-battery-diesel hybrid power system developed for the U.S. Army Rapid Equipping Force (REF) and the Expeditionary Energy and Sustainment Systems (E2S2) to provide power to Forward Operating Bases (FOBs). The CUBE is based on modular power electronic building blocks and includes power distribution and protection components, an isolation transformer, magnetics and other filter components, a liquid cooling system, a control platform based on field-programmable gate array (FPGA) and real-time controllers, and a touchscreen user interface. The CUBE is able to integrate four 5-kW to 10-kW PV arrays, one 30-kW battery pack, and two 30-kW diesel generator sets to power a 60-kW peak load. The onboard power electronics include PV maximum power point tracking (MPPT) converters, battery charge/discharge converters, and a three-phase inverter capable of smoothly transitioning between operation as the grid-forming unit and operation in parallel with the diesel generators. The CUBE is approximately 3 feet wide by 6 feet long by 5 feet high and is installed on a 15-kW tactical quiet generator (TQG) skid.

The goal of the CUBE is to minimize diesel fuel use while maintaining reliable and high-quality power. The CUBE was installed at the National Renewable Energy Laboratory's (NREL’s) Energy Systems Integration Facility (ESIF) along with two TQGs, a lithium-ion battery pack, a PV simulator, programmable load banks, and a precision fuel flow meter. Two 24-hour tests were performed, one with the complete CUBE system and one with the TQGs only, to validate fuel savings and demonstrate the CUBE’s ability to deliver reliable and high-quality power. The tests were performed using a load profile from actual measured load data at an emulated FOB as well as a measured solar irradiance profile. In addition to the 24-hour tests, the CUBE was subjected to a series of load steps and a forced black start to demonstrate power quality during all modes of operation, during transitions between different modes, and during load steps themselves. In particular, the tests demonstrate power quality during transition from TQG as grid-forming unit to CUBE as grid-forming unit and vice versa.

This report is organized as follows:

- Overview of CUBE power and control architectures
- Description of experimental installation and setup
- Description of the particular dispatch settings used for the 24-hour tests
- Description of the load and solar profiles
- Presentation and discussion of 24-hour test results
- Presentation and discussion of the mode transition, black start, and load step response test results
- Conclusions and future work.

Power Architecture

The CUBE provides three key functionalities: (1) power conversion, (2) power distribution, and (3) power protection. The power conversion and distribution functionalities are depicted in the block diagram shown in Figure 1. The diagram includes voltage specifications for the various inputs/outputs.

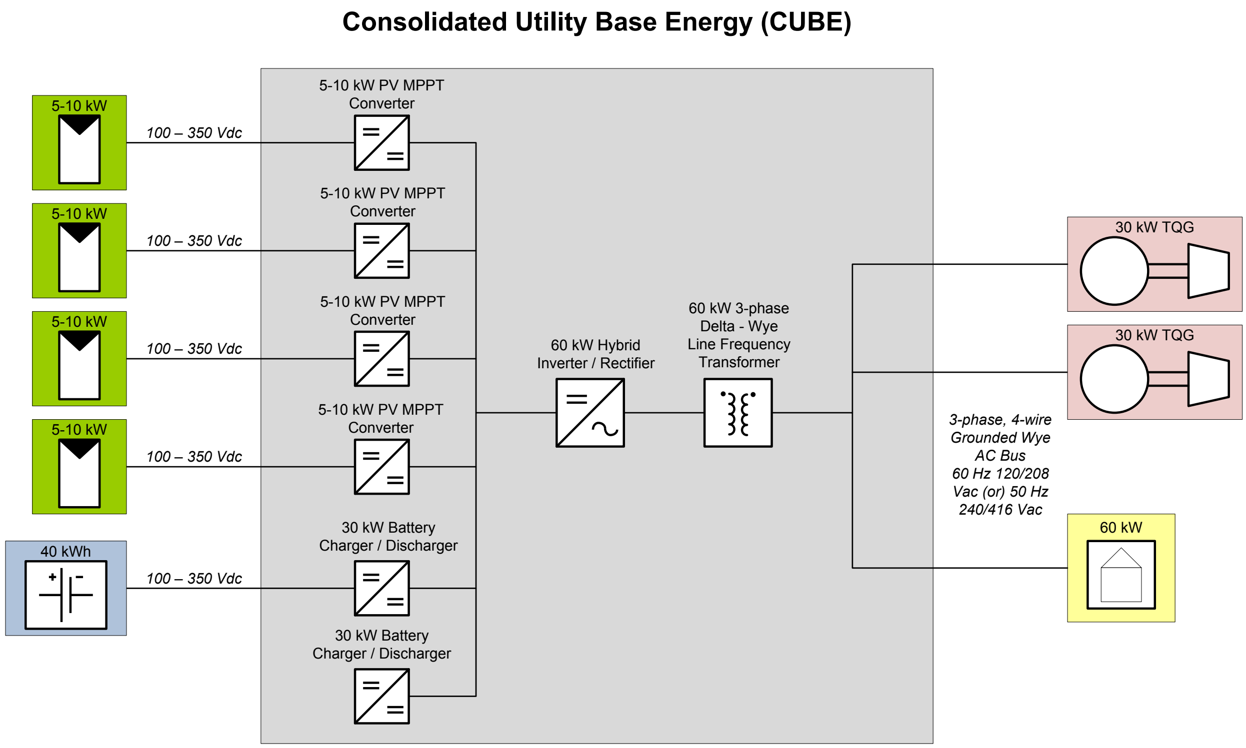


Figure 1. CUBE block diagram.

The power electronic converters shown in Figure 1 are built using Semikron SKAI modules. These modules include the insulated-gate bipolar transistor (IGBT) power semiconductors, DC link capacitors, gate drivers with low-level protection, and voltage, current, and temperature sensors. The control platform is based on National Instruments CompactRIO (cRIO) modules, each of which includes an FPGA backplane and a real-time processor. Power electronic topologies and filter components were selected for each interface, and modulation and feedback control algorithms were developed to provide the required converter functionalities. These include four PV converters (PVCs) to provide MPPT for the PV inputs, one battery charge/discharge converter (BCD) to interface with the battery, and one three-phase bi-directional inverter, called the hybrid inverter/rectifier (HIR), which can operate either as the grid-forming unit or in parallel with the diesel generators. A line frequency transformer is connected to the HIR output to provide isolation between the AC and DC busses and to provide a neutral connection for single-phase loads.

The CUBE power protection functionality is provided by the components shown in Figure 2. Protection components include circuit breakers for over-current protection, surge protection devices for lightning protection, and over-voltage relays. The circuit breakers are also included on all power inputs to serve as isolating devices for lock-out-tag-out (LOTO) during maintenance activities. Power connections to the CUBE are made using MIL Spec circular connectors.

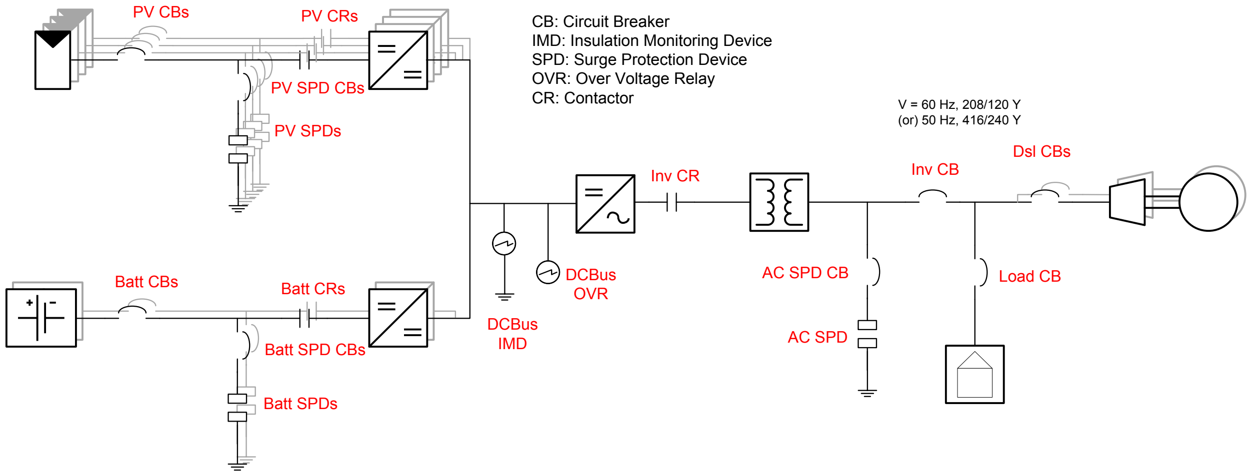


Figure 2. CUBE power protection components.

Control Architecture and Operation

The CUBE consists of three power-generating component groups: diesel generator(s), PV array(s), and battery pack(s). The System Operating Mode is defined by which component groups are on-line and can be one of the following eight modes:

- Off
- Diesel Only
- Diesel + PV
- PV Only
- Diesel + Battery
- Battery Only
- Diesel + PV + Battery
- PV + Battery.

The CUBE control architecture is hierarchal with three functional and two hardware levels. The functional levels are (1) Local Control, (2) Mode Handling, and (3) Component Dispatch. The hardware levels include (1) a Local Controller for each power electronic interface, and (2) a Supervisory Controller.

The Local Control algorithms include the pulse-width modulation (PWM) or space vector modulation (SVM) algorithms necessary to generate the gate drive commands for the power electronics and the proportional-integral-derivative (PID) algorithms necessary to operate the interface in various feedback control modes (such as voltage control, current control, or MPPT) . These low-level algorithms are implemented in the FPGA backplanes of each of the Local Controllers.

The Mode Handling algorithms determine *how* to operate the individual CUBE components. This means specifying the appropriate feedback control mode for each converter, not only for steady-state operation in a given System Operating Mode, but also when the system is transitioning from one System Operating Mode to another. In addition, the Mode Handling algorithms also determine the appropriate set point for each of the converter feedback control modes during mode transitions. The goal of the Mode Handling algorithms is to control the various power-electronics and rotating-machine-based components of the hybrid power system in a way that ensures delivery of high-quality power, no matter which components are on-line. During mode transitions in particular, commands to each of the local controllers must be properly and precisely sequenced to ensure stable and smooth transitions. These mid-level algorithms are implemented in the real-time processor of the Supervisory Controller.

Finally, the Component Dispatch algorithms determine *when* to start and stop individual components with the goal of minimizing diesel fuel consumption while ensuring that the load is always met. In addition, the Component Dispatch algorithms also determine the set point for each of the converter feedback control modes during steady-state operation in a given System Operating Mode. These high-level algorithms are implemented in the real-time processor of the Supervisory Controller.

Experimental Setup

The CUBE was installed in the Power Systems Integration Laboratory (PSIL) at NREL's ESIF along with two TQG sets and a battery pack. Figure 3 shows the complete system installed in the PSIL.

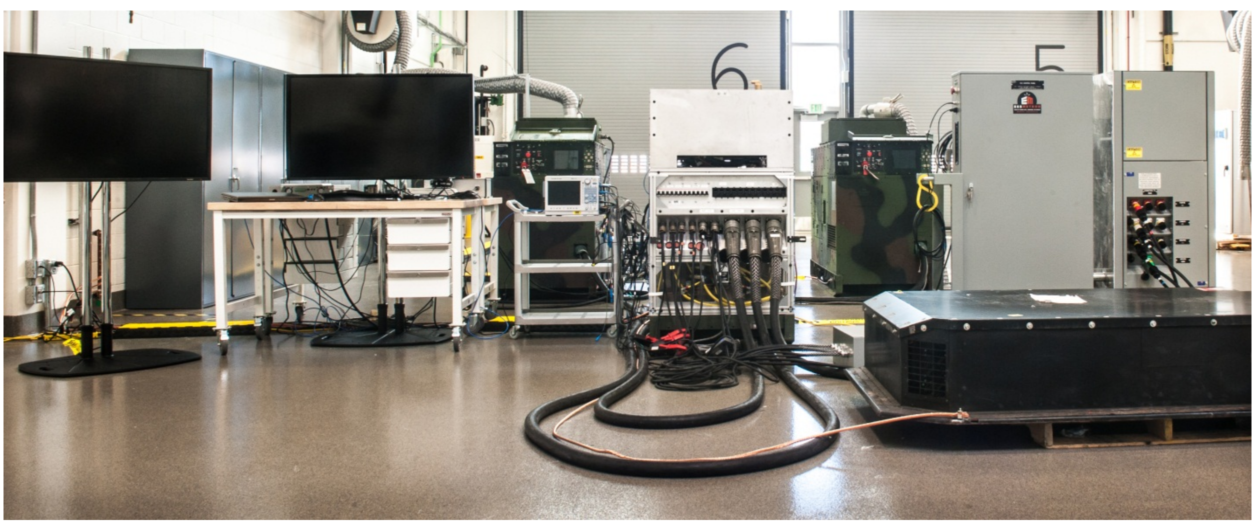


Figure 3. CUBE installed at the ESIF. ***Photo by Dennis Schroeder, NREL.***

Equipment Descriptions

CUBE

The CUBE is shown front and center in Figure 3. A close-up view is shown in Figure 4.

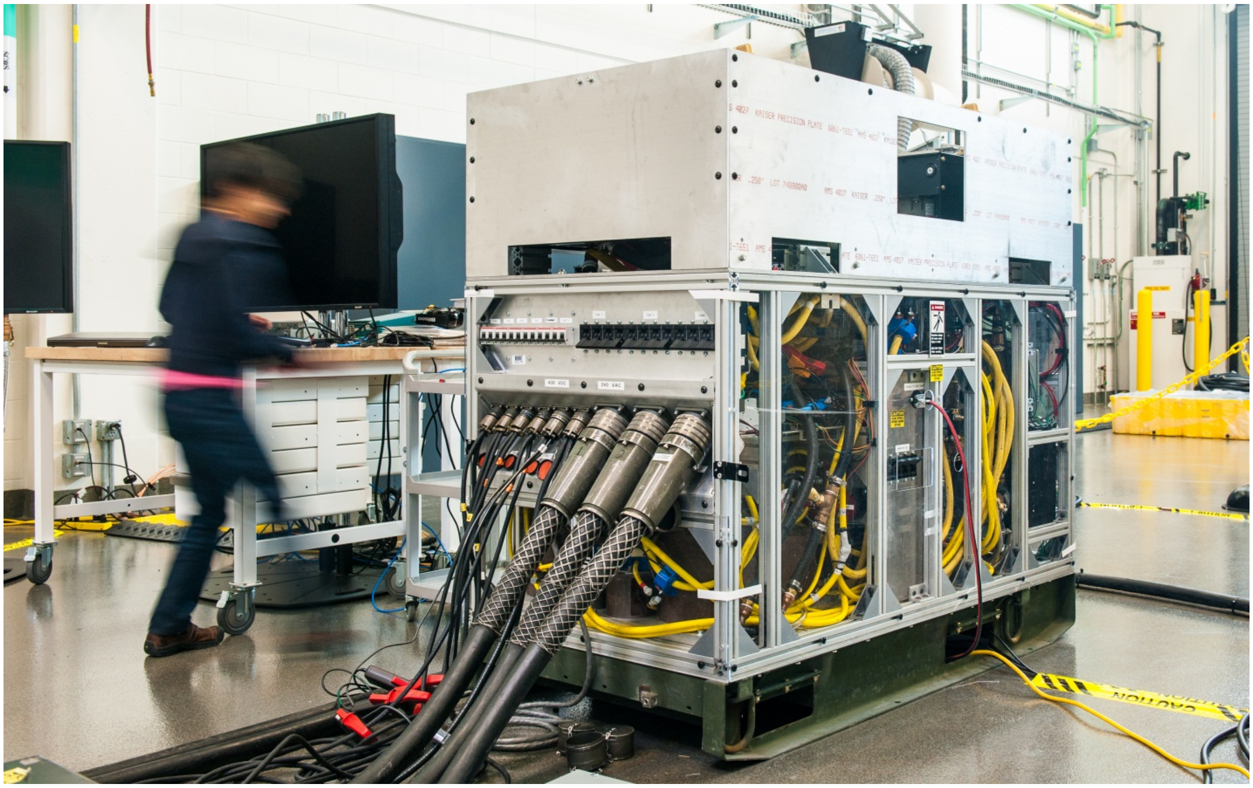


Figure 4. Close-up of CUBE. ***Photo by Dennis Schroeder, NREL.***

- Manufacturer: NREL
- Model No: Prototype
- Power: 60 kW
- Voltage: 120/208 Vac or 240/416 Vac
- Frequency: 60 Hz or 50 Hz.

Diesel Generators

The two 30-kW TQGs can be seen behind the CUBE in Figure 3.

- Manufacturer: L-3 Communications Westwood Corporation
- Model No: MEP-805B
- Power: 30 kW
- Voltage: 120/208 Vac or 240/416 Vac
- Frequency: 60 Hz or 50 Hz.

Each TQG was equipped with a remote start/stop kit (RSK). The RSKs allowed remote operation of the TQGs via external dry contacts. Figure 5 provides a close-up of the two TQGs with RSKs mounted on top.

- Manufacturer: L -3 Communications Westwood Corporation
- Model No: 29972-1.

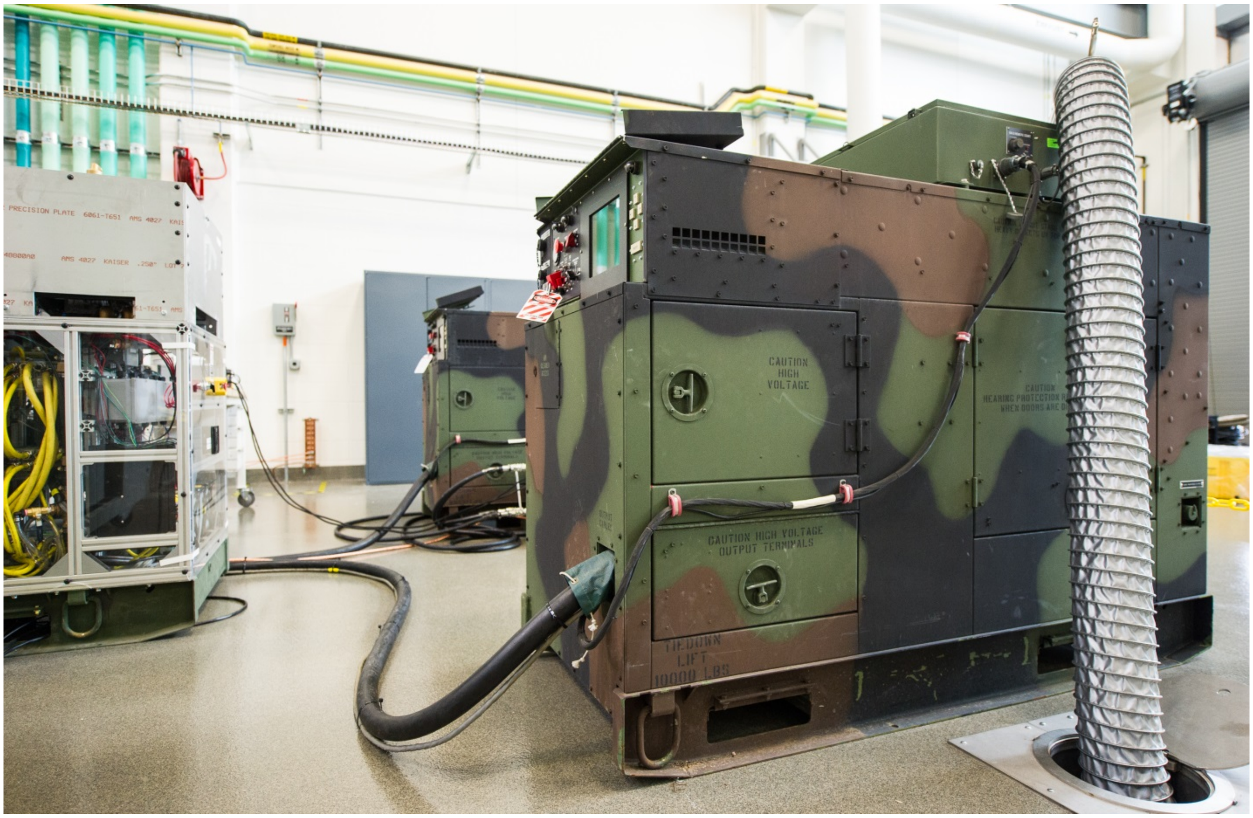


Figure 5. Close-up of TQGs with RSKs. ***Photo by Dennis Schroeder, NREL.***

Battery Pack

The battery is the rectangular black box in the lower right of Figure 3. This is an 80-kWh A123 lithium-ion pack originally used in an electric delivery van.

- Manufacturer: A123
- Chemistry: Nanophosphate lithium-ion
- Model No: 16 series-connected modules, Model No. 6s13p G1.OC3
- Nominal Voltage: 326 Vdc
- Nominal Capacity: 260 Ah
- Maximum Discharge Current: 612 A for 10 sec, 300 A for 30 sec, 180 A continuous
- Maximum Charge Current: 300 A.

During the CUBE 24-hour tests, the CUBE dispatch parameters were selected to limit battery power to 30 kW and available energy to 40 kWh in order to emulate a smaller battery pack.

PV Simulator

A PV simulator was used to simulate each of the four PV inputs to the CUBE. A PV simulator is a high-bandwidth DC power supply that can be programmed to emulate the terminal characteristics of an arbitrary PV array. The PV simulator used for the CUBE testing is an Ametek 100-kW TerraSAS. The 100-kW TerraSAS actually consists of ten 10-kW modules, each of which can output up to 1,000 V and 10 A. Two modules were connected in parallel for each PV input to the CUBE.

- Manufacturer: Ametek
- Model No: 5702443-01
- Module specifications:
  - Model No: ETS 1000/10
  - Voltage: 1,000 Vdc
  - Current: 10 Adc

Load Banks

The CUBE load output was connected to two outdoor load banks via the ESIF Research Electrical Distribution Bus (REDB). Connection to the REDB itself was made via the gray Data Acquisition Cart (DAQ Cart) located on the right side of Figure 3. (Note: The DAQ Cart is not required for CUBE operation, but provided an automatic means of connecting/disconnecting the CUBE from REDB to meet ESIF safe installation requirements.) The load banks themselves are three-phase RLC load banks rated at 250 kW / 250 kVAR inductive / 250 kVAR capacitive at 277/480 V. The ratings at 120/208 V are 46 kW / 46 kVAR inductive / 46 kVAR capacitive. The inductive and capacitive steps were not used for the CUBE 24-hour tests.

- Manufacturer: LoadTec
- Model No: OSW4c-0390.7-600v34-456D-50w
- Power: 46 kW / 46 kVAR inductive / 46 kVAR capacitive at 120/208 Vac
- Load step resolution: 10 W at 120/208 Vac.

Fuel Flow Meter

A precision coriolis mass flow meter was used to measure fuel consumed by one of the TQGs. Fuel consumed by the other TQG was computed based on the measured fuel use curve of the metered TQG. A photo of the meter is shown in Figure 6. The meter includes an electronic control module that is not shown.

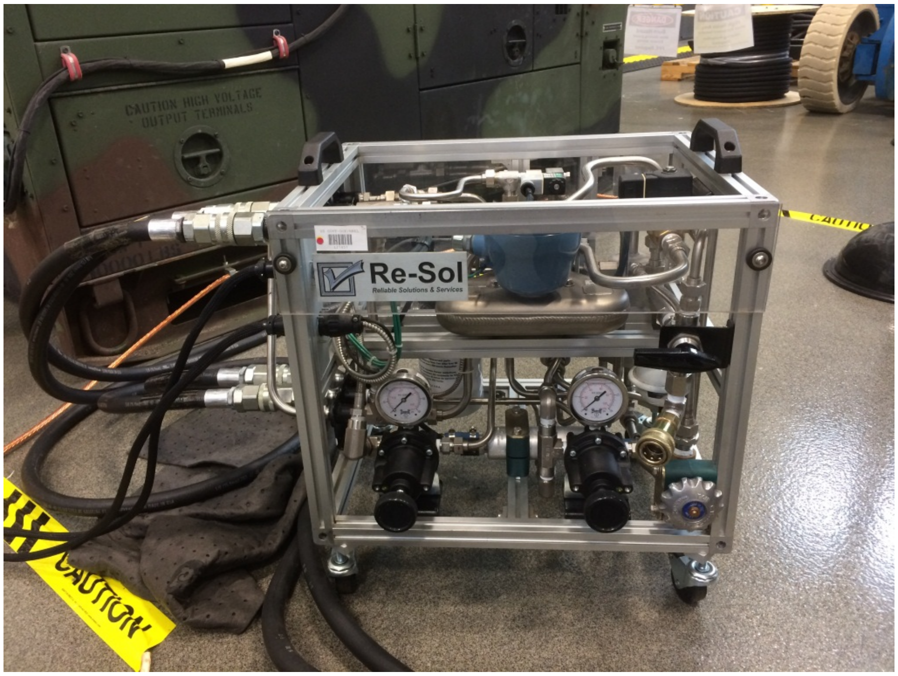


Figure 6. Fuel flow meter. ***Photo by Mariko Shirazi, NREL.***

- Manufacturer: Re-Sol (Reliable Solutions and Services)
- Model No: RS940
- Output: Calibrated so that 4-20 mA = 0-25 kg/hr.

External 12-V and 24-V Power Supplies

Three external 24-V power supplies were used in the experiment setup.

CUBE Liquid-Cooling System 24-V Power Supply

An external 24-V power supply was required to power the CUBE liquid-cooling system. Current from the supply was monitored to determine the parasitic cooling power consumption. Future modifications to the CUBE will allow self-generation of the 24-V power for the liquid cooling system.

- Manufacturer: Chroma
- Model No: 62024P-100-50
- Voltage: 100 Vdc
- Current: 50 Adc.

A123 Control Power 12-V Power Supply

An external 12-V power supply was required to power the A123 battery control system. Steady-state current consumption was on the order of 100 mA and therefore not monitored. In the future, the controller will be powered from one of the CUBE control power batteries.

- Manufacturer: BK Precision
- Model No: 1694
- Voltage: 30 Vdc
- Current: 30 Adc.

Re-SOL Fuel Meter Remote Enable 24-V Power Supply

The fuel flow meter required a remote 24-Vdc Enable signal.

- Manufacturer: Tektronix
- Model No: PWS4323
- Voltage: 32 Vdc
- Current: 3 Adc.

Data Acquisition System

A Yokogawa DL850 "ScopeCorder" was used to measure and record data.

- Manufacturer: Yokogawa
- Model No: DL850-D-HE/M1HD1/G2/G3/P4.

The DL850 frame accepts up to eight input modules, with two channels per module. The following Yokogawa input modules were used:

- 701260 High-Voltage 100 kS/s 16-bit Isolated Analog Input Modules with RMS
- 701250 High-Speed 10 MS/s 12-bit Isolated Analog Input Module.

The following voltage and current probes were used:

- Yokogawa 700929 10:1 Passive Voltage Probe, Bandwidth: DC – 100 MHz
- Yokogawa 701930 Current Probe, Bandwidth: DC – 10 MHz
- AEMC MR561 150/1500 A AC/DC Current Probes, Bandwidth: DC – 10 kHz
- Fluke i400s AC Current Clamp, Bandwidth: 510 kHz.

For the 24-hour test, all signals were recorded at 10 kS/s and were low-pass filtered prior to sampling to filter out switching-induced noise. The signals and respective probes, input modules, and channel bandwidth (BW) limits for the 24-hour tests are listed in Table 1.

Table 1. DAQ Signals, Probes, Input Modules, and Bandwidth Limits for the 24-Hour Tests

Ch.	Signal	Probe	Input Mod.	BW Limit
1	AC bus Phase A voltage	Yokogawa 700929 voltage probe	701260	10 kHz
2	Battery voltage	Yokogawa 700929 voltage probe	701260	1 kHz
3	PV1 voltage	Yokogawa 700929 voltage probe	701260	1 kHz
4	PV2 voltage	Yokogawa 700929 voltage probe	701260	1 kHz
5	PV3 voltage	Yokogawa 700929 voltage probe	701260	1 kHz
6	PV4 voltage	Yokogawa 700929 voltage probe	701260	1 kHz
7	Battery current	Yokogawa 701930 current probe	701260	1 kHz
8	PV1 current	AEMC MR561 current probe	701260	1 kHz
9	PV2 current	AEMC MR561 current probe	701260	1 kHz
10	PV3 current	AEMC MR561 current probe	701260	1 kHz
11	PV4 current	AEMC MR561 current probe	701260	1 kHz
12	Inverter Phase A current	Fluke i400s current clamp	701260	10 kHz
13	TQG1 Phase A current	Fluke i400s current clamp	701260	10 kHz
14	TQG2 Phase A current	Fluke i400s current clamp	701260	10 kHz
15	Cooling System 24 V PS current	AEMC MR561 current probe	701250	5 kHz
16	Fuel Flow Meter output	4-20 mA across 500 ohm 0.1% resistor	701250	5 kHz

For the load steps and black start tests, all signals were recorded at 100 kS/s and were low-pass filtered prior to sampling to filter out switching-induced noise. The signals and respective probes, input modules, and channel BW limits for the load steps and black start are listed in Table 2.[1]

[1] Note that the channel BW limits remain low to filter out switching-induced noise; however, the high sampling rate of 100 kS/s was still necessary to facilitate higher-resolution frequency computations.

Table 2. DAQ Signals, Probes, Input Modules, and Bandwidth Limits for the Mode Transition, Black Start, and Load Response Tests

Ch.	Signal	Probe	Input Mod.	BW Limit
1	AC bus Phase A voltage	Yokogawa 700929 voltage probe	701260	10 kHz
2	Battery voltage	Yokogawa 700929 voltage probe	701260	1 kHz
3	PV1 voltage	Yokogawa 700929 voltage probe	701260	1 kHz
4	PV2 voltage	Yokogawa 700929 voltage probe	701260	1 kHz
5	PV3 voltage	Yokogawa 700929 voltage probe	701260	1 kHz
6	PV4 voltage	Yokogawa 700929 voltage probe	701260	1 kHz
7	Battery current	Yokogawa 701930 current probe	701260	1 kHz
8	PV1 current	AEMC MR561 current probe	701260	1 kHz
9	PV2 current	AEMC MR561 current probe	701260	1 kHz
10	PV3 current	AEMC MR561 current probe	701260	1 kHz
11	PV4 current	AEMC MR561 current probe	701260	1 kHz
12	Inverter Phase A current	Fluke i400s current clamp	701260	10 kHz
13	TQG1 Phase A current	Fluke i400s current clamp	701260	10 kHz
14	TQG2 Phase A current	Fluke i400s current clamp	701260	10 kHz
15	DC Bus Voltage	Yokogawa 700929 voltage probe	701250	5 kHz
16	HIR Control Mode	Direct Connect (0 – 10 V)	701250	500 kHz

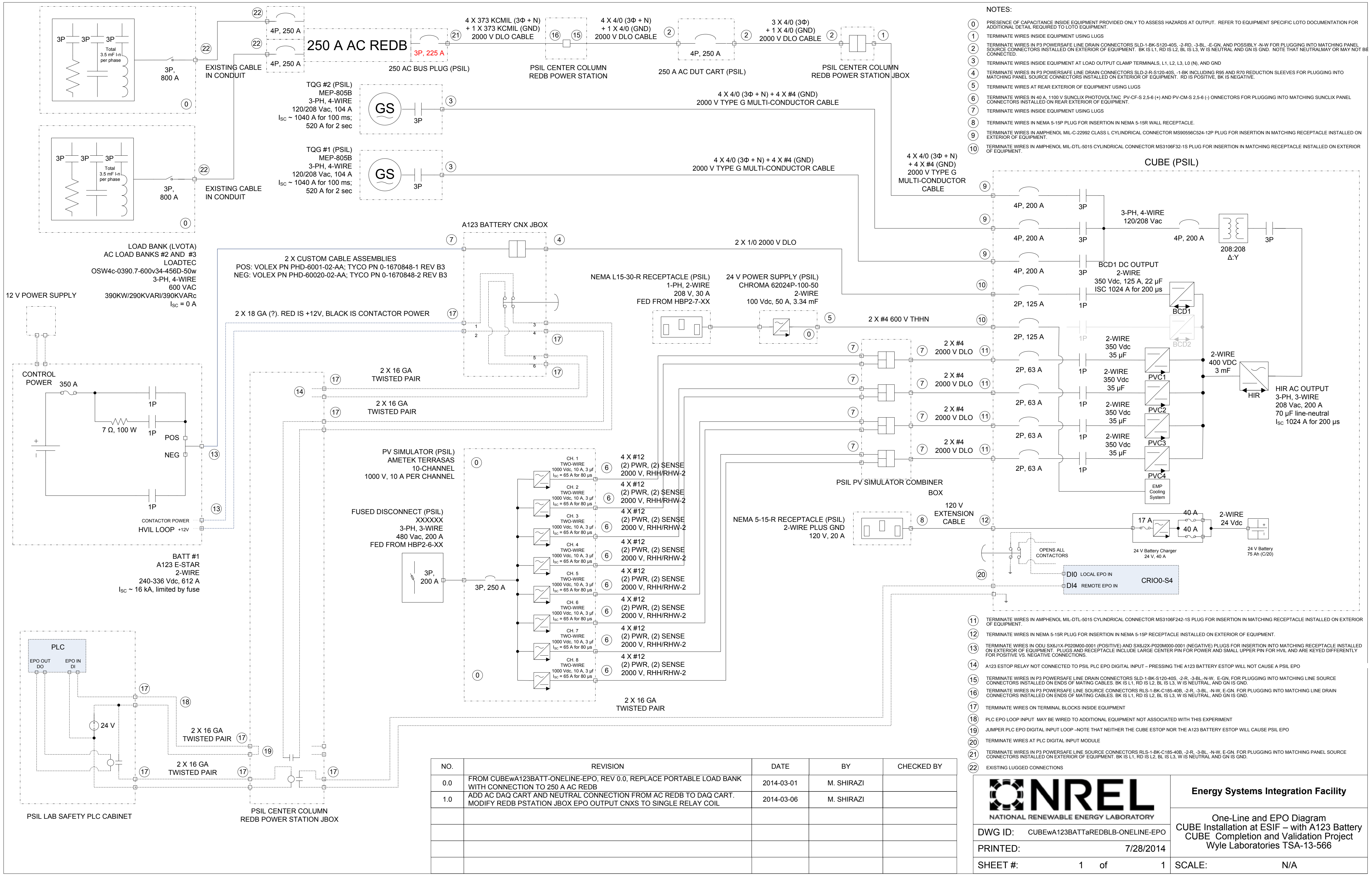
Because the signal lists in Table 1 and Table 2 use all 16 of the DL850 channels, it was not possible to measure all three phase voltages, inverter currents, and TQG1 and TQG2 currents; instead, only Phase A voltage and currents were measured. However, this was sufficient because the 24-hour tests were performed with a balanced three-phase load.

System Installation

The system was installed at the ESIF according to the one-line drawing shown in Figure 7. This drawing shows all power and Emergency Power Off (EPO) connections. The EPO connections were necessary to meet ESIF safe installation requirements. Not shown in Figure 7 are the communication and analog cabling between the CUBE and the various power components:

- CAN communications cable between the CUBE Supervisory Controller and the A123 Battery Control Module
- 24 V TQG Start/Stop command from the CUBE Supervisory Controller to each TQG RSK
- 24 V TQG Contactor Open command from the CUBE Supervisory Controller to each TQG
- 24 V TQG Contactor Status from each TQG to the CUBE HIR Local Controller.

Also not shown is the paralleling cable connecting the two TQGs. The paralleling cable enables real and reactive power sharing between the generators and is required for parallel operation.



NO.	REVISION	DATE	BY	CHECKED BY
0.0	FROM CUBEwA123BATT-ONELINE-EPO, REV 0.0, REPLACE PORTABLE LOAD BANK WITH CONNECTION TO 250 A AC REDB	2014-03-01	M. SHIRAZI	
1.0	ADD AC DAQ CART AND NEUTRAL CONNECTION FROM AC REDB TO DAQ CART. MODIFY REDB PSTATION JBOX EPO OUTPUT CNXS TO SINGLE RELAY COIL	2014-03-06	M. SHIRAZI	

Figure 7. One-line diagram of complete CUBE installation at the ESIF.

Dispatch Settings

Most of the CUBE dispatch parameters are user-settable. A brief description of the most relevant parameters as well as the particular setting used for the CUBE 24-hour test is provided in Table 3.

Table 3. Relevant CUBE Dispatch Parameter Descriptions and Settings

Parameter	Effect on Battery Charge/Discharge and PV Curtail Set Points	Effect on Diesel Dispatch	Effect on Battery Dispatch	Setting
Minimum Allowed Instantaneous % Diesel Load	If battery is not on-line or if battery is full, CUBE will curtail PV to keep 1-second diesel load above this %. If battery is on-line and not full, CUBE will instead charge battery to do the same, allowing charge rates up to the battery maximum allowed pulse charge rate. If actual 1-second charge rate exceeds 95%[2] of the battery maximum allowed pulse charge rate, CUBE will curtail PV to keep charge rate below that % of maximum.	None	None	10%
Minimum Allowed Continuous % Diesel Load	If battery is not on-line or if battery is full, CUBE will curtail PV to keep 1-minute average diesel load above this %. If battery is on-line and not full, CUBE will instead charge battery to do the same, allowing charge rates up to the battery maximum allowed pulse charge rate. If actual 1-minute average charge rate exceeds 90%[2] of the battery maximum allowed pulse charge rate, CUBE will curtail PV to keep charge rate below that % of maximum.	None	If battery is not empty[3] and 20-minute average diesel load drops below this %, CUBE will dispatch battery.	20%
Maximum Allowed Instantaneous % Diesel Load	If battery is on-line and not empty, CUBE will discharge battery to keep 1-second diesel load below this %, allowing discharge rates up to the battery maximum allowed pulse discharge rate.	CUBE will dispatch sufficient diesel capacity to ensure 1-second diesel load does not exceed this %. (Note: The actual diesel capacity required at any given time depends on whether the battery is on-line or not. However, CUBE always computes diesel capacity required both as if the battery were not on-line and as if the battery were on-line. These values are used to determine whether or not to dispatch the battery).	If battery is not empty and one or more diesels could be shut off if the battery were brought or kept on-line, CUBE will dispatch battery.	100%
Maximum Allowed Continuous % Diesel Load	If battery is on-line and not empty, CUBE will discharge battery to keep 1-minute average diesel load below this %, allowing discharge rates up to the battery maximum allowed pulse discharge rate.	CUBE will dispatch sufficient diesel capacity to ensure 20-minute average diesel load does not exceed this %. (Note: The actual diesel capacity required at any given time depends on whether the battery is on-line or not. However, CUBE always computes diesel capacity required both as if the battery were not on-line and as if the battery were on-line. These values are used to determine whether or not to dispatch the battery).	If battery is not empty and one or more diesels could be shut off if the battery were brought or kept on-line, CUBE will dispatch battery.	100%
CUBE Maximum Allowed Pulse Battery Charge kW	This value is compared to the SOC-dependent maximum charge rate sent by the battery BMS. The smaller of the two values becomes the battery maximum allowed pulse charge rate, used to limit battery charge rates when charging to keep diesel generators above user-specified minimum % load.	None	None	30 kW

[2] These are actually user-specified percentages, but actual values listed here for simplicity.
[3] If battery is not already on-line, an additional criterion is that battery is not at low SOC.

Parameter	Effect on Battery Charge/Discharge and PV Curtail Set Points	Effect on Diesel Dispatch	Effect on Battery Dispatch	Setting
CUBE Maximum Allowed Pulse Battery Discharge kW	This value is compared to the SOC-dependent maximum discharge rate sent by the battery BMS. The smaller of the two values becomes the battery maximum allowed pulse discharge rate, used to limit battery discharge rates when discharging to keep diesel generators below user-specified maximum % load.	Used to determine diesel capacity required when battery is on-line. CUBE will attempt to dispatch sufficient diesel capacity to ensure 1-second battery discharge rate does not exceed this value.	None	31[4] kW
CUBE Maximum Allowed Continuous Battery Discharge kW	None	Used to determine diesel capacity required when battery is on-line. CUBE will dispatch sufficient diesel capacity to ensure 20-minute average battery discharge rate does not exceed this value.	None	10.4[5] kW
Load Safety Factor	None	CUBE will dispatch sufficient diesel capacity to meet the last 20-minute peak load multiplied by this value.	None	1.0
Maximum Load Step	None	CUBE will dispatch sufficient diesel capacity to meet the last 20-minute average load plus this value.	None	20.0 kW
Maximum Connected Real Load	None	This is the maximum connected kW load, i.e., the sum of all loads that are physically connected to the power system. The CUBE will not dispatch additional diesel capacity to meet loads greater than this value.	None	60.0 kW
TQG Minimum Run-Time	None	CUBE will not shut off any diesel generator that has been running for less than this number of minutes.	None	20 minutes
Battery EMPTY SOC	None	If battery SOC reaches this value, CUBE will dispatch sufficient diesel capacity to cover the load without the battery pack plus additional diesel capacity as necessary to charge the battery.	Once sufficient diesel capacity is on-line, CUBE will "undispatch" the battery and instead begin dedicated charging.	20%
Battery LOW SOC	None	If battery SOC reaches this value, CUBE will dispatch sufficient diesel capacity to cover the load without the battery.	Once sufficient diesel capacity on-line, CUBE will "undispatch"[6] the battery. If there is sufficient diesel capacity on-line, CUBE will also begin dedicated charging of the battery.[7]	30%
Battery FULL SOC	If battery SOC reaches this value, CUBE will set the battery maximum allowed pulse charge rate to zero and will instead curtail PV to maintain minimum instantaneous and continuous % diesel load.	None	CUBE will stop dedicated charging of the battery once the battery reaches this SOC.	95%

Additional explanations:

- *CUBE Maximum Allowed Continuous Battery Discharge kW* is a particularly relevant parameter as it dictates the extent to which the batteries are allowed to supply the average load. Setting this parameter to zero results in a "peak-shaving"[8] dispatch strategy where the batteries are only intended to meet short-term requirements caused by fluctuations in the load and PV output and/or to provide time to start another diesel generator. Using power system terminology, the batteries are only used to provide "regulating reserve"[9] (above that already provided by any headroom in the on-line diesel capacity) to accommodate the variability and uncertainty in the load and available PV power. Setting the parameter to a large value results in a "cycle-charging" dispatch strategy where the batteries can supply the entire load and the diesels will cycle on/off to charge the batteries. Determining the optimal parameter value depends how the optimization criteria (diesel fuel use, operating costs, equipment maintenance intervals, equipment lifetime, etc.) are weighted and will

[4] This parameter refers to DC kW value. The AC kW output will be around 30 kW due to losses in the power electronics.
[5] This parameter refers to DC kW value. The AC kW output will be around 10 kW due to losses in the power electronics.
[6] "Undispatch" when applied to the battery pack means the battery is no longer available to provide power; however, it may be kept on-line for dedicated charging.
[7] In this case, CUBE will not start another diesel generator to charge the battery, but instead will use excess diesel capacity already on-line to charge the battery.
[8] The terms "peak-shaving" and "cycle-charging" as used in this document refer to particular dispatch strategies for the batteries—in particular, under what circumstances battery capacity can be used to replace diesel capacity. This is distinct from the term as used in the electric power system industry to refer to the process of reducing the amount of electricity purchased from the utility during times of maximum demand on the utility.
[9] Note that the batteries were not used to supply "contingency reserves." In fact, neither the TQG Only nor the Complete CUBE 24-hour test included contingency reserves. Future efforts will evaluate the use of battery capacity versus diesel capacity to provide contingency reserve.

be very specific to the power system configuration and load and resource profiles. Allowing continuous discharge up to 10 kW was a somewhat arbitrary decision to emulate primarily a peak-shaving strategy but allowing the battery to supply a small portion of the load on a continuous basis. In fact, as will be shown in the 24-hour test results, the 10 kW allowed continuous discharge had little if any effect, and results would have been very similar had the *CUBE Maximum Allowed Continuous Battery Discharge kW* parameter been set to 0 kW. Thus, the 24-hour test effectively demonstrates results of a pure peak-shaving dispatch strategy.

- Usable battery capacity is from *Battery LOW SOC* to *Battery FULL SOC*. It was desired to run the 24-hour tests with a 40-kWh battery, thus the range should have been 50% for the 80-kWh battery. The specified values of 30% and 95% respectively result in a range of 65%, or 52 kWh. However, as will be shown in the next sections, the total kWh supplied by the battery was only 8 kWh, so the wider operating range had no effect.
- Both the *Load Safety Factor* and the *Maximum Load Step* parameters are intended to cover variability in the load. In cases where the load is dominated by relatively large individual loads cycling on/off, such as the case for FOB loads dominated by electronic control units (ECUs), it makes sense to rely on the *Maximum Load Step* parameter and set the value to the largest expected individual load. The 20 kW value was selected based on the load step sizes observed in the actual load profile.

Load and Solar Profiles

Load Profile

The goal of the CUBE is to minimize diesel fuel use while maintaining reliable and high-quality power. While hourly load data could be used to validate fuel savings, higher-resolution data are necessary to replicate the true variability of FOB loads and thus demonstrate the ability of the CUBE dispatch strategy to ensure the load is always met. One-minute load data were obtained from the Army Material Systems Analysis Activity (AMSSA) and used to program the ESIF load banks. The data were collected at the *Army Network Integration Evaluation (NIE) 13.2* in April–May 2013 at Fort Bliss, Texas, and consists of measured load data to the following 18 rigid shelters erected to emulate a typical FOB:

- Administrative
- Tactical Operations Center (TOC) / Command
- Dining
- Hygiene 1 (shower, shave, latrine)
- Hygiene 2
- Hygiene 3
- Hygiene 4
- Kitchen 1
- Kitchen 2
- Billet 1
- Billet 2
- Billet 3
- Billet 4
- Billet 5
- Billet 6
- Billet 7
- Billet 8
- Billet 9
- Billet 10
- TriCold Refrigerated Container.

The individual shelter loads were summed to represent the aggregate load profile of a typical FOB. Data were collected from April 24, 2013, to May 20, 2013. The 24-hour period from April 28 at 05:00 through April 29 at 04:59 was selected for the 24-hour test. Although there were occasional short gaps in the data interspersed throughout the entire month, there were no gaps during the selected time period.

The April 28–29 data were also selected due to the fact that the peak load during the selected 24-hour period was 59 kW, just under the CUBE 60-kW rating. However, it was later observed that the actual measured load was typically about 5% and up to 7% greater than the load bank setting. Therefore, the load profile was scaled to a peak of 55 kW. In addition, because each load bank is only rated to 46 kW at 120/208 V, and because only one load bank could be programmed with a load profile, it was necessary to run one of the load banks at a constant 9 kW. This required imposing a minimum 9-kW load setting. Any scaled load values less than 9 kW were instead set to 9 kW. This only affected 16 of the 1,440 1-minute data points. Figure 8 plots the commanded load profile versus actual measured load during the TQG Only and Complete CUBE 24-hour tests.

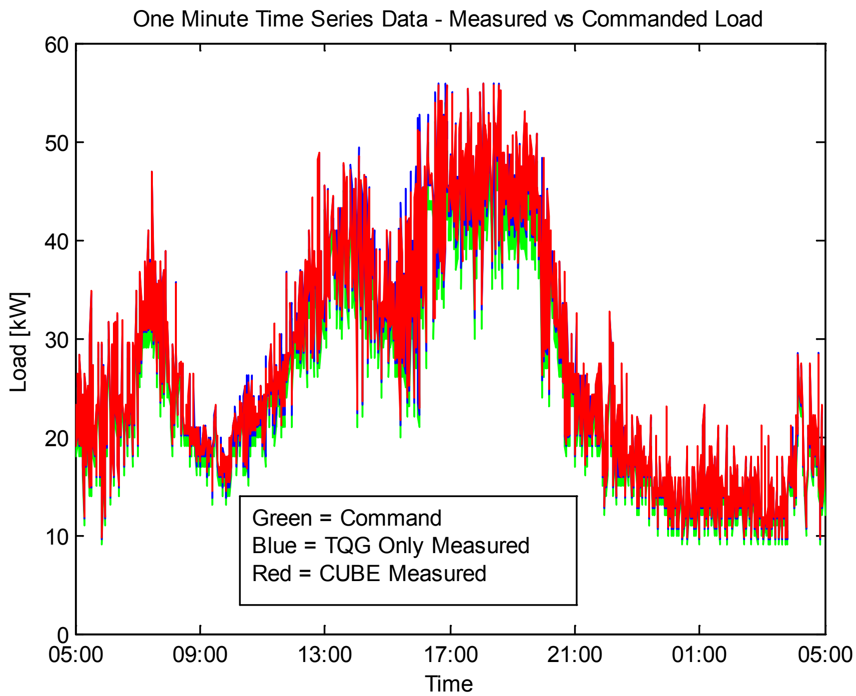


Figure 8. Commanded load profile along with actual measured load during the TQG Only and Complete CUBE 24-hour tests.

Table 4 summarizes the maximum and minimum measured versus commanded loads. It can be seen that the maximum measured load values are less than the expected 5%–7% above the commanded load. This is due to the fact that the actual AC bus voltage for both the TQG Only and CUBE tests was slightly less than 120 V, resulting in power de-rating of the load banks. The mean voltage for both cases was 118 V, while the minimum voltages were 116 V and 114 V, respectively. Depending on the actual voltage at the time of the load step, the load banks were likely limited to 42–44 kW, resulting in maximum achievable load commands of 51–53 kW. This would have affected at most 12 of the 1,440 1-minute data points.

Table 4. Maximum and Minimum Commanded vs. Measured Loads

	Command	TQG Only Measured	CUBE Measured
Max kW	55.0	55.9	55.8
Min kW	9.0	9.5	9.7

The variability of the final selected load profile is shown in Figure 9 and Figure 10. Figure 9 shows the 1-minute data overlaid with a moving 20-minute and 1-hour averages. Figure 10 shows the size of the load steps from one minute to the next and from the last 20-minute average to the next 1-minute load value. These figures show the large variability that can be expected in FOB loads but that may not be apparent using low-resolution (15-minute or longer) load data. High-resolution data are necessary in order to test the ability of the dispatch strategy to maintain reliable power in the presence of these load variations.

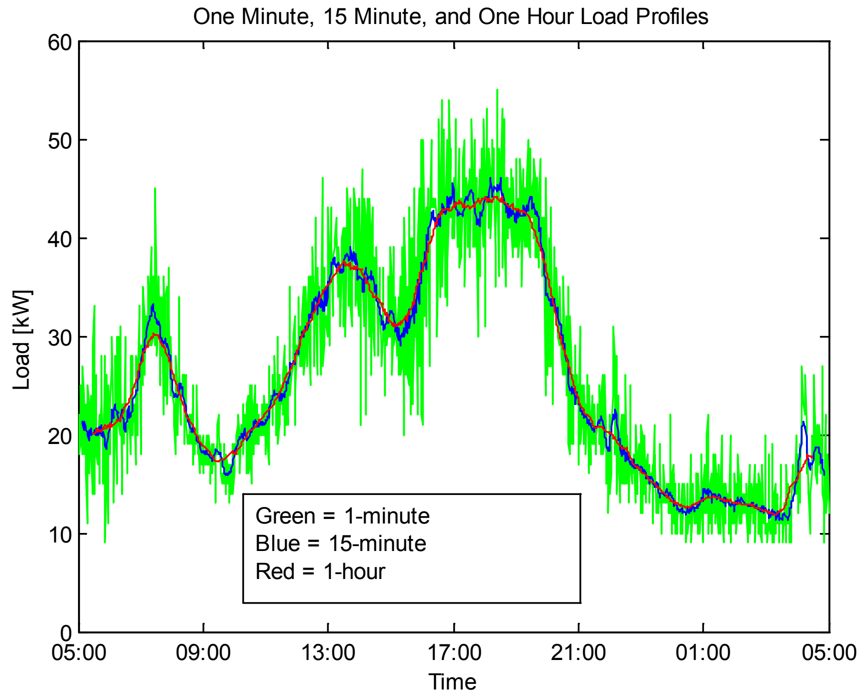


Figure 9. One-minute, 15-minute, and 1-hour load profiles.

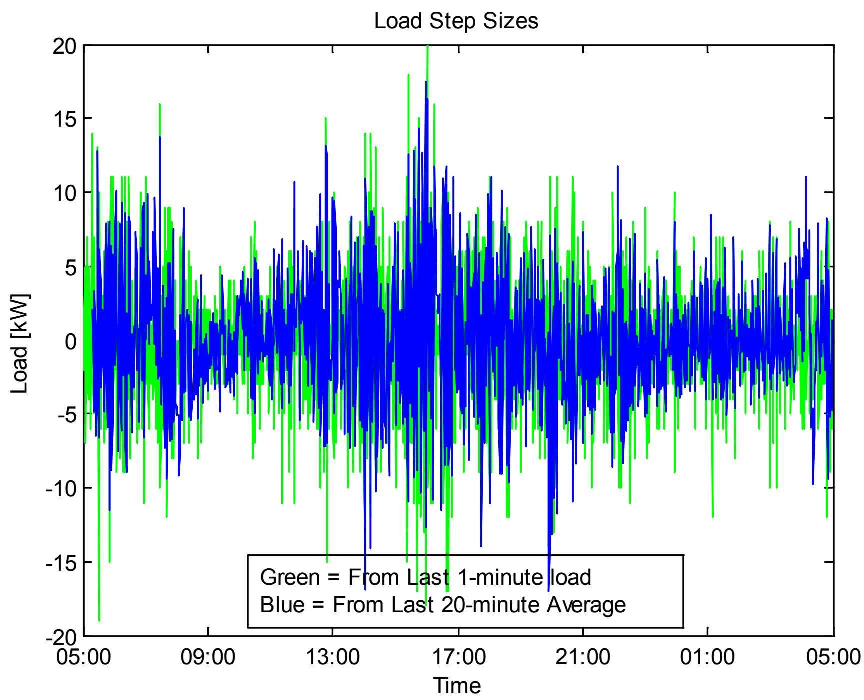


Figure 10. Load step sizes from last 1-minute load and from last 20-minute average load to next 1-minute load.

Solar Profile

Similar to the load data, hourly solar irradiance data could be used to validate fuel savings, but higher-resolution data are preferred to replicate the true variability of solar conditions. One-minute irradiance and temperature data measured at NREL's Solar Radiation Research Laboratory (SRRL) were used to program the ESIF PV simulator. The data were taken from August 1, 2009, a clear, sunny day. The peak global horizontal irradiance value was 995 W/m^2; however, the data were scaled to a peak of 1,045 W/m^2. The scaled irradiance profile is shown in Figure 11.

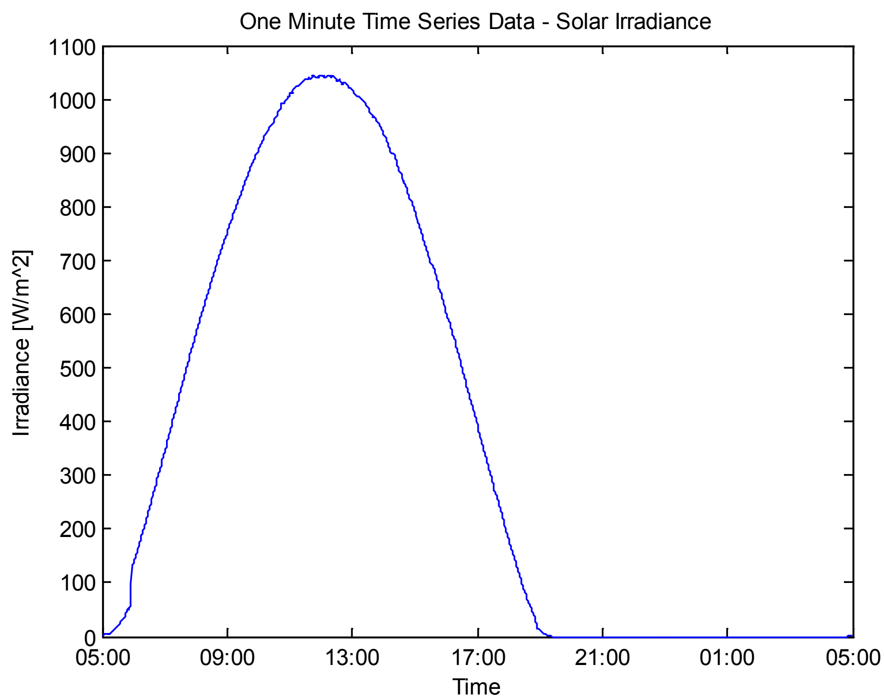


Figure 11. Solar irradiance profile.

Each of the four pairs of modules of the PV simulator was programmed with the irradiance profile in Figure 11 and the following array parameters:

- Open-circuit voltage V_{OC} = 330 V
- Short-circuit current I_{SC} = 20 A
- Fill-factor FF = 0.80

At 1,000 W/m^2 this results in 5.28 kW peak for each PV input to the CUBE, or 21.1 kW peak total. The peak of 1,045 W/m^2 of the programmed irradiance profile resulted in a slightly higher peak PV input of 21.7 kW. It should be noted that the 21.1 kW peak rating is for power into the CUBE PV DC/DC converter. The actual array rating would typically be on the order of 10%–20% higher to account for de-rating factors including PV module nameplate DC rating, PV module mismatch, losses across diodes and connections, losses in the DC wiring, and soiling of the PV panels.

24-Hour Tests

Baseline Establishment

Two 24-hour tests were performed, one with the complete CUBE system and one with the TQGs only, to validate fuel savings and demonstrate the CUBE's ability to deliver reliable and high-quality power. There were three possible options for establishing the baseline TQG Only fuel consumption:

- Manually start and run both TQGs continuously as necessary to meet the peak load
- Manually shut a TQG off during parts of the day where only one TQG is needed
- Operate the TQGs with automated dispatch, applying the same dispatch criteria as applied for the complete CUBE system.

As the intent of these tests was to demonstrate achievable fuel savings relative to current practice/equipment, the first approach above was selected to establish the baseline fuel consumption. From the load profile in Figure 9, it would have been possible to shut one of the generators off between 11 p.m. and 5 a.m. However, for this to be a practical approach for FOB operations, it would need to be guaranteed that the load would never exceed 30 kW during that time period *every single day*; i.e., this would require perfect knowledge of the load at least during that time period. Instead, typical FOB operations run generators continuously as necessary to meet the peak load.

More obviously, an automated dispatch approach would require, if not the CUBE, some sort of centralized controller capable of implementing the dispatch algorithms and automatically starting/stopping the generators. The automated case would have been an interesting comparison in and of itself; however, with the load profile shown in Figure 9 and with the *Maximum Load Step* dispatch parameter set to 20.0 kW as shown in Table 3, both TQGs still would have been continuously operated.

Data Processing

The Complete CUBE 24-hour test was performed June 16–17, 2014, and the TQG Only 24-hour test was performed June 23–24, 2014. The 16 channels of data specified in the Data Acquisition System section of this report were recorded at 10 kS/s using Yokogawa's DL850E Acquisition Software v1.01. The data were recorded and saved in 10-minute files in the native Yokogawa .wdf file format. Each file was 188 MB, for a total of 27 GB of raw data for each 24-hour test. The .wdf files were then converted to .csv files using Yokogawa's Xviewer software v1.75. Each .csv file was around 840 MB, for a total of 118 GB for each 24-hour test.

MATLAB R2012b was used to process all the data and plot results. The .csv files were initially processed to produce cycle-by-cycle (60 Hz) power flow data from the 10 kS/s waveform data. Specifically, the 10 kS/s waveforms were processed based on zero crossings to compute cycle-by-cycle power, RMS voltages and currents for AC waveforms, average voltages and currents for DC waveforms, and frequency of the AC waveforms. With 10 kS/s waveforms, the accuracy of the frequency computations would only be +/- 0.36 Hz. However, the zero crossings were interpolated to improve the accuracy of the frequency computations. Finally, 1-minute data were produced from the cycle-by-cycle data by aligning the 1-minute windows with the measured load steps and selecting the median data point in each 1-minute window. The median was selected as opposed to the mean because as the load steps were not all exactly 1 minute, it was difficult to ensure the 1-minute averaging windows were always exactly aligned with load steps, resulting in incorrect mean values.

In addition to normal post-processing efforts, there were also gaps in the TQG Only 24-hour test data that had to be filled. Specifically, the data had the following missing and/or corrupt sections:

- One 3-minute period of missing data due to re-start of the data acquisition software
- One 30-minute period and one 16-minute period of corrupt fuel flow data due to malfunction of the fuel flow meter
- Last 62 minutes of data missing due to fuel flow meter failure and subsequent termination of 24-hour test.

To make a complete 24-hour data set, the load commands corresponding to the missing and/or corrupt data periods were identified and the actual measured data set was searched to find identical load values. The corresponding measured data points were then inserted where there was missing data or used to replace the corrupt data points.

TQG Fuel Use Curves

Because fuel flow was metered to TQG1 only, it was necessary to compute TQG2 fuel consumption based on TQG2 power output. As the TQGs did not share load exactly equally, it would have been incorrect to simply double TQG1 fuel use whenever TQG2 was on-line. Instead, TQG2 fuel consumption was computed two ways:

1. Using the TQG1 fuel use curve as determined using a curve fit to the 1-minute fuel use/TQG power data collected during the TQG Only 24-hour test. A best-fit equation relating kg/hr to kW was determined allowing computation of TQG2 fuel use at each measured power level.
2. Using previously measured no-load fuel consumption and the actual load share of TQG2 for each time step. In this case TQG2 fuel use was computed from TQG1 fuel use by subtracting the no-load fuel consumption, multiplying by the TQG2 load share percentage, then adding back the no-load fuel consumption.

To determine the fuel use curve for the former method, the 1,440 1-minute fuel flow data points from the TQG Only 24 hour test were plotted against the 1-minute TQG1 power values. The MATLAB *polyfit* command was used to perform curve fits up to order five (orders greater than five were ill-conditioned). The results are shown in Figure 12 (a)–(e). Text boxes in each plot display the fit coefficients as well as the 2-norm of the residuals (error between the actual data and the predicted data at each point). In addition to the 24-hour data points, these curves include "Test Points" that were single data points collected prior to the 24-hour tests.

The norm of the residuals for all the higher-order fits are similar in magnitude and less than half of that of the linear fit. While the norm does get slightly smaller for orders greater than two, deviation from the previously measured (but not included in the data used for the curve fit) norm becomes greater. Therefore, the second-order curve in Figure 12 (e) was used to compute TQG2 fuel consumption for both the CUBE and TQG Only 24-hour tests. However, the fuel use curve is valid for steady-state operation only and can only be applied to the 1-minute TQG2 power values. The cycle-by-cycle power data include power transients during load steps, which are not reflected in the fuel flow data. Therefore, computation of cycle-by-cycle fuel flow data was performed using the second method listed above. This method relied on the previously and repeatedly measured TQG1 no-load fuel consumption of 2.172 kg/hr. TQG2 is assumed to have the same no-load fuel consumption.

Finally, the fuel flow meter outputs fuel consumption in kg/hr. However, the data were converted to gal/hr, assuming a density of 0.840 kg/l.

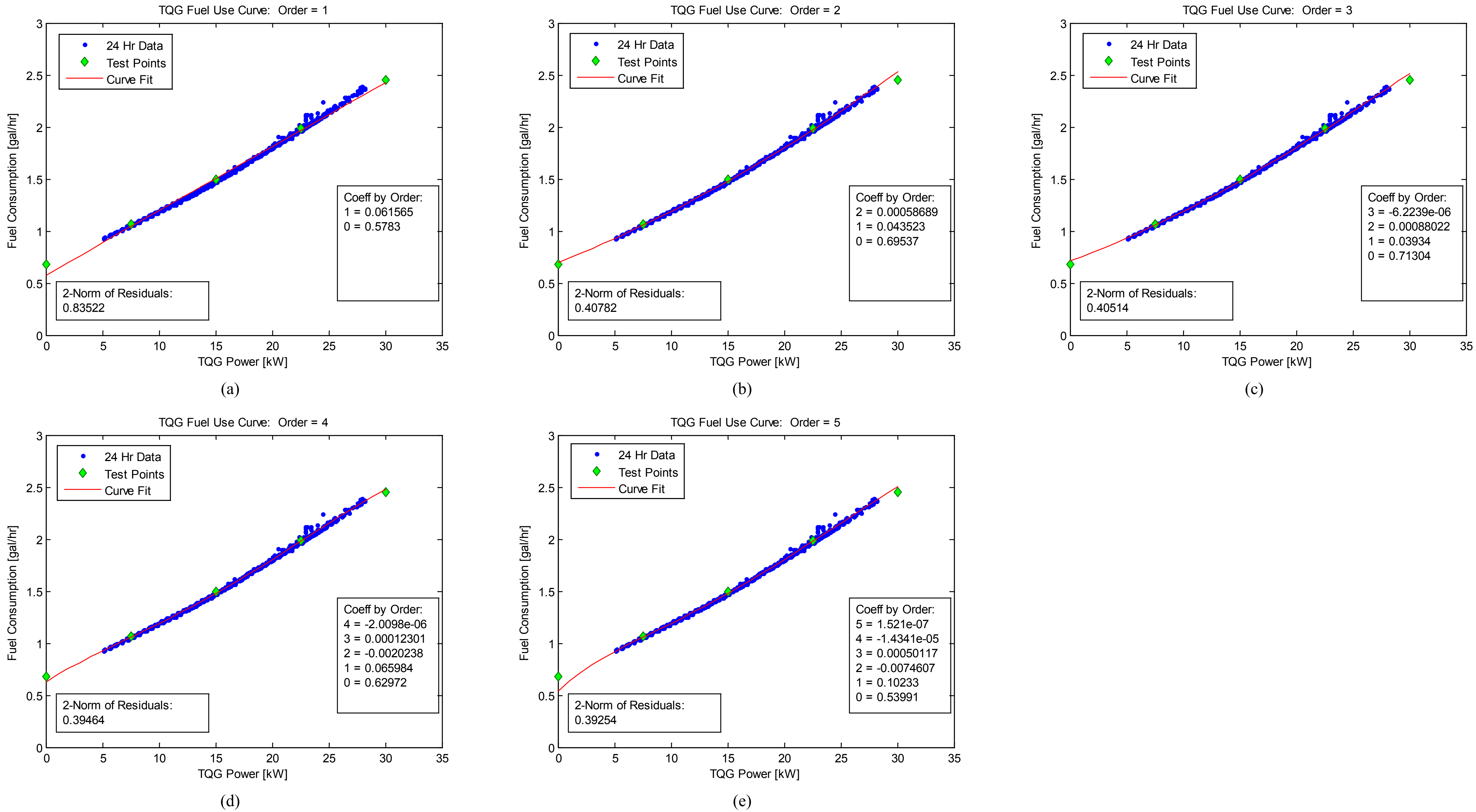


Figure 12. TQG fuel use curves with (a) linear (b), second- (c), third- (d), fourth-, and (e) fifth-order fits.

Results

The results from the TQG Only and Complete CUBE 24-hour tests are shown in the following tables/figures:

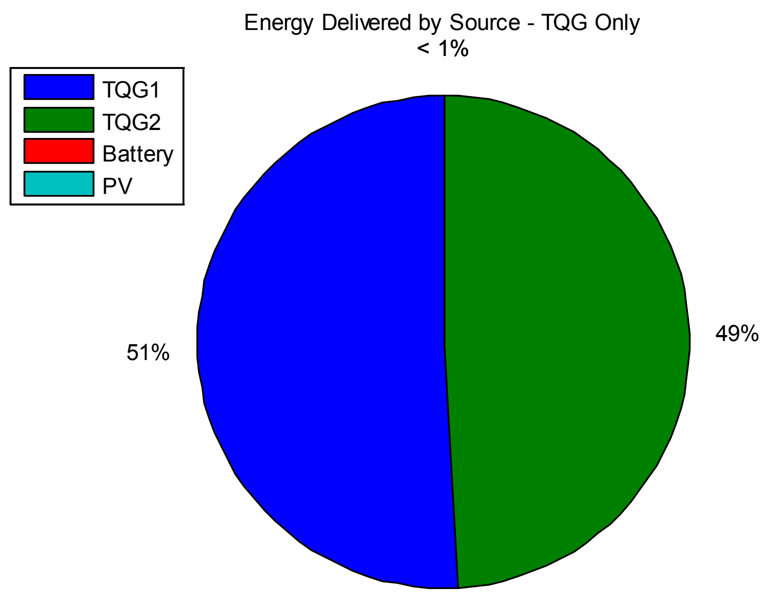
- Total energy values, fuel use, TQG run-time and number of starts, and min/max voltage and frequency are shown in Table 5.
- Pie charts illustrating energy delivered by source, shown as a percentage of total energy delivered to the load, are shown in Figure 13.
- Time-series plots of cycle-by-cycle and 1-minute power flow and fuel use are shown in Figure 14.
- Time-series plots of cycle-by-cycle and 1-minute voltage and frequency are shown in Figure 15.
- Time-series plots in 3-hour zoomed intervals of cycle-by-cycle battery are shown in Figure 16.
- Log-scale histograms of cycle-by-cycle battery power are shown in Figure 17.
- Log-scale histograms of battery charge/discharge event energies and durations are shown in Figure 18.
- Log-scale histograms of cycle-by-cycle and 1-minute frequency are shown in Figure 19.
- Log-scale histograms of cycle-by-cycle and 1-minute voltage are shown in Figure 20.

Table 5. Summary of TQG Only and Complete CUBE System 24-Hour Test Results

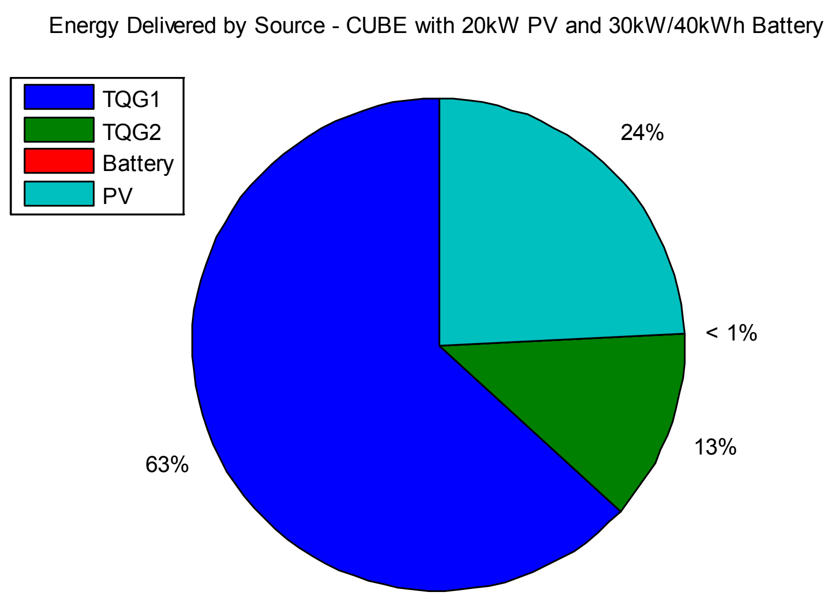
	TQG Only	CUBE plus 21 kW PV and 30 kW/40 kWh Battery
Load Energy [kWh]	649	653
Cooling Energy [kWh]	0	3.0
TQG1 Energy [kWh]	331	413
TQG2 Energy [kWh]	318	82
Total TQG Energy [kWh]	649	495
Fuel Consumed [gal] Method 1	67.8	46.7
Fuel Consumed [gal] Method 2	67.8	46.5
TQG1 Run-Time [hrs]	24.0	24.0
TQG2 Run-Time [hrs]	24.0	4.0
No. of TQG1 Starts	1	1
No. of TQG2 Starts	1	2
Average Voltage [V]	118.3	118.3
Max Voltage [V]	119.9	123.4
Min Voltage [V]	116.1	114.2
Voltage Standard Deviation [V]	0.20	0.23
Average Frequency [Hz]	59.96	60.01
Max Frequency [Hz]	60.80	61.73
Min Frequency [Hz]	59.12	58.55
Frequency Standard Deviation [Hz]	0.017	0.033
Batt DC Energy In [kWh]	0	-8.7
Batt DC Energy Out [kWh]	0	8.5
Net DC Batt Energy [kWh]	0	-0.2
Net AC Batt Energy [kWh]	0	-0.2
Battery Charge/Discharge Events	NA	519
Initial Battery SOC [%]	NA	84.5
Final Battery SOC [%]	NA	87.5
PV1 DC Energy [kWh]	0	44
PV2 DC Energy [kWh]	0	44
PV3 DC Energy [kWh]	0	44
PV4 DC Energy [kWh]	0	44
Total PV DC Energy [kWh]	0	176
Total PV AC Energy [kWh]	0	159
Inv Energy In [kWh]	0	-3.0
Inv Energy Out [kWh]	0	161
Net Inv Energy [kWh]	0	158

Comments regarding the data in Table 5:

- Total fuel use was computed using both the measured fuel-use curve approach (Method #1) and the TQG2 load-share approach (Method #2). The two methods resulted in identical total fuel use values for the TQG Only case, but slightly different values for the Complete CUBE case.
- Load energy is slightly higher for the CUBE case versus the TQG Only case. This may be due to the fact that the CUBE case was run with slightly higher voltage (due to imprecision in the TQG manual voltage adjustments). In addition, there was more variability in the voltage during CUBE operation with PV. Because power to the load is proportional to voltage squared, the higher voltages would result in additional load energy.
- After subtracting the total energy consumed by the CUBE liquid cooling system, the load energy for the CUBE case would be approximately equal to the load energy for the TQG Only case. Based on this, there was no need to increase the CUBE fuel consumption to account for the externally supplied power to the cooling system.
- The AC-side battery and PV energy values were computed from their respective DC energy values, assuming an efficiency of 90%.
- Battery charge/discharge events were defined by battery charge/discharge values of magnitude greater than or equal to 200 W.
- The battery SOC values listed in the table were obtained from the A123 Battery's Battery Management System (BMS). Over the 24-hour CUBE test period, there was a net increase of 3.0% in battery SOC. Based on this and an 80-kWh nominal battery, one would expect net energy into the battery of 2.4 kWh. However, the battery energy in, energy out, and net energy as computed from the 24 hour data showed essentially net zero kWh in/out. Possible explanations include:
    - Noise in the battery voltage and/or current signals within the bandwidth limit specified for the CUBE DAQ may have introduced errors in the battery power computations.
    - The battery SOC as determined by the BMS may be based on more than just energy in/out. In addition, because the battery is used, the actual battery capacity may be less than 80 kWh.



(a)



(b)

Figure 13. Energy delivered by source, as a percentage of total energy delivered to the load, during the (a) TQG Only and (b) Complete CUBE 24-hour tests.

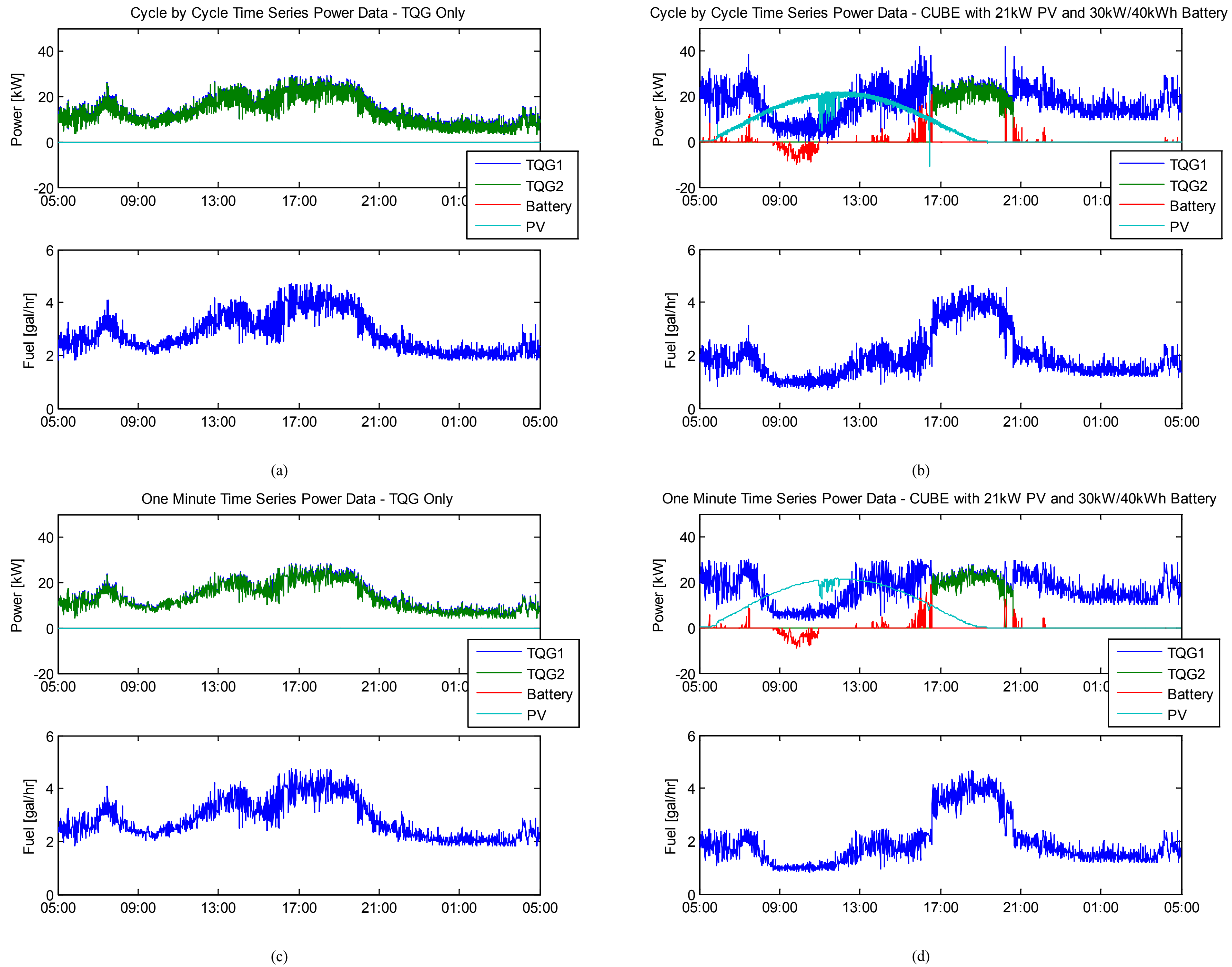


Figure 14. Time-series plots of cycle-by-cycle and 1-minute power flow and fuel use data for the (a) and (c) TQG Only and (b) and (d) Complete CUBE 24-hour tests.

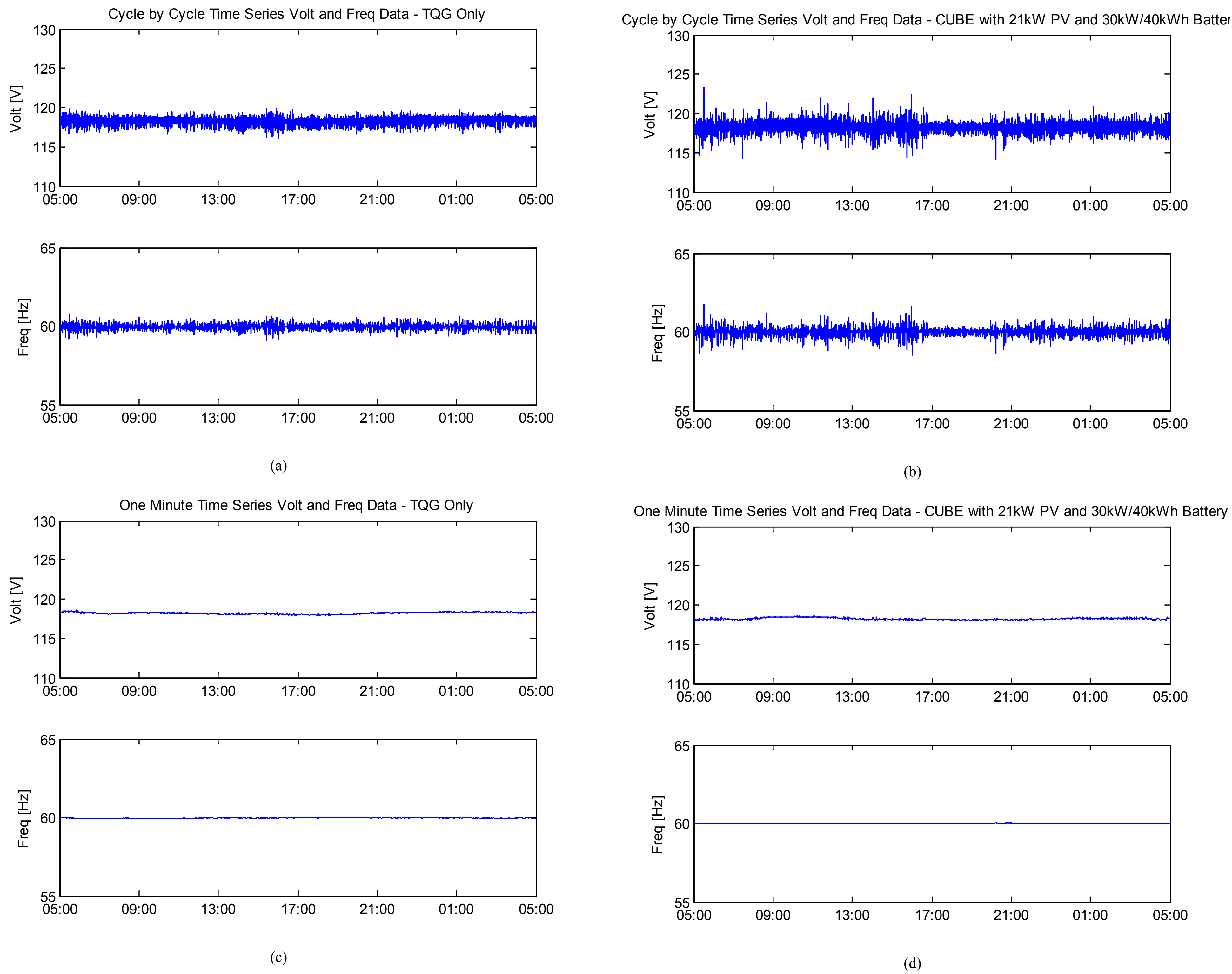
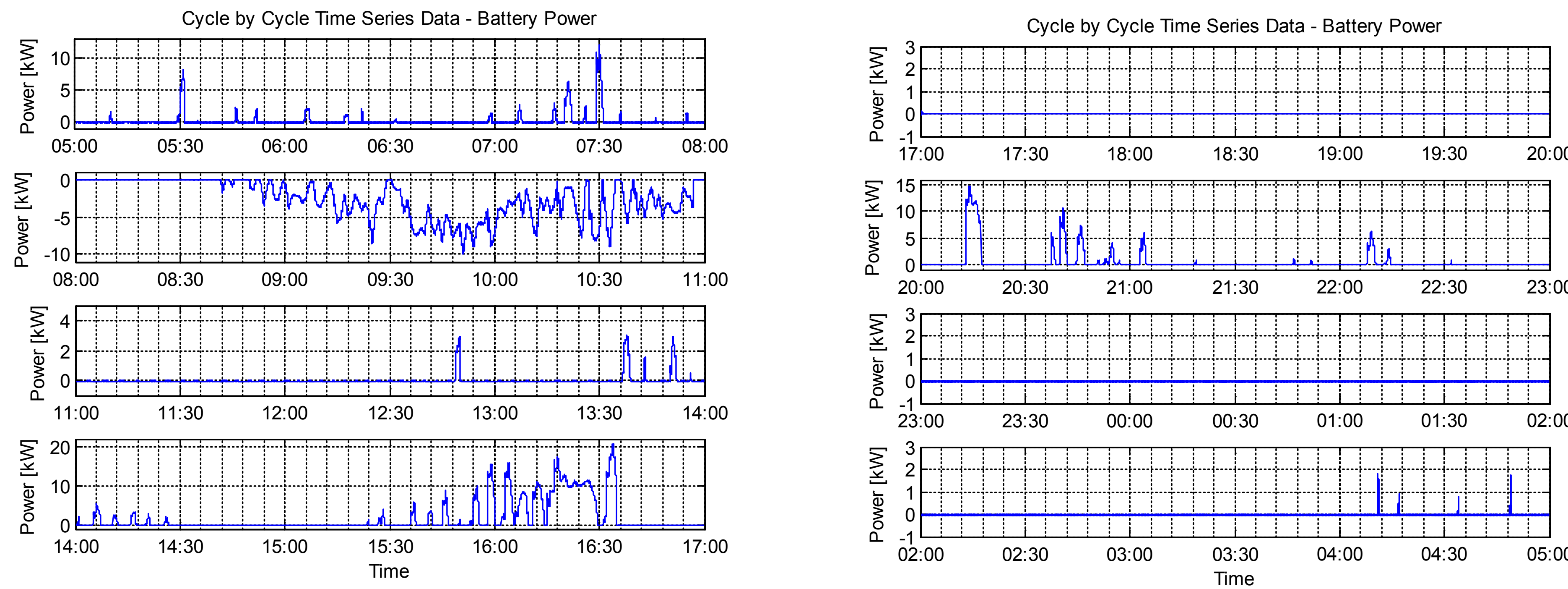


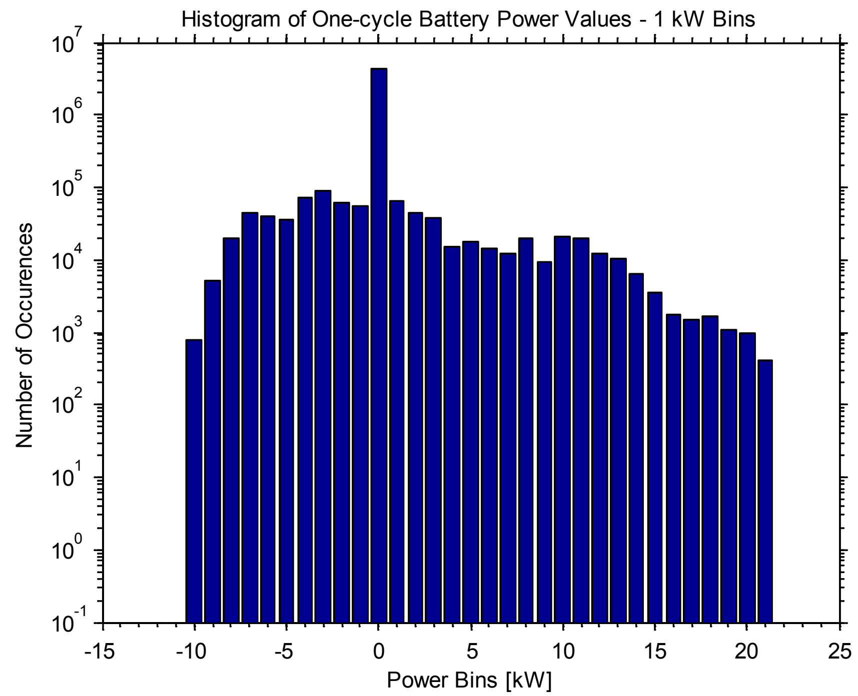
Figure 15. Time-series plots of cycle-by-cycle and 1-minute voltage and frequency data for the (a) and (c) TQG Only and (b) and (d) Complete CUBE 24-hour tests.



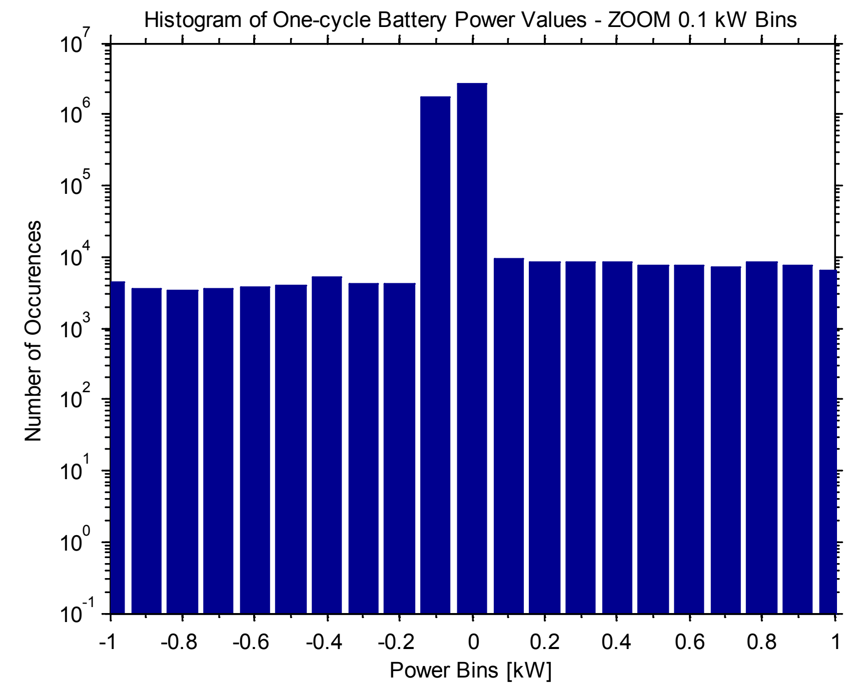
(a)

(b)

Figure 16. Time-series plots in 3-hour zoomed intervals of the cycle-by-cycle battery power flow data for the Complete CUBE 24-hour test.



(a)



(b)

Figure 17. Histogram of cycle-by-cycle battery power flow data for the Complete CUBE 24-hour test with (a) 1-kW bins and (b) 0.1-kW bins. Number of occurrences is plotted on logarithmic scale.

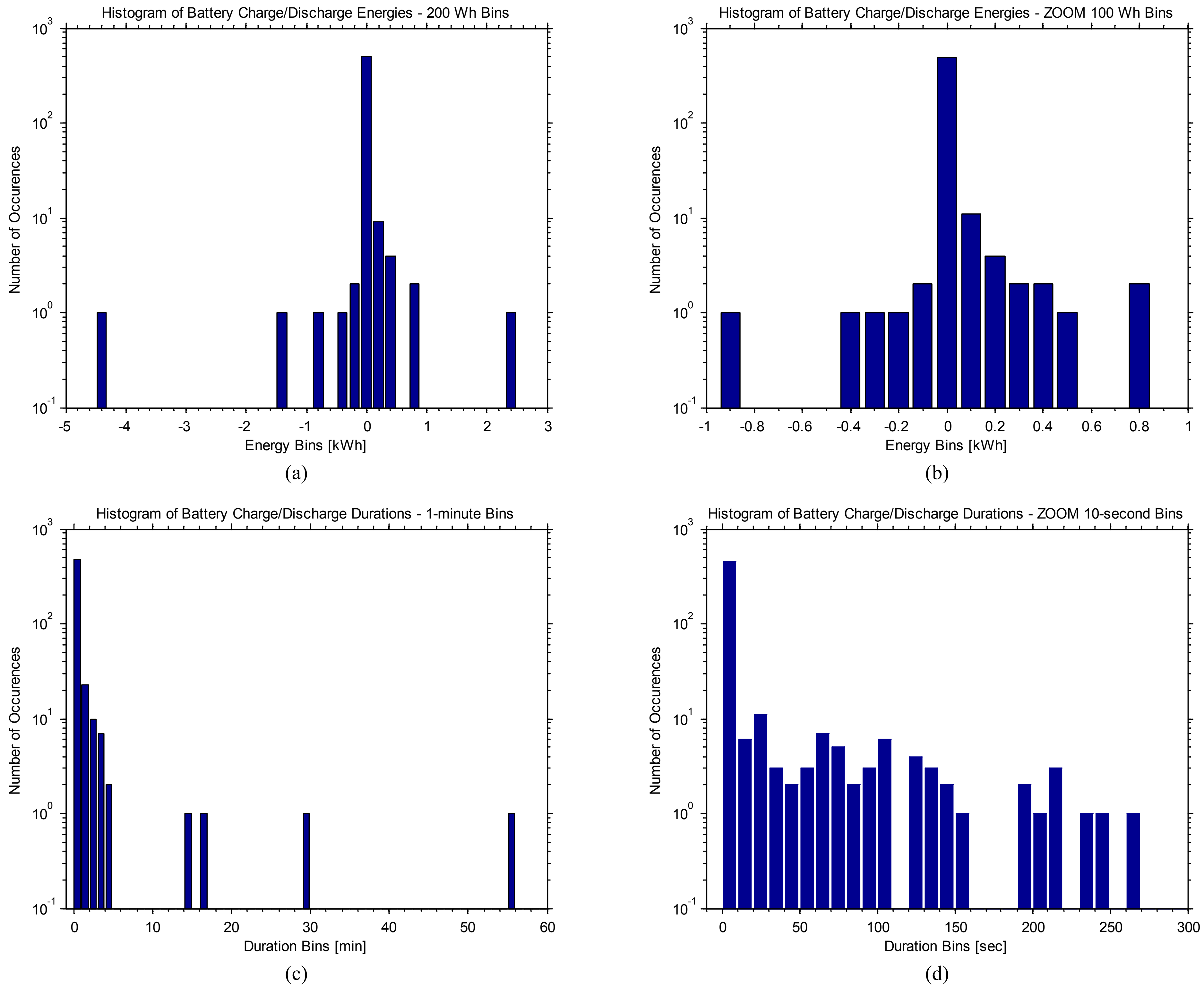


Figure 18. Histograms of battery charge/discharge event energies and durations, with (a) 200-Wh bins and (b) 100-Wh bins for the energy histograms and (c) 1-minute and (d) 10-second bins for the duration histograms. Number of occurrences is plotted on logarithmic scale.

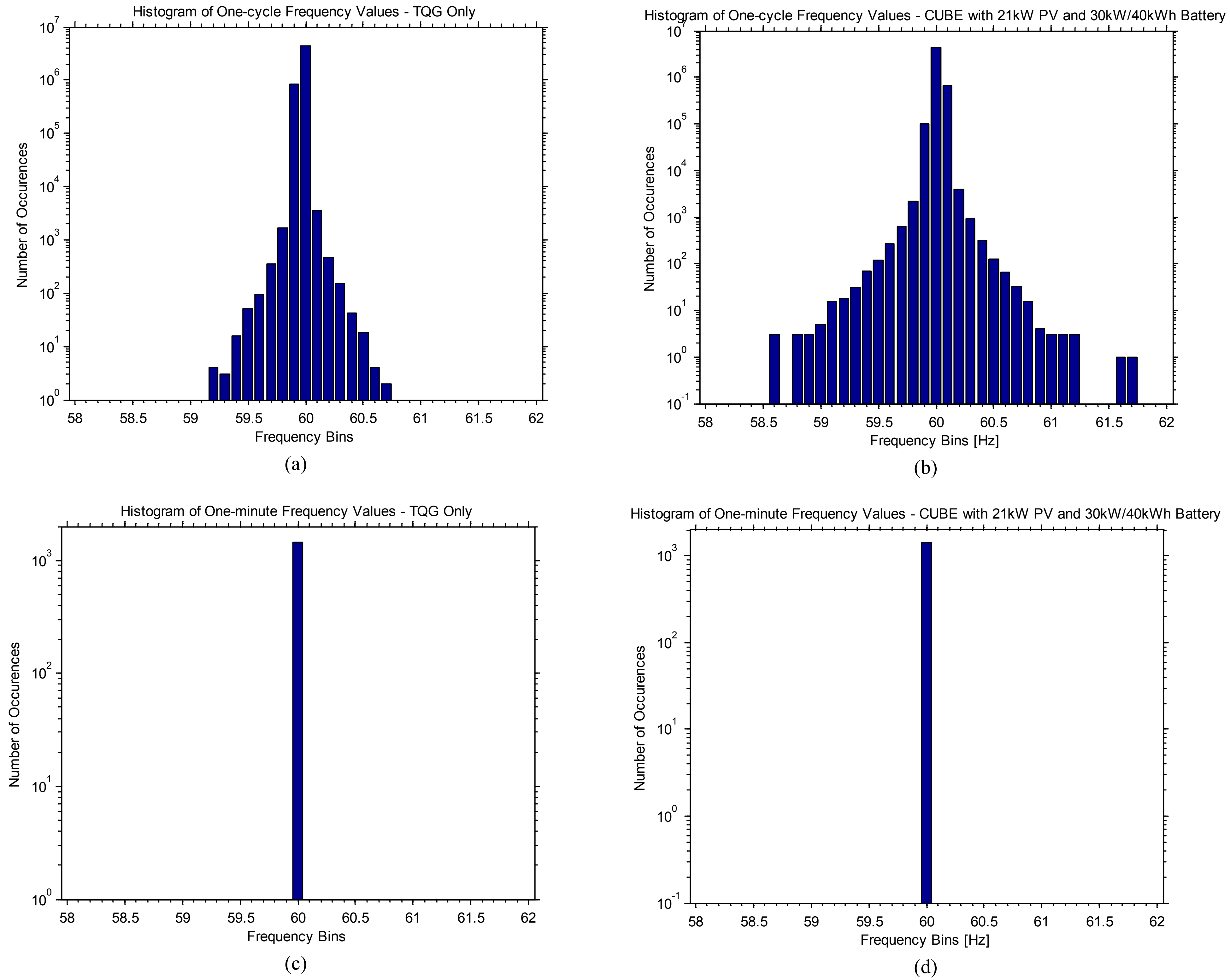


Figure 19. Histograms of cycle-by-cycle and 1-minute frequency data for the (a) and (c) TQG Only and (b) and (d) Complete CUBE 24-hour tests. Bins are 0.1 Hz wide centered on 0.1-Hz increments. Number of occurrences is plotted on logarithmic scale.

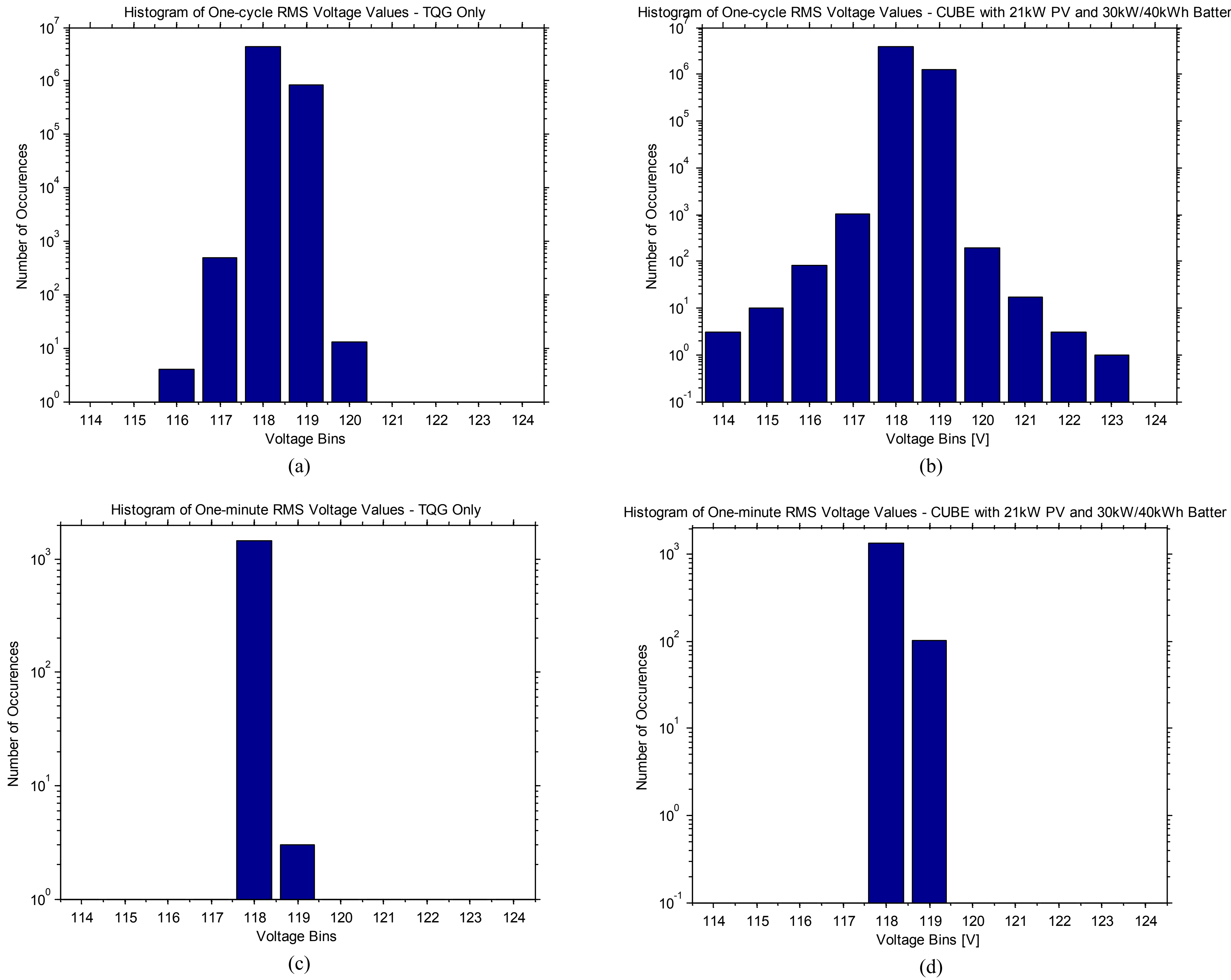


Figure 20. Histograms of cycle-by-cycle and 1-minute voltage data for the (a) and (c) TQG Only and (b) and (d) Complete CUBE 24-hour tests. Bins are 1 V wide centered on 1-V increments. Number of occurrences is plotted on logarithmic scale.

Discussion of Results

Over the 24-hour period, the CUBE saved just over 21 gallons, or 31%, relative to the TQG Only case. In addition, the CUBE reduced total TQG run hours by 20 hours, or 42%, relative to the TQG Only case. These benefits were accomplished at the expense of only one additional TQG start.

Breakdown of Fuel Savings

Over the 24-hour period, the CUBE saved just over 21 gallons, or 31%, relative to the TQG Only case. However, total energy delivered by PV was only 24% of the total energy delivered to the load. This can be explained as follows: Using the measured TQG no-load fuel consumption of 2.172 kg/hr (0.68 gal/hr), the fuel savings achieved by only running TQG2 for 4 hours would be 13.7 gallons. The remaining fuel savings would be achieved from displaced power provided by the PV. To estimate this amount, a linear fuel-use curve must be assumed. However, the second-order curve fit in Figure 12 shows better correlation than the first-order curve fit. The average of the first-order coefficients of the first- and second-order curve fits is 0.05 gal/hr/kW. Using this value, the 158 kWh contribution from PV would have saved 7.9 gal for a total estimated savings of 21.6 gallons, or 32%. This closely matches the results presented in this report. We can therefore conclude that about 63% of the fuel savings was achieved by using the battery to prevent starting another TQG, while about 37% was the direct result of PV power displacing TQG power.

Power Quality

The time-series as well as the histogram plots of voltage and frequency show greater cycle-by-cycle variability in both voltage and frequency for the CUBE case versus the TQG Only case. However, the 1-minute data do not exhibit this same increased variability. The 1-minute RMS voltage values for both the TQG Only and the CUBE cases are always within 117.5–119.5 V. The 1-minute frequency values for both the TQG Only and the CUBE cases are always within 59.95–60.05 Hz. Note that the average RMS voltage for both the TQG Only and the CUBE case was slightly less than 120 V. This was due to imprecision in the manual adjustment of the TQG voltage set points.

Battery Usage

The following results from the CUBE 24-hour test indicate that despite the dispatch parameter settings, the battery was used almost entirely for peak shaving, i.e., to provide regulating reserve.

- From Table 5, the total battery throughput (energy processed by the battery—in, then out) was less than 9 kWh, less than 1.4% of the total energy delivered to the load[10].
- The histograms of battery charge/discharge event energies in Figure 18 show that the vast majority (note logarithmic scale) of charge/discharge events were less than 100 Wh. In fact, all but three of the 519 charge/discharge events were less than 1 kWh. In addition, the maximum event energy was less than 5 kWh.

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[10] Note that the pie chart in Figure 1is based on AC energy supplied, which is less than DC energy due to efficiency of the BCD and HIR converters.

- The histograms of battery charge/discharge event durations in Figure 18 show that the vast majority (note logarithmic scale) of charge/discharge events lasted less than 10 sec. In fact, all but four of the 519 charge/discharge events lasted less than 5 minutes. In addition, the longest duration event lasted less than 1 hour. The four events can be identified in the 3-hour battery power zooms in Figure 16.

Details of battery operation over the 24 hours as plotted in the 3-hour zoomed windows of Figure 16 can be correlated to the following:

- From approximately 05:00–08:00, the battery was discharged at low power levels for short amounts of time to keep the TQG below the specified maximum % load. Without the battery, a second generator would have been needed to supply this power.
- From approximately 08:30–11:00, the battery was charged to absorb excess PV power and keep the TQG above the specified minimum % load. At approximately 11:00, the battery became full (SOC = 95%) and could no longer accept charge. Instead, PV was curtailed from approximately 11:00–12:00 to keep the TQG above the specified minimum % load.
- From approximately 13:30–14:30, the battery was again intermittently discharged to keep the TQG below the specified maximum % load. Near 15:30, the battery began discharging more and more until TQG2 was started near 16:30.
- TQG2 was shut down just after 20:00. The battery was discharged near 15 kW to keep TQG1 below the specified maximum % load. However, TQG2 was started back up again within 5 minutes and ran for approximately another 30 minutes before it was shut off again just after 20:30. The fact that the TQG shut off for such a short time was likely due to lack of hysteresis in the diesel generator on/off criteria. This hysteresis will be incorporated in future CUBE dispatch algorithms.
- From 20:30–22:30, the battery was again discharged at low power levels for short amounts of time to keep TQG1 below the specified maximum % load.
- The battery was taken off-line near 23:00 and not brought back on until near 04:00. From 04:00–05:00, the battery again began discharging at very low power levels for very short amounts of time as the morning load began to ramp up.

Cycle Charging vs. Peak Shaving

As shown in Figure 21, the PV and load profiles were not optimally aligned. Certainly, greater fuel savings could have been achieved had the profile peaks been aligned. However, from a practical point of view, the misalignment begs the question of whether greater fuel savings could have been achieved had the battery been used in a cycle-charging dispatch strategy, where the battery is charged when there is excess PV power (available PV power is greater than the portion of the load above that the TQG is required to supply) and then discharged at relatively high continuous power levels to avoid running one or more TQGs. This also would have lowered the SOC at the beginning of the next day so that all available PV power could be used to charge the battery, whereas for this CUBE 24-hour test, the battery started the day with a relatively high SOC (84.5%), which limited how much energy it could accept and resulted in the curtailing of PV power.

The greatest fuel savings are achieved by shutting off one or more TQGs. An additional 2.7 gallons could have been saved by never starting TQG2. In addition, had the battery started the day at a lower SOC, as would be expected in a cycle-charging strategy, the PV would never have been curtailed. However, unless TQG1 was also shut off, this in and of itself would not have resulted in additional fuel savings. Instead, the extra PV power would have gone into charging the battery. Therefore, if the size of the battery did not allow TQG1 to shut off for a significant amount of time, the estimated fuel savings would only increase by 2.7 gallons, from 21.6 gallons to 24.3 gallons, or an increase in estimated fuel savings of 4%, from 32% to 36%. The real benefit of a cycle-charging dispatch strategy would be if the size of the battery allowed both TQGs to be shut off for certain periods of the day. Future CUBE testing efforts will investigate the fuel savings achievable using a cycle-charging dispatch strategy.[11]

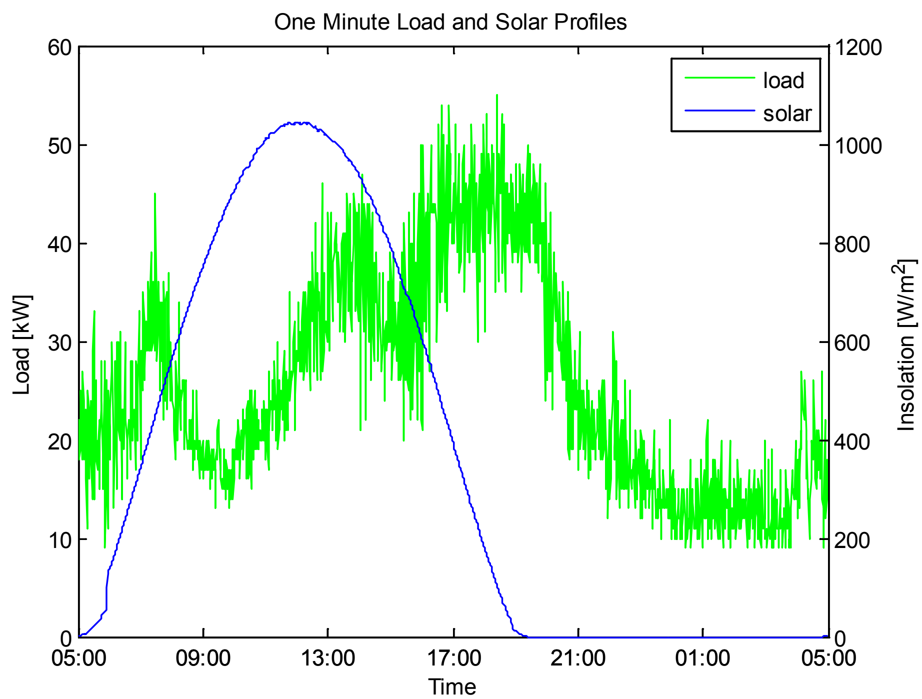

Figure 21. Alignment of load and solar profiles.

Diesel-Off Operation

The Maximum Load Step dispatch parameter in Table 3 was selected based on the load steps observed in Figure 10. The CUBE will dispatch sufficient diesel capacity to meet the last 20-minute average load plus the Maximum Load Step. Figure 10 shows the maximum step from the last 20-minute average load to the next 1-minute load value was no more than ±17 kW. Therefore, the Maximum Load Step dispatch parameter was set equal to 20 kW. In addition, the minimum 20-minute average load was 11 kW. This, combined with the fact that the battery was only allowed to discharge up to 30 kW AC, meant that diesel capacity required would never drop less than zero and the system would not enter diesel-off operation. This was a consequence of the

[11] Note that any additional fuel savings will come at the expense of higher battery throughput. The benefits associated with the reduced fuel consumption would have to be compared to the costs associated with the increased battery throughput.

particular load profile, as well as the need to maintain a minimum of 9 kW at all times due to the necessity of running one of the load banks at constant load. Future CUBE testing efforts will investigate operation with alternate load profiles. However, it should be pointed out that performance of the CUBE in all operating modes, including diesel-off, and during transitions between any two operating modes, including transitions from CUBE Inverter as grid-forming unit to TQG as grid-forming unit, have previously been demonstrated. The CUBE was able to perform all mode transitions while maintaining high power quality.

Contingency vs. Regulating Reserves

During the CUBE 24-hour test, the battery was used to provide regulating reserve above that already available as headroom in on-line diesel capacity. Regulating reserve is used to ensure power balance during normally occurring variability and uncertainty in the load and variable generation (in this case, PV power). Contingency reserve, on the other hand, is used to ensure power balance when the power system is subjected to an extreme event such as loss of a generating unit. Neither the TQG Only nor the Complete CUBE 24-hour tests included contingency reserves. However, contingency reserves are critical to ensure power reliability. Future efforts will identify an appropriate amount of contingency reserve to incorporate (such as loss of one TQG) and evaluate the use of battery capacity versus diesel capacity to provide this contingency reserve.

Mode Transition, Black Start, and Load Step Response Tests

In addition to the 24-hour tests, the CUBE was subjected to a series of load steps and a forced black start to demonstrate power quality during all modes of operation, during transitions between different modes, and during the load steps themselves.

The load steps and black start tests had three goals. First, a stepped load profile was selected to trigger the dispatch strategy to perform the following:

- Transition to/from diesel-off operation (thus transitioning from TQG as grid-forming unit to CUBE as grid-forming unit and vice versa)
- Start/stop the second TQG
- Charge battery to keep TQG above minimum specified % load
- Discharge battery to keep TQG below maximum specified % load.

In addition, tests were also performed to demonstrate CUBE ability to black start the load with the battery only. Finally, 23 kW load steps were applied both with TQG Only on-line and with Battery Only on-line to compare the load step responses.

Dispatch Settings

The only differences in dispatch settings for the mode transition and black start tests from the 24-hour test setting shown in Table 3 were that (1) the *Maximum Load Step* parameter was set to 0 kW instead of 20 kW to allow transition to diesel-off operation even in the presence of a 20-kW load and (2) the *TQG Minimum Run-Time* parameter was set to 3 minutes instead of 20 minutes to allow a shorter cycling time for demonstration purposes.

Data Processing

The CUBE mode transition and black start tests were performed June 21, 2014. The 16 channels of data specified in the Data Acquisition System section of this report were recorded at 100 kS/s using Yokogawa's DL850E Acquisition Software v1.01. The data were recorded and saved in 1-minute files in the native Yokogawa .wdf file format. The .wdf files were then converted to .csv files using Yokogawa's Xviewer software v1.75.

MATLAB R2012b was used to process all the data and plot results. The 100 kS/s data are directly plotted to show instantaneous waveform quality. In addition, the data were processed to produce cycle-by-cycle (60 Hz) power flow data from the 100 kS/s waveform data. Specifically, the kS/s waveforms were processed based on zero crossings to compute cycle-by-cycle power, RMS voltages and currents for AC waveforms, average voltages and currents for DC waveforms, and frequency of the AC waveforms. With 100 kS/s waveforms, the accuracy of the frequency computations would be +/- 0.04 Hz. In addition, the zero crossings were interpolated to further improve the accuracy of the frequency computations.

Mode Transition Test

Results

The results from the mode transition test are shown in the following tables/figures:

- Maximum and minimum cycle-by-cycle RMS voltage and frequency are shown in Table 6.
- Time-series plot of cycle-by-cycle power values, voltage, and frequency during the entire test is shown in Figure 22.
- Time-series plots of instantaneous AC and DC waveforms (collected at 100 kS/s) during the entire test are shown in Figure 23 and Figure 24.
- 20-second cycle-by-cycle and 200-ms instantaneous AC waveform zooms of the transition from TQG to CUBE as grid-forming unit are shown in Figure 25 (a) and (c), and from CUBE to TQG as grid-forming unit in Figure 25 (b) and (d).
- Zooms of TQG load control via PV curtailment versus battery charging are shown in Figure 26. Zooms include 20-second cycle-by-cycle zoom in Figure 26 (a), 20-second instantaneous DC waveform zoom in Figure 26 (b), and 200-ms instantaneous AC waveform zooms in Figure 26 (c) and (d).

The load step profile during the mode transition test can be seen in the turquoise trace in the top plot of Figure 22. The solar irradiance was held constant at 1,000 W/m^2 during the entire test, and the PV power can be seen in the green trace in the middle plot of Figure 22.

Table 6. Maximum and Minimum RMS Voltage and Frequency During the Mode Transition Test

Parameter	Value
Max Voltage [V]	124.7
Min Voltage [V]	112.5
Max Frequency [Hz]	61.14
Min Frequency [Hz]	58.66

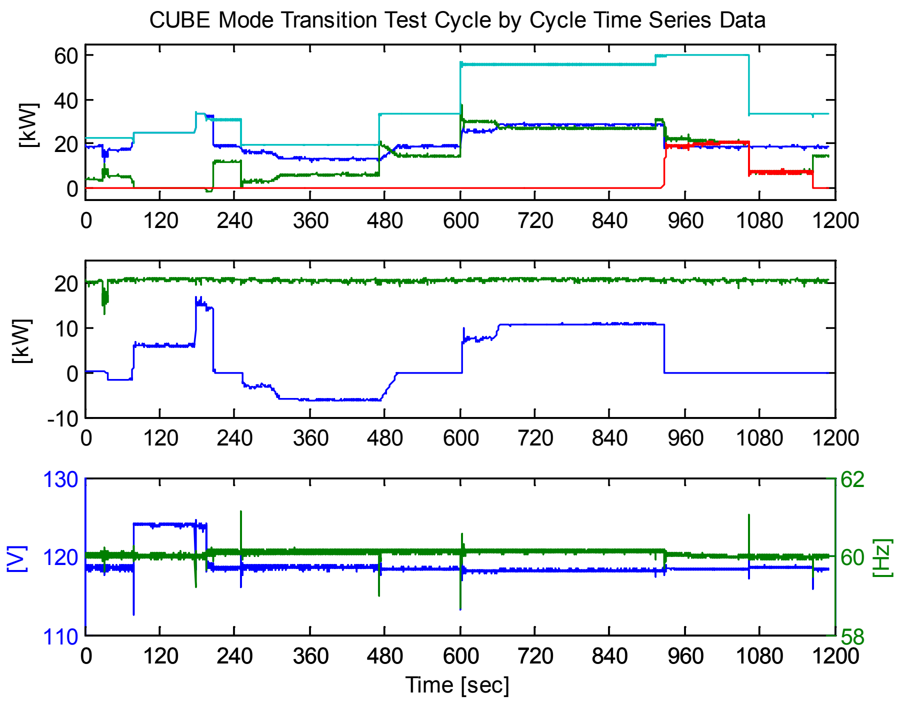

Figure 22. Cycle-by-cycle time-series data during the entire mode transition test. Top plot = AC power values (blue = inverter, green = TQG1, red = TQG2, turquoise = load); middle plot = DC power values (blue = battery, green = PV); bottom plot = RMS voltage and frequency (blue = voltage, green = frequency).

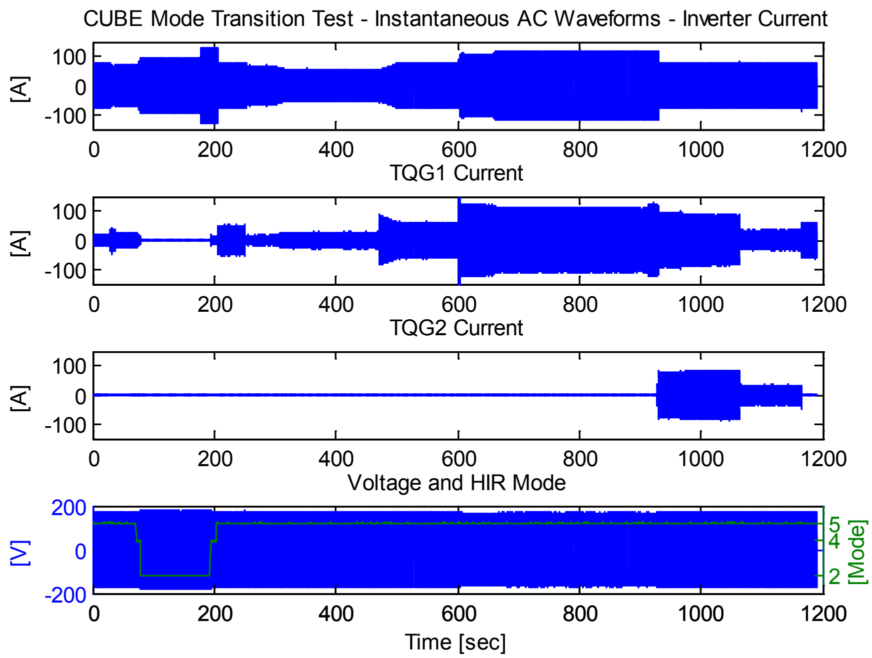

Figure 23. Instantaneous AC waveforms during the entire mode transition test. First plot = Inverter Current; second plot = TQG1 Current; third plot = TQG2 Current; fourth plot = Voltage and HIR Mode. HIR Modes: Mode = 2: AC voltage control mode (grid-forming unit); Mode = 4: current control mode; Mode = 5: DC Bus voltage control mode.

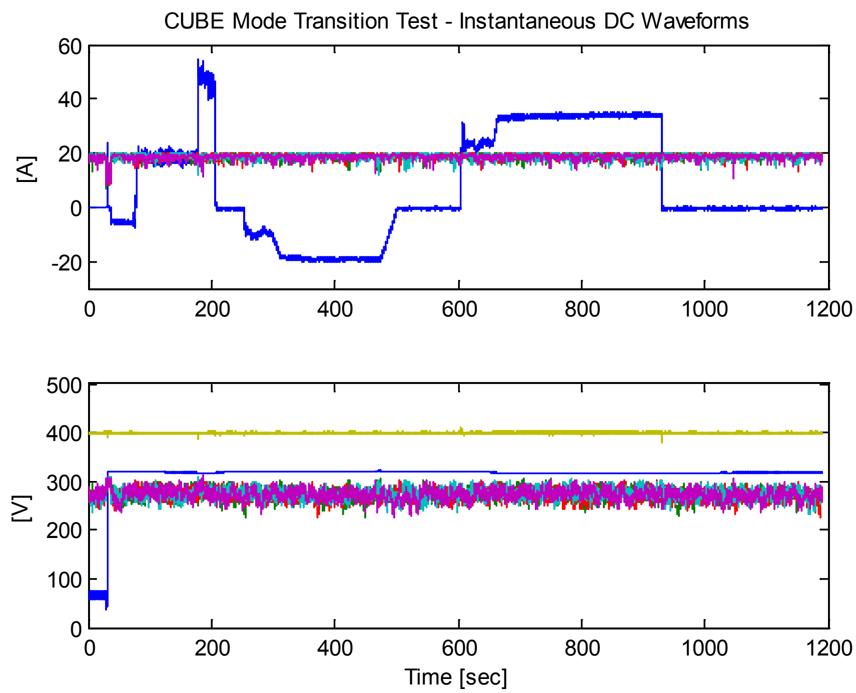

Figure 24. Instantaneous DC waveforms during the entire mode transition test. Top plot = Currents (blue = battery, green = PV1, red = PV2, turquoise = PV3, purple = PV4); bottom plot = Voltages (blue = battery, green = PV1, red = PV2, turquoise = PV3, purple = PV4, artichoke green = DC Bus).

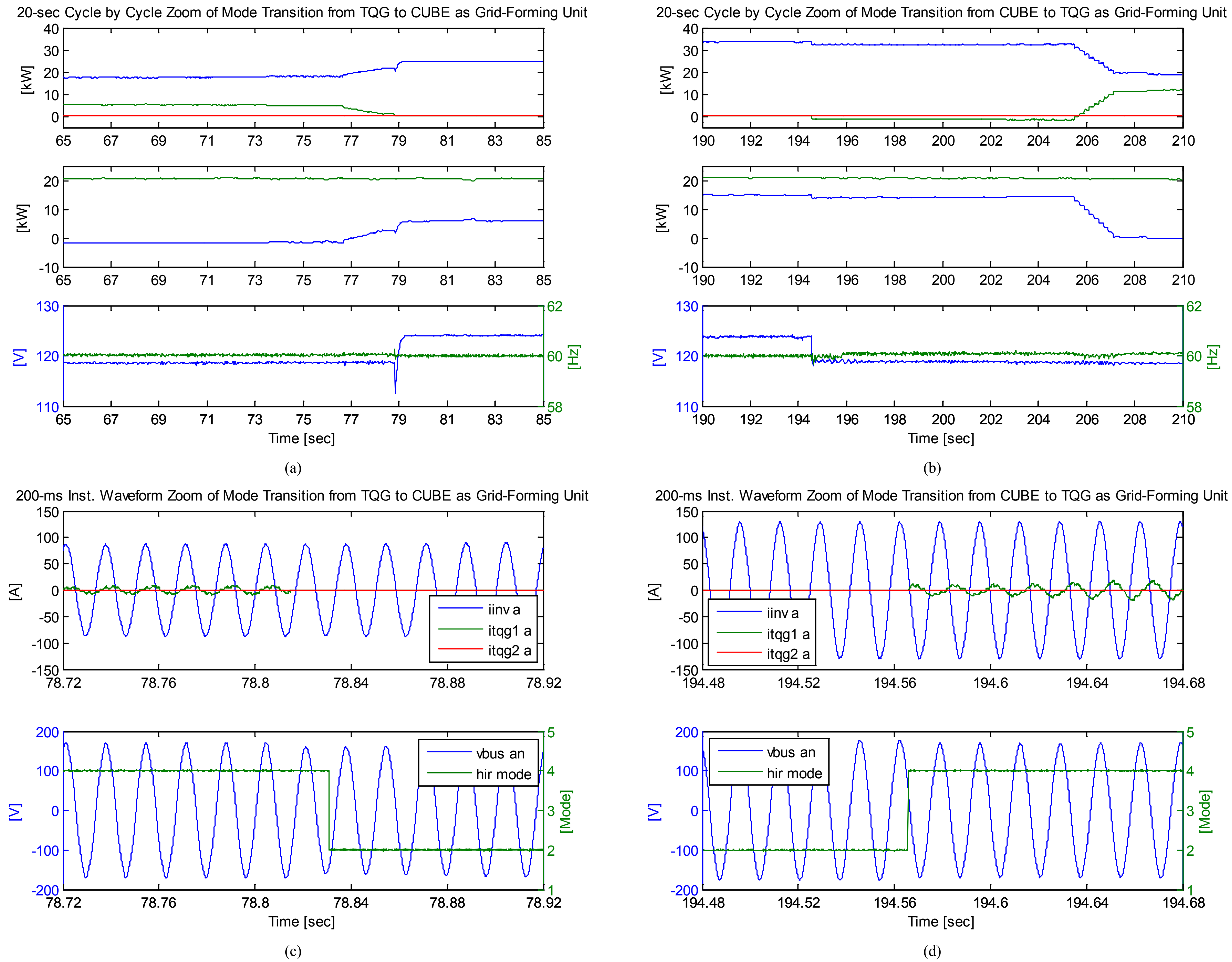

Figure 25. 20-second cycle-by-cycle and 200-ms instantaneous waveform zooms of mode transitions (a) and (c) from TQG as grid-forming unit to CUBE as grid-forming unit and (b) and (d) from CUBE as grid-forming unit to TQG as grid-forming unit. For the cycle-by-cycle plots: top plot = AC power values (blue = inverter, green = TQG1, red = TQG2, turquoise = load); middle plot = DC power values (blue = battery, green = PV); bottom plot = RMS voltage and frequency (blue = voltage, green = frequency). For the instantaneous plots: top plot = current waveforms (blue = inverter, green = TQG1, red = TQG2); bottom plot = voltage waveforms and HIR mode (blue = voltage, green = HIR Mode). HIR Modes: Mode = 2: AC voltage control mode (grid-forming unit); Mode = 4: current control mode; Mode = 5: DC Bus voltage control mode. The actual transition from TQG to CUBE as grid-forming unit occurs near 75 seconds, while the actual transition from CUBE to TQG as grid-forming unit occurs near 195 seconds.

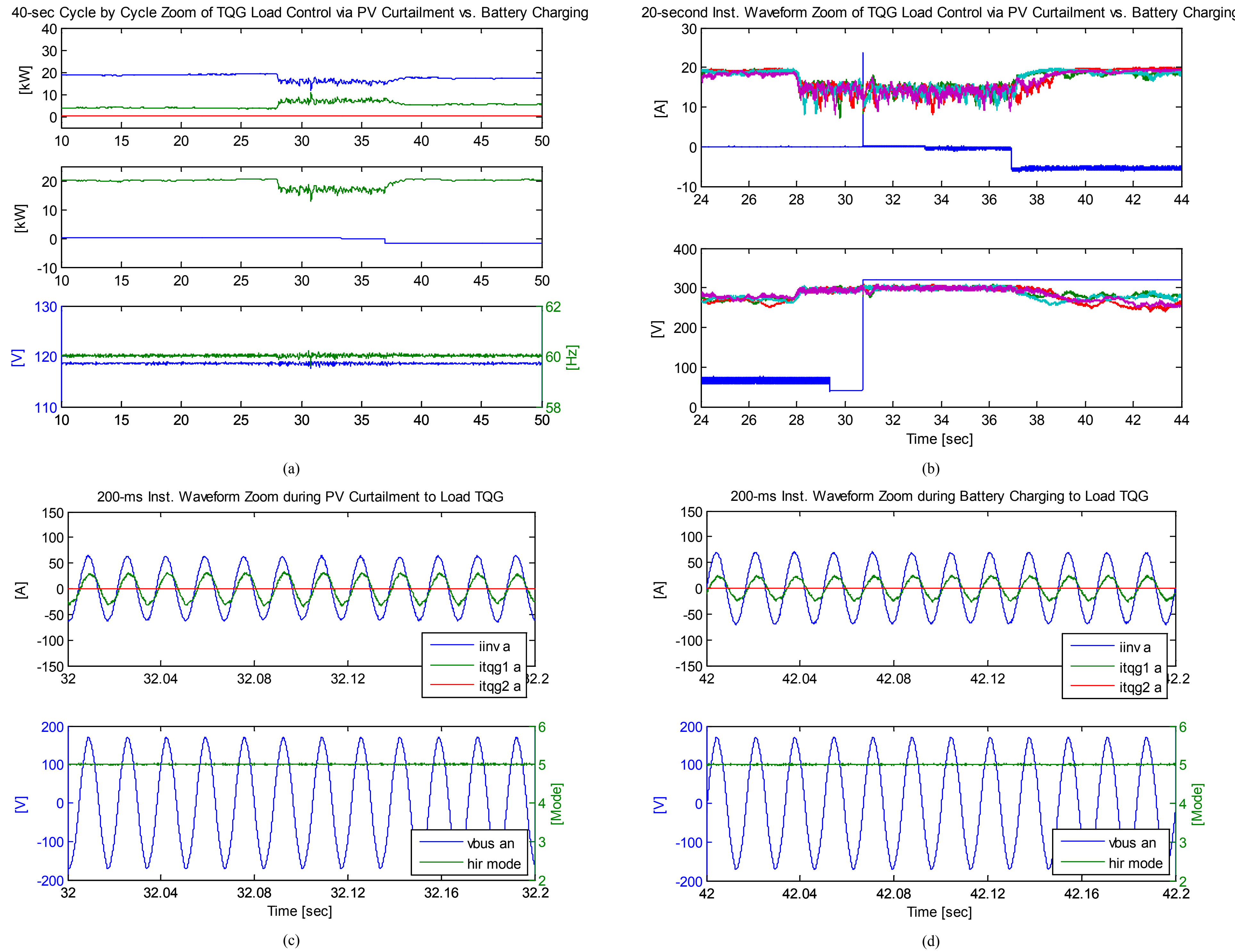

Figure 26. Zooms during PV curtailment and battery charging to load TQG. (a) 20-second cycle-by-cycle zoom during PV curtailment followed by battery charging; (b) 20-second instantaneous DC waveform zoom during PV curtailment followed by battery charging; (c) 200-ms instantaneous AC waveform zoom of PV curtailment; and (d) 200-ms instantaneous AC waveform zoom of battery charging. For the cycle-by-cycle plots: top plot = AC power values (blue = inverter, green = TQG1, red = TQG2, turquoise = load); middle plot = DC power values (blue = battery, green = PV); bottom plot = RMS voltage and frequency (blue = voltage, green = frequency). For the instantaneous AC plots: top plot = current waveforms (blue = inverter, green = TQG1, red = TQG2); bottom plot = voltage waveforms and HIR mode (blue = voltage, green = HIR Mode). HIR Modes: Mode = 2: AC voltage control mode (grid-forming unit); Mode = 4: current control mode, Mode = 5: DC Bus voltage control mode. For the instantaneous DC plots: top plot = Currents (blue = battery, green = PV1, red = PV2, turquoise = PV3, purple = PV4); bottom plot = Voltages (blue = battery, green = PV1, red = PV2, turquoise = PV3, purple = PV4, artichoke green = DC Bus).

Discussion

The system was initially operated manually (no automated dispatch) for 20 minutes with TQG1 and 20 kW of PV[12] and 23 kW of load. This was to build up the 20-minute historical power values required by the dispatch strategy to correctly determine when to start/stop components. At time zero, the data acquisition was started. Shortly thereafter, the CUBE was placed into automated dispatch.

Test Profile Summary

The following actions and responses can be observed in Figure 22 as well as Figure 23 and Figure 24:

- Initially, PV is operating with MPPT and supplying 19 kW, and TQG1 is supplying 4 kW to meet the 23-kW load.
- At 28 seconds, the CUBE is placed into automated dispatch.
- Immediately afterwards, the CUBE performs the following:
    - Curtails PV to increase the TQG load above the minimum allowed continuous value of 6 kW (20%)
    - Dispatches the battery in preparation for shutting TQG1 off, although the battery does not actually come on-line until 3 seconds later (at 31 seconds).
- Nine seconds later (at 37 seconds), the CUBE switches from curtailing PV to charging the battery in order to keep TQG load at the minimum allowed continuous value of 6 kW (20%). The PV returns to MPPT operation.
- At 76 seconds, the CUBE ramps up battery discharge power to unload the TQG, and then at 79 seconds takes the TQG off-line, transitioning the system from TQG as grid-forming unit to CUBE as grid-forming unit. The voltage steps from 119 V to 124 V when the CUBE becomes the grid-forming unit. This was not intentional and is likely due to a difference between the manually adjusted TQG voltage set point and the programmed CUBE voltage set point, but it does facilitate identification of the actual transition point. This also has the additional effect of increasing the constant resistance load from 23 kW to 25 kW.
- At 177 seconds, the load is stepped from 25 kW to 33 kW.
- Immediately afterwards, the CUBE starts TQG1, although the TQG does not actually come on-line until 18 seconds later (at 195 seconds). When the TQG comes on-line, the CUBE transitions the system from CUBE as grid-forming unit to TQG as grid-forming unit, and then ramps battery discharge power down to load the TQG. Again, probably due to a difference between the manually adjusted TQG voltage set point and the programmed CUBE voltage set point, the voltage steps from 124 V to 119 V, and the load decreases from 33 kW to 31 kW when the TQG becomes the grid-forming unit.

[12] Note that PV output power was slightly less than the peak during the 24-hour test due to slightly lower irradiance.

- At 250 seconds, the load is stepped from 31 kW to 19 kW. The load on TQG1 decreases from 12 kW to 1 kW.
- Three seconds later (at 253 seconds), the CUBE begins charging the battery to increase TQG load and:
    - Immediately charges battery to increase TQG load to the minimum allowed instantaneous value of 3 kW (10%)
    - Over next 23 seconds (until 315 seconds), gradually increases battery charge to increase TQG load to the minimum allowed continuous value of 6 kW (20%).
- At 472 seconds, the load is stepped back from 19 kW to 33 kW. The load on TQG1 increases from 6 kW to 20 kW.
- Over the next 31 seconds (until 503 seconds), the CUBE gradually reduces battery charge kW to 0 kW, decreasing TQG load to 15 kW.
- At 602 seconds, the load is stepped from 33 kW to 56 kW. The load on TQG1 increases from 15 kW to 37 kW.
- Three seconds later (at 605 seconds), the CUBE begins discharging the battery to decrease TQG load and:
    - Immediately discharges battery to decrease TQG load to the maximum allowed instantaneous value of 30 kW (100%)
    - Over the next 60 seconds (until 665 seconds), gradually increases battery discharge to decrease TQG load to the maximum allowed continuous value of 27 kW (90%).
- At 914 seconds, the load is stepped from 56 kW to 60 kW. The load on TQG1 increases from 27 kW to 31 kW.
- Immediately afterwards, the CUBE starts TQG2, although the TQG does not actually come on-line until 12 seconds later (at 926 seconds).
- At 929 seconds, CUBE reduces battery discharge kW to 0 kW as the TQGs are operating below the maximum allowed continuous value of 27 kW each (90%).
- The TQGs do not initially share load equally. From 930 seconds to 1,018 seconds, the TQGs are manually adjusted to achieve equal load sharing.
- At 1,064 seconds, the load is stepped back from 60 kW back to 33 kW. The load on both TQG1 and TQG2 drops from 21 kW each to 7.5 kW each.
- 102 seconds later (at 1,165 seconds), the CUBE opens the TQG2 contactor and shuts TQG2 down.

Table 6 shows that the cycle-by-cycle frequency values remain within ±1.35 Hz of the nominal 60 Hz during the entire mode transition test profile. The cycle-by-cycle voltage values show a larger deviation. However, this is due in part to the fact that the CUBE was regulating to 124 V, while the TQG was regulating to 119 V. As the recorded min/max values were 112.5 V and 124.7 V, respectively, it is reasonable to assume that the cycle-by-cycle voltages otherwise would have remained within ±6.5 V of nominal.

Transition Zooms

A critical challenge in any non-droop-controlled power system is maintaining power quality during transitions from one grid-forming unit to another. Figure 25 (a) and (c) plot 20-second cycle-by-cycle and 200-ms instantaneous AC waveform zooms of the transition from TQG as grid-forming unit to CUBE as grid-forming unit; Figure 25 (b) and (d) repeat this for the transition from CUBE as grid-forming unit to TQG as grid-forming unit. The 20-second plots show the CUBE unloading/loading the TQG to facilitate a soft transition. In particular, during a transition from TQG to CUBE as grid-forming unit, the CUBE first unloads the TQG by ramping the Inverter output current to the measured load before transitioning. Conversely, during a transition from CUBE to TQG as grid-forming unit, the CUBE first sets the inverter output current command to the measured load current, then brings TQG on-line and transitions the inverter from AC voltage control to AC current control, and then ramps the battery output power down to zero.

The 200-ms plots show that high waveform quality is maintained during the transitions.[13] In addition, the 20-second plots show that system frequency remains essentially constant during the transitions. As previously mentioned, the difference in actual voltage level when CUBE is the grid-forming unit versus TQG is due to a difference between the manually adjusted TQG voltage set point and the programmed CUBE voltage set point. As also previously discussed, as the load is a constant resistance, this has the effect of instantaneously increasing or decreasing the load as soon as the transition takes place. Figure 25 (a) shows the small step up in load when transitioning from TQG to CUBE as grid-forming unit Figure 25 (b) shows the small step down in load when transitioning from CUBE to TQG as grid-forming unit. During the latter case, the inverter continues to output the load current measured just prior to the transition. This results in the inverter temporarily outputting more power than the available load, motoring the TQG at around 1.5 kW for approximately 10 seconds. This and the observed load steps are artifacts of the probable voltage set point maladjustment. Proper adjustment of voltage set points should eliminate these artifacts.

On the other hand, Figure 25 (a) shows there is a 100-ms voltage dip during the transition from TQG to CUBE as grid-forming unit. Figure 25 (c) shows there is a corresponding lag of approximately one cycle (17 ms) from the TQG contactor opening (as evidenced by TQG current going to zero) and the HIR switching to AC voltage control mode. This lag likely contributed to the voltage dip observed in Figure 25 (a). There is no similar lag or voltage dip in the transition from TQG to CUBE as grid-forming unit. This remains an issue for further research.

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[13] The 200-ms instantaneous waveform zooms show that instead of being identically zero, the TQG current is non-zero and lagging by approximately 90° at the mode transitions. In addition, there is no corresponding increase/decrease in the inverter current scope trace when the TQG goes off-line/comes on-line. This is due to the fact that the CUBE measures and controls inverter current on the inverter side of the isolation transformer, while the scope is displaying inverter current on the load side of the isolation transformer. Whenever the inverter is on-line with the TQG, the inverter is commanded to operate at a power factor of the currently measured load (here, always unity). As this is controlled on the inverter side of the transformer, the TQG must provide all the reactive power necessary to magnetize the transformer. This explains the non-zero phase shifted current just before the TQG goes off-line and just after it comes on-line. When the TQG is off-line, the inverter must instead provide the reactive power necessary to magnetize the transformer. However, the step in current would be observed on the inverter side of the isolation transformer, not the load side where the scope inputs are connected. This explains why there is no corresponding change in the inverter current scope trace when the TQG goes off-line/comes on-line.

TQG Load Control via PV Curtailment vs. Battery Charging

Figure 26 includes zooms of TQG load control via PV curtailment versus battery charging. In these plots, load control via PV curtailment is active from 28 seconds to 37 seconds. At 37 seconds, the system switches to load control via battery charging, and the PV resumes MPPT operation. From these zooms, as well as the overall test profile in Figure 22, it can be seen that while TQG load control via battery charging performs very well, load control via PV curtailment is subject to power oscillations.

During curtailment, the CUBE forces the PV inputs to operate on the open-circuit portion of the PV current-voltage (IV) curve. On this portion of the curve, a PV array behaves more like a voltage source than a current source, with small changes in voltage resulting in large changes in current. The increased variability observed during PV curtailment may be due to one or both of the following factors:

- The CUBE perturbs PV voltage to implement both MPPT and curtailment. It may be necessary to reduce the size of the voltage perturbations during operation on the open-circuit portion of the IV curve where small changes in voltage result in large changes in current.
- The PV simulator operates as a current source. The effective bandwidth of the simulator may be much lower when forced to operate on the open-circuit portion of the PV IV curve where a PV array looks like a voltage source. Thus, there may be a lag in response, resulting in oscillations about the desired curtailment level. This would not be observed during operation with a real PV array and may require reducing the CUBE PV MPPT update rate during operation with the PV simulator.

Regardless, the increased power variability during PV curtailment results in increased frequency and voltage variability on the AC bus. However, the voltage and frequency deviations remain low magnitude (±0.17 Hz[14], ±0.75 V), and there is no observable change in AC waveform quality as shown in Figure 26 (c) and Figure 26 (d).

Black Start Test

Results and Discussion

For the black start test, the CUBE was started up in Battery Only mode with a 23 kW load. The results are shown in the following figures:

- Table listing voltage and frequency regulation parameters during the black start is shown in Table 7.
- Two-second cycle-by-cycle power, voltage, and frequency data are shown in Figure 27.
- Two-second instantaneous current and voltage waveform data are shown in Figure 28.
- 200-ms instantaneous current and voltage waveform data zoon are shown in Figure 29.

During Battery Only operation with 23 kW load, the CUBE regulates voltage at the nominal values of 124.0 V and 60.00 Hz. In Table 7, the voltage settle times were computed as the time

[14] This excludes the excursions of up to +0.22 Hz / -0.40 Hz when the battery comes on-line at 31 seconds. This is unrelated to the PV curtailment and lasts less than 200 ms.

for voltage to reach and remain within 1 V of the steady-state value for at least three cycles. The frequency settle times were computed as the time for the frequency to reach and remain within 0.1 Hz of the steady-state value for at least three cycles. Table 7 shows that the CUBE is able to reach steady-state frequency within 60 ms and steady-state voltage within ¼ second from start-up. In addition, Figure 29 shows the CUBE is able to almost immediately achieve and maintain high waveform quality during Battery Only (diesel-off) operation.

Table 7. Voltage and Frequency Regulation During CUBE Black Start

Parameter	Value
Maximum Voltage [V]	125.0
Maximum Frequency [Hz]	60.20
Voltage Overshoot [V]	+1.0
Frequency Overshoot [Hz]	+0.20
Voltage Settle Time [ms]	225
Frequency Settle Time [ms]	58

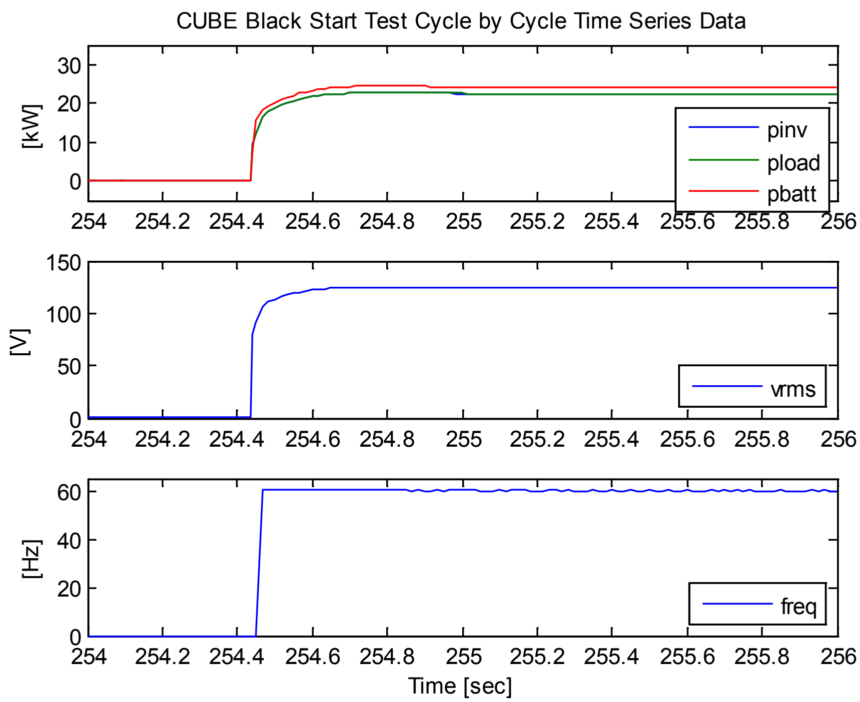


Figure 27. 20-second cycle-by-cycle power, voltage, and frequency data during the CUBE black start test. Top plot = power values (blue = inverter, green = load, red = battery); middle plot = RMS voltage; bottom plot = frequency.

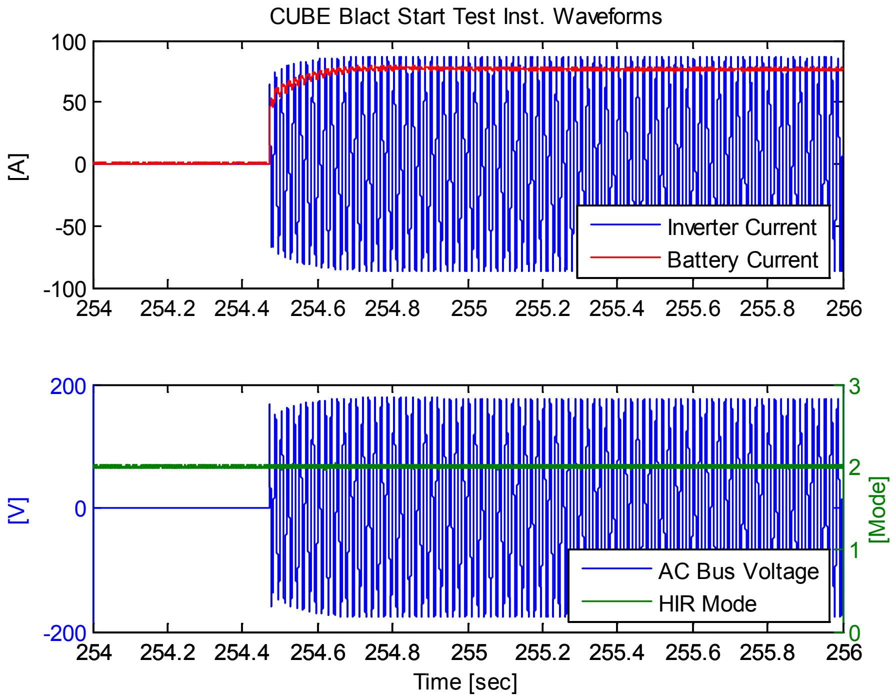


Figure 28. 20-second instantaneous waveforms during the CUBE black start test. Top plot = current waveforms (blue = inverter, red = battery); bottom plot = AC voltage waveforms and HIR mode (blue = AC voltage, green = HIR Mode). HIR Modes: Mode =1: Off; Mode = 2: AC voltage control mode (grid-forming unit).

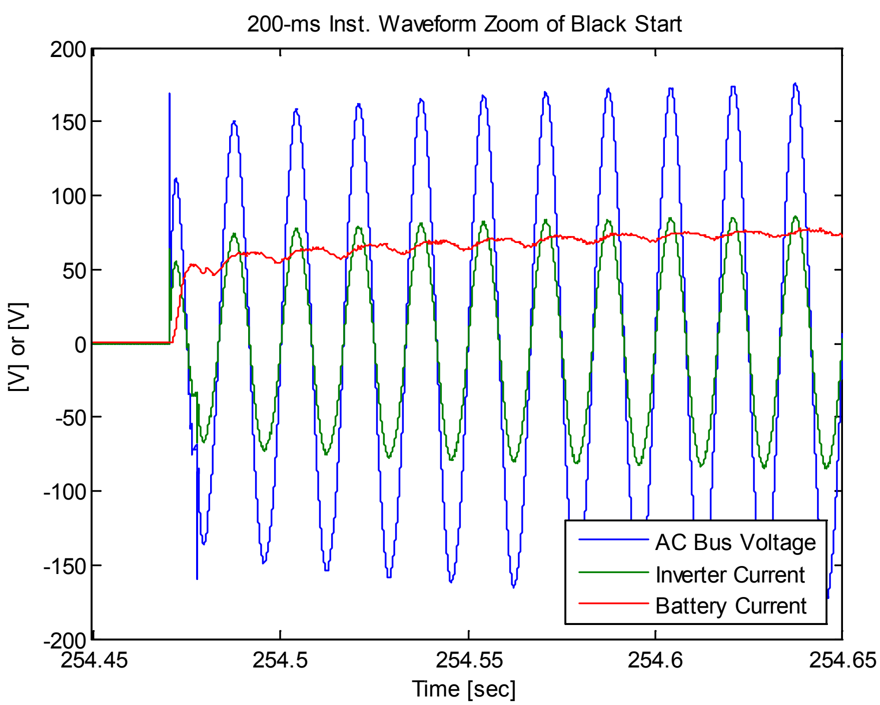


Figure 29. 200-ms instantaneous waveform zoom during the CUBE black start test. Blue = AC voltage; green = inverter current; red = battery current.

Load Step Response Tests

Results and Discussion

23-kW load steps up and down were applied both while operating with TQG1 only and while operating with the battery only. The results are shown in the following tables/figures:

- Summary of voltage and frequency regulation parameters during steady-state as well as the load steps for the TQG Only versus the Battery Only cases is given in Table 8.
- Magnitude frequency spectra during steady-state operation at no load and at 23 kW for (a) and (c) the TQG Only case, and (b) and (d) the Battery Only case are shown in Figure 30.
- Magnitudes of the first 50 harmonics at no load and 23 kW for (a) and (c) the TQG Only case, and (b) and (d) the Battery Only case are shown in Figure 31.
- Two-second cycle-by-cycle power, voltage, and frequency plots during load steps up and down for (a) and (c) the TQG Only case, and (b) and (d) the Battery Only case are shown in Figure 32.
- Two-second and 200-ms instantaneous zooms during load steps up for (a) and (c) the TQG Only case, and (b) and (d) the Battery Only case are shown in Figure 33.[15]
- Two-second and 200-ms instantaneous zooms during load steps up for (a) and (c) the TQG Only case, and (b) and (d) the Battery Only case are shown in Figure 34.

In Table 8, the steady-state average and standard deviation values are based on averages over 21-second windows of the cycle-by-cycle data. The fast Fourier transform (FFT) results in Table 8, Figure 30, and Figure 31 were computed by taking the FFT of the 100 kS/s instantaneous waveform data over the same 21-second period. The Total Harmonic Distortion (THD) result includes harmonics up to the 50^{th} order. The magnitudes of the fundamental and harmonics are based on the RMS of all components within ±0.5 Hz of the actual fundamental or harmonic frequency. The voltage settle times were computed from the cycle-by-cycle data as the time for voltage to reach and remain within 1 V of the steady-state value for at least three cycles. The frequency settle times were computed from the cycle-by-cycle data as the time for the frequency to reach and remain within 0.1 Hz of the steady-state value for at least three cycles.

Discussion:

- Table 8 shows that the TQG and the CUBE are equally capable of maintaining voltage and frequency within tight limits during steady-state operation.
- Table 8 and Figure 31 show that the TQG and the CUBE are capable of maintaining high power quality during steady-state operation, with the CUBE able to provide about 25% lower THD than the TQG.

[15] Note: There is a 200-ms discrepancy in the load step times for the TQG Only case between the cycle-by-cycle plots in Figure 32 (a) and (c) and the instantaneous plots in Figure 33 and Figure 34 (a) and (c). This was likely introduced by the interpolation process to obtain the cycle-by-cycle data, resulting in small differences in time that may build up over the 25 minutes of data.

- The average RMS voltage is 6–7 V higher for the Battery Only case than for the TQG Only case. This was previously observed during the Mode Transition tests and is likely due to a difference between the manually adjusted TQG voltage set point and the programmed CUBE voltage set point.
- The presence of the 10-kHz switching components can be seen in the frequency spectrum plots of Figure 30 (b) and (d) for the CUBE case versus (a) and (c) for the TQG Only case. The CUBE spectrum includes "carrier" as well as sideband spikes centered at the switching frequency of 10 kHz and its harmonics of 20 kHz, 30 kHz, and 40 kHz (up to Nyquist frequency of 50 kHz). The sideband spikes occur at ± 60 Hz and its harmonics and are replicas of the baseband frequency. This is a typical frequency spectrum for the pulse-width modulated output of a switched-mode power supply. As these components occur at very high frequencies (above the 160th harmonic of the fundamental 60 Hz) and are heavily attenuated, they have virtually no effect on the power system operation.
- Voltage regulation is the ability of equipment to maintain constant output voltage despite changes in load and can be quantified using the following equation:

  $$VR = \frac{|V_{nl}| - |V_{fl}|}{|V_{fl}|} \times 100$$

  where V_{nl} = voltage at no load
  V_{fl} = voltage at full load[16]

  Using the above equation and the RMS voltage values in Table 8, the voltage regulation of the TQG can be computed as 0.4%, while that of the CUBE inverter can be computed as 1.4%. The CUBE is unable to achieve as tight of voltage regulation as the TQG. This is likely due to the fact that the CUBE inverter is regulating voltage on the inverter side of the isolation transformer and is thus unable to compensate for the voltage drop across the transformer. It is possible to relocate regulation to the line side of the isolation transformer; however, this introduces additional dynamics into the CUBE inverter feedback loops and would require the loops to be re-tuned.
- Both Table 8 and Figure 32 show that during both load steps up and down, the CUBE exhibits approximately 3 times larger voltage transients than the TQG and takes 3–4 times longer to return voltage to nominal. Despite the unfavorable comparison, however, it should be pointed out that the CUBE is still able to return voltage to nominal within 200 ms. In addition, Figure 32 shows that the CUBE is able to recover voltage smoothly, whereas the TQG introduces oscillations in voltage during the recovery process.
- Both Table 8 and Figure 32 show that during both load steps up and down, the CUBE exhibits larger frequency transients than the TQG, but is able to return frequency to nominal much more quickly. The CUBE is able to return frequency to nominal within 50 ms, while the TQG takes ¾ to 1 second (over 15 times as long).
- The 200-ms instantaneous zooms in Figure 33 and Figure 34 show that the TQG and the CUBE are equally capable of maintaining high waveform quality during a load step, with any transient-induced spikes limited to the first half-cycle only.

[16] The results here are based on 23 kW versus a full load of 30 kW.

Table 8. Voltage and Frequency Regulation during Steady State and Load Steps

Load Condition	Parameter	TQG Only	Battery Only
No Load Steady State	Average RMS Voltage from Time Series [V]	118.7	125.7
	Voltage Standard Deviation [V]	0.08	0.03
	Fundamental Voltage RMS from FFT [V]	118.6	125.2
	Voltage THD from FFT [%]	2.42	1.83
	Average Frequency from Time Series [Hz][17]	59.98	60.00
	Frequency Standard Deviation [Hz]	0.029	0.021
23 kW Load Steady State	Average RMS Voltage from Time Series [V]	118.2	124.0
	Voltage Standard Deviation [V]	0.03	0.04
	Fundamental Voltage RMS from FFT [V]	118.0	123.5
	Voltage THD from FFT [%]	1.77	1.29
	Average Frequency from Time Series [Hz]	59.99	60.00
	Frequency Standard Deviation [Hz]	0.014	0.017
23 kW Step Up	Max Voltage [V]	120.3	125.7
	Min Voltage [V]	113.7	110.5
	Max Frequency [Hz]	60.04	60.29
	Min Frequency [Hz]	58.00	57.38
	Voltage Deviation [V]	-4.5	-13.5
	Frequency Deviation [Hz]	-1.99	-2.62
	Voltage Settle Time [ms]	68	166
	Frequency Settle Time [ms]	821	50
23 kW Step Down	Max Voltage [V]	123.5	143.3
	Min Voltage [V]	116.0	123.9
	Max Frequency [Hz]	62.25	62.99
	Min Frequency [Hz]	59.93	59.53
	Voltage Deviation [V]	+4.8	+17.6
	Frequency Deviation [Hz]	+2.25	+2.99
	Voltage Settle Time [ms]	49	201
	Frequency Settle Time [ms]	780	50

[17] Note: Using a 21-second window, the resolution of the resulting FFT is only 0.05 Hz. Therefore, the fundamental frequency from the FFT is not presented in this table.

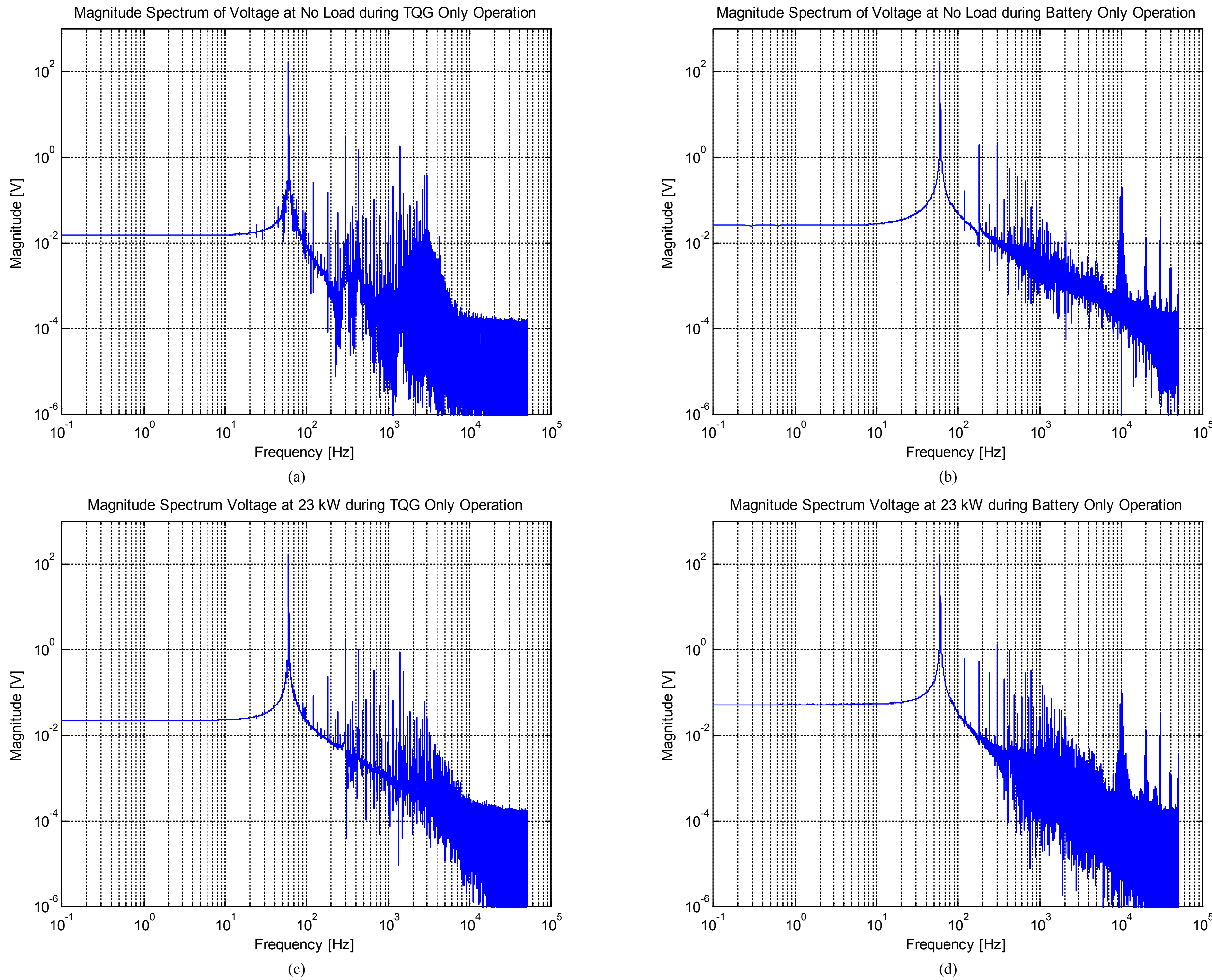
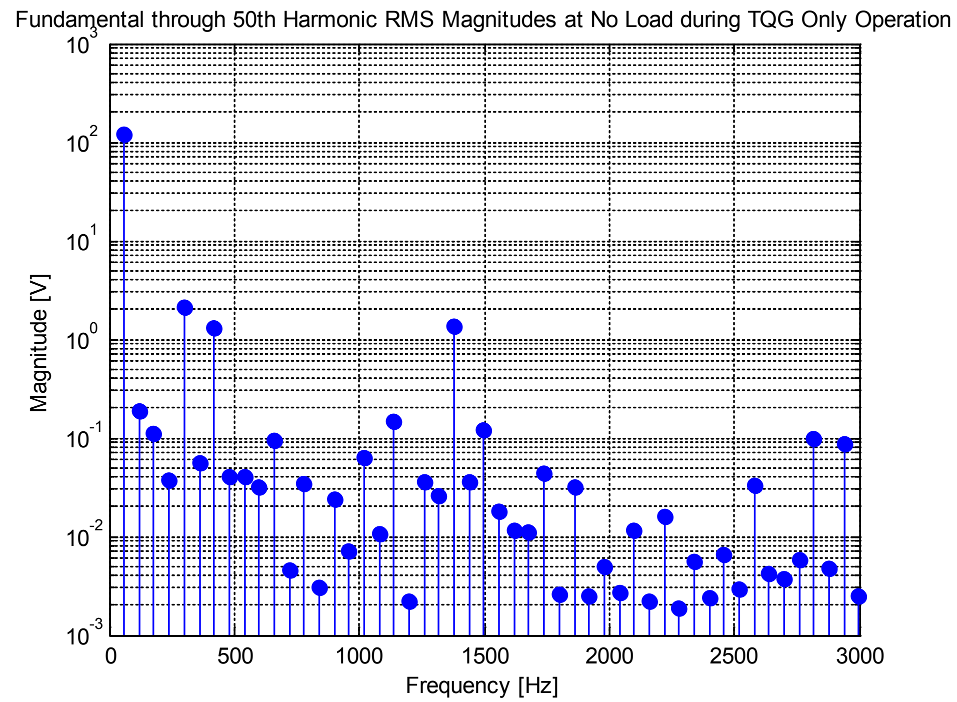
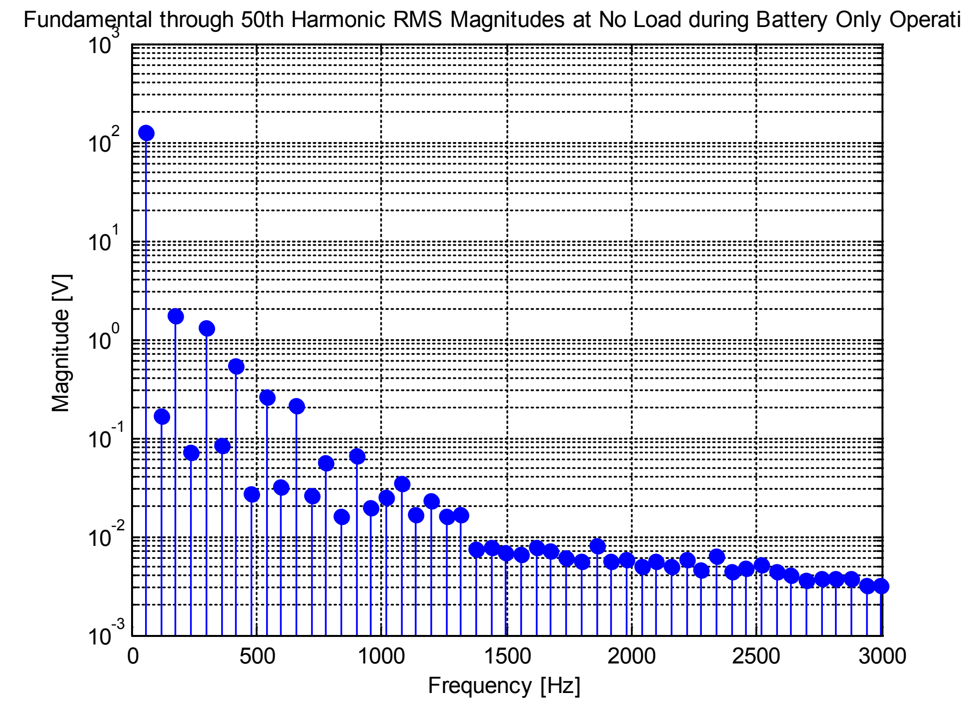


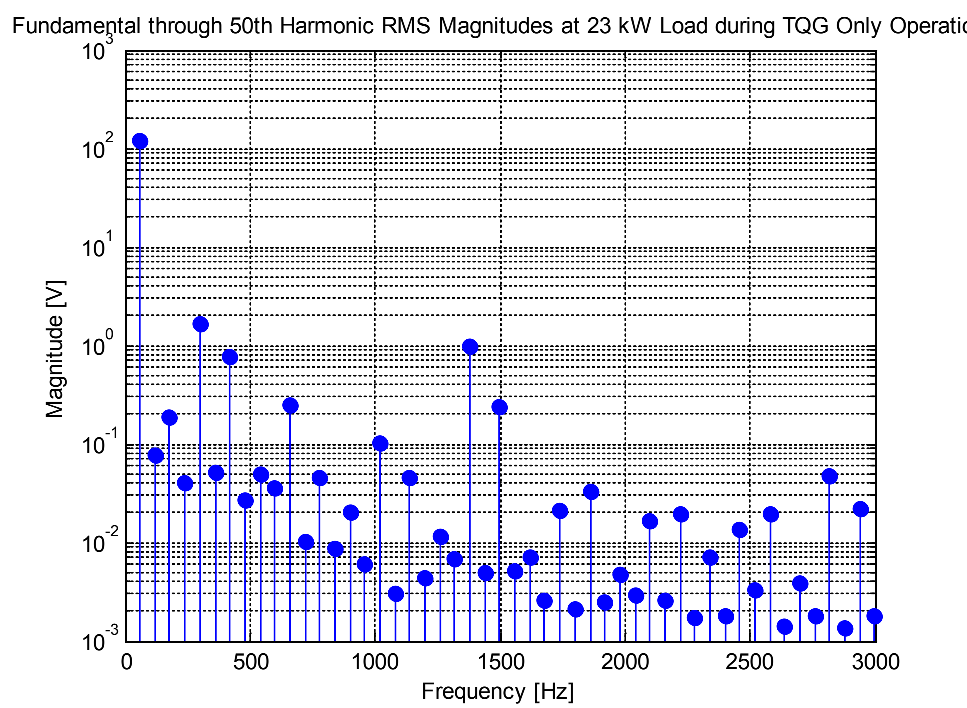
Figure 30. Magnitude frequency spectrum computed using 100 kS/s data over 21-second windows for (a) and (c) TQG Only at no load and 23 kW load, and (b) and (d) Battery Only at no load and 23 kW load.



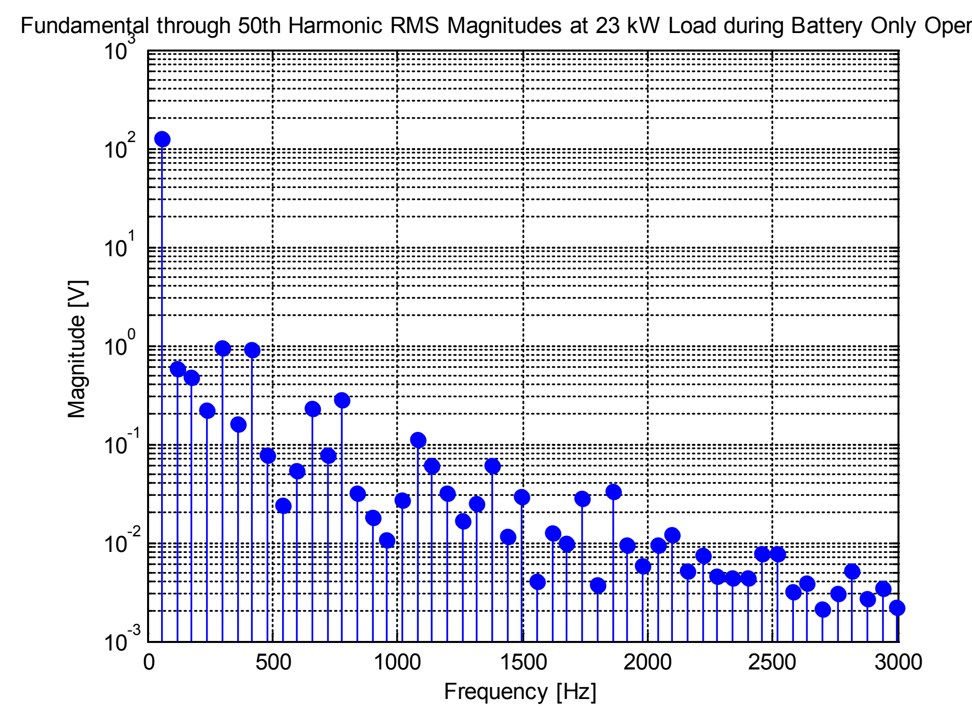
(a)



(b)



(c)



(d)

Figure 31. Magnitudes of first 50 harmonics computed using 100-kS/s data over 21-second windows for (a) and (c) TQG Only at no load and 23 kW load, and (b) and (d) Battery Only at no load and 23 kW load.

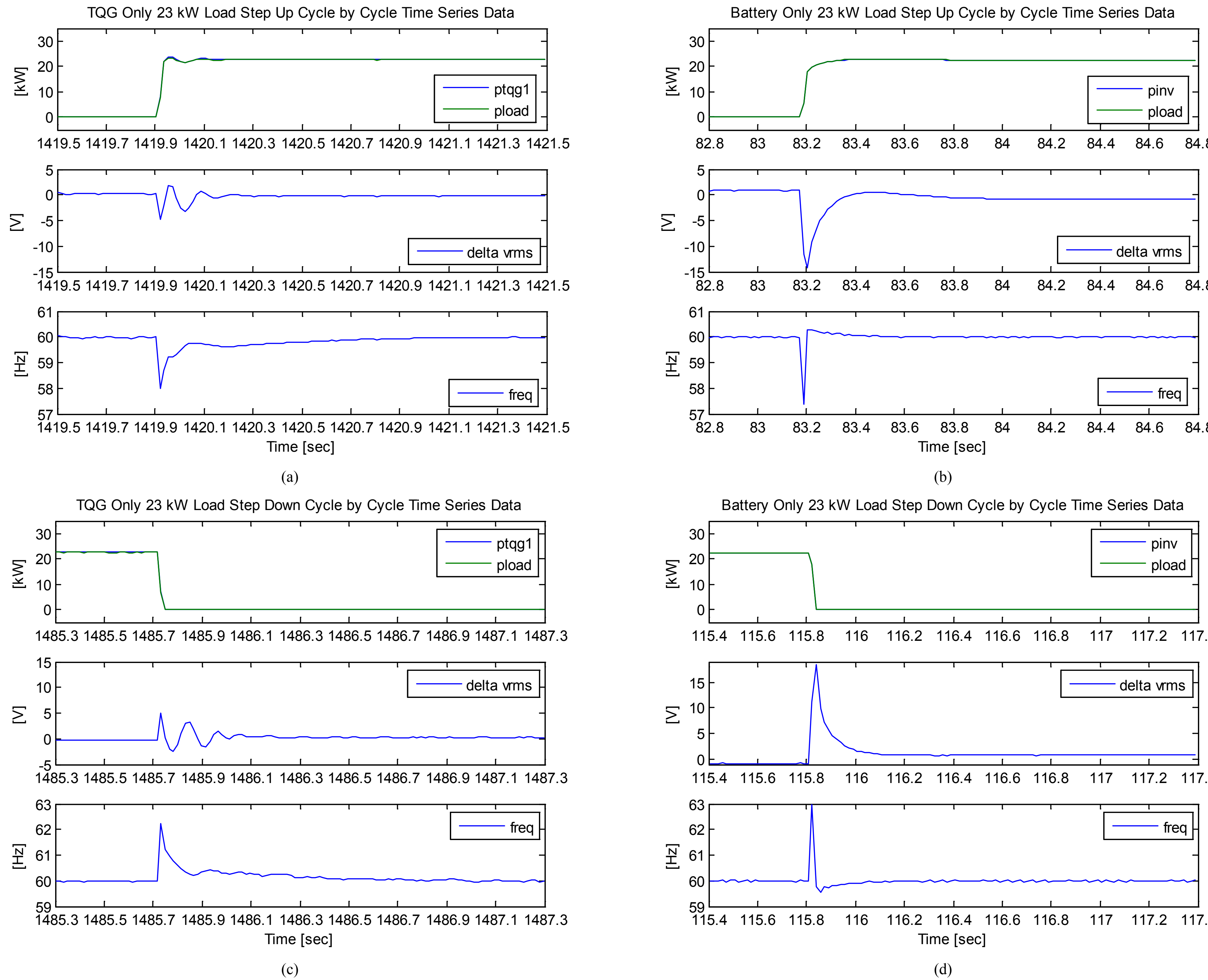


Figure 32. Two-second cycle-by-cycle power, voltage, and frequency data during the CUBE load response tests for (a) and (c) TQG Only load steps up and down, and (b) and (d) Battery Only load steps up and down. Top plot = power values (blue = inverter or tqg, green = load); middle plot = RMS voltage; bottom plot = frequency.

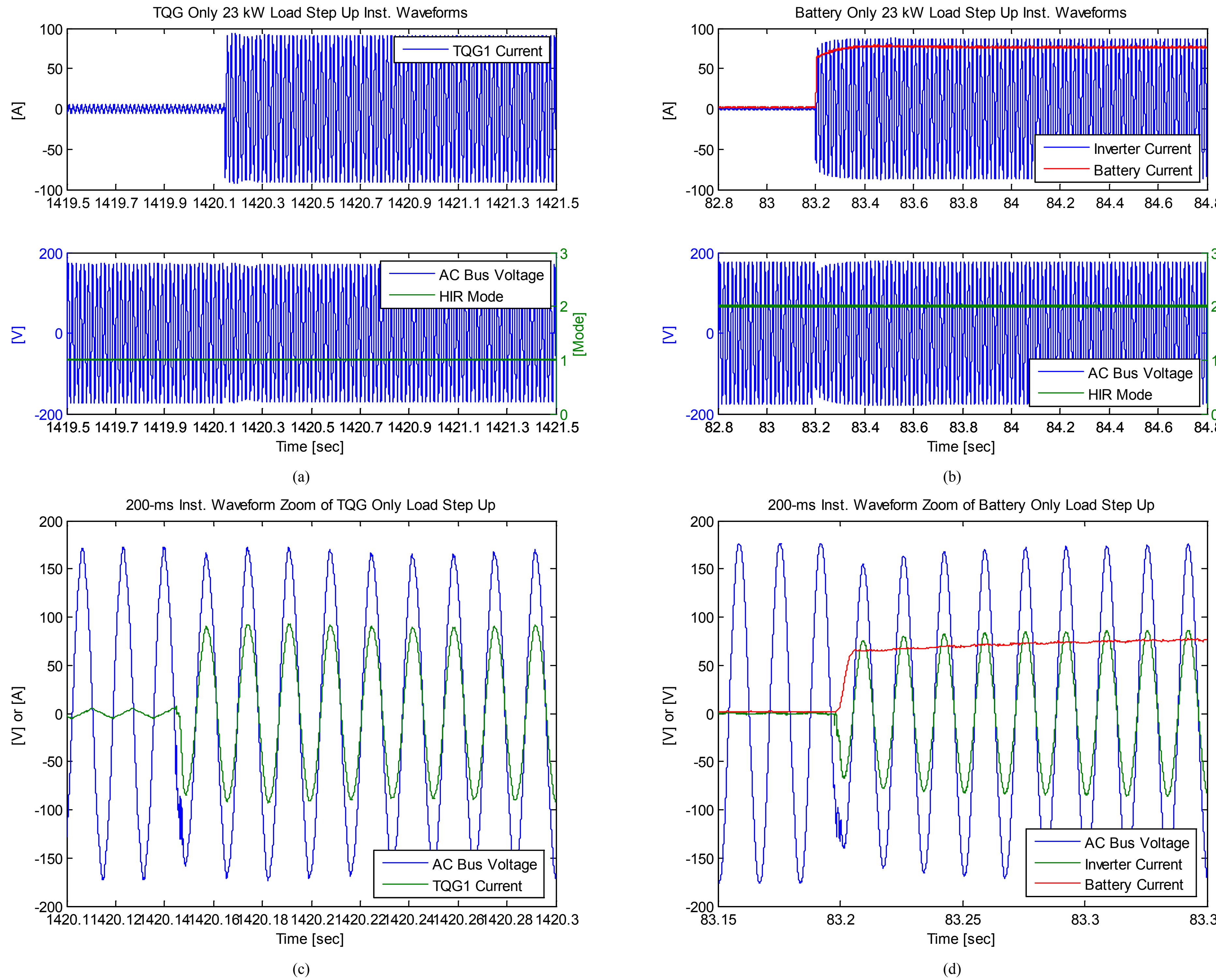


Figure 33. Two-second and 200-ms instantaneous waveform plots during the load steps up for (a) and (c) TQG Only, and (b) and (d) Battery Only. Blue = AC voltage; green = TQG or inverter current; Red = battery current.

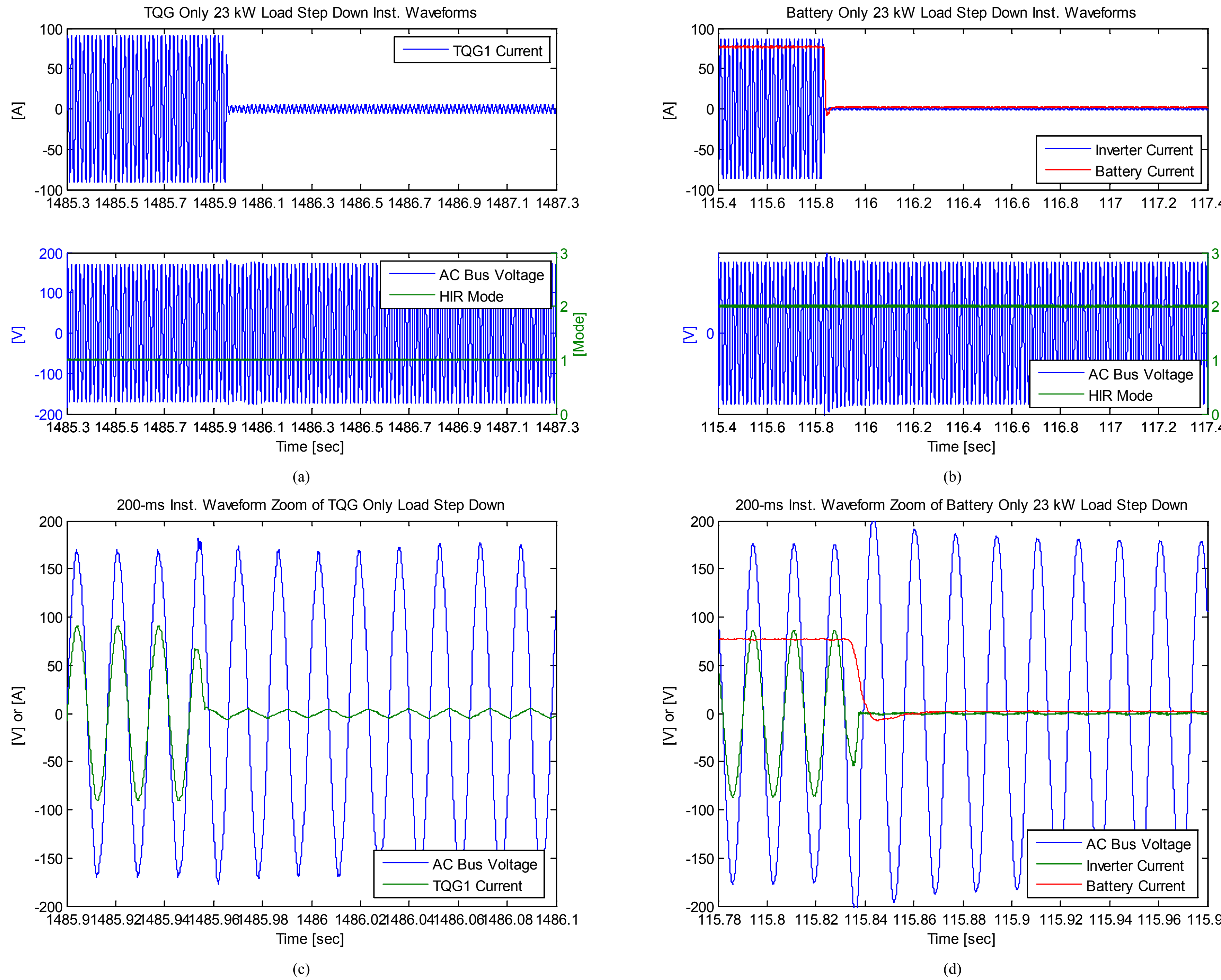


Figure 34. Two-second and 200-ms instantaneous waveform plots during the load steps down for (a) and (c) TQG Only, and (b) and (d) Battery Only. Blue = AC voltage; green = TQG or inverter current; red = battery current.

Conclusions and Future Work

Using measured load and solar profiles, the CUBE was able to achieve 31% fuel savings and 42% reduction in diesel run-time relative to the diesel-only case. These benefits were achieved with minimal battery throughput, with minimal cycling of diesel generators, and while maintaining power quality comparable to that provided by the diesel generators alone. In addition, the CUBE was able to maintain high power quality in all modes of operation, most notably during transitions from diesel generator as grid-forming unit to CUBE as grid-forming unit and vice versa, and during a black start onto a load. These are promising results that hint at the ability of a CUBE-based power system to substantially reduce diesel fuel consumption at a FOB. However, these results were based on one dispatch strategy, one load profile, and one solar profile. The CUBE installation at the ESIF with a PV simulator and programmable load banks allows generation of repeatable test conditions and thus facilitates the evaluation of alternate dispatch strategies, notably cycle charging versus peak shaving. In addition, the same equipment allows testing under alternate test conditions and thus facilitates the evaluation of any one dispatch strategy and of CUBE performance in general under varying load and/or solar profiles, notably intermittent (cloudy-day) solar profiles. Future efforts will pursue both of these opportunities to further validate the utility of the CUBE. In addition, future efforts will also evaluate the use of battery capacity versus diesel capacity to provide not only regulating but also contingency reserve.