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Microgrid Plant Control Design and Development

Final Scientific/Technical Report

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Unlimited Distribution

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Abstract

This report discusses the technical performance of the proposed microgrid at Potsdam, New York, and the enhanced microgrid controller platform. The test objectives were outlined by the DOE, and summary results and discussion are given for each objective. The findings show that the proposed Potsdam, NY microgrid would have a significant impact on the regional CO_2 emissions, the amount of imported energy from the utility, and the resiliency of the critical loads. Additionally, the enhanced microgrid control system developed for this project was tested to be compliant with IEEE 1547 standards, and able to generate revenues to help offset energy costs by way of participation in ancillary services.

Acknowledgement

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Acronyms and Nomenclatures

ANSI	American National Standards Institute
BESS	Battery Energy Storage System
BTU	British Thermal Unit
CAIDI	Customer Average Interruption Duration Index
CB	Circuit Breaker
CHIL	Control Hardware in the Loop
CO_2	Carbon Dioxide
DER-CAM	Distributed Energy Resources - Customer Adoption Model
DG	Distributed Generation
DOE	Department of Energy
DR	Demand Response
DUT	Device Under Test
EI	Eastern Interconnection
eMCS	enhanced Microgrid Control System
ES	Energy Storage
ESIF	Energy Systems Integration Facility (at NREL)
FOA	Funding Opportunity Announcement
FOM	Fixed Operations and Maintenance
GE	General Electric International, Inc. / GE Energy Consulting
GE GRC	GE Global Research Center
GHG	Greenhouse Gases
HR	Heat Rate
IEEE	Institute of Electrical and Electronics Engineers
ISO	Independent System Operator (for regional electric grid)
kW	kilowatt
kWh	kilowatt-hour
LBNL	Lawrence Berkeley National Laboratory
lb	Pounds (British Imperial Mass Unit)
L/HFRT	Low/High Frequency Ride-through
L/HVRT	Low/High Voltage Ride-through
MG	Microgrid
MHz	Mega Hertz

Acronyms and Nomenclatures - Continued

MIT-LL	Massachusetts Institute of Technology – Lincoln Laboratory
MMBtu	Millions of BTU
MW	Megawatts
MWh	Megawatt Hour
NETL	National Energy Technology Laboratory
NG	National Grid
NOX	Nitrogen Oxides
NREL	National Renewable Energy Laboratory
NYS DPS	New York State Department of Public Service
NYS DHSES	New York State Division of Homeland Security and Emergency Services
NYSERDA	New York State Energy and Research Development Authority
NYISO	New York Independent System Operator
PCC	Point of Common Coupling (same as POI)
PHIL	Power hardware in the loop (suggests that the DUT is power equipment)
PLL	Phase Lock Loop
POI	Point of Interconnection (same as PCC)
PRM	Potsdam Resilient Microgrid
pu	per unit
PV	Photovoltaic
ROCOF	Rate of Change of Frequency
RTAC	Real-time Automation Controller
RTDS	Real-time Digital Simulation
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SNL	Sandia National Laboratories
SO2	Sulfur Dioxide
SUNY	State University of New York
Therm	Unit of Thermal Load and Generation
VOM	Variable Operations and Maintenance
V&F	Voltage and Frequency

1 Executive Summary

This project, titled "Microgrid Plant Control Design and Development", had an overall objective of advancing the state-of-the-art in the control, protection, and dispatch of assets within a community microgrid during both grid tied, and grid independent modes. The associated Test Plan had an overall objective of assessing the proposed enhanced Microgrid Control System's (eMCS) performance as per the Department of Energy (DOE) guidelines specified by Funding Opportunity Announcement (FOA) DE-FOA-0000997.

The key technical objective of this microgrid controller development and testing project was the microgrid controller's participation in ancillary services to generate a meaningful revenue stream. Other objectives of the project were the evaluation of the protection performance of the microgrid controller through hardware testing and the assessment of the environmental and energy efficiency impact of the target microgrid community (Potsdam, NY). The key metrics being tracked by the DOE were energy efficiency, CO_2 reductions, and reducing outage time. The target community's primary concern for the microgrid controller was the assurance that critical services were made available to the community during times of natural disasters via an economic solution.

The project adds to the body of knowledge by:

- documenting the microgrid aggregation and bids process which resulted in ancillary service market revenues, and
- sharing the microgrid description, analytical performance, and model data with the larger community.

The results of the project show that the proposed microgrid controller could achieve the objectives of the test and analysis plan. The key finding of interest was that the microgrid controller could use the local distributed resources (Natural Gas based, energy storage, or renewable sources) to generate revenues. This study used New York ISO West pricing data for ancillary services. The study varied grid import energy pricing from 45 to 90 [$/MWh], and Natural Gas pricing from 4.4 to 7.7 [$/MMBTU]. The results showed that the microgrid's energy expenditures could be drastically reduced by implementing optimal dispatch algorithms and ancillary service participation. The annual energy savings are shown in the below figure and are dependent upon the pricing of electricity and natural gas, so each microgrid's actual performance may differ.

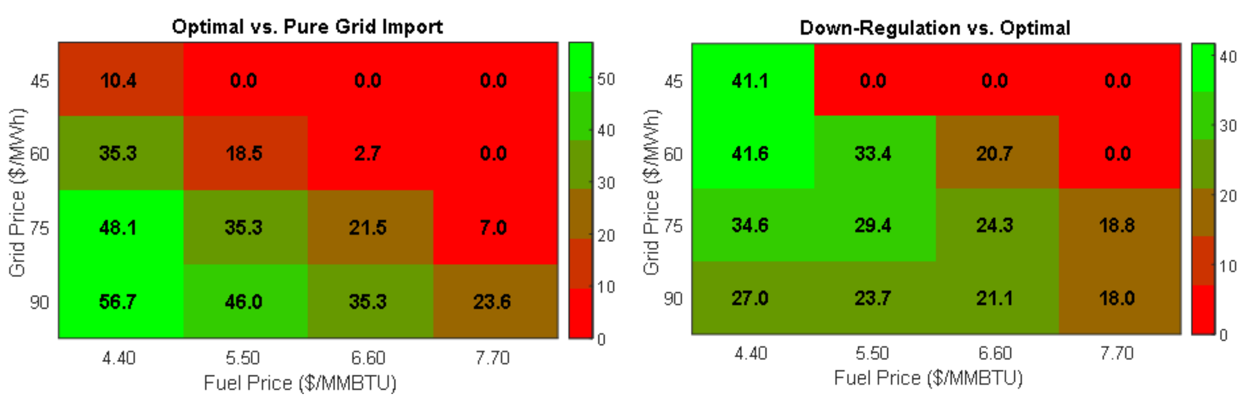

Figure 1 Percent annual electricity cost savings for two operating modes, for various grid purchase prices ($/MWh), and Natural Gas pricing ($/MMBTU), showing how optimal dispatch and regulation participation can reduce the baseline electricity costs.

2 Technical Objectives

As previously stated, the overall objective of this project was to develop an advanced microgrid controller that would allow U.S. communities to develop/design and deploy commercial-scale microgrids to achieve their specific objectives for reliable, sustainable, and economic energy resilience. To accomplish this objective, the eMCS was developed to satisfy the performance and functional criteria contained in DE-FOA-0000997. In addition, this FOA specified performance of a feasibility study (with participating community collaboration) for demonstration/deployment of the developed microgrid system/controller. The GE lead team conducted such a study for the proposed Potsdam microgrid. The Feasibility Study is included in Appendix 5.1 of this report.

2.1 DOE Specific Objectives

To achieve the DOE specific objectives, GE would develop and test an enhanced Microgrid Control System that provided high quality power delivery with resiliency to a local community in grid-independent mode, and valuable grid services to the local utility with increased efficiency and reliability when in grid-connected mode.

The eMCS developed by GE was evaluated on how it met the following tangible benefits:

Application Specific Benefits: (by analysis)

Reducing outage time of critical loads (target ≥ 98% reduction from baseline)

Reducing regional CO_2 emissions to serve the loads (target 20% and above)

Reducing utility supplied energy to the microgrid (target 20% and above)

Technical Features: (simulation and lab testing)

Compliant with the following technical requirements and standards from the FOA:

C1: disconnection from the grid under abnormal conditions, as per IEEE 1547

C2: resynchronization to the grid during restoration efforts, as per IEEE 1547

C3: power quality during microgrid operation, by dispatching real & reactive power

C4: protection in both grid-tied and -independent modes, via coordination

C5: dispatch of the assets for transition, economic, and environmental considerations

C6: meet resilience targets as defined by the local community

2.2 Summary of Accomplishments

The Feasibility Study and the Test Plan outlined a set of analysis activities which validated the benefit claims from Section 2.1.

The first step in the project was to establish a baseline for the various modes of operation for the example community of Potsdam, NY, against which the benefits of the microgrid with the proposed eMCS were assessed or measured.

The second step was to test the proposed eMCS's ability to analytically or measurably meet the claims relative to the baseline condition. The following tables give further description for the project objectives listed above in Section 2.1. Table 1 and Table 2 show the main performance requirements for the eMCS along with data requirements and the outcomes of the testing.

Table 1 DOE Microgrid and Microgrid Controller Objectives and Outcomes

Performance Objective	Metric	Data Requirements	Outcome
Reducing regional CO_2 emissions	% reduction in regional CO_2 emissions	regional generation mix, asset data from target community & renewable integration plan	-30% to -50% (relative to Eastern Interconnect averages)
Reducing utility supplied energy	% reduction in utility supplied energy	generation asset data from target community & renewable asset production data	-60% to -90% (with additional 4MW of Natural Gas generators)
Reduced outage time for critical loads	% reduction in SAIDI outage time	voltage and frequency power quality recordings, assessment of system reliability & fuel stores	"significant" reduction from historical norms

Table 2 Microgrid Controller Functional Requirements and Outcomes

Performance Objective	Metric	Data Requirements	Outcome
C1. Disconnection	disconnection times	measurements of point of interconnect (POI) response	IEEE 1547 compatible
C2. Reconnection	Frequency, Voltage and phase angle difference	measurements of voltage & frequency (both sides of POI)	ANSI C84.1, IEEE1547compatible
C3. Power Quality	Voltage and frequency values	measurements of voltage & frequency, and support generation	ANSI standard ranges
C4. Protection	fault response (both internal and external to microgrid)	measurements of disconnect timing relative to other protection devices	Not specifically addressed.
C5. Dispatch	sufficiency of resources, cost of operation, asset response	Meter measurements, cost of fuel, ancillary service prices, cost of electricity	Reduced costs through DG's and Ancillary Services revenues.
C6. Resilience	availability of essential loads	historical events, SAIDI estimates	"significant" reduction from historical norms

2.3 Discussion of Accomplishments

This section comments on the outcomes of the project relative to the success criteria.

2.3.1 Reducing regional CO_2 emissions

The analysis of the project discovered that the proposed Potsdam microgrid would operate its renewable energy and local DG assets to displace imported electricity by 60~94%, and reduce CO_2 emissions by 32~50% based upon the Eastern Interconnect performance [gr/kWhe].

Note: the Potsdam microgrid features both hydro and solar resources which fulfill about 10% of energy demand of the critical loads. These resources were automatically leveraged and resulted in a "Net Load" profile which was then served by either utility import or local natural gas generation.

But if the term "region" was reduced to just the NYISO power pool, then the proposed Potsdam microgrid would have a negative impact on CO_2 emissions (increase by 62~120%), due to the NYISO power pool having a much lower CO_2 emissions rate per unit of energy served than the Eastern Interconnect. See Section 5.1.3 of the Feasibility Study in the Appendix of this report for more discussion of this outcome.

2.3.2 Reducing utility supplied energy

The project discovered that the proposed Potsdam microgrid would likely operate its DG assets to displace imported electricity, and drastically reduce utility supplied energy (by 60~94%). But this analysis used two commercial rates for electricity and average rates for Natural Gas. The proposed microgrid is a collection of 5 to 6 separate commercial customers who all have different rate structures from the local utility National Grid. The actual reduction in energy imports to the microgrid will be a function of the aggregated billing model. See Section 5.1.3 of the Feasibility Study in the Appendix of this report for more discussion of this outcome.

2.3.3 Reduced outage time for critical loads

The project found that calculating the outage time for the critical loads within the distribution network of the microgrid was a difficult process which was not supported by typical electric power metrics or tools. The below response was extracted from the Feasibility Study and performance assessment portion of the project.

> The distribution system engineering experts on the study team did consider the problem of quantifying the distribution system reliability impact of microgrids. Their consensus was that none of the currently available software tools and models have the required functionality that would account for the distribution system and feeder reliability impact of microgrids (i.e., impact on SAIFI, CAIDI, etc.) during normal (blue sky) days. It is expected that microgrids will help reduce the duration of electric power interruptions to critical loads and the associated interruption costs during normal (blue sky) days.

For more details, see Section 5.1.4 of the Feasibility Study in the Appendix of this report.

2.3.4 C1. Disconnection

The project found that the microgrid controller was capable of being IEEE1547 compliant. This performance is a function of the easily programmed disconnection response of the relay controller portion of the eMCS.
The project also found that the communications protocols and equipment could easily add significant delays due to poor pass through bandwidths, so care at the system level is vital to meeting this performance. See Section 3.6 of this report for more discussion.

2.3.5 C2. Reconnection

The project found that the microgrid controller was capable of being ANSI C84.1k, and IEEE1547 compliant. This performance function is easily programmed into the relay controller portion of the eMCS.
As with the Disconnection function, the communications protocols and equipment could easily add significant delays due to poor pass through bandwidths, so care at the system level is vital to meeting this performance. See Section 3.6 of this report for more discussion.

2.3.6 C3. Power Quality

The project found that the eMCS could address both real and reactive power quality during operation in island mode. The testing was simplified to monitor only the RMS magnitude of voltage and the frequency. The eMCS focused on the dispatch of assets to address real or reactive power issues while the actual regulation of the voltage and frequency was left to the primary microgrid generator with V&F control mechanisms.

2.3.7 C4. Protection

This project did not specifically test fault protection performance. Fault abatement and coordination is a well understood science and the eMCS has built in protection relay capabilities with ability to coordinate with upper and lower protection devices.

2.3.8 C5. Dispatch

This project found that the eMCS could successfully reduce the net annual electricity bill for the critical load by way of optimal dispatch algorithms and by allocating a portion of the generation assets for Up or Down Regulation services.

2.3.9 C6. Resilience

Testing during the project also revealed that the reliability impact of the microgrid could not be properly quantified without further detailed analysis. It was self-evident that the resiliency performance of the Potsdam Microgrid vastly improves the up-time of microgrid critical loads by enabling power availability during prolonged outages of the larger grid, such as those that could be experienced from weather related emergencies.

Figure 2 The eMCS platform in a standard computer rack with touch screen interface; team members Michael Englert and Chaitanya Baone looking on.

3 Methodology and Conclusions

This section of the report describes how the team addressed the original hypothesis, and highlights any issues or departures from the original plan. This section also presents facts and figures to support the efforts conclusions.

3.1 Baseline Characterization for Target Microgrid Community

The baseline conditions for the target community of Potsdam, NY were established and included the following:

- Description of critical loads, as defined by the stakeholders in Potsdam, NY.
- Description of the local generation assets, both today's installed base and proposal for future units which will enable more critical loads to be served.
- Description of the electric load profile, which was collected for the critical loads.
- Description of the NYISO -A and -B generation mixes to get baseline regional emissions.

The results of this analysis are included in the Feasibility Study found in the Appendix to this report.

3.2 Renewable integration

The target community of Potsdam, NY has integrated 1.1 MW of hydro power and 2 MW of solar power, which represent about 35% of the critical load of the proposed microgrid participants. These assets are being included into the proposed microgrid as key power producers. Additional renewable energy is being considered and these can also be included into the microgrid network. See the Feasibility Study in the Appendix for more discussion.

3.3 Testing Methods for the eMCS

Several testing methods were used and are highlighted in Table 3 and the following sub-sections.

Table 3 Performance Assessment Summary and listing of test cases

Objective	Method	Comments / Cases	Test Location	Test Plan/Cases
Reducing CO_2 emissions	Simulation and analysis of baseline vs. proposed microgrid operation	historical NY ISO production data and local asset generation data as inputs	GE Schenectady, NY	Analytical Report
Reducing utility supplied energy	analysis of baseline vs. proposed microgrid,	historical NY ISO production data and local asset generation data as inputs	GE Schenectady, NY	Analytical Report
Reduced outage time	analysis of baseline vs. proposed microgrid and SAIDI comparison	baseline outage data from Potsdam, NY, and National Grid SAIDI estimates	GE Schenectady, NY	Analytical Report
C1. Disconnection	both CHIL & power hardware testing	cover a wide range of potential events with CHIL, and reduced set with power hardware	GE Niskayuna, NY NREL Golden, CO	Test Plan Document Case A, B, C
C2. Reconnection	both CHIL & power hardware testing	cover a wide range of potential events with CHIL, and reduced set with power hardware	GE Niskayuna, NY NREL Golden, CO	Test Plan Document Case D, E
C3. Power Quality	Simulations, CHIL and power hardware testing	Limited set of tests at power, with complementary testing using CHIL	GE Niskayuna, NY NREL Golden, CO	Test Plan Document Case F, G
C4. Protection	CHIL and power hardware testing	cover a wide range of potential events with CHIL, and reduced set with power hardware	GE Niskayuna, NY NREL Golden, CO	Test Plan Document Case I, J
C5. Dispatch	Software Simulations	historical pricing data and typical operational scenarios	GE, Niskayuna, NY	Test Plan Document Case K, L, M
C6. Resilience	Software Analysis	Software analysis and simulations will be used to estimate SAIDI	GE, Schenectady, NY	Analytical Report

3.3.1 Software Simulation

The software simulation method used only computers and raw data to evaluate the approximate performance of the eMCS (or of the proposed microgrid in Potsdam, NY). This testing method was reserved for evaluating the performance objectives with the highest level of systemic impact, regional CO_2 emissions and energy consumption from the utility, versus local production.

Preliminary analysis used the DER-CAM tool, while system-wide impact studies used GE MAPS™ which has a full model of the Eastern Interconnect and NYISO and provided system-wide efficiency, average CO_2 emissions, and marginal CO_2 emissions that would be replaced by the microgrid emissions.

Pre-testing of eMCS functionalities, such as Asset Dispatch, was conducted in a MATLAB simulation environment.

3.3.2 Control Hardware in the Loop

The project used the actual control hardware with artificially derived inputs and emulated output responses to evaluate the protection functions of the eMCS. The eMCS controller was connected to RTDS equipment while the rest of the utility and microgrid assets were represented in a software model within the RTDS system. Electromechanical and electromagnetic models were used as appropriate to test the functionalities of the Protection module and transient responses.

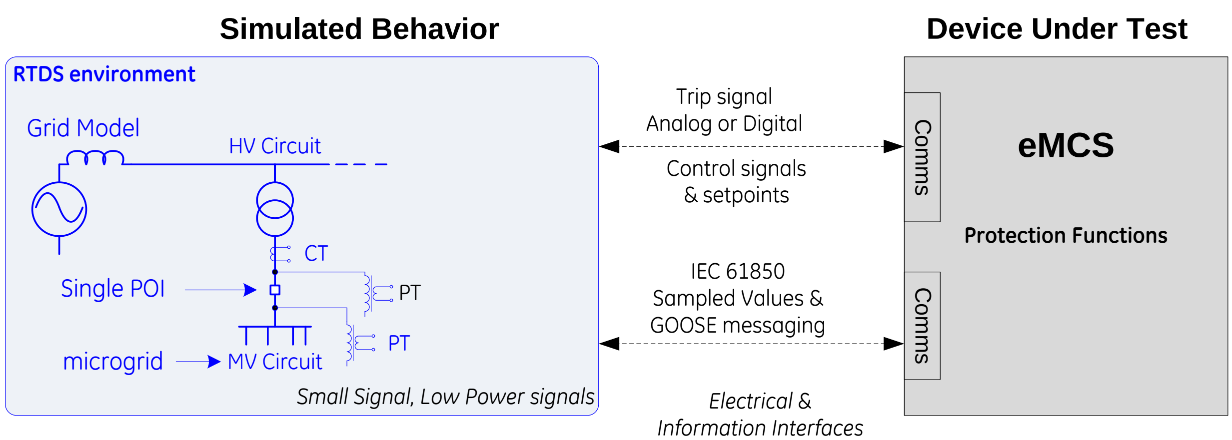

Figure 3 Example of a Control Hardware in the Loop configuration as would be used in the Grid Technologies Lab in Niskayuna, NY.

3.3.3 Power Hardware Testing

The actual control hardware and small set of power hardware was used to evaluate a subset of the protection and power quality aspects of the eMCS. The power hardware testing was used to: 1) validate CHIL method by selecting a sub-set of the scenarios and running them through real hardware and then comparing CHIL results with the test results; 2) incorporate high fidelity reactions and interactions from real hardware into the eMCS validation, such as hardware time response, communication delays, and control decision latencies.

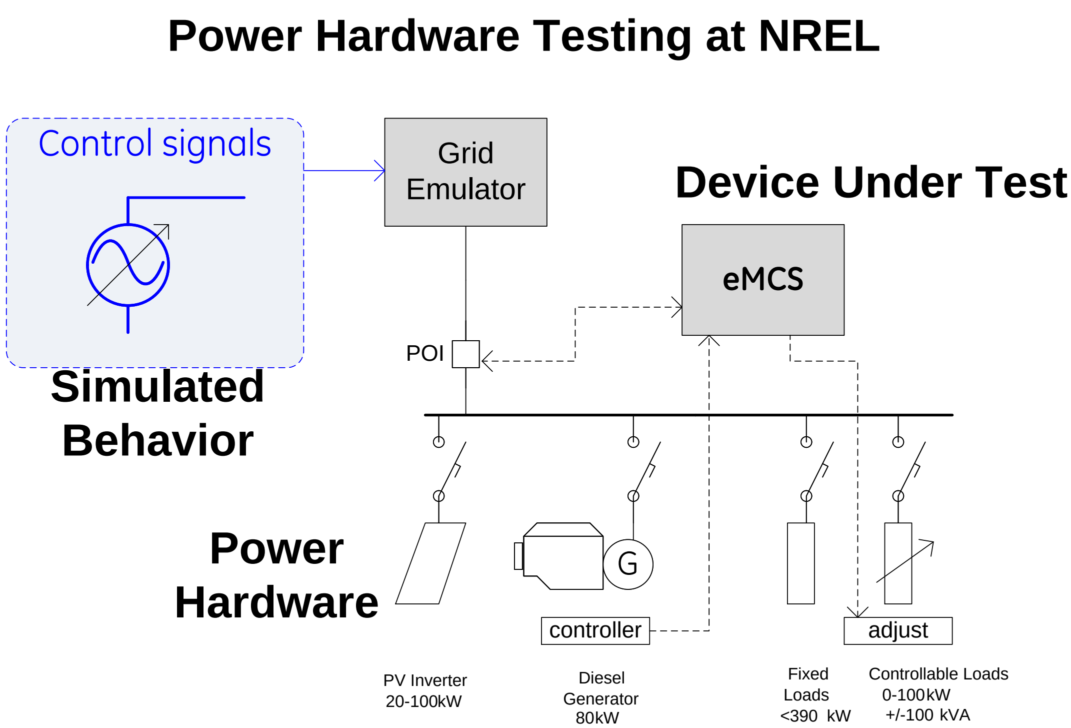

Figure 4 Example of a power hardware test configuration as would be used in the ESIF Lab in Golden, CO.

At NREL, power hardware testing was completed on a single 480 Vac bus connected to an independently controlled, three-phase grid emulator. The power hardware devices included, a 480V POI breaker, one diesel generator, one controllable/programmable load bank with real and reactive power capability, and one fixed load bank. The programmable load banks will be used to simulate real and reactive loads and generate dynamic load profiles. Details of the test setup are provided in Appendix 5.2.4.

3.4 Deviations from Plan

The original Test Plan addressed all the DOE objectives. However, due to timing and expenditure limitations, the C4. Protection functions were considered as low priority and so were not tested. Moreover, this objective did not specifically address unique features of the eMCS, and the industry has sufficient rules and best-practices to address fault current protection with blocking and trip transfer actions from higher and lower level protection equipment.

Voltage flicker and unbalanced load test conditions will not be part of the project's testing regime. These power quality issues will be addressed by the assets in the microgrid, such as transformers, generators, and protective relays. The supervisory eMCS only has limited influence on the steady state voltage and frequency values by way of managing the overall loading of the primary regulating asset. The eMCS will dispatch other generators, loads or assets based upon the relative loading of the primary regulating asset.

3.5 Storage of Results

The GE lead team organized a secure web based storage site (GE Box) for all data pertaining to the below tests in accordance with Section 1-D of the FOA. This site is controlled by the PI, and access can be provided on request.

3.6 Results of Testing

This section gives a summary of the results from the Analysis and Testing portions of the project. More detailed results are shown in Section 5 (Appendix) of this document.

3.6.1 Reducing outage time of critical loads

No specific test data was collected for this objective. Rather analytical tools were used to assess the reduction in outage time for the community defined critical loads in the target microgrid. See the Appendix for more analytical results and discussion.

3.6.2 Reducing regional CO_2 emissions

No specific test data was collected for this objective. Rather analytical tools were used to assess the reduction in regional CO_2 emissions by the operation of local generation and renewable sources in the target microgrid. See the Appendix for more analytical results and discussion.

3.6.3 Reducing utility supplied energy to the microgrid

No specific test data was collected for this objective. Rather analytical tools were used to assess the reduction in utility supplied energy by the operation of local generation and renewable sources in the target microgrid. See the Appendix for more analytical results and discussion.

3.6.4 C1: Disconnection from the Grid Under Abnormal Conditions

In view of the uncertainty around the final technical requirements for voltage and frequency ride-through (L/HVRT and L/HFRT), the GE project team used IEEE 1547a-2014 as the latest set of standards that apply to the POI relay. For the planned testing, the clearing times of the POI relay for abnormal frequency and voltage conditions were consistent with the following tables (Table 4 and Table 6), which were extracted from the above referenced standard. Trip times and trip limits for voltage and frequency tests in this section were based on IEEE 1547a-2014, and are consistent with in the parameters specified by the FOA.

Abnormal grid voltages and frequencies were imposed at the POI (switch S1) with a Grid Simulator and the response of the eMCS was recorded. The expected behavior was the disconnection of the microgrid by operation of switch S1 (POI) in accordance with the requirements depicted in Table 4. The eMCS had industry standard access to voltage readings on both sides of the POI for synchronization monitoring.

Table 4 Default response to abnormal voltages, extracted from IEEE-1547a2014-Table1

Default settings[a]		
Voltage range (% of base voltage[b])	Clearing time (s)	Clearing time: adjustable up to and including (s)
$V < 45$	0.16	0.16
$45 \leq V < 60$	1	11
$60 \leq V < 88$	2	21
$110 < V < 120$	1	13
$V \geq 120$	0.16	0.16

[a] Under mutual agreement between the EPS and DR operators, other static or dynamic voltage and clearing time trip settings shall be permitted
[b] Base voltages are the nominal system voltages stated in ANSI C84.1-2011, Table 1.

Reviewers of this test noted that once the POI is opened, the microgrid potential drops to zero and service to the microgrid's loads is terminated. This condition is acceptable to the stakeholders of the target microgrid for several reasons listed here:

1) the target community microgrid in Potsdam, NY was focused on supporting the critical loads during times of prolonged natural disasters and a short interruption in power was acceptable. The restoration of power to the critical loads on the microgrid after a POI opening event was not part of this test plan, which focused on IEEE 1547 protective response.

2) the community microgrid was also focused on the economical operation of the generator assets to reduce overall cost of providing energy. This strategy often required that the dispatchable generating assets be running at power levels less than the sum of the critical loads, or not at all. Under these conditions, a protective action by the POI would rationally result in a loss of service to the loads. Note: GE has demonstrated "fast load shed" capability whereby the protective relay disconnects excess loads in a least priority order to ensure service to as many loads as possible once the POI is opened.

3) the cause of the abnormal voltage condition is not specified in the test, and the conditions of the microgrid network and elements is not known, so the test was run with the assumption that the POI should open to separate the grid from the microgrid, independent of the condition of the assets or the operation of any local generation units.

Other tests showing "bumpless" transfer to island operation are covered in a separate section (3.6.4.3 Planned Disconnect)

3.6.4.1 Case A: Off-nominal Voltages

Off-nominal voltages were tested against IEEE Standard 1547a-2014 – see Table 4. The eMCS was configured to follow the default settings. Multiple tests were conducted where voltage was stepped out from a nominal value of 1.0 per unit, to voltages outside of grid code. Raw data files have been stored on GE Box for later reference and the file names can be found in Table 5, which also summarizes voltage step magnitude and measured eMCS clearing time – T_2. Post processed results of all the tests can be found in Appendix 5.3.1.

Table 5 Summary of Case A test results

Raw file name	Post processed	Voltage [% of base]	Clearing time T_2 [s]
CaseA1_SmallOV_DL850_20161207_1125.mat	See: 5.3.1.1	115	0.8
CaseA2_LargeOV_DL850_20161207_1127.mat	See: 5.3.1.2	125	0.04
CaseA3_SmallUV_DL850_20161207_1114.mat	See: 5.3.1.3	85	1.8
CaseA4_LargeUV_DL850_20161207_1118.mat	See: 5.3.1.4	75	1.8
CaseA5_LargeUV_DL850_20161212_1323.mat	See: 5.3.1.5	55	0.8
CaseA6_LargeUV_DL850_20161212_1330.mat	See: 5.3.1.6	45	-0.361
CaseA7_LargeUV_DL850_20161212_1332.mat	See: 5.3.1.7	0	0.04

Example of a post processed voltage event is shown on Figure 5. The first subplot shows RMS voltages of grid simulator (U_{GS}) and microgrid (U_{MG}) during voltage event. Second subplot shows active (P_{POI}) and reactive (Q_{POI}) power flowing at POI during the event. Last subplot represents status of digital signals captured during the event which are used for time delay measurements. The digital channels are configured following:

- CH0: GS_{Trig} – pulse signal that is generated when grid simulator reference voltage or frequency is changing

- CH1: CB_U < 422V – output of digital comparator showing that voltage measured by Circuit Breaker and send to DUT (eMCS) crossed the threshold defined in IEEE 1547a-2014. In this example the threshold is 88% of nominal phase to phase voltage 480V
- CH2: DUT_{Trip} – is a signal received from eMCS that, if active, triggers CB to close
- CH3: Signal indicating that CB close command is active

CB is responsible for measurements of RMS voltages at both ends of switch S1 (POI). eMCS analyzes the measurement and initiates tripping action. Post processed data shows the following time delay measurements using annotations:

- T_1: Delay between grid event to the instance of time when voltage measured by CB and send to DUT crosses adequate limit defined in IEEE 1547a-2014.
- T_2: Delay introduced by DUT between reception of measurement sample exceeding the limit and trip command received by RTAC
- T_3: Delay introduced by RTAC and CB between receiving a trip command from DUT and grid blackout – instance of time when voltage at microgrid collapses

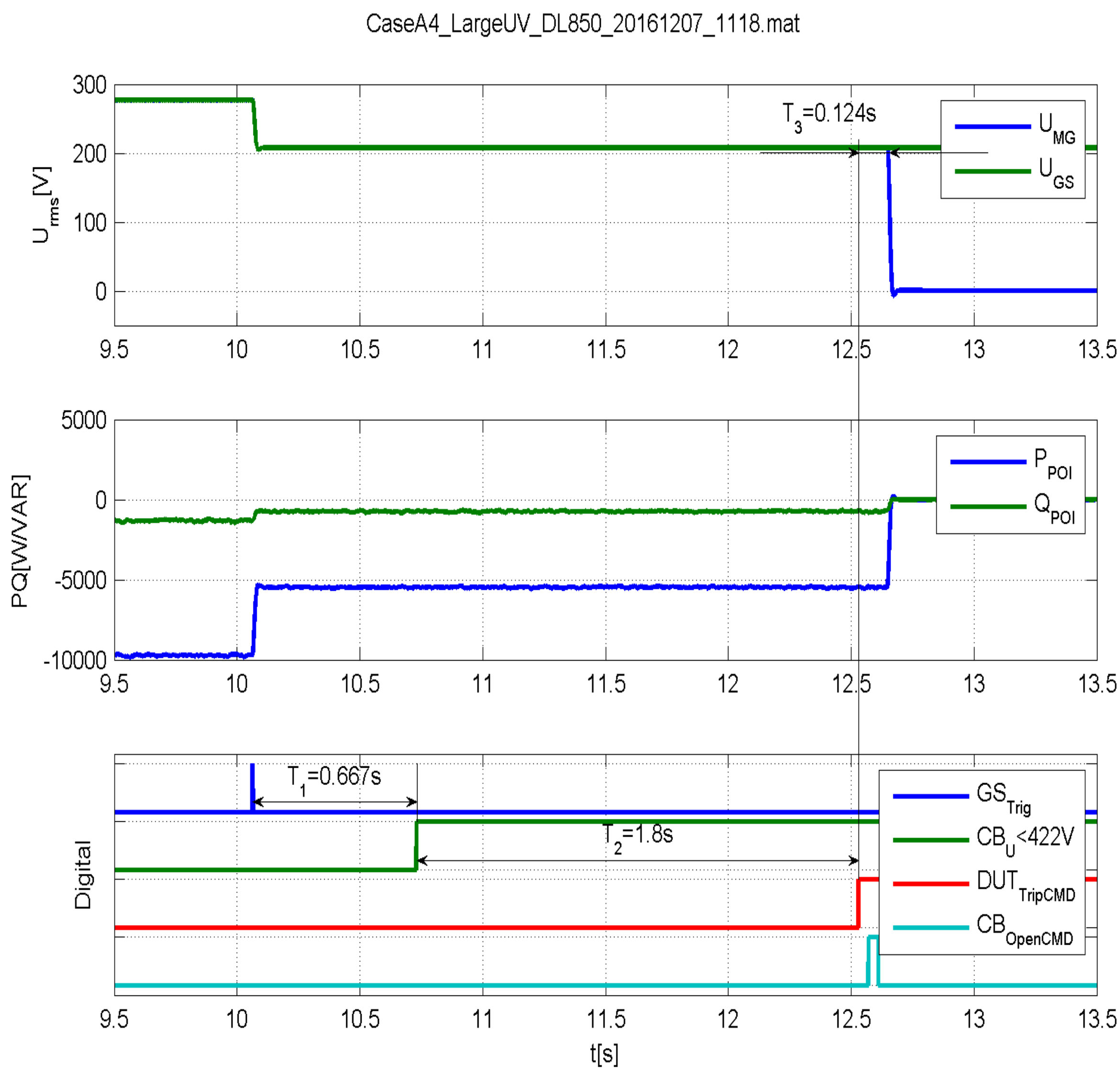

Figure 5 Example of under-voltage event and clearing time measurements

3.6.4.2 Case B: Off-nominal Frequency

Off nominal frequency events are tested against IEEE Standard 1547a-2014 – see Table 6.

Table 6 - Default response to abnormal frequencies
(Extracted from IEEE 1547a-2014 - Table 2)

	Default settings		Ranges of adjustability	
Function	Frequency (Hz)	Clearing time (s)	Frequency (Hz)	Clearing time (s) adjustable up to and including
UF1	< 57	0.16	56 – 60	10
UF2	< 59.5	2	56 – 60	300
OF1	> 60.5	2	60 – 64	300
OF2	> 62	0.16	60 – 64	10

The FOA specified that the microgrid controller comply with the IEEE-1547a-2014 standard, even though it may not be appropriate for community Microgrid use. The quote from the FOA is given here for reference.

> A fundamental requirement is that the microgrid controller complies with the IEEE 1547™ series of interconnection standards, including any revisions or applicable emerging standards that may become available during the course of the proposed effort.

The GE lead team used a modern relay controller which is programmable and can accommodate any present interconnect timing diagrams or potential future or custom interface requirements. This assessment of the test was seen as a low risk endeavor with well-known performance expectations.

Multiple tests were conducted where frequency was stepped from nominal (1.0 per unit) to frequencies outside of grid code. Raw data files have been stored on GE Box for reference and their names can be found in Table 7, which also summarizes frequency step magnitude and measured eMCS clearing time – T_2. Post processed results of all the tests can be found in Appendix 5.3.1.

Table 7 Summary of Case B tests results for off-nominal frequencies.

Raw file name	Post processed	Frequency [Hz]	Clearing time T_2 [s]
CaseB1_SmallUF_DL850_20161212_1354.mat	See: 5.3.1.8	58	1.8
CaseB2_SmallOF_DL850_20161212_1359.mat	See: 5.3.1.9	61.5	1.8
CaseB3_LargeUF_DL850_20161212_1357.mat	See: 5.3.1.10	56.5	0.037
CaseB4_LargeOF_DL850_20161212_1400.mat	See: 5.3.1.11	62.5	0.037

Example of post processed frequency event is shown in Figure 6. First subplot shows frequency of grid simulator (f_{GS}) and microgrid (f_{MG}) during frequency event. Frequencies have been extracted from raw data using PLL post processing. Second subplot shows active (P_{POI}) and reactive (Q_{POI}) power flowing at POI during the event that is helpful for identification of instance of time when switch S1 (POI) was opened. Last subplot represents status of digital signals captured during the event which are used for time delay measurements. The digital channels are configured the same way as for off-voltage events – see previous subchapter.

The Circuit Breaker (CB) is responsible for measurements of frequencies at both ends of switch S1 (POI). The eMCS analyzes the measurement and initiates tripping action. Post processed data shows following time delay measurements using annotations and time measurements (T_1 to T_3), whose definitions are the same as in previous subchapter.
The test also shows that the microgrid settles to 57Hz after the POI opens due to the generator controllers internal droop characteristic when matching the load wihin the now islanded microgrid.

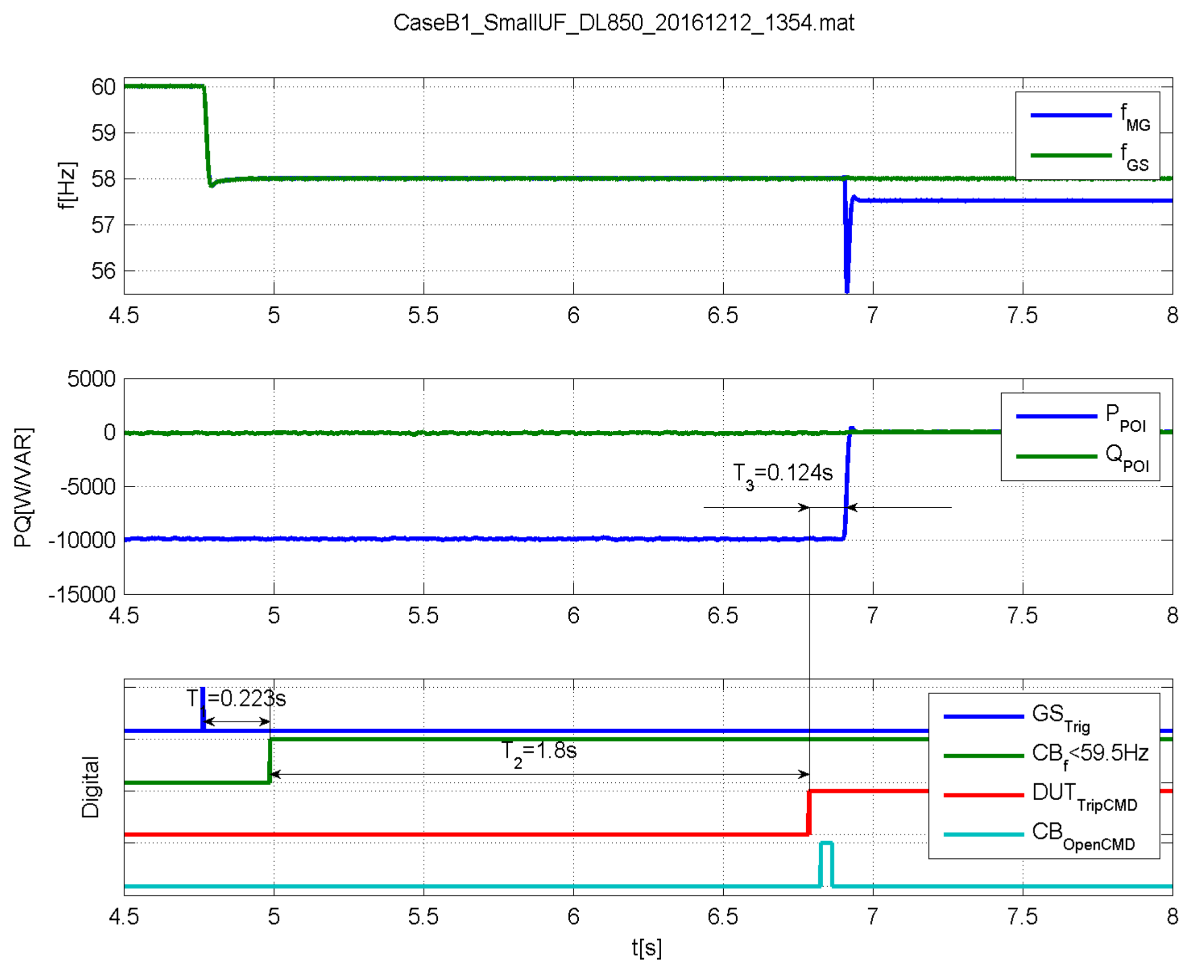

Figure 6 Example of under-frequency event and clearing time measurements

3.6.4.3 Case C: Planned disconnect

Planned disconnect was a procedure where the eMCS was responsible for preparing the microgrid to disconnect from the grid so that during the transition, power at the POI is minimum. The test procedure assumed various cases including situations, where prior to the planned disconnect request, the microgrid was importing power (Case C2 & C4) or exporting power (Case C1 & C3). Two of the cases were allowed enough available sheddable loads to balance the generation and loads in the microgrid (Case C1 & C2). But, the other two cases didn't provide a sufficient amount of sheddable loads (Case C3) or these loads were following the command too slowly (Case C4). Raw data has been stored in GE Box with the file names as indicated in Table 8, and post processed data can be found in Appendix 5.3.1.

Table 8 Summary of planned disconnection tests.

Raw file name	Post processed
CaseC1_PDExp_DL850_20161212_1455.mat	See: 5.3.1.12
CaseC2_PDImp_DL850_20161212_1440.mat	See: 5.3.1.13
CaseC3_PDExp_DL850_20161212_1500.mat	See: 5.3.1.14
CaseC4_PDImp_DL850_20161212_1448.mat	See: 5.3.1.15

The test procedure for each test case assumed:

1. Generation of planned disconnect command from RTAC
2. Observation of load shedding scheme implemented by eMCS
3. Measurement of delay after which switch S1 (POI) is opened
4. Measurement of frequency and voltage deviation during the transition
5. Disabling the planned disconnect event to observe a procedure of reconnection
6. Observing reconnection procedure and synchronization delays

Example of post processed event is shown in Figure 7. The first subplot shows RMS voltages of grid simulator (U_{GS}) and microgrid (U_{MG}). Second subplot shows frequency of grid simulator (f_{GS}) and microgrid (f_{MG}) during the test. Frequencies have been extracted from raw data using PLL post processing. Third subplot shows angle difference between microgrid and grid simulator voltage ($\Delta\theta$). Fourth subplot shows active (P_{POI}) and reactive (Q_{POI}) power flowing at POI. Last subplot represents status of digital signals captured during the event which are used for time delay measurements. The digital channels are configured as follows:

- CH0: HMI_{PD} – planned disconnect command requested from HMI
- CH1: DUT_{Trip} – is a signal received from eMCS that, if active, triggers CB to close
- CH2: $CB_{OpenCMD}$ - Signal indicating that CB close command is active

Plots are annotated with following time measurments:

- T_4: Delay between PD command from HMI to trip command from DUT
- T_5: Reconnection delay between instance when trig condition no longer exists (in this case planned disconnect) and releasing of the trip command by DUT (allowing resynchronization procedure to start)
- T_6: Time needed to resynchronize and reconnect the microgrid to grid

One will note that the microgrid voltage and frequency have variation on them once the POI is opened at t=42 seconds, until it recloses at t=73 seconds. This variation was due to a poorly tuned generator controller attached to the primary diesel generator in the ESIF power hardware test lab, and was not an artifact of the eMCS supervisory level microgrid controller.

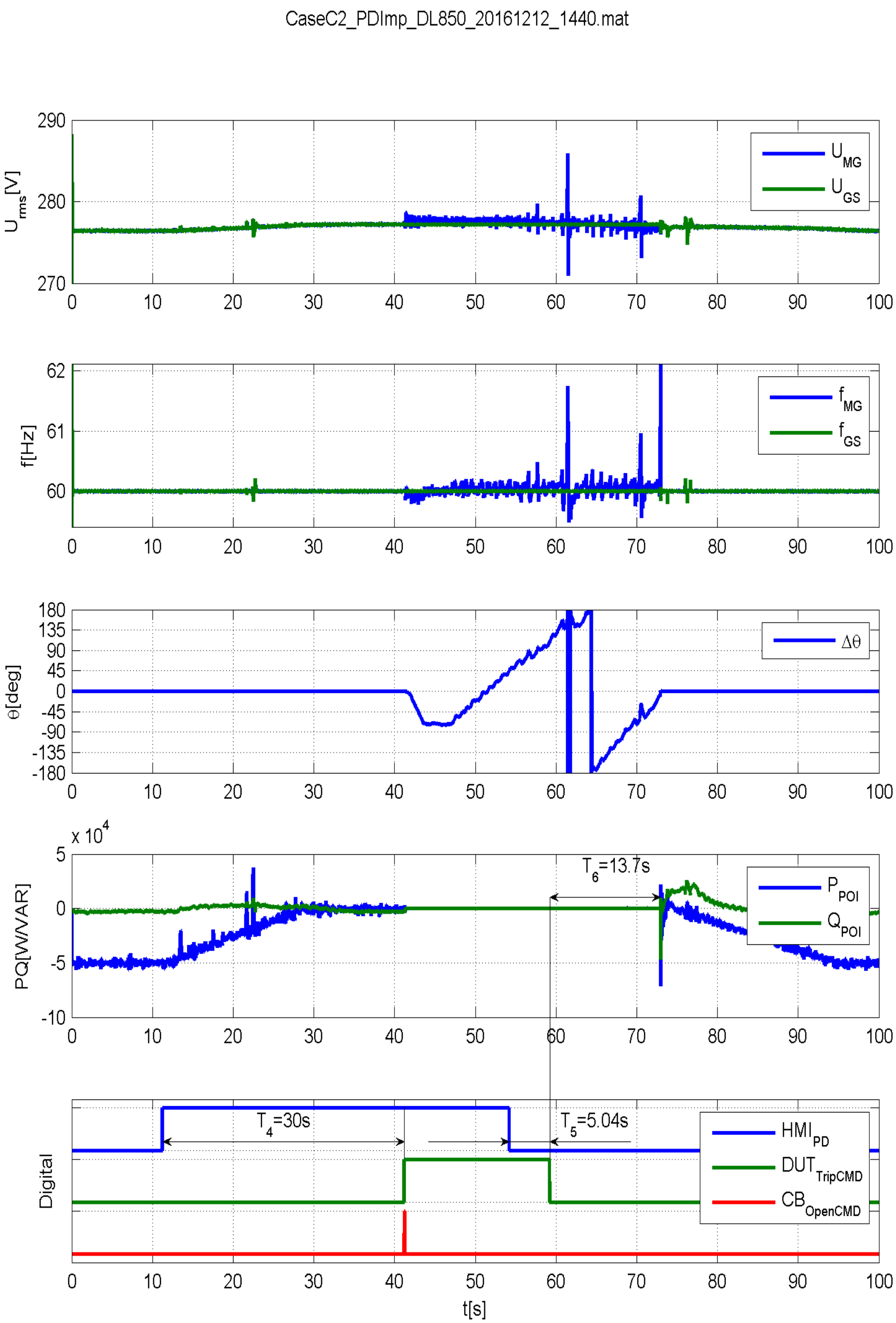

Figure 7 Example of planned disconnect event post processing

3.6.4.4 Discussion

The following figures (Figure 8 & Figure 9) summarize all off-nominal voltage and frequency tests conducted by GE (CHIL) and NREL (PHIL), and compares the results with IEEE 1547a-2014 limits using T_2 clearing time. All measurement points are situated with reasonable margin (160-200ms) from limit. In reality, this amount of time is enough to realize $T_1 + T_3$ so that entire clearing time would fit within limits.

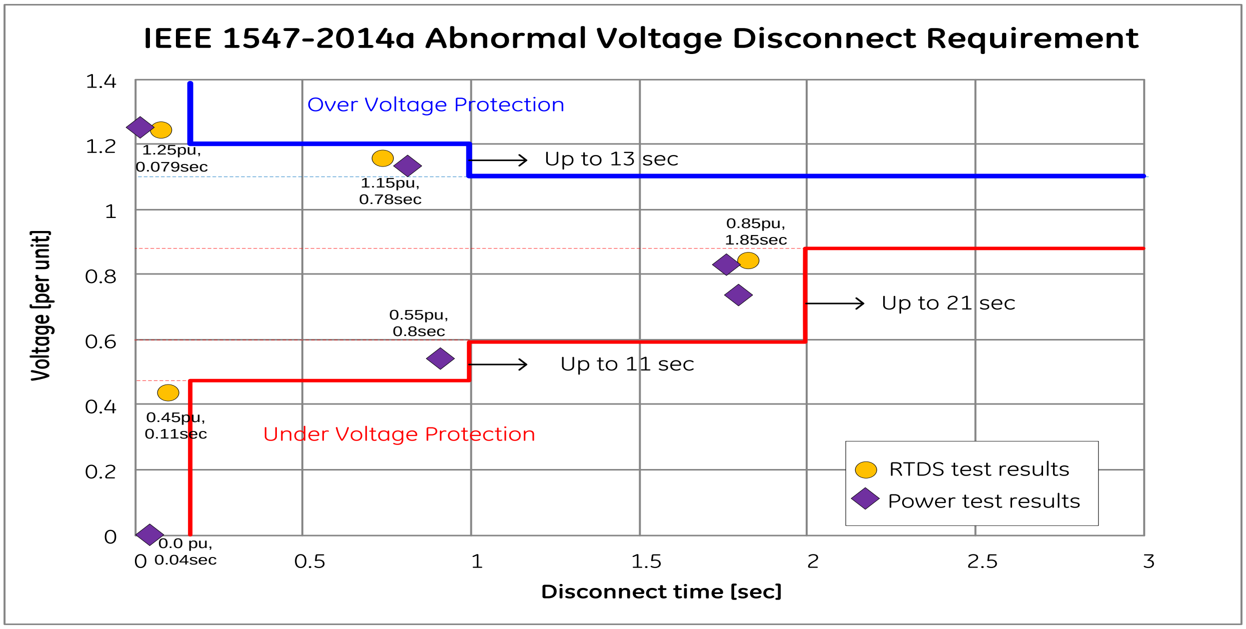

Figure 8 Summary of Off-nominal Voltage disconnect performance, where all recorded conditions fell within the protection envelope.

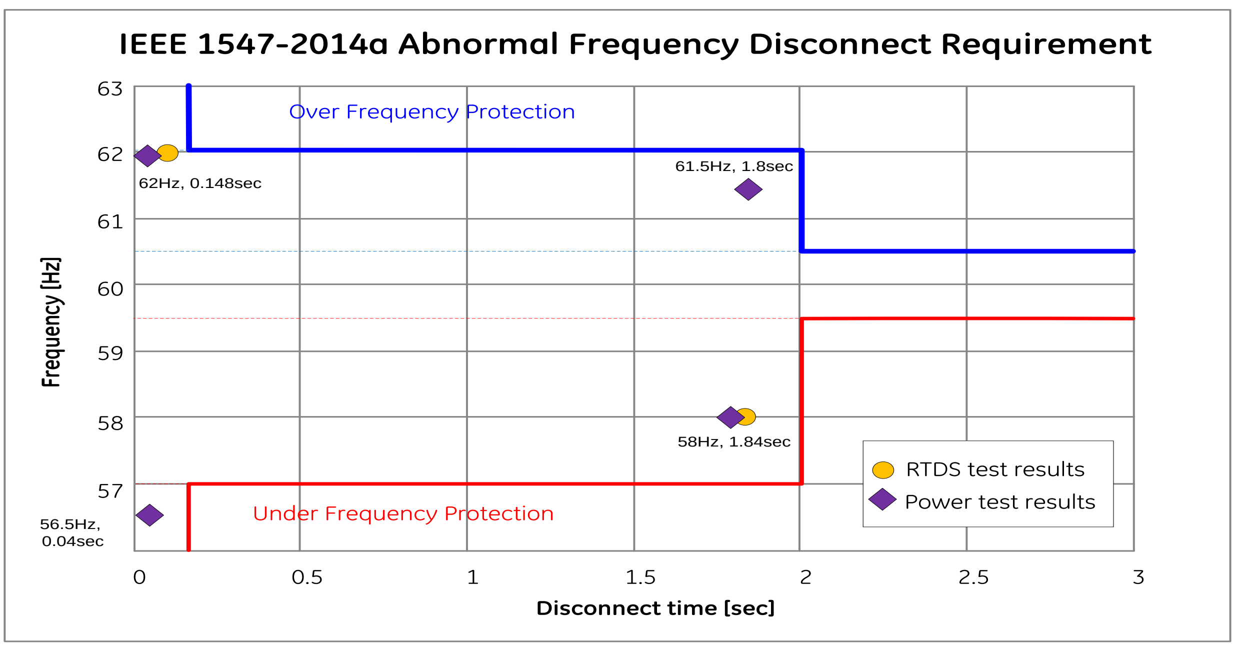

Figure 9 Summary of Off-nominal Frequency disconnect performance, where all recorded conditions fell within the protection envelope.

The clearing time of the off-nominal voltage or frequency event is normally the time between the instant when value is going off nominal to the time when switch is being opened, which means sum of T_1, T_2 and T_3. In NREL test environment, the sum exceeds the limit defined in the standard for most of the cases. However, it is due to the testbed setup delays which should have been optimized in real world environment. These delays include:

- T_1: Delay caused by CB voltage measurement filter delay – it is recommended that eMCS internal voltage measurements should be used instead
- T_3: CB opening delay
- T_1 and T_3: Communication delay due to RTAC-CB Modbus communication – fast and deterministic communication is recommended, e.g. IEC61850 GOOSE.

Case A6 was the only exception where a measured clearing time became negative because the circuit breaker opened even before the voltage measured by CB crossed 45% limit. The reason for that is a slow filter implemented to measure voltages by CB and the fact that tripping action was initiated earlier due to crossing 60% threshold more than 1 second before. This test case was neglected while drawing above figures.

Planned disconnect test cases C1 and C2 have shown proper operation of eMCS load shedding mechanism allowing for smooth seamless transition between grid connected and island mode and back. Disconnection delay (T_4) was identified to be fixed to 30s (as shown on Figure 7). Seamless transition can be achieved if there is enough sheddable load and these loads can follow eMCS command within this time frame. Case C4 shows the situation where there is not enough sheddable load to match actual generation with fixed load which cannot be controlled by eMCS. The result of that was circuit breaker disconnection with significant power at POI causing generator's load step resulting in frequency deviation up to 58Hz. NREL recommends that in that case eMCS should attempt to control generator's active and reactive power to match loads prior to the event as during the test execution generator was not controlled by eMCS. Case C3 shows the situation where there was enough sheddable load to balance generation and fixed load. However, sheddable loads where ramping too slowly to achieve balance before time T_4 has passed. The result of that was circuit breaker disconnection with significant power at POI causing generator's load step resulting in frequency deviation up to 64.5Hz.

3.6.5 C2: Resynchronization to the grid during restoration efforts

This test was accomplished by establishing a stable islanded mode, then modulating the grid frequencies and voltages and observing the eMCS's ability to resynchronize with the grid. The difference in voltage, frequency and phase angles were measured.

3.6.5.1 Case D: Delayed Reconnection

Delayed reconnection (reclosing delay time) is implemented to delay reclosing after the cause of disconnection is absent. Two tests were done showing reconnection from island which was blacked out (Case D1) and from island operation with genset (Case D2). Raw data have been stored in GE Box with the file names as indicated in Table 9, and post processed data can be found in Appendix 5.3.2.

Table 9 Summary of delayed reconnection tests.

Raw file name	Post processed
CaseD1_DelayReconBlack_DL850_20161207_1226.mat	See: 5.3.2.1
CaseD2_DelayReconIsland_DL850_20161207_1551.mat	See: 5.3.2.2

The procedure for each test case assumed:

1. Generation of grid condition outside of grid code that requires disconnection (Frequency step from 59.55Hz to 59.45Hz
2. Waiting for disconnection
3. Bringing grid voltage back within grid code limits (Frequency step from 59.45Hz to 59.55Hz)
4. Measurement of delay reconnection time
5. Resynchronization to grid

Note: the test methodology for implementing changes in frequency and the methods to record response time are not well standarized for these tests. The tests at the ESIF facilty used a “step change” in frequency method, rather than a ROCOF slope based method.

Example of post processed event is shown in Figure 10. The first subplot shows RMS voltages of grid simulator (U_{GS}) and microgrid (U_{MG}). Second subplot shows frequency of grid simulator (f_{GS}) and microgrid (f_{MG}) during the test. Frequencies have been extracted from raw data using PLL post processing. Third subplot shows angle difference between microgrid and grid simulator voltage (Δθ). Fourth subplot shows active (P_{POI}) and reactive (Q_{POI}) power flowing at POI. Last subplot represents status of digital signals captured during the event which are used for time delay measurements.

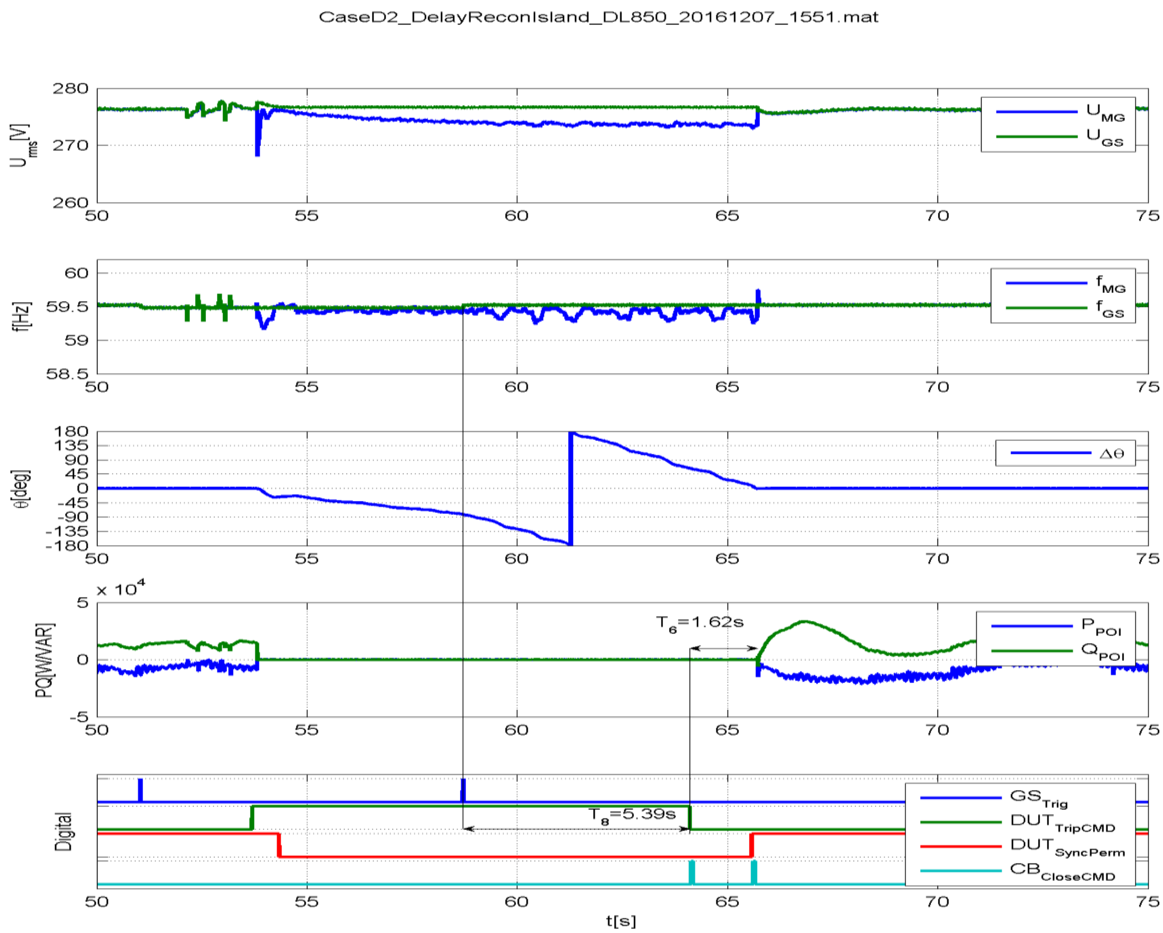

Figure 10 Case D2: Delayed Reconnection – Island seamless transition

The digital channels are configured as follows:

- CH0: GS_{Trig} – pulse signal that is generated when grid simulator reference voltage or frequency is changing
- CH1: DUT_{Trip} – is a signal received from eMCS that if active (high) triggers CB to close
- CH2: $DUT_{SyncPerm}$ – sync permissive signal generated from DUT based on grid and microgrid voltage measurements comparison and synchronisation criterias
- CH3: $CB_{CloseCMD}$ - Signal indicating that CB close command is active

Plots are annotated with following time measurments:

- T_6: Time needed to resynchronize and reconnect the microgrid to grid
- T_7: Reconnection delay between instance when trip condition from DUT no longer exists (frequency violation measured by DUT) and releasing of the trip command (allowing resynchronization)
- T_8: Reconnection delay between instance when trip condition no longer exists (frequency violation measured at grid side) and releasing of the trip command (allowing resynchronization) - includes both reconnection delay and CB measurements delay

3.6.5.2 Case E: Synchrocheck

Synchrocheck is testing if values of voltages at grid and microgrid side are aligned enough to allow reconnection. Synchrocheck verifies multiple physical values and permissive signal is generated only if all of them are met. Raw data have been stored in GE Box with the file name as indicated in Table 10 and post processed data can be found in Appendix 5.3.2.

Table 10 Summary of synchrocheck tests.

Raw file name	Post processed
CaseE1_SyncheckPhase1_DL850_20161207_1427.mat	See: 5.3.2.3
CaseE2_SyncheckPhase2_DL850_20161207_1440.mat	See: 5.3.2.4
CaseE3_SyncheckOverFreq_DL850_20161207_1447.mat	See: 5.3.2.5
CaseE4_SyncheckUnderFreq_DL850_20161207_1453.mat	See: 5.3.2.6
CaseE5_SyncheckUnderVolt_DL850_20161212_1550.mat	See: 5.3.2.7
CaseE6_SyncheckOverVolt_DL850_20161212_1634.mat	See: 5.3.2.8

Multiple tests were executed to verify each synchrocheck function:

- Phase margin (Case E1 & E2) – was tested by setting voltage and frequency of both sides of switch S1 (POI) very close to each other thus satisfying frequency and voltage criterion at all times. The slight frequency difference across the PIO allowing the phase margin to slip through angle 0˚ for the test.
- Frequency margin (Case E3 & E4) – was tested by setting voltage setpoints of both sides of switch S1 (POI) equal. Initially frequency is slipping slightly (within synchrocheck margin) so when angle crosses 0˚ $DUT_{SyncPerm}$ is being generated. After stepping the frequency so that difference is out of frequency margin it can be observed that $DUT_{SyncPerm}$ is not generated anymore.
- Voltage margin (Case E5 & E6) – was tested by setting frequencies so that these are slipping. When angle crosses 0˚ a $DUT_{SyncPerm}$ becomes active indicating that all synchrocheck conditions are met. Initially voltages are offset but still within voltage margin so that $DUT_{SyncPerm}$ signal is active. After stepping one of the voltages, so it is out of margin, the $DUT_{SyncPerm}$ signal is no longer active.

Example of post processed event is shown on Figure 11. The first subplot shows RMS voltages of grid simulator (U_{GS}) and microgrid (U_{MG}). Second subplot shows frequency of grid simulator (f_{GS}) and microgrid (f_{MG}) during the test. Frequencies have been extracted from raw data using PLL post processing. Third subplot shows angle difference between microgrid and grid simulator voltage (Δθ). Last subplot represents status of digital signals captured during the event which are used for time delay measurements.

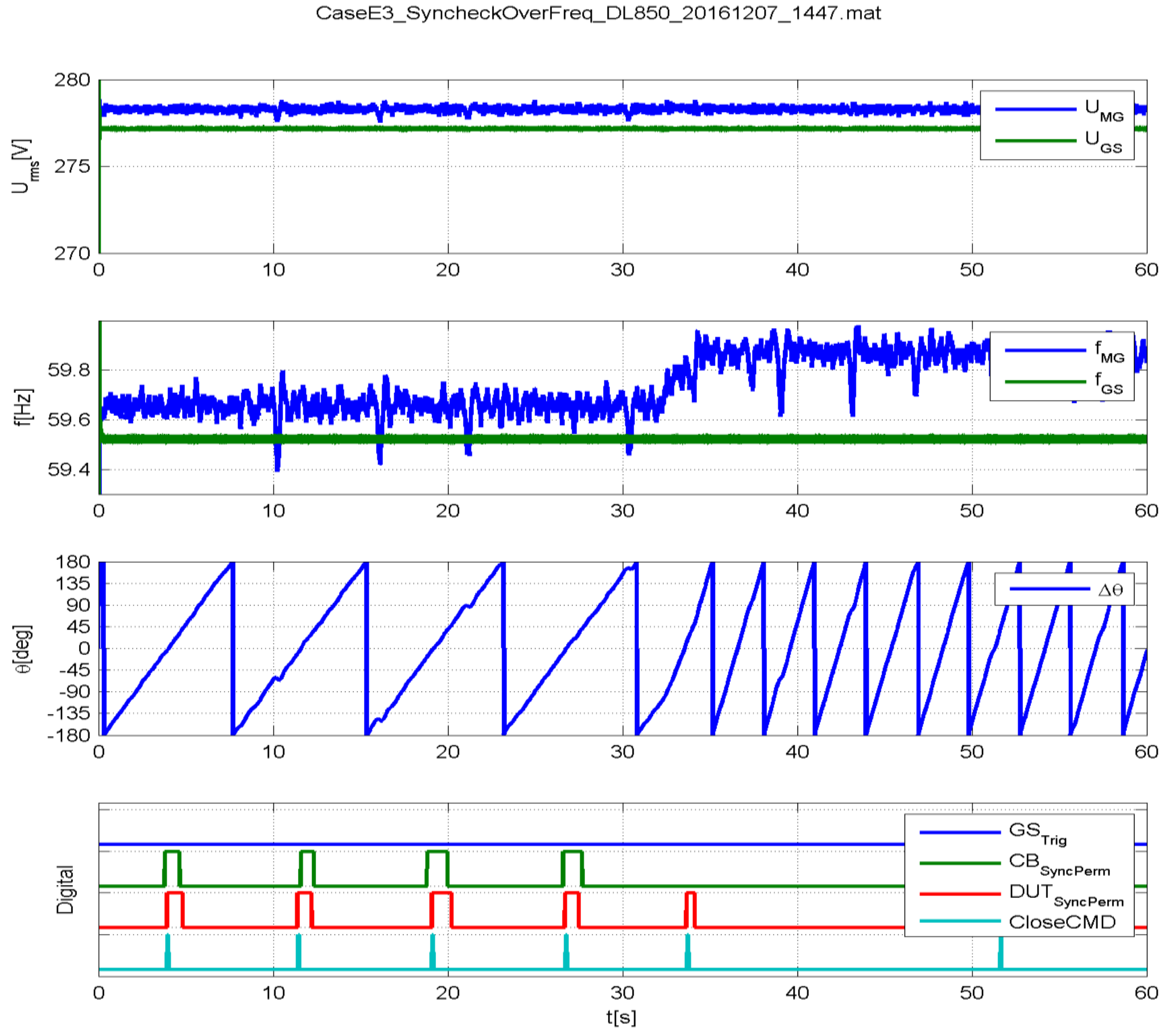

Figure 11 Example synchrocheck post processed test result

The digital channels are configured according to the following signal criteria:

- CH0: GS_{Trig} – pulse signal that is generated when grid simulator reference voltage or frequency is changing
- CH1: $CB_{SyncPerm}$ – sync permissive signal generated from CB used as a redundancy to $DUT_{SyncPerm}$
- CH2: $DUT_{SyncPerm}$ – sync permissive signal generated from DUT based on grid and microgrid voltage measurements comparison and synchronization criteria
- CH3: $CB_{CloseCMD}$ - Signal indicating that CB close command is active

3.6.5.3 Discussion

Delayed reconnection was successfully verified and shows that eMCS delays reconnection after the reason of disconnection disappeared by time T7 which equals 5s. After this time trip command is released, resynchronization to grid can begin if sync permissive is active – all synchrocheck tests were successful.
In the case of island powered by genset (Case D2) a reconnection to grid happens after synchrocheck criteria are met. Reconnection time measured for that case was T6 = 1.62s.
For the blackout island scenario (Case D1), a reconnection to grid happens immediately after trip command is inactive because CB synchrocheck is configured to allow automatic deadbar detection. One issue with DUT sync permissive signal is that it was never active when microgrid was in blackout thus sync permissive would never allow reconnection to the grid. NREL suggested modification of DUT logic to accommodate such an instance.
Synchrocheck tests (Cases E1-E6) validated that synchrocheck correctly compares all quantities of voltages measured at both sides of S1 (POI) switch: voltage, frequency and phase. It allows margin on each of these values.

3.6.6 C3: power quality during microgrid operation

Power Quality issues like flicker, THD and harmonics are best mitigated at the individual load or asset level, and hence will not be included in the testing scope of eMCS. Utility assets like transformers have an inherent capability to filter these high frequency power quality problems. Instead, this test plan will assess the eMCS's ability to assist the main generator which is regulating V&F while in island mode. The test will measure steady state voltage and frequency variation while solar and loads are modulated over time. See Appendix 5.3.3 for more details.

3.6.6.1 Case F: Real Power Dispatch

Real power dispatch tests were conducted with switch S1 (POI) opened, and generator supplying power to load bank. Fixed resistive load (FL) was slowly varied, eventually exceeding generator's optimal operating area (20kW – 80kW). When this happened DUT is expected to shed some variable load (VL), request additional generation or activate some additional loads. At NREL, an active power command received from DUT ($P_{DISPATCH}$) for that purpose was added to load bank thus causing visible load steps which should eventually keep generator's load within its predefined limits. Two tests were performed showing events where a $P_{DSIPATCH}$ was positive (Case F1) and negative (Case F2). Positive value means that either additional generation or load shed is requested by DUT while negative value means additional dump load shall be activated or load sink is commanded, e.g.: to BESS. Raw data have been stored in GE Box with the file name as indicated in Table 11, and post processed data can be found in Appendix 5.3.3.

Table 11 Summary of real power dispatch tests.

Raw file name	Post processed
CaseF1_RealDispatchPos_DL850_20161213_1357.mat	See: 5.3.3.1
CaseF2_RealDispatchNeg_DL850_20161213_1408.mat	See: 5.3.3.2

Example of post processed event is shown in Figure 12. The first subplot shows RMS voltage of microgrid (U_{MG}) while at second subplot, frequency of microgrid (f_{MG}) during the test is shown. Third plot shows fixed load active power (P_{FL}) and generator's active power (P_{GEN}) together with its nominal operation limit. Next subplot shows reactive powers as well. The diference between fixed load and generator power is measured dispatched power ($P_{DISPATCH}$ and $Q_{DISPATCH}$) which follows commands of DUT.

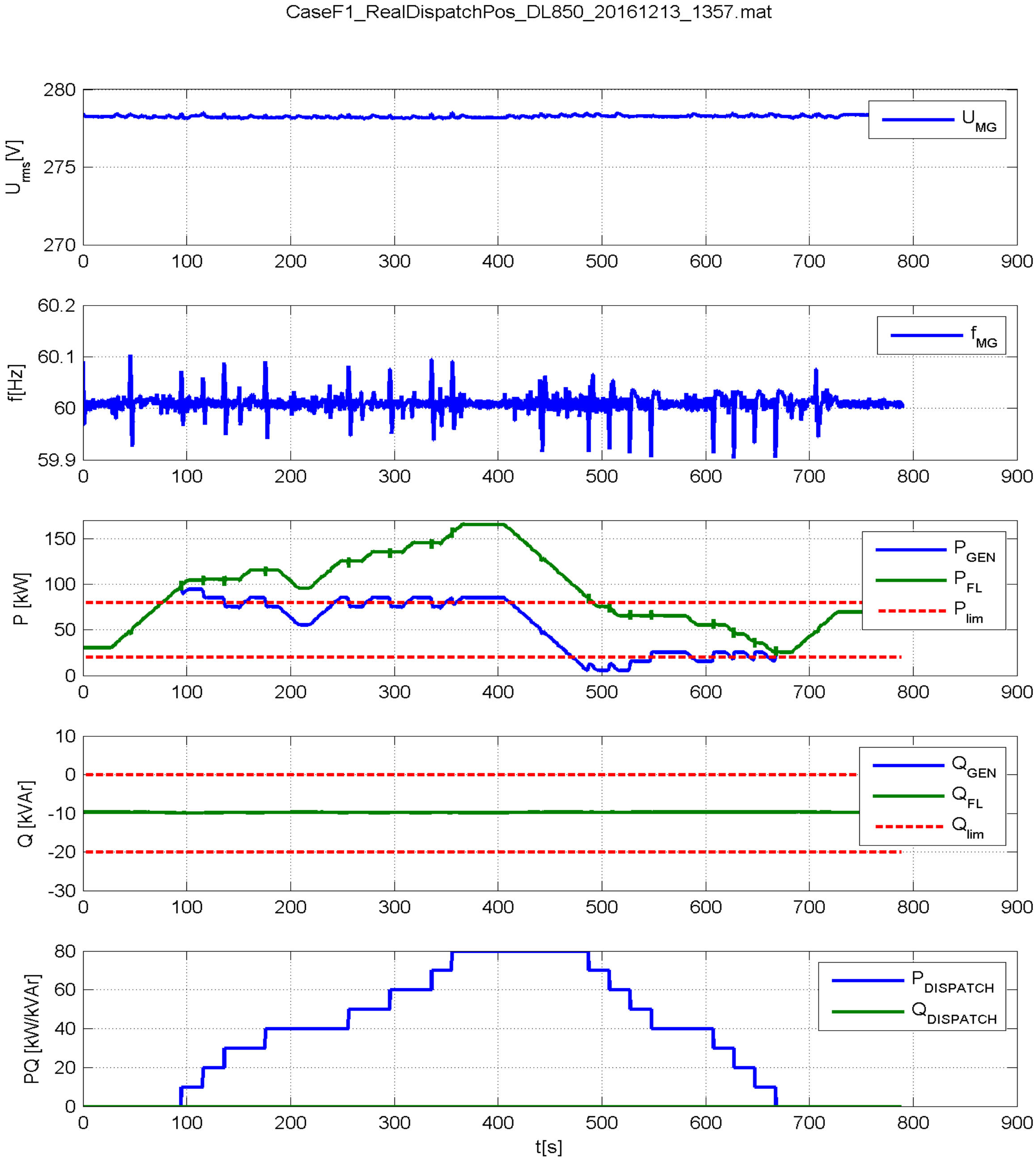

Figure 12 Case F1: Real Power Dispatch – dispatching more load not to exceed generator max power

3.6.6.2 Case G: Reactive Power Dispatch

Reactive power dispatch tests were conducted with switch S1 (POI) opened. Fixed reactance load (FL) was slowly varied eventually exceeding generator's optimal operating area (-20 kVAR – 0 kVAR). When this happened DUT is expected to shed some reactive variable load (VL) or request VARs from controllable inverters. At NREL a reactive power command received from

DUT ($Q_{DISPATCH}$) for that purpose was added to load bank fixed load thus causing visible load steps which should eventually keep generator's reactive power within its predefined limits. Two tests were performed showing a case where active power was close to minimum (Case G1) and maximum (Case G2) of its active power range. Raw data has been stored in GE Box with the file names as indicated in Table 12, and post processed data can be found in Appendix 5.3.3.

Table 12 Summary of reactive power dispatch tests.

Raw file name	Post processed
CaseG1_ReactiveDispatch25kW_DL850_20161213_1426.mat	See: 5.3.3.3
CaseG2_ReactiveDispatch75kW_DL850_20161213_1442.mat	See: 5.3.3.4

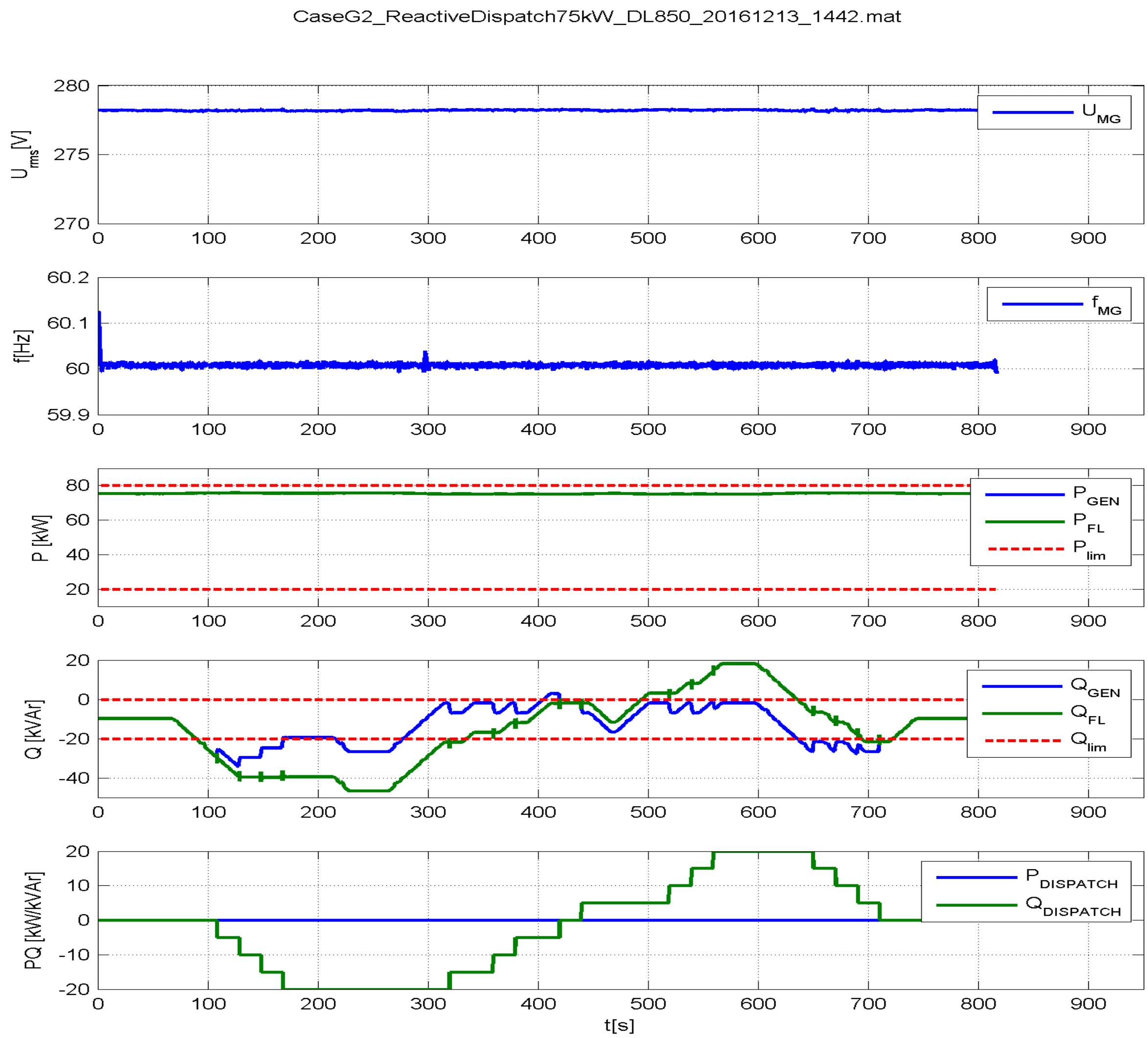

Figure 13 Case G2: Reactive Power Dispatch – dispatching to keep generator within limits at near nominal real power

One will notice that the frequency of the microgrid has more variation in Figure 13 versus Figure 12. This is due to the poorly tuned generator control unit on the main diesel generator which was sensitive to the amount of power output from the unit in each test. It was not an artifact of the supervisory level microgrid controller (eMCS).

3.6.6.3 Discussion

Both active and reactive power controller allowed generator to operate in its nominal range:

- Active power: 20 - 80kW
- Reactive power: -20 – 0kVAR

Both powers were overshooting limits for short periods of time when load was changing rapidly, but after roughly 2 minutes, the generator was operating within limits again. This overshooting may be considered acceptable, assuming the generator has short term overload capabilities and load change variations do not exceed certain ramp rates for given installation.

The note can be made that, usually, a generator's operating range is specified in active power and maximum power factor thus allowing reactive power to be significantly higher at higher active power. However, as long as the reactive power limit is configured to meet power factor requirement at lowest possible active power, the power factor requirement is always met.

3.6.7 C4: protection in both grid-tied and -independent modes,

Provisions were planned for the ground fault tests in a safe manner and within the capabilities of the grid simulators used for testing. Many provisions were not possible due to safety or equipment damage concerns, so line to ground fault tests were relegated to simulated tests. The eMCS responses to certain faults were not tested.

3.6.7.1 Case I: Internal Fault

Test was not applied at the ESIF test bed due to logistical and safety concerns.

3.6.7.2 Case J: External Fault

A test was run to verify DUT response to external fault request. The results are shown in Figure 14. The first subplot shows RMS voltages of grid simulator (U_{GS}) and microgrid (U_{MG}) during voltage event. Second subplot shows active (P_{POI}) and reactive (Q_{POI}) power flowing at POI during the event. Last subplot represents status of digital signals captured during the event which are used for time delay measurements. The digital channels are configured as follows:

- CH0: $EXT_{TripCMD}$ – external trip signal sent to DUT
- CH1: $DUT_{TripCMD}$ – is a signal received from eMCS that if active triggers CB to close
- CH2: $CB_{OpenCMD}$: Signal indicating that CB open command is active

Post processed data shows following time delay measurements using annotations:

- T_9: Delay introduced by DUT between reception of measurement sample exceeding the limit and trip command received by RTAC. It includes communication and processing delays.
- T_3: Delay introduced by RTAC and CB between receiving a trip command from DUT and grid blackout – instant of time when voltage at microgrid collapses

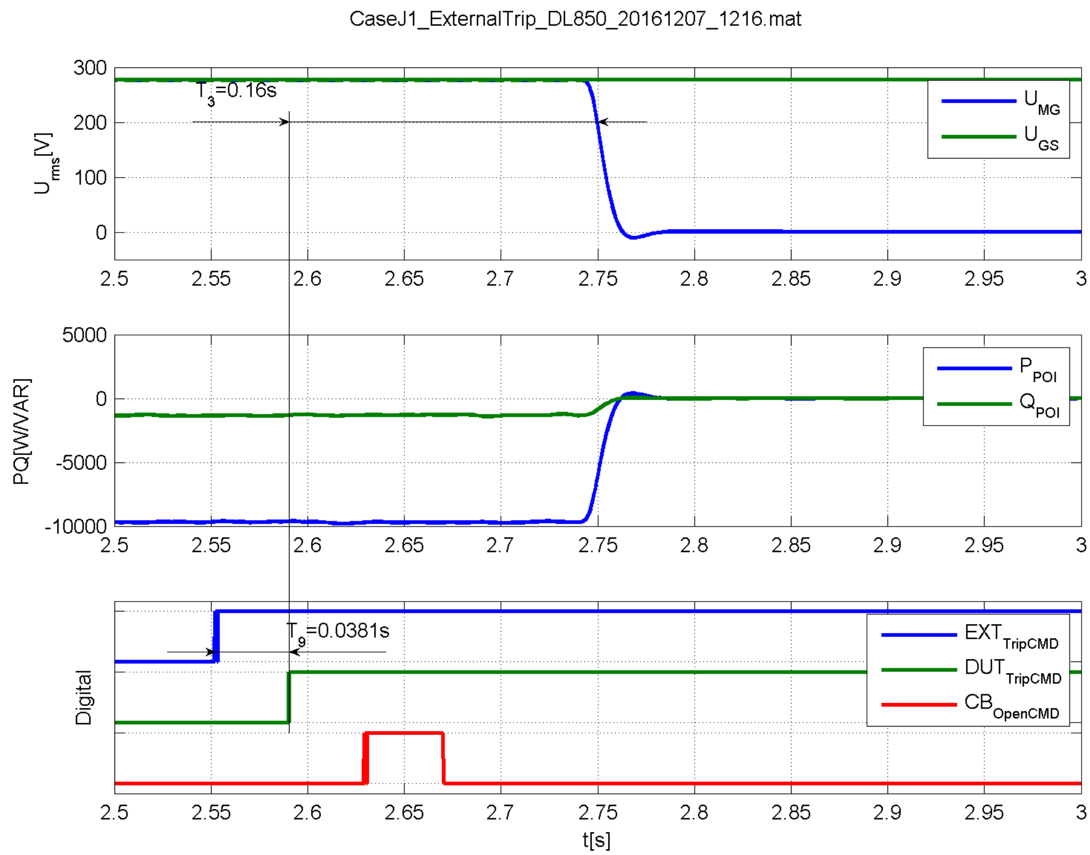

Figure 14 Case J1: External fault

3.6.7.3 Discussion

Case J1 shows that DUT reacts immediately on external trip request and commands CB to trip. Breaker opens after a time T_3=160ms from reception of trip command from DUT.

3.6.8 C5: Dispatch of the Assets

The goal of the Asset Dispatch module is to determine the best mix of generation assets that serve to reduce the overall cost of electricity for the community when in grid-tied mode, and support as much critical load as possible during islanded mode. Specifically, the Asset Dispatch module has the following objectives:

1. Reduce the net energy cost at the community level during grid-tied mode by scheduling and dispatching local assets in relation to imported electricity and fuel prices.
2. Increasing revenues for the community by participating in grid ancillary services during grid-tied mode by scheduling and dispatching local assets.

At the core of the Asset Dispatch module is a model predictive control algorithm that solves an optimization problem to meet objective functions, while also meeting constraints on individual assets. A prediction routine is also part of the Asset Dispatch module which can forecast load, renewable power production, weather effects and ancillary service prices based on historical data. All of this information is used to determine an “optimal” real-time dispatch as well as day ahead schedule to meet local energy demands of the microgrid and make revenue through participation in grid ancillary services.

3. Testing – Operational Modes

The test cases K and L listed in the test plan were tested as described below. To rigorously demonstrate the performance of the developed dispatch module as well as satisfy the required test scenarios in the Test Plan, the simulator can be run in several operating modes:

4. Optimal Dispatch

The purpose of this mode is to find the most cost-effective mix of power produced by local generating assets and power imported from the bulk grid that offset the local microgrid connected load. The optimizer establishes operating points for each local generator as well as power imported from the grid during each simulation interval. A typical simulation interval is 15 minutes over the course of a two-hour prediction horizon. New predicted data including forecasted load and available renewables is inputted into the optimizer at the end of each prediction horizon. Additional inputs to the optimizer contain fixed parameters and constraints including: number of local generators in the system, maximum and minimum power of each generator, efficiency as a function of generator operating point, as well as ramp-up and ramp-down rates of each generator. The table below summarizes the ratings of the assets used in this test.

Table 13 Ratings of six natural gas generators used in the simulations.

Generator	Maximum Power (MW)	Minimum Power(MW)	Ramp-Up Rate (MW/s)	Ramp-Down Rate (MW/s)	Minimum Load Efficiency (MWh/kg)	Maximum Load Efficiency (MWh/kg)
1	0.29	0.1289	0.1	0.1	0.0042	0.0061
2	0.37	0.0714	0.1	0.1	0.0033	0.0052
3	1.4	0.21	0.1	0.1	0.0059	0.0064
4	1.4	0.21	0.1	0.1	0.0059	0.0064
5	2	0.3	0.1	0.1	0.006	0.0064
6	2	0.3	0.1	0.1	0.006	0.0064

Moreover, the bulk grid is considered as an infinite source of energy along the simulation interval. The cost function to be minimized during this interval is as follows:

$$Cost = C(Lgen) + C(Ggen)$$

where: $C(Lgen)$ = cost of local generation, $C(Ggen)$ = cost to import from the grid.

The figure below shows an example net load profile for the microgrid used during this test.

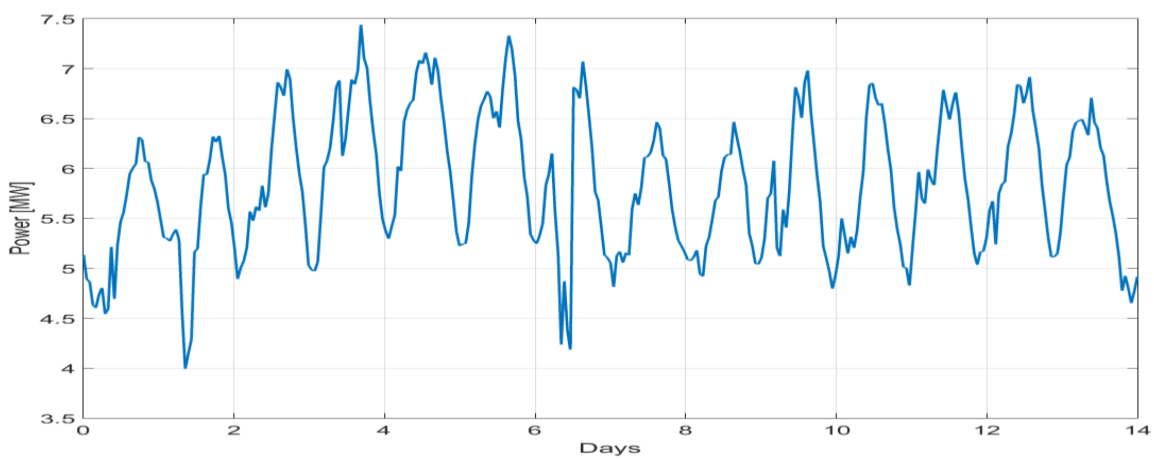

Figure 15 Example Net Load Profile (Load – PV - Hydro) for 2-week period.

Optimal Dispatch with Up-Regulation

In this mode, the goal is to determine the optimal dispatch of assets to meet local energy demand of the microgrid vs. making revenue through participation in ancillary services. In the future when microgrids will be allowed to participate in ancillary service markets, this tool can be used to assist the microgrid operators/owners to determine the optimal day-ahead bids in such markets. The optimization objective is modified from the dispatch module as follows:

$$Cost = C(Lgen) + C(Ggen) + C(Preg_{gen}) - R(Rgen)$$

where: $C(Lgen)$ = cost of local generation,

$C(Ggen)$ = cost to import from the grid,

$R(Rgen)$ = revenue to be made through participation in the ancillary service up-regulation market,

$C(Preg_{gen})$ = cost of fuel dedicated to up-regulation by local generators.

We differentiate between $C(Lgen)$ and $C\left(Preg_{gen}\right)$ as follows: both variables represent the cost of running local assets in the aggregated system, but $C(Lgen)$ pertains only to the portion of power committed to meet the local energy demand of the microgrid, while $C\left(Preg_{gen}\right)$ accounts for additional fuel consumed during periods of up-regulation.

The figure below shows the typical clearing price for two weeks in one of NYISO's regions.

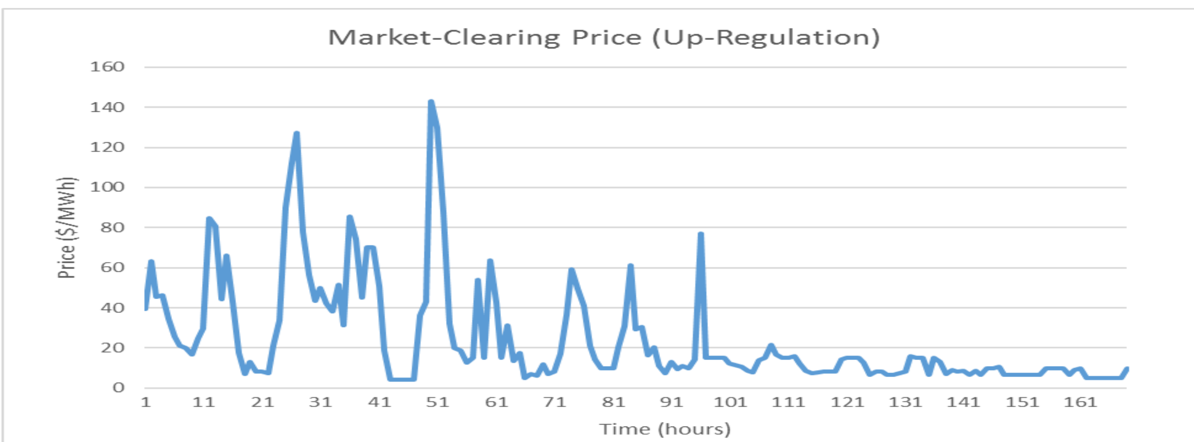

Figure 16 NYISO up-regulation market-clearing prices for two weeks in January 2014 (168 hours).

Optimal Dispatch with Down-Regulation

This mode is similar to the up-regulation mode, except that in this case the microgrid will be paid for **reducing** generation during times they are called, and so the cost function to be minimized is as follows:

$$Cost = C(Lgen) + C(Ggen) + C\left(Preg_{grid}\right) - C(Preg_{gen}) - R(Rgen)$$

where: $C(Lgen)$ = cost of local generation,

$C(Ggen)$ = cost to import from the grid,

$C\left(Preg_{grid}\right)$ = cost to import from the grid during times of down-regulation

$C(Preg_{gen})$ = savings corresponding to reduced local generation being used for regulation that would have otherwise been used to meet local energy demand

$R(Rgen)$ = revenue to be made through participation in the ancillary service down-regulation market.

We include the term $C(Preg_{gen})$ and invert its sign because to perform down-regulation a resource must increase the amount of power imported from the grid through the POI (to decrease the total available power in the bulk grid) thus decreasing the amount of local generation serving the load. The term $C(Preg_{gen})$ corresponds to the dollar amount saved on fuel by this decrease in local generation and $C\left(Preg_{grid}\right)$ corresponds to the cost of additional power imported from the grid to get credit for down-regulation.

Optimal Dispatch Up AND/OR Down Regulation

There are several ways to determine an optimal up and down bid schedule and it depends on the rules of each ISO's ancillary service market. For each hour in the simulation, the module determines the most profitable up-regulation bid and down- regulation bid. It is up to the microgrid owner/operator to place a bid in one (or both) of these day-ahead markets if he/she chooses. If the markets are **independent**, it makes logical sense to place a bid into the most lucrative of the two during that simulation step ensuring maximum revenue. Placing a maximum bid into both markets (and subsequently being called) could cause a deficiency in quantity of local generation at a given simulation interval. If the regulation market is **symmetric**, we recommend bidding the smaller absolute regulation value to ensure maximum/minimum power constraints are not violated in any interval.

Average Fixed Efficiency Dispatch

Typically, a generator's efficiency will vary depending on whether it is lightly or fully loaded. In this mode, all generators are assumed to have a fixed average efficiency irrespective of operating point. This simple method of dispatch is called "merit-order" approach. Ramp rates, minimum/maximum power constraints are still obeyed and the option to import power from the grid is available. There is no ancillary service market participation in this dispatch approach.

Pure Grid Import

The pure grid import dispatch solution only considers the bulk grid when meeting the critical microgrid load. This constraint is enforced by setting the maximum and minimum power of each generator to be zero, so that the optimizer does not use local plants as generating assets. This operating mode is chosen to show how the dispatch changes as a function of changing grid buy price. Because of the inability to use local generation, an increase in grid buy cost increases the total cost of supporting the load in this mode.

Design of Experiments

The team formulated a design-of-experiments to meet the test criteria in the Test Plan. For each simulation interval, the team chose four interesting grid buy prices and four interesting fuel prices for a total of 16 runs for the selected simulation time (day, month, year). The 16 runs were repeated for each mode described above excluding the Time-of-Day Dispatch which compares a fixed fuel price with three "peak-time" prices. The experiment contains 5 simulations: the whole year of 2014, one day in winter; January 29, 2014, one day in the spring; March 5, 2014, one day in the summer; August 7, 2014, one day in the fall; November 6, 2014. The results are compiled below.

Annualized Results: 2014 Simulated Data

Figure 17 and Figure 18 below show the annualized cost results for running all the design-of-experiment cases for all the operating modes described above.

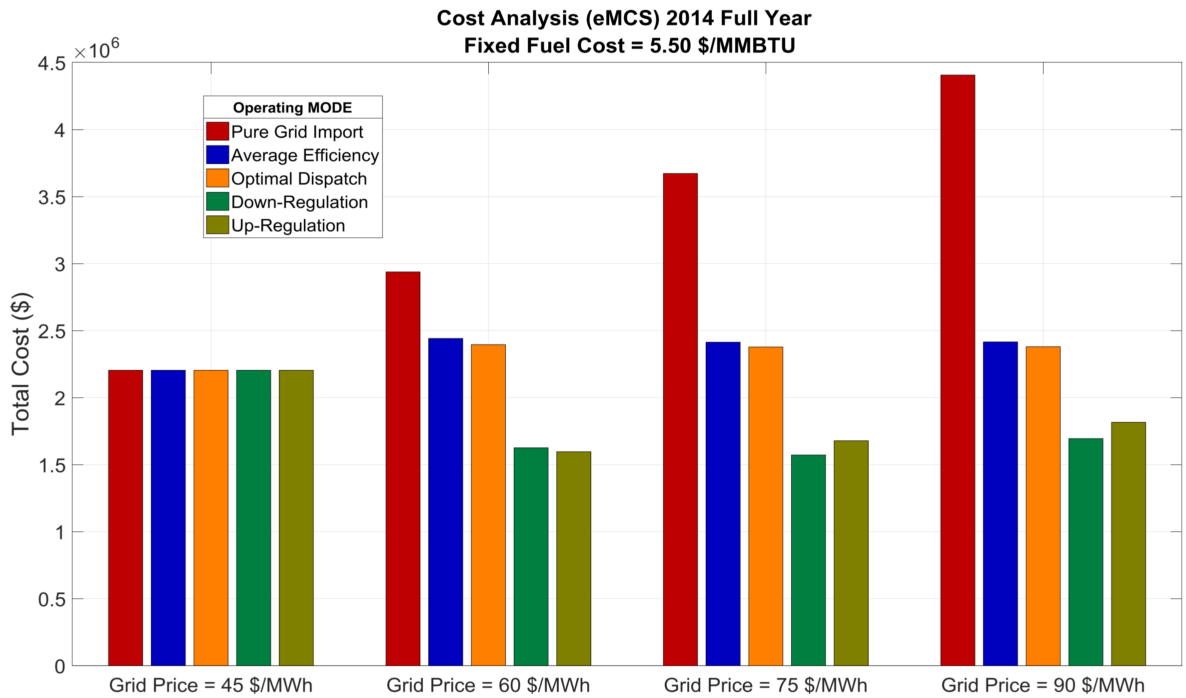

Figure 17 Accumulated annual cost to operate the Potsdam critical loads, with fixed Natural Gas fuel price and varying grid purchase prices: red=100% import from utility, blue=average efficiency dispatch, orange=optimal dispatch, green=down regulation, olive=up regulation.

When the price to purchase power from the grid is low relative to fuel price, more power from the grid is used to offset the local load. As the grid price increases, there is a heavy reliance on local generation as the main generation asset within the microgrid. We also see that it is not cost-effective to participate in the regulation markets when the grid-purchase price is low. The cost of putting fuel into the generators to perform up-regulation, for example, does not offset the low cost of supporting the local load with power purely from the grid. Because the job of the optimizer is to minimize the cost, it will not recommend a bid during this instance.

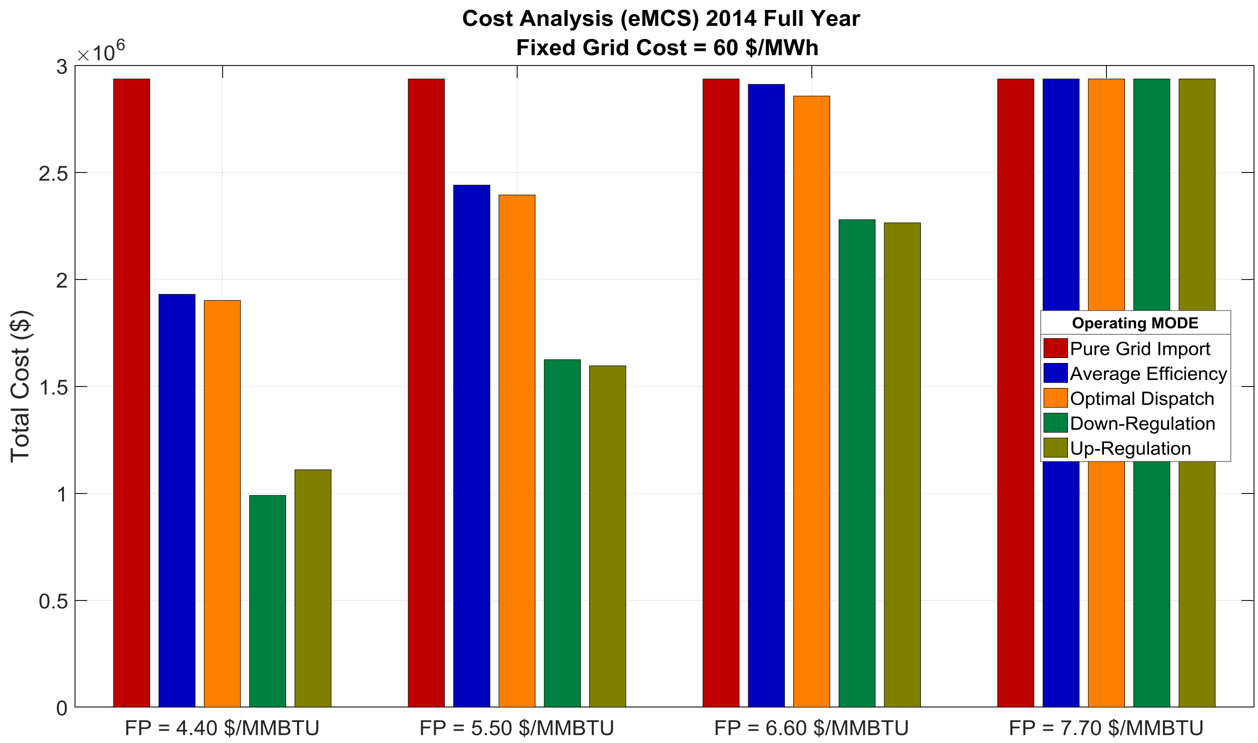

Figure 18 Accumulated annual to operate the Potsdam critical loads, with fixed electric import prices and varying Natural Gas fuel purchase prices: red=100% import from utility, blue=average efficiency dispatch, orange=optimal dispatch, green=down regulation, olive=up regulation.

When the cost of fuel for the local generators is low relative to grid pricing, a heavy reliance on local generation to support the local load is indicated. As the fuel price increases, imported power from the grid becomes more cost-effective. As the price of fuel goes up, the total cost in average fixed efficiency and optimal dispatch cases increases as well. In the left-middle stack, for example, an increase in fuel cost is not enough to choose grid power as the sole generating asset. Incremental increases (moving towards the right) in the cost of fuel show that there is less reliance on local generators as grid power becomes the sole form of generation.

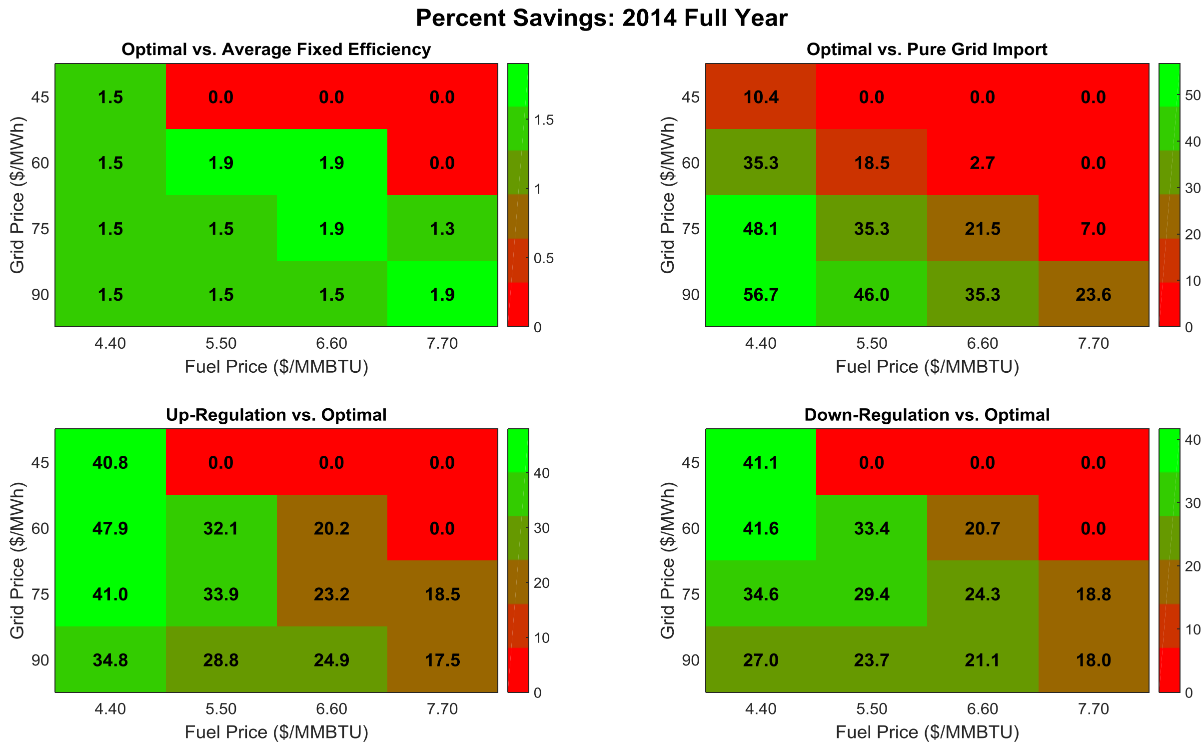

Figure 19 Percent annual electricity savings relative to four operating modes for various grid purchase price ($/MWh), and Natural Gas pricing ($/MMBTU).

The charts of Figure 19 depict Percent Savings of one mode of operation versus another. Top-left: Optimal Dispatch vs. Average Fixed Efficiency Dispatch; the optimal solution is always equal to or better than the fixed efficiency solution. Top-right: low fuel prices relative to grid prices offer a clear alternative to completely purchasing power from the grid. Bottom-left: participating in the up-regulation market shows as much as 47.9% savings over the already optimal solution. Bottom-right: participating in the down-regulation market shows as much as 41.6% savings over the already optimal solution.

3.6.9 Typical Day (January 29, 2014) Results

Figure 20 shows the dispatch profiles of local generation and grid imported power over the course of one day in January. The fuel price and grid price are 6.60 $/MMBTU and 60 $/MWh respectively for each dispatch. Top-left: irrespective of the grid purchase price, the load is completely served by the bulk grid because the option to run local assets is not available. Top-right/Middle left: the average fixed efficiency and optimal dispatch solutions show similar profiles throughout the course of the day because the only variable difference between the two is efficiency as a function of operating point. Middle-right: When the market-clearing price is high in the up-regulation market, the optimizer recommends an hourly bid. We see the trend that when the market-clearing price is high, much of the local load will be served through bulk grid import. The local generation is considered as a reserve in this case, where the optimizer wants to dedicate as much local generation as economically possible to the up-regulation market. Bottom-left: When the market-clearing price is high in the down-regulation market, the optimizer recommends an hourly bid. The opposite phenomena (from up-regulation) is true in this case. When the market-clearing price is high, the optimizer will use local generation as the primary source of serving the load; keeping the option to import more power from the grid (thus lowering local generation) during times of down-regulation.

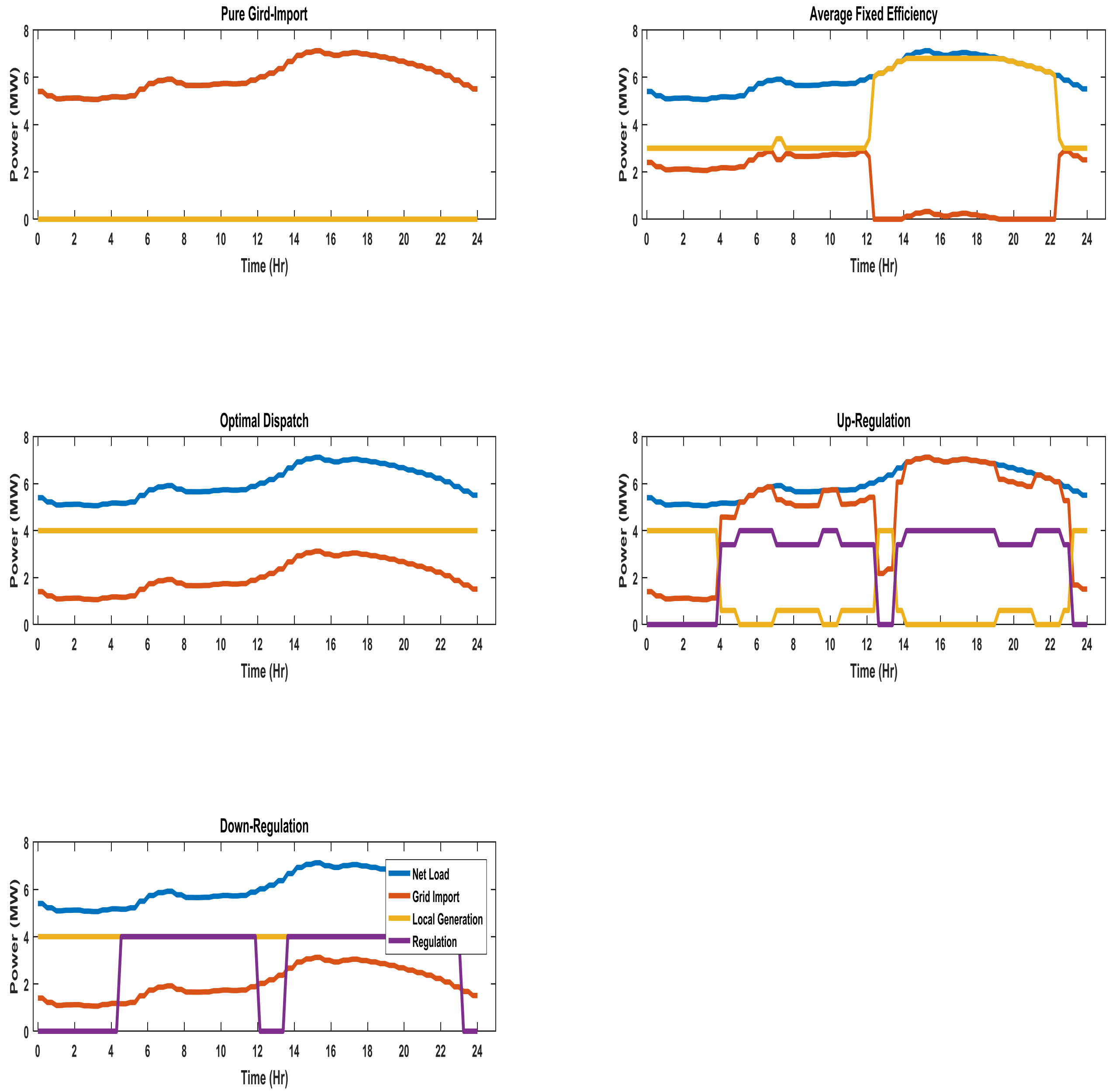

Figure 20 Power dispatch for a typical day, showing how local generation is operated and allocated for the different operating models: blue=net load, orange = grid import, yellow = local generation, purple = allocation to regulation services.

3.6.10 Time-of-Day Pricing Dispatch Results

Figure 21 illustrates the dispatch profile for local generation and grid imported power for one day in the winter of 2014. We define "peak time" between the hours of 10am-4pm and define a different grid purchase price for those times. As the peak time pricing increases, we see less of the local load supported by the bulk grid, and more by the local generating assets. The optimal dispatch solution is shown below with no participation in the ancillary service markets.

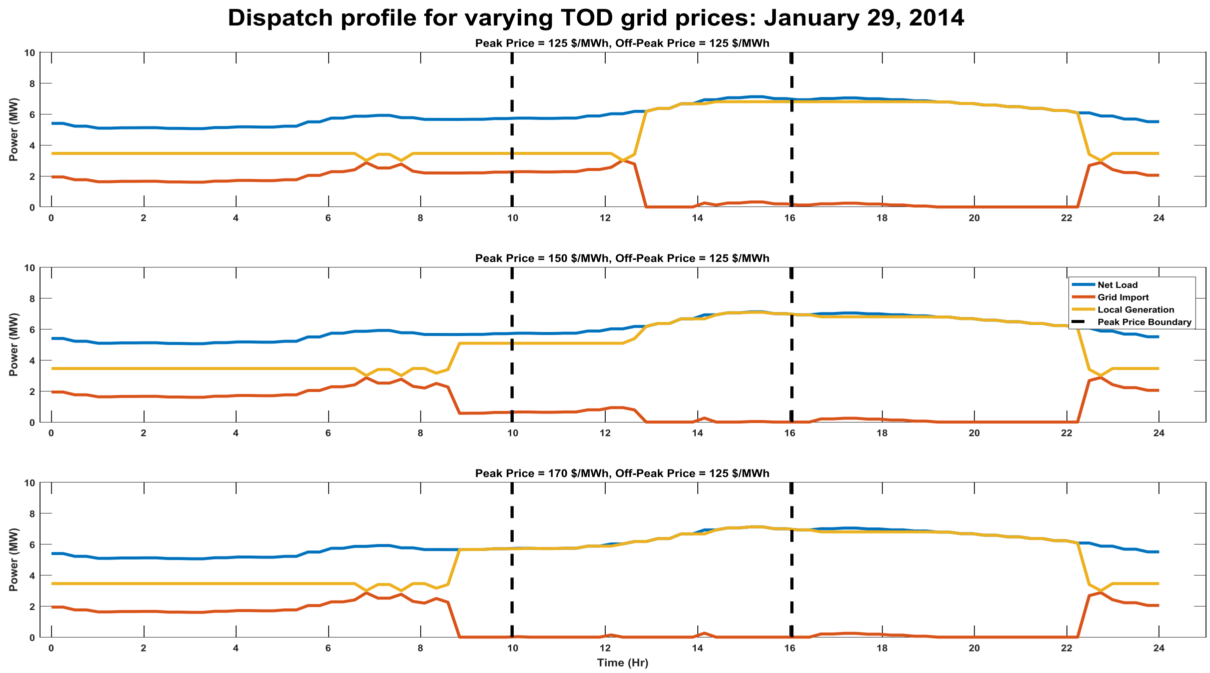

Figure 21 Power dispatch for a typical day with TOD rates from 10AM to 4PM, showing how local generation is operated and allocated at different peak energy pricing: blue=net load, orange = grid import, yellow = local generation, purple = allocation to regulation services.

3.6.10.1 Case K: Optimal Dispatch for reduced cost of electricity

Summarized above, with more details in Appendix 5.4.

3.6.10.2 Case L: Optimal Day-ahead Scheduling to participate in ancillary services

Summarized above, with more details in Appendix 5.4.

3.6.10.3 Case M: Constrained Dispatch Scheduling due to participation in Demand Response

The project did not test the eMCS with the Demand Response service due to schedule challenges.

3.6.11 C6: meet resilience targets as defined by the local community

No specific tests of the eMCS are proposed to assess its resiliency.
Rather the proposed Potsdam, NY microgrid with underground ring bus to the critical loads is assumed to be more resilient, particularly when long term outage of the transmission system is impacted (weather related power supply failure).

4 Output of the Project

4.1 Publications

GE team member, Santosh Veda, presented on the challenges with the development of microgrid controller at the NREL workshop, Advanced Grid Technologies for Distribution Systems. This workshop on July 7-10, 2015 also gave the team an opportunity to tour the ESIF lab and its capabilities for the Draft Test Plan.

A team member, Chaitanya Baone, presented at the IEEE International Smart Grid Technology meeting in Minneapolis, MN, September 2016. The paper was titled “Optimal Day-ahead Scheduling for Microgrid Participation in Frequency Regulation Markets”

The PI, Herman Wiegman, participated in the “Energy in the 21st Century” conference at SUNY-Syracuse, Environmental Science and Forestry, on April 8, 2016

http://www.energy21symposium.org/home.aspx

A team member, Naresh Acharya, participated in a panel session “Measuring and Enabling Resiliency using Microgrids” at the 2016 IEEE PES meeting in Boston, MA, on July 20, 2016.

GE team member, Santosh Veda, participated in the IEEE 2030 meetings. These IEEE standards are dedicated to the specification and testing of microgrid controllers.

GE Energy Consulting published a report describing the technical assessment of the target microgrid: Potsdam Resilient Microgrid Performance Analysis & Feasibility Study (see Appendix 5.1).

4.2 Networks and Collaborations

This project provided the opportunity to work with the community of Potsdam, and share in their collaboration with National Grid and New York REV staff to further develop the proposed microgrid.

Members of the GE team worked closely with the LBNL DER-CAM software development team. GE used the DER-CAM software to analyze the proposed Potsdam microgrid and provided feedback.

Members of the GE team consulted with the NREL Microgrid Controller Challenge team during the planning phase.

4.3 Patent Application

A patent disclosure was submitted to the GE patent system titled: “A Method to Determine Optimal Participation of Microgrids in Ancillary Service Markets,” with reference number GE-GRC 69084. This patent recognized that a portion of the invention was supported by this Government funded project.

4.4 Technology Transfer to Product Platform

The technology developed during this project by the GE Global Research team is being transferred to GE Grid Solutions which will offer a microgrid control product for the market.

5 Appendices

Appendix 5.1: Feasibility Study

Appendix 5.2: One Line Diagrams & Asset Descriptions

Appendix 5.3: NREL Detailed Test Results

Appendix 5.4: Asset Dispatch – Detailed Results

5.1 Feasibility Study

Background

In 2014, the Department of Energy (DOE) Office of Electricity Delivery and Energy Reliability (OE) issued a funding opportunity announcement (FOA) seeking proposals for development of an advanced microgrid controller. Among the expectations of DE-FOA-0000997 was the preparation of a feasibility plan (in collaboration with a participating community) for possible deployment and demonstration of the developed controller and associated microgrid design.

This report presents findings of a feasibility study conducted as part of the "Microgrid Plant Control Design and Development" project (DE-OE0000728), funded by the DOE and managed by GE Global Research Center (GE GRC). The study leveraged concurrent efforts for the "Potsdam Resilient Microgrid" (PRM) project which was funded by the New York State Energy Research and Development Authority (NYSERDA) and National Grid. The PRM project team included Clarkson University and GE Energy Consulting who were also team members for the DOE-funded project that resulted in development of the enhanced microgrid control system (eMCS).

Information in this section of the report was prepared by General Electric International, Inc. (GEII); acting through the GE Energy Consulting group based in Schenectady, NY, and submitted to GE Global Research. Technical and commercial questions and any correspondence concerning this portion of the document (Appendix 5.1) should be referred to:

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Executive Summary

In addition to validating eMCS functionality, this feasibility study assessed the likelihood of the future proposed resilient microgrid in the Potsdam community to meet DOE-specified microgrid performance goals on emissions, energy efficiency, and reliability. The principal DOE microgrid performance objectives considered in this study include:

- Reducing the net regional generation emissions over today's baseline operation,
- Improving the net regional energy efficiency over today's baseline operation, and
- Reducing the outage time to "critical" loads.

To establish metrics for measuring achievement of the above objectives, the feasibility study relied on available data, reasonable assumptions, and the mix of supply and demand side resources selected for the Potsdam Resilient Microgrid.

The study also included a comparative analysis of the system-wide generation, fuel consumption, criteria pollutant (i.e., NOX and SO_2), and greenhouse gas[1] (GHG) (i.e., CO_2 / carbon) emissions as further described in Section 5.1.2 and 5.1.3 of this Feasibility Study.

The GE Multi-Area Production Simulation (GE MAPS) model was used to determine the system-wide energy annual efficiency and emissions metrics.

In a similar analysis, the proposed microgrid was simulated using the Distributed Energy Resource Customer Adoption Model (DER-CAM) tool developed by the DOE's Lawrence Berkeley National Laboratory (LBNL).

The study considered two microgrid scenarios based on two different, but currently available, utility electricity rates. The two scenarios resulted in drastically different operations of the microgrid in terms of relative portions of on-site generation versus power purchased from the utility during the year of simulated operation.

The key takeaway from this study is that the microgrid performance metrics, as defined in this study, are highly dependent on a number of drivers such as electricity rates, fuel price, and DG efficiency. These factors, which are discussed in more details in Section 5.1.2 and 5.1.3 of this Feasibility Study, not only impact the emissions rate of the proposed microgrid, but also determine its operation and the relative amount of power purchased from the utility (versus on-site generation), which in turn impacts the relative energy efficiency and average heat rate of the microgrid.

Following is a brief summary of the principal findings for the two microgrid scenarios considered for the study. Additional details are provided in Section 5.1.3 of this Feasibility Study.

- utility power purchase was reduced significantly,
- microgrid CO_2 emission rates were reduced significantly in comparison to the average CO_2 emission rates of EI U.S. Pools,
- microgrid CO_2 emission rates were considerably higher than those of NYISO,
- compared to the EI U.S. Pool and NYISO average emission rates, both scenarios would result in more NOX emissions, and
- both microgrid scenarios resulted in lower SO_2 emission rates compared to the EI U.S. Pool and NYISO averages.

5.1.1 Introduction

5.1.1.1 Feasibility Study Objectives

As stated previously, the feasibility study involved assessment of the ability of the proposed future microgrid in the Potsdam NY community to meet the DOE-specified performance objectives regarding microgrid emissions, energy efficiency, and reliability. Additionally, an objective of this study is to develop and test the eMCS using the Potsdam Resilient Microgrid design for demonstration. Consequently, the study relied on the configuration, criteria, and specifications defined for the PRM project.

The objective of the NYSERDA/NG funded PRM project is to develop a functional design for a resilient microgrid that will provide reliable power for critical loads and essential services, and allow the Potsdam community to act as a hub for emergency operations during North Country

[1] GHGs include other types of gases, which are not considered in this study.

disaster conditions, such as the ice storms, major snow events, and microbursts experienced during recent years.

The PRM impact analysis was intended to quantify the overall effect of the Potsdam microgrid in terms of energy efficiency, emissions, and reliability.

This report presents the results of the analysis performed to quantify the DOE microgrid performance metrics, which included the following:

- Changes in microgrid's emissions over baseline operation without the microgrid generation,
- Changes in microgrid's energy efficiency over baseline operation without the microgrid generation, and
- Changes in the outage time to "critical" loads.

5.1.1.2 Feasibility Study Approach

A two-phase approach was developed to enable quantification of the first two metrics (emissions and energy efficiency). The third metric (reduced outage times) could not be quantified, but a qualitative assessment of this metric is provided in Section 5.1.4.

The feasibility study included application of two distinct models:

- GE Multi-Area Production Simulation (GE MAPS), and the
- Distributed Energy Resource-Customer Adoption Model (DER-CAM)

Using data for 2015, the GE MAPS model was used to simulate a year of operation of the Eastern Interconnection (EI) power systems, which covers the whole eastern part of the U.S. east of the Rockies; and includes the territory of the NYISO power system. The GE MAPS analysis provided the EI U.S. Pools and NYISO system-wide baselines for electricity consumption, fuel efficiency, and criteria pollutant (NOX and SO_2) and GHG (CO_2) emissions.

The DER-CAM tool was used to simulate the operation of the proposed Potsdam Resilient Microgrid in grid-connected mode for the same year, except for a two-week period in September. During this time the microgrid operated in islanded mode to simulate a prolonged outage (two weeks) on the main grid. The microgrid operation included on-site renewable and natural gas based generation throughout the year, and load curtailment during the islanded mode. This analysis provided the microgrid's operation based energy efficiency and emission rates.

As the study progressed, it became clear that utility energy supply, fuel efficiency, and emissions metrics were highly dependent on the underlying assumptions on electricity tariffs, fuel prices, and DG generation efficiencies. To demonstrate this dependency, two different electricity tariff scenarios were modeled (refer to Section 5.1.2.3).

5.1.1.3 Note on Reliability

While performing this feasibility study, it became evident that a detailed analysis (to adequately quantify the reliability impact of the proposed microgrid) was beyond the scope of this project. However, it is readily apparent that the configuration of the proposed PRM allows critical loads to be supplied with uninterrupted power during outages caused by extreme weather conditions or similar emergencies.

5.1.1.4 Proposed Potsdam Microgrid Configuration

As mentioned previously, this feasibility study (for DOE project DE-OE0000728) leveraged the design of the proposed Potsdam Resilient Microgrid, which was developed during a parallel project funded by NYSERDA and National Grid. In essence, the features/functions of eMCS were developed based on objectives for control of the planned PRM assets. Additionally, simulated testing of the microgrid controller was performed in accordance with the proposed PRM configuration.

The configuration of the proposed Potsdam Resilient Microgrid is described in the final scientific/technical report for the DOE-funded project DE-OE0000728. That design includes a new underground system for power and communications, interconnecting approximately 10 facilities located on the Clarkson University campus, the SUNY Potsdam campus, at Canton-Potsdam Hospital, Village of Potsdam buildings, Potsdam Central School, plus commercial providers of fuel, food, and other essential commodities and emergency services. Planned PRM assets include three existing renewable energy resources (one solar and two hydro), several natural gas-fueled generators (with CHP), and a BESS. The target for self-sustained islanded operation of the resilient microgrid is provision of uninterrupted power for at least two weeks during emergency (i.e., utility outage) periods.

When not islanded, it is intended that the microgrid will operate in concert with the existing distribution system to optimize the value of the interconnected renewable and stationary generation, energy storage (if any), and load control systems to the benefit of their owners, and the electric system.

A deliverable for the PRM project is a design, with cost estimates (within a +/- 30% range), for a self-sustaining resilient underground microgrid in Potsdam, NY, with the intent to propose its further development, demonstration, and implementation to a future New York State or federal program.

The primary goals of the NYSERDA/National Grid study are to:

- Design a resilient community microgrid in the NY North Country to improve disaster response
- Construct a National Grid underground system for resilient power and communications (to be developed by National Grid)
- Interconnect 10 entities: Clarkson University, SUNY Potsdam, Canton-Potsdam Hospital, Potsdam Central School, Village of Potsdam buildings, plus commercial providers of fuel, food, and other essential emergency services.

A resilient microgrid would be a key component in the North Country region addressing New York State's goal of significantly improving disaster response capability. It would also serve as a model for other regions of the state.

5.1.1.5 DOE Microgrid Objectives

For the Feasibility Study and subsequent performance evaluation, the DO expected a plan of how the developed eMCS controller and the proposed microgrid would be implemented (in the target community of Potsdam) so as to reduce:

- outage time of critical loads
- regional CO_2 emissions to serve the loads
- utility supplied energy to the microgrid

The DOE microgrid objectives and the data requirements and the "desired" performance metrics are shown in Table 5-1.

Table 5-1: DOE Microgrid Objectives

Performance Objective	Metric	Data Requirements	Success Criteria
Reducing regional CO_2 emissions	% reduction in regional CO_2 emissions	regional generation mix, asset data from target community & renewable integration plan	>20% reduction
Reducing utility supplied energy	% reduction in utility supplied energy	Asset data from target community & renewable integration plan	>20% reduction
Reduced outage time for critical loads	% reduction in SAIDI outage time	V&F power quality simulations, assessment of system reliability & fuel stores	98% reduction

However, since the objective of the Potsdam Resilient Microgrid is to provide uninterrupted power during at least two weeks of grid outage (such as those that may occur during ice storms, major snow events, and microbursts) that have been experienced in the Potsdam area during the recent years, it is not guaranteed that the PRM will necessarily meet the DOE Microgrid Objectives.

This study evaluated the microgrid performance metrics, which in the case of CO_2 emissions, and subject to the underlying assumptions of main drivers and interpretation of the baseline, fall short of the DOE targets.

5.1.2 Analysis Methodology

5.1.2.1 Study Approach

As part of the feasibility study, the amount of emissions that would be produced by the local utility's generation (to supply microgrid loads that would otherwise be supplied by microgrid resources) was determined. Pollutant levels from microgrid resources (to supply loads within the proposed microgrid) were similarly derived. A comparative analysis was then made of the system-wide generation, fuel consumption, criteria pollutant (i.e., NOX and SO_2), and greenhouse gas[1] (GHG) (i.e., CO_2 / carbon) emissions of the utility-based generation versus the microgrid supply and demand side resources. The goal of this analysis was to ascertain whether the microgrid loads could be adequately supplied from microgrid resources while reducing the amount of emissions that would otherwise be produced by an equivalent amount of utility generation.

To determine system-wide energy annual efficiency and emissions metrics, the GE MAPS model, was used to simulate the Eastern Interconnection (EI) power systems, which includes the territory served by the New York Independent System Operator (NYISO). The simulation included load (within the proposed microgrid) that would ordinarily be supplied by the local utility, but without the microgrid supply side and demand side resources. The hourly GE MAPS model was run using available data for the year 2015 and the analysis determined the system-wide baseline of energy efficiency and emission rates that were used for comparison with operation of the proposed microgrid.

In a similar analysis, the proposed microgrid was simulated using the DER-CAM tool, developed by the DOE's Lawrence Berkeley National Laboratory's (LBNL). This analysis involved simulated operation of the proposed microgrid with on-site generation and load curtailment for the year 2015 (subject to two weeks of greater grid outage).

5.1.2.2 GE MAPS System-Wide Simulation

In the first phase of the study, the system wide and baseline metrics were determined by simulating the operational performance of the Eastern Interconnection power systems for the year 2015 using GE MAPS. EI covers the whole eastern part of the U.S. east of the Rockies and includes the Canadian provinces east of Alberta; and covers the territory of the NYISO power system.

The version of GE MAPS models used includes a complete representation of the EI transmission system and its major constraints. It also includes an up-to-date representation of all the major grid scale conventional and renewable generation, projected fuel prices, forecasted area loads, and operational reserve requirements of all the markets. Assuming no on-site microgrid generation, the main outputs of the GE MAPS include the following items (calculated for a full 2015 simulation, both for the EI U.S. Pools and for NYISO):

- Grid Purchase (kWh) to meet Microgrid Load
- Microgrid MG Generation + Load Curtailment >> Assumed to be zero
- System-Wide Average Heat Rate (Btu/kWh)
- System-Wide NOX Emissions (lb/MWh)
- System-Wide SO_2 Emissions (lb/MWh)
- System-Wide CO_2 Emissions (lb/MWh)

The Average Heat Rates were calculated as the ratio of system-wide fossil fuel consumption (Btu) divided by the system-wide generation (kWh).
The Emission Rates were calculated as the ratio of the system-wide emissions in British Pounds (lb) divided by the system-wide generation (kWh).

5.1.2.3 DER-CAM Microgrid Simulation

In the second phase of the study, two scenarios of microgrid operations were simulated for 2015, using DER-CAM. The two scenarios were based on two current National Grid electricity rate schedules:

- Scenario A: National Grid Rate Schedule SC-3A (for large commercial customers), which included a Monthly Demand Charge
- Scenario B: National Grid Rate Schedule SC-7 (for customers selling power to the grid), which included both a monthly demand charge and a daily on-peak demand charge.

In both scenarios, the proposed microgrid could run in grid-connected and islanded mode, with underlying fuel prices and electricity rates determining the amount of electricity generated on-site versus power purchased from the utility during normal (blue sky) days.

The annual simulation also included two weeks of greater grid outage in September, during which the microgrid could run in islanded mode with no power purchase from the utility. In islanded mode, the microgrid could also implement a load curtailment option.

Similar to the system-wide metrics, the following microgrid-specific metrics were calculated for the two scenarios:

- Grid Purchase (kWh) to meet part of Microgrid Load
- Microgrid MG Generation + Load Curtailment >> non-zero
- Microgrid Average Heat Rate (Btu/kWh)
- Microgrid NOX Emissions (lb/MWh)
- Microgrid SO_2 Emissions (lb/MWh)
- Microgrid CO_2 Emissions (lb/MWh)

The Average Heat Rates were calculated as the ratio of fossil fuel consumption of the purchased utility power plus the fossil fuel consumption of the on-site generation (Btu) divided by the microgrid annual load (kWh).

The Emission Rates were calculated as the ratio of the emissions of the purchased utility power plus the emissions of the on-site generation in British Pounds (lb) divided by the microgrid annual load (kWh).

5.1.2.4 Study Scenarios & Metrics

Combining the GE MAPS and DER-CAM analysis results, the overall study scenarios and performance metrics consisted of the following:

- EI U.S. Pools: Metrics calculated for the U.S. portion of the Eastern Interconnection with microgrid load but without any microgrid generation (running GE MAPS)
- NYISO: Metrics calculated for NYISO territory with microgrid load but without any Microgrid generation (running GE MAPS)
- Scenario A: Metrics calculated for the microgrid operation with microgrid load and with microgrid generation based on National Grid Rate Schedule SC-3A (running DER-CAM)
- Scenario B: Metrics calculated for the microgrid operation with microgrid load and with microgrid generation based on National Grid Rate Schedule SC-7 (running DER-CAM)

5.1.2.5 Utility Rates and Fuel Prices

DER-CAM requires the electric and gas utility rates and DG natural gas and diesel fuel prices in order to determine the least cost generation mix of the microgrid under both interconnected and islanded operational modes.
The following tables summarize the utility rate and fuel price assumptions used in the DER-CAM model. The values used are based on assumed National Grid rates applicable to medium to large commercial customers.

Applicable electric utility and supplier rates are:

- National Grid SC-3A (Large Commercial Customers, such as Clarkson University)
- National Grid SC-7 (Customers with internal DG such as SUNY Potsdam)

The Base Case modeling assumption is that without any distributed generation in operation (and no outages) the SC-3A will be the applicable electric rate schedule. But with operational distributed generation and buy and sell with the larger grid, SC-7 would be the applicable electric rate schedule. The proposed microgrid is assumed to be a Primary Class customer normally supplied from a 2.2 – 15 kV distribution feeder. The electricity rates used in the DER-CAM modeling are presented in the following tables.

Table 5-2: National Grid SC-3A Electric Rate Schedule

Service Classification	Monthly Customer Charge	Monthly Demand Charge	Miscellaneous Other Charges	Average On-Peak Hourly Supplier Price	Average Off-Peak Hourly Supplier Price	Daily On-Peak Demand Charge
	($)	($/kW-Month)	($/kWh)	($/kWh)	($/kWh)	($/kW-Day)
SC-3A	1,000.00	9.18	0.0200	0.0415	0.0284	N/A

Table 5-3: National Grid SC-7 Electric Rate Schedule

Service Classification	Monthly Customer Charge	Contract Demand Charge	Miscellaneous Other Charges	Average On-Peak Hourly Supplier Price	Average Off-Peak Hourly Supplier Price	Daily On-Peak Demand Charge
	($)	($/kW-Month)	($/kWh)	($/kWh)	($/kWh)	($/kW-Day)
SC-7	1,000.00	3.71	0.0200	0.0415	0.0284	0.2691

Fuel prices used in the DER-CAM model are presented in Table 5-4. Natural Gas prices are from Enbridge St. Lawrence Gas – PSC No.3 Gas, Service Classification No. 10, Distributed Generation – Non-Residential. Diesel prices are taken from NYSERDA's website[2].

Table 5-4: Natural Gas and Diesel Prices

Fuel Category	Price	Price	Price
	NG ($/Therm) Diesel ($/Gallon)	($/kWh Equivalent)	($/MMBtu Equivalent)
NG - Summer DG Rate (April – October)			
Demand Charge	0.444200		
Commodity Charge	0.005090		
Effective Summer Rate	0.449290	0.015334	4.49
NG - Winter DG Rate (November – March)			
Demand Charge	0.444200		
Commodity Charge	0.006446		
Effective Summer Rate	0.450646	0.015380	4.51
Diesel	3.11	0.076344	22.37

In the above table the price of Natural Gas is for the fuel used for operation of distributed generation units fueled by Natural Gas, including any back-up generator, internal combustion/reciprocating engines, gas turbines, steam turbines, and CHP units.

Price of Diesel fuel is for fuel used for operation of backup generation units fueled by Diesel fuel. Please note the almost 5 to 1 ratio of Diesel price to Natural Gas price.

2 http://www.nyserda.ny.gov/Cleantech-and-Innovation/Energy-Prices/On-Highway-Diesel/Weekly-Diesel-Prices

5.1.2.6 Microgrid Distributed Generation Characteristics

During the year, microgrid load is met by a combination of on-site generation and power purchase from the utility. Therefore, microgrid performance metrics are based on a combination of on-site generation and power purchased from the utility. Microgrid resources, in addition to fossil-fuel generation, also include hydro and solar power. Load curtailment is applied during the two-week islanded mode.

To calculate microgrid performance metrics, it is necessary to calculate the total generation, fossil fuel consumption, NOX emissions, SO_2 emissions, and CO_2 emissions, from all of the sources used to meet the load of the microgrid - which is a combination of power purchased from the utility and on-site supply-side. It should be noted that the microgrid performance metrics are calculated based on per unit of microgrid load.

Table 5-5 presents the microgrid distributed generation characteristics. Heat Rate and Emission Rates shown in Table 5-5 were used in determining the fuel consumptions and emissions of the on-site microgrid fossil fuel based generation. The data used are from a GE Jenbacher Gas IC Engine, namely, GE Jenbacher JMS 320 GS-N.L., 1800 RPM, with a nameplate capacity of 1,050 kW.

The data is from a publicly available source, namely the State of Connecticut[3] (and not from an internal GE source).

Table 5-5: Microgrid DG Characteristics – Fuel Based

Heat Rate	(Btu/kWh)	9,760
NOX Emission	(lb/MMBtu)	0.1527
SO_2 Emission	(lb/MMBtu)	0.0006
CO_2 Emission	(lb/MMBtu)	116.88

Heat Rate and Emission Rates for the power purchased from the utility are based on the average grid system-wide rates determined by GE MAPS simulation. These rates were calculated for the total of EI U.S. Pools and for NYISO only.

Table 5-6 presents the same metrics in per load based units, by converting the (lb/MMBtu) values to (lb/MWh) values using the assumed DG Heat Rate.

Table 5-6: Microgrid DG Characteristics – Load Based

Heat Rate	(Btu/kWh)	9,760
NOX Emission	(lb/MWh)	1.4904
SO_2 Emission	(lb/MWh)	0.0059
CO_2 Emission	(lb/MWh)	1,140.75

[3] Source: "air_emissions_from_smaller-scale_electric_generation_resources_review.xlsx" http://www.ct.gov/deep/lib/deep/air/regulations/proposed_and_reports/air_emissions_from_smaller-scale_electric_generation_resources_review.xlsx

5.1.3 Microgrid Performance Metrics

5.1.3.1 Comparison to EI U.S. Pools and NYISO

Table 5-7 presents the results of the study. The first two sets of rows present the performance metrics calculated for the whole EI territory and for the NYISO territory. The other two sets of rows show the results for the two previously described scenarios (A and B) relating to National Grid rate schedules SC-3A and SC-7 respectively.

Table 5-7: Microgrid Performance Metrics

Scenario	Metric	Unit	Value	Relative to EI	Relative to NYISO
EI - No MG Generation	Utility Purchase	(kWh)	63,857,206	0.0%	0.0%
EI - No MG Generation	MG Generation + Load Shed	(kWh)	0	0.0%	0.0%
EI - No MG Generation	Average Heat Rate	(Btu/kWh)	8,676	0.0%	21.9%
EI - No MG Generation	NOX Emissions	(lb/MWh)	0.7513	0.0%	290.7%
EI - No MG Generation	SO_2 Emissions	(lb/MWh)	1.6298	0.0%	2167.4%
EI - No MG Generation	CO_2 Emissions	(lb/MWh)	1,424.39	0.0%	225.2%
NYISO - No MG Generation	Utility Purchase	(kWh)	63,857,206	0.0%	0.0%
NYISO - No MG Generation	MG Generation + Load Shed	(kWh)	0	0.0%	0.0%
NYISO - No MG Generation	Average Heat Rate	(Btu/kWh)	7,118	-18.0%	0.0%
NYISO - No MG Generation	NOX Emissions	(lb/MWh)	0.1923	-74.4%	0.0%
NYISO - No MG Generation	SO_2 Emissions	(lb/MWh)	0.0719	-95.6%	0.0%
NYISO - No MG Generation	CO_2 Emissions	(lb/MWh)	438.00	-69.2%	0.0%
Microgrid Scenario A	Utility Purchase	(kWh)	3,801,155	-94.0%	-94.0%
Microgrid Scenario A	MG Generation + Load Shed	(kWh)	60,056,051	0.0%	0.0%
Microgrid Scenario A	Average Heat Rate	(Btu/kWh)	7,500	-13.6%	5.4%
Microgrid Scenario A	NOX Emissions	(lb/MWh)	1.2419	65.3%	545.8%
Microgrid Scenario A	SO_2 Emissions	(lb/MWh)	0.0091	-99.4%	-87.3%
Microgrid Scenario A	CO_2 Emissions	(lb/MWh)	967.87	-32.1%	121.0%
Microgrid Scenario B	Utility Purchase	(kWh)	26,994,109	-57.7%	-57.7%
Microgrid Scenario B	MG Generation + Load Shed	(kWh)	36,863,098	0.0%	0.0%
Microgrid Scenario B	Average Heat Rate	(Btu/kWh)	7,020	-19.1%	-1.4%
Microgrid Scenario B	NOX Emissions	(lb/MWh)	0.7704	2.5%	300.6%
Microgrid Scenario B	SO_2 Emissions	(lb/MWh)	0.0331	-98.0%	-54.0%
Microgrid Scenario B	CO_2 Emissions	(lb/MWh)	712.63	-50.0%	62.7%

Table 5-8 presents only the power generation and CO_2 emission changes of the two microgrid scenarios relative to EI and NYISO.

Table 5-8: Microgrid Performance Metrics - Abridged

Scenario	Metric	Unit	Value	Relative	Relative

				to EI	to NYISO
EI - No MG Generation	Utility Purchase	(kWh)	63,857,206	0.0%	0.0%
EI - No MG Generation	MG Generation + Load Shed	(kWh)	0	0.0%	0.0%
EI - No MG Generation	CO_2 Emissions	(lb/MWh)	1,424.39	0.0%	225.2%
NYISO - No MG Generation	Utility Purchase	(kWh)	63,857,206	0.0%	0.0%
NYISO - No MG Generation	MG Generation + Load Shed	(kWh)	0	0.0%	0.0%
NYISO - No MG Generation	CO2 Emissions	(lb/MWh)	438.00	-69.2%	0.0%
Microgrid Scenario A	Utility Purchase	(kWh)	3,801,155	-94.0%	-94.0%
Microgrid Scenario A	MG Generation + Load Shed	(kWh)	60,056,051	0.0%	0.0%
Microgrid Scenario A	CO_2 Emissions	(lb/MWh)	967.87	-32.1%	121.0%
Microgrid Scenario B	Utility Purchase	(kWh)	26,994,109	-57.7%	-57.7%
Microgrid Scenario B	MG Generation + Load Shed	(kWh)	36,863,098	0.0%	0.0%
Microgrid Scenario B	CO_2 Emissions	(lb/MWh)	712.63	-50.0%	62.7%

Table 5-9 presents the performance metrics of all EI U.S. Pools for comparison. As can be seen, NYISO appears to have the lowest average heat rate (a measure of energy efficiency), and the lowest NOX, SO_2, and CO_2 emission rates among all of the U.S. Pools.
This finding implies that if a microgrid's performance is measured against the average performance metrics of its regional pool, then New York microgrids' performance metrics may appear to be worse than the performance metrics of microgrids in other regional pools, simply due to the overall higher efficiency and cleaner generation of the NYISO.

Table 5-9: Performance Metrics of EI U.S. Pools

EI U.S. Pools	Average Heat Rate (Btu/kWh)	Average NOX Emissions (lb/MWh)	Average SO2 Emissions (lb/MWh)	Average CO2 Emissions (lb/MWh)
FRCC	8,063	0.3317	0.6527	2,026.99
ISONE	7,979	0.1999	0.2072	561.19
MISO	8,814	0.9917	2.6089	2,045.91
NYISO	7,118	0.1923	0.0719	438.00
PJM	9,212	0.7841	1.9400	1,149.27
SERCE	9,282	0.4596	0.4074	860.05
SERCN	8,672	0.9728	1.8604	1,303.53
SERCSE	8,229	0.2960	0.2997	1,024.75
SPP	8,177	1.2797	2.1629	1,865.25
Grand Total	8,676	0.7513	1.6298	1,424.39

The following section presents the key observations from the study and provides more detailed description of the tabulated results.

5.1.3.2 Observations and Conclusions

The following observations are made based on the results of the study summarized in the tables of the previous section:

- Potsdam Resilient Microgrid achieves high reduction in power purchased from the utility in both microgrid scenarios. Microgrid Scenario A results in 94.0% reduction in power purchased from the utility, while Scenario B results in 57.7% reduction. These reductions are highly dependent on the underlying utility rate schedules, microgrid delivered fuel prices, and efficiency of the microgrid distributed generation. Consequently, the results for this specific microgrid cannot easily be generalized to other situations or microgrids in other locations.
- Both microgrid scenarios achieve significantly lower carbon footprint due to high CO_2 reductions compared to the EI U.S. Pools' average CO_2 emission rates, namely, 32.1% reduction for microgrid Scenario A and 50.0% reduction for Scenario B.
- Microgrid Scenario A which had minimal power purchase from the utility, achieved an average CO_2 emission rate of 967.87 lb/MWh, which is actually less than the average CO_2 emission rate of most EI U.S. Pools.
- Microgrid Scenario B, which purchased about 42% of its energy needs from the utility, achieved an average CO_2 emission rate of 712.63 lb/MWh, which is actually less than the average CO_2 emission rate of all EI U.S. Pools except for ISONE and NYISO.
- Hence, compared to the average CO_2 emission rates of most U.S. regions, the two microgrid scenarios achieved lower CO_2 emission rates.
- However, both microgrid scenarios do poorly relative to the NYISO average CO_2 emission rate: Microgrid Scenario A's CO_2 emission rate is higher by 121.0%, and microgrid Scenario B's CO_2 emission rate is higher by 62.7%.
- The main reason for the higher CO_2 emissions rates of the two microgrid scenarios compared to the NYISO is that, to begin with, NYISO has a very low average CO_2 emission rate compared to the EI U.S. Pool average, and indeed it appears to be one the lowest CO_2 emitting power pools on per MWh basis, as shown in Table 5-9.
- As indicated earlier, the average CO_2 emissions of the microgrid on-site generation was assumed to be 1,140.75 lb/MWh (based on a GE Jenbacher IC engine), which is substantially higher than the average CO_2 emissions of most of the EI U.S. Pools. Inclusion of renewable energy in the microgrid, which in Potsdam consists of hydro and solar resources, resulted in lowering the average microgrid CO_2 emission rate. In fact, due to high emission rate of on-site fossil generation, more power purchase from the utility would reduce the microgrid average CO_2 emission rate.
- Therefore, to lower the microgrid emission rate, the main two options are (a) to employ more renewable energy resources, and (b) to install more efficient and cleaner fossil-fuel based generation.
- Relative to the EI U.S. Pools, the NYISO market appears to be more efficient (i.e., lower average heat rate), and have a lower NOX, SO_2, and CO_2 emission rates. Hence, the two microgrid scenarios do better than most of the EI U.S. pools but do not fare as well compared to the NYISO averages.
- Therefore, if a microgrid's performance is measured against the average performance metrics of its regional pool, then New York microgrids' performance metrics may appear to be worse than the performance metrics of microgrids in other regional pools, simply due to the overall higher efficiency and cleaner generation of the NYISO.

- Both microgrid scenarios improved on the EI average heat rate, but only Scenario B did better than the NYISO average heat rate. The average heat rate depends on the underlying heat rates of the constituent generation resources in the system and in the microgrid. The reason Scenario B did better than Scenario A is that Scenario A had minimal purchase from the utility in contrast to Scenario B which purchased 42% of its electricity needs from the utility. Although the microgrid had on-site hydro and solar resources, in general, the microgrid fossil-based generation resources which are mainly reciprocating/internal combustion engines, have a relatively higher heat rates. Hence, Scenario B achieved a better balance between on-site power generation versus utility purchase, resulting in a lower average heat rate.
- Under both microgrid scenarios, the NOX emission rates appear to be significantly higher that than the average EI U.S. Pools and NYISO average emission rates. This has to do with high NOX emission rate of the GE Jenbacher engine (i.e., 1.4904 lb/MWh), which is the case for most similarly sized natural gas fueled distributed generation of similar type, relative to grid-scale generation plants with NOX abatement and control technologies.
- Under both microgrid scenarios, the SO_2 emission rates decrease compared to the average SO_2 emission rates of EI U.S. Pools as well as the NYISO. This is due to the very low SO_2 emission rate of the GE Jenbacher engine (i.e., 0.0059 lb/MWh), which is the case for most similarly sized natural gas fueled distributed generation of similar types, relative to the grid-scale generation plants most of which already have SO_2 abatement and control technologies.

Key takeaways from this study are that microgrid performance metrics, as defined in this study, are highly dependent on a number of drivers, which mainly include the following:

- Applicable Utility Electricity Rates
- Delivered Fuel Prices
- Generation Efficiency (i.e., Heat Rate) of microgrid's fossil-fueled distributed generation
- Emission Rates of criterial pollutant (i.e., NOX and SO_2) and GHG (e.g., CO_2) of microgrid's fossil-fueled distributed generation
- Relative size of renewable energy resources in the microgrid

The first three factors, determine the operation of the proposed microgrid and relative amount of power purchase from the utility versus on-site generation, which in turn impact the relative energy efficiency and average heat rate of the microgrid. All five factors impact the emission rates of the microgrid. As shown, even in a single microgrid, one may observe a significant change in microgrid performance metrics under different electricity rate scenarios.

This study can be followed up by performing additional sensitivity analysis in order to evaluate the impact of change in other drivers such as fuel prices, heat rate, and emission rates, in order to demonstrate the range of variations in microgrid performance metrics.

5.1.4 View on Microgrid Reliability

In the course of performing this feasibility study, it was determined that quantification of the reliability impacts of the Potsdam Microgrid would be a daunting task and outside the resource and time constraints of the project, particularly since no established methodology for performing reliability impact analysis of a microgrid was identified. However, a qualitative view on what is

required for going forward is provided herein, with a subjective judgment that by definition, a resilient microgrid would definitely reduce the outage times of the critical microgrid loads.
There are three general types of reliability:

- Impact on bulk power system
- Impact on the distribution system
- Impact on the microgrid itself

It is expected that individual microgrids will have very minor impact on the reliability of the bulk power/transmission system, or even at the ISO/RTO level. Inclusion of a single microgrid in bulk system reliability analysis and simulation, such as one using the GE Multi Area Reliability Simulation (GE MARS) model, would appear as “noise”. Deploying more microgrids in the NY State would have a more tangible impact in aggregate, but to our knowledge, there are no studies that have looked at the bulk power reliability impact of more widely deployed microgrids. Models such as GE MARS can be enhanced to include microgrids and DG in order to account for their impact on bulk power reliability, and also to determine DG “capacity valuation”, which can be used in qualification of DG and microgrids in ISO capacity markets.

The principal reliability impact of microgrids would be expected to be on the distribution system. The distribution system engineering experts on the study team did consider the problem of quantifying the distribution system reliability impact of microgrids. Their consensus was that none of the currently available software tools and models has the required functionality that would account for the distribution system and feeder reliability impact of microgrids (i.e., impact on SAIFI, CAIDI, etc.) during normal (blue sky) days. It is expected that microgrids will help with reduction of the interruption durations of the critical loads and also the associated interruption costs during normal (blue sky) days.

Furthermore, it is believed that the industry has yet to develop a “resiliency” metric. The Potsdam Microgrid is being designed as a “resilient microgrid”, i.e., to be able to provide continuous power to critical facilities during emergencies and grid outages lasting up to two weeks. The industry reliability metrics (i.e., SAIFI, CAIDI, etc.) are not applicable to resilient microgrids during system-wide emergency/outage periods, mainly because an islanded microgrid looks like unserved load from the utility’s perspective. Hence, developing a “resiliency” metric would be something novel.

A possible follow-up study would be first to do an evaluation and assessment of various existing modeling tools and identify the best tool suitable for evaluation of distribution level reliability impact analysis during the blue-sky days. If such a tool cannot be found, the results of the study could then be used to adapt/enhance the model(s) with the appropriate functionality that would enable them to evaluate the distribution system reliability. In any event, developing and defining a “resiliency metric” would be essential.

Regarding a microgrid’s own reliability, it is readily apparent that the resiliency feature of the Potsdam Resilient Microgrid would vastly improve the reliability of the electricity supply to critical loads by enabling uninterrupted power during any prolonged outages of the main grid. Simply put, the Potsdam Resilient Microgrid would ride through the grid outages, and then only be subject to forced outage rates of its own on-site generation.

5.2 One Line Diagrams & Asset Descriptions

5.2.1 Proposed Potsdam, NY microgrid

The proposed Potsdam, NY microgrid includes the assets listed in Table 10, and shown on the one-line diagram of Figure 22. The load description is given in Figure 23 through Figure 25. More detail is given in the Feasibility Study included in this report as Appendix 5.1.

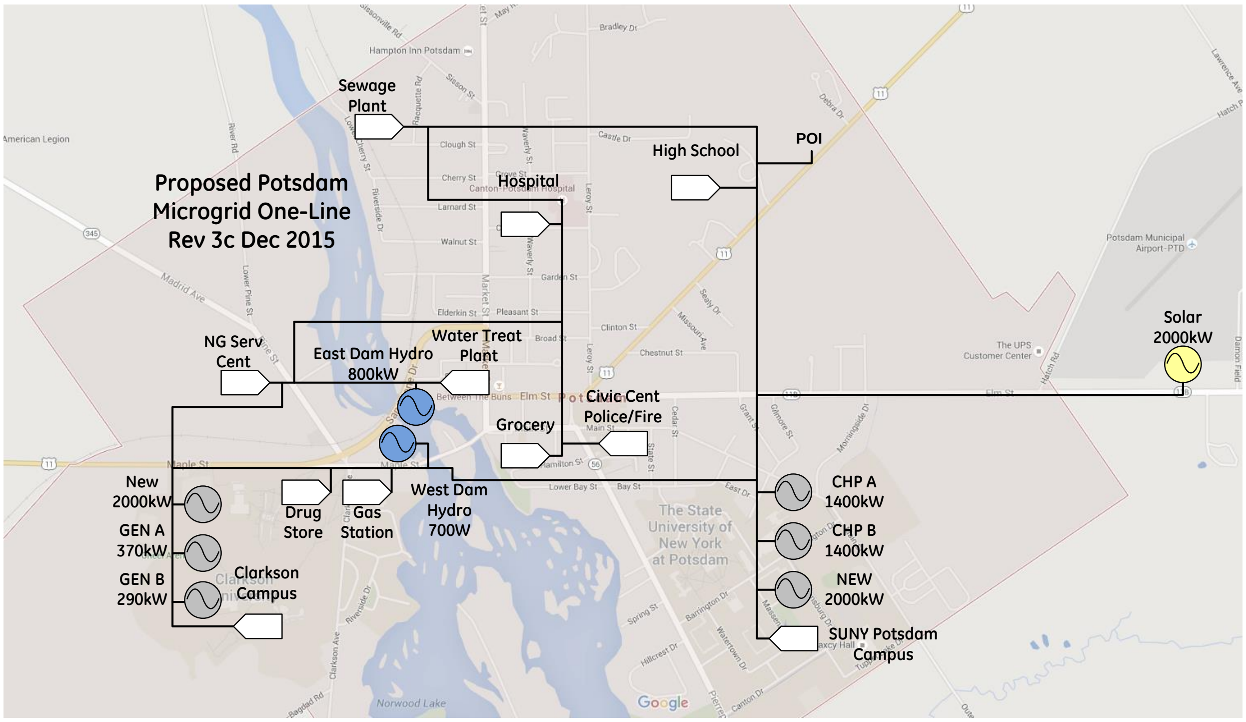

Figure 22 Proposed one-line diagram overlaid on a map of the community (Google Maps)

Table 10 List of key generation assets for the proposed Potsdam, NY microgrid *

Microgrid Asset	Type	Rating	Comment
East Dam	River Hydro	800 kW**	400 kW off season
West Dam	River Hydro	700 kW**	350 kW off season
Clarkson Gen A	CNG CHP	370 kW	
Clarkson Gen B	CNG CHP	145 kW	
SUNY CHP A	CNG CHP	1400 kW	
SUNY CHP B	CNG CHP	2000 kW	blackstart, V&F control capable
Clarkson PV	Solar	2000 kW	at airport
Clarkson NEW	CNG CHP	1000 kW	proposed addition
SUNY NEW	CNG CHP	1000 kW	proposed addition
EngStor NEW	BESS	1000 kW	optional addition at NG serv. cent.

* detailed descriptions of assets are given in the Feasibility Study of Appendix 5.1.
** seasonal variation, spring rating given

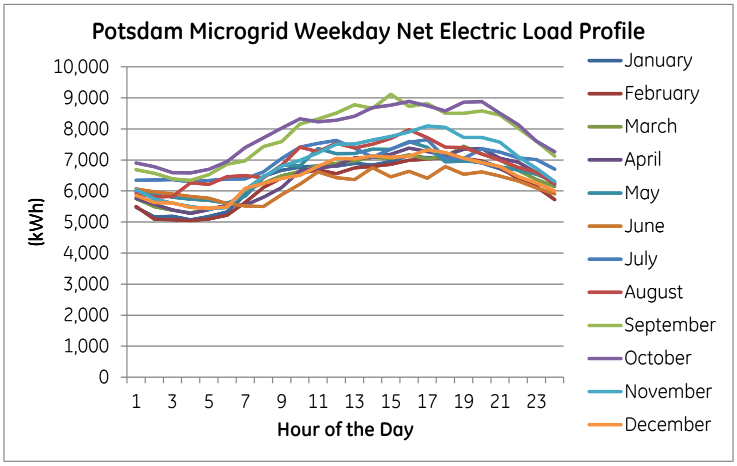

Figure 23 Potsdam microgrid participant weekday load profiles.

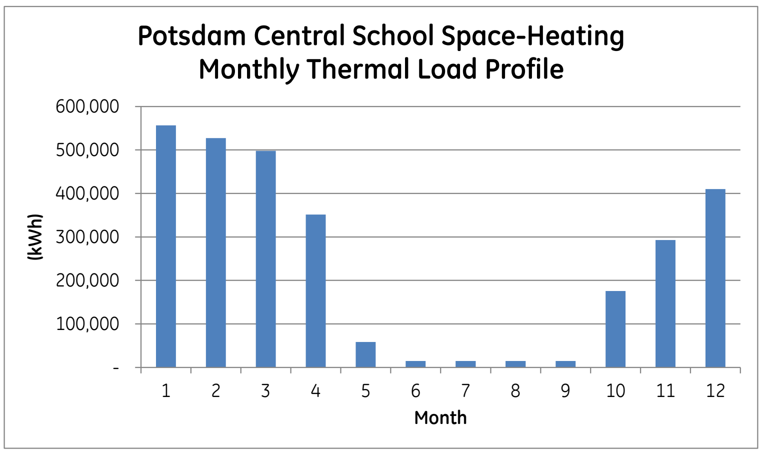

Figure 24 Potsdam Central School space-heating annual load profile.

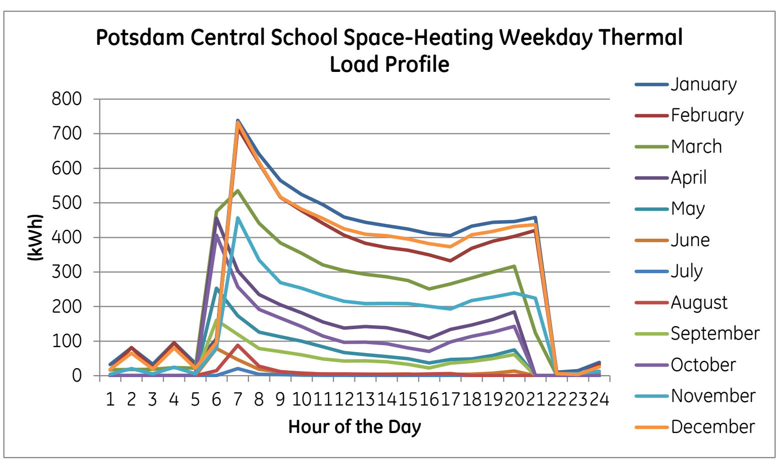

Figure 25 Potsdam Central School space-heating weekday load profile

5.2.2 Asset Models for Simulations

The below list of generation assets in Table 11 lists the key parameters that were used during the simulation testing of the dispatch function.

Table 11 List of generation assets for use in the dispatch simulation testing

Fuel [type]	Max Pow [MW]	Min Pow [MW]	Up Ramp [MW/s]	Down Ramp [MW/s]	Eff Min P [MWh/kg]	Eff Max P [MWh/kg]	Comment
diesel	0.3	0.15	0.1	0.1	0.00403	0.00442	general model
diesel	0.6	0.3	0.1	0.1	0.00423	0.00459	general model
diesel	1	0.5	0.1	0.1	0.00426	0.00474	general model
diesel	1.6	0.8	0.1	0.1	0.00417	0.00447	general model
CNG	0.34	0.102	0.001	0.001	0.00385	0.00570	Jenbacher J208
CNG	0.4	0.060	0.034	0.034	0.00308	0.00493	Waukesha VGF
CNG	0.63	0.189	0.003	0.003	0.00385	0.00586	Jenbacher J312
CNG	0.85	0.255	0.003	0.003	0.00385	0.00586	Jenbacher J316
CNG	1.2	0.180	0.102	0.102	0.00308	0.00493	Waukesha VHP
CNG	1.4	0.210	0.070	0.070	0.00585	0.00638	Jenbacher J420
CNG	2.4	0.360	0.012	0.012	0.00600	0.00640	Waukesha 275GL+
CNG	2.7	1.350	0.008	0.008	0.00385	0.00694	Jenbacher J616
CNG	4.4	2.200	0.015	0.015	0.00385	0.00709	Jenbacher J624

5.2.3 RTDS virtual one-line diagram

The GE power system lab performed CHIL testing with the assets shown on the one-line diagram of Figure 26.

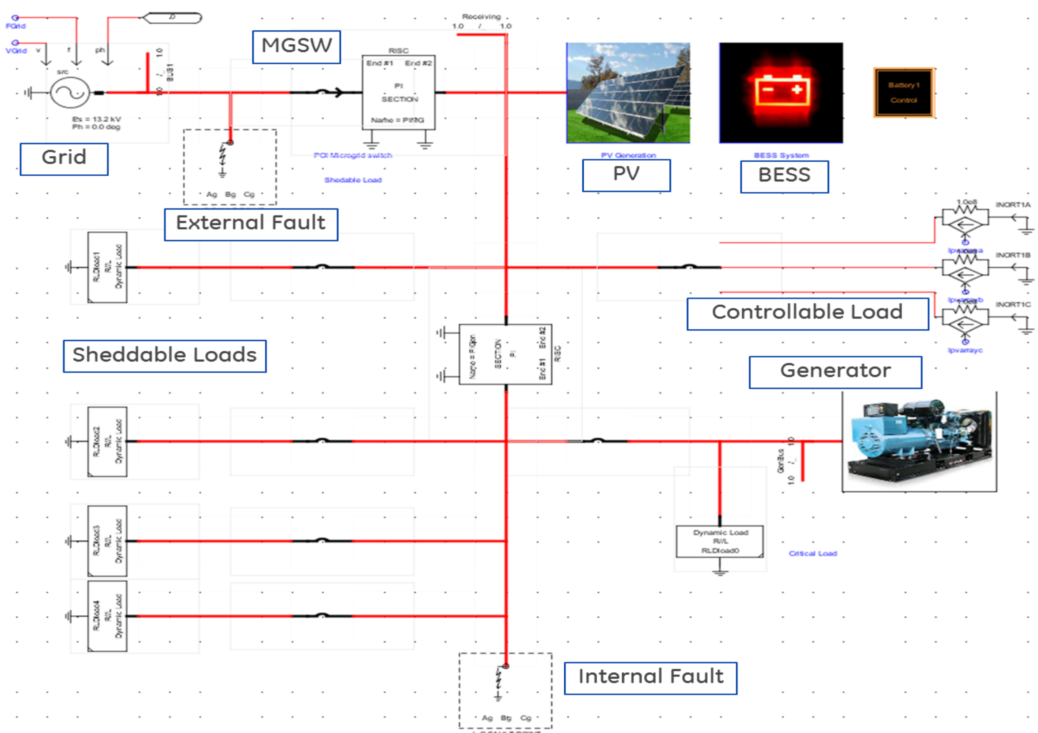

Figure 26 Real Time Digital Simulation one-line diagram with typical elements.

Control hardware to RTDS interface via IEC 61850 over Ethernet.

Signals include:

RMS voltages on either side of the POI
RMS currents through the POI
instantaneous frequency on either side of the POI
power production from the generator, status of the disconnect relay
power production from the PV system, status of the disconnect relay
power production from the BESS, status of the disconnect relay
RMS currents through the Controllable Load
RMS currents through the Sheddable Loads

5.2.4 NREL one-line diagram

The NREL ESIF lab supported power hardware testing with the assets shown by the one-line diagram of Figure 27.

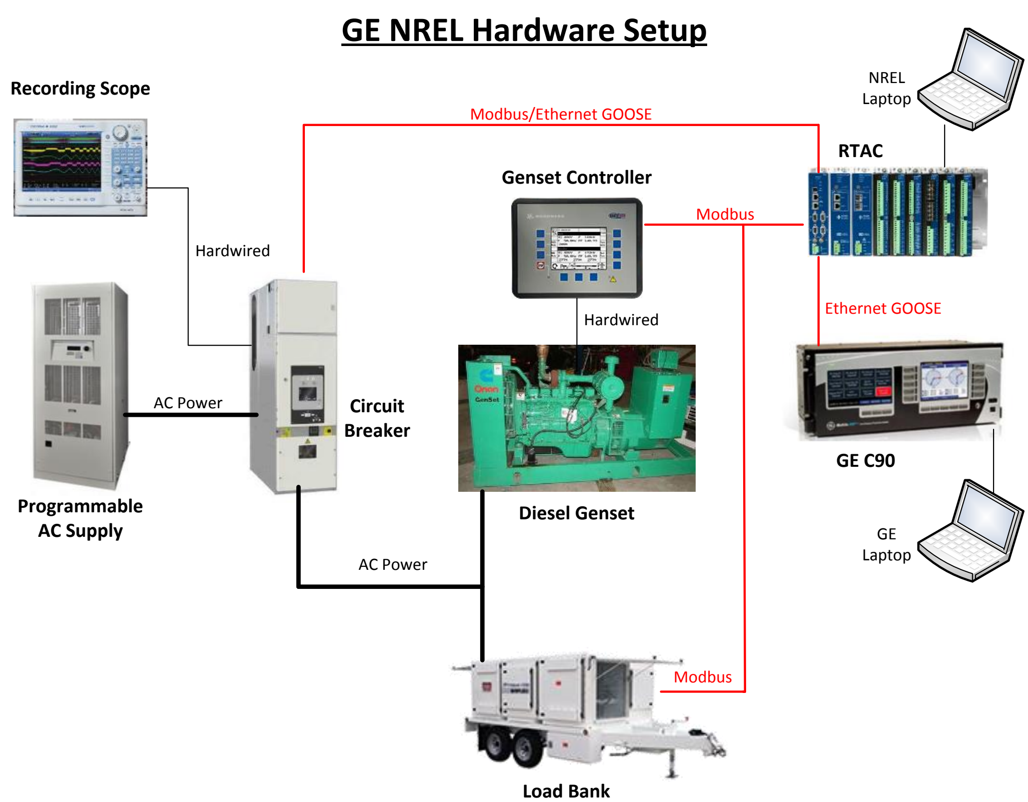

Figure 27 One-line diagram of the power hardware test system at NREL

NREL Hardware Specifications

1. Grid simulator: Amatek RS90
2. Circuit breaker: ABB SACE eMAX 2
3. Real Time Automation Controller: SEL−2241 RTAC Module

4. Diesel Generator: Onan Cummins 80kW Diesel Generator, Model DGDA-3387423, 277/480 Vac, 120 A, 60 Hz, 0.8 power factor
5. Genset Controller: Woodward
6. Load Bank: OSW4c-0390.7-600v34-456D-50w, 390kW, 390kVARi, 390kVARc, 600 Vac (maximum), 3-Phase, 4-Wire, 45-65Hz
7. Recorder: Yokogawa DL850
8. Device Under Test: GE C90

NREL Proposed Hardware Communication Methods

1. Modbus TCP:
    a. Load bank
    b. Woodward
    c. ABB CB
2. IEC 61850 Goose
    a. ABB CB
    b. DUT: GE C90

5.3 NREL detailed test results

5.3.1 Disconnection from grid

5.3.1.1 Case A1: Small Over-voltage

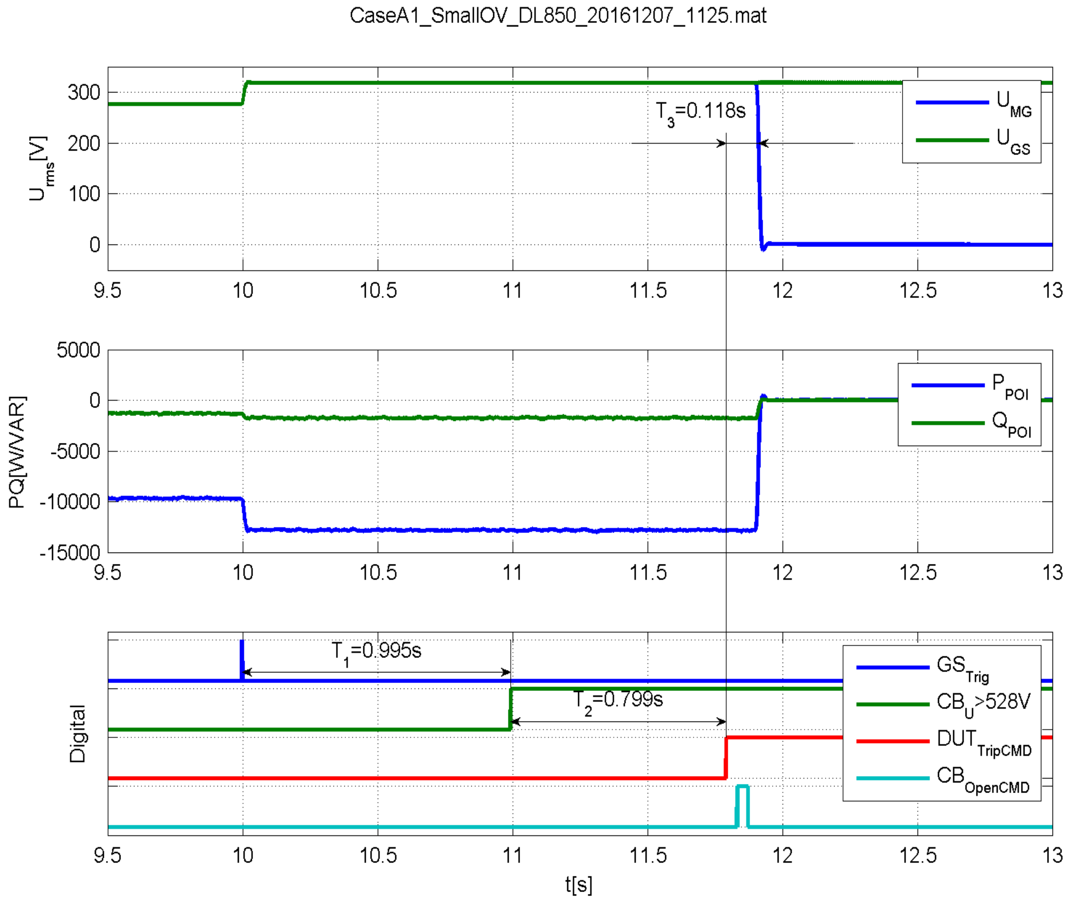

Figure 28 Case A1: Small Over-voltage post processed test results

5.3.1.2 Case A2: Large Over-voltage

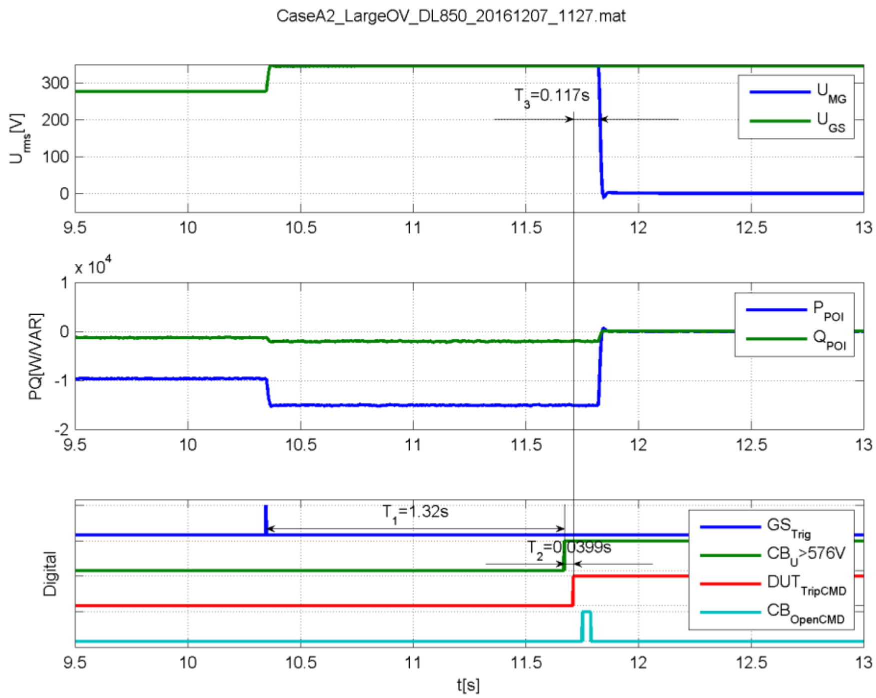

Figure 29 Case A2: Large Over-voltage

5.3.1.3 Case A3: Small Under-voltage

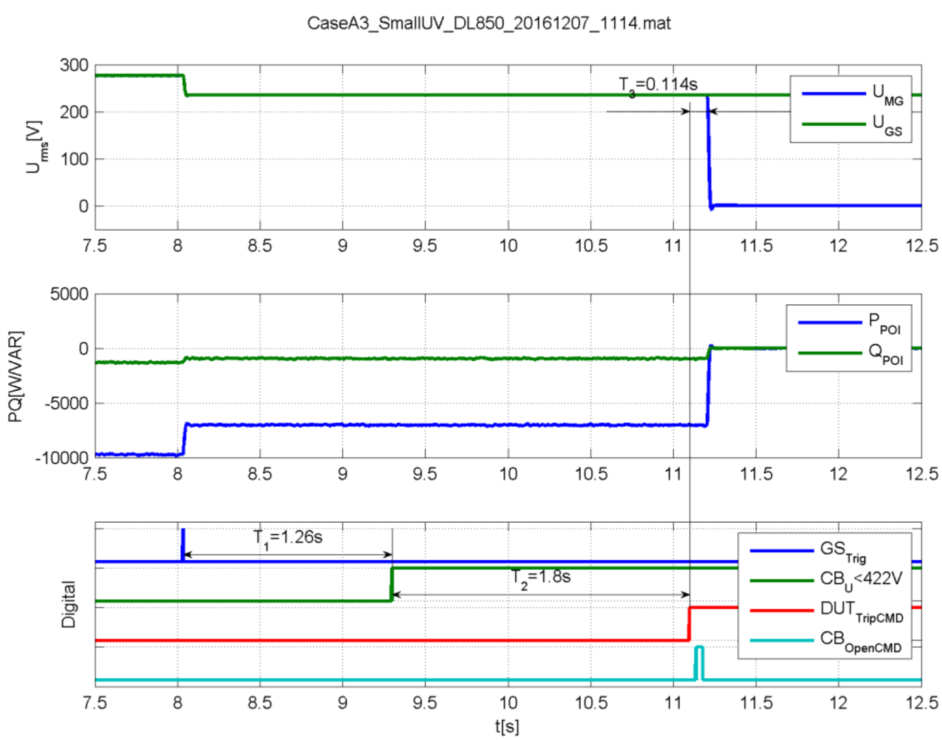

Figure 30 Case A3: Small Under-voltage

5.3.1.4 Case A4: Large Under-voltage

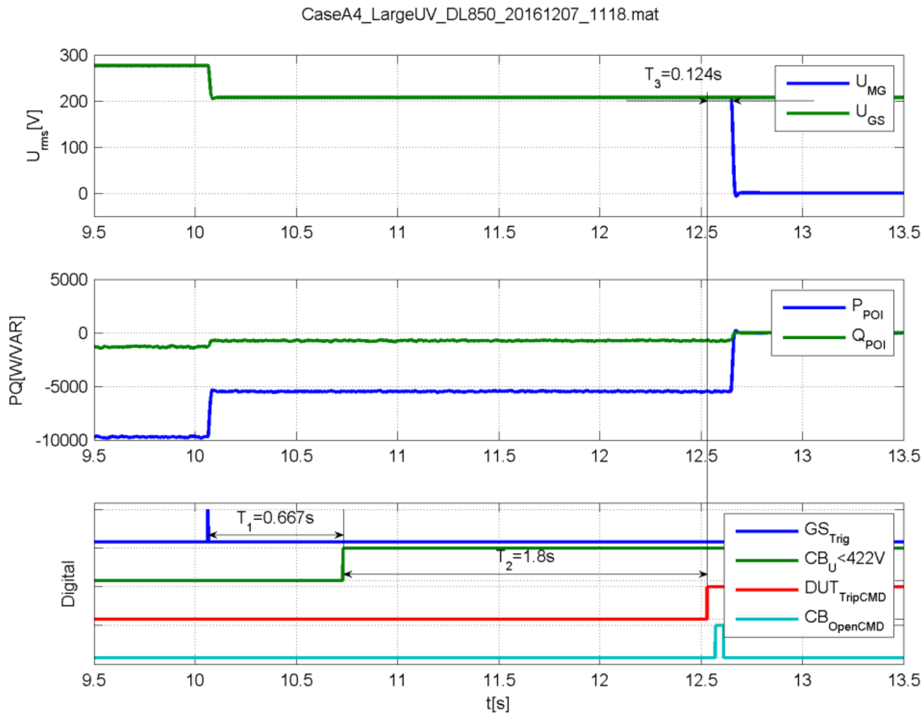

Figure 31 Case A4: Large Under-voltage

5.3.1.5 Case A5: Large Under-voltage

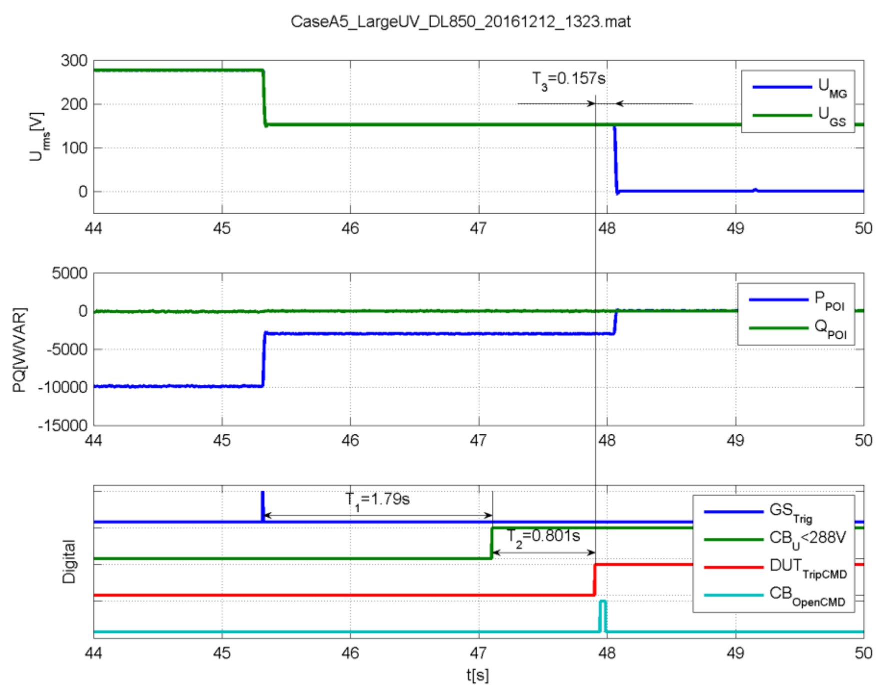

Figure 32 Case A5: Large Under-voltage

5.3.1.6 Case A6: Large Under-voltage

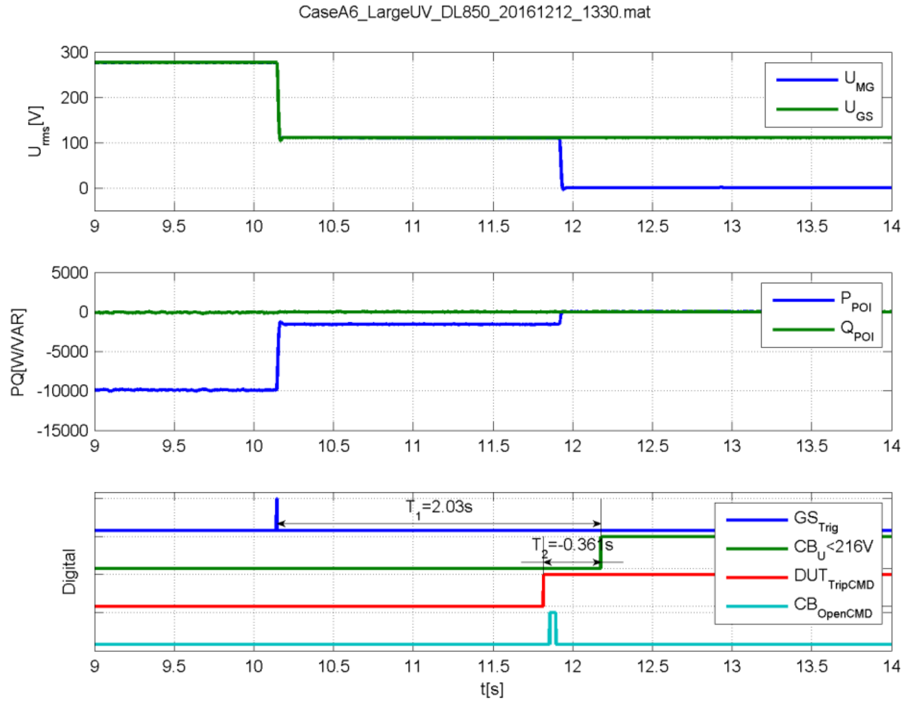

Figure 33 Case A6: Large Under-voltage

5.3.1.7 Case A7: Zero voltage event

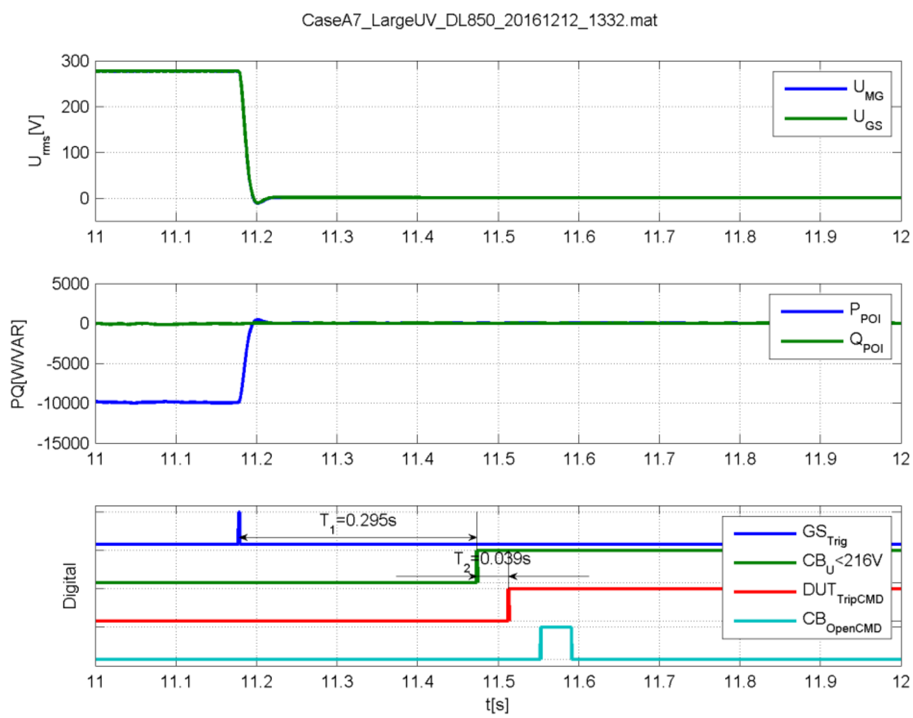

Figure 34 Case A7: Zero voltage event

5.3.1.8 Case B1: Small Under-frequency

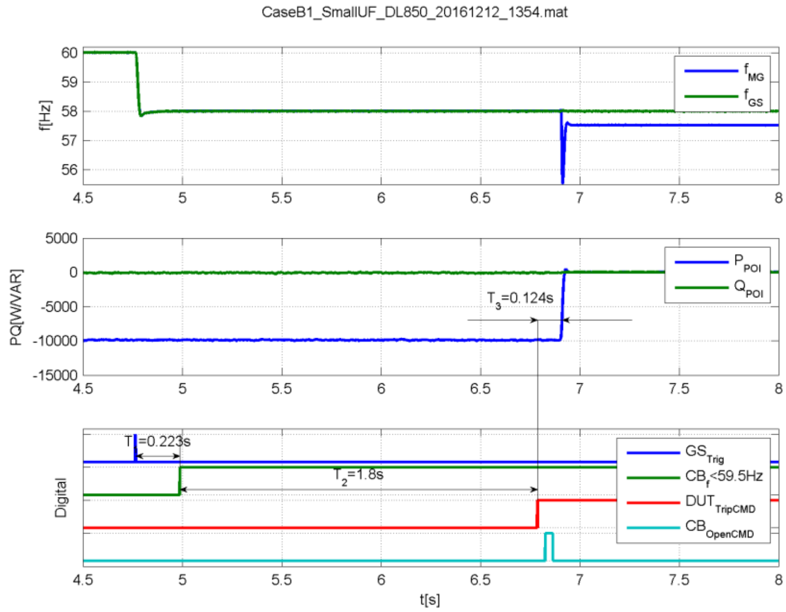

Figure 35 Case B1: Small Under-frequency

At t = 7 seconds, microgrid generator operating in frequency droop mode, not in isochronous V/f control mode.

5.3.1.9 Case B2: Small Over-frequency

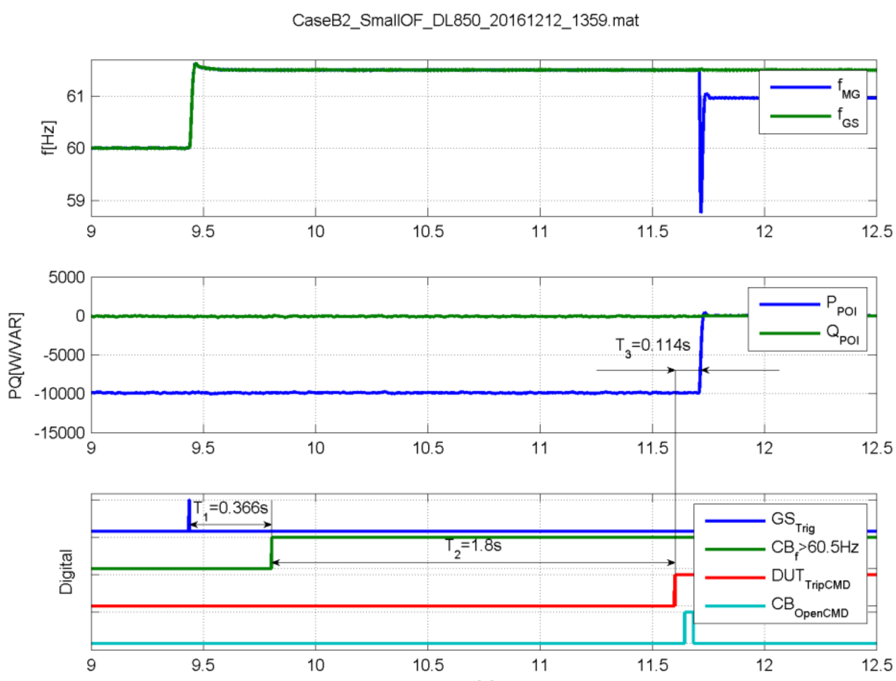

Figure 36 Case B2: Small Over-frequency

At t = 7 seconds, microgrid generator operating in frequency droop mode, not in isochronous V/f control mode.

5.3.1.10 Case B3: Large Under-frequency

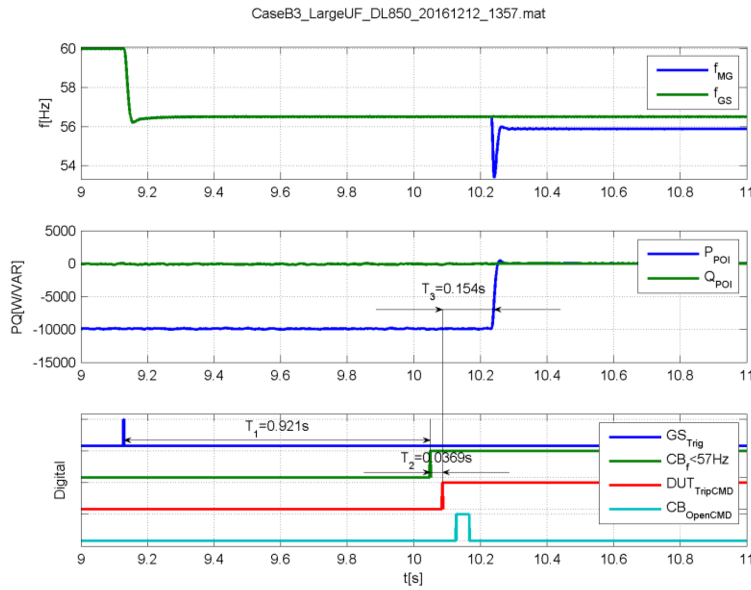

Figure 37 Case B3: Large Under-frequency

At t = 7 seconds, microgrid generator operating in frequency droop mode, not in isochronous V/f control mode.

5.3.1.11 Case B4: Large Over-frequency

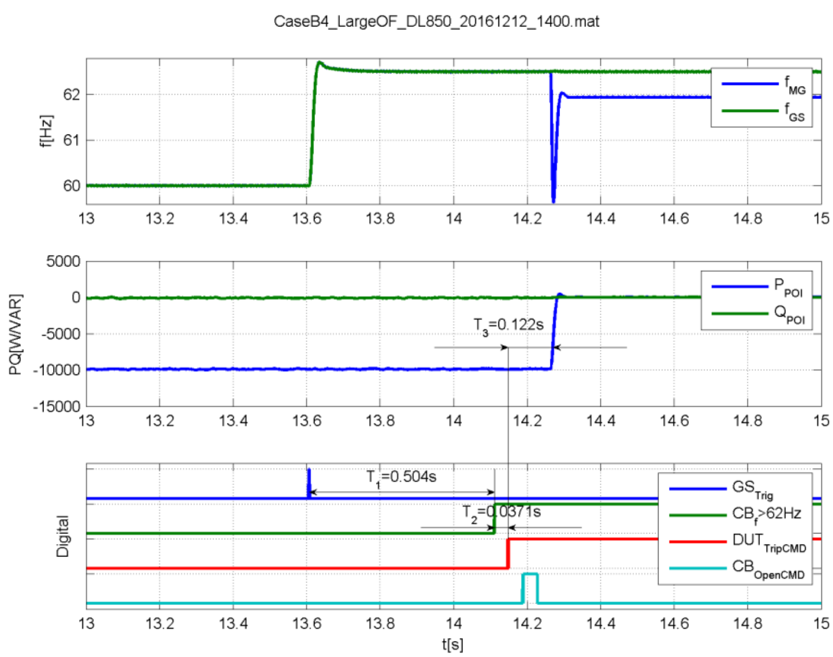

Figure 38 Case B4: Large Over-frequency

5.3.1.12 Case C1: Planned Disconnection at net POI export

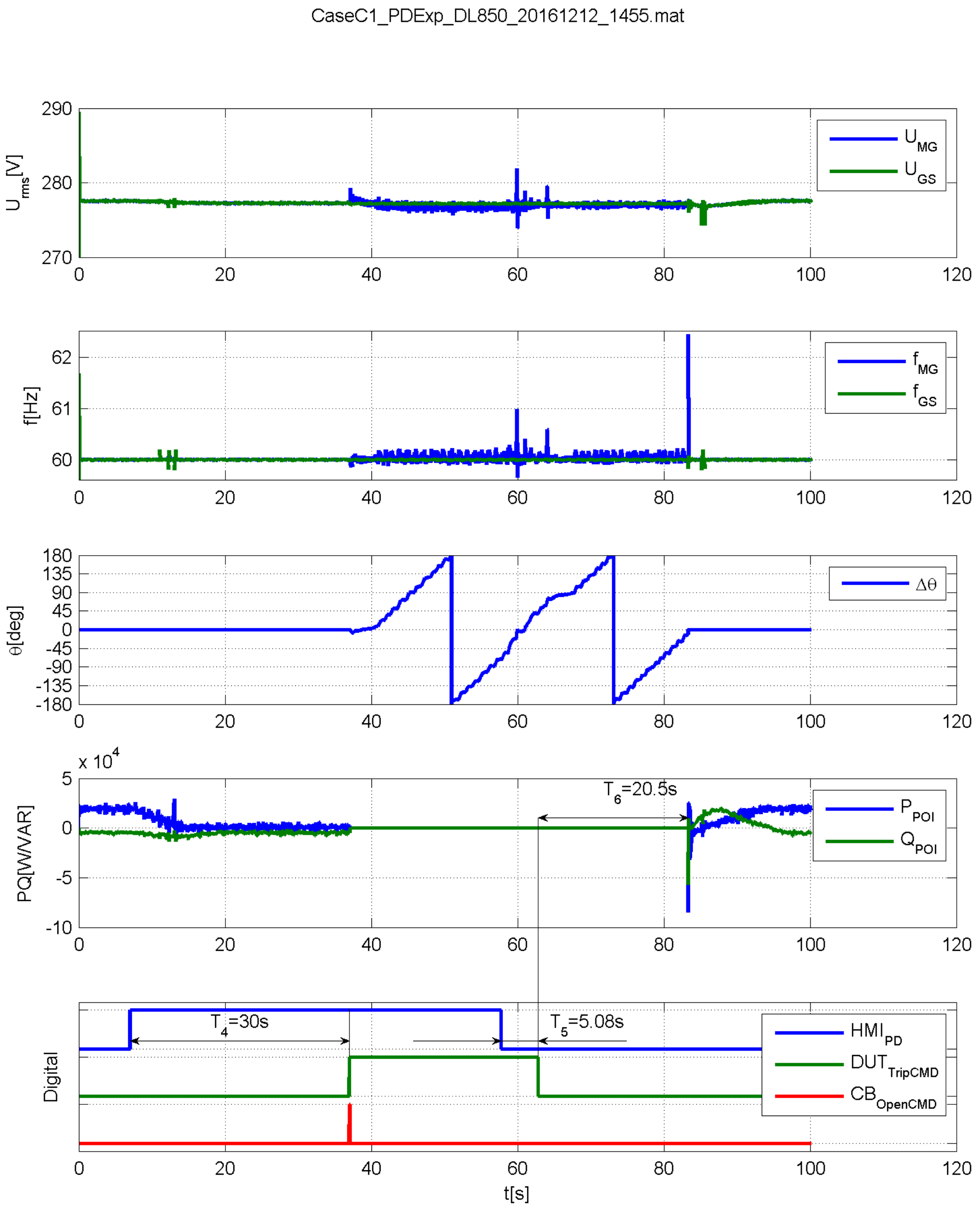

Figure 39 Case C1: Planned Disconnection at net POI export

Between t = 40 to t = 80 seconds, the voltage and frequency of the microgrid are established by the generator control unit which had mistuned parameters.

5.3.1.13 Case C2: Planned Disconnection at net POI import

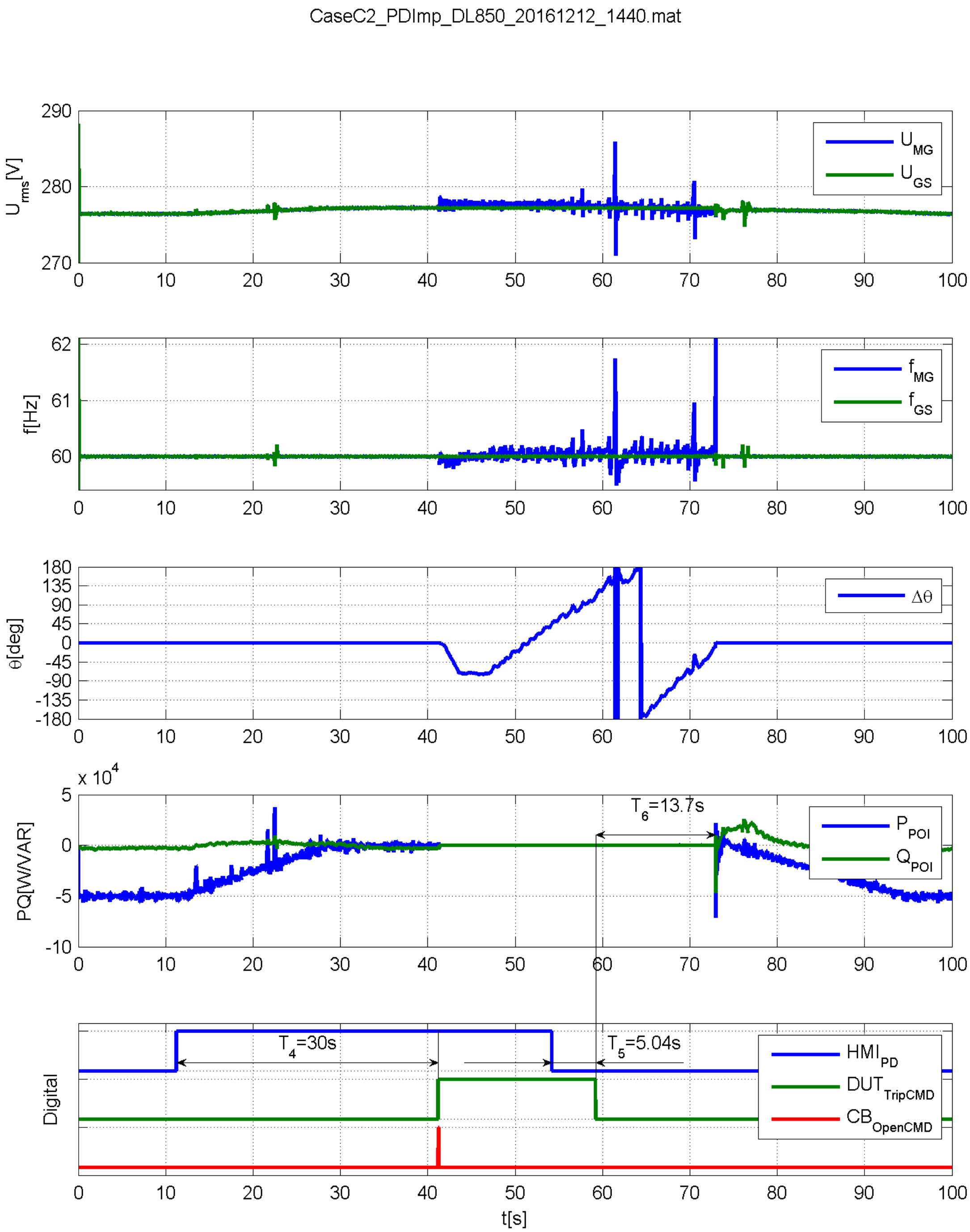

Figure 40 Case C2: Planned Disconnection at net POI import

Between t = 40 to t = 80 seconds, the voltage and frequency of the microgrid are established by the generator control unit which had mistuned parameters.

5.3.1.14 Case C3: Planned Disconnection at net POI export without balance of generation and load

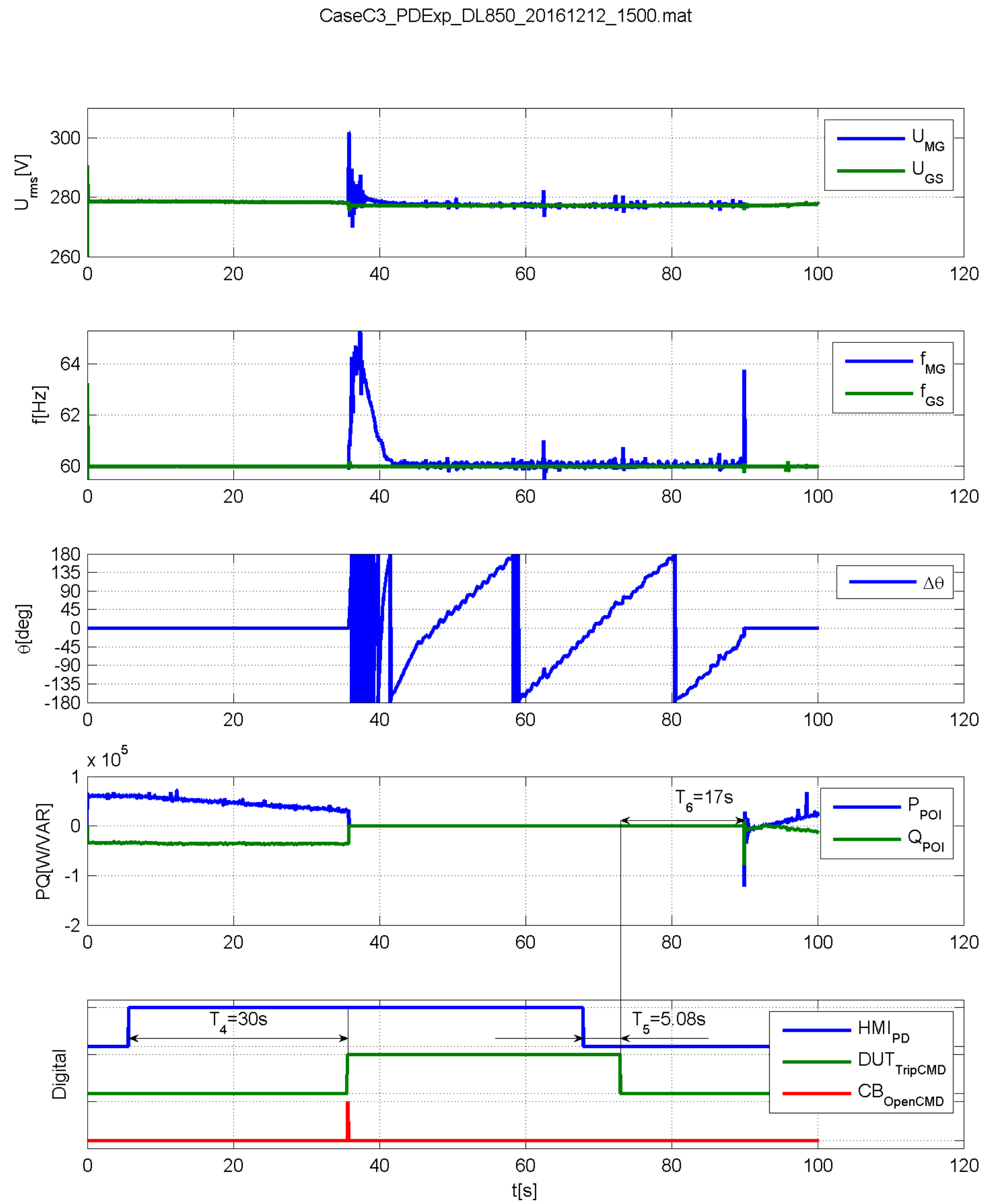

Figure 41 Case C3: Planned Disconnection at net POI export without balance of generation and load

Between t = 35 to t = 85 seconds, the voltage and frequency of the microgrid are established by the generator control unit which had mistuned parameters.

5.3.1.15 Case C4: Planned Disconnection at net POI import without balance of generation and load

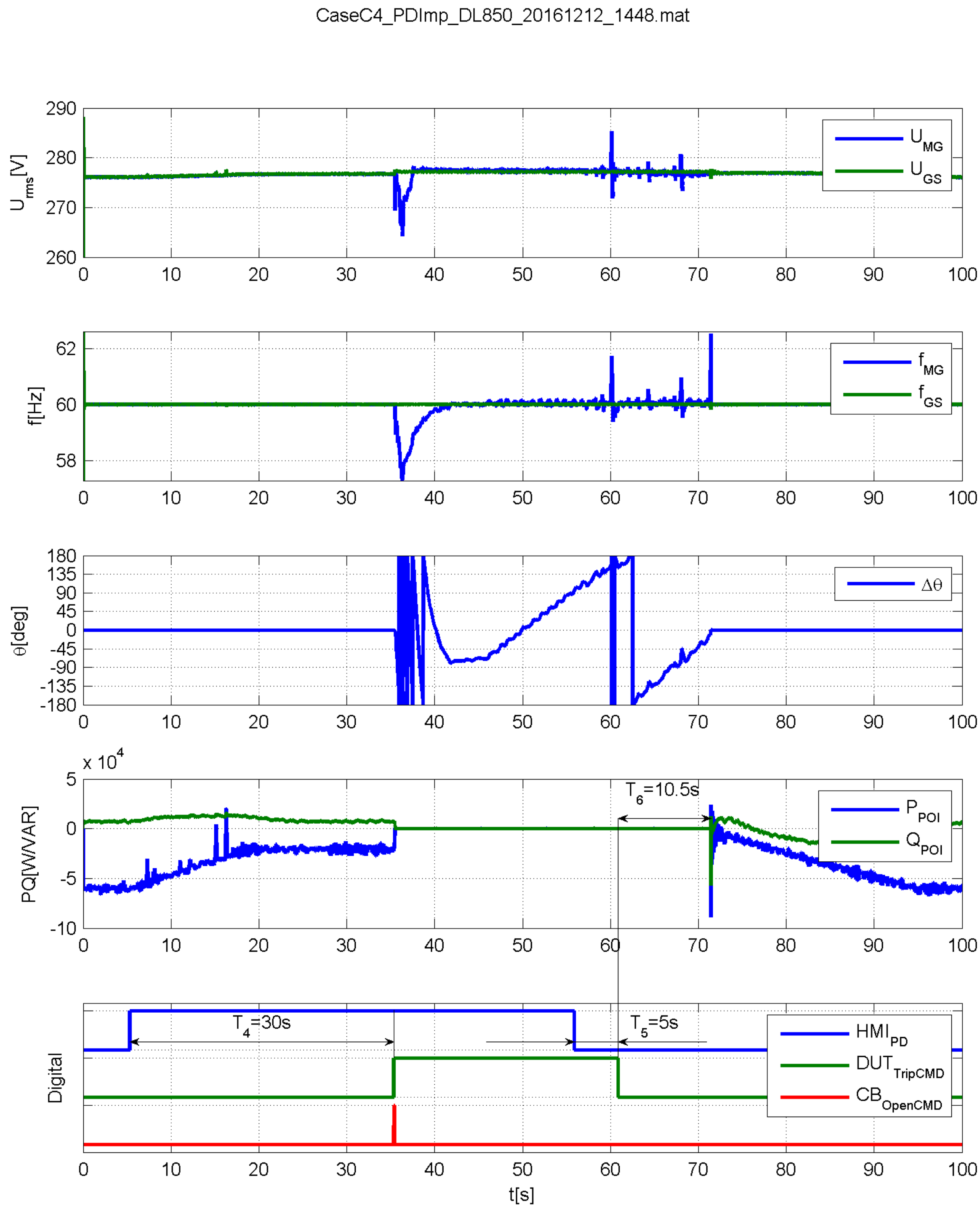

Figure 42 Case C4: Planned Disconnection at net POI import without balance of generation and load

5.3.2 Resynchronization/Reconnection

5.3.2.1 Case D1: Delayed Reconnection – Island blackout and black start

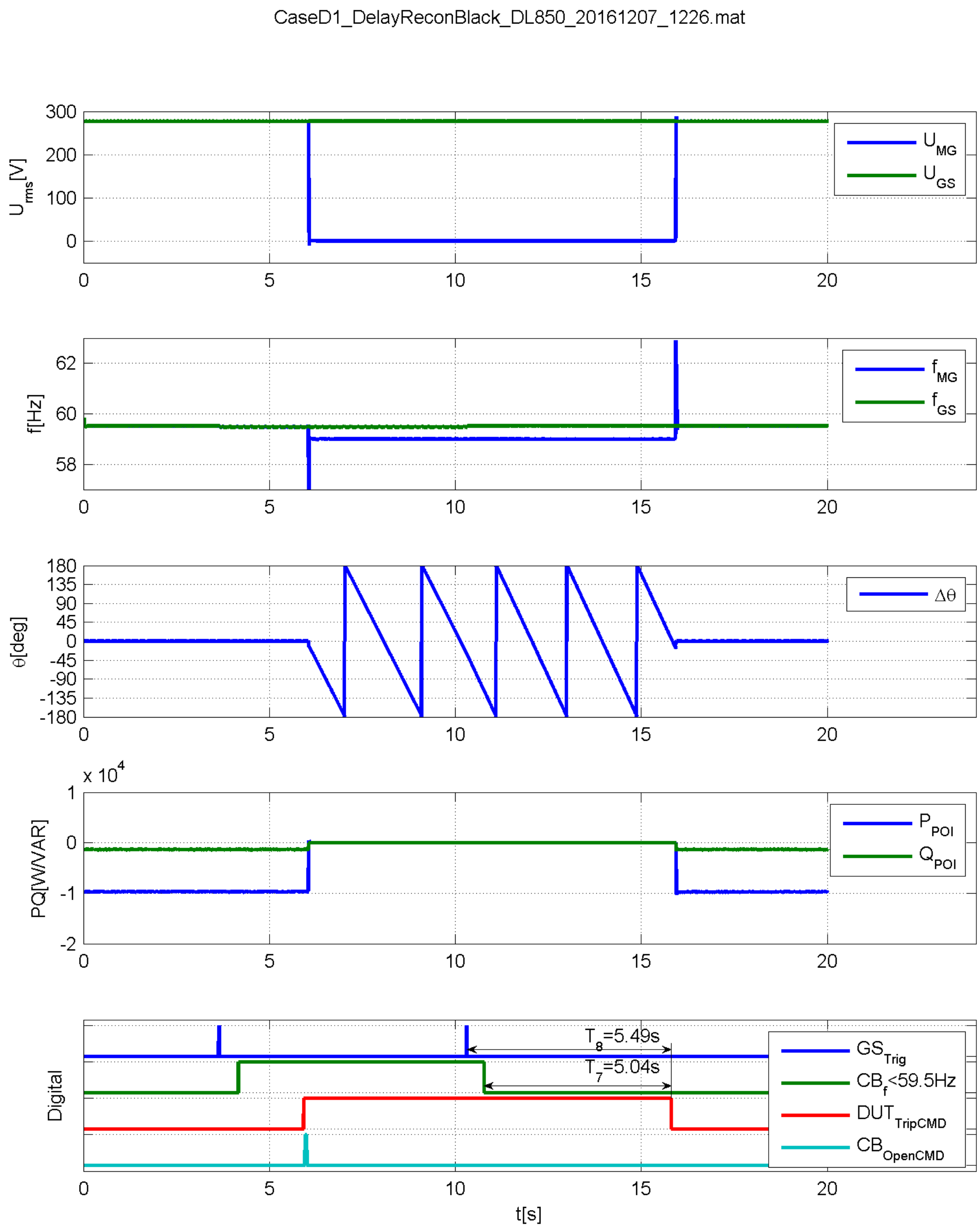

Figure 43 Case D1: Delayed Reconnection – Island blackout and black start

5.3.2.2 Case D2: Delayed Reconnection – Island seamless transition

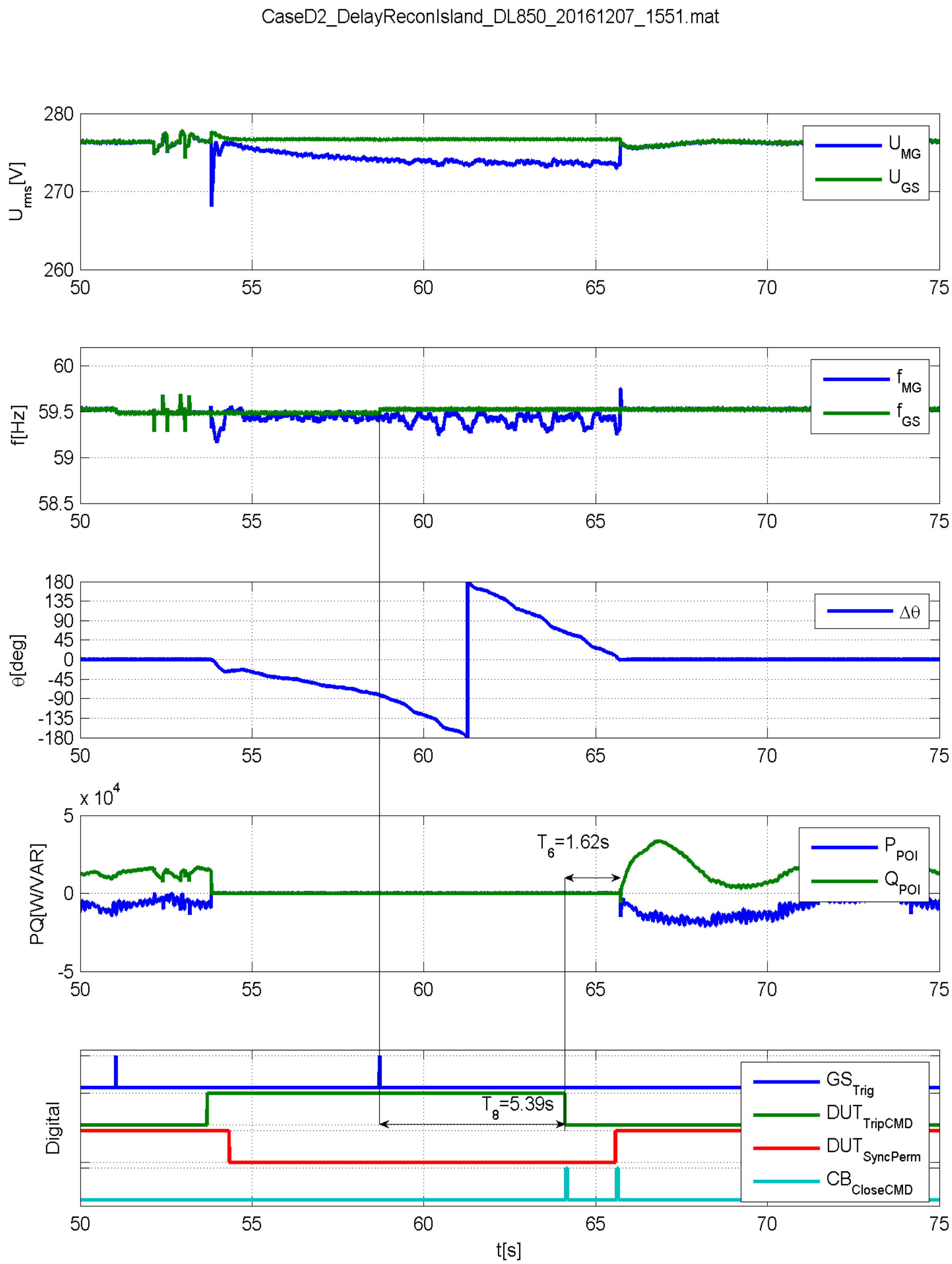

Figure 44 Case D2: Delayed Reconnection – Island seamless transition

5.3.2.3 Case E1: Synchrocheck– phase criterion while microgrid is below grid frequency

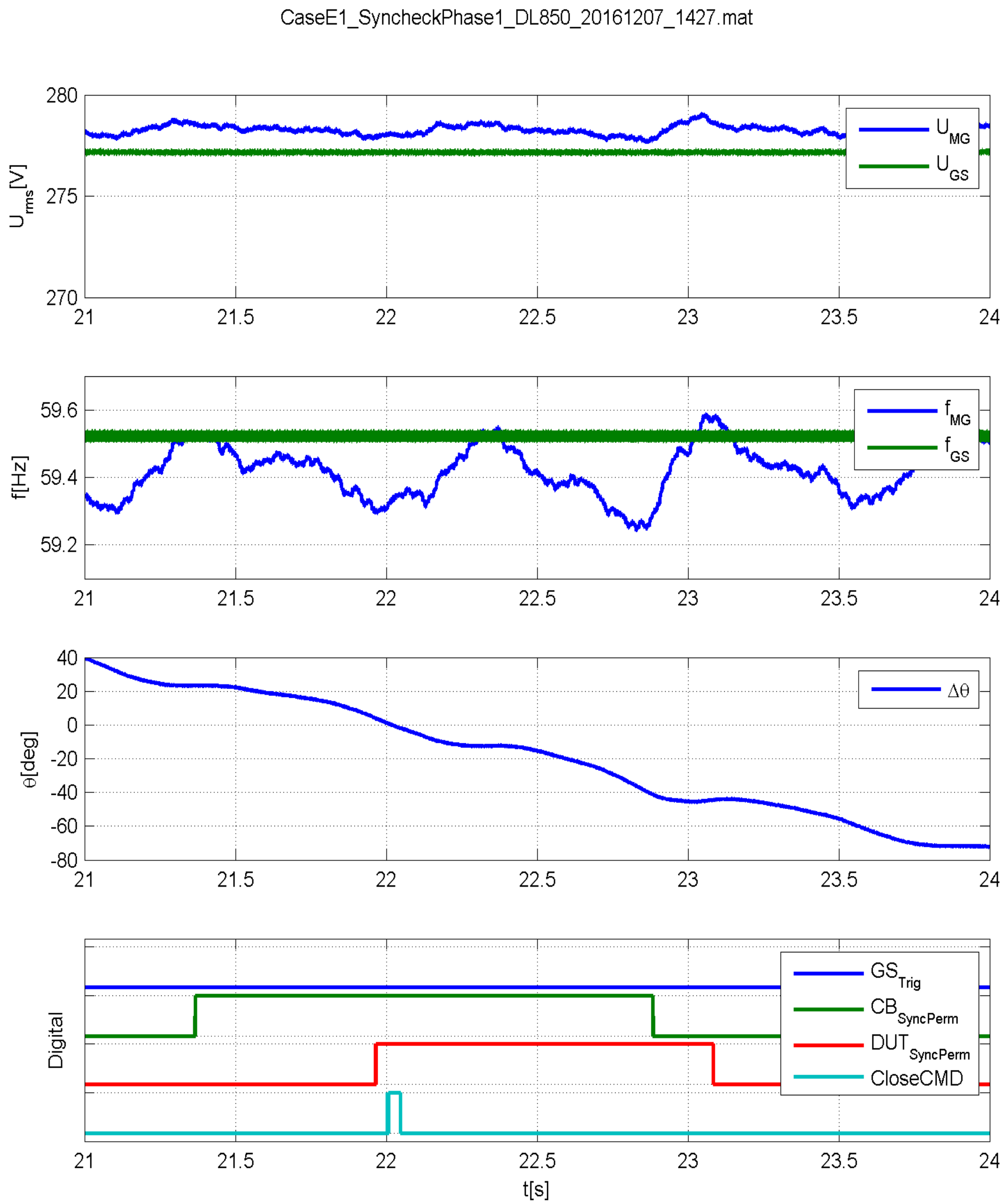

Figure 45 Case E1: Synchrocheck– phase criterion while microgrid is below grid frequency

5.3.2.4 Case E2: Synchrocheck – phase criterion while microgrid is above grid frequency

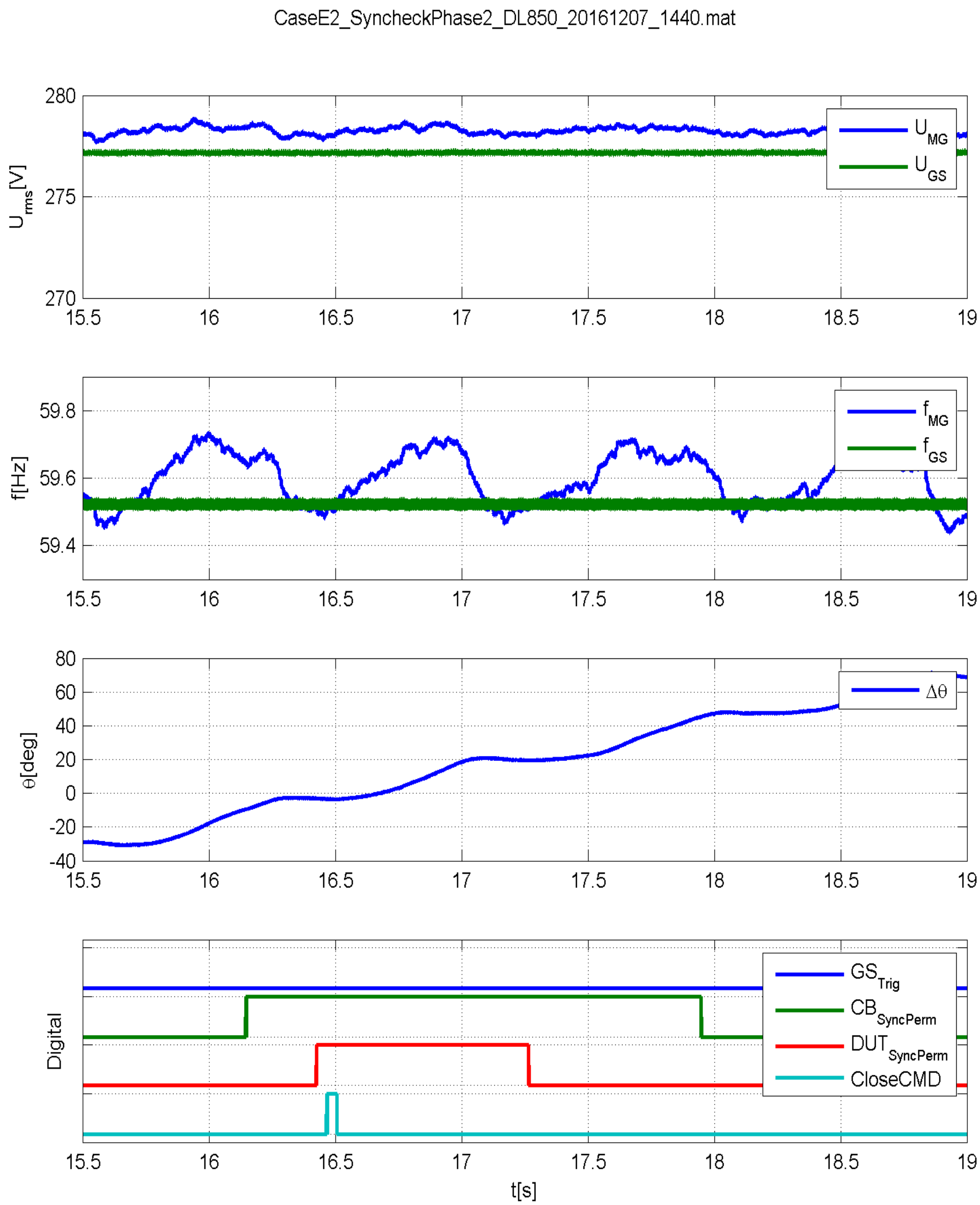

Figure 46 Case E2: Synchrocheck – phase criterion while microgrid is above grid frequency

5.3.2.5 Case E3: Synchrocheck – frequency criterion while microgrid is above grid frequency

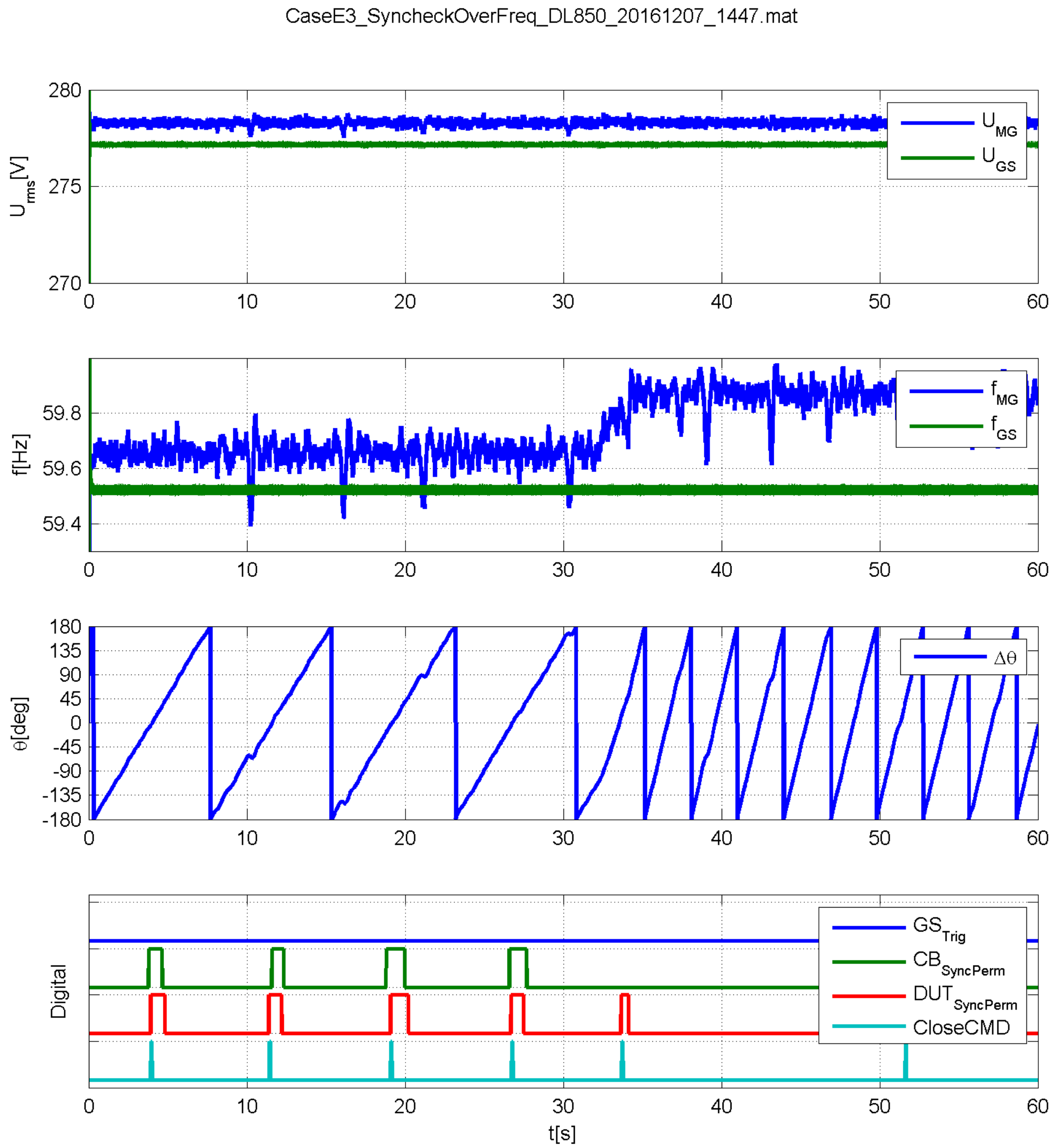

Figure 47 Case E3: Synchrocheck – frequency criterion while microgrid is above grid frequency

5.3.2.6 Case E4: Synchrocheck – frequency criterion while microgrid is under grid frequency

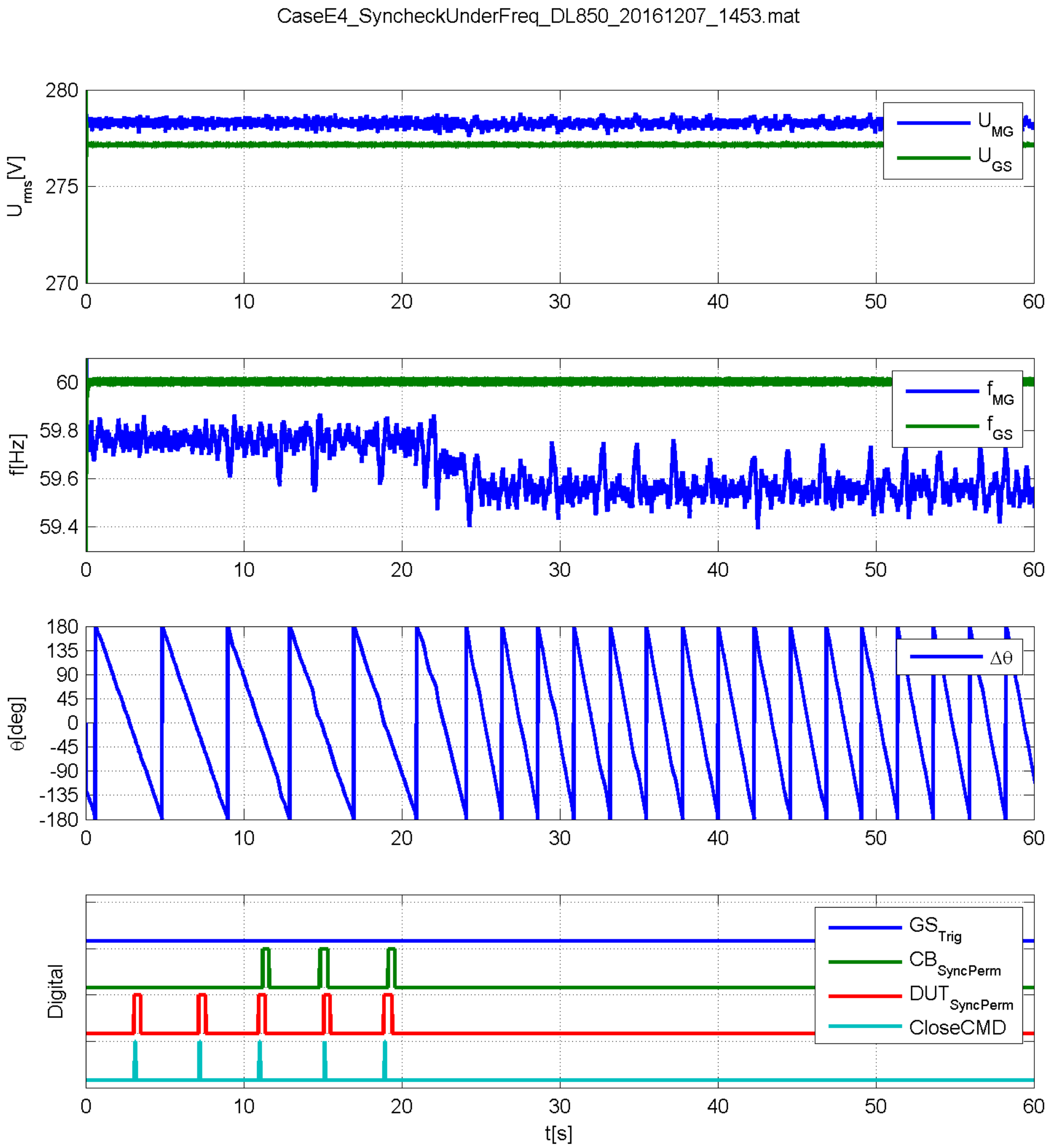

Figure 48 Case E4: Synchrocheck – frequency criterion while microgrid is under grid frequency

5.3.2.7 Case E5: Synchrocheck – voltage criterion while microgrid is under grid voltage

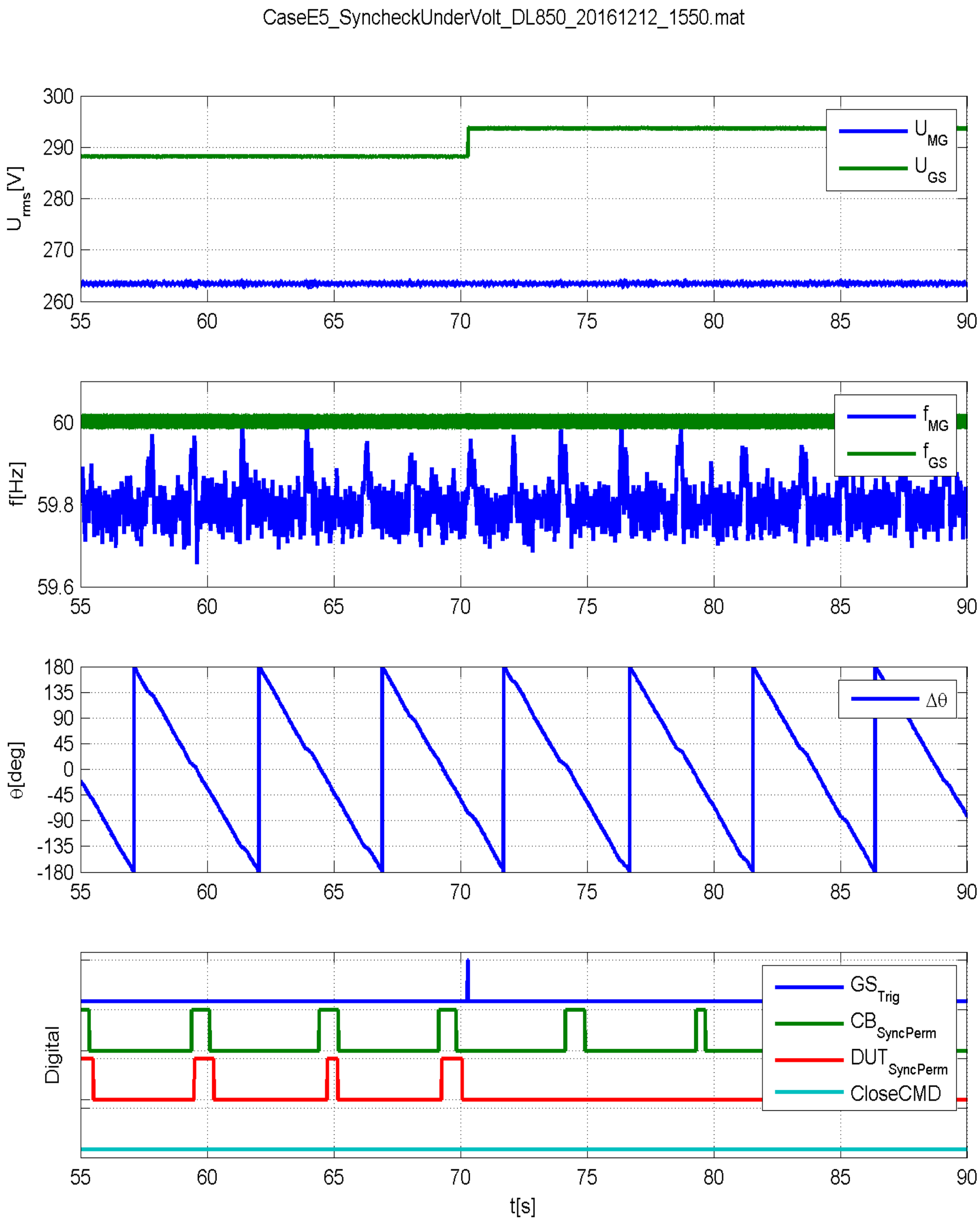

Figure 49 Case E5: Synchrocheck – voltage criterion while microgrid is under grid voltage

5.3.2.8 Case E6: Synchrocheck – voltage criterion while microgrid is above grid voltage

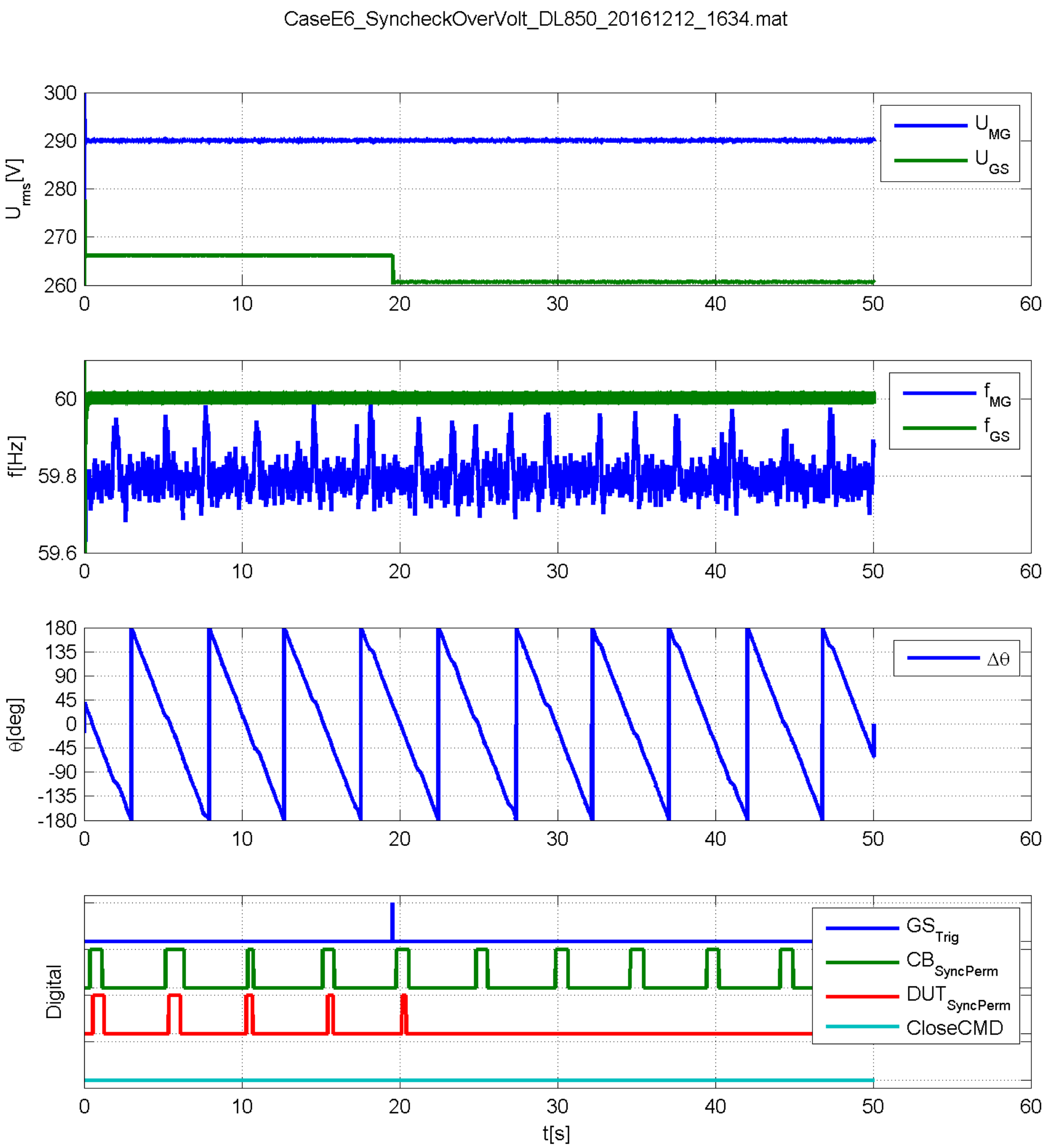

Figure 50 Case E6: Synchrocheck – voltage criterion while microgrid is above grid voltage

5.3.3 Steady State Power Quality

5.3.3.1 Case F1: Real Power Dispatch – dispatching more load not to exceed generator max power

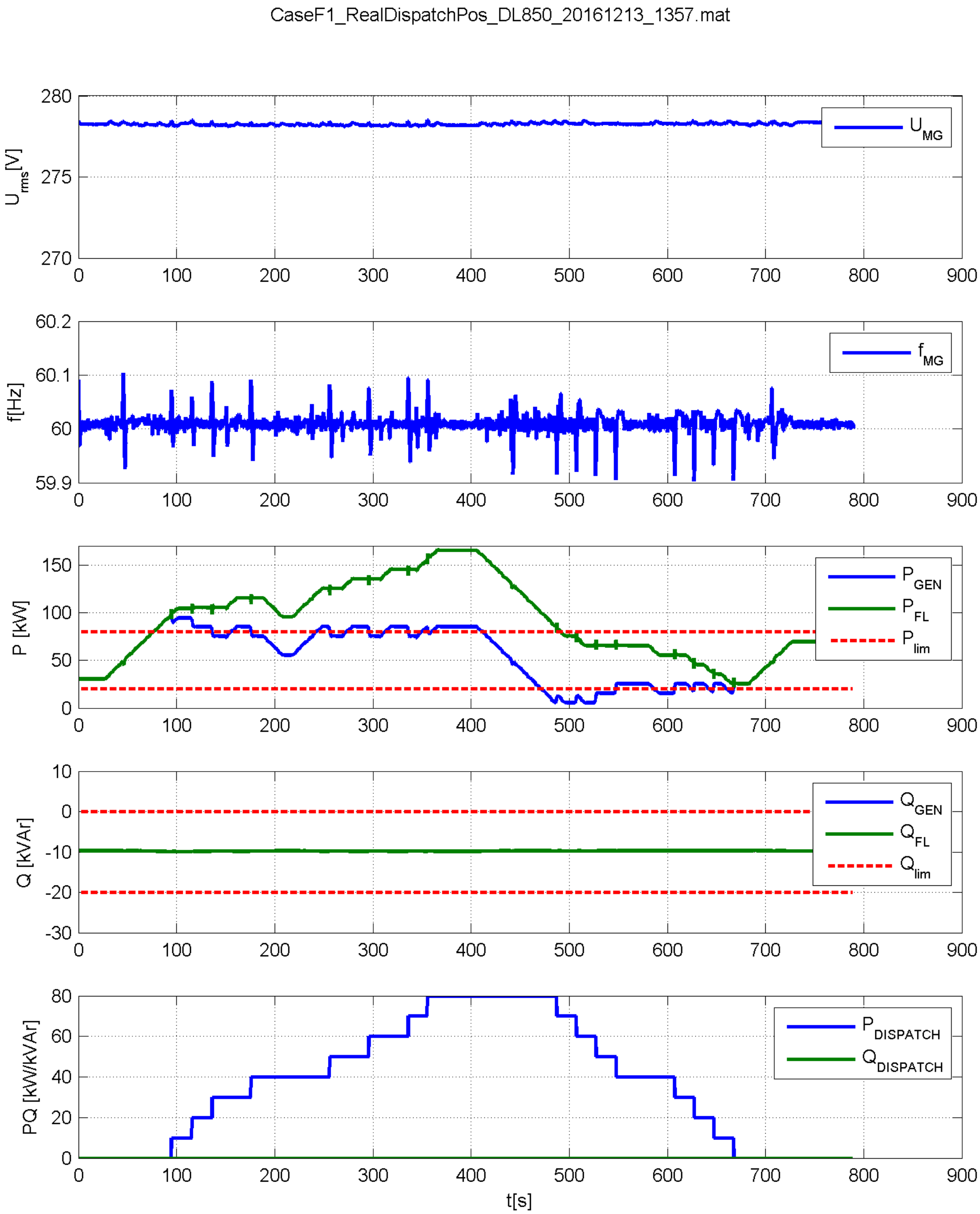

Figure 51 Case F1: Real Power Dispatch – dispatching more load not to exceed generator max power

5.3.3.2 Case F2: Real Power Dispatch – dispatching less load to keep minimum generator power

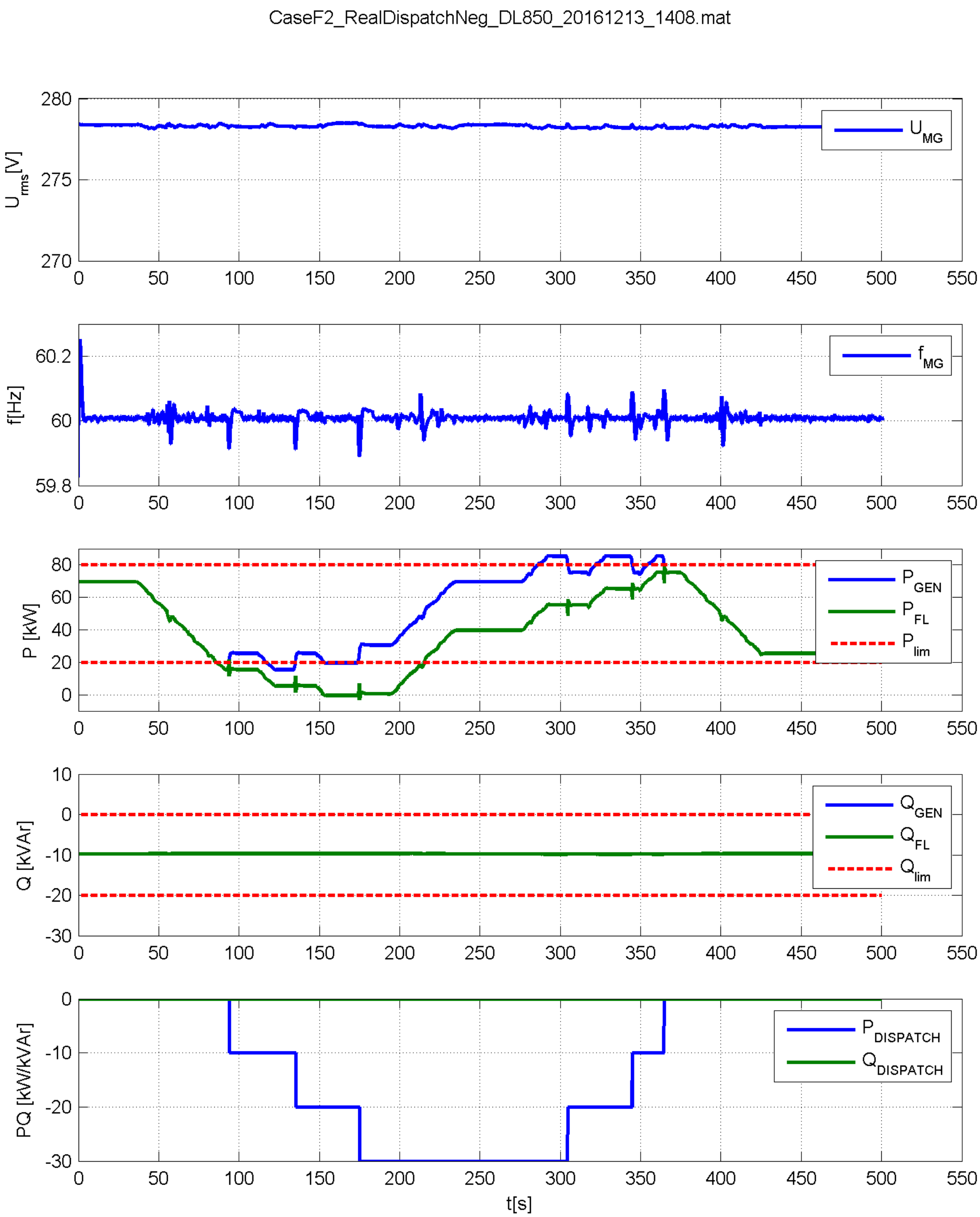

Figure 52 Case F2: Real Power Dispatch – dispatching less load to keep minimum generator power

5.3.3.3 Case G1: Reactive Power Dispatch – dispatching to keep generator within limits at small real power

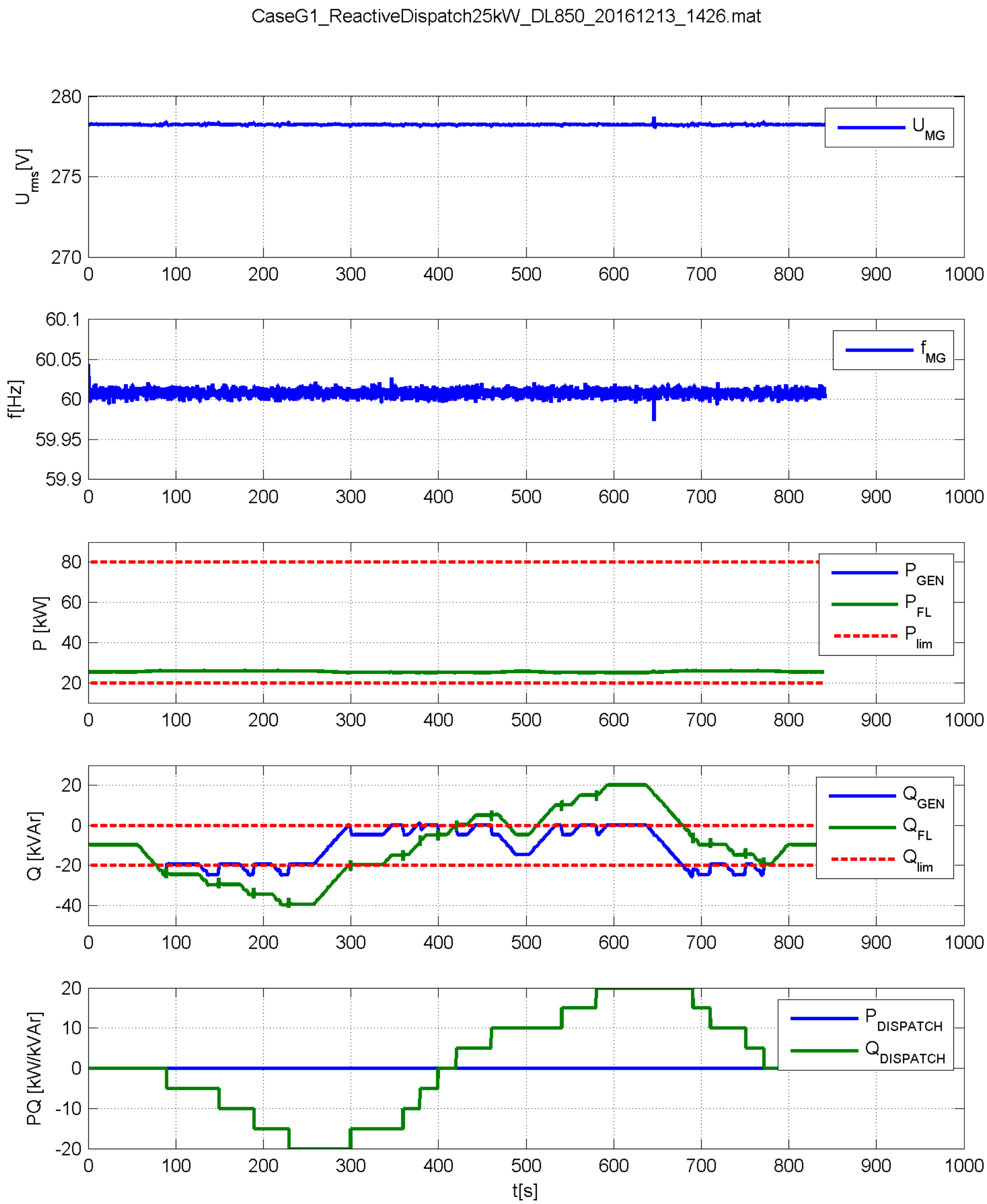

Figure 53 Case G1: Reactive Power Dispatch – dispatching to keep generator within limits at small real power

5.3.3.4 Case G2: Reactive Power Dispatch – dispatching to keep generator within limits at near nominal real power

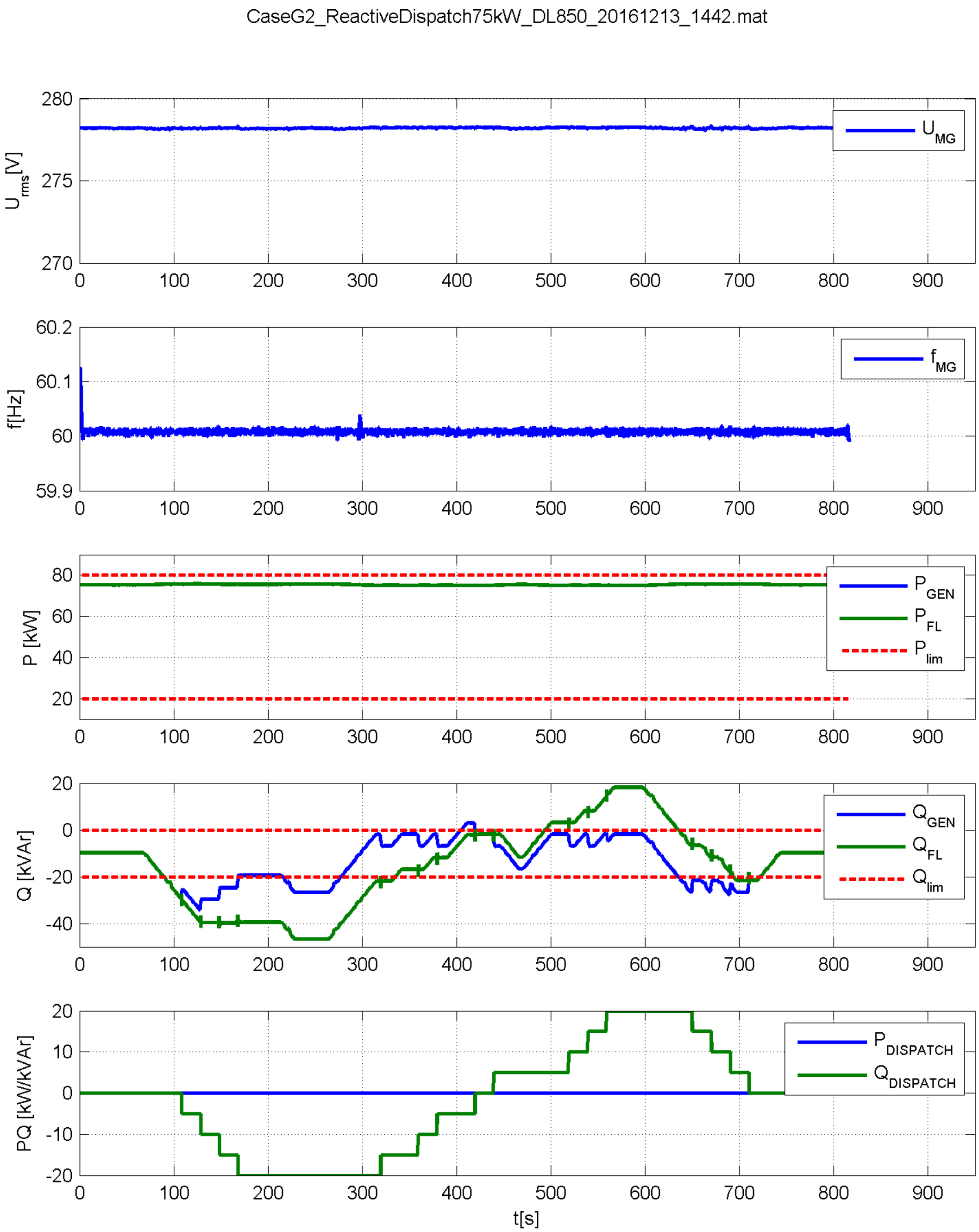

Figure 54 Case G2: Reactive Power Dispatch – dispatching to keep generator within limits at near nominal real power

5.3.4 Protection coordination

5.3.4.1 Case J1: External fault

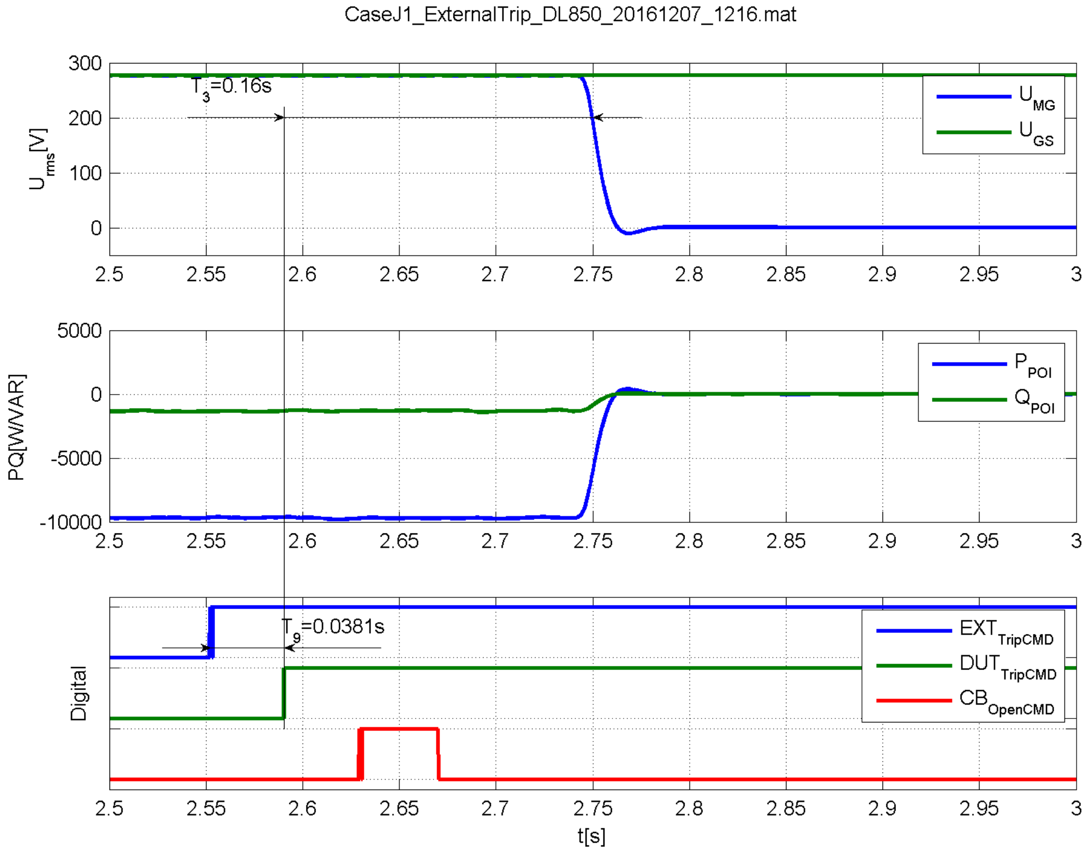

Figure 55 Case J1: External fault

5.4 Asset Dispatch – Detailed Results

Seasonal Results – Fall: November 6, 2014

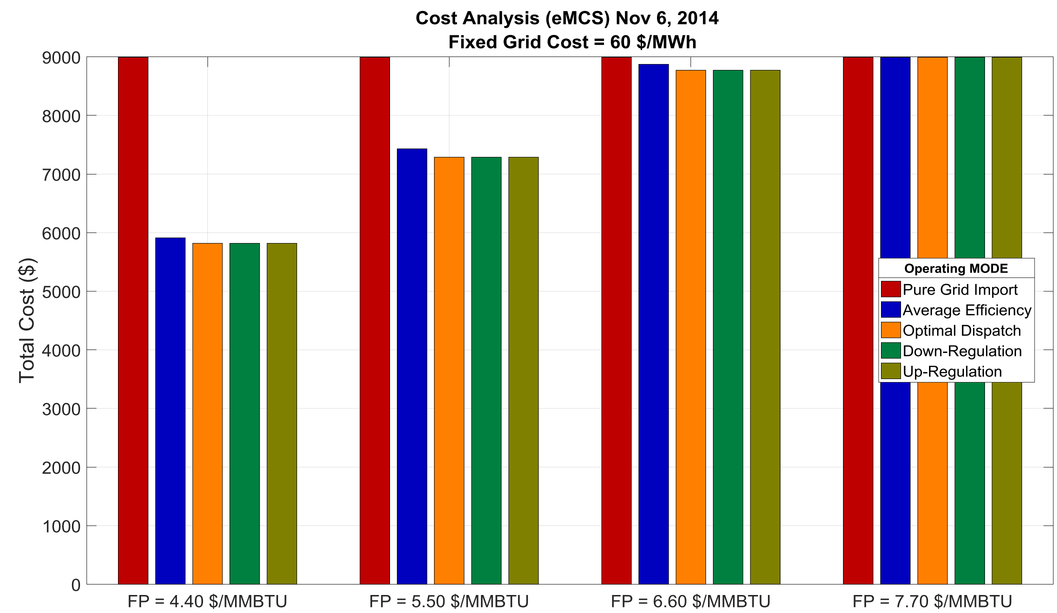

Figure 56 Total cost: Fixed Grid Cost with varying fuel prices, design of experiments.

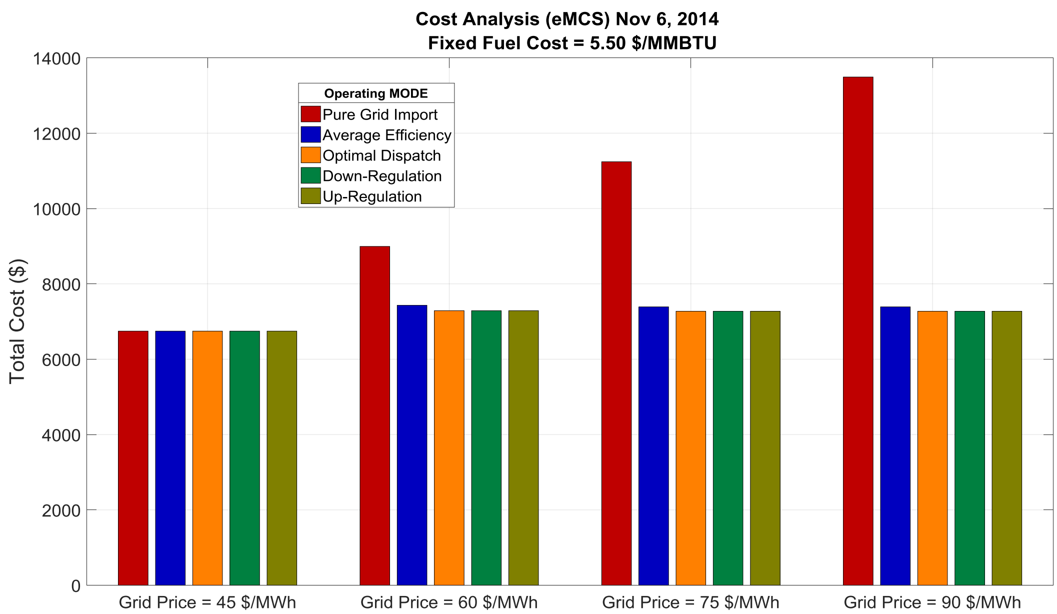

Figure 57 Total cost: Fixed Fuel Cost with varying grid prices, design of experiments.

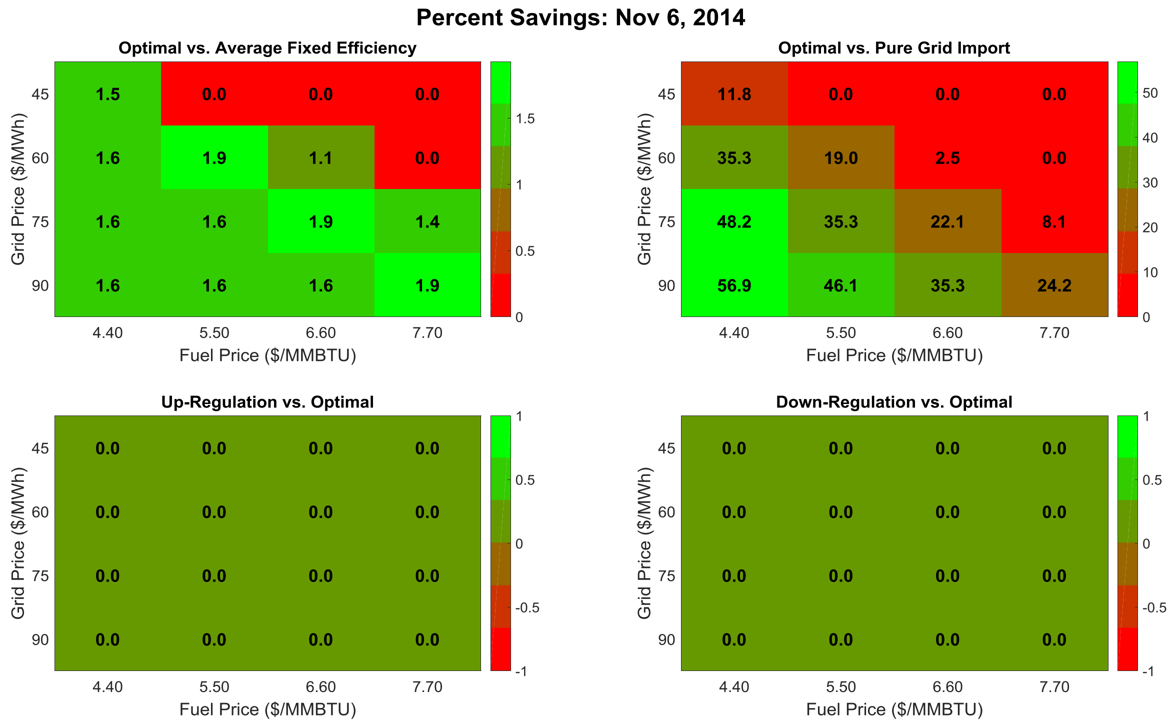

Figure 58 Percent annual electricity savings relative to four operating modes for various grid purchase price ($/MWh), and Natural Gas pricing ($/MMBTU).

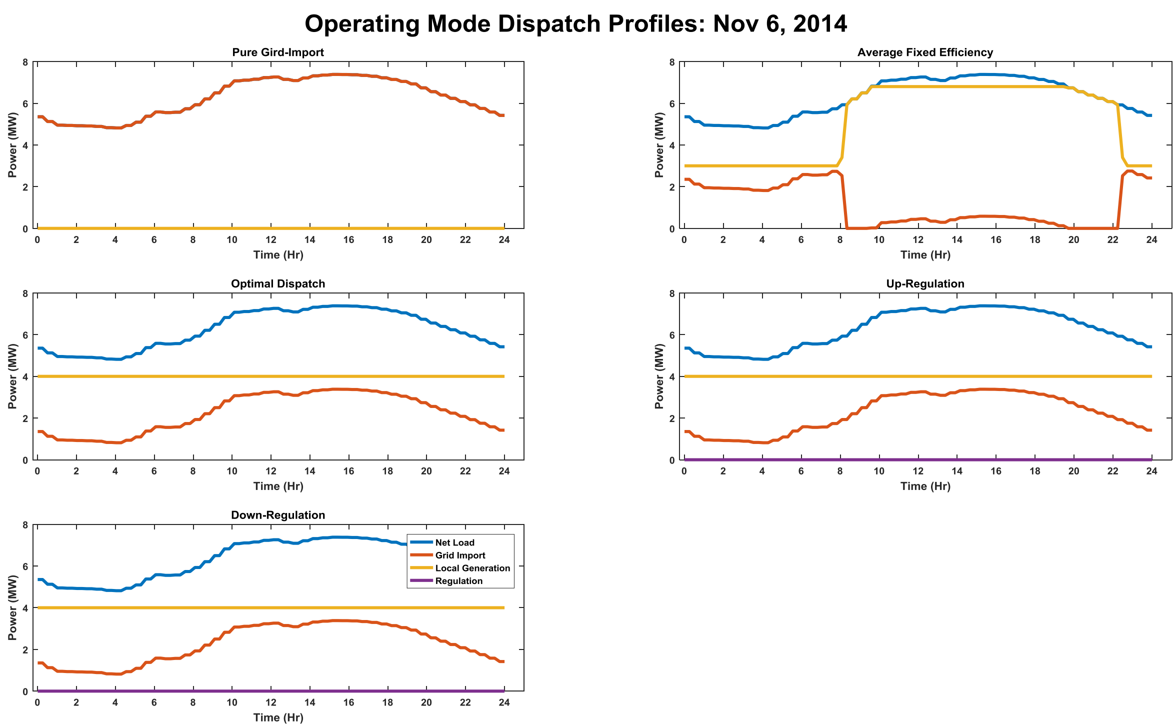

Figure 59 Dispatch profiles, various operating modes.

Seasonal Results – Summer: August 7, 2014

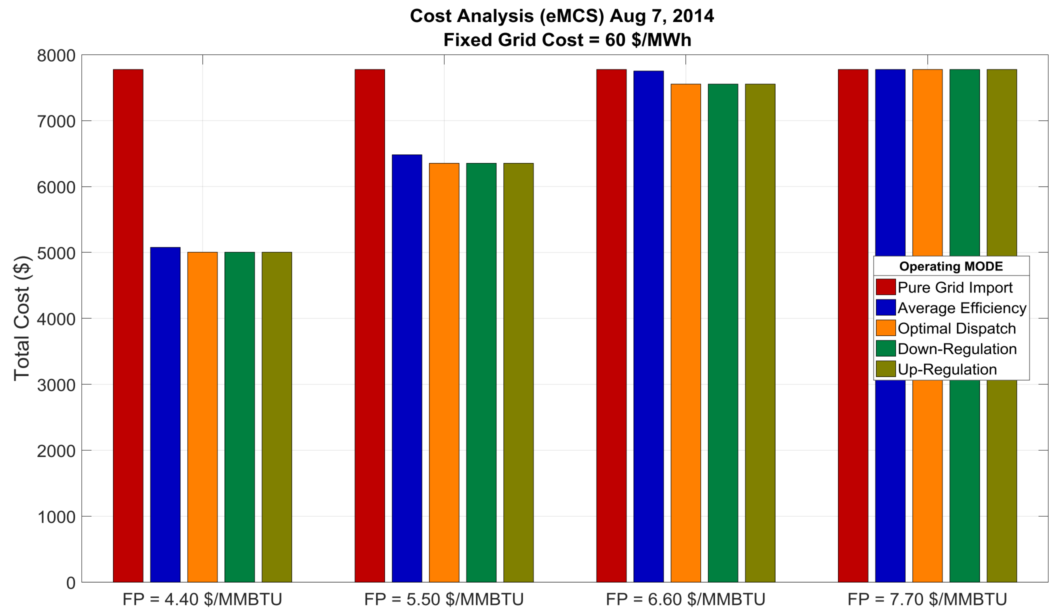

Figure 60 Total cost: Fixed Grid Cost with varying fuel prices, design of experiments.

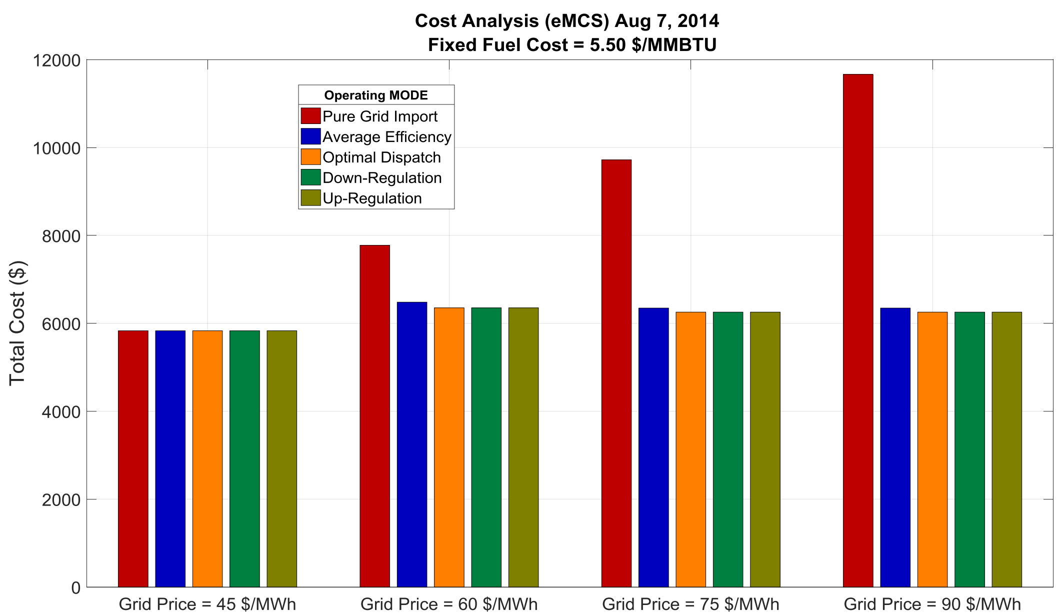

Figure 61 Total cost: Fixed Fuel Cost with varying grid prices, design of experiments.

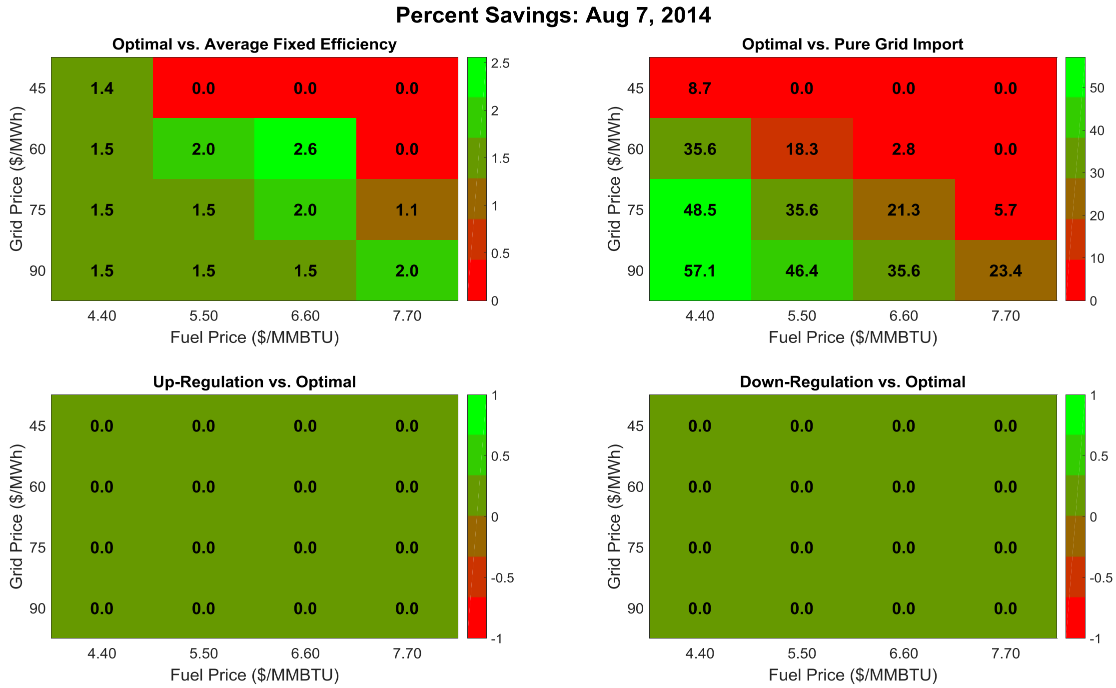

Figure 62 Percent annual electricity savings relative to four operating modes for various grid purchase price ($/MWh), and Natural Gas pricing ($/MMBTU).

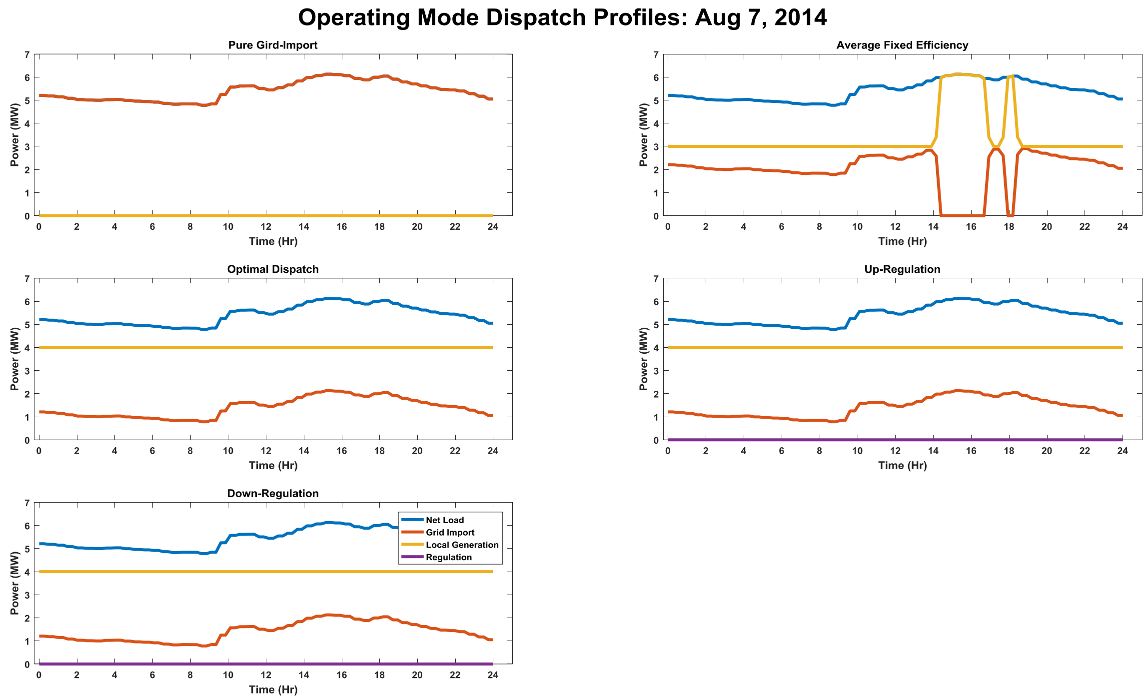

Figure 63 Dispatch profiles, various operating modes.

Seasonal Results – Spring: March 5, 2014

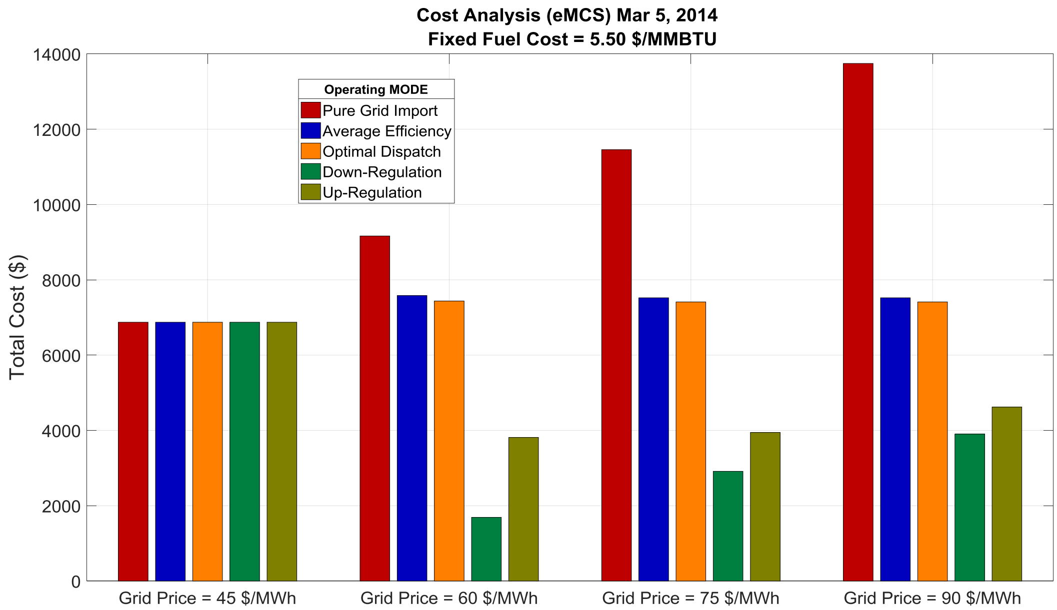

Figure 64 Total cost: Fixed Grid Cost with varying fuel prices, design of experiments.

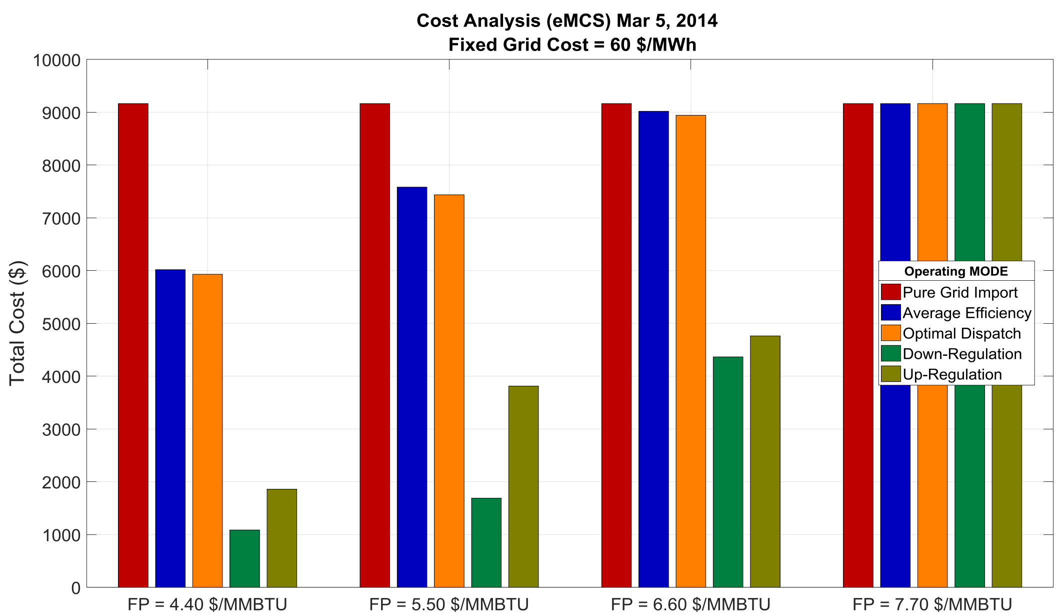

Figure 65 Total cost: Fixed Fuel Cost with varying grid prices, design of experiments.

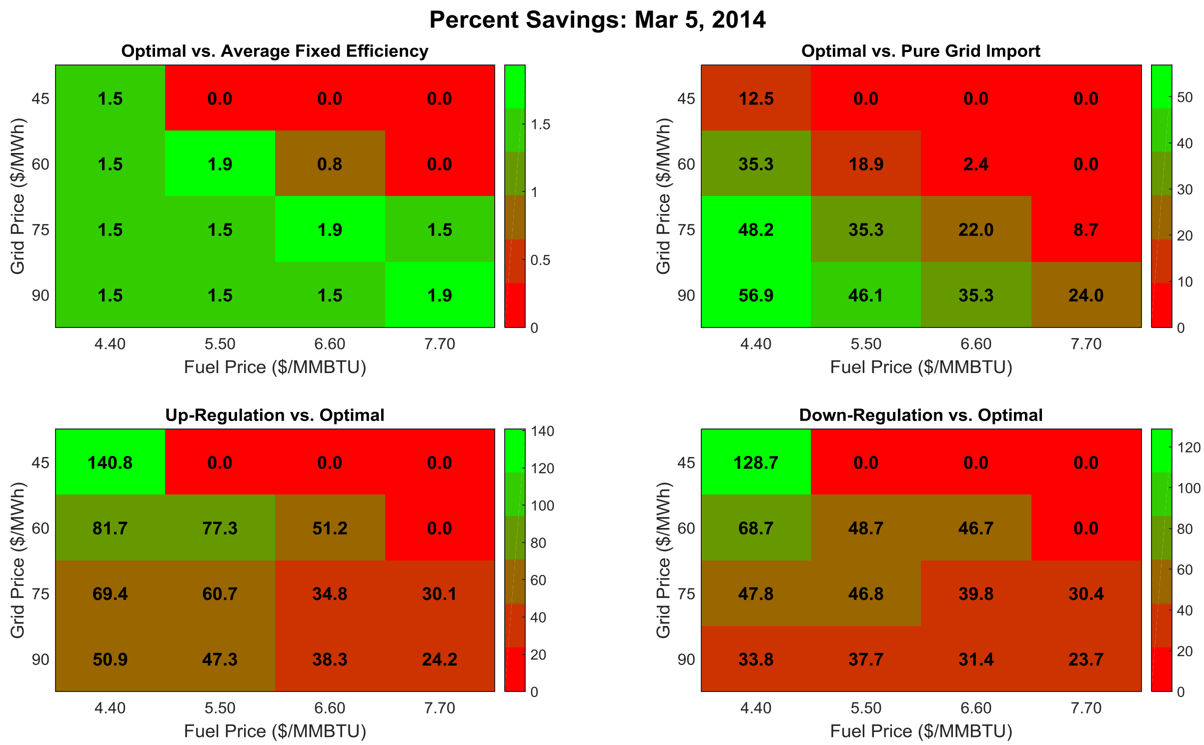

Figure 66 Percent annual electricity savings relative to four operating modes for various grid purchase price ($/MWh), and Natural Gas pricing ($/MMBTU).

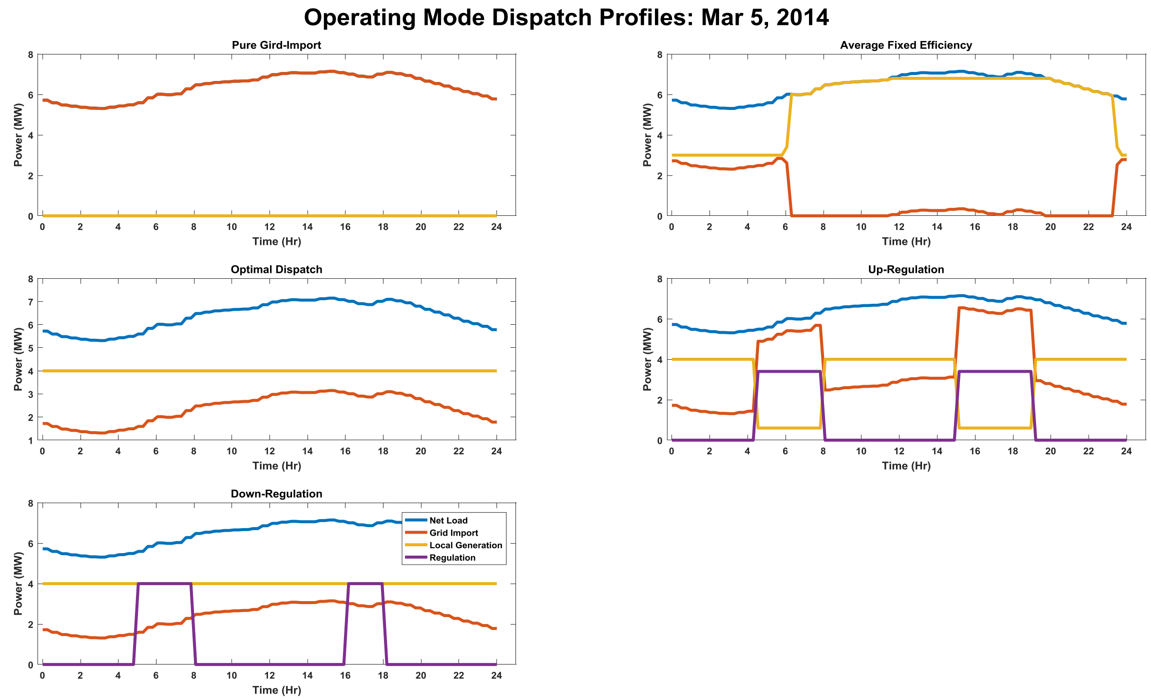

Figure 67 Dispatch profiles, various operating modes.

Seasonal Results – Winter: January 29, 2014

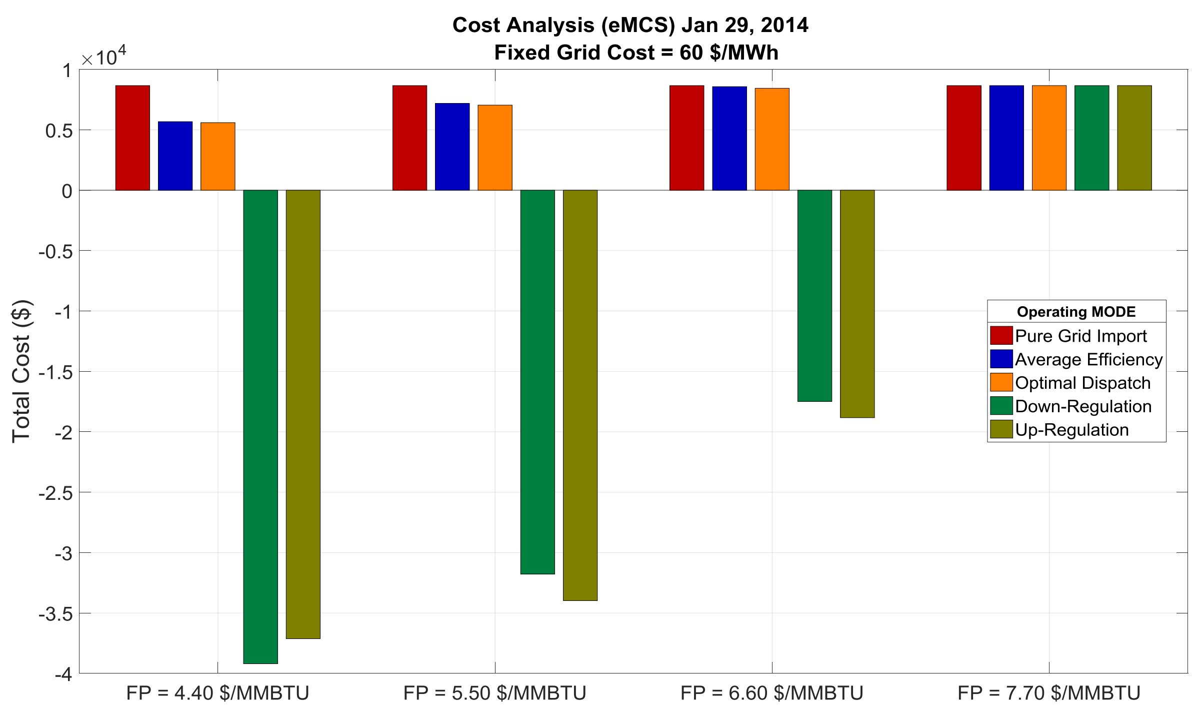

Figure 68 Total cost: Fixed Grid Cost with varying fuel prices, design of experiments.

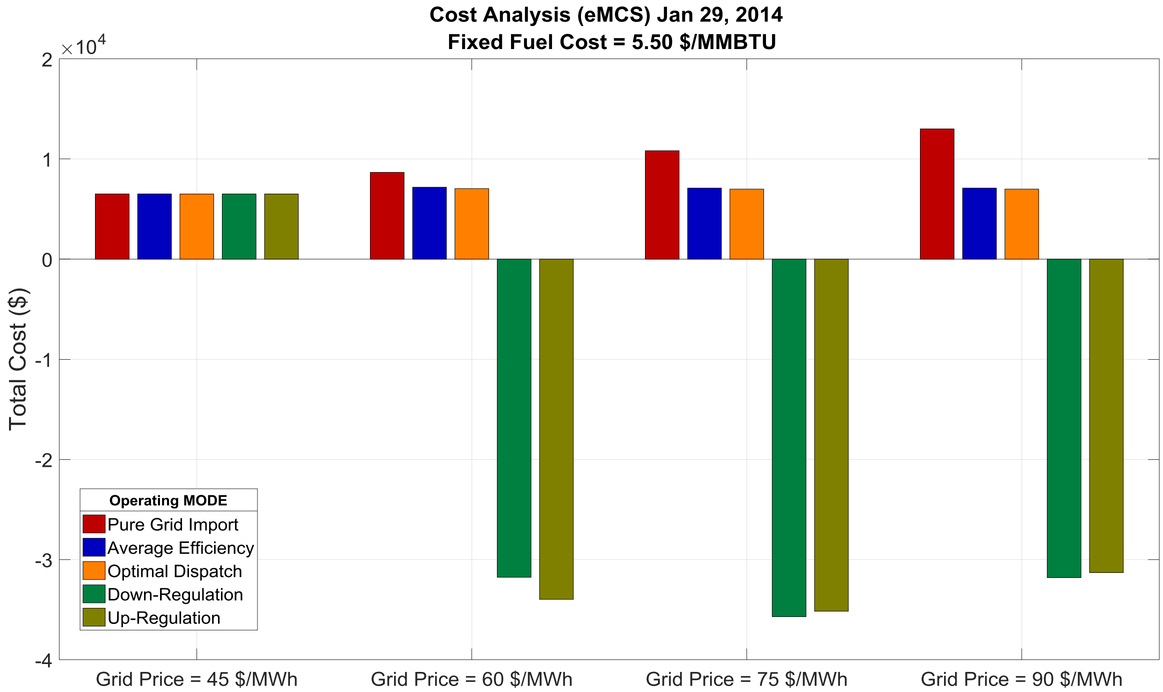

Figure 69 Total cost: Fixed Fuel Cost with varying grid prices, design of experiments.

Figure 70 Percent annual electricity savings relative to four operating modes for various grid purchase price ($/MWh), and Natural Gas pricing ($/MMBTU).

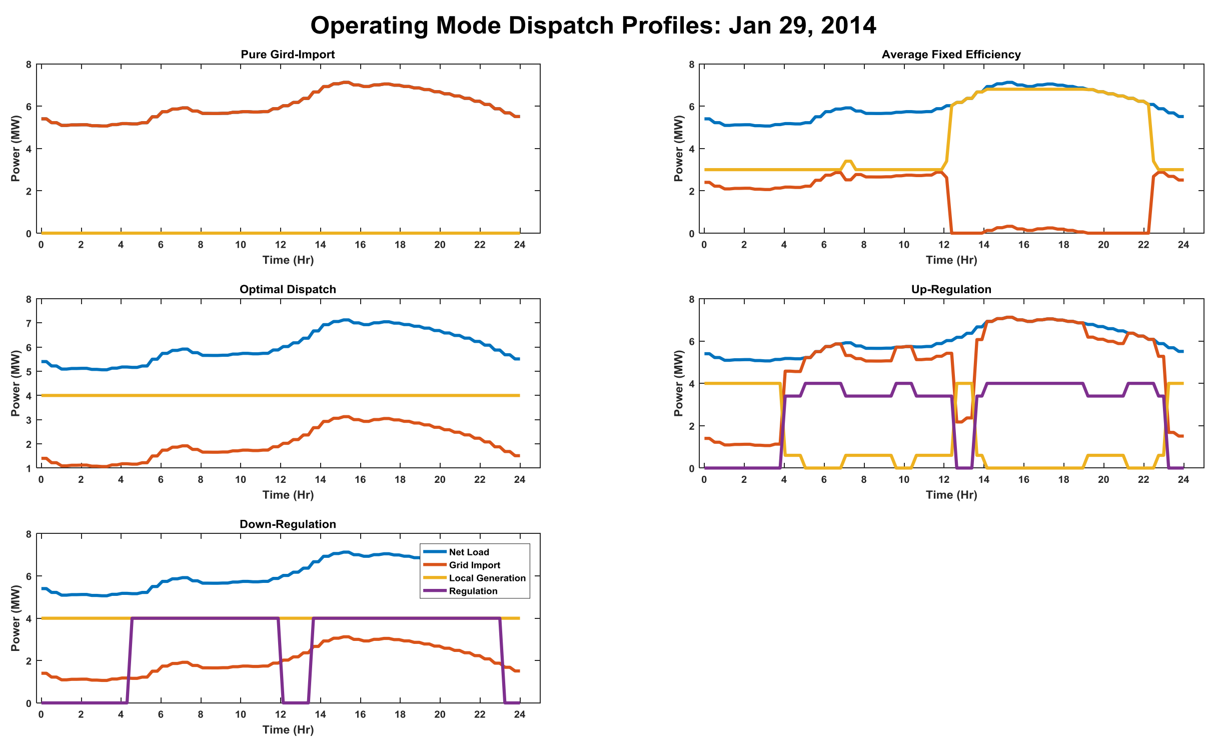

Figure 71 Dispatch profiles, various operating modes