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Network Innovation Allowance (NIA) Project DESERT:

Solar PV-Battery Hybrid System – Test Report

Operated within the Enhanced Frequency Control Capability Scheme (EFCC)

Conducted at the Rainbows Solar PV Power Plant, Willersey

BELECTRIC GmbH

Document Version 0.3; 06-03-2019

Document Version:	vs0.0	03.12.2018
	vs0.1	26.01.2019
	vs0.2	11.02.2019
	vs0.3	06.03.2019
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List of Abbreviations

BCS	:	Battery Control System
CCGT	:	Combined cycle gas turbine
CET	:	Central European Time
DNO	:	Distribution network operator
EFCC	:	Enhanced frequency control capability
GB	:	Great Britain
GCP	:	Grid connecting point
GHI	:	Global horizontal irradiance
GMT	:	Greenwich Mean Time
GS	:	Grid simulator
MPP	:	Maximum power point
PMU	:	Phasor measurement unit
POA	:	Plane of array
SOC	:	State of Charge
TNO	:	Transmission network operator
UK	:	United Kingdom
WAMS	:	Wide area measurement system

1 Introduction

Enhanced Frequency Control Capability (EFCC) is a project by National Grid UK that aims to develop and investigate a new innovative monitoring and control system for fast and localized frequency response service from established distributed generation sources like photovoltaic system, wind energy converters, demand-side management and combined cycle gas turbines (CCGT).

The project uses EFCC control scheme which is a distributed monitoring-control scheme that uses wide-area phasor measurements systems to perform dynamic control in the power network. It aims to reduce the inter-regional frequency variation and angular separation in a low inertial transmission system, thus reducing the unscheduled inter-regional power flow and lowering the risk of power system splitting during system perturbation. The design approach enables the control system to have regional and system observability in the transmission network which allows easy identification of an actual frequency event and a local disturbance. This is achieved by evaluating the regional RoCoF and the system RoCoF respectively. In response to an event, the established distributed generation units in the affected regions are requested to provide balancing power (local weighted frequency response) according to their capability during that time of a day.

Under the EFCC scheme, Belectric tested and trialled a local RoCoF-based frequency response service using a central inverter type large-scale PV plant located at Willersey, UK as a stand-alone system. During these tests the PV plant output power was curtailed below its maximum power point level so as to configure the PV plant to be capable of providing both positive and negative response services. This system had some limitations as the system could only provide frequency response services during the day, moreover long-time curtailment of the solar PV farm makes the control scheme uneconomical. The total performance of the system was found to be low due to 1:N communication line and active low pass filters present in the inverter hardware.

To increase the system performance Belectric successfully integrated a grid scale Energy Storage System in parallel with the solar PV plant. The PV-Battery hardware setup not only increases the overall system availability as it allows the system to provide frequency response service during day and night but also increases the total performance of the system due to faster battery response and additionally servicing a larger overall response with the solar PV system providing the negative response, therefore allowing the battery to use most of its energy for positive response only.

This report evaluates the performance of PV-Battery Hybrid System running the EFCC control and monitoring scheme and highlights the benefits, advantages as well as drawbacks/ limitations which may impede its working in the future.

2 Asset / Resource / Service background Information

To provide localized frequency response from a Photovoltaic-Battery Hybrid System under the EFCC scheme, Belectric used the following power resources:

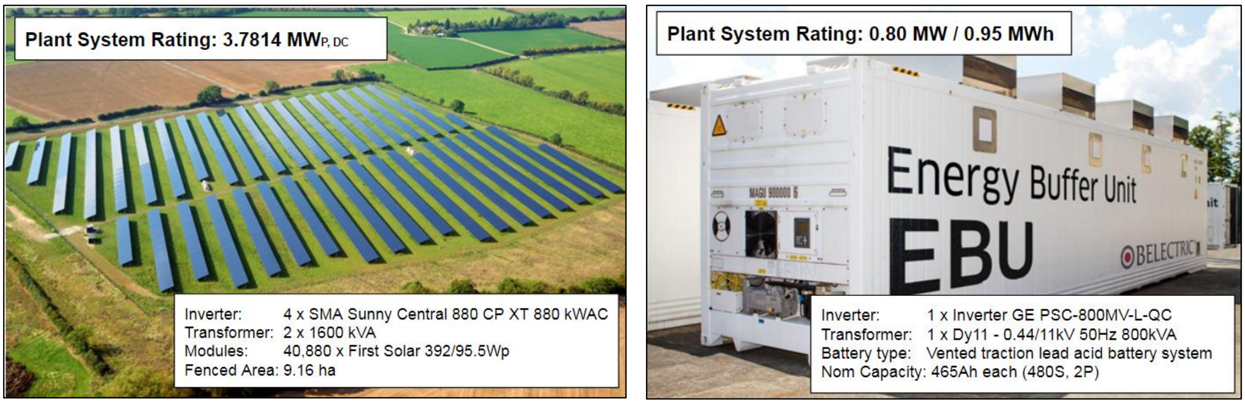


Figure 1: BELECTRIC's PV-Battery Hybrid System running under EFCC Control Scheme located at Willersey, UK

The Rainbows Solar PV Farm – A centralized architecture type 3.7814 $MW_{p,DC}$ solar PV power plant built by Belectric in 2014 and owned by Toucan Energy, located at Willersey, Gloucestershire, United Kingdom. The PV plant is tied to the 11 kV distribution grid of Western Power Distribution (WPD) through two Dy11y11 - 1,600 kVA multi-winding type transformers (0.36 kV/11 kV). The primary side of each transformer in the PV side is connected to two SMA Sunny Central 800CP XT inverters[1] with a nominal power of 880 kW. In total the PV farm has four such inverters.

Energy Buffer Unit –The Energy Buffer Unit (EBU) is a battery storage system which is located 750 m away from the Rainbows Solar PV Farm and is configured to work within the same PV farm communication network. The BELECTRIC EBU is a containerized battery, based on an advanced vented lead acid battery technology featuring a copper electrode core to minimize internal resistance, maximize power and lifetime. It has a capacity of 948 kWh and charges/discharges may be realized up to 1.5 C[2]. The battery system contains 960 lead acid cells with each of them monitored for voltage, temperature and hull integrity. The cell are combined in two strings (480 cells each), which means each string has a maximum voltage of 1022.4 V DC (1 kV DC string). The system uses a GE Prosolar PSC-800MV-L-QC[3] which has a rated AC voltage of 440 V and the AC power of 800 kVA. The inverter output is connected to the 11 kV distribution grid of Western Power Distribution through one 800 kVA Dy11 transformer (0.44 kV/11 kV). While loading, the cells degas hydrogen and oxygen and are therefore stored in a ventilated housing which is kept closed during the operation.

[1] SMA Sunny Central 800CP XT – PV Central Inverter Datasheet

[2] C Rating is an indicator of maximum continuous current charge/discharge rate of a battery. A battery with 1.5C rating means that the maximum recommended charging/discharging rate is 1.5 times the current capacity (Ah) of the storage.

[3] GE Prosolar PSC-800MV-L-QC – Central Inverter Datasheet

The EBU is separated in a control and a battery room. The control room contains the circuit breaker, the control panel and cabinets. The battery room is divided into a housed, ventilated tray area and a walkway.

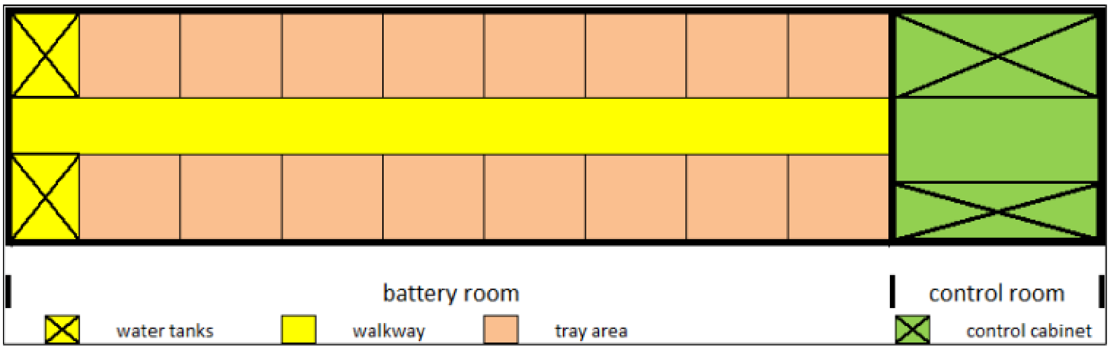


Figure 2: Energy Buffer Unit plan

The PV-Battery hybrid system running under the EFCC control scheme has in total five inverters installed, four of which are SMA inverters inside the PV farm while the EBU consist of one GE inverter. Figure 3 shows the schematic diagram of the PV-battery hybrid system at Willersey.

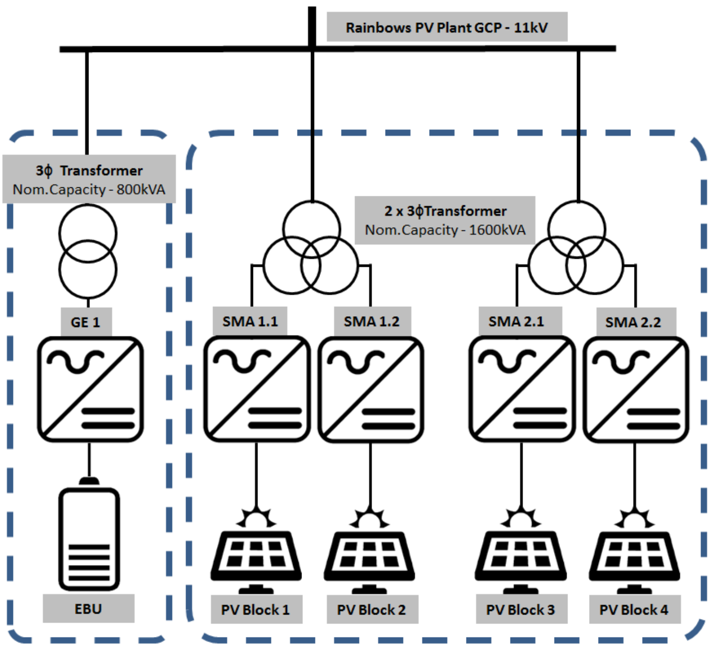


Figure 3: Schematic diagram of the PV-battery hybrid system running under EFCC control scheme at Willersey.

To provide fast frequency response from the PV-Battery hybrid system, Belectric uses its hybrid controller which is configured to control the output of PV and EBU inverter individually. The hybrid controller uses the established physical and LAN-cable connection with a communication protocol, MODBUS TCP, to control the plant's output. MODBUS TCP is a standard communication protocol between an energy management system and a PV power plant resource today.

3 EFCC control and communication setup

To configure the PV-Battery hybrid system for providing EFCC services, new control and measurement equipment's are installed. This includes new control hardware and logic and sensitive measuring modules, Figure 4 shows the implemented communication setup between the measuring systems, the GE Local Controller, the BELECTRIC Hybrid Controller and the grid scale PV-battery hybrid resource. The Hybrid Controller and the GE Local Controller constantly communicate with each other the fundamental information about the system's quantified available response.

With the aim to provide fast response services, the PV and the battery resource at Willersey are connected at a single grid connecting point (GCP) and are configured to behave as a single source under the EFCC control scheme. This allows easy internal management of the resource and gives the controller additional flexibility to activate the resource individually for reduced reaction times[4] and faster response times[5]. For this, the hybrid control system uses battery's reaction and response time for quantification of the available response power from the hybrid system. The right panel in Figure 4 shows the information sent to the Local Controller while Table 1 gives further details on the parameters to the GE Local Controller by the hybrid system during the day while during the night, when PV is not available, the battery system takes over to provide the response (details explained in section 4 – EFCC hybrid system control strategy on page number 13).

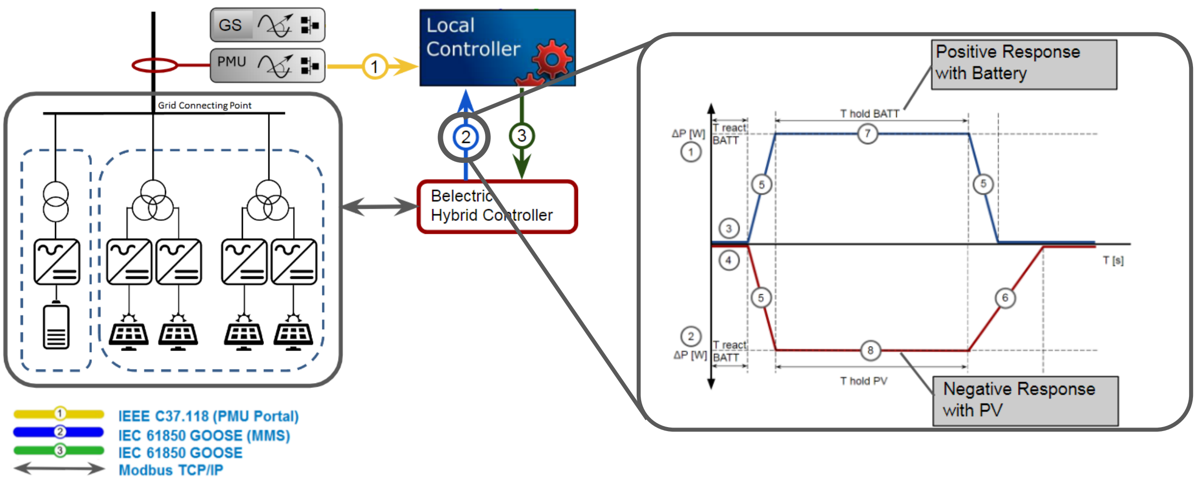


Figure 4: Communication setup between the EFCC distributed control scheme and the Belectric's PV-Battery hybrid system. The Belectric Hybrid Controller evaluates the response power capability of its hybrid resource and sends the eight parameters (e.g. quantified available power) to the GE Local Controller.

4 Reaction time – The length of time the PV-battery hybrid system takes to start its response after a power request signal from the LC is received. In case of low data resolution the reaction time is measured by observing the time difference between power request and the first data point at which the system/individual inverter records a change of power.

5 Response time – The length of time it the PV-battery hybrid system to provide full response from the time when the resource received the power request signal from the LC.

SNO	PARAMETERS
1	15 minute positive power availability [kW]
2	15 minute negative power availability [kW]
3	Battery positive reaction time [s]
4	Battery negative reaction time [s]
5	Battery ramp up/down rate [kW/s]
6	PV ramp down rate [kW/s]
7	Positive power hold time [s]
8	Negative power hold time [s]

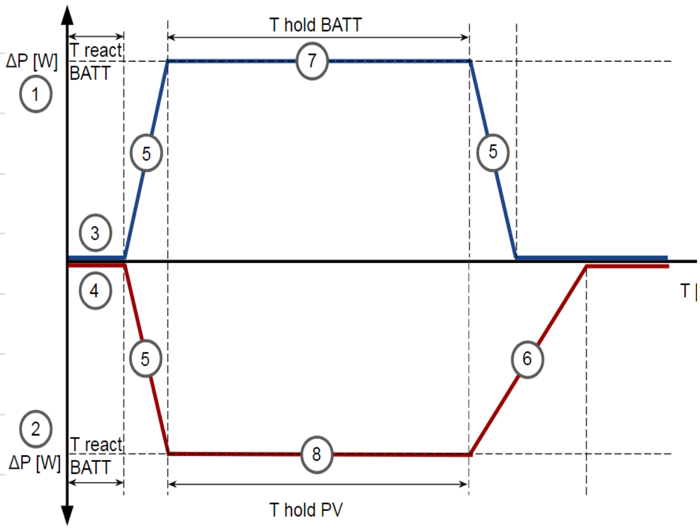


Table 1: Power availability parameters sent by the Belectric Hybrid Controller to the GE Local Controller to quantify the total available positive and negative response power of the PV-Battery hybrid system.

The phasor measurement unit (PMU) deployed at GCP, measures the regional transmission line parameters, i.e. frequency, voltage and its phasor angles. The installed RA331 Module, in combination with current and voltage transducers, measures the power output from the Rainbow Solar PV Plant at Willersey, while for the Energy Buffer Unit, Belectric battery control system (BCS) is configured to log the data with the fastest latency possible in the current system (details explained in section – 5 Data logging on page number 18).

A frequency event is detected by the GE Local Controller when the local RoCoF exceeds the configurable RoCoF event detection threshold. The default RoCoF event detection threshold is ± 0.1 Hz/s. This setting is chosen specifically for the EFCC testing scenario to trigger and respond to a real system event. Alternative settings can be implemented according to the required sensitivity.

As per the designed EFCC control scheme, once the frequency reaches the threshold limit of 49.7/50.2 Hz, the GE Local Controller evaluates the power availability parameters received from the EFCC power resource and sends a power request to the BELECTRIC Hybrid Controller through an established GOOSE communication protocol. The magnitude of the power request not only depends on the hybrid resource power availability but also on the type and intensity of the triggered frequency. The power request from the GE Local Controller is processed by the BELECTRIC Hybrid Controller and divided amongst the inverters in the PV-Battery hybrid system according to strategy described in section 4 EFCC hybrid system control strategy.

4 EFCC hybrid system control strategy

The expected nature of the power request from the GE Local Controller (under the EFCC control scheme) which is sent to the BELECTRIC Hybrid Controller during a frequency event is shown in the Figure 5. Once the RoCoF limit of ±0.1 Hz/s is exceeded and the frequency goes beyond the first threshold limit of 49.7/50.2 Hz, GE Local Controller sends the first power request corresponding to 20% of system availability to the BELECTRIC Hybrid Controller. The request increases in the form of a staircase if the frequency continues to deviate and crosses the higher thresholds.

Table 2 shows the frequency threshold limits for over and under frequency events. The power request from the GE Local Controller continues to increase until either RoCoF stops increasing or the fifth power step is activated. The fifth power step asks for 100% of available power. The power request is sustained for the time until the frequency is restored, followed by a 10 second ramp back.

The control has a failsafe mode for slower frequency events. The event is detected, and power request is send once frequency reaches the first threshold frequency of 49.7 Hz for under frequency events and 50.2 Hz for over frequency events.

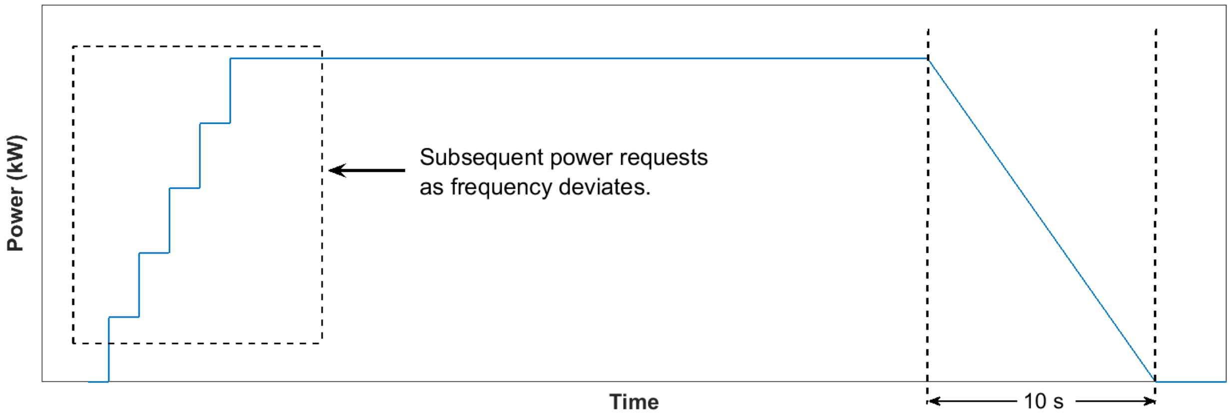


Figure 5: Generated stepped power request under the EFCC control scheme by the GE Local Controller to PV-battery hybrid system during a frequency event.

SNO.	OVER FREQUENCY THRESHOLD	NEGATIVE POWER REQUESTED	UNDER FREQUENCY THRESHOLD	NEGATIVE POWER REQUESTED
1	50.2 Hz	20% of positive availability	49.7 Hz	20% of negative availability
2	50.3 Hz	40% of positive availability	49.5 Hz	40% of negative availability
3	50.4 Hz	60% of positive availability	49.3 Hz	60% of negative availability
4	50.5 Hz	80% of positive availability	49.1 Hz	80% of negative availability
5	50.6 Hz	100% of positive availability	48.9 Hz	100% of negative availability

Table 2: Over frequency and under frequency event thresholds under the EFCC control scheme.

The EFCC hybrid response strategy for the PV-battery hybrid system is divided into two schemes. During the day the positive power availability of the system depends on the battery SoC level and battery inverter maximum power capability. As the positive power response is provided by the battery system this allows the PV system to work normally at maximum power point and run without affecting the overall PV plants performance ratio. This allows for a larger overall response.

The maximum positive and negative power availability from the EBU is set as 600 kW for the EFCC hybrid test. The negative power availability of the system during the day depends on the forecasted 15 minute balancing power by the PV inverter running at the Rainbows PV Solar farm.

At night, due to unavailability of PV resource, the EBU adjusts its SoC to provide positive and negative power response. This allows for a continuous system availability. The response strategy depends on the nature of the frequency event and on the daytime. Further information about the SoC management is provided later in this section.

Table 3 illustrates the response strategy implemented in EFCC PV-battery hybrid control scheme while Table 4 illustrated the power availability sent by the system during day and night.

SNO.	DAY/NIGHT	FREQUENCY RESPONSE STRATEGY		
1	Day	Under frequency event	:	Response from energy buffer unit
2		Over frequency event	:	Coordinative response from PV and EBU
3	Night	Under frequency event	:	Response from energy buffer unit
4		Over frequency event	:	Response from energy buffer unit

Table 3: PV-battery hybrid frequency response strategy under EFCC control scheme. This control strategy allows response from both PV and Battery system during the day and night thus increasing the system availablity with larger over all response from the system.

SNO.	DAY/NIGHT	SENT POWER AVAILABLITY		
1	Day	Positive power availability	:	As per EBU SoC level or inverter max. capability
2		Negative power availability	:	15 minute PV forecasting model
3	Night	Positive power availability	:	As per EBU SoC level or inverter max. capability
4		Negative power availability	:	As per EBU SoC level or inverter max. capability

Table 4: Power availability sent to the GE Local Controller from the individual power resources under the Hybrid system – EFCC control scheme.

During the day, when PV resource is available, the EBU provides power response for under frequency events by injecting power into the grid. For over frequency events, the PV system provides the negative power by reducing its power below MPP. Due to comparatively slower PV reaction time and lower ramp rates (see key learnings: EFCC PV stand-alone trials), the EBU is configured to provide initial ramp support and increases the overall performance of the system. The EBU with its high ramp rates responds to the EFCC power request initially and reduces its power in a coordinative manner once the PV inverter starts to respond thus maintaining a constant power at the GCP without exceeding the requested power request. Figure 6 illustrates the modelled and expected PV-battery hybrid response during an under frequency event at daylight.

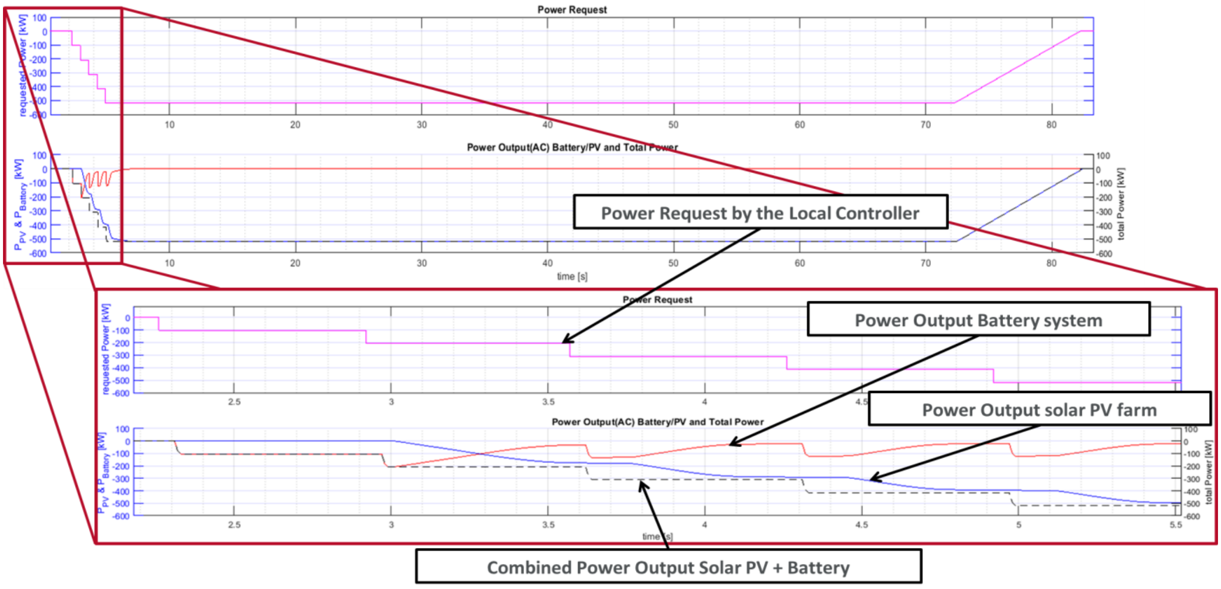


Figure 6: Illustration of simulated coordinative control response by the PV-battery hybrid system under the EFCC control scheme during the occurrence of an over frequency event when PV resource is available.

The energy buffer unit used during EFCC hybrid test trials has a workable SoC interval between 20% and 100%. To provide frequency response services at night, when photovoltaic system availability is false, the energy buffer unit reduces its SoC to 60%. That is the mean value in the workable battery SoC interval, thus configuring the storage system to have an ability to provide frequency response services in both directions by charging or discharging. The decision for day and night occurrences is taken by observing the historical sunrise and sunset times at Willersey, England. This allows the control system to evaluate the start and the end of the day while considering the seasonal change.

During the early morning the PV inverters are observed to be switching on and off due to low irradiance. To eliminate this situation of low irradiance levels the start of the day/night is adjusted 45 minutes after the sunrise and 45 minutes before the sunset at Willersey. The 45 minute window was taken by observing the historical data for the Rainbows PV plant using the PADCON Monitoring Web Portal.

In the implemented EFCC control scheme, the hybrid controller adjusts the battery SoC level for maximum availability. In the morning the SoC level of the energy storage system is increased to 90%. The remaining 10% SoC is kept free as buffer for the battery to absorb the power while enhancing the system ramp during over frequency events. While at night the battery reduces its SoC to 60% so that the system can provide frequency response services in both directions. Table 5 illustrates the overview on the energy storage SoC adjustments according to the day and night control scheme.

SNO	CONTROL SCHEME	TIME	SOC LEVEL
1	Day	Sunrise time + 45 minutes	90%
2	Night	Sunset time - 45 minutes	60%

Table 5: State of Charge levels of Energy Buffer Unit during the day and at night according to the implemented control strategy under the EFCC hybrid control scheme.

To expedite EFCC testing for PV-battery hybrid system, a simulation tool by GE is used – the PMU Simulator. This allows to test the system without waiting for a real frequency event to occur in the GB network. The PMU simulator, hereby referenced as the Grid Simulator (GS) is a substitute to real system events as it injects simulated frequency data with predefined RoCoF values and frequency nadirs[6] in the GE Local Controller.

Based on these simulated data, the GE Local Controller gives the power requests to the BELECTRIC Hybrid Controller according to the resource availability, type and magnitude of the simulated frequency event. Table 6 shows the list of over and under frequency events that can be simulated by the GE PMU Simulator.

SNO.	SIMULATED UNDER FREQUENCY EVENT	SIMULATED OVER FREQUENCY EVENT
1	0.15Hz/s ramp down to 49.65 Hz	0.15Hz/s ramp up to 50.25 Hz
2	0.15Hz/s ramp down to 49.45 Hz	0.15Hz/s ramp up to 50.35 Hz
3	0.15Hz/s ramp down to 49.25 Hz	0.15Hz/s ramp up to 50.45 Hz
4	0.15Hz/s ramp down to 49.05 Hz	0.15Hz/s ramp up to 50.55 Hz
5	0.15Hz/s ramp down to 48.85 Hz	0.15Hz/s ramp up to 50.65 Hz

Table 6: List of under and over frequency events which can be simulated by the GE PMU Simulator.

[6] Frequency nadir – Lowest or highest value of the frequency after a frequency disturbance/event.

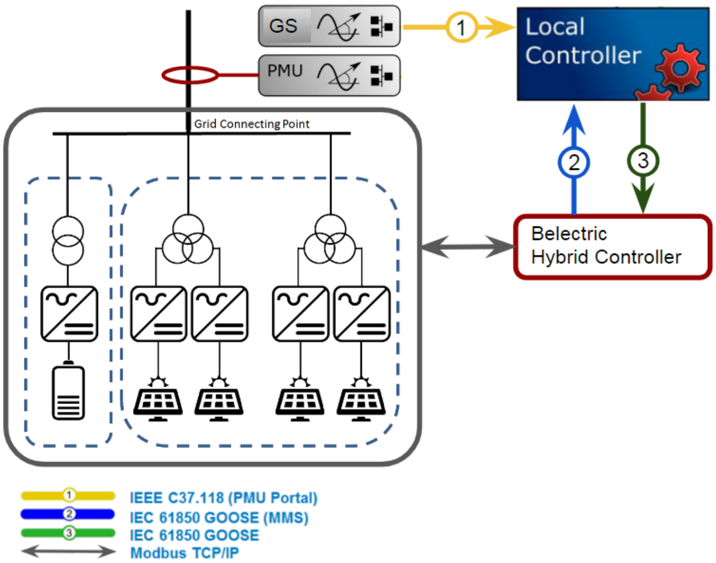


Figure 7: **Communication setup – PMU Simulator**. The simulator replaces the data input of the grid connected measurement system during some of the test. It simulates EFCC relevant frequency events to test and trial the connected equipment. The PMU still measures the power output of the solar PV farm.

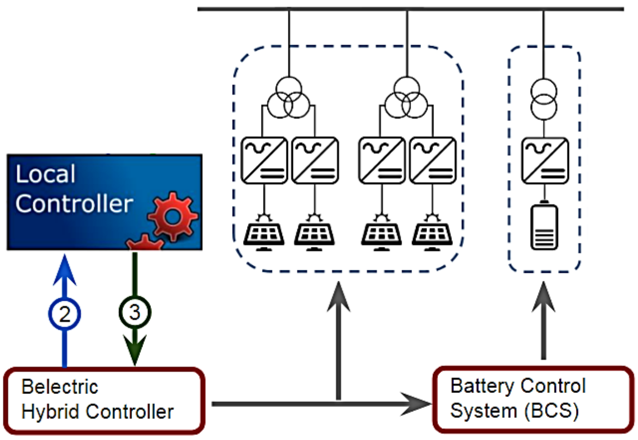


Figure 8: **Communication setup** – The BELECTRIC Hybrid Controller in the PV-Battery Hybrid system behaves as an Energy Management System (EMS) and communicates with the Photovoltaic inverters and the Battery Control System (BCS). The power request is divided by the EMS as per the control strategy and is given to PV inverters or the BCS which further controls the energy buffer unit and the GE Prosolar Inverter.

5 Data logging

The PV side is equipped with PADCON PV Monitoring equipment and a visualisation via the according PADCON Web portal (data granularity of 1 s) which gathers data from the SMA inverters and all the installed sensors which measures the environmental conditions at Rainbows PV Solar Park located at Willersey. Due to low data resolution of 1 s, the plant is further equipped with a GE RA331 data acquisition module which acquires the data from the PV side at an interval of 20 ms using voltage and current transformers. The GE RA331 does not measure the individual power output of each SMA inverter but measures the power output of the Rainbows PV farm at Willersey.

The energy buffer unit is equipped with the EBU SCADA system (data granularity – 1 s) which stores the electrical parameters from DC and AC side of EBU system. The SCADA system also gathers data from the battery management system which monitors voltage, temperature and hull integrity for each cell/string/system. In general, the SCADA systems are used to gather and process real-time data to remotely monitor the system and help detect issues and mitigate the downtime of the system. The SCADA systems for PV and battery storage plants have a data granularity of 1 s.

In the current hardware set up the energy buffer unit's response is evaluated by configuring the Battery Control System (BCS) to log EBU's active power along with the GPS synchronized timestamp at minimum possible latency. Furthermore, the BCS clock is synchronized with the Hybrid Controller and PMU which are synchronized with a GPS clock. As a result the individually logged data for PV inverter, energy buffer unit and transmission line parameters can be overlapped to find the overall response from the system during a frequency event in GB power network.

The BCS data logger logs the data with a data resolution ranging from 90 ms-160 ms. This uncertainty in the resolution range is introduced by communication traffic and the control system. Therefore, long term measurement equipment similar to the measurement system on the PV side will be configured and used in future applications. This will provide higher data granularity and will reduce the current uncertainty in the logging data.

6 Test description & objective

6.1 Precursor tests

The primary goal of the precursor tests is to investigate the individual dynamic performance of the PV-Battery inverter hardware. The individual precursor test on the PV and Battery system involves controlling the power output by changing the working point of the following inverters one at a time:

1. SMA inverters installed in the Rainbows solar PV power plant at Willersey, England.
2. GE inverter installed in the Energy Buffer Unit at Willersey, England.

The test is further divided into two categories to check the inverter control and the inverter power ramp rates. Each precursor test is described below.

A. Inverter control test

This is the first test on the hybrid system which provides a first glimpse of factors that potentially influence the final reaction time of the system. The purpose of this test is to validate the established communication settings between the BELECTRIC Hybrid Controller and the inverters in the PV-Battery hybrid system located at Willersey.

The tests include executing the following steps for both PV and EBU Inverter individually:

1. Regulating the active working point of the inverter(s).
2. Governing the shutdown/start up for each individual inverter unit.

The modifications are done to the inverter by the BELECTRIC Hybrid Controller through the developed MODBUS TCP client. The test passes if each individual inverter acknowledges the commands – with visible changes of the working point within a reasonable magnitude and time period. Reasonable means in this case that it is clear that the root cause of the change in the working point has happened because of a control command by the BELECTRIC Hybrid Controller.

The PV reaction is evaluated via the PMU / Phasor point App which have the data resolution of 20 ms while the battery reaction is evaluated by a dedicated SCADA system with data resolution of 1 s and also using the BCS data logging system which have a data logging granularity ranging from 90 ms – 160 ms.

B. Ramp rate test

The purpose of this test is to assess the inverter response rate and investigate the ramp rate of PV and battery inverter between different working points. During this test the inverters from each resource is individually forced to step up and down between different working points. The ramp up/down rates between each working step for the two sets of inverters are measured and evaluated. The PV inverter ramp rates are measured using the PMU / Phasor point App which has a data granularity of 20 ms while the energy buffer unit's inverter ramp rates are measured by processing the raw data saved by the BCS with logging interval ranging from 90 ms – 160 ms.

As the PMU / Phasor point App is deployed at grid connecting point the PV ramp rates are executed during constant irradiance and the rates are evaluated by looking at the change in the power from the PV plant at grid connecting point. At the energy storage side the ramp test can be performed at any time and evaluated with BCS data logging system.

This test passes if the Hybrid Controller communicates the power set points to the inverters and the inverter changes the power in accordance with the written working point.

6.2 Open loop test

The scope of open loop test is to assess the communication setup between BELECTRIC Hybrid Controller and GE Local Controller during frequency events. During this test the Hybrid Controller sends its power availability, ramp rates and durations to the GE Local Controller. The hardware is configured to run in open loop mode i.e. the photovoltaic and the energy buffer unit inverters do not accept or follow the power request from GE Local Controller to provide frequency response.

The purpose of the open loop test is to see whether the BELECTRIC Hybrid Controller and GE Local Controller have a successful communication and to check if the power request is received by the BELECTRIC Hybrid Controller without any loss of data packages during the simulated frequency events. The test also validates if the PV-battery hybrid system power availability is received by the GE Local Controller without unrepresentative delays.

For simulated frequency events, the GE PMU Simulator is used to inject known frequency signals with pre-defined RoCoF and frequency nadir into the installed Local Controller. With the GE PMU simulator, different under and over-frequency events which are listed in Table 6 on page number 16 are simulated. In parallel the Hybrid Controller evaluates the resource availability from the PV-Battery Hybrid System and sends the parameters to the GE Local Controller as per the response strategy mentioned on Table 4 on page number 14.

The test passes if GE Local Controller receives the BELECTRIC's actual positive and negative resource availability and the BELECTRIC Hybrid Controller receives a power request from the GE Local Controller for different simulated frequency events in accordance to its positive and negative power availability.

6.3 Hardware in the loop test (HiL)

The scope of the hardware in the loop test is to assess the hybrid system performance including the ramp rates, reaction time and the full power response time of the system to an actual power request from the GE Local Controller during a frequency event. This test is categorised in two cases:

A. Simulated frequency event during the night

During this test, positive and negative power availability of the battery system is sent to the GE Local Controller. Using the GE PMU simulator, different magnitudes of under and over frequency events are simulated. The battery system should respond to the power request by the GE Local Controller during simulated under and over frequency events. The test passes if the following steps are processed and executed.

1. Power request is received by BELECTRIC Hybrid Controller.
2. The power request is processed and written to the battery inverter according to the implemented strategy.
3. The battery inverter(s) set point values change based on the power request.
4. The response power is provided by the battery inverter.

B. Simulated frequency event during the day

During this test, positive and negative power availability of the overall PV-battery hybrid system is sent to the GE Local Controller. The battery system should response to the power request by the GE Local Controller when an under frequency event is simulated using the GE PMU Simulator, in addition the PV system should continue to run at MPP and remain unaffected.

On the other hand a coordinative response by the PV-Battery system (as illustrated in Figure 6 on page number 15) should be observed during a simulated over frequency event. The test passes if the following steps are processed and executed.

1. Power request is received by BELECTRIC Hybrid Controller.
2. The power request is processed and written to each individual inverter power register according to the implemented strategy.
3. The individual inverter(s) set point values change based on the power request.
4. The battery inverter power output changes and enhances the overall performance of the system.

7 Test Procedure

7.1 Precursor Test

On the PV side, all precursor tests are executed only on the inverter SMA 1.1 while on the Energy buffer unit side the tests are run on the GE Prosolar inverter. The BELECTRIC Hybrid Controller program communicates with the individual inverters through an established Modbus TCP connection. If any of the precursor tests fails, hardware in the loop (HiL) tests may not take place and fail by default because of the incapability of inverters to respond to control commands.

A. Inverter control test

○ PV inverter control test

To control the inverter output, a percentage set point is written to its power register by the BELECTRIC Hybrid Controller. When the inverter power output is 70% of its nominal power and '35' is written to the specific power register, the inverter starts to run at 35% of its nominal power value. This active set point control command can be sent to any specific connected SMA inverter for power regulation via Modbus TCP connection. The inverter control software has also been adjusted prior to the tests to correspond to such interference with the register values. Otherwise, the original setting of the inverter would have a fixed working point at MPP for maximum PV plant power output as it is normally intended for solar PV farms.

The changes to the active power set points are made to verify the procedure in general. The active power set point send during this test should always be lower than the percentage at which the inverter is running under MPP. The change in individual inverter power is observed via Phasor Point app, PADCON PV Web Portal and the BELECTRIC Hybrid Controller interface.

The test also includes shutting down the inverter by sending a power set point of 0 and restarting the inverters to check if the whole communication system reconnects automatically to the Hybrid Controller and maintains the previously written control statements. This is useful to assure that the control logic works after a failure in the system or during routine plant maintenance. All the control commands are sent via the BELECTRIC Hybrid Controller. The system behaviour is observed by the Phasor Point app, PADCON PV Web Portal or BELECTRIC Hybrid Controller interface.

PV inverter control in general is also tested with the help of Simply Modbus – a Modbus TCP Client Test Software and manually by the SMA web interface portal to have a fall back option if communication or control infrastructure partly fails.

- **Battery inverter control test**

During the inverter control test for the energy buffer unit, the battery storage system is charge with a power of 300 kW for 5 minutes this is followed by discharging the battery storage system at 300 kW for 5 minutes. The 5 minute charging and discharging test allows verifying the change in SoC level as well as the change in inverter working point. Moreover this process keeps the SoC level unaffected after the completion of the test. During the test, the GE Prosolar inverter should change its working point and the battery management system must continuously communicate with the Belectric Hybrid Controller and sends the power availability parameters.

The EFCC PV-battery power resource system does not have high resolution phasor measurement system deployed for Battery and Photovoltaic system individually. As a result, Belectric supervisory control and data acquisition system was used during the precursor test. Due to low data granularity, the EBU SCADA system was only used during the precursor test – Energy buffer unit inverter control test.

B. Ramp rate test

- **PV inverter ramp test**

SMA inverter 1.1 is forced to operate at lower working-points during the time of constant high irradiance of 600 W/m^2 or more. The working point is varied in 100 kW and 200 kW steps from 8 kW and to 600 kW. SMA inverter 1.1 is ramped down with 100 kW steps from 600 kW down to 8 kW and then ramped back up to its maximum power point (MPP) with the same 100 kW steps. The inverter is forced to operate at these working set points via command from the BELECTRIC Hybrid Controller.

The inverter is not ramped down to 0 kW as this causes the inverter to shut down and the PV plant becomes unavailable for at least a minute for the restart process. The inverter in the plant requires a minute to come up due to inverter’s grid-synchronization mechanisms before the start. The lowest power at which the installed inverters can run without shutting down is 8 kW (1% of its nominal power).

Due to PADCON PV Web portals low data resolution of 1 second the ramp rate of the inverter is investigated in parallel with high resolution data from GE RA331 data acquisition module which doesn’t measure the power from each inverter but instead measures the overall power of the PV plant at Willersey.

If the ramp rates vary by more than 5% the difference will be considered significant and taken into account for SMA inverter control.

- **Battery inverter ramp test**

To quantify the ramp rate of the storage system, GE Prosolar Inverter is forced to ramp up/down and the battery storage system is configured to charge and discharge at a constant power for small duration. The working point changes executed during the tests are illustrated in the Table 7. To test the ramp rate capability of the battery system under the real EFCC control scenario, stepped positive and negative ramp rates are executed. The battery inverter ramp rates are measured by processing data logged by the BCS at an uncertain interval from 110 ms – 160 ms.

SNO.	CONTROL SCHEME	POWER	SNO.	CONTROL SCHEME	POWER
1(a)	CHARGING	+ 120 kW	1(b)	DISCHARGING	- 120 kW
2(a)		+ 240 kW	2(b)		- 240 kW
3(a)		+ 360 kW	3(b)		- 360 kW
4(a)		+ 480 kW	4(b)		- 480 kW
5(a)		+ 600 kW	5(b)		- 600 kW

Table 7: Ramp test – List of working point shifts executed on the GE Prosolar inverter during the battery ramp rate test. The maximum positive/negative power availability by the energy buffer unit is ±600 kW. The working point shifts corresponds to the stepped power request of 20% of the battery availability generated by the GE Local controller.

7.2 Open Loop Test

During a frequency event the GE Local Controller sends a continuous power request to the BELECTRIC Controller. The objective of the Open Loop test is to check the communication response time of the hybrid control and inspect if the BELECTRIC Hybrid Controller can fetch and process the power requests without losing or delaying any power request. Along with that, the Open Loop test evaluates whether the Local Controller is receiving power availability from the BELECTRIC Hybrid Controller. If this test fails, then the hardware in the loop test fails automatically by default. The Open Loop test can be further divided into two sub categories which are described below.

A. Simulated frequency event during the night

During this test frequency event are simulated using GE PMU Simulator during the night, The Simulator is used to inject frequency signals with known RoCoF value and predefined frequency nadir during the time when PV system is unavailable. During this test under and over frequency events of different magnitude are simulated with a RoCoF of ± 0.15 Hz/s. The event detection RoCoF limit during this test is set to be ± 0.1 Hz/s. The GE Local controller should detect the event as the RoCoF crosses the above-mentioned threshold, the Local Controller assesses the power availability of the PV plant and the battery system followed by a power request to the BELECTRIC Hybrid Controller according to the response strategy mentioned in Table 2 on page number 14.

The test checks the functionality of the established GOOSE connection between the GE Local Controller and BELECTRIC Hybrid Controller in addition to this the test also verifies that the hybrid system sends its available power as per the response strategy. This is checked by comparing the Local Controller signal in Straton and the signal from the Hybrid Controller before, after, and during a simulated event. It is important that when the Local Controller changes its power request that the Hybrid Controller receives and processes this signal with a delay not exceeding 100 ms.

B. Simulated frequency event during the day

During this test frequency events are simulated using GE PMU Simulator during the day time. The simulator is used to inject frequency signals with known RoCoF value and predefined frequency nadir during the time when PV and battery systems are available. During this test under and over frequency events of different magnitude are simulated with a RoCoF of ± 0.15 Hz/s. The event detection RoCoF limit during this test is set to be ± 0.1 Hz/s. The GE Local controller should detect the event as the RoCoF crosses the above-mentioned threshold, the Local Controller assesses the power availability of the PV plant and the battery system followed by a power request to the BELECTRIC Hybrid Controller according to the response strategy mentioned in Table 2 on page number 14. The test checks the functionality of the established GOOSE connection between the GE Local Controller and BELECTRIC Hybrid Controller. In addition to this the test also verifies that the hybrid system sends its available power as per the response strategy. This is checked by comparing the Local Controller signal in Straton and the signal from the Hybrid Controller before, after, and during a simulated event. It is important that when the Local Controller changes its power request that the Hybrid Controller receives and processes this signal with a delay not exceeding 100 ms.

7.3 Hardware in the loop test

During the Hardware in the Loop Test the PV-Battery Hybrid response capabilities are tested. For this test only SMA inverter 1.1 on PV side and inverter GE Prosolar on battery side are set to respond to the GE Local Controller's power request. All the remaining PV inverters operate at MPP during the entire test. The event detection threshold is maintained at ±0.04 Hz/s and as the event is detected and frequency thresholds are reached - a power requests [in kW] (as illustrated in Figure 5 and in Table 2 on page number 14) is sent by the GE Local Controller to the Belectric Hybrid Control system. This power request is distributed amongst the available inverters according to the EFCC hybrid strategy mentioned in Table 3 on page number 14. The test is further subcategorised in two parts.

A. Simulated frequency event during the night

o Under frequency event

During this test simulated under frequency events are triggered using the GE PMU Simulator. The Local Controller sends positive power requests to the Hybrid Controller based on the power availability and according to the intensity of the simulated frequency event. The battery system should follow the power request and the GE Prosolar inverter in the storage side should change its working point and provide power into the grid.

o Over frequency event

During this test simulated over frequency events are triggered using the GE PMU Simulator. The Local Controller sends negative power requests to the Hybrid Controller based on the power availability and according to the intensity of the simulated frequency event. The battery system should follow the power request and the GE Prosolar inverter should change its working point by taking power from the grid.

B. Simulated frequency event during the day

o Under frequency event

During this test a simulated under frequency event is triggered. An under frequency event of 48.85 Hz with a RoCoF of - 0.15 Hz/s is simulated by the GE PMU Simulator. The Local Controller sends positive power requests to the Hybrid Controller based on the current power availability. The battery system should follow the power request and the GE inverter should change its working point by providing power into the grid as per the power request. While the PV system should continue to remain at MPP and the inverter remain uninfluenced.

o Over frequency event

During this test a simulated over frequency event is triggered. An over frequency event of 50.65 Hz with a RoCoF of + 0.15 Hz/s is simulated by the GE PMU Simulator. The Local Controller sends negative power requests to the Hybrid Controller based on the power availability. The battery and the PV system should provide a coordinative response. Due to faster reaction time of the battery hardware the battery system should follow the power request by charging as per the power request. The GE inverter should change its working point as per the power request. Once the slow PV response comes into the picture the battery system should dynamically complement its output to get a constant power at the grid connecting point.

8 Test Results

This section shows results obtained while testing the EFCC Control scheme on the Hybrid Controller. This section includes the results from the similar tests which were executed during the stand alone PV trials. These tests were performed and the results are added for the completion of the report.

8.1 Precursor Test

A. Inverter control test

o PV Inverter control test

SMA inverter 1.1's AC power output is controlled through BELECTRIC Hybrid Controller. The inverter test outcome is observed by the PADCON PV Web Portal and through GE RA331 data acquisition module installed at the Willersey. Table 8 shows the inverter control settings in the Hybrid Controller. Table 8 shows the inverter status in PADCON PV Web Portal. During the test SMA inverter 1.1 was forced to run at a reduced power and later was brought to its normal operation.

Inverter	Pre-Inverter Control Test	Inverter Control Test	Post-Inverter Control Test
Inverter[0]			
SetActPower_prozent	100	75	100
SetReactPower_prozent	0	0	0
Inverter[1]			
SetActPower_prozent	100	100	100
SetReactPower_prozent	0	0	0
Inverter[2]			
SetActPower_prozent	100	100	100
SetReactPower_prozent	0	0	0
Inverter[3]			
SetActPower_prozent	100	100	100
SetReactPower_prozent	0	0	0

Table 8: BELECTRIC Hybrid Controller Inverter settings during PV inverter control test

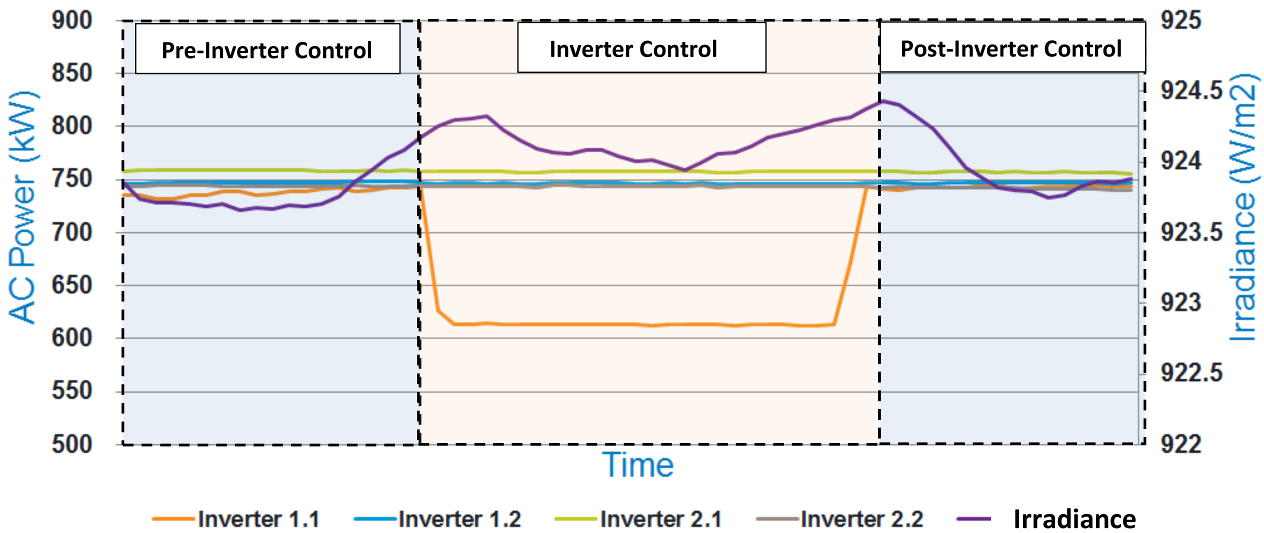


Figure 9: PADCON PV Web Portal SMA Inverter 1.1 status during PV inverter control test.

The results from the inverter control test are positive. The BELECTRIC Hybrid Controller communicated with the SMA inverter 1.1 and in response the SMA inverter 1.1 reduced the power output thus following the working point sent to it. Figure 9 illustrated the data obtained from the PADCON PV Web Portal. The inverter ramp rate evaluation is included in the next section.

- **Battery inverter control test**

The power output of the Energy Buffer Unit and the GE Prosolar inverter is controlled by the BELECTRIC supervisory control and data acquisition system. The test outcomes are observed by the graphical user interface and the measurement system present in the system. Due to low data resolution of 1s for the SCADA in this system, this system is used only for the precursor test – battery inverter control test.

The energy buffer unit system is forced to charge with 300 kW (AC) for 2 minutes followed by discharging into the power system for 2 minutes at 300 kW (AC). The results from the EBU control are found to be positive and the EBU changed its working-point during the process. Figure 10 and Figure 11 shows the results obtained during the EBU inverter control test.

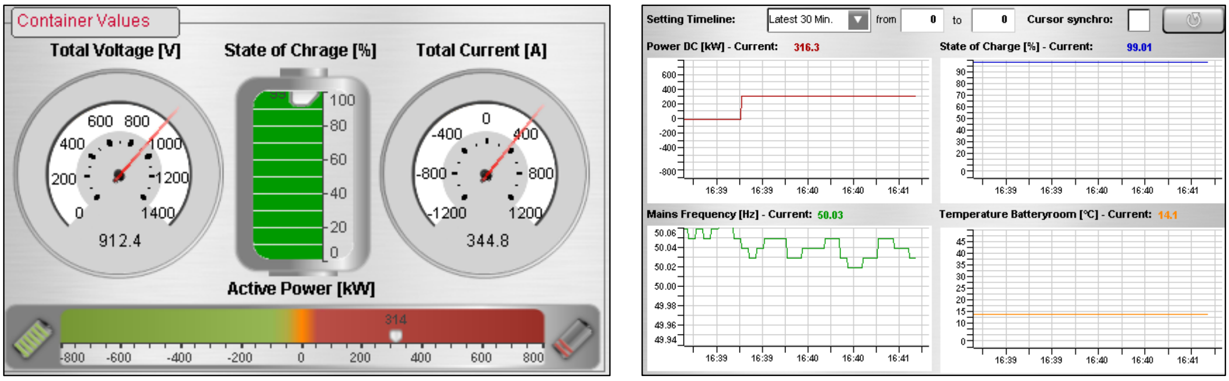


Figure 10: Energy Buffer Unit – Precursor Discharge Test. The EBU is configured to discharge into the grid with a power of 300 kW. To keep a constant power of 300 kW at the grid connecting point the battery system provides a power of 314 kW so as to compensate the inverter, transformer and cable losses.

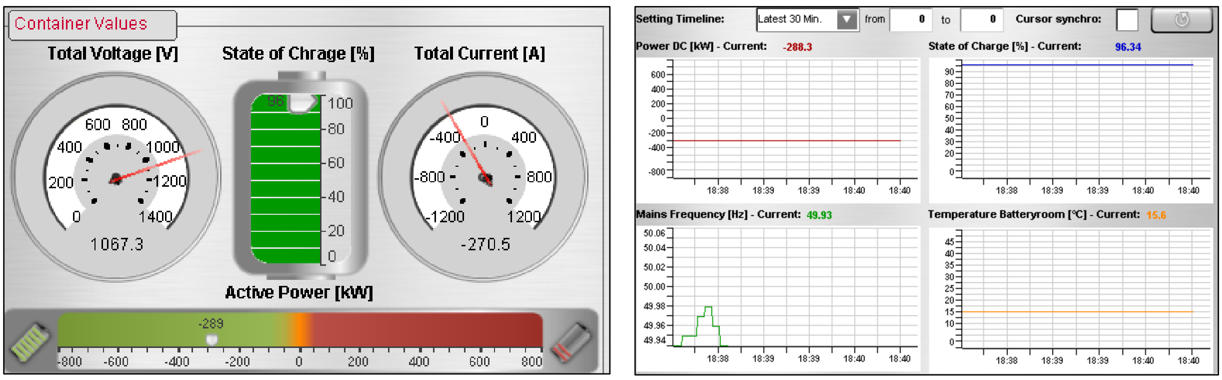


Figure 11: Energy Buffer Unit – Precursor Charge Test. The EBU is configured to charge with a power of 300 kW. To keep a constant negative power flow of 300 kW from at the grid connecting point the battery system absorbed a power of 289 kW so as to compensate the inverter, transformer and cable losses.

B. Ramp rate test

○ PV inverter ramp rates evaluation

Figure 12 shows the results from PADCON PV Web portal for the ramp test conducted on inverter 1.1. The completion of the lookup table test was successful. Through the BELECTRIC Hybrid Controller SMA inverter 1.1 was forcefully ramped down from 600 kW to 0 kW in steps of 100 kW. After successful ramp down the SMA inverter 1.1 is brought back to its initial state by ramping up in six 100 kW steps. The complete test is conducted numerous times for ramp rates evaluation.

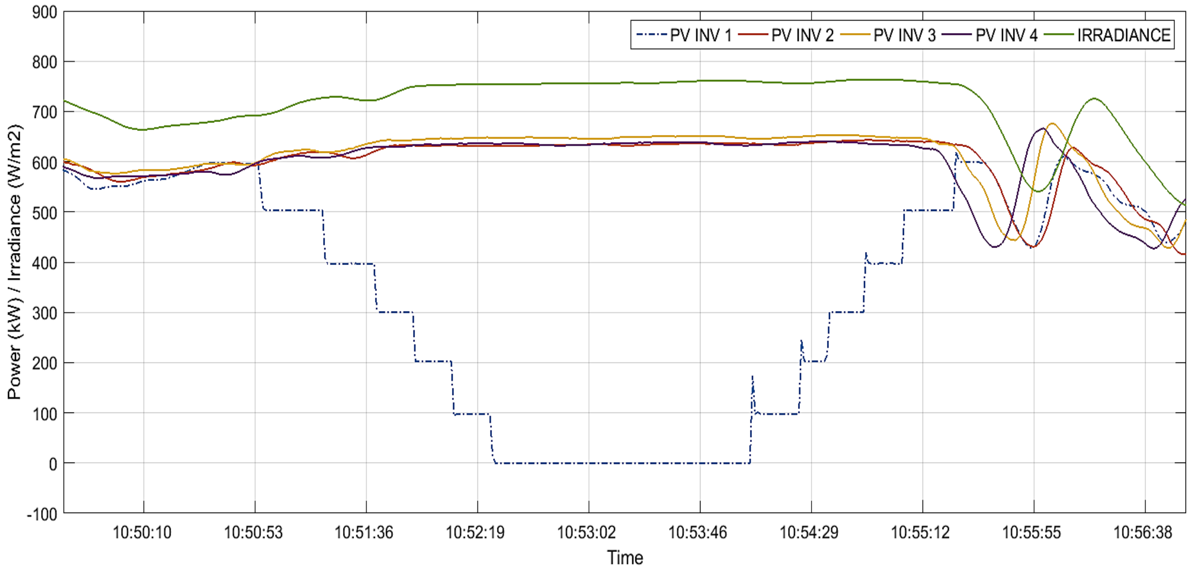


Figure 12: SMA Inverter 1.1 ramp rate test – 100 kW stepped working point shift using the BELECTRIC hybrid controller

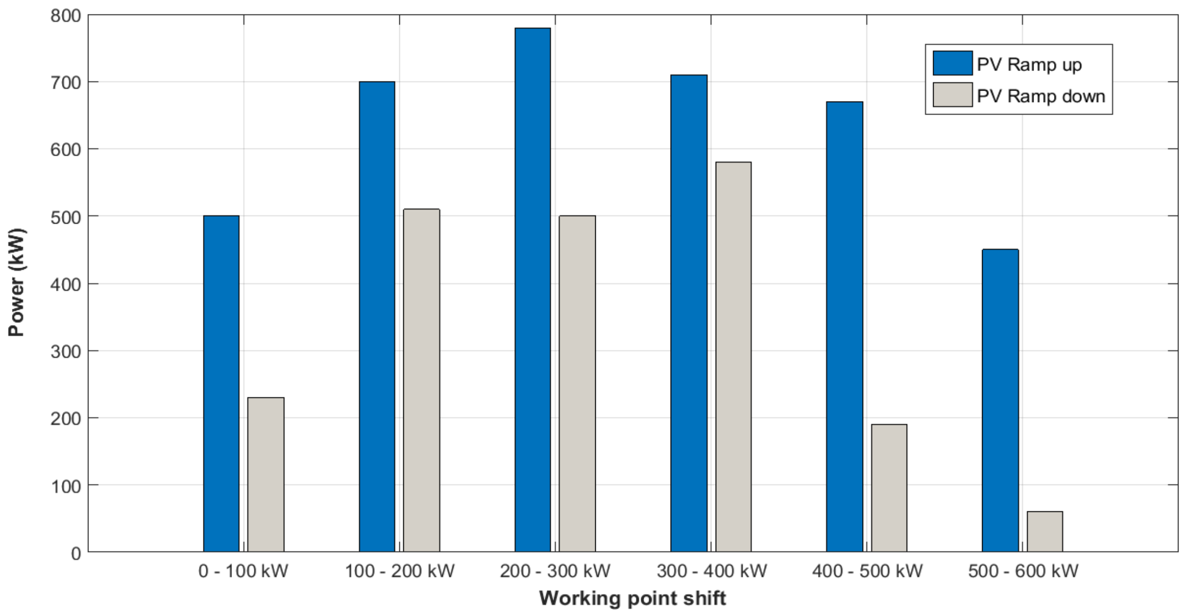


Figure 13: SMA Inverter 1.1 ramp rate test results

For ramp rate evaluation the PADCON Web Portal is not used due to limited data resolution of 1 s. As a result, data acquisition module RA331, which has a resolution of measuring 50 samples in a second, is used for this purpose. The RA331 measures the total power from the PV Plant in Willersey. To avoid errors during ramp measurement due to power fluctuation from the non-participating inverters, this test is executed during constant and high irradiance.

In a utility scale PV plant, a SCADA system with a data resolution of 1s is sufficient. For higher accuracy in ramp rate measurement a SCADA system with higher resolution is preferred so that the power change in individual inverter during inverter ramps can be observed. Realistically, at Willersey the usage of data acquisition module measuring the output of the PV plant for ramp rate measurement is reliable. This statement holds true only when the size of the resource is comparatively small. The PV plant currently running under EFCC scheme at Willersey has 4 inverters. A larger PV system with a higher number of inverters would reduce the accuracy of ramp rate measurement because of small variation in the output power from each non-participating inverter present in the PV farm due to variation in environmental conditions.

The findings showed that there is a significant difference in inverter ramp rates at different working points with an overall bell-shaped behaviour as shown in Figure 13. However, the ramp up rates measured is always faster than ramp down. After further investigation it was found that the results in Figure 13 don't show the actual behaviour of the system and the inverter ramp is a combination of two individual ramps which are given the name as the *fast ramp* and the *correction ramp.*

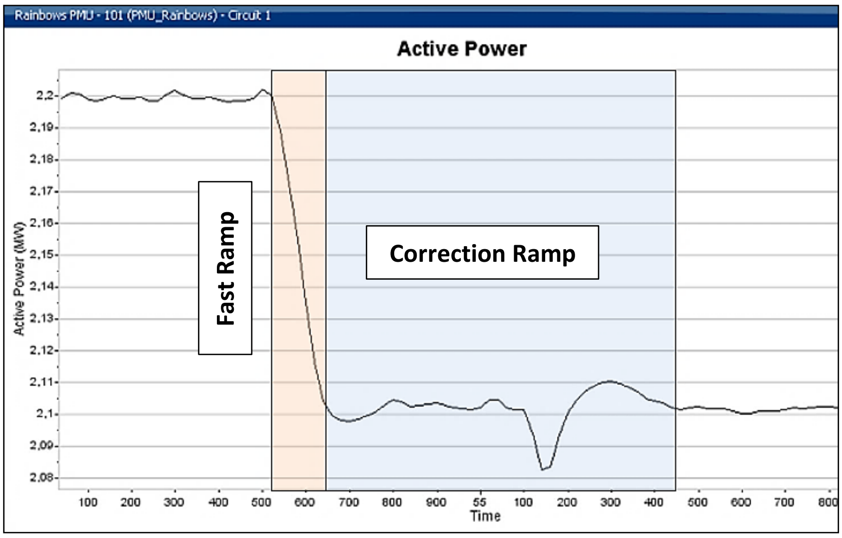


Figure 14: SMA Inverter 1.1 ramp test – 100 kW step down (working point shift) measured by the phasor measurement unit installed at Rainbows PV farm.

The inverter ramp up/down quickly until approx. 80% of its total ramp and as it approaches to the target working point it slows the ramp rates for accurate and precise working point placement. This behaviour can be seen in Figure 15, Figure 16 and Figure 17. The blue portion in the inverter ramps shows the slow *correction ramp* while the red portion in the graph depicts the *fast ramps*. Figure 17 shows that the fast ramp overshoots and crosses the working point. As a result, the correction ramp provided a negative ramp for accurate and precise working point placement.

Ramps without *correction ramps* were also measured during the test in some cases and these results were found to be unreproducible and clearly unpredictable. A possible reason regarding this hardware behaviour is that PV inverter with central architecture were neither designed nor intended to be used in fast frequency applications in previous years.

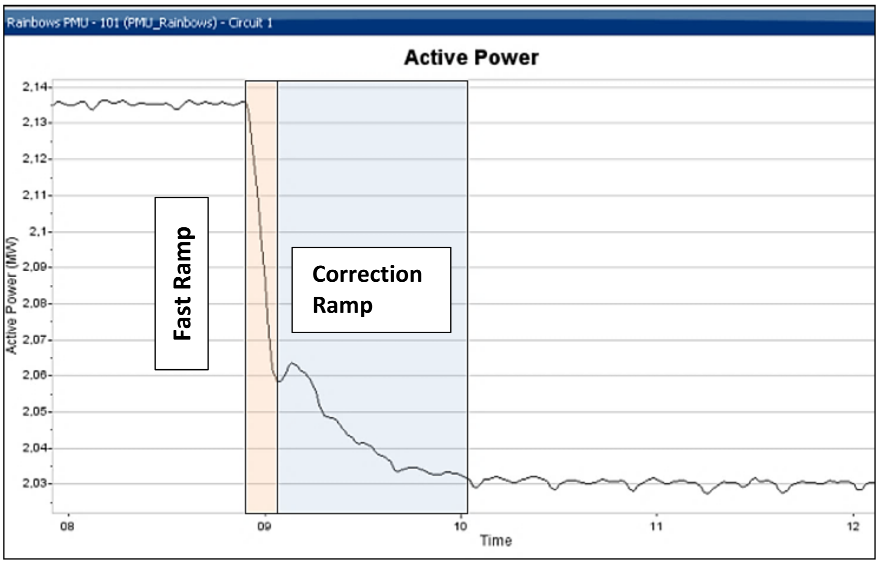


Figure 15: SMA Inverter 1.1 ramp test – 100 kW step down (working point shift) measured by the phasor measurement unit installed at Rainbows PV farm.

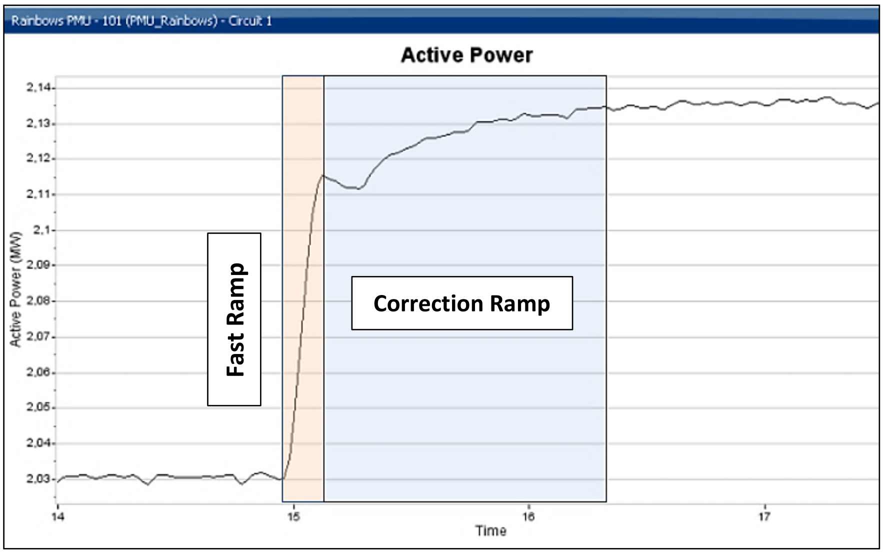


Figure 16: SMA Inverter 1.1 ramp test – 100 kW step up (working point shift) measured by the phasor measurement unit installed at Rainbows PV farm.

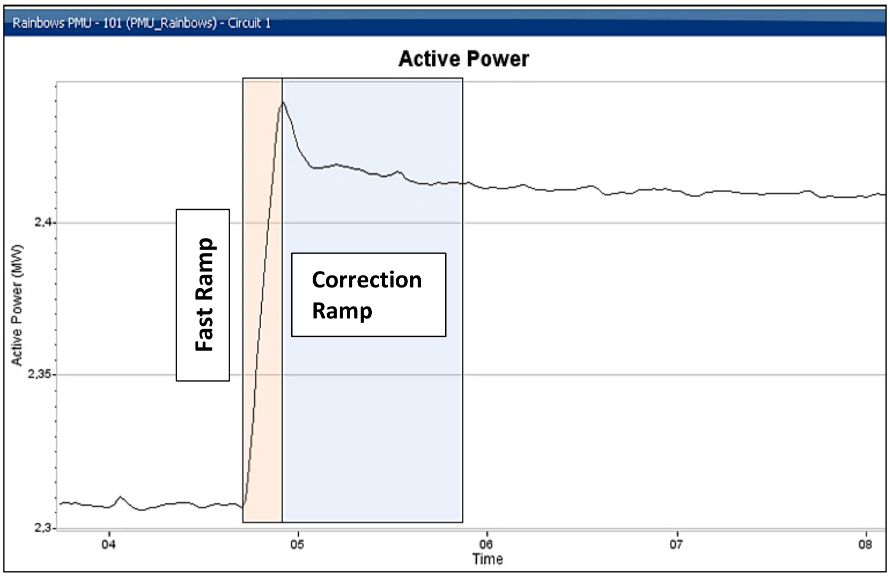


Figure 17: SMA Inverter 1.1 ramp test – 100 kW step up (working point shift) measured by the phasor measurement unit installed at Rainbows PV farm.

To quantify the magnitude of the *fast ramp* and percentage of power ramped during the same, several shifts in the working points were executed at different steps and fast ramps were calculated. Table 9 shows the results for *fast ramp.*

SNO	WORKING POINT (KW)	RAMP UP		RAMP DOWN	
		Fast Ramp Rate	**% Power**	**Fast Ramp Rate**	**% Power**
1	700-1	779 kW/s	108%[7]	772 kW/s	87%
2	500-1	730 kW/s	100%	722 kW/s	78%
3	400-1	1000 kW/s	93%	835 kW/s	78%
4	500-400	556 kW/s	80%	497 kW/s	77%
5	500-300	663 kW/s	86%	648 kW/s	80%
6	500-200	695 kW/s	88%	717 kW/s	87%
7	500-100	788 kW/s	80%	779 kW/s	81%

Table 9: Fast ramp rate investigation results

In general, the larger the working point shift the higher is the observed ramp rate for the fast ramp. During some tests the ramp up missed the target working point. As a result the correction ramp is negative. Generally fast ramp up rates were found to be higher than the fast ramp down. One possible reason for slower ramp down and faster ramp up could be due to the characteristic of the PV-I-V Curve.

[7] 108% as the Fast Ramp overshoots target set-point value.

Figure 18 shows the I-V characteristics of a sample PV cell at different irradiance and constant temperature. To reduce the power output the inverter shifts the operating point towards the right side of the curve by reducing the voltage at the DC terminal. Reducing the voltage and shifting the working point in the left direction can also result in power reduction. This practice is not generally done as the inverters are current limiting and shifting the operating point in the left increases the current. Also each inverter has to maintain a specific minimum voltage at its output terminal and reducing the voltage by shifting the operating point towards left might reduce the output voltage of the inverter in case its ramped down to a very low working point.

The voltage increase at the DC terminal is achieved by pulse-with-modulation technique. The slope of the PV-I-V curve starts to increase as the operating point moves in the right direction. Moreover the slopes are different at different irradiance levels. These slopes also changes according to the PV module temperature therefore during an inverter ramp down the control loop of the system take extra care in finding the correct working point as even a small terminal DC voltage variation may lead to huge power changes. While on the other hand, during inverter ramping up, the operating point is shifted back in the right direction towards the point A, B or C in Figure 18 by decreasing the voltage. As the slope in this direction is small the inverter control is able to place the working point at the target level quicker - therefore the ramp up rates are faster than the ramp down rates of an inverter. It was observed that the major portion of the power ramp was executed by the fast ramp. With the current data this can be approximated as 89% during the ramp up and 80% during a ramp down. Additional test results are attached in the appendix.

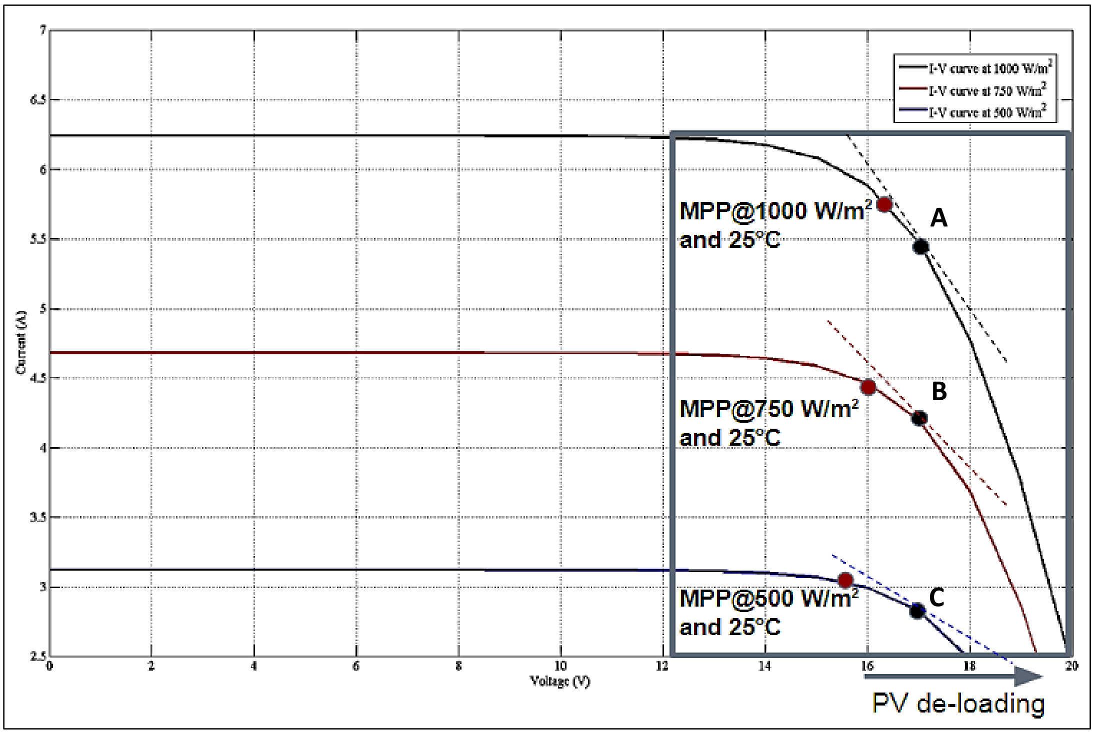
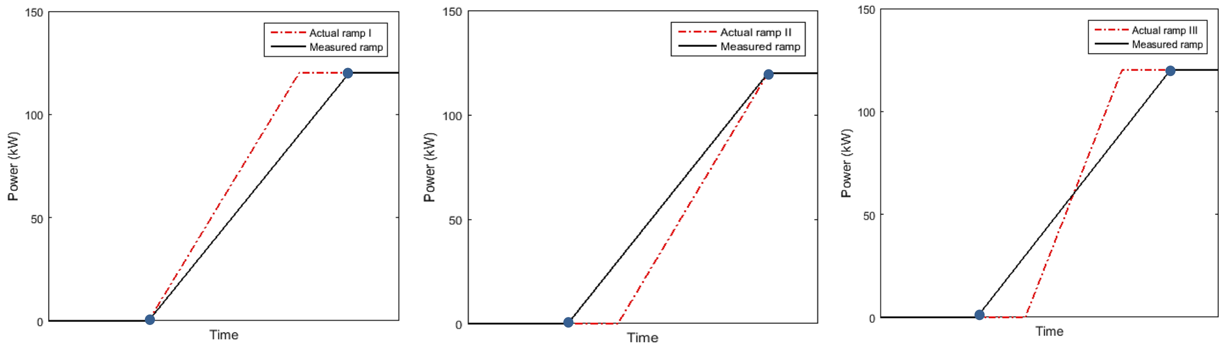


Figure 18: I-V Characteristics of a Photovoltaic cell

- **Battery inverter ramp rate evaluation**

The ramp test for the GE Prosolar inverter was successful and the inverter changed its working point as per the Table 7 on page number 24. After successfully executing the test, the battery inverter was brought back to its initial state. The complete test was conducted numerous times and the ramp rates were evaluated using the data logged by the BCS. Overall the battery inverter was found to be much faster than the PV inverter. The maximum ramp rate of 6.6 MW/s was observed during the execution of highest working point shift, i.e. from 0 kW to 600 kW.

The ramp rates evaluation for the energy buffer unit can have some degree of uncertainty due to unknown ramp-start and ramp-end time. The ramp rate was evaluated by assuming the ramps start and end time to be the one logged by the data logger. The actual behaviour of the energy buffer unit during the ramp rate could be different than the one represented by the logged data, this is illustrated in figure 19 using three possibilities: (a) when the inverter reaches its destination working point power before the data logger recorded. (b) When the inverter reaction time is longer than observed and (c) combination of the above cases.



(a) (b) (c)

Figure 19: Uncertainty in ramp rate evaluation due to low resolution data logging

To minimize this uncertainty the ramp rate evaluation was executed numerous times on the system and only the results which were logged with minimum data granularity (90-100 ms) were used. Furthermore, to reduce or totally eliminate the error due to uncertain ramp-start and ramp-end time, intermediate ramp rates were evaluated by using the test cases where the BCS logged one or more data points during the ramp. The data points logged during the ramp rate test, which allows for eliminating the uncertainty in ramp start and ending time. Figure 20 and Figure 21 shows sample ramp rates observed during the working point shift from 0 to -600 kW and from 0 to -240 kW while Table 10 and Table 11 shows the results for few selective ramp up and down tests (logged with minimum data granularity) which were executed on the energy buffer unit during the EFCC test trails.

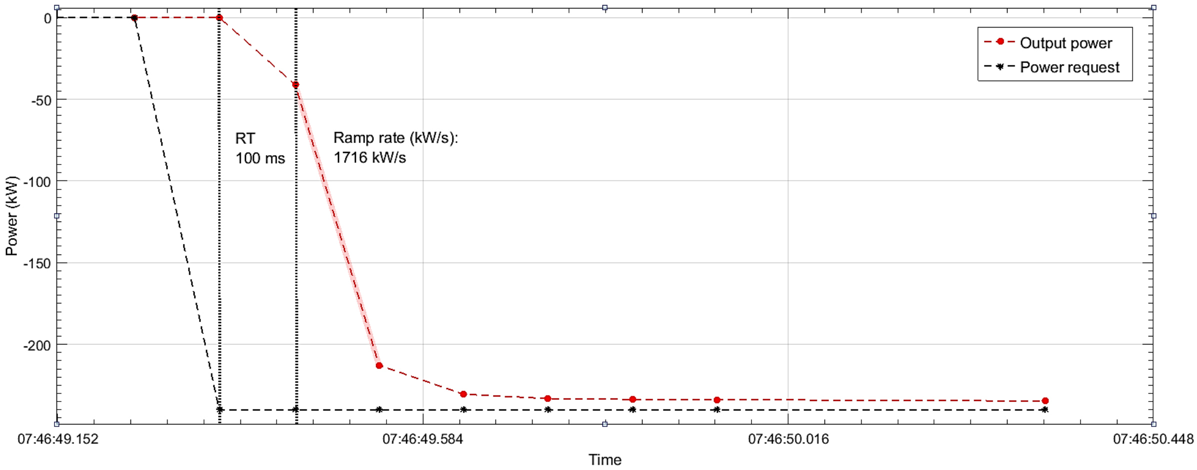


Figure 20: (Known ramp-start and stop time) Working point shift from 0 kW to -240 kW during ramp rate test. The inverter ramped down at a ramp rate of 1716 kW/s with observed reaction time of less than 100ms. Due to the minimum BCS data logging resolution of 100 ms the actual reaction and full response time of the system cannot be precisely determined by the measurement system and the ramp rate is actually higher.

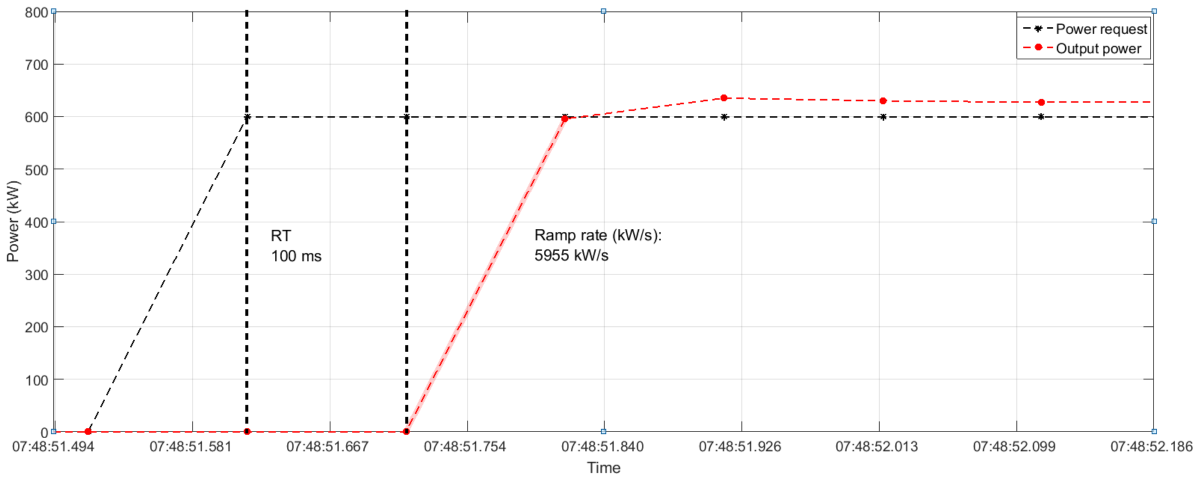


Figure 21: Working point shift from 0 kW to 600 kW during ramp rate test. The inverter ramped up at a ramp rate of 5955 kW/s with observed reaction time between 100 – 200 ms.

SNO.	WORKING POINT SHIFT	RAMP RATE TEST	
		Trial phase 1	Trial phase 2
1	0 – 600 kW	5463 kW/s	6635 kW/s

Table 10: Measured positive ramp rates of the GE Prosolar inverter by the BCS data logger. The results in the Table include tests which were recorded by the data logger with a data granularity of 90-100 ms.

SNO.	WORKING POINT SHIFT	RAMP RATE TEST	
		Trial phase 1	Trial phase 2
1	0 – - 600 kW	5512 kW/s	5612 kW/s

Table 11: Measured negative ramp rates of the GE Prosolar inverter by the BCS data logger. The results in the Table include tests which were recorded by the data logger with a data granularity of 90-100 ms.

8.2 Open loop test

During the open loop test the GE PMU Simulator is activated which is then used to inject simulated frequency and RoCoF values in the GE Local Controller. Using the GE PMU Simulator various over and under frequency events (mentioned in Table 2 on page number 14) are simulated. While the PV-Battery system real power availability is sent to the GE Local controller, the hardware is configured to run in open loop mode and the inverters does not process the power request. During the test under and over frequency events were simulated, in response the peak power requested from the GE Local controller is received and evaluated.

During the test the power request received from the GE Local Controller are found to be in accordance with the nature and magnitude of the frequency event and with the power availability sent from the hybrid resource. Table 12 and Table 13 show the results for open loop test during daytime (PV – available). Table 14 and Table 15 show the results obtained during the test performed at night (PV – unavailable). The snapshot of observed results from GE Local controller is attached in Figure 22.

SNO.	SIMULATED FREQUENCY EVENT – PMU SIMULATOR	SENT POS/NEG POWER AVAILABLE	RECEIVED POWER REQUEST	POWER REQUEST % AVAILABLE
1	0.15 Hz/s ramp down to 49.65 Hz	+600 / -446 kW	+120 kW	20%
2	0.15 Hz/s ramp down to 49.45 Hz	+600 / -490 kW	+240 kW	40%
3	0.15 Hz/s ramp down to 49.25 Hz	+600 / -349 kW	+360 kW	60%
4	0.15 Hz/s ramp down to 49.05 Hz	+600 / -527 kW	+480 kW	80%
5	0.15 Hz/s ramp down to 48.85 Hz	+600 / -550 kW	+600 kW	100%

Table 12: Open Loop Test results for simulated under frequency events and real power availability during the time when PV availability is true.

SNO.	SIMULATED FREQUENCY EVENT – PMU SIMULATOR	SENT POS/NEG POWER AVAILABLE	RECEIVED POWER REQUEST	POWER REQUEST % AVAILABLE
1	0.15 Hz/s ramp up to 50.25 Hz	+600 / -494 kW	-98 kW	20%
2	0.15 Hz/s ramp up to 50.35 Hz	+600 / -390 kW	-156 kW	40%
3	0.15 Hz/s ramp up to 50.45 Hz	+600 / -543 kW	-325 kW	60%
4	0.15 Hz/s ramp up to 50.55 Hz	+600 / -551 kW	-440 kW	80%
5	0.15 Hz/s ramp up to 50.65 Hz	+600 / -558 kW	-558 kW	100%

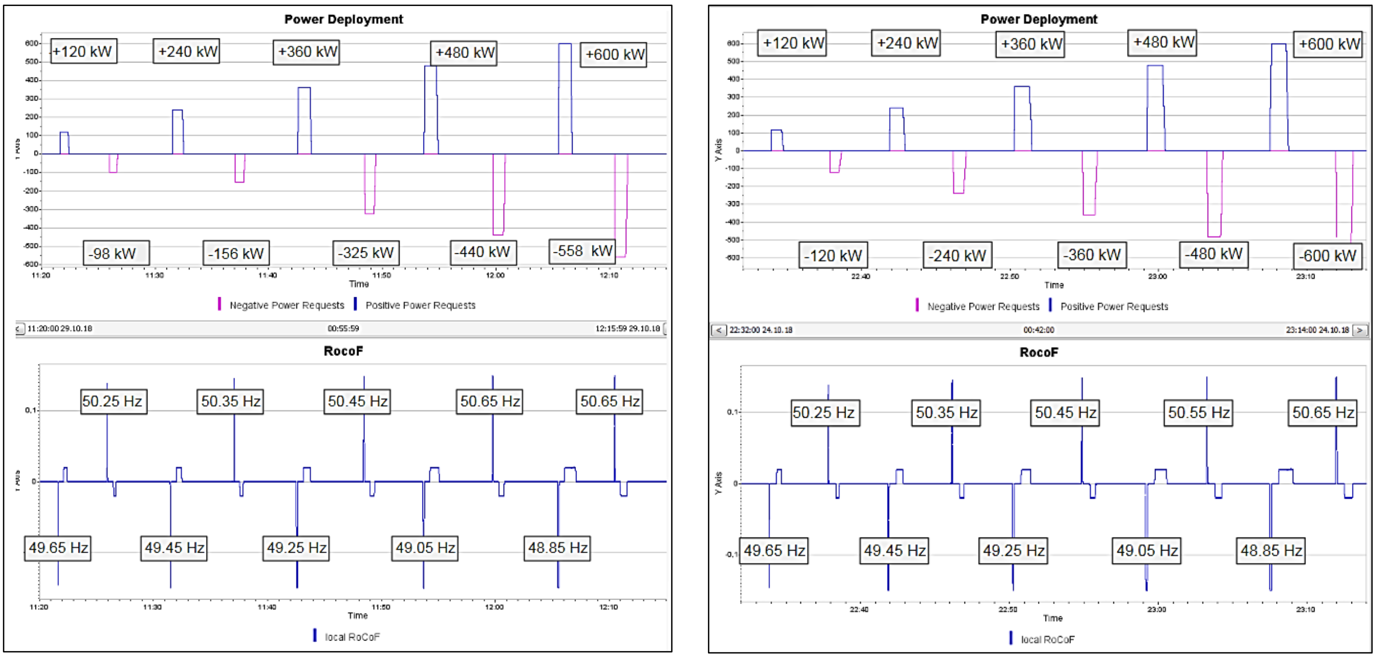
Table 13: Open Loop Test results for simulated over frequency events and real power availability during the time when PV availability is true.

NO.	SIMULATED FREQUENCY EVENT – PMU SIMULATOR	SENT POS/NEG POWER AVAILABLE	RECEIVED POWER REQUEST	POWER REQUEST % AVAILABLE
1	0.15 Hz/s ramp down to 49.65 Hz	+600 / -600 kW	+120 kW	20%
2	0.15 Hz/s ramp down to 49.45 Hz	+600 / -600 kW	+240 kW	40%
3	0.15 Hz/s ramp down to 49.25 Hz	+600 / -600 kW	+360 kW	60%
4	0.15 Hz/s ramp down to 49.05 Hz	+600 / -600 kW	+480 kW	80%
5	0.15 Hz/s ramp down to 48.85 Hz	+600 / -600 kW	+600 kW	100%

Table 14: Open Loop Test results for simulated under frequency events and real power availability during the time when PV availability is false.

SNO.	SIMULATED FREQUENCY EVENT – PMU SIMULATOR	SENT POS/NEG POWER AVAILABLE	RECEIVED POWER REQUEST	POWER REQUEST % AVAILABLE
1	0.15 Hz/s ramp up to 50.25 Hz	+600 / -600 kW	-120 kW	20%
2	0.15 Hz/s ramp up to 50.35 Hz	+600 / -600 kW	-240 kW	40%
3	0.15 Hz/s ramp up to 50.45 Hz	+600 / -600 kW	-360 kW	60%
4	0.15 Hz/s ramp up to 50.55 Hz	+600 / -600 kW	-480 kW	80%
5	0.15 Hz/s ramp up to 50.65 Hz	+600 / -600 kW	-600 kW	100%

Table 15: Open Loop Test results for simulated over frequency events and real power availability during the time when PV availability is false.



(a) (b)

Figure 22(a): **Open loop test for the PV and Battery Hybrid System during the day** – BELECTRIC Hybrid Controller receives positive power request according to the battery power availability and negative power request according to the PV power availability.

Figure 22(b)**: Open loop test for the PV and Battery Hybrid System at night** – BELECTRIC Hybrid Controller receives positive and negative power request according to the battery positive and negative power availability.

8.3 Hardware in Loop Test

To check the reaction time and the performance of the EFCC PV-Battery Hybrid system different simulated frequency events are triggered using the GE PMU Simulator. During the hardware in the loop test the PV, battery inverters are configured to change their working point according to the control signals by the Hybrid Controller and follow the power request received from the GE Local Controller for a combined response. Due to different control strategy during the day and in the night, the performance is checked by simulated over and under frequency events using GE PMU Simulator when both PV and battery systems are available for providing a response during the day, and during the night, when only the battery is capable of providing response in both the direction.

A. Simulated frequency events at night

○ Under frequency event

These tests were conducted after sunset with simulated under frequency events. The control system started reducing the SOC of the battery system 1 hour before the sunset time. At that time the system power availability changed to ±600 kW, 45 minutes before sunset, which means that the battery system took over to provide frequency response in the hybrid control system. The section particular shows one of the test results obtained during simulated frequency event with a RoCoF of -0.15 Hz/s and a frequency nadir of 48.85 Hz. The GE Local Controller requested a positive-stepped power request with maximum power of +600 kW. The GE Prosolar Inverter reaction time was less than 280 ms until full response to a single power step request. The Figure 23 shows the battery DC power which overshoots and undershoots during the discharging and charging process to keep the power at the GCP constant and to compensate for the electrical power losses.

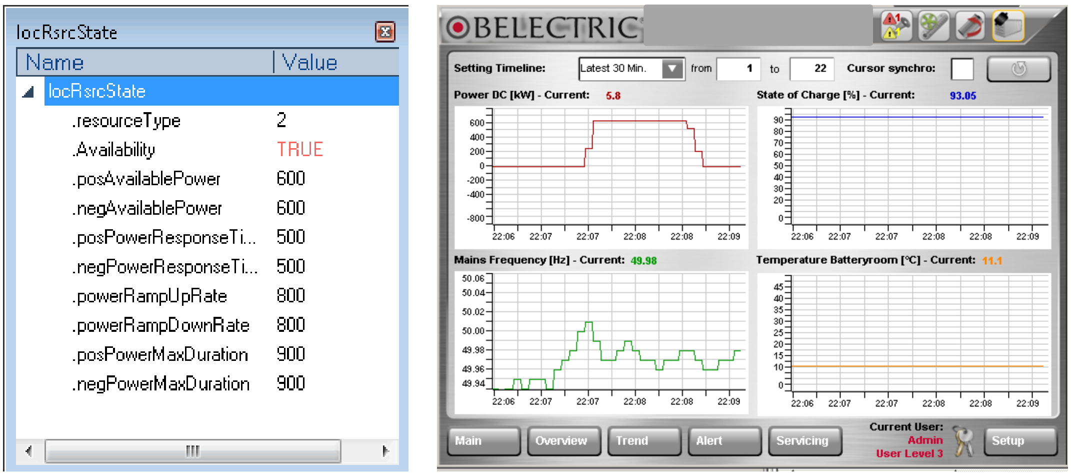
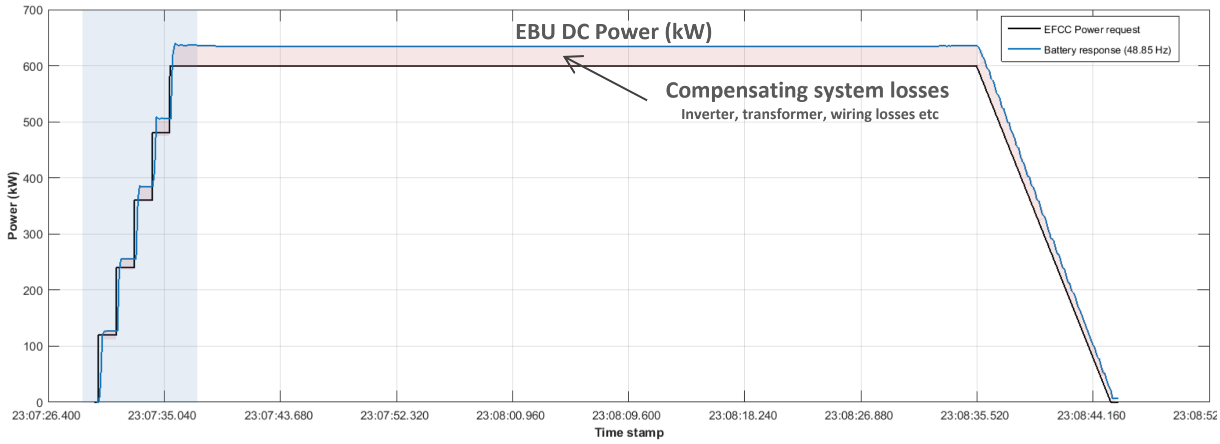
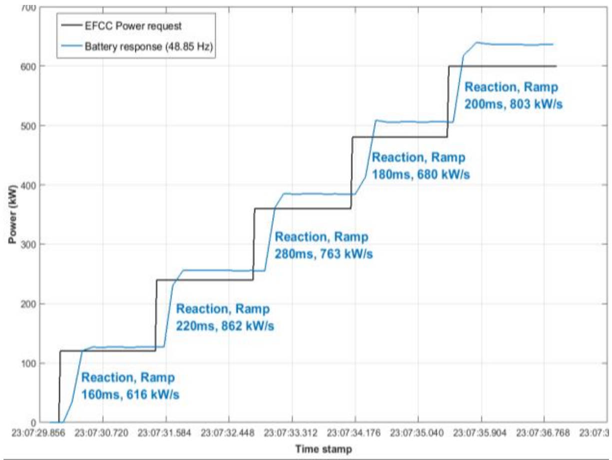


Figure 23: Illustration of battery reaction during hardware-in-the-loop test with simulated under frequency event (Frequency nadir – 48.85 Hz) during the unavailability of PV system. The battery takes over and maintains resource availability with a power availability of ± 600 kW.





SNO.	POWER STEP	REACTION TIME
1	0 – 120 kW	160ms
2	120 – 240 kW	220ms
3	240 – 360 kW	280ms
4	360 – 480 kW	180ms
5	480 – 600 kW	200ms

Table 16: Individual reaction time for each step by the hybrid controller logging system for the simulated under frequency event (with frequency nadir – 48.85 Hz)

- **Over frequency event**

This section shows exemplary one result obtained during the simulated frequency event with a RoCoF of +0.15 Hz/sec and a frequency nadir of 50.65 Hz. The GE Local Controller requested a stepped power request with maximum power of -600 kW. In response the GE Prosolar Inverter responded to the request with full power in less than 342 ms.

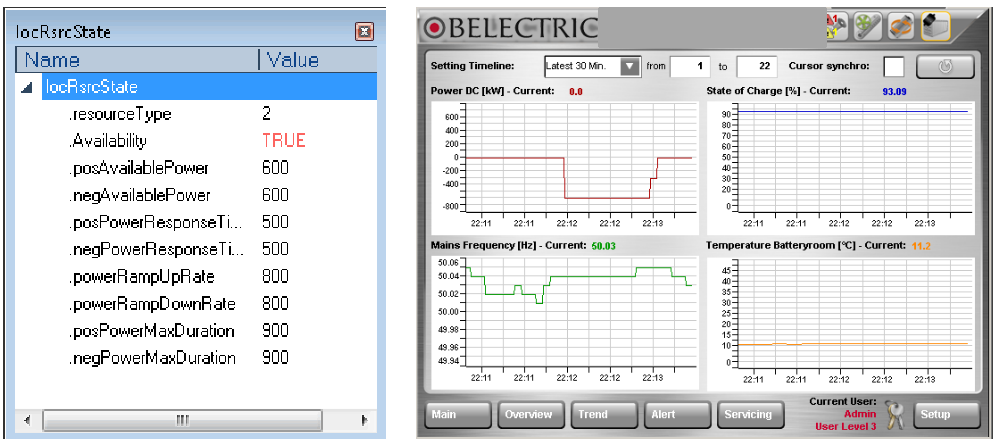
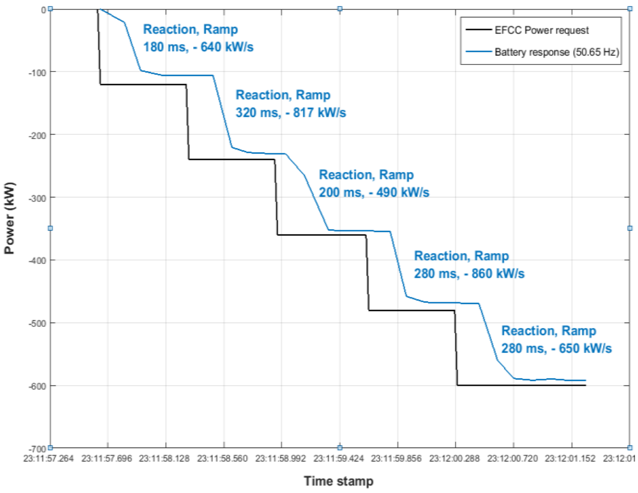


Figure 24: Exemplary illustration of battery response during hardware-in-the-loop test with simulated over frequency event (Frequency nadir – 50.65 Hz) during the unavailability of PV system. The battery takes over and maintains resource availability with a power availability of ± 600 kW.



SNO.	POWER STEP	REACTION TIME
1	0 – 120 kW	180ms
2	120 – 240 kW	320ms
3	240 – 360 kW	200ms
4	360 – 480 kW	280ms
5	480 – 600 kW	280ms

Table 17: Individual reaction time and step down ramp rate measured by the hybrid controller logging system during simulated over frequency event (with frequency nadir – 50.65 Hz).

The hardware in the loop tests at night were found to be successful and the energy buffer unit responded to all the under and over frequency events simulated using the GE PMU Simulator. The response from the energy buffer unit was tested numerous times; the reaction time and ramp rates were measured for each step.

The reaction time for the energy buffer unit was found to be in the range from 110 ms – 380 ms. The time until full response for the energy buffer unit was also found to be in the same range. Due to low data logging resolution the battery reaction time measured could have absolute error up to the least count of the data logging system ranging from 90 - 130 ms.

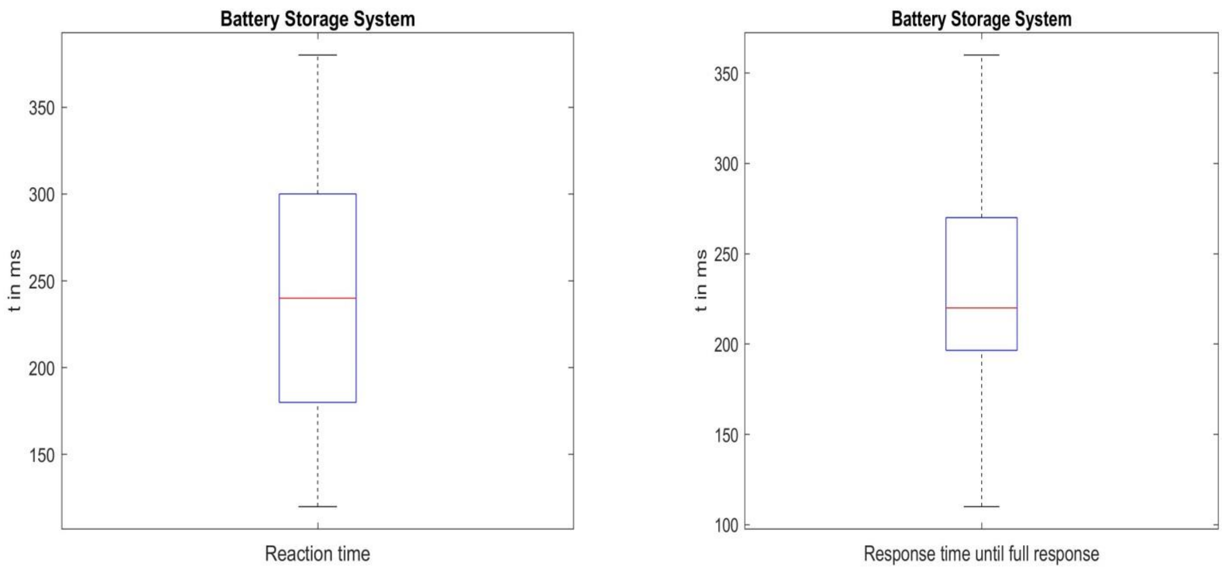


Figure 25: Box-Plot of the measured reaction times and time until full response of the battery system during hardware in the loop tests with simulated under and over-frequencies at night. A nearly immediate full response after receiving the control signal can be observed with data granularity between 90-130 ms.

Due to higher performance and faster response of the battery system as compared to the PV system (see EFCC PV stand-alone trials), the reaction time and ramp rate measurement of each power step was possible using the BCS data logger Table 16 and Table 17 show the measured reaction times for each power step by the energy buffer unit during the hardware-in-the-loop test, exemplary for simulated under frequency event (Frequency nadir – 48.85 Hz) and simulated over frequency event (Frequency nadir – 50.65 Hz).

Figure 26 and Figure 27 show the reaction times for exemplary tests for frequency events of 49.25 Hz, 49.05 Hz, 48.85 Hz and 50.45 Hz, 50.55 Hz, 50.65 Hz respectively, using the raw data from the BCS data logger. The figure shows some of the selective simulated under and over frequency tests which were tested during the EFCC hybrid system trials. The reaction time mentioned for each step has uncertainty due to observed data granularity range of 140 ms – 160 ms (particularly for this test set up). Therefore the measured reaction time of 300 ms in these exemplary cases could be between 160 ms to 300 ms due to the least count error which is associated with the precision and resolution of the instrument. The battery DC response power overshoots during the simulated under frequency events while during the over frequency events the battery DC response power undershoots. This is done in order to compensate the electrical losses, i.e transformer, inverter, winding losses etc. and to provide/absorb the power which is asked at grid connecting point.

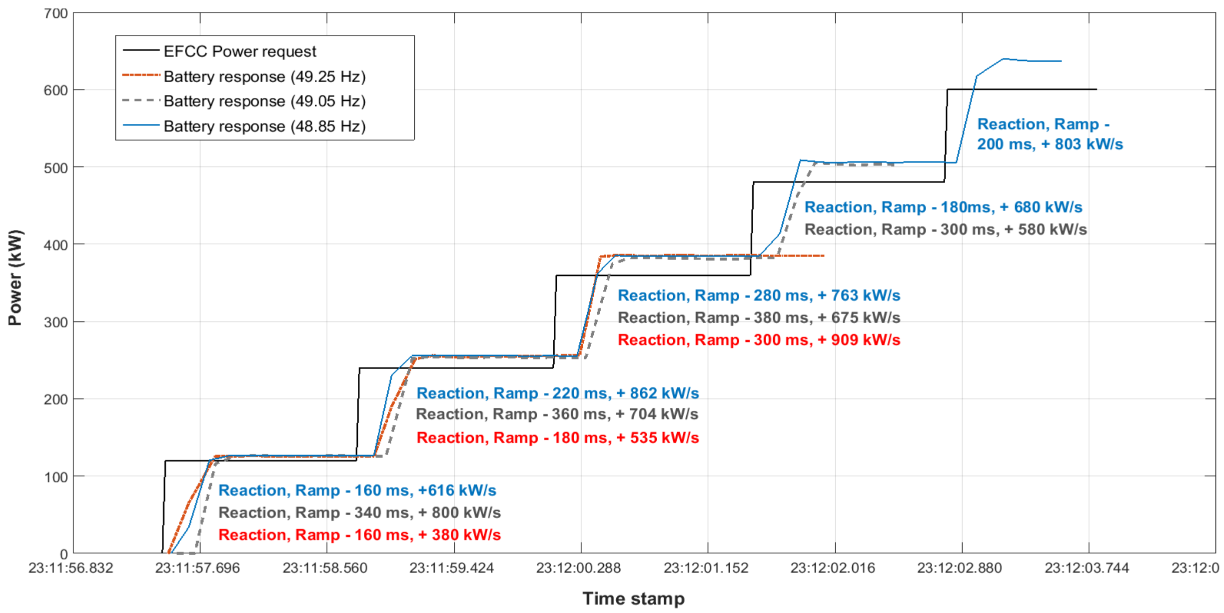


Figure 26: Evaluation of battery response with Illustrations of ramp rates and reaction time for each step during the under frequency events simulated by the GE PMU Simulator at night. The reaction time mentioned for each step has uncertainty due to observed data granularity range of 140 ms – 160 ms (particularly for this test).

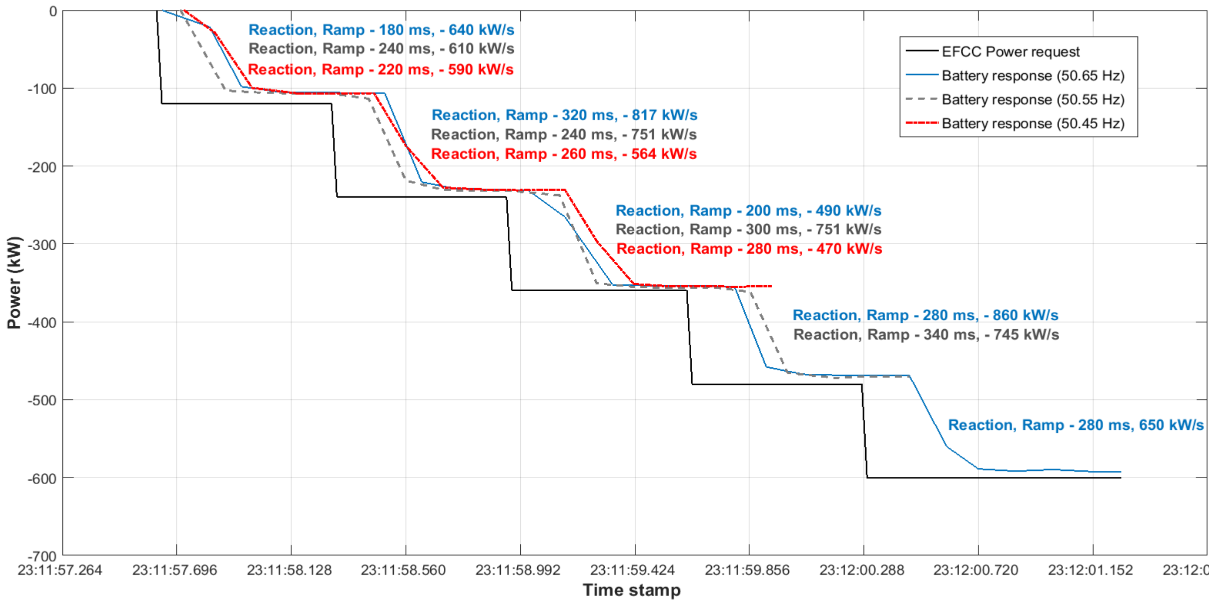


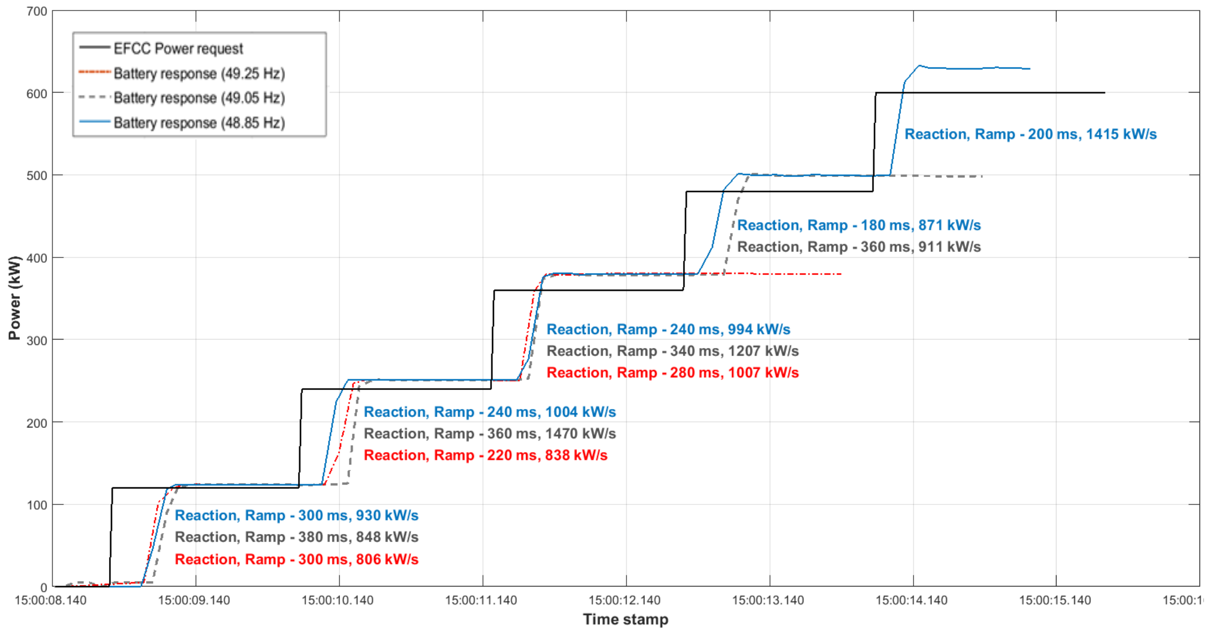
Figure 27: Evaluation of battery response with Illustrations of ramp rates and reaction time for each step during over frequency events simulated by the GE PMU Simulator at night. The reaction time mentioned for each step has uncertainty due to observed data granularity range of 140 ms – 160 ms (particularly for this test).

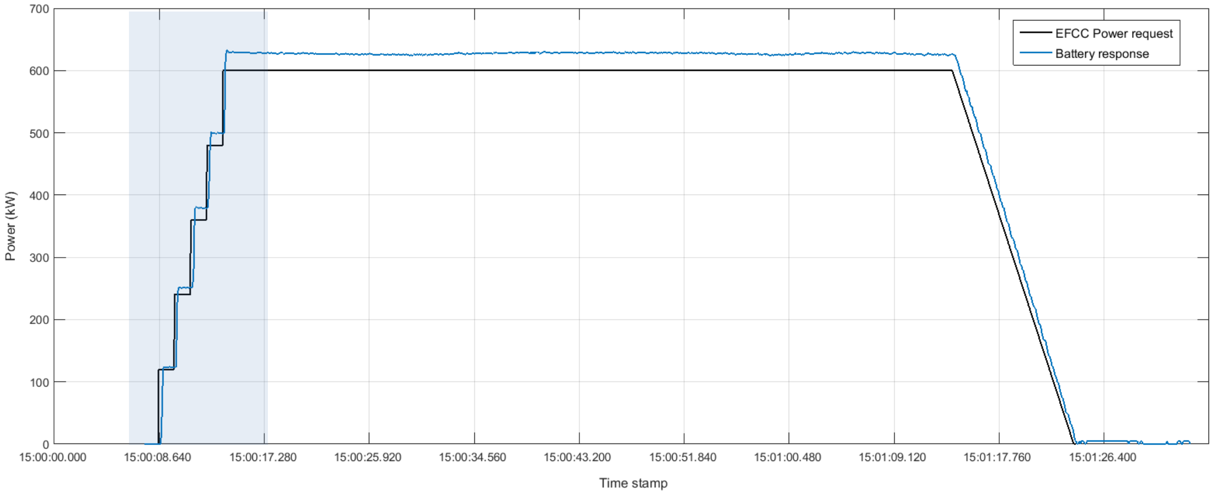
B. Simulated frequency events during the day

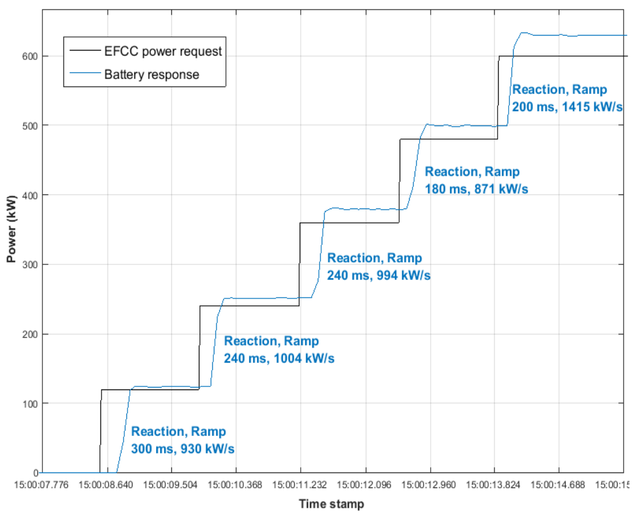
○ Under frequency event

During this test simulated over frequency events signals from the GE PMU Simulator are injected in the Local Controller during the time when PV availability is true. The system sends the positive power availability from the energy buffer unit while the negative power availability is sent according to the 15 minute forecast values for the solar PV system.

This section shows exemplary results obtained during simulated under frequency event with a RoCoF of -0.15 Hz/s and a frequency nadir of 48.85 Hz. During the test the GE local controller received a positive power availability of 124 kW from the PV system and a negative power availability of -600 kW from the energy buffer unit. The GE Local Controller requested a five step power request (with maximum power of 600 kW) from the BELECTRIC Hybrid Controller. In response, the GE Prosolar Inverter provided the power to the first step after a response time of 300 ms. The reaction times for each step are mentioned in Table 18:. The test was successful and the energy buffer unit responded to all simulated under frequency events during the day.







SNO.	POWER STEP	REACTION TIME
1	0 – 120 kW	300ms
2	120 – 240 kW	240ms
3	240 – 360 kW	240ms
4	360 – 480 kW	180ms
5	480 – 600 kW	200ms

Table 18: Individual reaction time and step down ramp rate measured by the hybrid controller logging system during simulated under frequency event (with frequency nadir – 48.85 Hz).

Figure 28: Evaluation of battery response with Illustrations of ramps and reaction times for each step during under frequency events during the day. The reaction time mentioned for each step has uncertainty to some extend due to observed data granularity range of 90 ms – 100 ms (particularly for this test).

- **Over frequency event**

During this test, simulated over frequency event signals are injected in the GE local controller during the time when PV availability holds true. The system sends the positive availability from the energy buffer unit while the negative availability is sent according to the 15 minute PV forecast values.

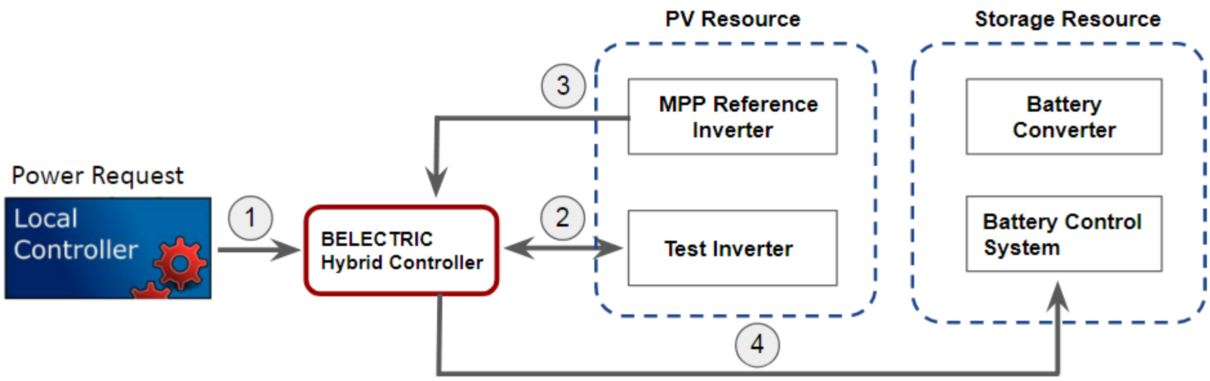


Figure 29: Simplified control flow chart for the PV-Battery hybrid resource to provide fast frequency response service under the EFCC control scheme.

Figure 29 illustrates the simplified control flow chart for the hybrid resource for (only) over frequency event during the time when PV is available.

1. The Local Controller detects the event and sends a negative power request to the BELECTRIC Hybrid Controller in accordance with the hybrid system power availability and the magnitude of the frequency event.
2. The BELECTRIC Hybrid Controller processes the power request and asks for the complete power from the solar PV inverter.
3. Due to slower PV inverter response time (derived from PV inverter ramp rates evaluation test. For further information, see also EFCC WP 2.3 PV Stand Alone – Test Report) the test inverter (PV SMA Inverter 1.1) and reference inverter running at maximum power point (PV SMA Inverter 1.2) are read continuously using the TCP/IP connection established within the hybrid power resource between the BELECTRIC controller and the SMA inverter 1.1.

   The arithmetic difference between the working points of the two PV inverters allows the hybrid controller to evaluate the response already provided by the PV system at any given time during a simulated over frequency event. This information is used to further evaluate the required residual response power to be provided for the complete EFCC response.

4. This residual power is sent to the battery control system which further processes the request and writes into the GE Prosolar inverter. The residual power during day (solar PV available, negative power request by the local controller) is evaluated by:

$$RP \ = PRQST + (MPP\ Inv\ 1.2 - Inv\ 1.1) \quad (1)$$

RP	-	Residual Power (kW) sent to Battery Control System.
PRQST	-	Negative EFCC power request from the Local Controller.
MPP Inv 1.2	-	Maximum power point value as a reference.
Inv 1.1	-	Power of the PV inverter running under EFCC test trials.

As the PV inverter 1.1 continues to ramp down, the BELECTRIC hybrid controller continuously reads the solar PV inverter parameters from its MODBUS interface, evaluates them and sends the residual power to the battery control system. This algorithm allows the battery storage system to provide initial fast ramp support as well as residual power provision throughout the power request. Once the difference between the PV Inverter 1.1 (test inverter) and PV Inverter 1.2 (reference inverter) is equal to the EFCC power request, i.e. once the PV system provides the complete EFCC response, the residual power equates to zero and the Battery Control system receive a power command of zero.

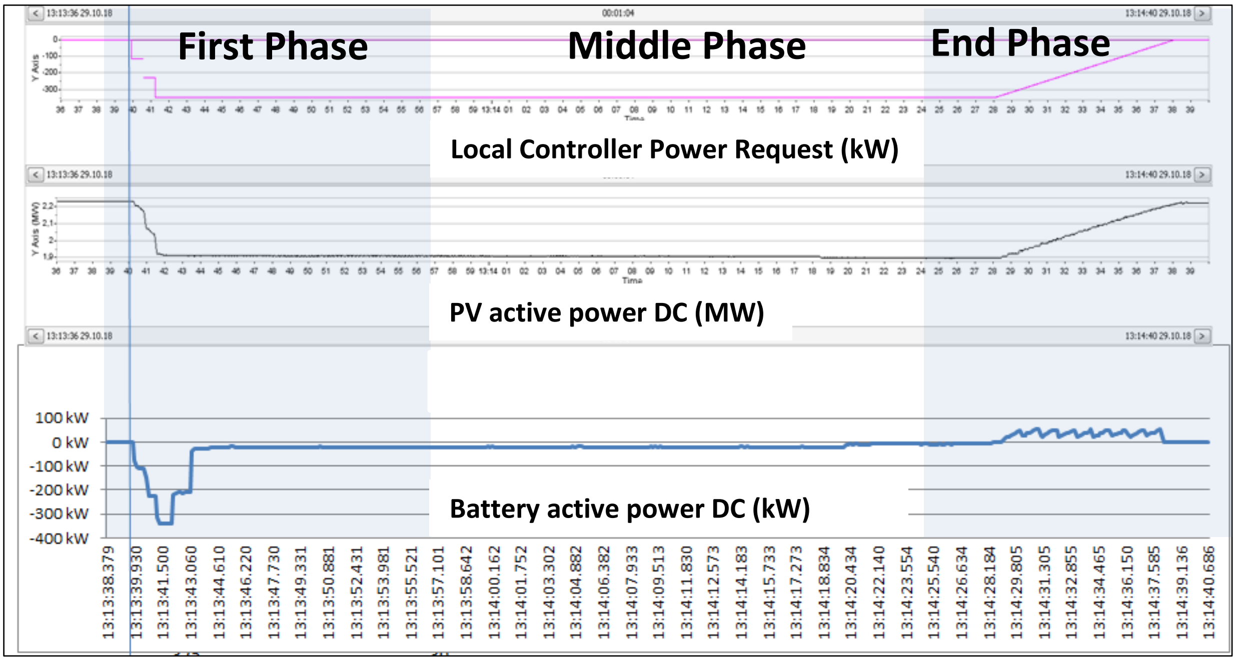


Figure 30: Frequency response service from PV-battery hybrid resource during over frequency event (frequency nadir: 50.45 Hz). During the test the hybrid system had a power availability of +600 kW / -574 kW. The local controller generated a 3 stepped power request with a negative peak request of -344 kW.

For the current implementation the system behaviour depends largely on the reference inverter. A small variation in the reference inverter power due to cloud movement changes the calculation and sends false residual power to the battery control system thus affecting the performance of the algorithm and the hardware. An enhanced algorithm is in the process of development which will exclude the dependency of reference inverter. This control scheme shall be implemented during the next phase of EFCC, i.e. moving from local response service to wide area response service.

The exemplary plotted results in Figure 30 and Figure 31 illustrate the currently implemented hybrid system performance during an over frequency event (50.45 Hz). During this exemplary test the hybrid system had a power availability of +600 kW (positive power provided by the battery) and -574 kW (negative power provided by the solar PV system). As a result of the magnitude of the frequency event, the local controller generated a three stepped power request with a negative peak request of -344 kW.

- **Combined response to power request - First phase**

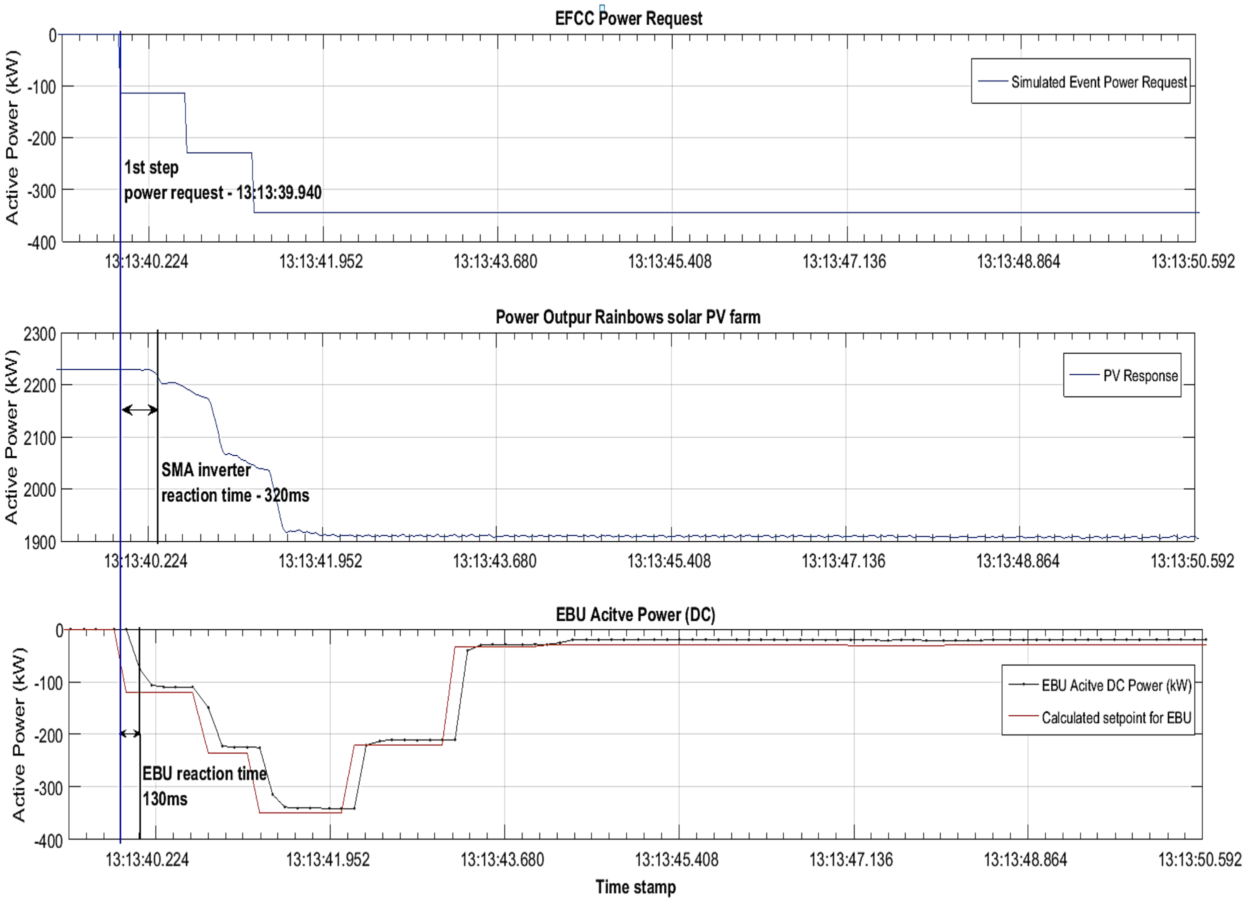


Figure 31: First phase - Response by the individual resources to a power request from the Local Controller.

During this exemplary test, the PV inverter's reaction time for the 1st power step was observed to be 320 ms while the storage system responded to the power request in 130 ms. 130 ms is the first available data log point from the BCS in this case and may therefore not be representative for the actual, faster reaction time. The data logging limitations and its interpretation is described in chapter 8.1 B Ramp rate test – Battery inverter.

Evaluating the data samples for the combined assets hybrid test during daylight the reaction time by both the solar PV system and the battery system was below 360 ms (PV: 356 ms; Battery: 243 ms) with the median under 285 ms for the solar PV system and 240 ms for the battery system – see Figure 32.

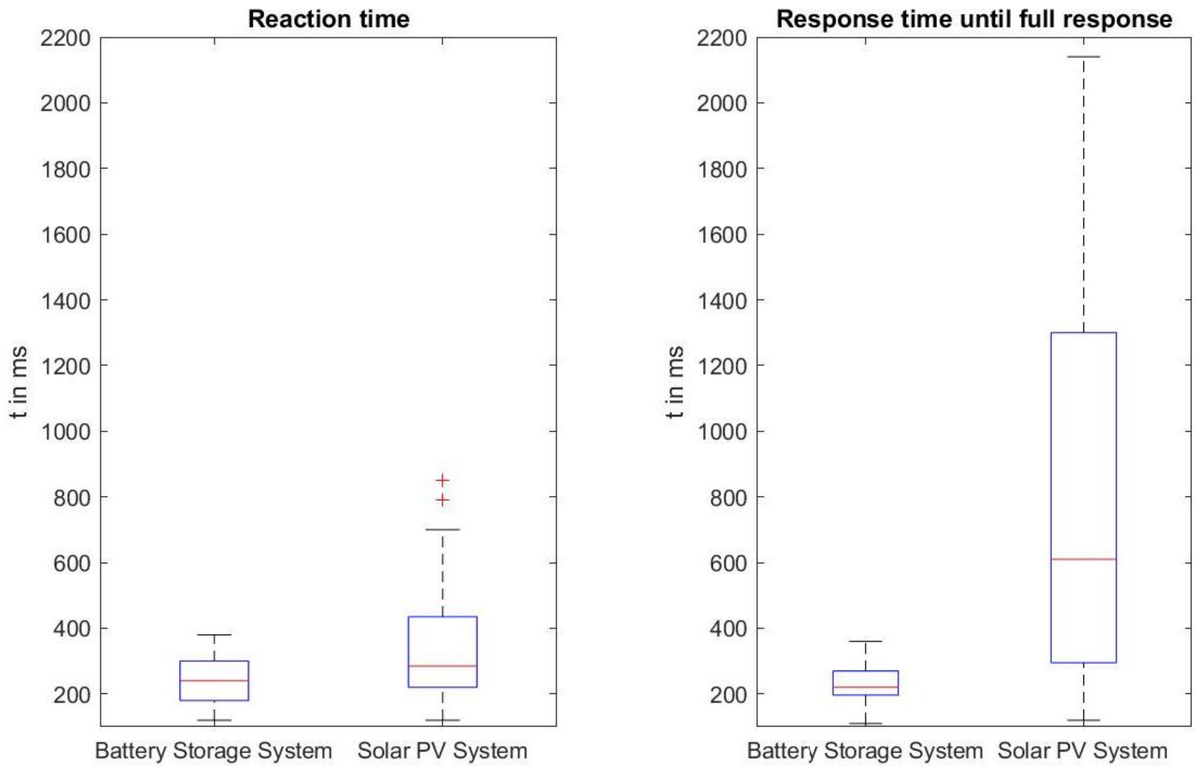


Figure 32: Reaction and response time analysis of the individual hybrid resources battery and solar PV system logged during the hardware in the loop test series.

Figure 32 illustrates the discrepancy in the response and reaction times between the battery system and the solar PV system visible. While both systems have a similar median reaction time the spread of the reaction time for the PV system is larger than it is for the battery system and therefore less deterministic. The reasons for this have been thoroughly described in the EFCC WP 2.3 Solar PV stand-alone report.

The discrepancy in the power delivery time becomes even more evident in the time overserved for each single system to provide the full response power. The battery provides the requested power nearly instantly when it receives the power request signal. In contrary, the time until full response for the solar PV system is about four times longer in average compared to the battery but also in a larger range with maximum values captured for full response at 2,140 ms.

This also highlights the advantage of the combined assets and the implemented control strategy. The battery system provides the fast ramp in the first phase as well as the initial response to the power request. In parallel the PV system processes the request and slowly ramps to take over the response provision from the battery.

While the reaction and response times of each individual power resources in the hybrid set-up were as expected, the overall energy buffer unit behaviour observed during the hardware in the loop EFCC hybrid mode was not as anticipated in the control strategy or after the initial EFCC Hybrid Simulation studies for the control algorithm (see Figure 6 on page number 15). In the simulation of the control algorithm the battery reduces its negative power output in the same amount as the PV curtails and the total response from the hybrid resource matches with the power request from the local controller

Figure 31 illustrates the hardware in the loop test results obtained during simulated under frequency event. From the figure it can be seen, in the EBU active power graph (DC), that the battery doesn't reduce its negative power in relation to the solar PV system power reduction to provide the desired response. Instead, the battery reduces its active negative power in several steps to get back to zero but only after the PV system is already providing the fully requested power. This leads to an over provision of negative power and an oscillation during the initial seconds of the power request of nearly 100% at one point, as shown in Figure 33.

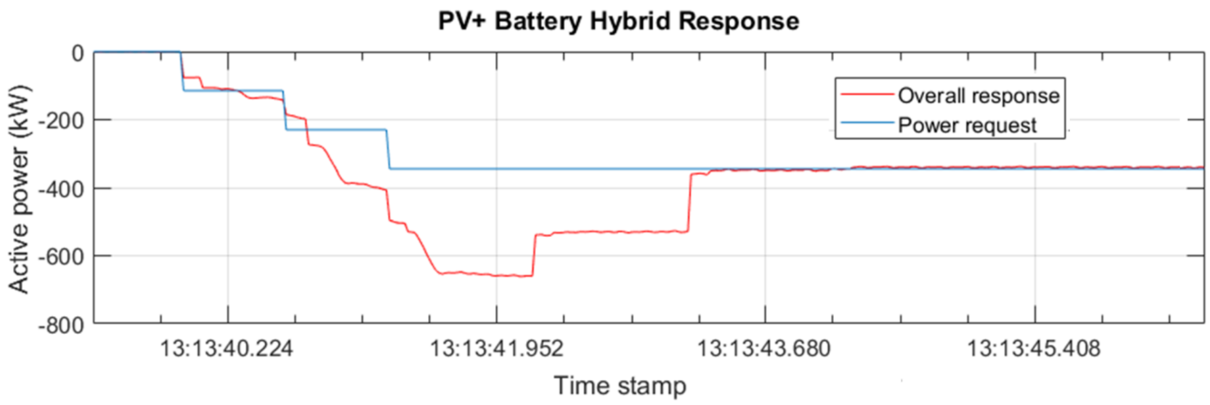


Figure 33: Overall combined hybrid response to the power request in the first phase. An overprovision in the first seconds can be observed due to solar PV inverter intern MODBUS reading latency.

The over frequency hybrid test during day was reproduced multiple times with different frequency events and environmental conditions but the system behaviour remained similar. After an extensive analysis on the cause of this reaction latency and the subsequent overprovision of response power it was concluded that the reason for this behaviour is due to the solar PV Inverter MODBUS reading interface update time as illustrated in Figure 34. The residual power sent to the battery system depends on the test inverter live power as shown in Figure 29 and Equation 1. The BELECTRIC Hybrid Controller communicates and reads the data from its MODBUS Interface, the 'Read registers'. The resolution for the read-register update can affect the performance.

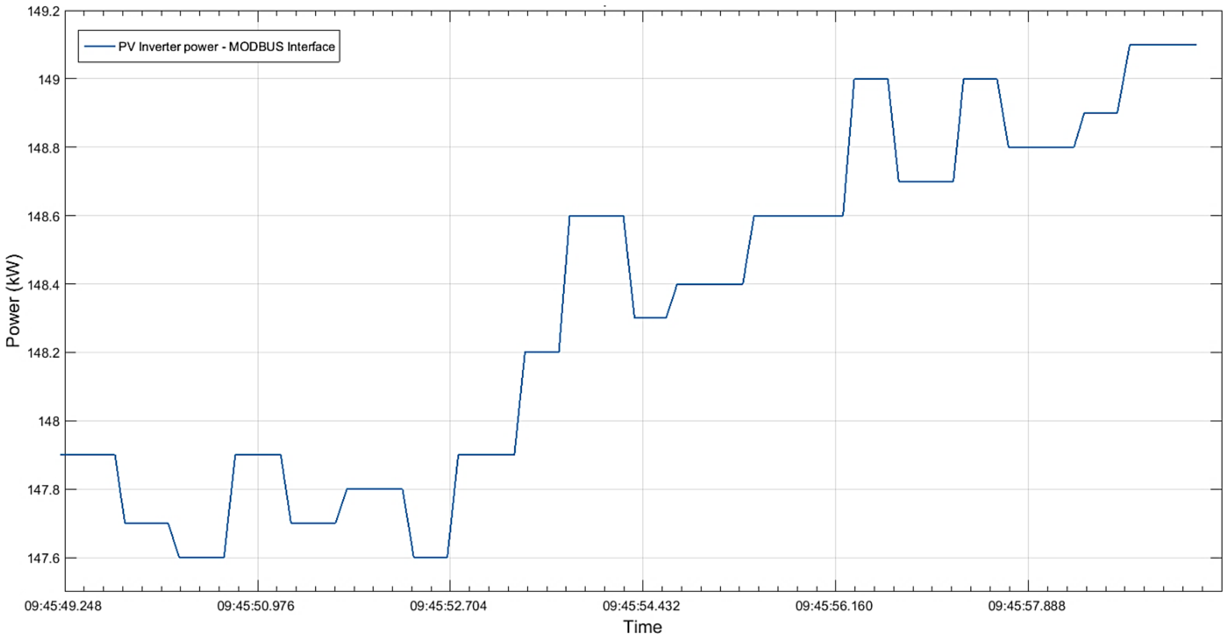


Figure 34: PV Inverter MODBUS interface – Reading power (kW) to evaluate the residual power during the EFCC hybrid over frequency test.

- **Combined response to power request - Middle phase**

The provision of response power in the middle phase of the response follows the power request nearly exactly for most of the power request duration, as shown in Figure 35. The logged deviations between power request and combined power provision in the middle phase is around +0.001% and -7.39%.

Examining Figure 31 of the single resource responses it can be seen that the battery not only provides ramp support but also supplies negative power in a small magnitude of around -20 kW throughout the whole response. A constant change in irradiance leads to an insufficient PV response which is subsequently covered by the battery to provide the full power of -344 kW as requested by the Local Controller.

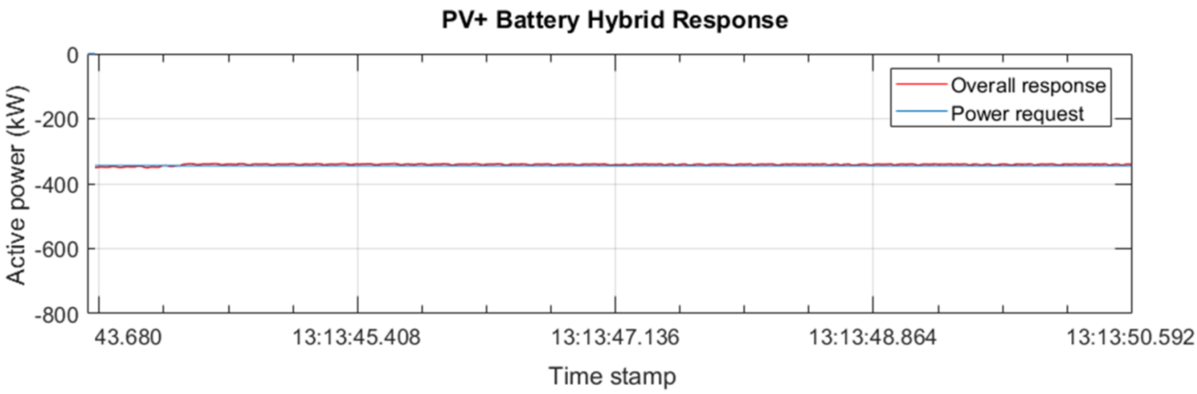


Figure 35: Overall combined hybrid response to the power request in the middle phase. The provision of negative power follows the given power request from the Local Controller with an error margin of 7.39%.

- **Combined response to power request - End phase**

While the first response ramp leads to an overprovision of response power, a similar, yet different behaviour of overprovision can be observed for the end phase of the power request. For the 10 second ramp back request (see Figure 30 on page number 47), it was observed that the evaluated residual power sent to the EBU during this period was not a step function as observed during the start of the response. Instead, the latency of the system components leads to spikes of overprovision of the hybrid system, see Figure 36.

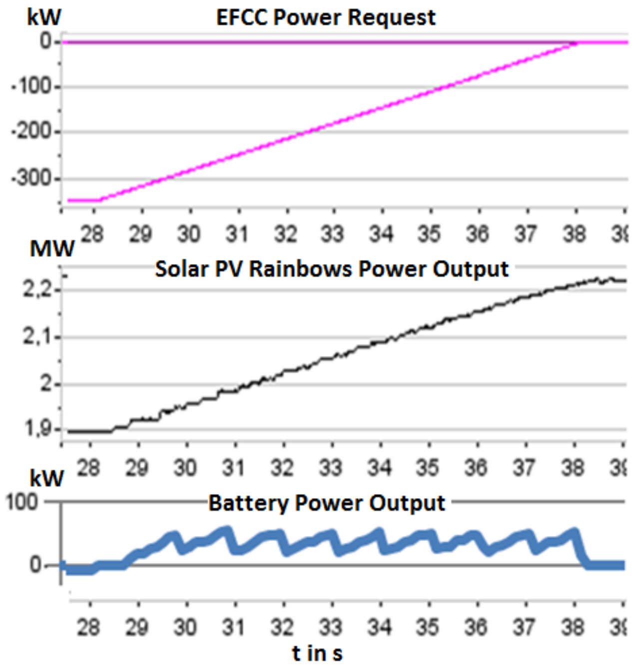


Figure 36: Overall combined hybrid response to the power request in the end phase. The battery supplements the solar PV response with short power spikes to provide the requested power.

Particularly in this case, during the ramp back at the end of the power request, the local controller commands the hybrid resource to reduce the negative power to zero. Although the solar PV inverters actual response is close to the required response, the EBU system provides additional power spikes, see Figure 36.

The reason for this is the same as for the response reaction latency in the first phase. The BELECTRIC Hybrid Controller reads a stepped power (see Figure 34) from the MODBUS interface. This means that even if the PV system would responds to the request perfectly, the control system reads a step change in the PV power. This is due to slow refreshing latency of the MODBUS interface which creates the impression that the PV system is responding slowly. This causes the EBU system to react and provide power spikes during each step in order to compensate for the slower response of the PV system in regards to the power request by the Local Controller.

Even though the PV inverter could follow the power request reduction from the Local Controller with its slower ramp rate, there is still a difference in the reaction timing. Simultaneously, the hybrid controller evaluates the residual power for the energy storage system during this power ramp back. As the ramp of the PV system is close to the power request but still lagging due to the lower solar system response time the resulting discharges of the battery can be seen as small spikes to compensate for the PV inverters slow response. An adaption of the control logic will solve this behaviour.

9 Conclusions and Learning Outcomes

The target in this project was to show that a hybrid system, consisting of Solar PV and Battery, can achieve a combined and controlled frequency response within 500 ms based on RoCoF detection. In the conducted tests it was shown that PV-Battery hybrid systems can be successfully integrated into the EFCC scheme and that a hybrid system creates additional value, faster overall response and increases the overall system availability in comparison to a stand-alone solar PV system.

Battery systems can successfully support large scale solar PV systems in the provision of system services on TSO and DNO level, where the battery may provide the fast reaction part of the response and the night time availability and could also aid in the provision of other services and may improve the usage of the grid connection of the PV farm as well.

For the implemented control strategy further optimisations are necessary to take into account the Solar PV inverter internal MODBUS interface updates which introduced a long latency in the control and lead to an overprovision of reactive power for short periods.

On PV side in general, the communication traffic on the MODBUS connection between control and inverter introduces a non-deterministic spread of reaction times and therefore highly affects the overall response time on PV side. This can be averted in in a hybrid system with an adequate control strategy that takes this issue into account and with appropriate measurement equipment.

For the standard 2014 central converter based solar PV farm, a use case to provide frequency response was not accommodated for during the design. The communication topology inside of a solar PV farm was therefore never meant to be fast. An update of the communication system and a retrofitting of the PV farm with a good network design with fast switches, and bridges is necessary to provide ancillary services.

In this project it was also shown that the retrofitting of a converter-based large-scale solar PV power plant is possible to provide frequency response and potentially other grid services.

The addition of a battery system to an already existing large-scale solar PV system to increase the availability and quality of the grid services provided was successful.

Further testing and trials will involve a combined RoCoF based response not only by the local solar and battery resource but also other response providers in different regions to take the local differences and resource availabilities into account and thereby providing a controlled response to sudden frequency deviations.

Other ongoing research will involve inverters to behave like synchronous machines, exhibiting a synthetic inertia to mitigate the detection delay of RoCoF based response and imitating very accurately the behaviour of synchronous generators to enable larger RE penetration after the phase out of synchronous generators. BELECTRIC and National Grid will engage in a R&D project on this topic in 2019.

Another option for future research projects in this research area is the provision of black start service from non-synchronous generation and storage assets such as the in this project used solar PV and battery system.

Appendix – A

PV Ramp Test 1 – Description:

1. SMA inv 1.1 running at MPP
2. Value written at output register 100
3. Inverter output: 550 kW.
4. SMA inv 1.1 ramped down/up to 8 kW.
5. Working point switching 100% - 1%

SNO	AVERAGE RAMP (KW/S)	FAST RAMP		SLOW RAMP (KW/S)	RAMP STATUS
		Ramp (kW/s)	Power %		
1	416	730	78%	135	Ramp Down
2	410	716	78%	140	Ramp Down
3	395	722	77.8%	132	Ramp Down
1	721	721	100%	-	Ramp Up
2	754	754	100%	-	Ramp Up

Table 12: Ramp Test 1 – The average fast ramp up was evaluated to be 737.5 kW/s (average power percent - 100%) while the average fast ramp down was evaluate to be 722.6 kW/s(average power percent - 78%)

PV Ramp Test 2 – Description:

1. SMA inv 1.1 running 500 kW. (FORCED)
2. Value written at output register 57
3. SMA inv 1.1 output: 503 kW.
4. SMA inv 1.1 ramped down/up to 400 kW.
5. Working point switching 57% - 45%

SNO	AVERAGE RAMP (KW/S)	FAST RAMP		SLOW RAMP (KW/S)	RAMP STATUS
		Ramp (kW/sec)	Power %		
1	90	482	76%	28	Ramp Down
2	88	466	77%	27	Ramp Down
3	107	543	77.3%	34	Ramp Down
1	70	532	83%	14	Ramp Up
2	96	580	80.9%	8	Ramp Up

Table 13: Ramp Test 2 – The average fast ramp up was evaluated to be 556 kW/s (average power percent - 80%) while the average fast ramp down was evaluate to be 497 kW/s (average power percent - 77%)

PV Ramp Test 3 – Description:

1. SMA inv 1.1 running 500 kW. (FORCED)
2. Value written at output register 57
3. SMA inv 1.1 output: 503 kW.
4. SMA inv 1.1 ramped down/up to 300 kW.
5. Working point switching 57% - 34%

SNO	AVERAGE RAMP (KW/S)	FAST RAMP		SLOW RAMP (KW/S)	RAMP STATUS
		Ramp (kW/s)	Power %		
1	245	660	81%	67	Ramp Down
2	212	655	79%	61	Ramp Down
3	282	631	81%	84	Ramp Down
1	179	620	87%	24	Ramp Up
2	181	663	87%	23	Ramp Up
3	155	708	85%	22	Ramp Up

Table 14: Ramp Test 3 – The average fast ramp up was evaluated to be 663 kW/s (average power percent - 86%) while the average fast ramp down was evaluate to be 648 kW/s (average power percent - 80%)

PV Ramp Test 4 – Description:

1. SMA inv 1.1 running 500 kW. (FORCED)
2. Value written at output register 57
3. SMA inv 1.1 output : 503 kW.
4. SMA inv 1.1 ramped down/up to 200 kW.
5. Working point switching 57% - 23%

SNO	AVERAGE RAMP (KW/S)	FAST RAMP		SLOW RAMP (KW/S)	RAMP STATUS
		Ramp (kW/s)	Power %		
1	357	719	88%	77	Ramp Down
2	421	715	85%	109	Ramp Down
1	202	701	86%	27	Ramp Up
2	295	689	90%	37	Ramp Up

Table 14: Ramp Test 4 – The average fast ramp up was evaluated to be 695 kW/s (average power percent - 88%) while the average fast ramp down was evaluate to be 717 kW/s (average power percent - 87%)

PV Ramp Test 5 – Description:

1. SMA inv 1.1 running 500 kW. (FORCED)
2. Value written at output register 57
3. SMA inv 1.1 output : 503 kW.
4. SMA inv 1.1 ramped down/up to 100 kW.
5. Working point switching 57% - 11%

The average fast ramp up was evaluated to be 788 kW/s (average power percent - 80%) while the average fast ramp down was evaluate to be 779 kW/s (average power percent - 81%)

PV Ramp Test 6 – Description:

1. SMA inv 1.1 running 700 kW. (FORCED)
2. Value written at output register 80
3. SMA inv 1.1 output : 701 kW.
4. SMA inv 1.1 ramped down/up to 8 kW.
5. Working point switching 80% - 1%

SNO	AVERAGE RAMP (KW/S)	FAST RAMP		SLOW RAMP (KW/S)	RAMP STATUS
		Ramp (kW/sec)	Power %		
1	640	783	89%	163	Ramp Down
2	632	761	85%	154	Ramp Down
1	663	779	107%	5	Ramp Up
2	672	789	109%	13	Ramp Up

Table 15: Ramp Test 4 – The average fast ramp up was evaluated to be 784 kW/s (average power percent - 108%) while the average fast ramp down was evaluate to be 772 kW/s (average power percent - 87%)

PV Ramp Test 7 – Description:

1. SMA inv 1.1 running 400 kW. (FORCED)
2. Value written at output register 45
3. SMA inv 1.1 output : 406 kW.
4. SMA inv 1.1 ramped down/up to 8 kW.
5. Working point switching 45 % - 1%

SNO	AVERAGE RAMP(KW/S)	FAST RAMP		SLOW RAMP (KW/S)	RAMP STATUS
		(Ramp kW/s)	Power %		
1	352	827	79%	116	Ramp Down
2	296	843	77%	102	Ramp Down
1	526	1000	92%	41	Ramp Up
2	391	1000	94%	23	Ramp Up

Table 15: Ramp Test 4 – The average fast ramp up was evaluated to be 1000 kW/s (average power percent - 93%) while the average fast ramp down was evaluate to be 835 kW/s (average power percent - 78%)

Appendix – B

Open loop test – Under frequency events during day

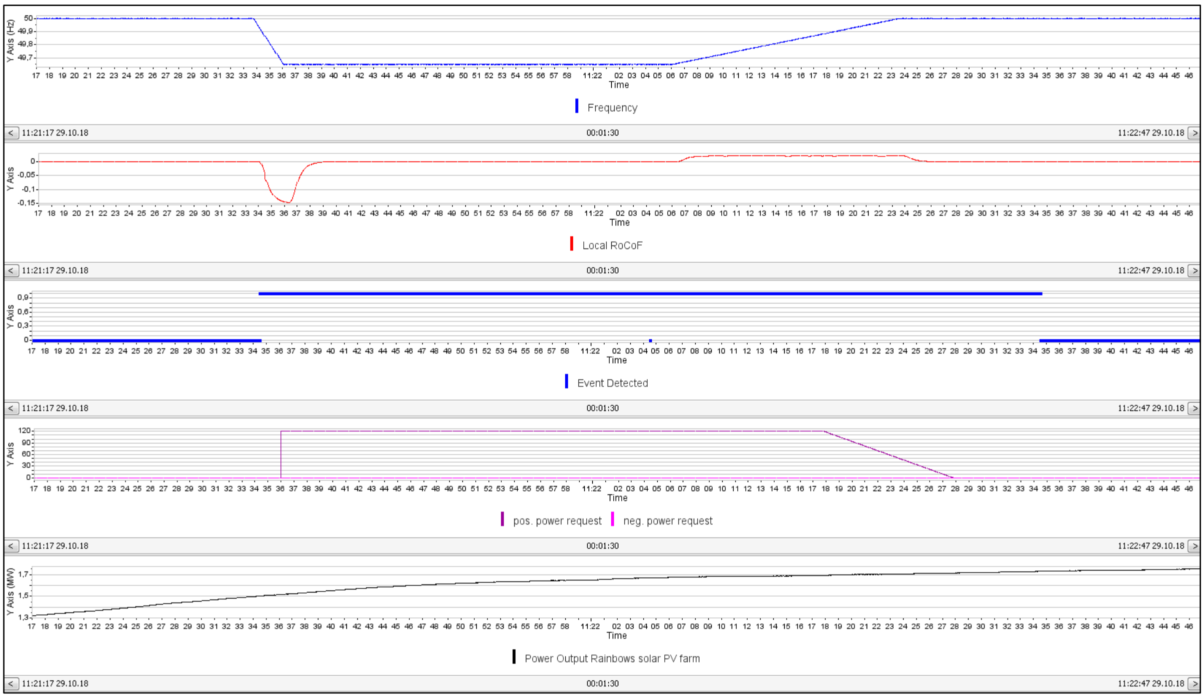


Figure 37: Open loop test – Simulated under frequency event (Frequency nadir of 49.65 Hz). The system holds a power availability of +600/-325 kW. GE Local controller sends a power request equivalent to 20% of positive power availability. (120 kW)

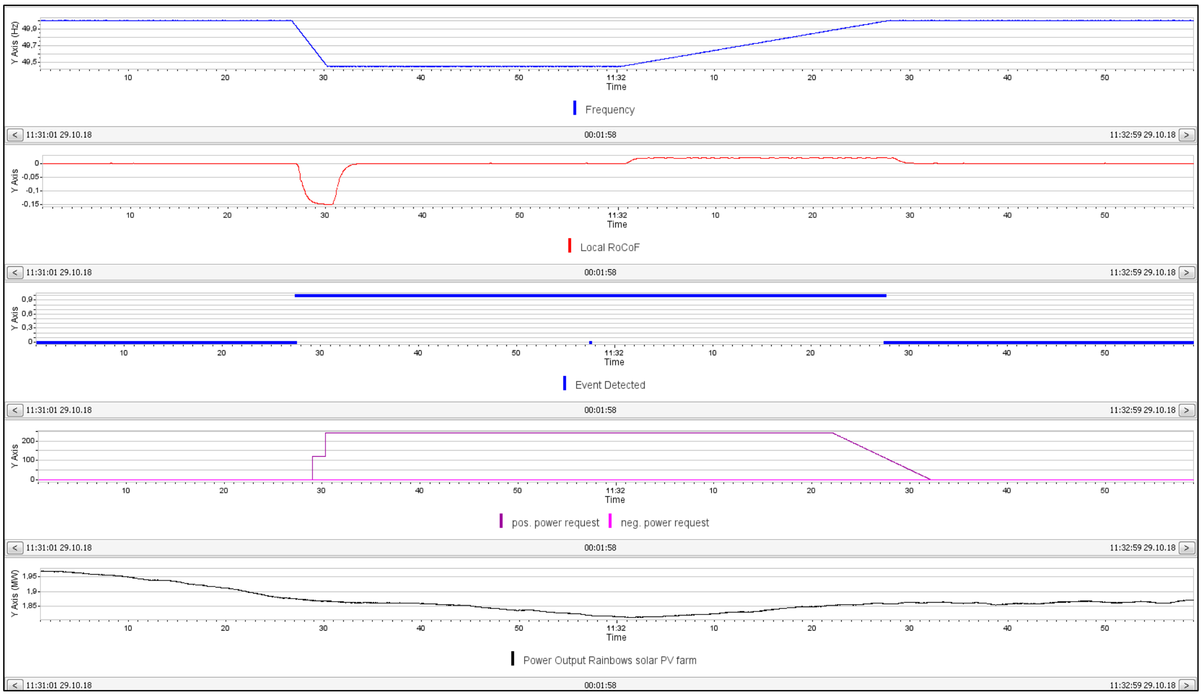


Figure 38: Open loop test – Simulated under frequency event (Frequency nadir of 49.45 Hz). The system holds a power availability of +600/-355 kW. GE Local controller sends a power request in two steps with an equivalent peak request of 40% of positive power availability. (240 kW)

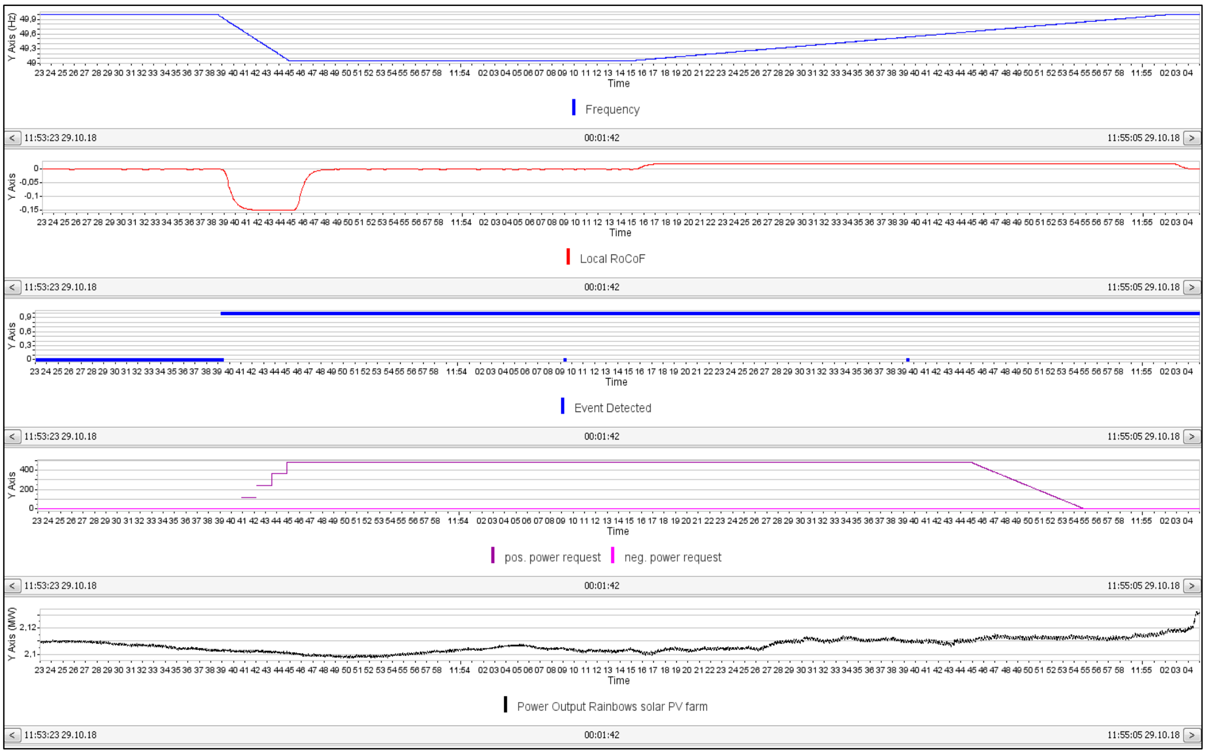


Figure 39: Open loop test – Simulated under frequency event (Frequency nadir of 49.05 Hz). The system holds a power availability of +600/-381 kW. GE Local controller sends a power request in four steps with an equivalent peak request of 80% of positive power availability. (480 kW)

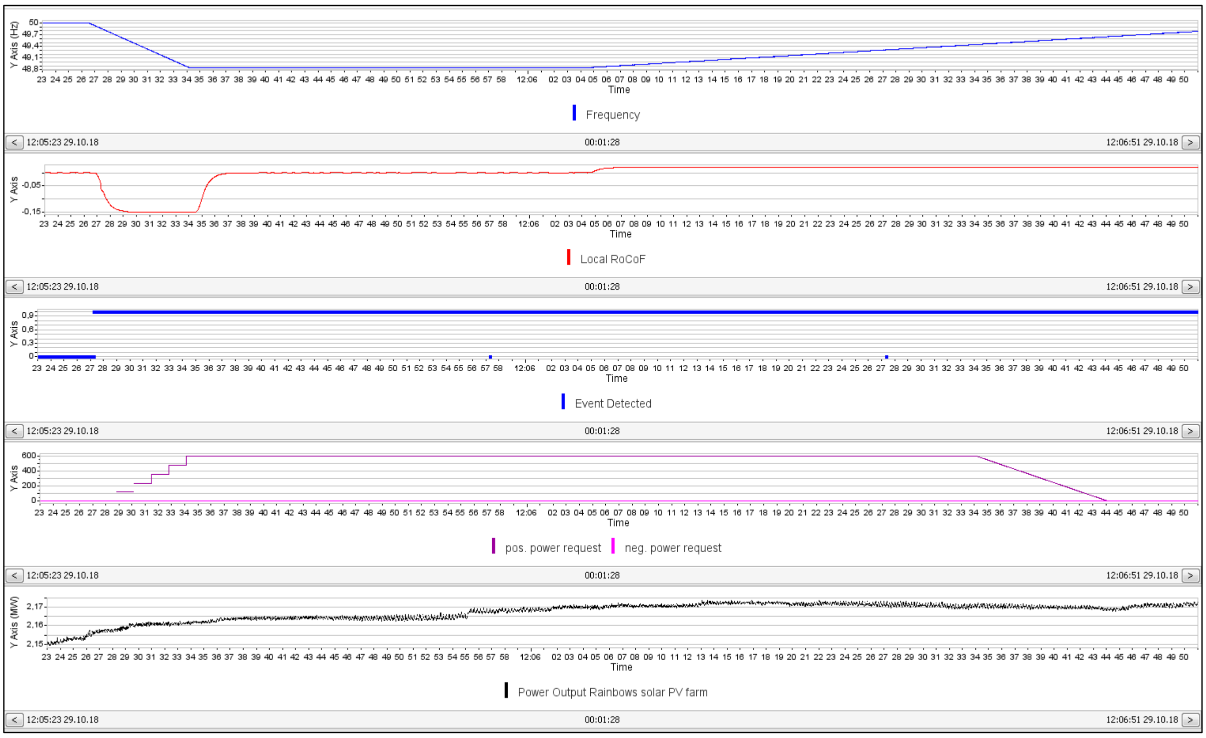


Figure 40: Open loop test – Simulated under frequency event (Frequency nadir of 48.85 Hz). The system holds a power availability of +600/-395 kW. GE Local controller sends a power request in five steps with an equivalent peak request of 100% of positive power availability. (600 kW)

Open loop test – Over frequency events during day

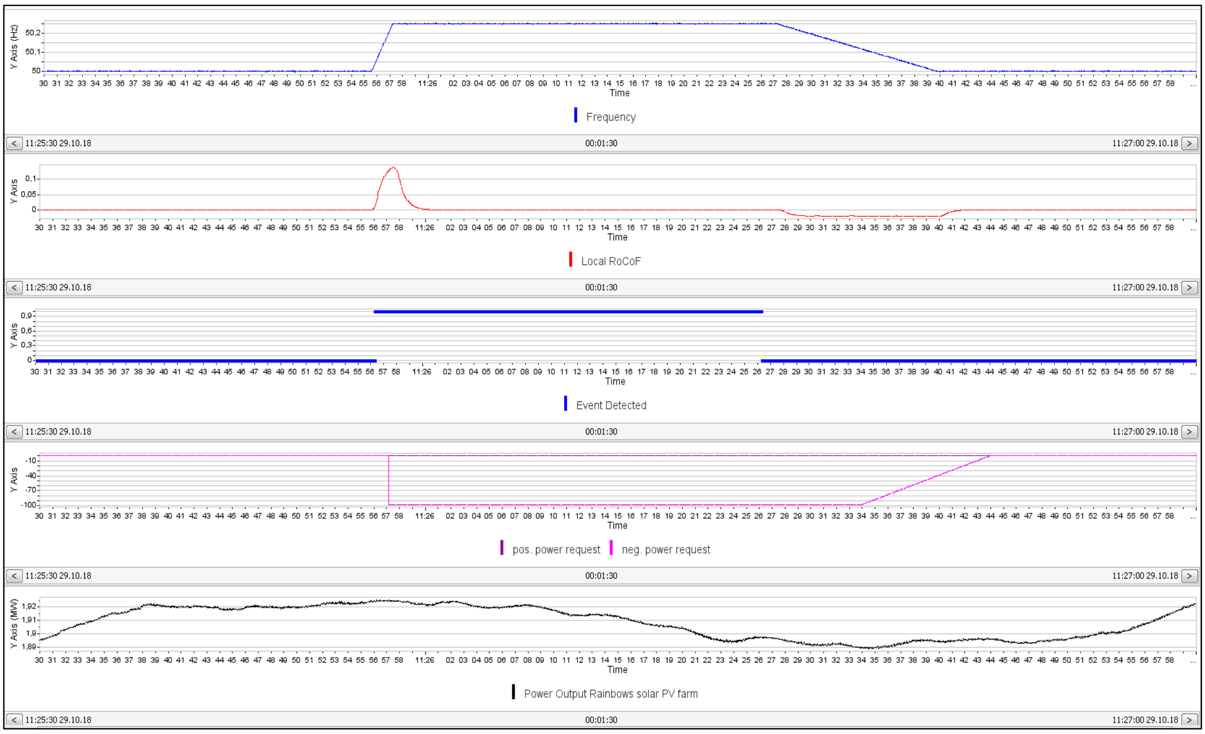


Figure 41: Open loop test – Simulated over frequency event (Frequency nadir of 50.25 Hz). The system holds a power availability of +600/-500 kW. GE Local controller sends a power request in one step with an equivalent peak request of 20% of negative power availability. (-100 kW)

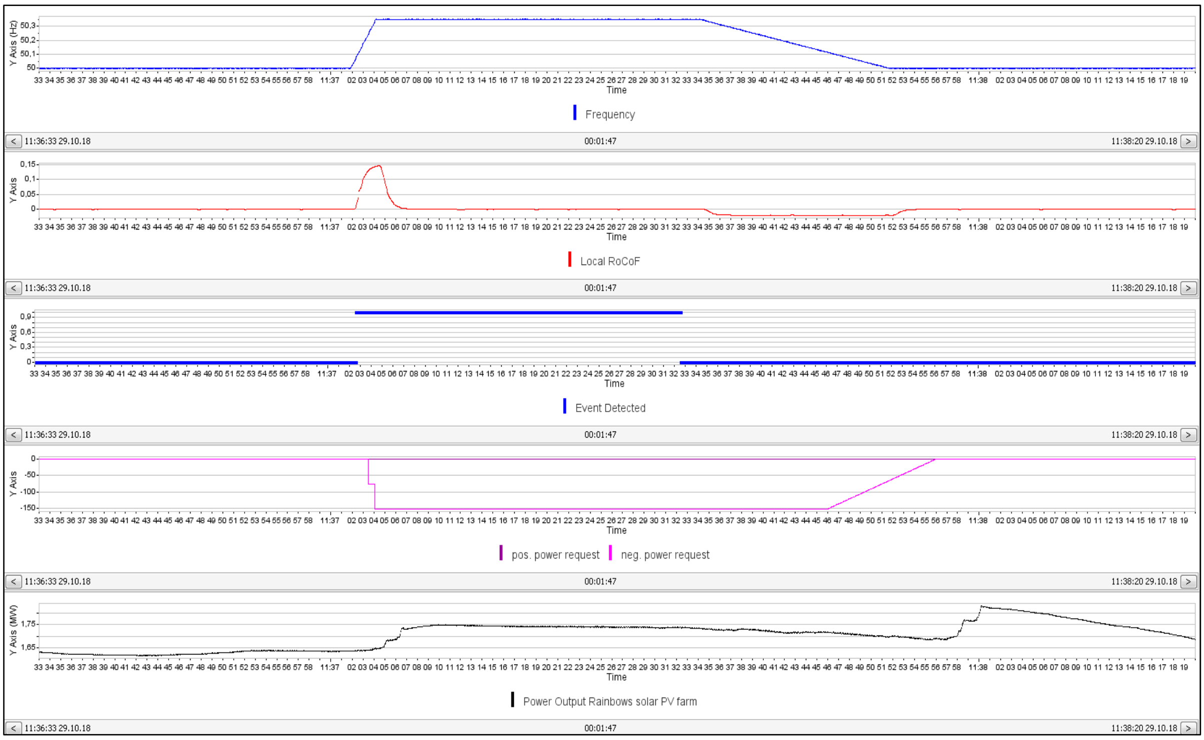


Figure 42: Open loop test – Simulated over frequency event (Frequency nadir of 50.35 Hz). The system holds a power availability of +600/-375 kW. GE Local controller sends a power request in two steps with an equivalent peak request of 40% of negative power availability. (-150 kW)

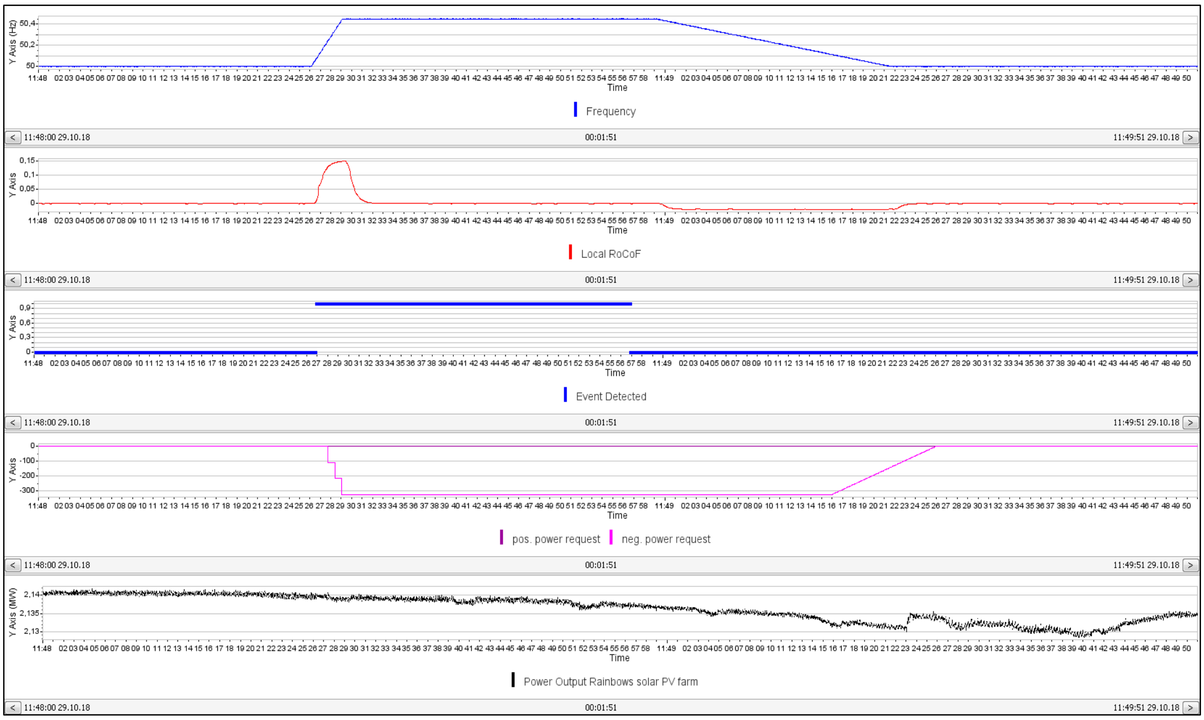


Figure 43: Open loop test – Simulated over frequency event (Frequency nadir of 50.45 Hz). The system holds a power availability of +600/-541 kW. GE Local controller sends a power request in three steps with an equivalent peak request of 60% of negative power availability. (-325 kW)

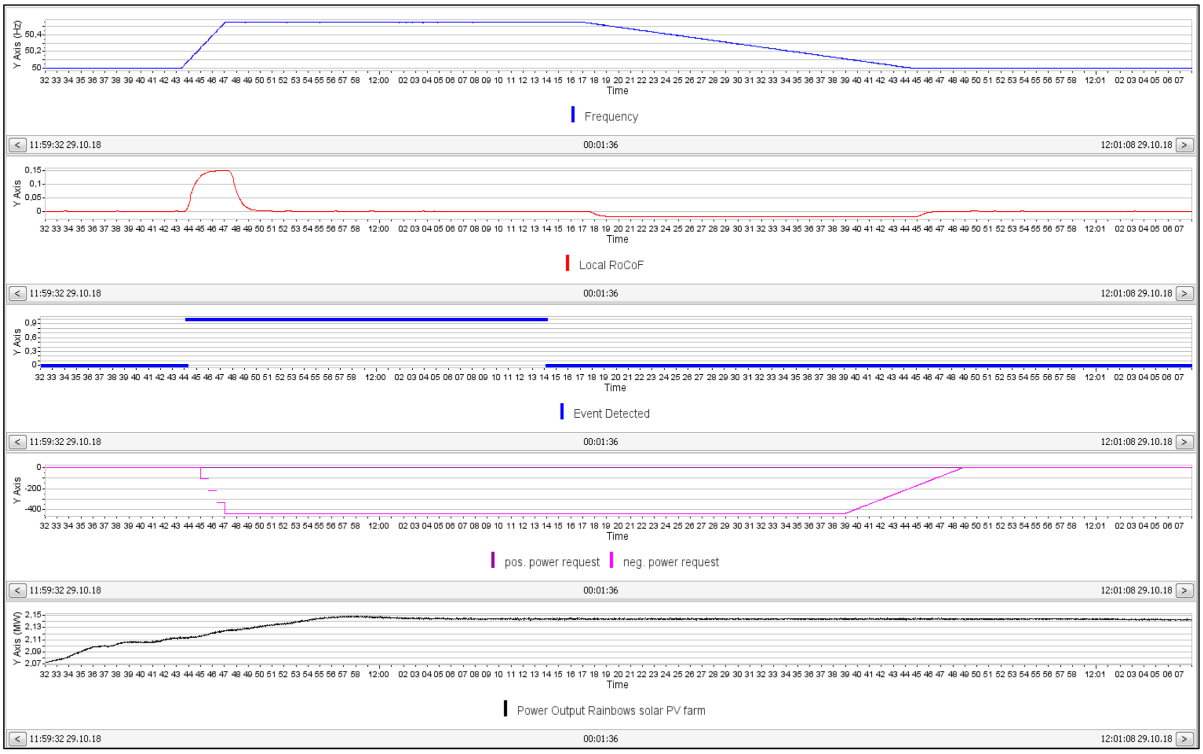


Figure 44: Open loop test – Simulated over frequency event (Frequency nadir of 50.55 Hz). The system holds a power availability of +600/-550 kW. GE Local controller sends a power request in four steps with an equivalent peak request of 80% of negative power availability. (-440 kW)

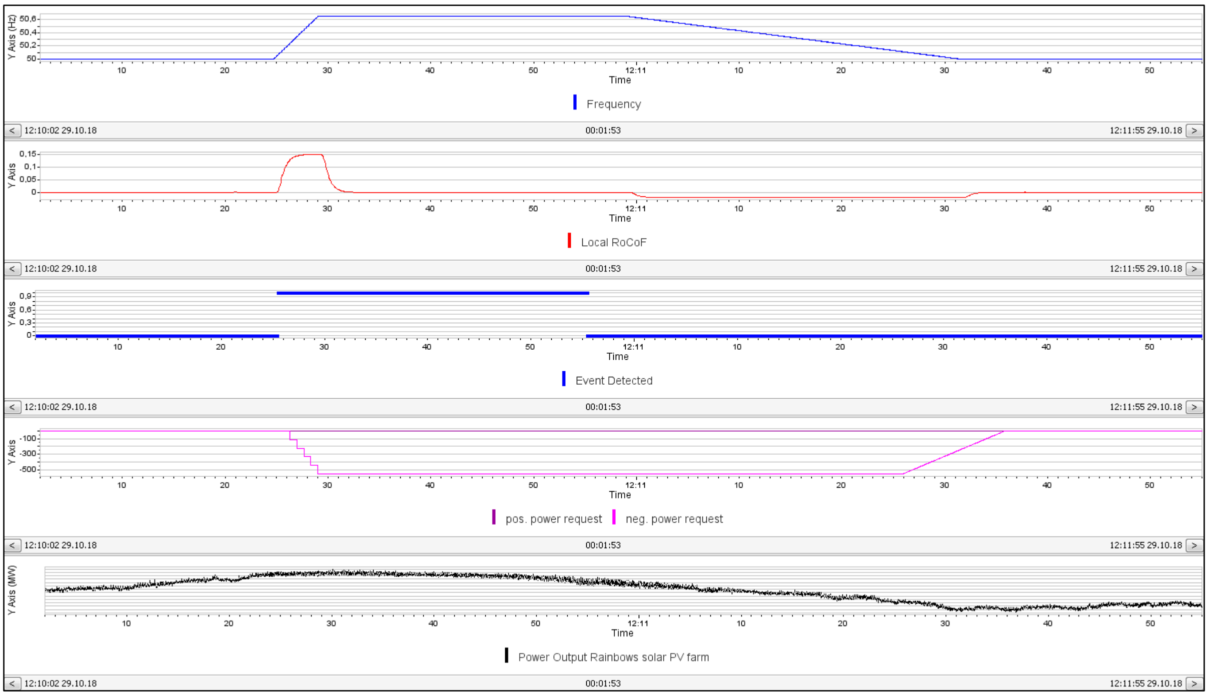


Figure 45: Open loop test – Simulated over frequency event (Frequency nadir of 50.65 Hz). The system holds a power availability of +600/-559 kW. GE Local controller sends a power request in five steps with an equivalent peak request of 100% of negative power availability. (-557 kW)

Open loop test – Under frequency events during night

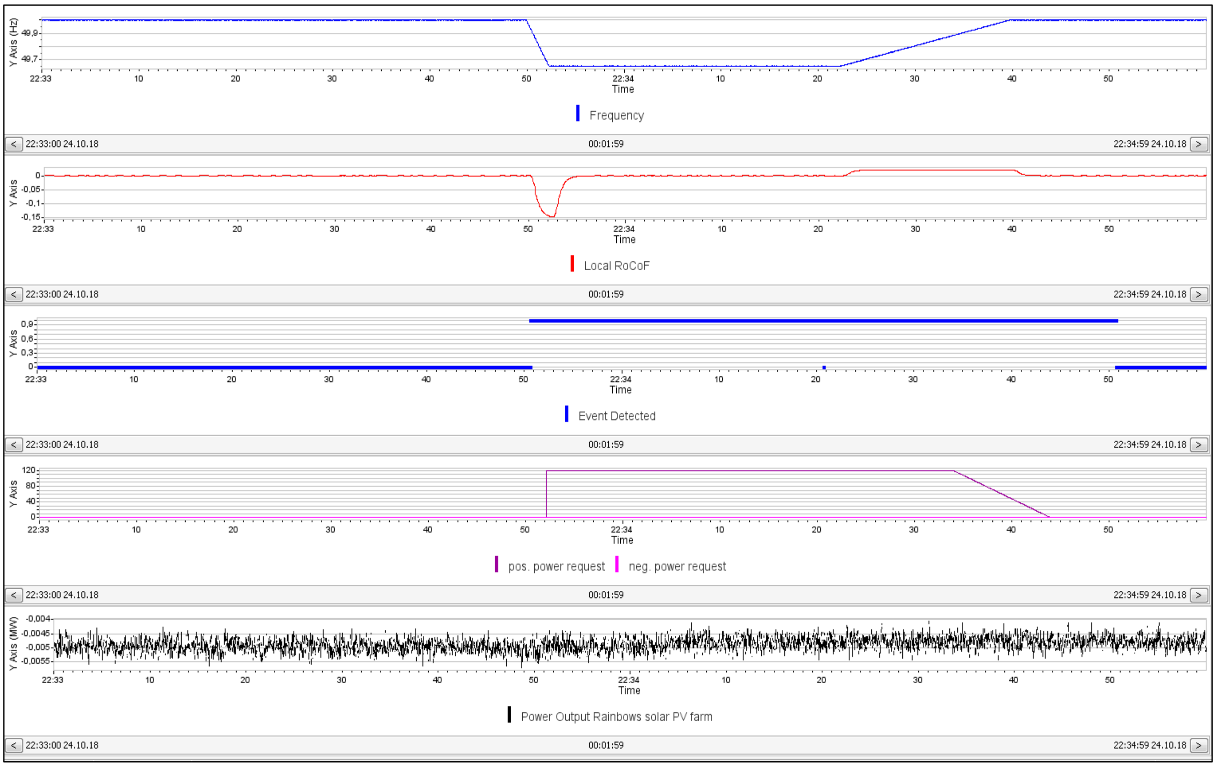


Figure 46: Open loop test – Simulated under frequency event (Frequency nadir of 49.65 Hz). The system holds a power availability of +600/-600 kW. GE Local controller sends a power request in one step with an equivalent peak request of 20% of positive power availability. (120 kW)

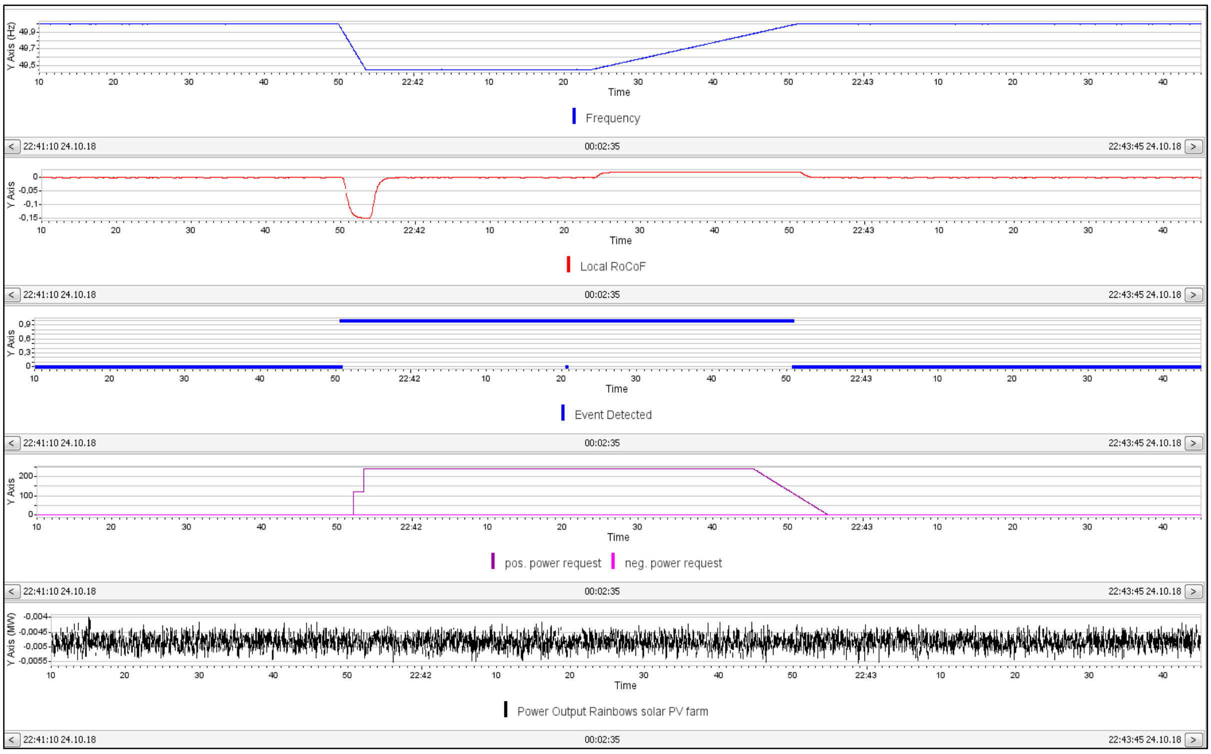


Figure 47: Open loop test – Simulated under frequency event (Frequency nadir of 49.45 Hz). The system holds a power availability of +600/-600 kW. GE Local controller sends a power request in two steps with an equivalent peak request of 40% of positive power availability. (240 kW)

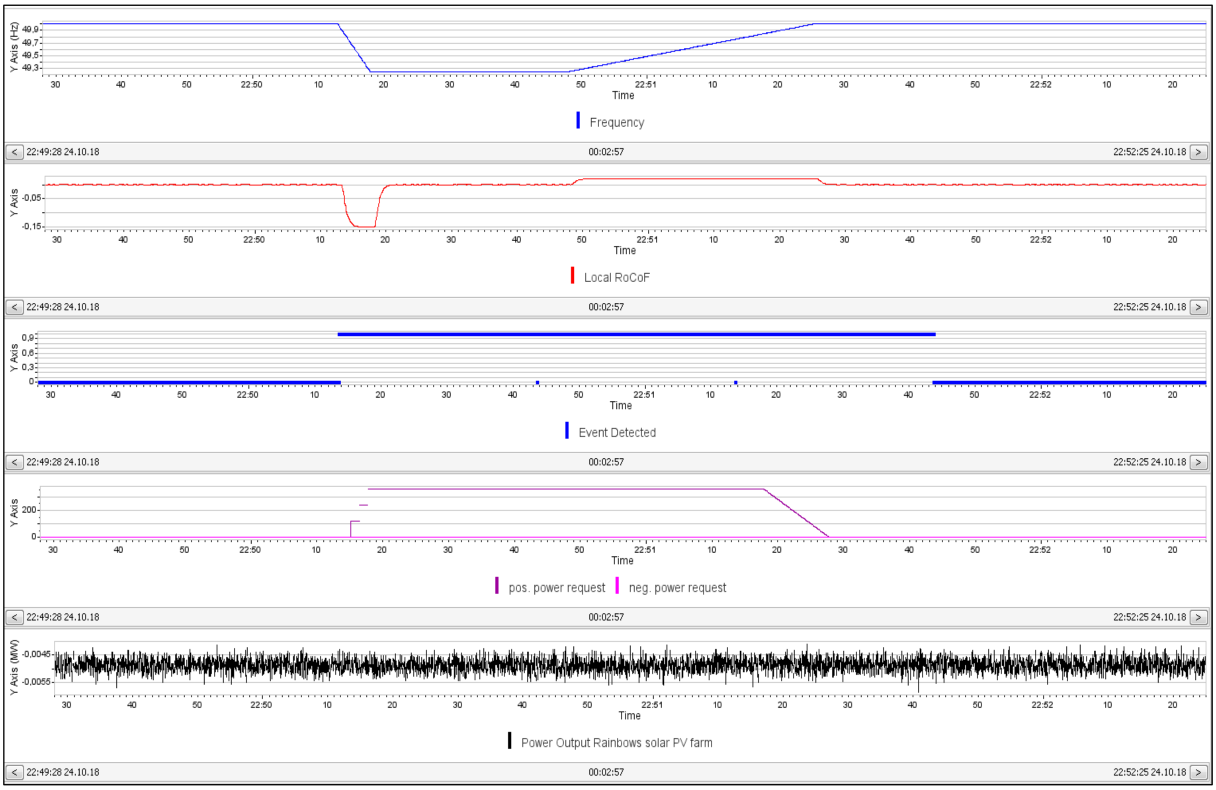


Figure 48: Open loop test – Simulated under frequency event (Frequency nadir of 49.25 Hz). The system holds a power availability of +600/-600 kW. GE Local controller sends a power request in three steps with an equivalent peak request of 60% of positive power availability. (360 kW)

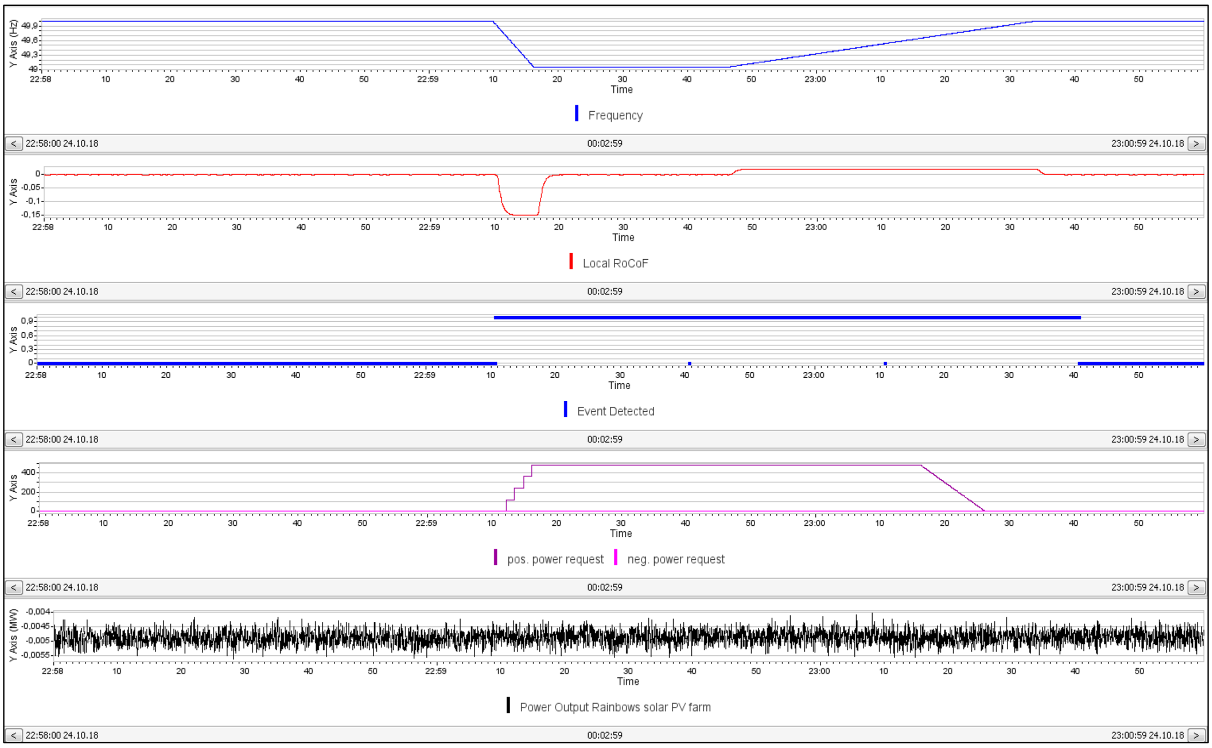


Figure 49: Open loop test – Simulated under frequency event (Frequency nadir of 49.05 Hz). The system holds a power availability of +600/-600 kW. GE Local controller sends a power request in four steps with an equivalent peak request of 80% of positive power availability. (480 kW)

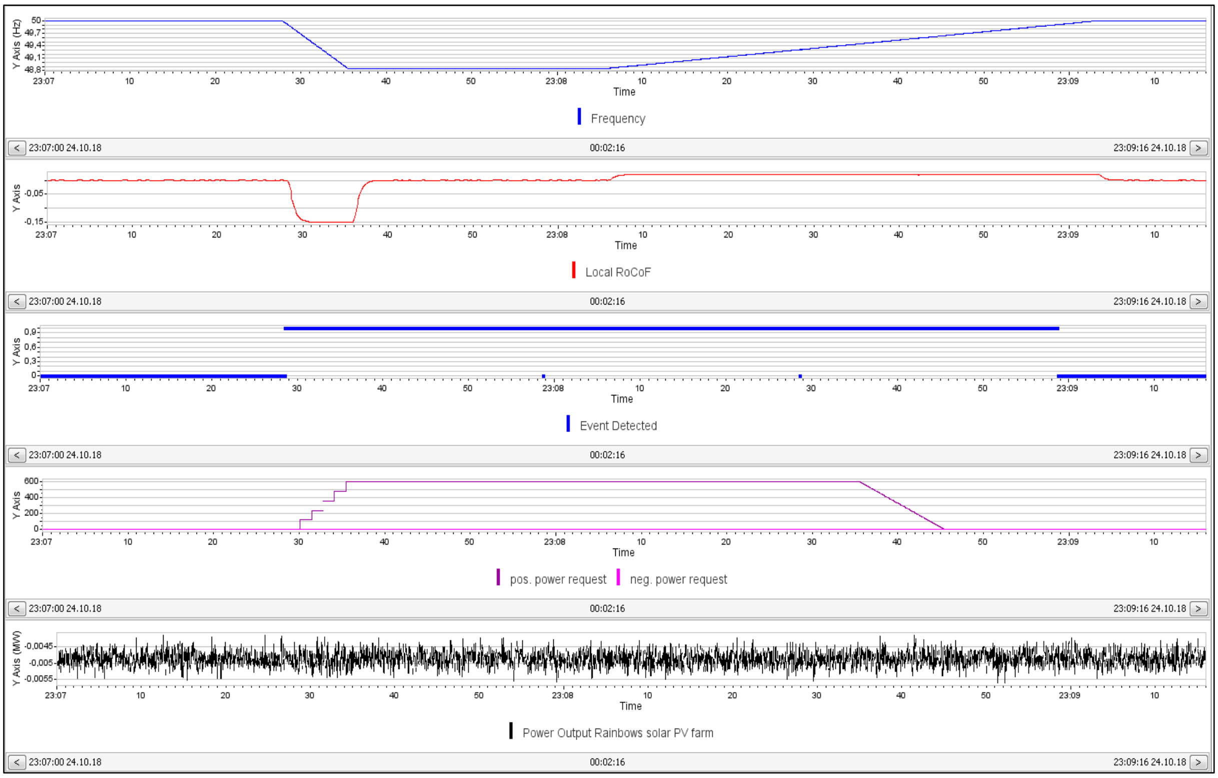


Figure 50: Open loop test – Simulated under frequency event (Frequency nadir of 48.85 Hz). The system holds a power availability of +600/-600 kW. GE Local controller sends a power request in five steps with an equivalent peak request of 100% of positive power availability. (600 kW)

Open loop test – Over frequency events during night

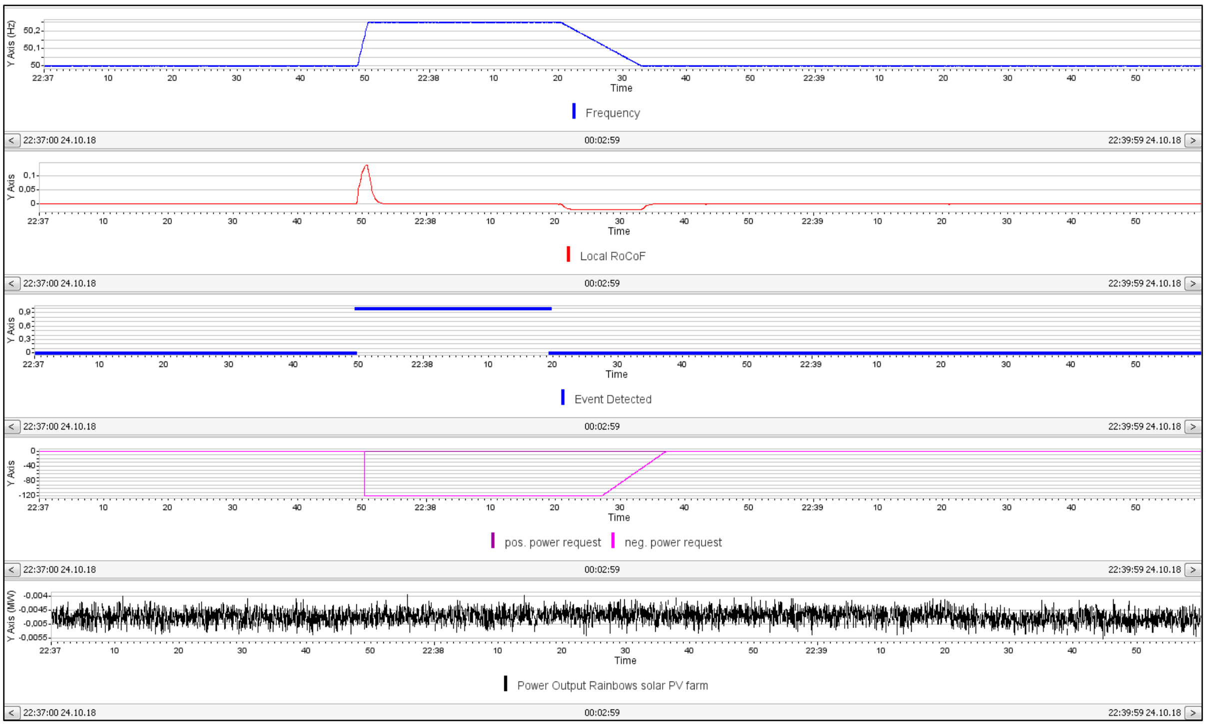


Figure 51: Open loop test – Simulated over frequency event (Frequency nadir of 50.25 Hz). The system holds a power availability of +600/-600 kW. GE Local controller sends a power request in one step with an equivalent peak request of 20% of negative power availability. (-120 kW)

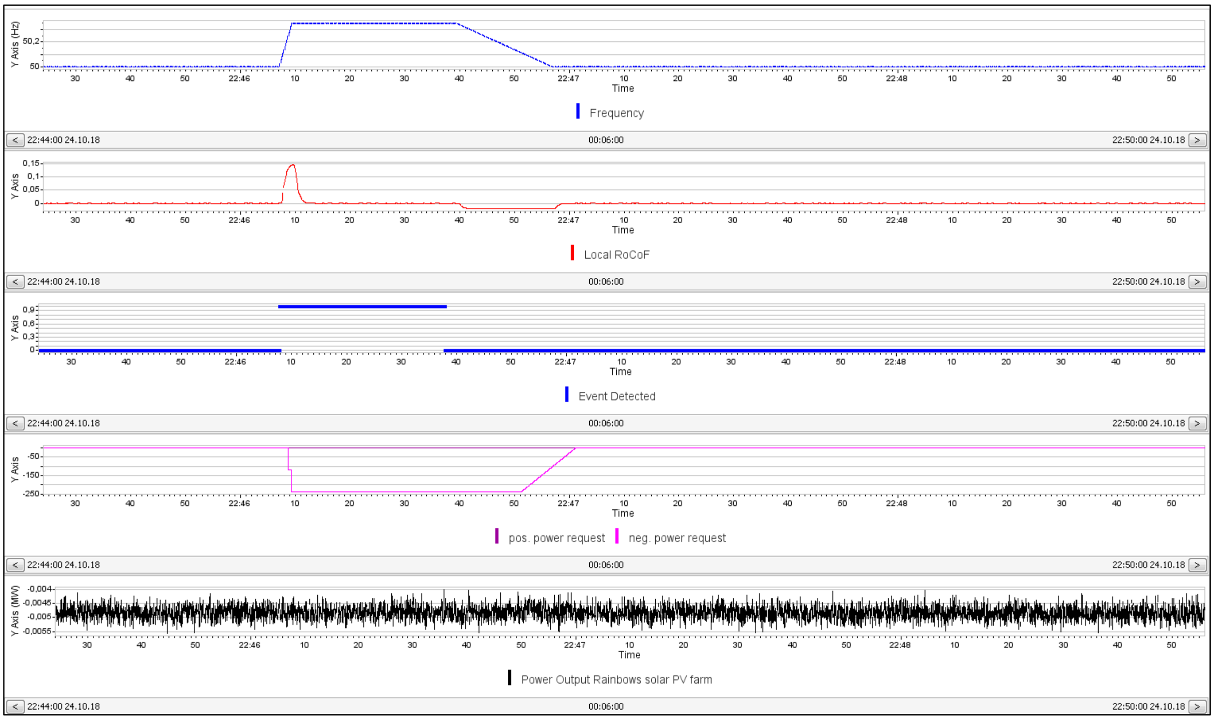


Figure 52: Open loop test – Simulated over frequency event (Frequency nadir of 50.35 Hz). The system holds a power availability of +600/-600 kW. GE Local controller sends a power request in two steps with an equivalent peak request of 40% of negative power availability. (-240 kW)

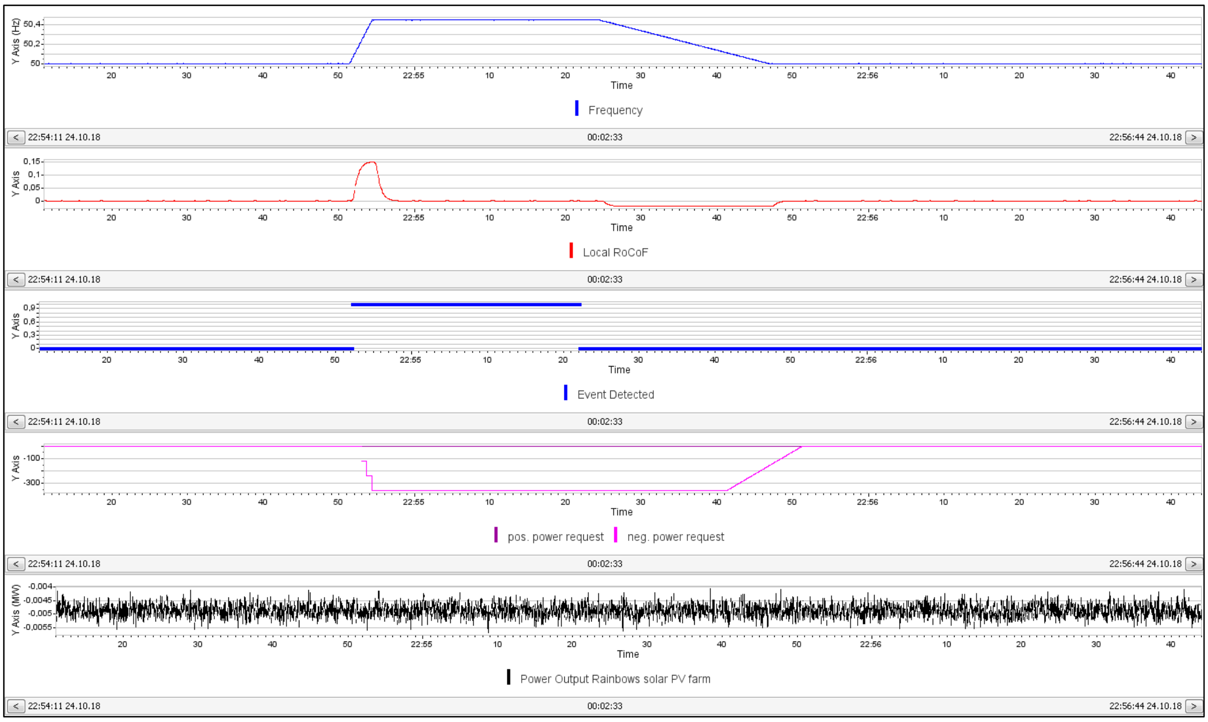


Figure 53: Open loop test – Simulated over frequency event (Frequency nadir of 50.45 Hz). The system holds a power availability of +600/-600 kW. GE Local controller sends a power request in three steps with an equivalent peak request of 60% of negative power availability. (-360 kW)

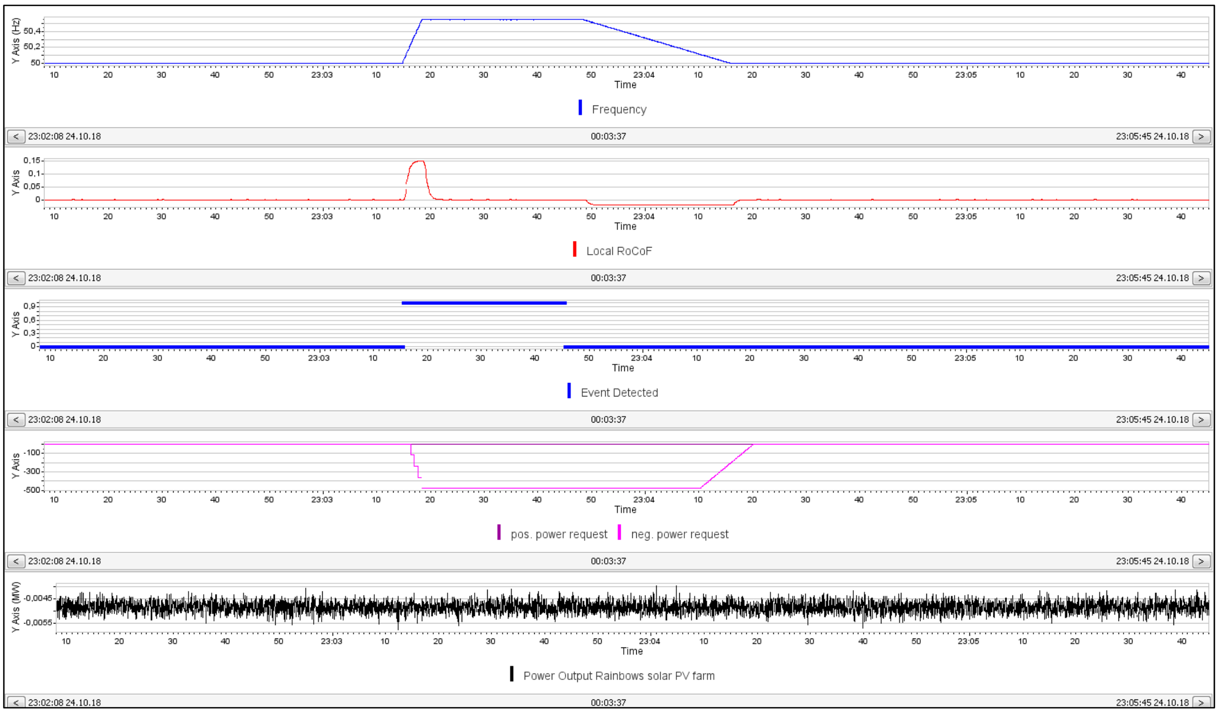


Figure 54: Open loop test – Simulated over frequency event (Frequency nadir of 50.55 Hz). The system holds a power availability of +600/-600 kW. GE Local controller sends a power request in four steps with an equivalent peak request of 80% of negative power availability. (-480 kW)

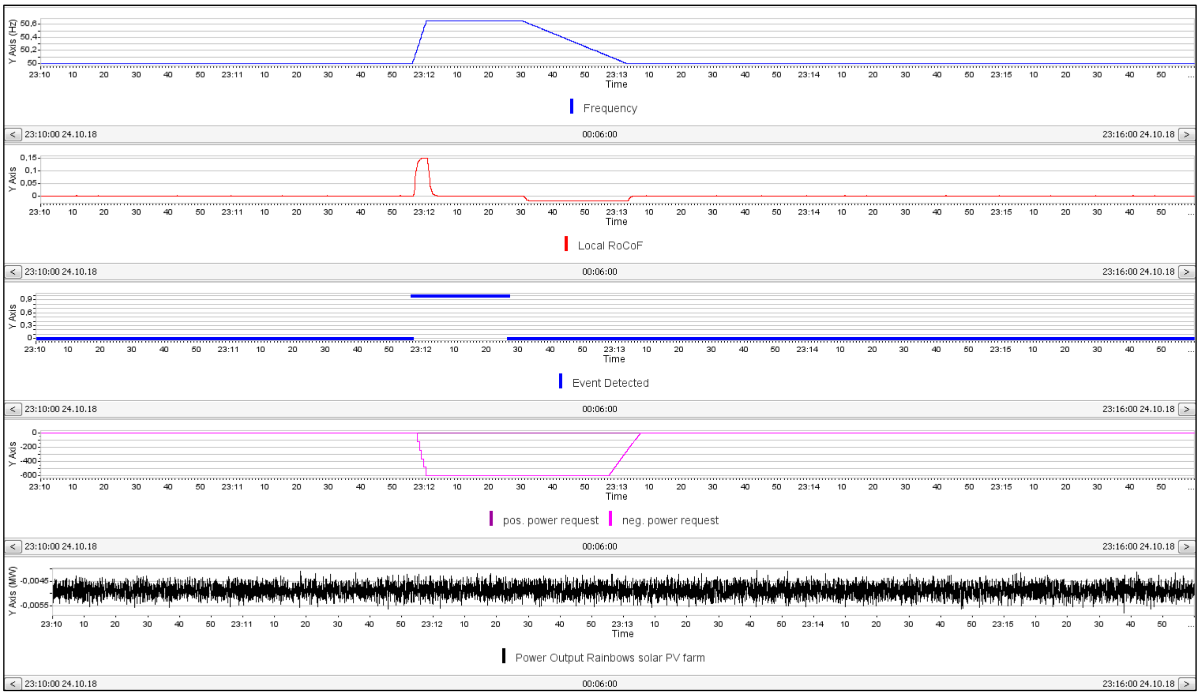


Figure 55: Open loop test – Simulated over frequency event (Frequency nadir of 50.65 Hz). The system holds a power availability of +600/-600 kW. GE Local controller sends a power request in five steps with an equivalent peak request of 100% of negative power availability. (-600 kW)