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Network Innovation Competition:
Enhanced Frequency Control Capability (NIC EFCC)

WP2.3 PV Stand Alone - Test Report

Conducted at the Rainbows Solar PV Power Plant, Willersey

BELECTRIC GmbH

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Table of Content

List of Tables

List of Figures

List of Abbreviations

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
TNO	:	Transmission network operator
UK	:	United Kingdom
WAMS	:	Wide area measurement system

1. Introduction

Today the power grid in the United Kingdom is stirring towards renewable energies with an idea of decarbonizing the electricity sector. To reduce the dependency on fossil fuel and to fight against the climate change, which is the most pressing issue at the moment, Great Britain has a rigorous carbon reduction target. Low carbon sources and renewable energies sources are already deployed across the nation. On 21st April 2017, Great Britain power system experienced its first 24-hour period without coal-fired power generation unit since the 1880s. With a deployment of more than 700 offshore turbines, Great Britain leads the world in offshore wind. The system recorded a generation of 35.7% of total British electricity demand from wind in March 2018 when the national demand was 858GWh. The same year in May, solar energy provided a record-breaking 8.7 GW which corresponded to 24.3% of Great Britain's demand. The nation has set an ambitious 2030 carbon reduction target of reducing the carbon emission by 57% on 1990 levels.

Foreseeable, the conventional synchronous generation units are replaced by fluctuating and power electronic/inverter based renewable energy systems. This fundamental change in the power system introduces stress to the total energy pool thereby affecting the generation-consumption energy balance system. Decommissioning of conventional synchronous generators and replacing them with systems like photovoltaic system or wind turbine which provides minimum or no system inertia, influence the frequency stability of the system during the occurrence of sudden transient disturbance. This brings up the challenge of low system inertia which makes frequency more vulnerable and increases the risk of frequency changes with high rate of change of frequency (RoCoF). To cope with this problem a faster and localised frequency response service will be required which will reduce phase angle difference between the regions of a power system and also assures that the frequency doesn't go beyond the normal permissible limit before the primary frequency service and governor actions provides full response.

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 local frequency response service in connection with a Wide Area Measurement Systems (WAMS) from established distributed generation sources like photovoltaic system, wind energy converters, demand-side management and combined cycle gas turbines (CCGT).

This report evaluates the performance of a grid-connected centralized inverter type PV plant under the EFCC control-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 power plant under the EFCC scheme, a 3.7814 $MW_{p,DC}$ solar PV power plant built by Belectric in 2014 and owned by Toucan Energy, is used – the Rainbows Solar PV Farm which is located at Willersey, Gloucestershire, United Kingdom.

It is a centralized architecture type PV plant. A centralized architecture type PV plant uses either a single inverter for the whole system or one for each sub section, depending on the size of the solar PV plant. This is the most common type of architecture for large-scale commercial and utility-scale solar PV projects in Britain. Due to the small number off inverter hardware in the centralized architecture type system, compared with string architecture type system, a centralized architecture type PV plant provides easier access for plant monitoring and inverter control. An aerial view of the Rainbows solar PV plant used under the EFCC scheme is shown in Figure 1.

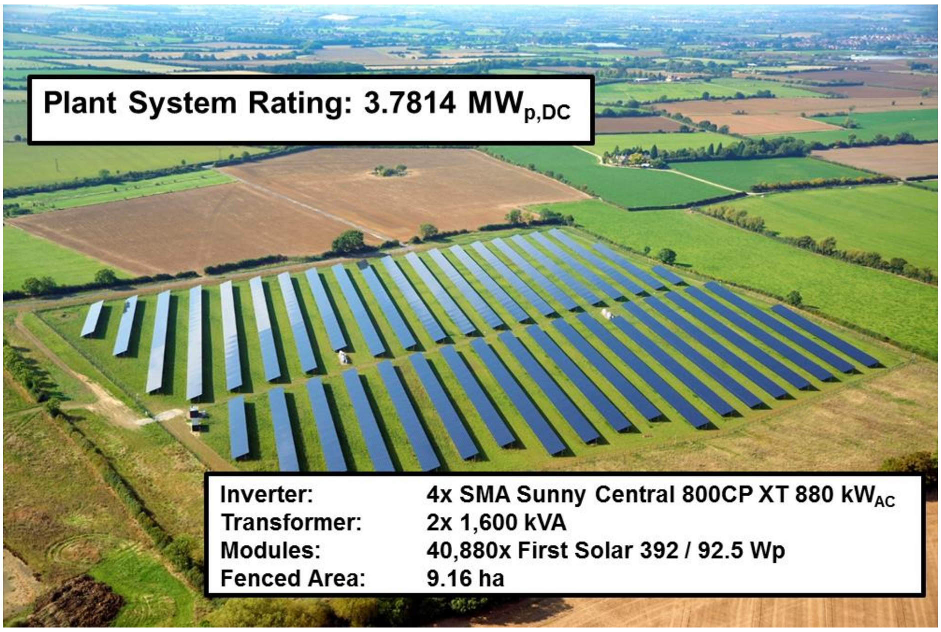


Figure 1: The Rainbows solar PV power plant in Willersey, UK.

This plant is tied to the 11 kV distribution grid of Western Power Distribution (WPD) through two 1,600 kVA transformers (0.36 kV/11 kV). The primary side of each transformer is connected to two inverters (SMA Sunny Central 800CP XT[1]) with a nominal power of 880 kW.

The PV plant is divided into four blocks and in total consists of 40,880 First Solar 92.5 Wp PV Modules. Figure 2 illustrates exemplary the electrical layout of the Rainbows PV plant.

[1] SMA Sunny Central 800CP XT – www.sma.de/en/products/solarinverters/sunny-central-800cp-xt-850cp-xt-900cp-xt.html

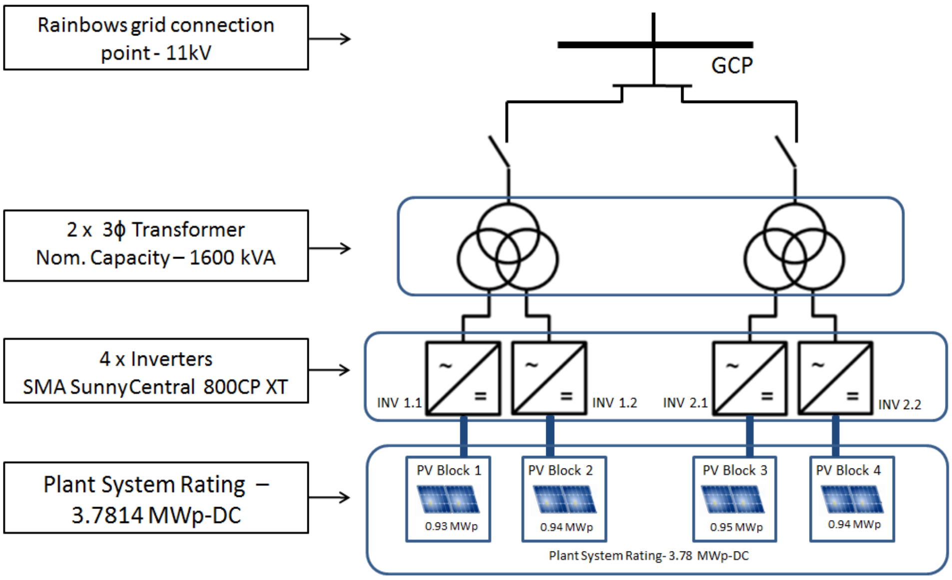


Figure 2: Single Line Diagram - Rainbows PV Power Plant.

To provide fast frequency response each of the four inverters is directly controlled by the BELECTRIC Hybrid Controller through a LAN-cable connection with an established communication protocol, MODBUS TCP, which is the standard communication protocol in PV power plants between the energy management system and the inverters today.

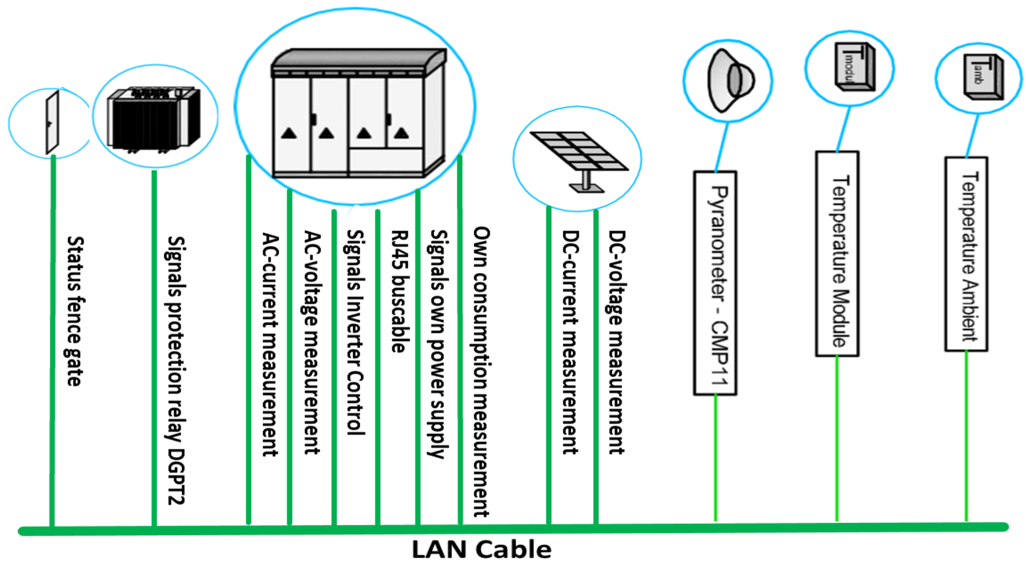


Figure 3: Communication set-up and connected components on a solar PV farm

On this LAN-cable connection, exemplary shown in Figure 3, starting from the communication box of a solar PV farm, are several recipients and senders of data and information which are needed to monitor and control the solar PV farm. These include: temperature sensors for ambient temperature, temperature sensors of each single module, irradiance data from the few pyranometers, DC voltage and current data from the modules, AC current and voltage data from the inverters, own consumption measurement data, signals from the protection relays and also the status of the fence gate for example. This is the standard set up of a commercial large scale solar PV farm with centralised converter technology to maximise energy output. The standard UK solar PV farm was not planed and built to provide fast frequency response in the first place. That has already some implications on the outcome of the test and trials.

To adapt and improve the Rainbows solar PV farm to provide fast frequency services within the EFCC scheme, new control and measurement equipment was installed and implemented. This includes sensitive measuring modules, new control hardware and logic, as well as a cloud-camera-based solar PV forecasting system. Figure 4 shows the communication setup which is now implemented between the measuring system, the GE Local Controller, the BELECTRIC Hybrid Controller and the PV inverters at the PV plant in Willersey. Between the Hybrid Controller and the Local Controller exists a constant exchange of fundamental information (shown in the right panel of Figure 4 and in more detail in Table 1).

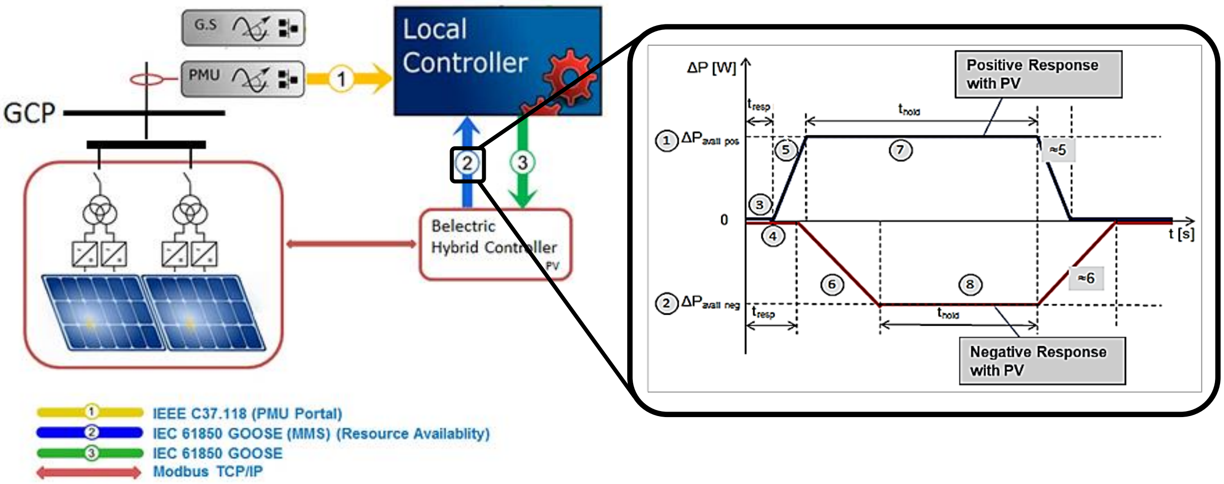


Figure 4: Communication Scheme.

The phasor measurement unit (PMU), which is deployed at the grid connecting point (GCP), measures the regional frequency, the voltage and its phasor angles. The installed RA331 Module, in combination with current and voltage transducers, measures also the power output at the grid connecting point.

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 set to be ±0.1 Hz/s. This setting was chosen specifically for the EFCC testing scenario to trigger and respond to a real system event. Alternative settings can be implemented in accordance with the required sensitivity. This was also used in the solar PV tests.

Once the frequency reaches the threshold of 49.7/50.2 Hz, the GE Local Controller sends the positive or negative power request to the BELECTRIC Hybrid Controller through established GOOSE communication. This power request is processed by the BELECTRIC Hybrid Controller and divided amongst the inverters in proportion with the individual power production at that time. As a result, the inverter changes its working point and provides the balancing power.

A solar PV system's power availability is not constant throughout the day. The GE Local Controller's power request must therefore be in accordance with the PV systems response capability. The PV system running under EFCC scheme sends its quantified availability through eight parameters which are listed in table 1. An Exemplary screenshot of the transferred values can be seen in Figure 5.

SNO.	PARAMETERS
1	Positive power availability for next 15 minutes [kW]
2	Negative power availability for next 15 minutes [kW]
3	Positive response time [s]
4	Negative response time [s]
5	Power ramp up rate [kW/s]
6	Power ramp down rate [kW/s]
7	Positive power hold time [s]
8	Negative power hold time [s]

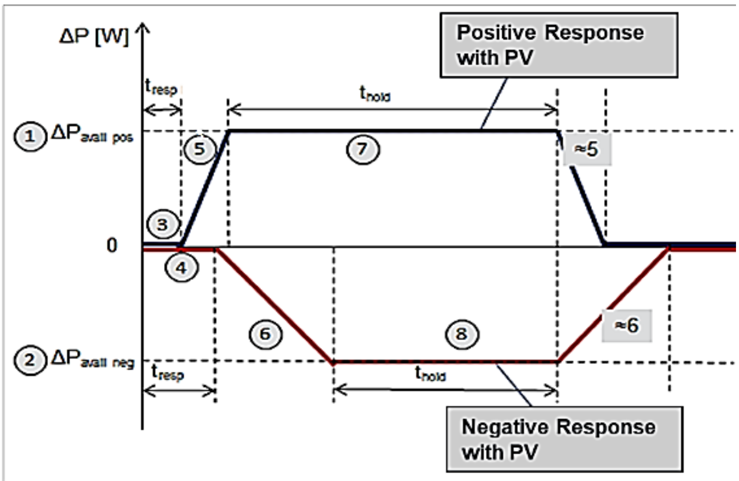


Table 1: Quantified power availability sent by PV resource running under EFCC control scheme.

To provide the available power for the whole duration of the power hold time an estimation of positive and negative power availability by the resource for the next 15 minute is done by a short term solar PV power forecasting system. The Hybrid Controller sends a 15 minute forecasted available positive and negative power along with the response time, ramp rate and power hold time to the GE Local Controller via the established GOOSE communication protocol.

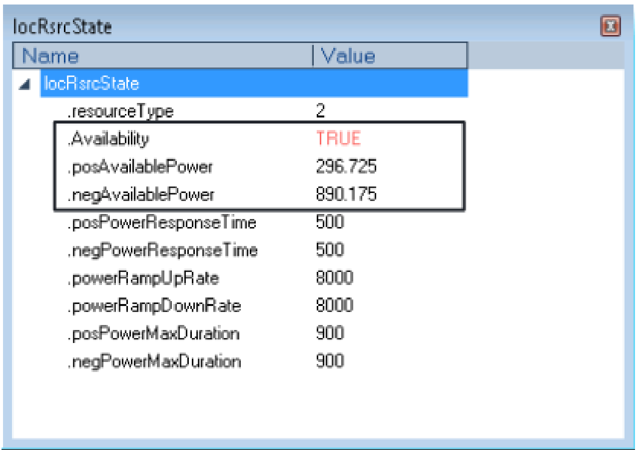


Figure 5: Example of the power availability status sent to the GE Local Controller.

The expected power request is shown in the Figure 6. The request increases by 20% of PV's power availability every time the frequency crosses on of the thresholds given in table 2. This continues until the RoCoF stops increasing. After this, the power request is sustained for the time until the frequency is restored, followed by a 10 second ramp down.

The system also has a failsafe mode for slower frequency events. The event is detected, and a power request is send as the frequency reaches 49.7/50.2 Hz.

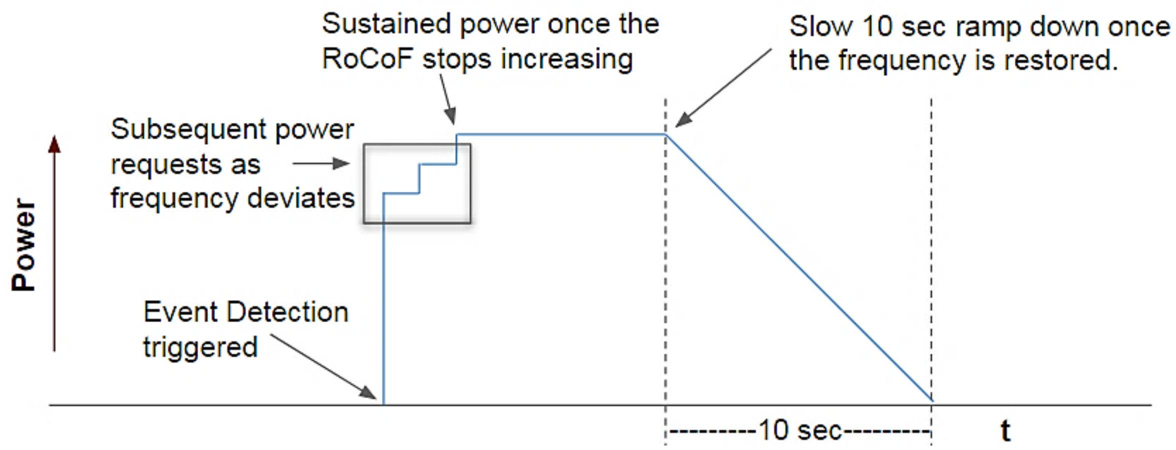


Figure 6: Nature of the power request from the GE Local Controller.

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

Table 2: Frequency thresholds for GE Local Controller power request.

To expedite the EFCC testing for PV stand alone trials, a simulation tool by GE is used – the PMU Simulator. This allows testing the system at any time without waiting for a real frequency event to occur in the GB network. The PMU simulator (hereby referenced as the Grid Simulator (G.S)) is a substitute for real system events as it injects simulated frequency data with predefined RoCoF values and frequency nadir[2] 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 PV resource availability, nature and the magnitude of the

[2] Frequency nadir - lowest or highest value of the frequency after a frequency event.

simulated frequency event. Over and under frequency events that can be simulated by the GE PMU Simulator are shown in the table 3.

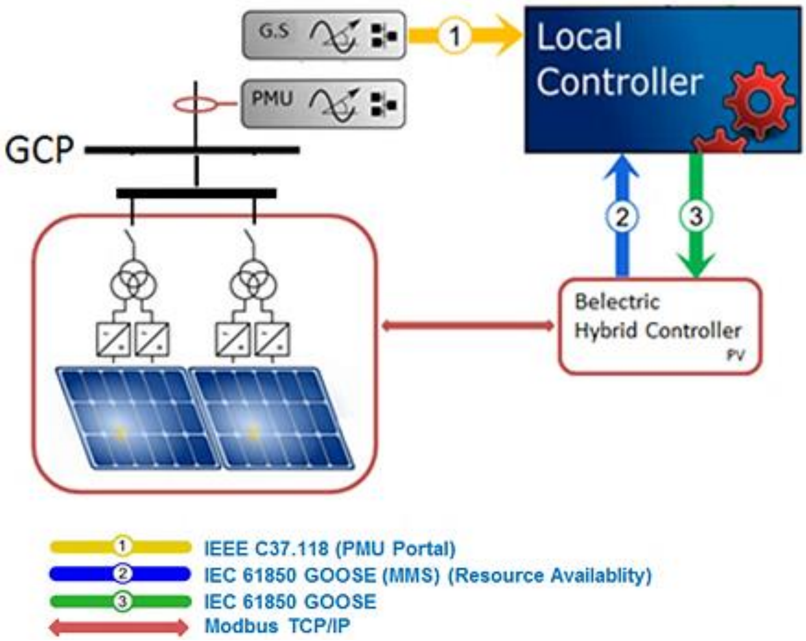


Figure 7: Communication setup - PMU Simulator. The simulator replaces the data input of the grid connected measurement system during some of the test. It simulates EFCC relevant frequency events to test and trial the connected equipment. The PMU still measures the power output of the solar PV farm.

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

Table 3: PMU Simulator, Simulated event list.

3. Power Forecasting and Reference Maximum Power Point

As seen in table 1, the grid-connected resource sends the positive and negative power availability to the Local Controller whose higher-level control systems generates the resource availability portfolio for multiple local controllers of different resources within a region. The Belectric Hybrid Controller sends a 15 minute forecasted available positive and negative power to the GE Local Controller.

3.1 steadyEye sky imager camera

To quantify the next 15 minutes of availability from the PV resource, the PV plant was additionally equipped with a steadyEye sky imager camera[3] which assesses the cloud movement and estimates the global horizontal irradiance (GHI) available in the next 15 minutes. Such hardware is not yet widely used in a utility scale PV plants but was specifically deployed on site for the EFCC control scheme. It is a maturing technology that can be implemented in new and existing solar PV power plants.

The installed steadyEye sky imager camera gives 15 minute forecasted GHI probability values from p10 to p90. To prevent regular overestimation of the forecasted power, p40 values were used in the power forecasting model. That means that the probability of the real power exceeding the forecasted power is 4 in 10. An overestimation would result in a wrongfully high available power which the solar PV farm would not be able to deliver in case of a power request by the EFCC system. A slight yet constant underestimation is therefore preferred.

3.2 Rainbows solar PV farm Matlab PV Model

Since the panels in the Rainbows PV plant at Willersey are tilted on an angle of 20° facing south, the forecasted p40 GHI values are converted to Plane of Array (POA-20°Tilt-South) by a sophisticated model and then given to the BELECTRIC in-house MATLAB PV Model which uses real time simulation and hardware-in-the-loop approach to simulate the behaviour of the Rainbows PV Power Plant. For calculating the 15 minute forecasted power availability of the Rainbows PV farm this model gathers real time data from the installed sensor box which provides environmental inputs like PV cell temperature, Inverter temperature, and the irradiance value [W/m^2] measured by the pyranometers. The model then calculates the power in kW, generated by each simulated inverter operating at its maximum power point (MPP) when exposed to an irradiance value W/m^2.

[3] steadyEye sky imager camera - steady-sun.com/wp-content/uploads/Fiche-SteadyEye-A4-EN.pdf

This PV model was used to evaluate the following parameters:

1. **Reference MPP power**

   A certain percentage of inverter curtailing is important, whenever the capability to provide both positive and negative power response is required. This is done by continuously writing the new reduced working point at the power register of the inverter hardware. To make sure that the hardware always keeps a positive power availability of e.g. 20%, the inverter is forced to reduce its power by 20% from its MPP value. In order to curtail the output power, the BELECTRIC Hybrid Controller needs to know the MPP power (Reference MPP power) of the inverter even if the inverter is curtailed and not running at MPP. The MATLAB PV Model, which simulates the behaviour of each inverter, is used to calculate the theoretical MPP reference power for each inverter. This evaluated power was then used to write the new reduced working point into the register to reduce the inverter power output by 20% from this MPP power.

2. **Short term PV power forecast**

   To evaluate the 15 minute forecasted PV power availability, the same PV Model was given the irradiance input from the steadyEye sky imager camera. The 15 minute forecasted GHI values were converted into POA and given to the PV model to get an estimation of short term 15 minute forecasted power availability from the PV plant in Willersey.

3.3 Evaluation of combined forecast by sky camera and PV model

The sky imager camera + PV model set-up was tested over the duration of several months. The results were quite unfavourable. Upon further investigation, the in-house PV Model's reference MPP evaluation was found to have a high accuracy while the accuracy of the steadyEye sky imager camera was insufficient for this application. As a result, the evaluated 15 minute forecasted PV power by the in-house MATLAB PV model was unacceptable and had a high margin of error with the data given by the sky imager (See Appendix: Accuracy test results for sky imager camera and in-house PV model).

Therefore, the sky imager was deactivated and replaced by an underestimating statistical forecast model for the 15 minute forecast (see chapter 3.4). This model observes the inverters power fluctuations in the past and assigns a weight to the lowest measured inverter power depending upon the magnitude of the observed fluctuations. The MPP was thereafter provided by a reference inverter.

As mentioned, the PV model itself was found to be accurate and effective in simulating the MPP of the inverters when given actual irradiance data by the pyranometers (Error margin of <5%; see for example Figure 8; see also Appendix: Accuracy test results for in-house PV model).

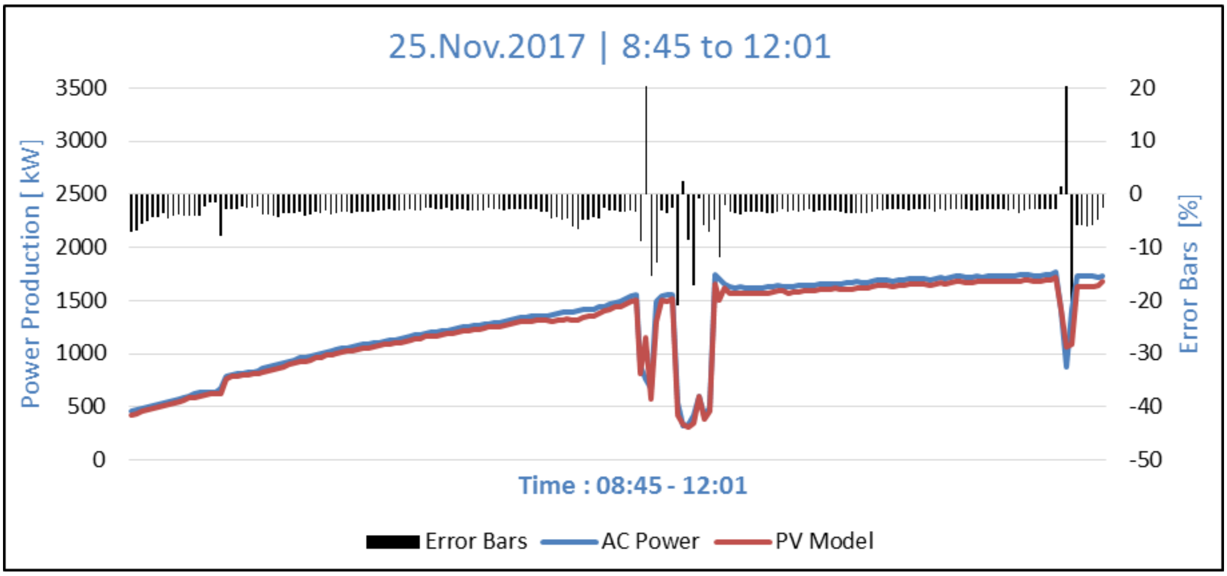


Figure 8: Exemplary evaluation of the accuracy of the Rainbows solar PV farm output, calculated by the PV Model vs. the actual measured solar PV farm output. Sudden changes in the irradiation by e.g. cloud movement lead to short reductions in accuracy. In general, the accuracy of the Rainbows solar PV farm Model was found to be above 95%.

Nevertheless, the PV Model running in the background was eventually also deactivated after evaluating the first results of the curtailment tests to reduce the system latency time in the given set-up (further discussed in section 6.1, sub-section C). The MPP was thereafter provided by an un-curtailed reference inverter.

Using one of the inverters as a reference inverter for MPP tracking for both the PV model as well as for the forecast model reduces reaction and cycle time within the control logic. Inverter 2.1 was configured to run constantly at MPP. The measured data from this inverter is used within the control logic as the MPP reference point.

This approach improved data quality, reduced complexity and, even more importantly, it reduced the reaction time tremendously. On the other hand, this solution subsequently reduces the total response capability of the solar PV farm by the amount of the possible response power of this MPP-fixed reference inverter.

3.4 Evaluation of the underestimating statistical forecast model

The underestimating statistical forecast model that was subsequently implemented into the control logic for the 15 minute forecast can be very accurate for given weighted variables. The main purpose of the forecast model is to forecast the available positive and negative power for the next 15 minutes at each given moment.

It is designed to underestimate future irradiance to reduce the amount of cases in which a sudden drop in irradiation reduces the available power below the expected available power by the LC. The triggering of a power request in such circumstances could lead to an insufficient answer by the PV power plant.

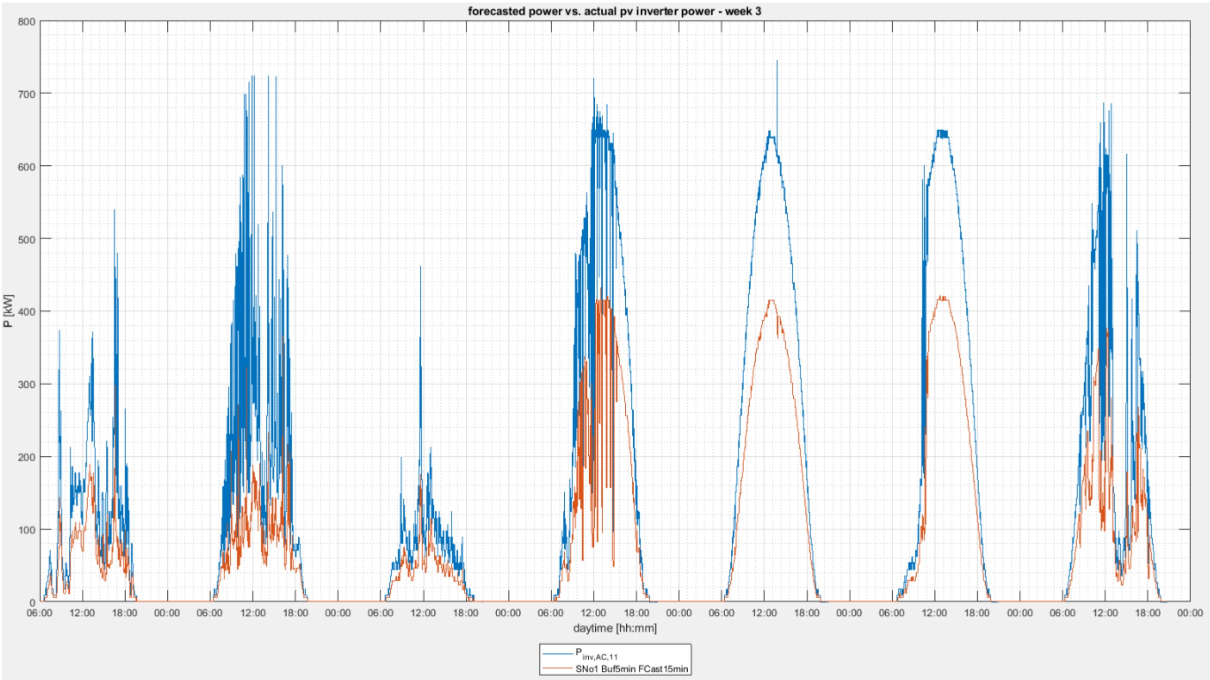


Figure 9: Real power output (blue graph) vs. forecasted power output (orange graph) for irradiance data of one week in April 2018 at the Rainbows solar PV farm.

Figure 9 shows the accuracy of the implemented model with the given weight vector for the power and irradiance data for an exemplary week in April 2018. The blue line represents the actual power output by one inverter of the Rainbows solar farm. The orange line represents the calculated power by the forecast model.

The model is fairly accurate for different weather situations. Day 2 and 4 in Figure 9 were quite cloudy for example with a constantly changing irradiance and power output, contrary to the sunny days 5 and 6. The model doesn’t forecast to 100% of actual power to consider the probability of sudden changes in irradiance. The confidence level limits the max. power forecast and therefore constantly underestimates.

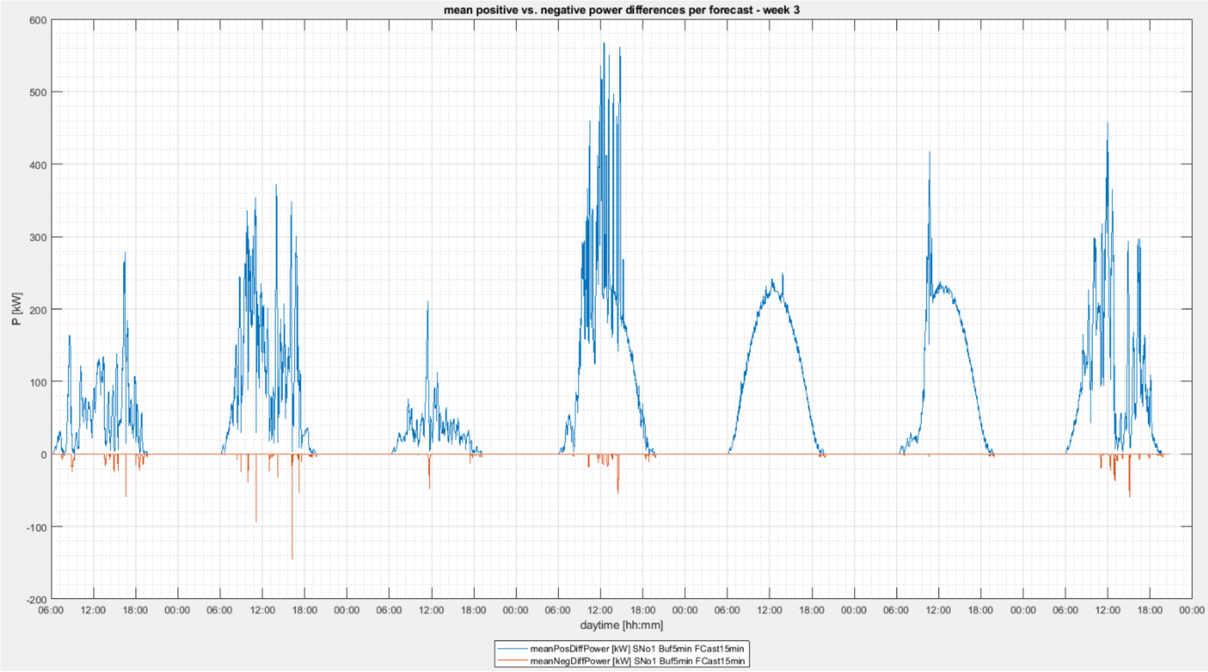


Figure 10: Mean positive and negative power differences of the forecast model. The blue graph shows the mean magnitude of the underestimation. Smaller magnitudes are preferred but underestimation happens constantly due to the confidence level. Negative differences are shown in orange. Here it is preferred to have them never at all to prevent sending a false value to the LC that cannot be accomplished in case of a power request.

The more unstable the weather situation the larger is the amount of errors produced by the model as shown in Figure 10. The LC calculates the power request based on the power availability estimated by this forecast. The orange bars indicate a second in which the forecasted power was larger than the actual power output in this moment. In these seconds the system wouldn't be able to react with full power to a power request by the LC in case of an event.

The blue line in Figure 10 is the difference to the actual available power. Due to the use of an underestimating model the power availability is below the actual power output most of the times.

It can also be seen that at the end of each day the forecast model regularly produces an error as it predicts a larger power output as is actually produced as the sun sets.

Important is also the maximum magnitude of the errors made by the model. Large power differences are undesirable. Small differences are preferred so that even in the case of a wrong forecast value a significant amount of the power request can still be fulfilled. This can exemplary be evaluated in Figure 11. The model was hereby tested with several weighted vectors and forecast and buffer times.

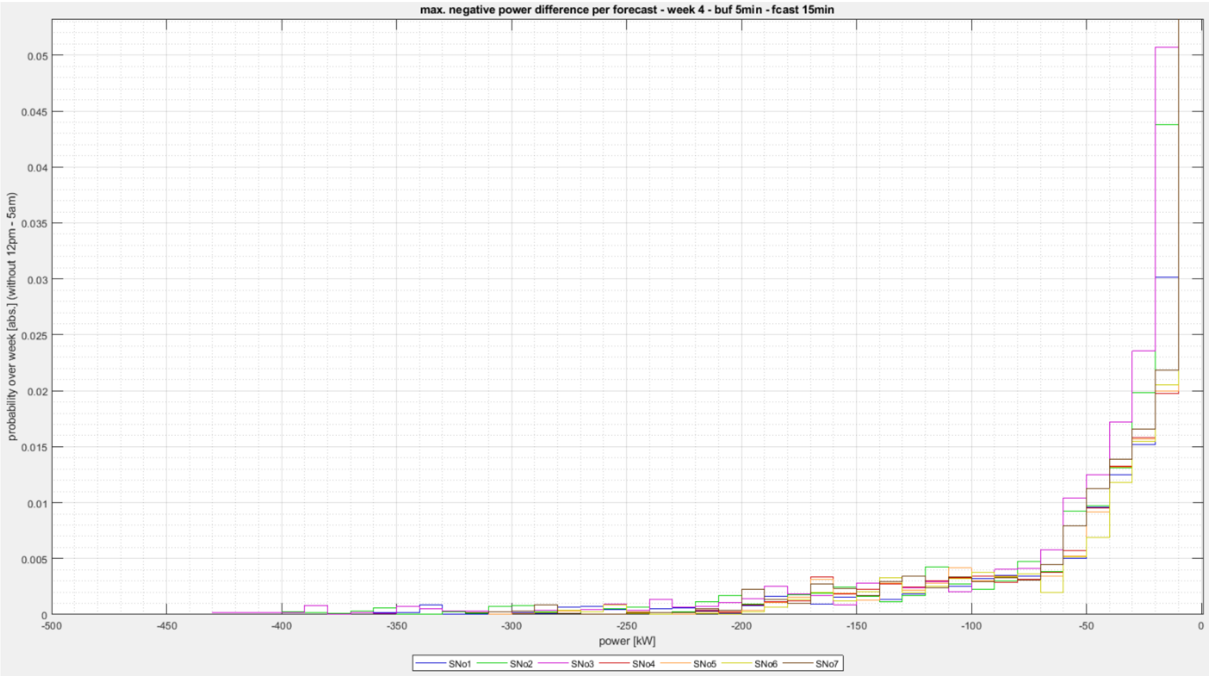


Figure 11: Maximum negative power difference histogram per forecast for several weight vectors for a buffer time of 5 min and forecast duration of 15 min. Data base is one week in April 2018.

In the histogram in Figure 11, the amount of forecasts with different weighted vectors (Set Number 1-7 (SNo 1-7)) is presented over its maximum and mean values. The amount of forecasts is normalized into a probability value. The probability includes the time for a whole week dataset of one inverter with 880 kW_{max} available power. For example: -100 kW with 0.001 probability means the probability of an overestimated forecast with a 100 kW negative peak difference in its forecast time, respectively to the actual inverter output during the forecast time, is likely to happen in 0.1% of the whole weeks' time (excl. 12 pm to 5 am – no sunshine), if a power forecast could be requested in any of its time steps.

In Figure 11 is an exemplary stair chart histogram of one week of data for several weighted vectors (SNo 1-7) for 5 min buffer time and 15 min forecast time. It can be seen that the majority of errors has a magnitude below 50 kW. A power request in these situations by the LC would therefore result in just a small difference in the delivered power by the PV farm. On the other hand there are a few incidents with differences up to 430 kW, which is undesirable.

Other buffer and forecast times will result in different magnitudes with e.g. a large percentage of max. power differences between 100 kW and 50 kW and max. magnitude of errors above 500 kW.

However, it does not consider the exact day or daytime, when the risk of a high difference is the biggest. This can be better seen in the overview plots. The model has several variables that can be changed according to the objective that needs to be optimised. This can either be to maximise the power output of the power plant in case of an event; a longer forecasting time to evaluate future system behaviour by e.g. the TSO or DSO; or to minimise the error margin or the error magnitude.

In general, it can be said that

- smaller data base / buffer time[4] decreases accuracy
- longer forecast duration decreases accuracy
- the more accurate the forecast shall be, the less power available is signalled to the LC
- long forecast duration decreases maximum power availability

Most of these points are dictated by the nature of forecasts. These points were verified in an extensive data analysis with different weight vectors and the irradiance data of several weeks.

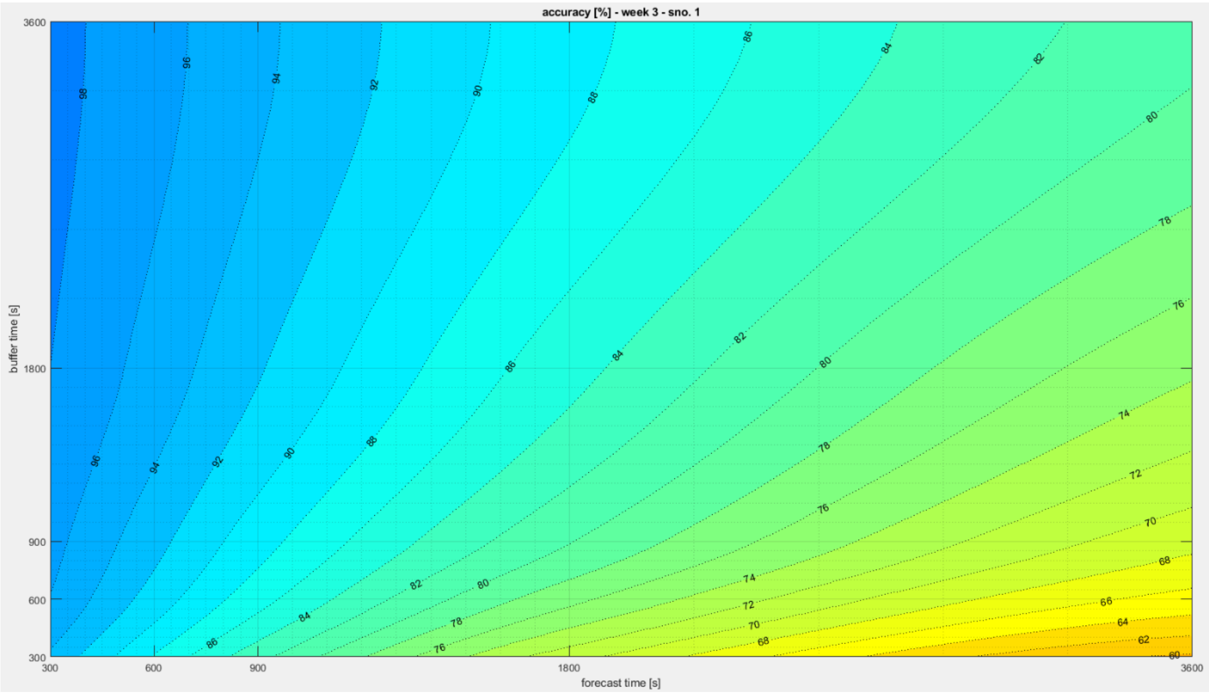


Figure 12: Accuracy map for the weighted vector SNo 1 that is used in the forecast model of the EFFC project for several buffer times and different forecast durations. Blue indicates a high accuracy, red a low accuracy. Data base is one week in April 2018.

Figure 12 is the accuracy map for the weight vector SNo 1 that is used in the current setup. It has an accuracy of ≈84% for 5 min buffer time and 15 min forecast time. In these 15 min is the power availability value that is send to the LC in 84% correct for all seconds of the next 15 min.

As Figure 12 shows, the accuracy varies widely for the different variations of forecast duration time and buffer time – from 98% accuracy down to 60% accuracy. The analysis of larger data sets also showed weeks of only 48% accuracy for the 60 min forecast (see Figure 14).

By changing the amount of time and data in which the forecast gives an estimate of the lowest future irradiance value the implemented forecast model could effectively become ≈90% accurate for 15 min values or even 98% accurate for 5 min forecasts, given a 60 min buffer time.

[4] The buffer time is the timeframe from which we analyse the data of the past.

The downsides in these cases are

a) larger data usage
b) longer calculation time
c) less available power

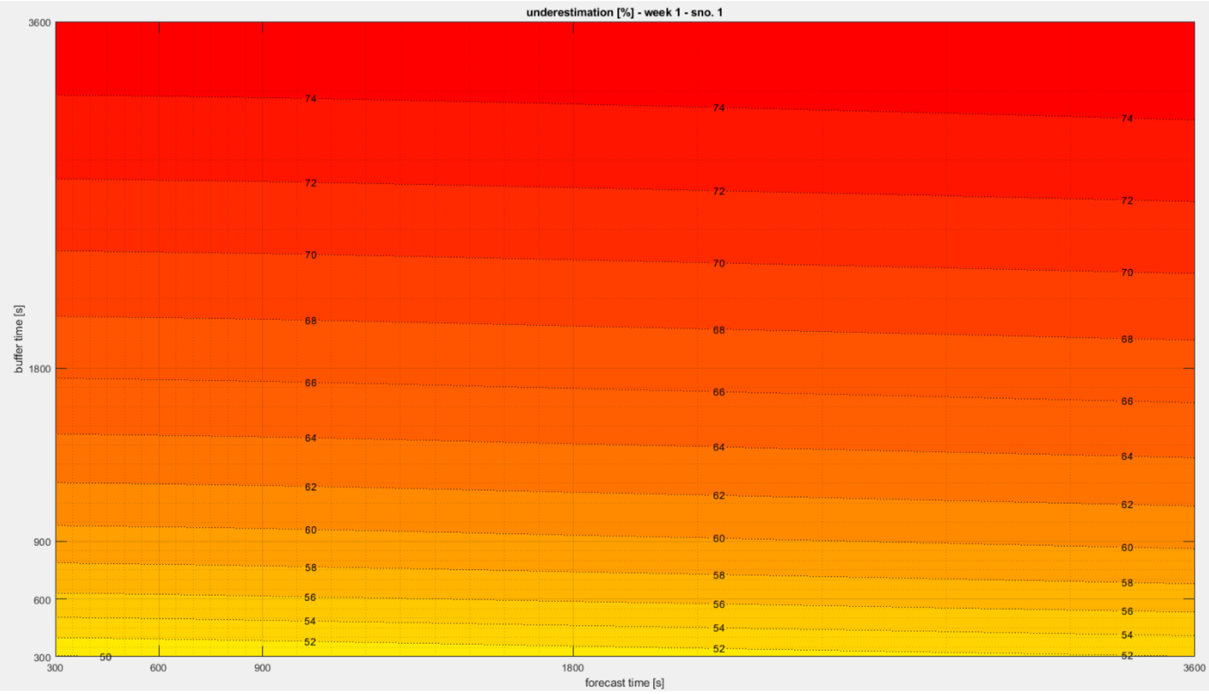


Figure 13: Underestimation map for SNo 1. The larger the buffer time the larger the amount of underestimated power. Less is preferred. Forecast duration only has a small influence. Data base is one week in April 2018.

Point c) can be seen in Figure 13. It is shown that the shorter the buffer time the less underestimation happens. Meaning that the amount of power that is essentially registered in the LC as available power, is higher and therefore a larger reaction to system events can be produced.

The chosen buffer time in the EFCC test set up was 5 min as it reduces calculation time and at the same time increases the amount of available power for the test phase.

While in Figure 14 it is shown that with large forecast times the probability of overestimation increases, so the accuracy decreases, Figure 13 indicates that the underestimated power stays nearly on the same level for increasing forecast times.

Evidently, the higher the buffer time, the higher are the differences between min. and max. values and the more are we reducing the forecasted power. The accuracy gets higher as the forecasted power is reduced and the probability of overestimation decreases. On the other hand this curtailment of the forecast increases the losses through underestimation.

With high forecast times the probability of overestimation increases, so the accuracy decreases, whereas the underestimated power/energy stays nearly on the same level, surprisingly.

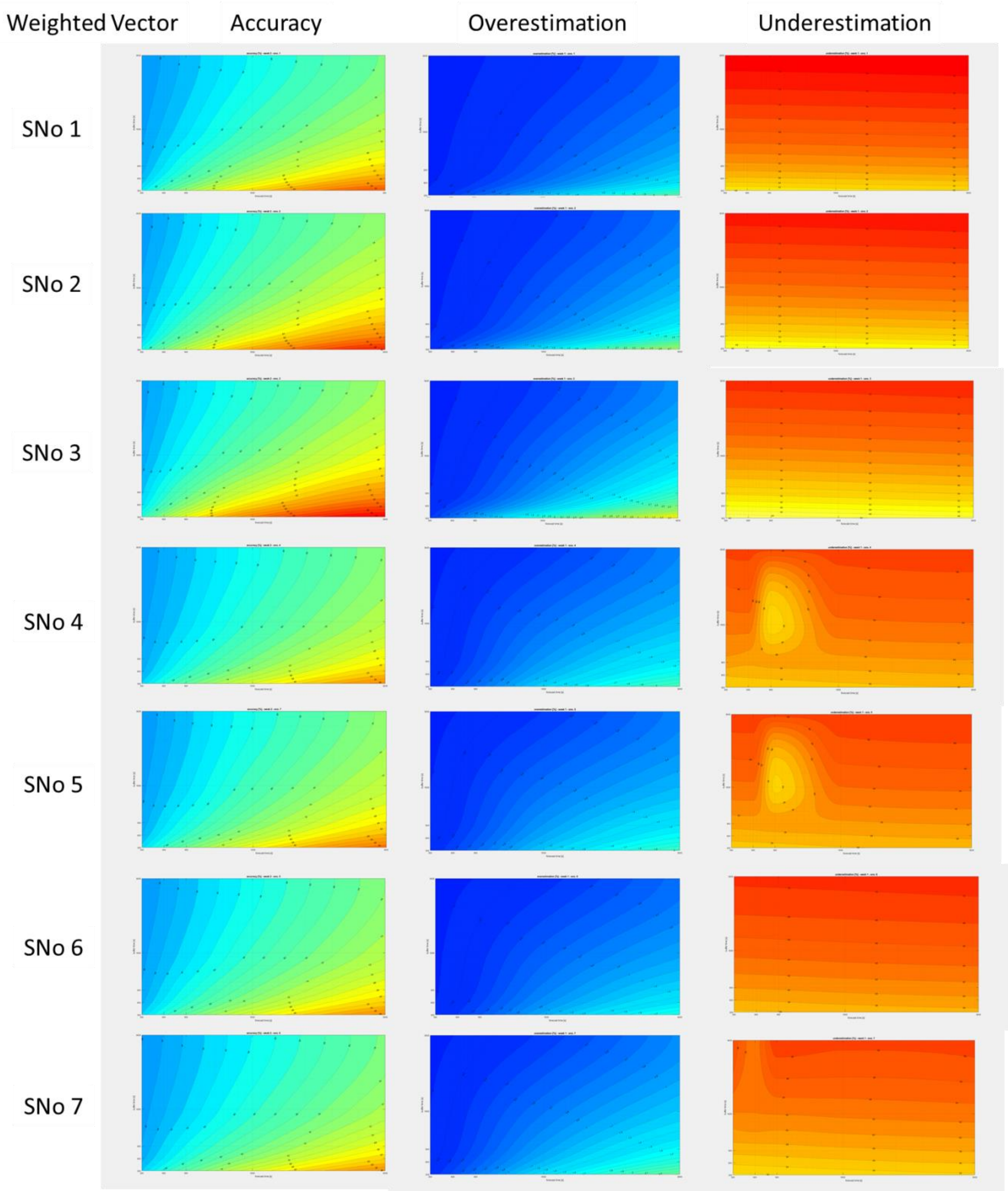


Figure 14: Accuracy, overestimation and underestimation values of the underestimating forecasting model for seven exemplary weights vectors applied to 7 days of irradiance in April 2018.

Highest average accuracies are achieved with SNo 6., smallest average underestimation with SNo 3., smallest average overestimation with SNo 6 and the in the EFCC control logic applied SNo 1. On the other hand, SNo 6 has the most unfavourable underestimation.

The final application has to be beneficial for both the power plant operator and the TSO. There is a trade-off between accuracy, duration of forecast time, and buffer time on the one hand, and maximum available power on the other hand. The PV plant owner might prefer a forecast that gives an overall larger amount of available power while the TSO prefers a longer forecast time with a high accuracy.

Depending on the focus of optimization, sets of different buffer and forecast times can be chosen.

If it is more crucial not to overestimate the forecasted power, small forecast times and large buffer times are to be preferred.

If optimization shall be focused on few energy losses through curtailment of the forecast, while the overestimation should stay as small as possible as well, both forecast and buffer times must be small.

An economical comparison should be performed, to compare financial penalties of overestimation to financial losses of underestimation if applied to an actual service especially for positive response. In case of negative response underestimation will not be so much of a problem due to absence of no-service-costs and due to the large amount of potentially available PV power plants for this service.

It is not possible to reduce the overestimation or underestimation to zero as breakdowns and ramp ups can't be predicted with the presented model.

It would be important to consider a dynamic approach to the model. If the live data is monitored, whether power ramps down or ramps up, coefficients may be changed dynamically. SNos with increasing factors with increasing differences are to be preferred for ramp up, whereas SNos with decreasing factors are to be preferred for ramp down.

Additionally, incorporating daytimes and seasons (or even the average year profile of irradiance exposures) and adjusting coefficients proportionally with the radiation trend, would be a complement approach towards a more dynamic model.

On the other hand, forecasting irradiance through clouds or weather events remains challenging. A cloud camera or meteorological real-time data should be used to detect such breakdowns if reaction and response times of these methods are fitting to the application. Currently, these approaches are to slow for very fast frequency response services. The implemented underestimating forecast model provides a fast and relatively accurate approach for the delivery of a future power set point.

4. Test Description & Objectives

4.1 Precursor Tests

The primary goal of the precursor tests is to investigate the dynamic performance of the inverter hardware. The tests involve controlling the power output of SMA inverters installed in the Rainbows solar PV power plant at Willersey, England. The tests evaluate power ramp rates, inverter response times as well as curtailment capability of the inverters. Each precursor test is described below.

A. Inverter Control Test

This is the first test on the live 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 setting between the BELECTRIC Hybrid Controller and the inverters at Rainbows PV Power Plant.

The tests include regulating the active working point of the live solar PV inverters and governing shutdown/start up for each individual inverter units. The modifications are done to the inverters by the BELECTRIC Hybrid Controller through the developed MODBUS TCP client. Additionally the web interface by manufacturer SMA for their inverters, which gives a browser access to the system, was also tested prior as a manual fall back option to bring the system up again in case of a communication breakdown during testing.

The test passes if each individual inverter acknowledges the commands – with clear and 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. Other reasons to shift the working point, as a change in irradiation, can be excluded as the main cause if the magnitude, duration and timing of the shift is in no means relatable to the control command. To verify, that a shift in the working point has happened due to a control command and not due to a change in the GHI, the inverter 2.1 was assisting as an un-commanded inverter. By comparing these two inverters, a clear variation in timing, magnitude and duration can be observed which attests the controllability of the specific inverter.

The reaction to the commands is evaluated via the PMU / Phasor point App and additionally also with the PADCON PV Web portal which is a SCADA system developed by PADCON GmbH for data monitoring on solar PV power plants.

B. Ramp Rate Test

The purpose of this test is to assess the inverter response and investigate the inverter ramp rate between different working points. During this test an inverter is forced to step up and down between different working points. The ramp up/down rates between each working step is measured and compared.

If the ramp rates at different working points are found to be similar the test will conclude there is no significant impact on the inverter ramp rates at different working points. If the ramp rates vary significantly the Hybrid Controller will be programmed to account for this variety, when it controls the inverters and communicates with the GE Local Controller. During the writing of these active power set-point changes, the response time of the inverter will also be measured from the PMU/ Phasor point App

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.

C. Curtailment Test

The objective of the curtailment test is to evaluate whether the inverters can follow the command to curtail their power output from its maximum power point and run at a lower set point thus providing both positive and negative response power. The inverter power curtailment is uneconomical as it reduces the PV Performance Ratio which directly affects the cash flow. The PV Performance Ratio is the prime focus of every investor body as it represents the actual power generation versus the expected power generation. For the EFCC control scheme this test is divided into two parts: Hard Curtailment and Soft Curtailment.

a. Hard Curtailment Test

During hard curtailment test a specific-constant working point is given to the PV inverter. The Inverter is not allowed to increase power production above a limit. When the solar irradiance is higher, the inverter output is clipped. When the inverter output power is clipped during this time the inverter has the ability to provide positive and negative power on demand. The corresponding power values are sent constantly to the GE Local Controller. Positive power availability is only given during the times the power output is clipped. The available positive power is the difference between the set working point and the MPP of either a reference inverter or the PV Model. If the power output of the inverters is below the clipping point, the positive available power is zero.

b. Soft Curtailment Test

The soft curtailment test on the other hand requires a forecasting system, a model to evaluate the power produced by an inverter during its operation at MPP. The soft curtailment is a relation to actual possible maximum output of the solar PV farm. To curtail the inverter by 50% for example, a set point ‘MPP*0.5’ is written to its power register.

The working point of the curtailed inverter is changed in references to its theoretical MPP. This can be done by a PV plant model that calculates the Maximum Power Point. The same can be achieved by taking MPP reference from another identical inverter running at its maximum power point in the same PV plant, as a reference point for the curtailment.

Soft curtailment is preferred to hard curtailment as it allows provision of positive and negative power availability throughout the day. Hard curtailment would also change the usual behaviour of a PV plant stronger. If a control scheme with hard curtailment approach is assumed to be implemented across the GB network, this would cause problems in the power forecasting models used by the system operators to estimate the power generated by the distributed PV generation units deployed across many regions. This forecasting is essential to evaluate network load.

During this soft curtailment test Inverter 1.1 is requested to operate at a reduced power set point of 50% of MPP during daylight, therefore reserving a 50% positive power buffer to participate in providing positive power frequency response all the time during daylight. The test will pass if the inverter changes its working point as instructed by the BELECTRIC Hybrid Controller and stays below or at the limit (Hard curtailment) or continues to change its working point based on irradiance level and a reference MPP (Soft curtailment).

4.2 Open Loop Test

The scope of the Open Loop test is to assess the communication setup between BELECTRIC’s Hybrid Controller and GE Local Controller during frequency events. During this test the PV power plant sends its regular availability, ramp rates and durations to the GE Local Controller but the inverters do not accept or follow the power request from GE Local Controller to provide frequency response and therefore the solar PV farm continues to run uninfluenced.

The purpose of the Open Loop Test is to see whether the BELECTRIC Hybrid Controller and GE Local Controller have successful communication and to check if during a real/simulated frequency event a power request is received by the BELECTRIC Hybrid Controller without any loss of data packages and to validate if the power availability of the PV plant is received by the GE Local Controller without unrepresentative delays. This test can be classified in the following categories.

A. Simulated Frequency Event

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. Through the GE PMU simulator, different under- and over-frequency events which are listed in chapter 2, table 3 are simulated. This test is further categorised in two cases:

a. Simulated positive and negative power availability

During this test BELECTRIC Hybrid Controller sends simulated positive and negative resource availability to the GE Local Controller. Over and under frequency events are simulated by the GE PMU simulator. During this time, the PV resource sends simulated/synthetic power availability to the Local Controller and behaves as if the resource has frequency response capability. As the event is detected, the Local Controller should send a power request signal to the Hybrid Controller in accordance with the sent simulated power availability.

The test passes if GE Local Controller receives the BELECTRIC's simulated positive and negative resource availability and if the BELECTRIC Hybrid Controller receives power requests from the GE Local Controller after simulated frequency events.

b. Real positive and negative power availability

During this test one inverter is soft-curtailed to a percentage of MPP and BELECTRIC Hybrid Controller sends inverters real positive and negative resource availability to the GE Local Controller. Over and under frequency events are simulated through the GE PMU simulator.

The test will pass 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 actual positive and negative power availability.

B. Real Frequency Event

During a real frequency event open loop test is the GE PMU Simulator disabled and the GE Local Controller communicates with the Phasor Measurement Unit (PMU). Real positive and negative power availability of the PV plant is sent by the BELECTRIC Hybrid Controller to the GE Local Controller. When an actual frequency event occurs in the grid, the Local Controller sends a power request to the BELECTRIC Hybrid Controller as per the system's capability at that instant. The test will pass if the GE Local Controller receives the real resource availability and the BELECTRIC Hybrid Controller receives power requests from the GE Local Controller according to the sent 'real resource availability' during a frequency event.

4.3 Hardware in the Loop Test (HiL)

The scope of the hardware in the loop test is to assess the inverter performance and test the inverter response to an actual power request from the GE Local Controller during a frequency event. This test is categorized in two cases:

A. Simulated Frequency Event

During this test, real positive and negative power availability of the inverter is sent to the GE Local Controller. Through the GE PMU simulator, different magnitudes of under and over frequency events are simulated. The PV Power Plant will respond to the power request by the GE Local Controller during a simulated 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 the inverter power register.
3. The inverter set point values change based on the power request.
4. The inverter power output changes.

B. Real Frequency Event

During the hardware in the loop test real positive and negative power availability will be sent to the GE Local Controller. The PV Power Plant will respond to the power request received by the GE Local Controller when a real event is detected by the Phasor Measurement Unit. This test is important to evaluate the detection of real frequency event by a Local Controller and examine whether the BELECTRIC Hybrid Controller – GE Local Controller exchanges real time data while the system is connected to the PMU and the actual control command is received and processed by the inverters. 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 inverter power register.
3. The inverter set point values change based on the power request.
4. The inverter power output changes.

5 Test Procedure

5.1 Precursor Test

All precursor tests are executed only on inverter 1.1 and inverter 1.2 through the BELECTRIC Hybrid Controller program which communicates with the 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

During the test, only inverter 1.1 participates. 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 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 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 the working point stay 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.

Inverter control in general is also tested with the help of Simply Modbus - 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.

B. Ramp Rate Test

For the Ramp Test 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. Inverter 1.1 is ramped down with 100 kW steps from 600 kW down to 8 kW and then ramped back up to MPP with the same 100 kW steps. The inverter is forced at these working set points via the BELECTRIC Hybrid Controller.

The inverter is not ramped down to 0 kW as this causes the inverter to shut down and the resource becomes unavailable for at least a minute. The inverter in the plant requires a minute to come back up due to PV plants 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 the PMU which is connected at the grid connecting point and doesn’t measure the power from each inverter but instead measures the overall power.

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

C. Curtailment Test

During this test inverter 1.1 is controlled and curtailed while the other three inverters are allowed to run at MPP. The test is categorized in two cases.

a. Hard Curtailment

This test is executed during high irradiance when the inverter is producing more than 80% of its nominal AC power output. Inverter 1.1 output power is curtailed, and the inverter is forced to run at 75% of nominal AC power output. After running Inverter 1.1 in hard curtailment mode through a period of varying irradiances the inverter is ramped back up to MPP.

b. Soft Curtailment

In this test inverter 1.1 is de-loaded and forced to run at given percentage of Maximum Power Point. The MPP changes continuously with the change in irradiance. Therefore the power set point percentage, with respect to the nominal power of an inverter running at MPP, also changes.

To curtail an inverter to 50% with respect to its MPP for example, the same in-house MATLAB PV Model is used to know the reference MPP power and the de-loaded set point is evaluated from the reference MPP power which is written to the inverter. The set point is written continuously which results in the inverter running at 50% of its MPP in this test scenario.

Different curtailment values are possible for the given PV plant, from 1% of nominal power up to 99%.

After running Inverter 1.1 soft curtailed through a period of varying irradiances with a difference of at least 100 W/m^2 the inverter is ramped back up to MPP. The behaviour of the inverter is observed via PADCON PV Web Portal. If the test is successful inverter 1.1 will follow inverter 2.1's working point but with a 50% curtailment.

5.2 Open Loop Test

During a frequency event the GE Local Controller sends a continuous power request to 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 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

In the Open Loop test with simulated frequency event the GE PMU Simulator is used to inject the frequency signals. 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 event should be detected by the Local Controller as the RoCoF crosses the above-mentioned threshold, the Local Controller assesses the power availability of the PV plant and sends a power request to the BELECTRIC Hybrid Controller accordingly.

a. Simulated positive and negative power availability

The Hybrid Controller sends a simulated power availability of ±2000 kW to the GE Local Controller. The GE PMU Simulator is used to inject the frequency signal to simulate over/under frequency events.

b. Real positive and negative power availability

The Hybrid Controller sends PV Plants real power availability in kW to the GE Local Controller. The GE PMU Simulator is used to inject the frequency signal to simulate over and under frequency events of different magnitude. This test checks the functionality of the established GOOSE connection between the GE Local Controller and BELECTRIC Hybrid Controller. 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. Real Frequency Event

In the Open Loop test with real frequency event the PMU is connected to the GE Local Controller and examines the grid. This test is executed to examine if the GE Local Controller sends the correct power request to the BELECTRIC Hybrid Controller, in accordance with the real PV availability, changing positive and negative power. This test is allowed to run until an actual frequency event occurs during the sunshine hours. GE Local Controller event detection threshold settings for the test were set as ±0.04 Hz/s as the RoCoF threshold and 50.2 Hz / 49.7 Hz as the frequency thresholds.

During the entire test simulated power availability, which behaved like real power availability, was send to the GE Local Controller. This was achieved by allowing the inverter 1.1 to operate at MPP, the inverter output power was shred to half and the positive power availability from the inverter is calculated by evaluating the difference between $Inv\ 1.1\ Power_{MPP} - 0.5*Inv\ 1.1\ Power_{MPP}$ while the inverter's negative power availability is calculated by evaluating $Inv\ 1.1\ Power_{MPP} + Inv\ 1.2\ Power_{MPP}$. Due to the changing and unsteady MPP power of the inverters, this approach allowed to generate varying positive and negative power availability without losing energy by curtailing the inverter hardware.

To evaluate whether the GOOSE connection between the GE Local Controller and BELECTRIC Hybrid Controller is working, data sent and received from both controllers in real time is compared.

5.3 Hardware in the Loop Test

During the Hardware in the Loop Test the inverter response capabilities are tested. For this test only inverter 1.1 and inverter 1.2 are set to respond to the GE Local Controller's power request. The other two inverters operate at MPP during the entire test where inverter 2.1 is used to access the reference MPP.

To expedite the tests the Local Controller is made sensitive to smaller events and the event detection threshold is changed from ±0.1 Hz/s to ±0.04 Hz/s. As the event is detected and frequency thresholds are reached a power requests [in kW] is sent by GE Local Controller to the BELECTRIC system. This power request is proportionally distributed amongst the available inverters. The test is subcategorized in two parts.

A. Simulated Frequency Event

Inverter 1.1 takes part in this test and is allowed to run at MPP. An over frequency event of 50.35 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 Inverter power availability. The

Hybrid Controller receives a signal to curtail power accordingly. The results of this active power curtailment can be observed through the PMU app or PADCON PV Web Portal. If this test is not successful, the real frequency event hardware in the loop test may not take place.

B. Real Frequency Event

Inverter 1.1 and inverter 1.2 participate in this test. Inverter 1.1, which is curtailed by 20% of the reference MPP made available by inverter 2.1, provides positive power response while inverter 1.1 and inverter 1.2 both together provide negative power response. During this test the Local Controller will be connected to the PMU which is measuring real frequency events in the grid. When a real frequency event occurs in the grid the Local Controller will send power requests to the Hybrid Controller based on the total power availability at that time. If the Hybrid Controller receives a signal to curtail power it will do so, following the Local Controller's commands. The results of this active power curtailment will then be observed through the PMU.

6 Results & Testing Outcomes

6.1 Precursor Test

A. Inverter Control Test

Inverter 1.1's AC power output was controlled through the BELECTRIC Hybrid Controller. The inverter test outcome was observed by the PADCON PV Web Portal and through the PMU at the Willersey grid connection point. Figure 15(a) shows the inverter settings in the Hybrid Controller. Figure 15(b) shows the inverter status in PADCON PV Web Portal. During the test inverter 1.1 was forced to run at a reduced power and then again was brought back up to its normal operation.

Pre-Inverter Control Test **Inverter Control Test** **Post-Inverter Control Test**

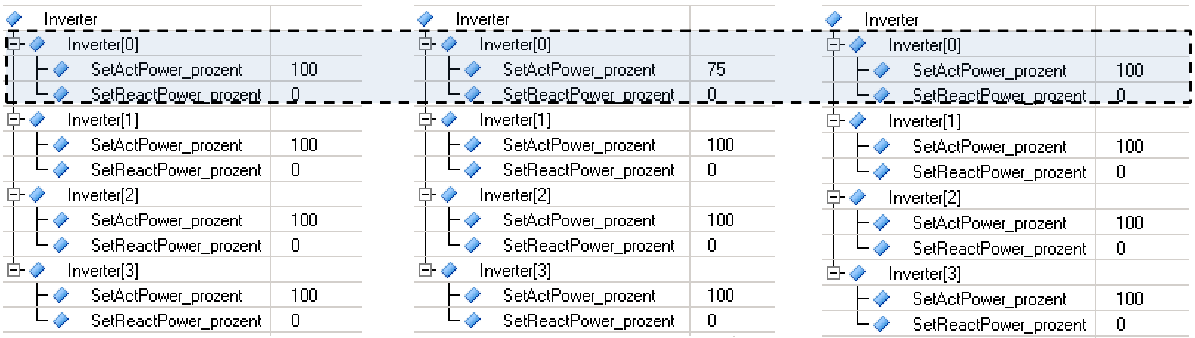


Figure 15(a) BELECTRIC Hybrid Controller Inverter settings.

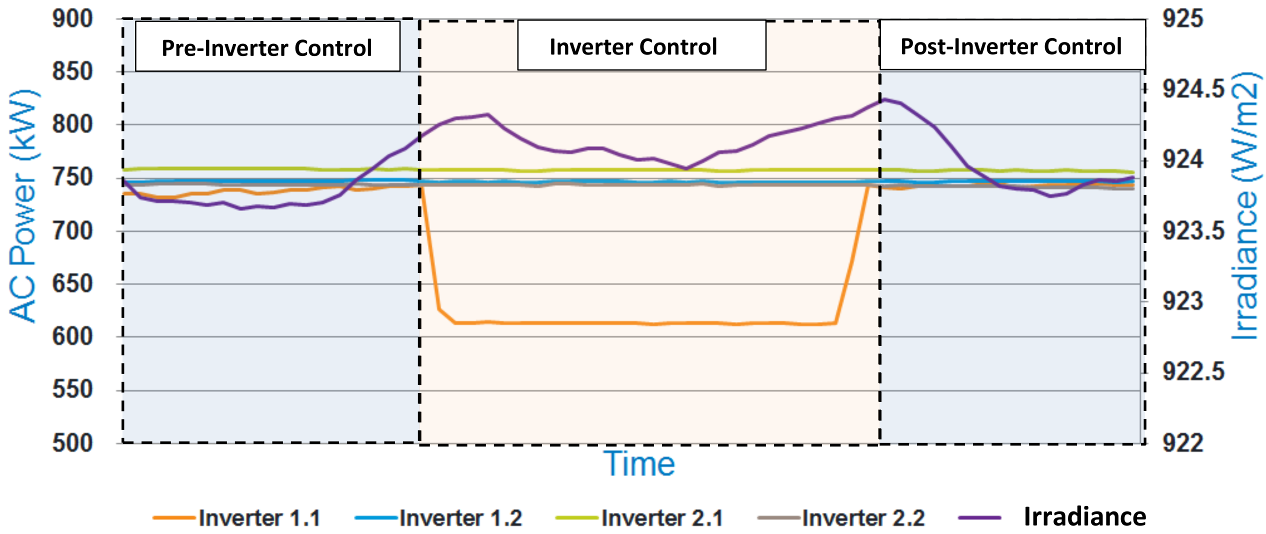
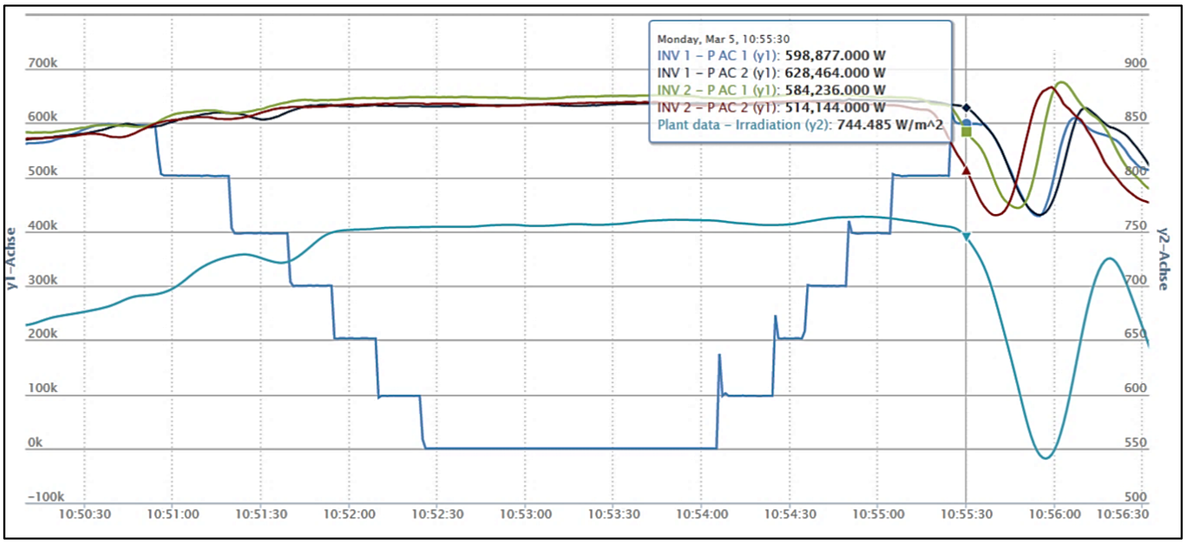


Figure 15(b): PADCON PV Web Portal Inverter status.

The results from the inverter control test were found to be positive. The BELECTRIC Hybrid Controller communicated with the inverter 1.1 and in response inverter 1.1 reduced the power output thus following the working point sent to it. Figure 15(b) was obtained by the data from the PADCON PV Web Portal. The inverter ramp rate evaluation is included in the section Ramp Rate Test.

B. Ramp Rate Test

Figure 16(a) 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 inverter 1.1 was forcefully ramped down from 600 kW to 0 kW in steps of 100 kW. After successful ramp down the inverter 1.1 was brought back to its initial state by ramping up in six 100 kW steps. The complete test was conducted numerous times and the ramp rates were evaluated.



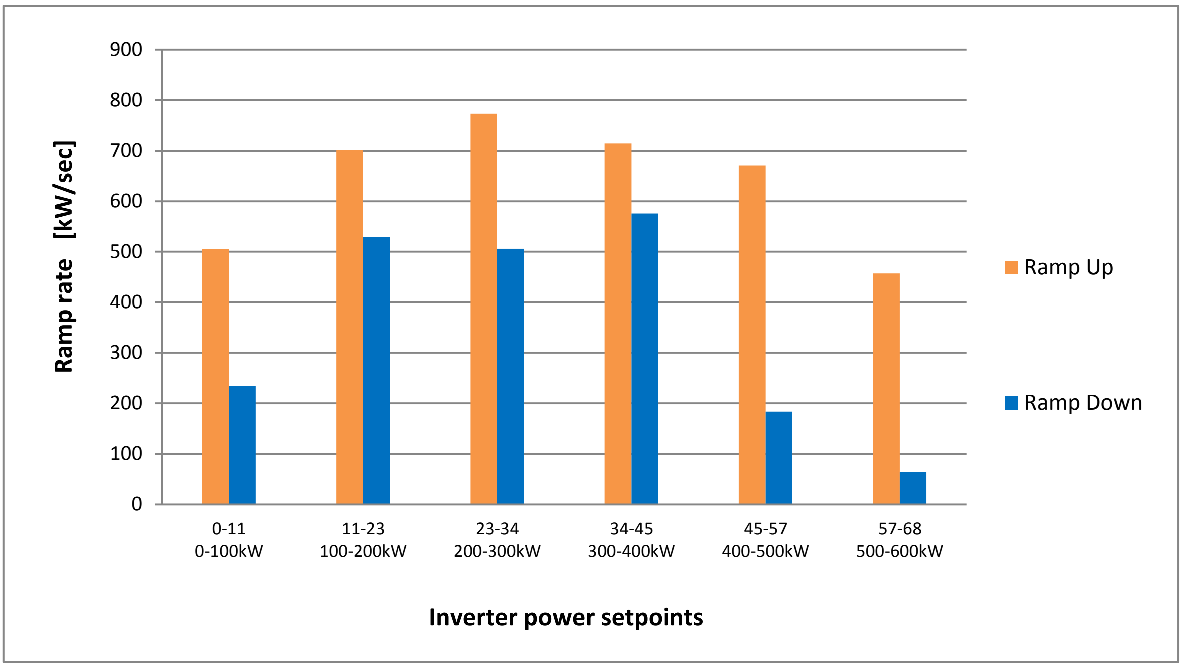


Figure 16(a): Inverter ramp test 100 kW Steps (b): Inverter Ramp Rates at different working points.

For ramp rate evaluation the PADCON Web Portal was not used due to limited data resolution of one second. As a result, data from the PMU, which has a resolution of measuring 60 samples in a second, was used for this purpose. The PMU is connected at the grid connecting point therefore it doesn't measure the power from each inverter individually but 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 was executed during constant and high irradiance.

In a utility scale PV plant is a SCADA system with a data resolution of 1 second 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 PMU usage for ramp rate measurement is reliable. This statement holds true only when the PMU is positioned at GCP of each resource running under EFCC control scheme and when the size of the resource is comparatively small. The PV plant currently running under EFCC scheme at Willersey has only 4 inverters. A comparatively bigger PV system with 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 16(b). However, the ramp up rates measured were always faster than ramp down. After some further investigation it was found that the results in Figure 16 don’t show the actual behaviour of the system and the inverter ramp is a combination of two individual ramps which were given the name as the *fast ramp* and the *correction ramp.*

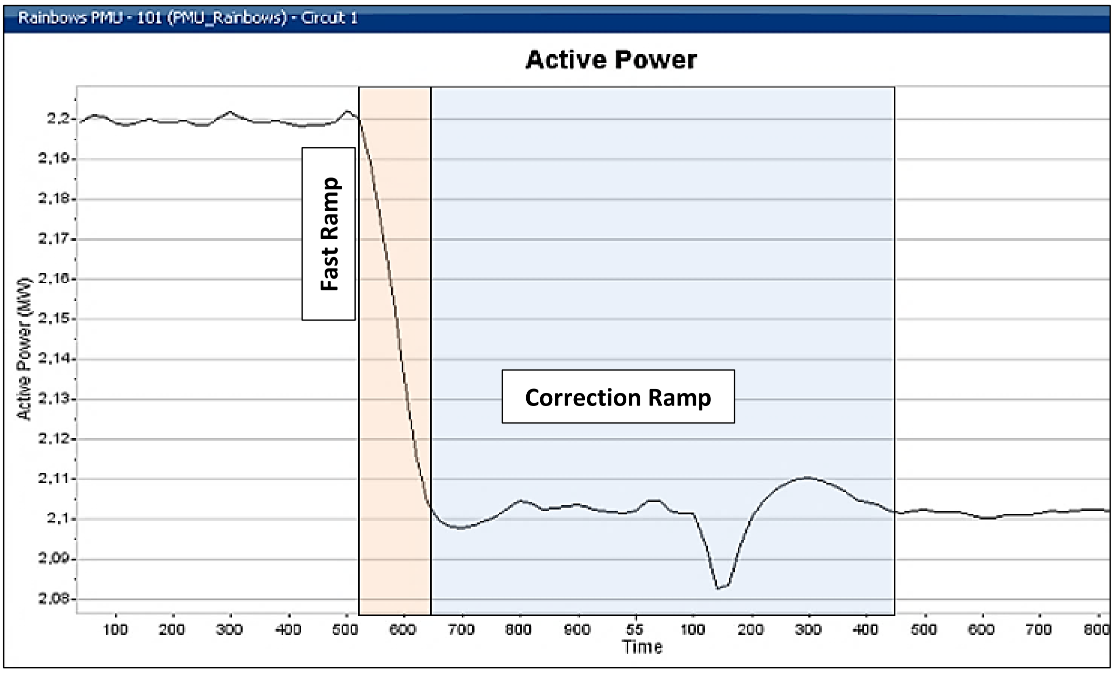


Figure 17(a): Inverter 1.1 Ramp Test, 100 kW sample step down ramp measured by the PMU.

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 17(a), 17(b) and 17(c). 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(d) 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 inverters operating as a current source and with an unknown MPPT curve in the PV-solar-panels were neither designed nor intended to be used in fast frequency applications in previous years.

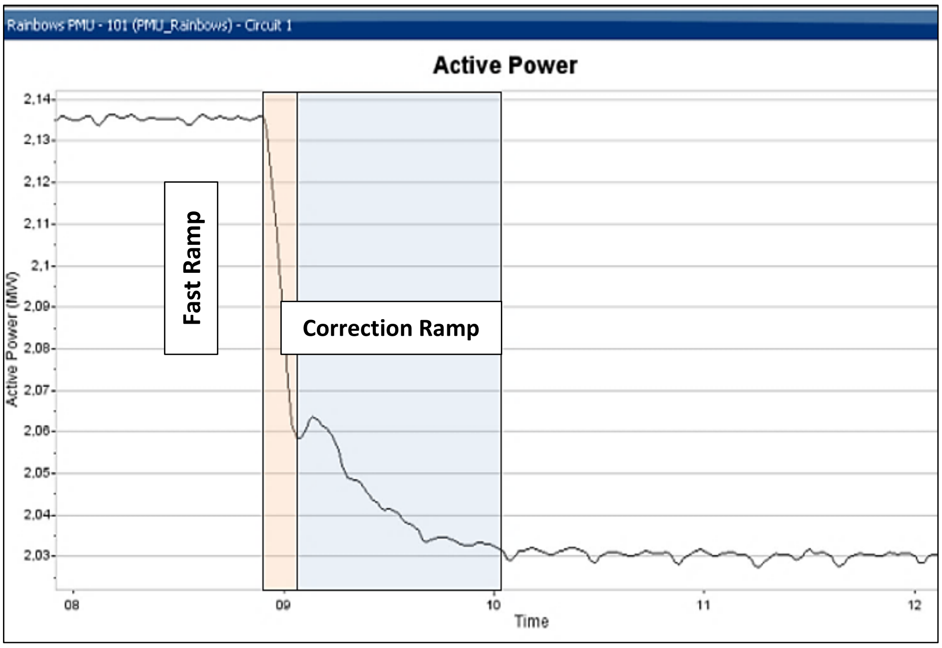


Figure 17(b): Inverter 1.1 Ramp Test, 100 kW sample step down ramp measured by the PMU

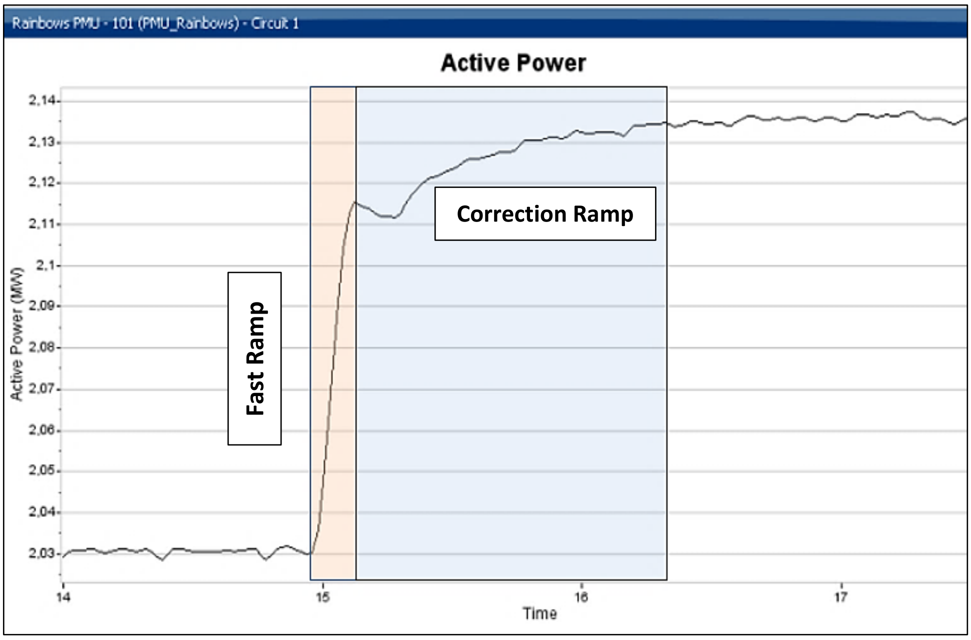


Figure 17(c): Inverter 1.1 Ramp Test, 100 kW sample step up ramp measured by the PMU.

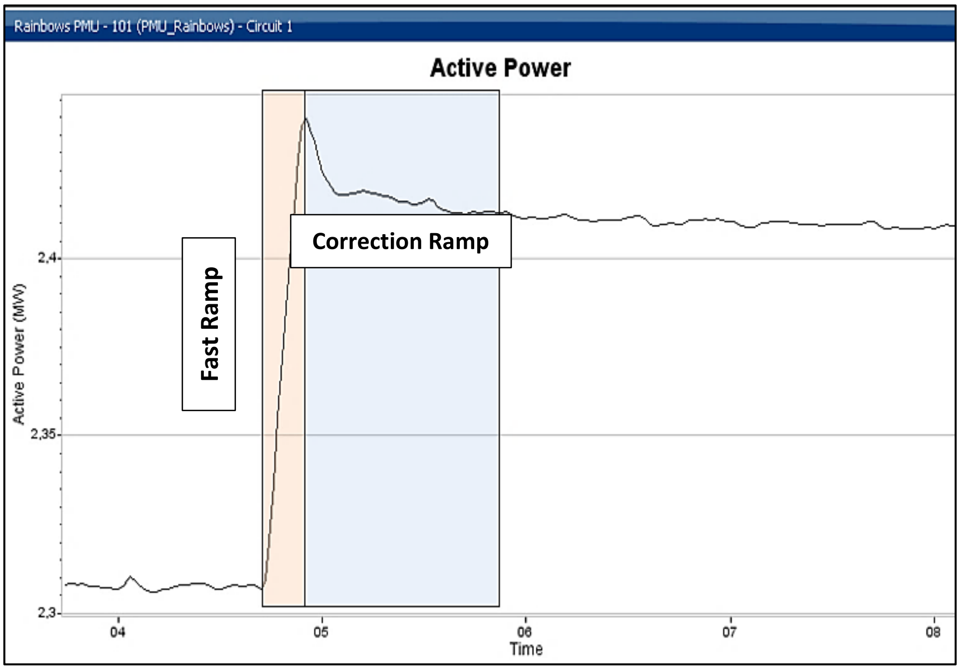


Figure 17(d): Inverter 1.1 Ramp Test, 100 kW sample step up ramp measured by the PMU.

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 4 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/sec	108%[5]	772 kW/sec	87%
2	500-1	730 kW/sec	100%	722 kW/sec	78%
3	400-1	1000 kW/sec	93%	835 kW/sec	78%
4	500-400	556 kW/sec	80%	497 kW/sec	77%
5	500-300	663 kW/sec	86%	648 kW/sec	80%
6	500-200	695 kW/sec	88%	717 kW/sec	87%
7	500-100	788 kW/sec	80%	779 kW/sec	81%

Table 4: 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 power ramp up missed the target working point as a result the correction ramp was 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.

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

[5] 108% as the Fast Ramp overshoots target set point

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 has to make 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 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.

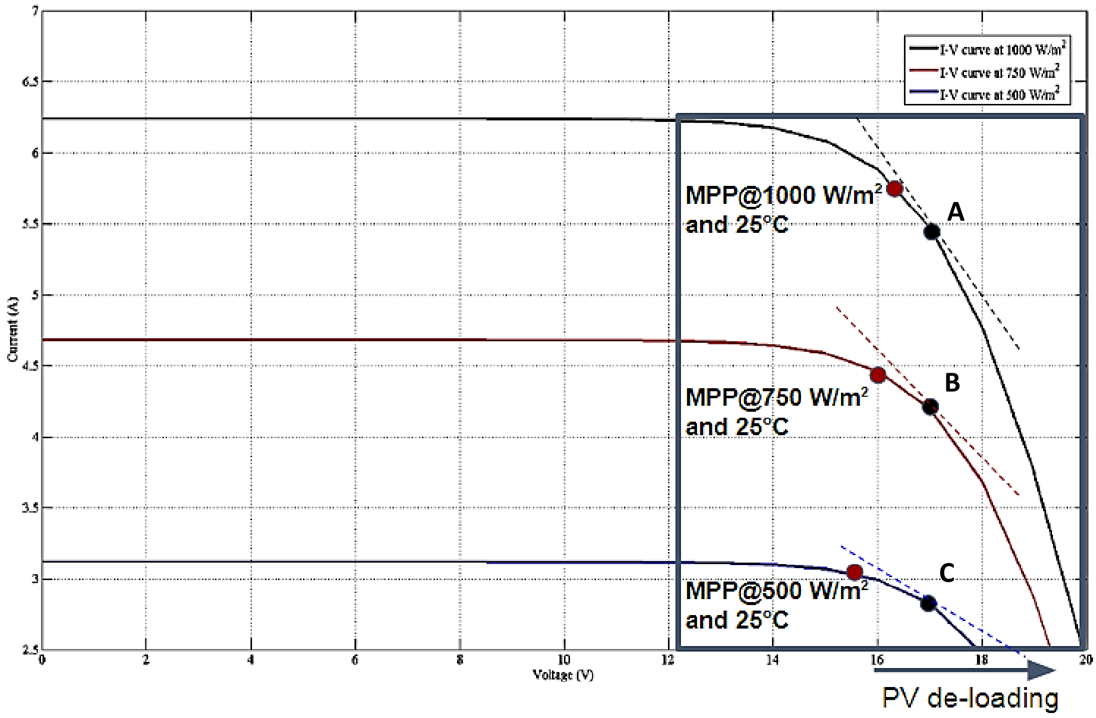


Figure 18: PV-I-V Curve Characteristic.

C. Curtailment Test

The curtailment test is necessary to de-load the PV plant so as to examine the capability of a solar PV farm to provide positive power response. The following section shows the curtailment test result.

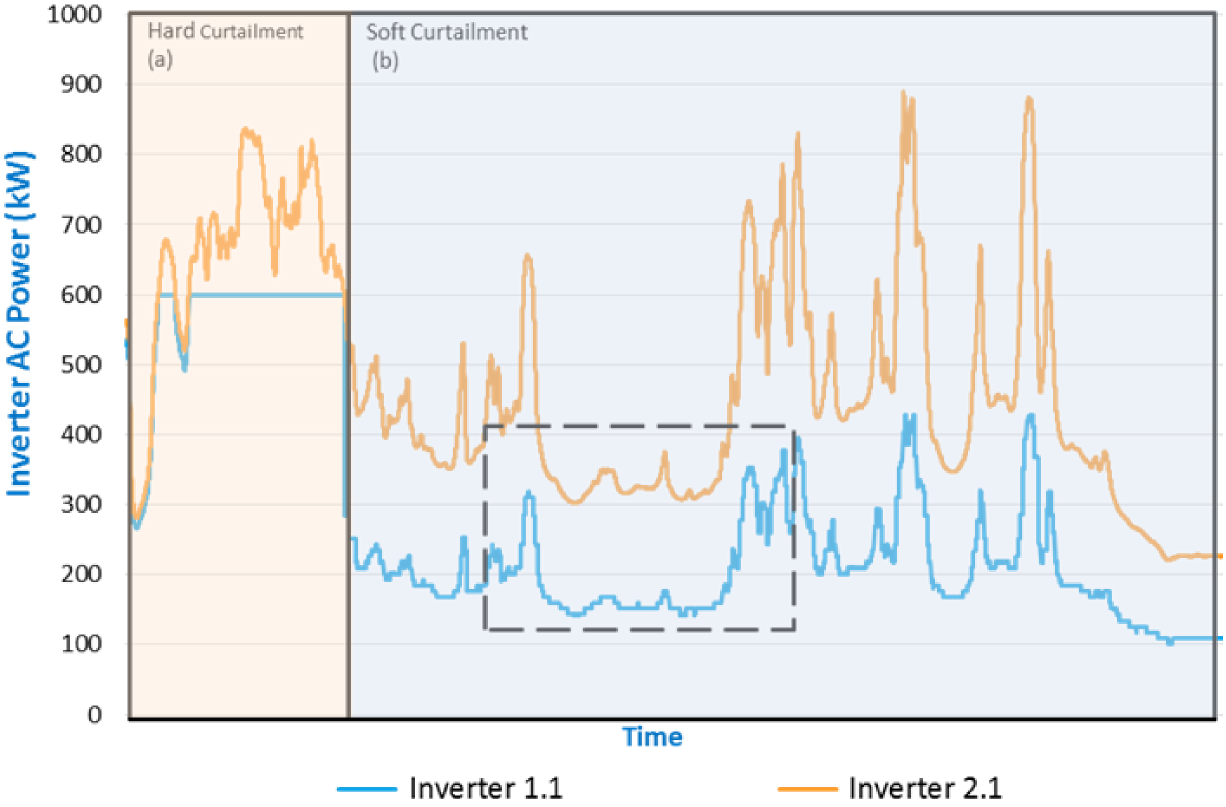


Figure 19(a): Curtailment Test Results for Inverter 1.1.

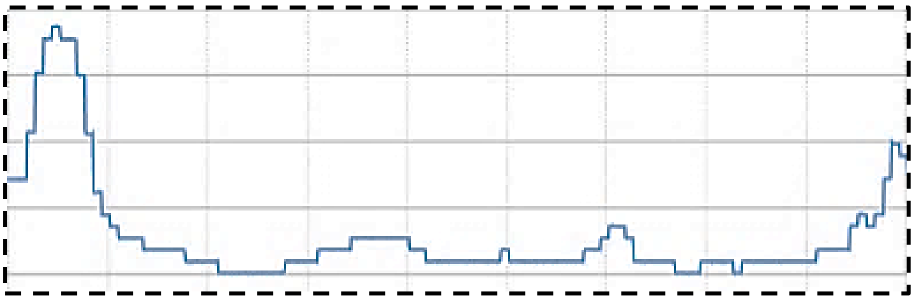


Figure 19(b): Curtailment Test Results for Inverter 1.1 from PADCON PV Web Portal (Zoomed).

a. Hard Curtailment Test

During the Hard curtailment test the Inverter 1.1 was given a constant working point value of 68%, forcing the inverter not to produce more than 68% of the nominal power which results in a hard curtailment at 598 kW. This is visible in Figure 19 - Hard curtailment section (a) where the Inverter 1.1 power is clipped at 598 kW. During hard curtailment the inverter could provide positive power response only when the irradiance is high enough to produce more power than 598 kW.

b. Soft Curtailment Test

During the latter half the Hybrid Controller settings were changed to soft curtailment. Figure 19, Soft Curtailment Section (b), shows the results for the soft curtailment of Inverter 1.1. The inverter power was continuously curtailed to a power limit of 50% of MPP. During this time, the Inverter 1.1 was always readily available to provide both positive and negative power response where the magnitude of power availability was dependent on the solar irradiance. The MPP was tracked either by the BELECTRIC in-house PV Model or a reference MPP provided by an un-curtailed inverter.

For the EFCC Scheme, the hard curtailment approach has some flaws as the EFCC control scheme system must be communicated the hard-curtailed point, secondly the inverters would not always be available for positive power response and thirdly this curtailment approach changed the system behaviour. The system performance was not like a regular PV resource anymore. This could introduce problems in power forecasting models used by TNOs and DNOs. It was therefore concluded to not further pursue the hard curtailment as a tool to provide positive response power.

During the initial trials of the soft curtailment procedure a rather long time during curtailment steps was observed. The curtailment set point was following the reference MPP in large and long steps. A substantial delay in the reaction time to changes in the irradiance was also observed – see Figure

20. This influences the validity of the availability data send from the Hybrid Controller to the Local Controller significantly as the provision of positive response can’t be assured at each given time. We’ve found the reason for this to be the large processing and response latency of the in-house PV Model running in the background for tracking and providing the reference MPP.

As a result of the aforementioned latency issue it was decided to deactivate the PV model. The reference MPP is now provided by a reference inverter, Inverter 2.1. The reason behind specifically choosing Inverter 2.1 that it has an equal number of solar panel connected to it as Inverter 1.1.

Figure 20(a) and (b) shows the behaviour of Inverter 1.1 before and after the deactivation of the PV model. It can be observed that the reactions to changes in the irradiance are quicker and the system is also more responsive to changes of the MPP. It can also be observed that the solar PV farm is now consistently available to provide a positive response even if a sudden reduction in the irradiance occurs. The disadvantage of this method is that one inverter of the solar PV farm cannot take part in the curtailment as it provides the reference MPP value. This method reduces the maximum possible positive response of a solar PV farm as not all inverters can be curtailed.

As the power registers accepts a percentage value of its nominal power as a set point, the minimum resolution of power change during soft curtailment test was found to be 8 kW. This behaviour can be observed in Figure 20(b).

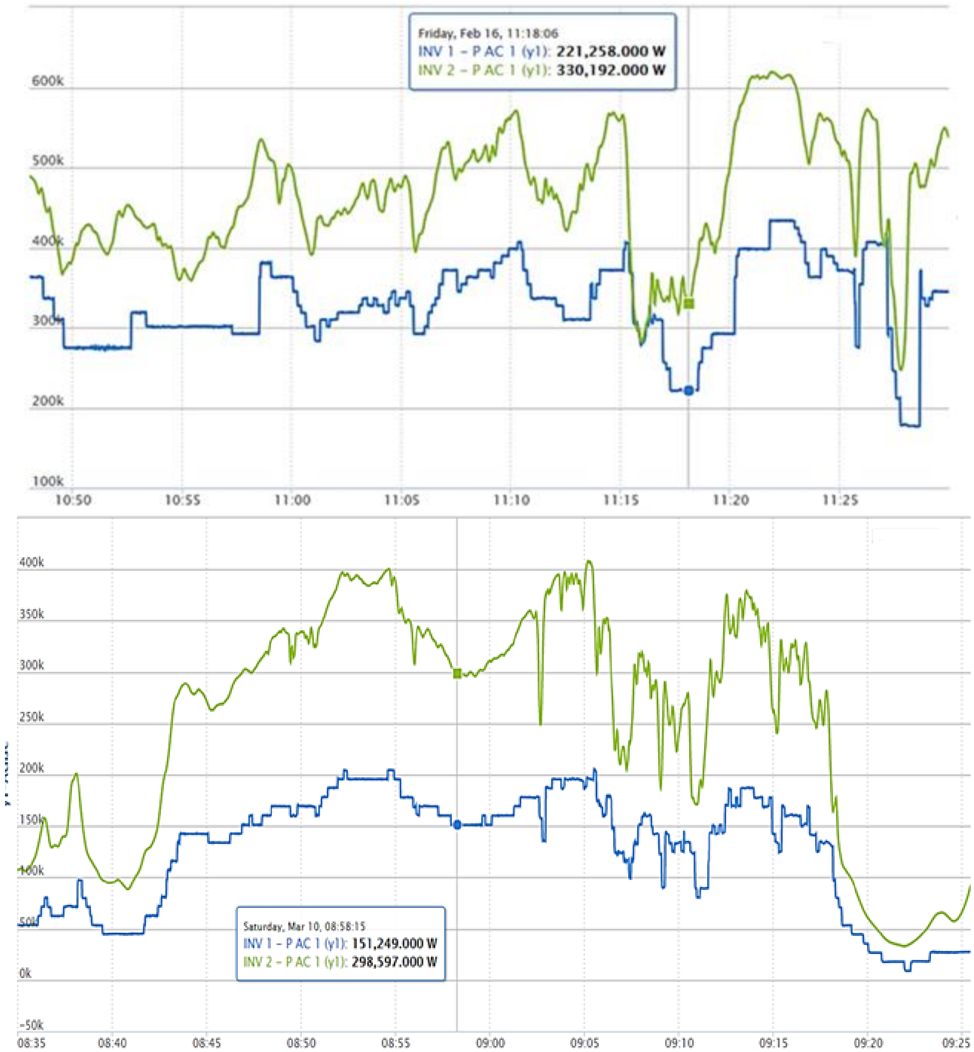


Figure 20: Inverter response during soft curtailment when (a) PV Model in the background or (b) PV model deactivated.

6.2 Open Loop Test

A. Simulated Frequency Event

a. Simulated positive and negative power availability

During this test a non-fluctuating simulated power availability is sent by the BELECTRIC Hybrid Controller to the GE Local Controller while various over and under frequency events were simulated by injecting signals through the GE PMU Simulator. Power requested by the GE Local Controller is recorded and observed. During the test all simulated frequency cases were executed, table 5 and 6 show the results obtained during the test. The observed PMU results snapshot table are attached in the appendix.

SNO.	SIMULATED FREQUENCY EVENT – PMU SIMULATOR	SENT POS/NEG POWER AVAILABLE	RECEIVED POWER REQUEST	POWER REQUEST % AVAILABLE
1	0.15Hz/s ramp down to 48.85 Hz	+3500/-3500 kW	+3200 kW	91.4%
2	0.15Hz/s ramp down to 49.05 Hz	+3500/-3500 kW	+2700 kW	77.1%
3	0.15Hz/s ramp down to 49.25 Hz	+3500/-3500 kW	+1900 kW	54.2%
4	0.15Hz/s ramp down to 49.45 Hz	+3500/-3500 kW	+1280 kW	36.5%
5	0.15Hz/s ramp down to 49.65 Hz	+3500/-3500 kW	+630 kW	18%

Table 5: Open Loop Test results for simulated under frequency events and simulated power availability.

SNO.	SIMULATED FREQUENCY EVENT – PMU SIMULATOR	SENT POS/NEG POWER AVAILABLE	RECEIVED POWER REQUEST	POWER REQUEST % AVAILABLE
1	0.15Hz/s ramp up to 50.65 Hz	+3500/-3500 kW	-3200 kW	91.4%
2	0.15Hz/s ramp up to 50.55 Hz	+3500/-3500 kW	-2700 kW	77.1%
3	0.15Hz/s ramp up to 50.45 Hz	+3500/-3500 kW	-1900 kW	54.2%
4	0.15Hz/s ramp up to 50.35 Hz	+3500/-3500 kW	-1280 kW	36.5%
5	0.15Hz/s ramp up to 50.25 Hz	+3500/-3500 kW	-630 kW	18%

Table 6: Open Loop Test results for simulated over frequency events and simulated power availability.

b. Real positive and negative power availability

During this test the established communication was tested. Table 7 and 8 show the simulated event signals which were injected into the GE Local Controller through the GE PMU Simulator. The BELECTRIC Hybrid Controller continuously sent the inverter's real power availability to the GE Local Controller. In response, the peak power request received was found to be in accordance with the nature and magnitude of the frequency event and with the power availability sent to the GE Local Controller. An exemplary screenshot from the PMU data is shown in Figure 21. The observed PMU results from this table are attached in the appendix.

SNO.	SIMULATED FREQUENCY EVENT – PMU SIMULATOR	SENT POS/NEG POWER AVAILABLE	RECEIVED POWER REQUEST	POWER REQUEST % AVAILABLE
1	0.15Hz/s ramp down to 48.85 Hz	+300 / -195 kW	+ 293 kW	97.6%
2	0.15Hz/s ramp down to 49.05 Hz	+300 / -195 kW	+ 234 kW	78%
3	0.15Hz/s ramp down to 49.25 Hz	+300 / -195 kW	+ 175 kW	58.3%
4	0.15Hz/s ramp down to 49.45 Hz	+300 / -195 kW	+ 117 kW	39%
5	0.15Hz/s ramp down to 49.65 Hz	+300 / -195 kW	+ 58.6 kW	19.5%

Table 7: Open Loop Test results for simulated under frequency events and real power availability.

SNO.	SIMULATED FREQUENCY EVENT – PMU SIMULATOR	SENT POS/NEG POWER AVAILABLE	RECEIVED POWER REQUEST	POWER REQUEST % AVAILABLE
1	0.15Hz/s ramp up to 50.65 Hz	+110 / -492 kW	- 489 kW	99.5%
2	0.15Hz/s ramp up to 50.55 Hz	+111 / -491 kW	- 391 kW	79.6%
3	0.15Hz/s ramp up to 50.45 Hz	+110 / -489 kW	- 293 kW	59.9%
4	0.15Hz/s ramp up to 50.35 Hz	+109 / -489 kW	- 195 kW	39.8%
5	0.15Hz/s ramp up to 50.25 Hz	+110 / -488 kW	- 97 kW	19.8%

Table 8: Open Loop Test results for simulated over frequency events and real power availability.

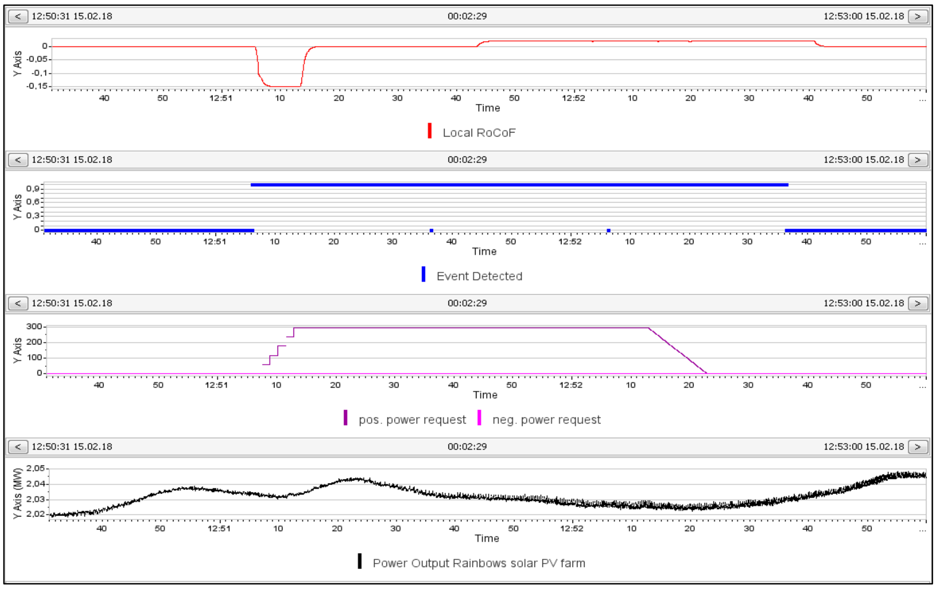


Figure 21: Open Loop - Under Frequency Event (48.85 Hz) Power Availability ±300 kW| Requested -293 kW.

B. Real Frequency Event

The system in Britain experienced a frequency event on 12.07.2018 at 14:26 (CET) – see Figure 22. The PMU installed the GCP of the solar PV resource measured a RoCoF of -0.07 Hz/s with the frequency nadir at 49.69 Hz. As the system was configured to send positive/negative power availability to the GE Local Controller (as described in the section 5.2 B) a power request of 60 kW was send by the Local Controller to the BELECTRIC Hybrid Controller once the frequency reached 49.7 Hz. To assess the power request behaviour, PADCON PV Web portal which has a 1 second time resolution was used to get an estimate of power production by each inverter at that moment. The four inverters in the PV Plant produced 612 kW, 608 kW, 653 kW and 741 kW while the POA irradiance was measured to be 736 W/m^2. As only Inverter 1.1 was simulated to provide a positive power availability of 0.5*MPP, i.e. 306 kW, the power request behaviour of 60 kW can be quantified as 19.60% of positive power availability. That was found to be correct as of the steps detailed in table 2. Figure 22 shows the corresponding PMU display.

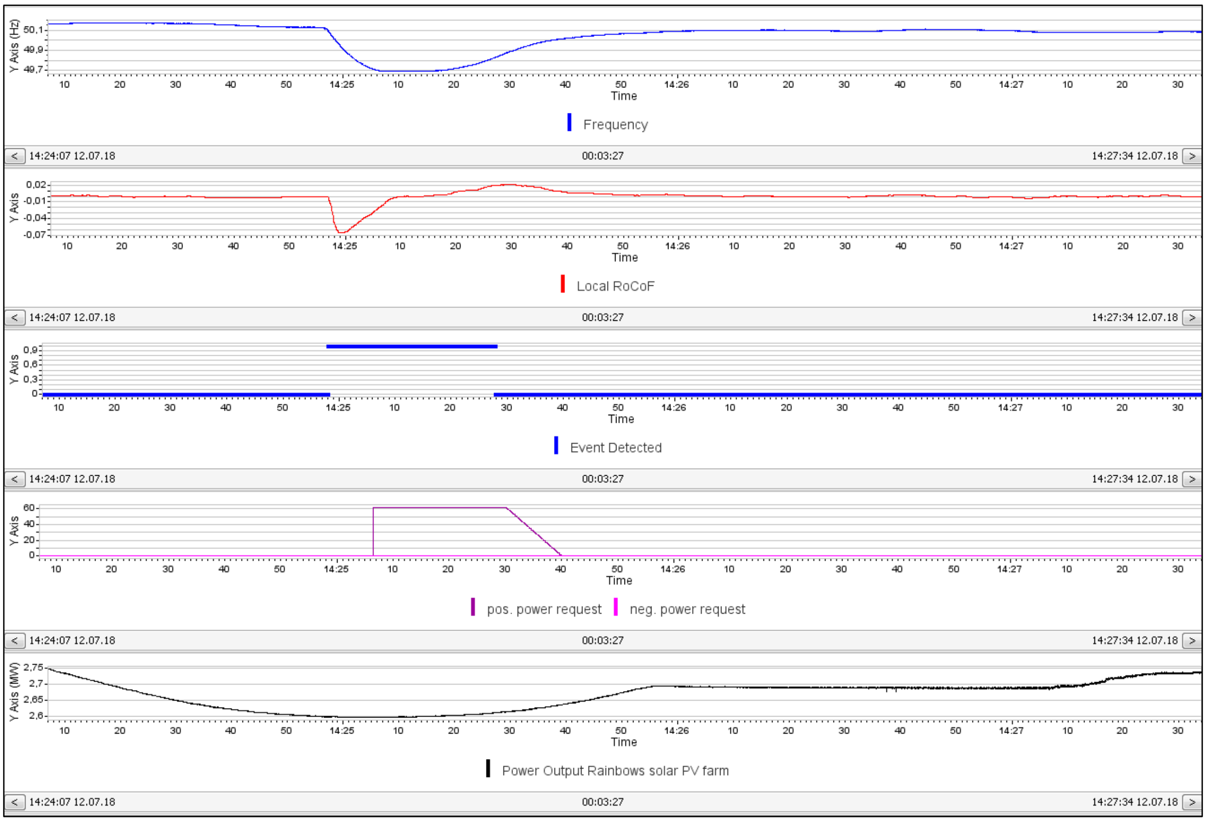


Figure 22: Under frequency event and positive power request on the 12th of July 2018.

6.3 Hardware in the Loop Test (HiL)

A. Simulated Frequency Event

During the course of the project time several simulated events have been conducted due to the rare appearance of real events. These simulated events where done to measure the inverter reaction and response times and to test the overall system behaviour in general and specifically after changes to the control logic have been introduced.

In the following chapter two examples of the results will be presented. One is an over-frequency event of 50.35 Hz with un-curtailed inverters and one is an under-frequency event of 49 Hz with curtailed inverters.

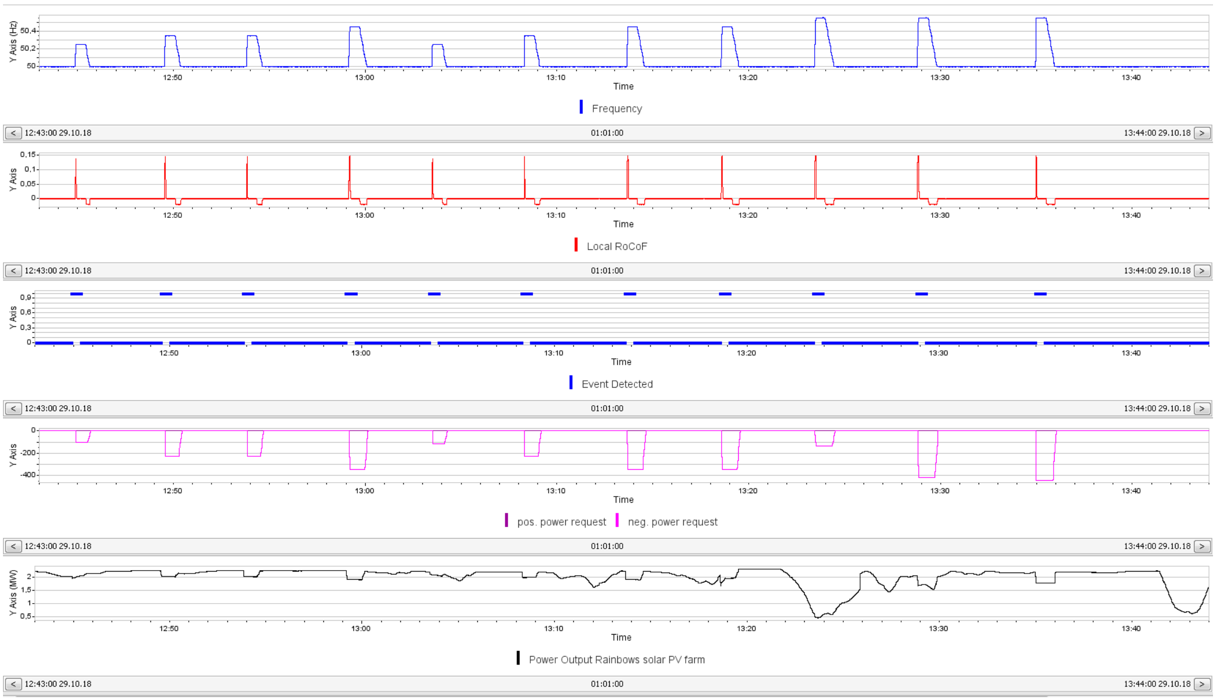


Figure 23: Exemplary series of tests with several simulated under-frequency events.

An exemplary series of tests with simulated frequency events can be seen in Figure 23. For each simulated event, the reaction and response times of the solar PV plant have been sampled and analysed. As mentioned earlier, in case of changes in the irradiances the test does not provide meaningful data. Such cases can be seen for the first, fifth and ninth hump, where sudden changes in the irradiance didn't allow for a correct determination of the reaction time.

Un-curtailed PV power plant, simulated over-frequency event, 50.35 Hz, reaction time 750 ms

Inverter 1.1 running at MPP participated in this simulated HiL test shown in Figure 24. For this test, real power availability is sent to the GE Local Controller by the BELECTRIC Hybrid Controller. On the other side was the GE PMU Simulator configured to inject a simulated event with a +0.15 Hz/s ramp up to 50.35 Hz.

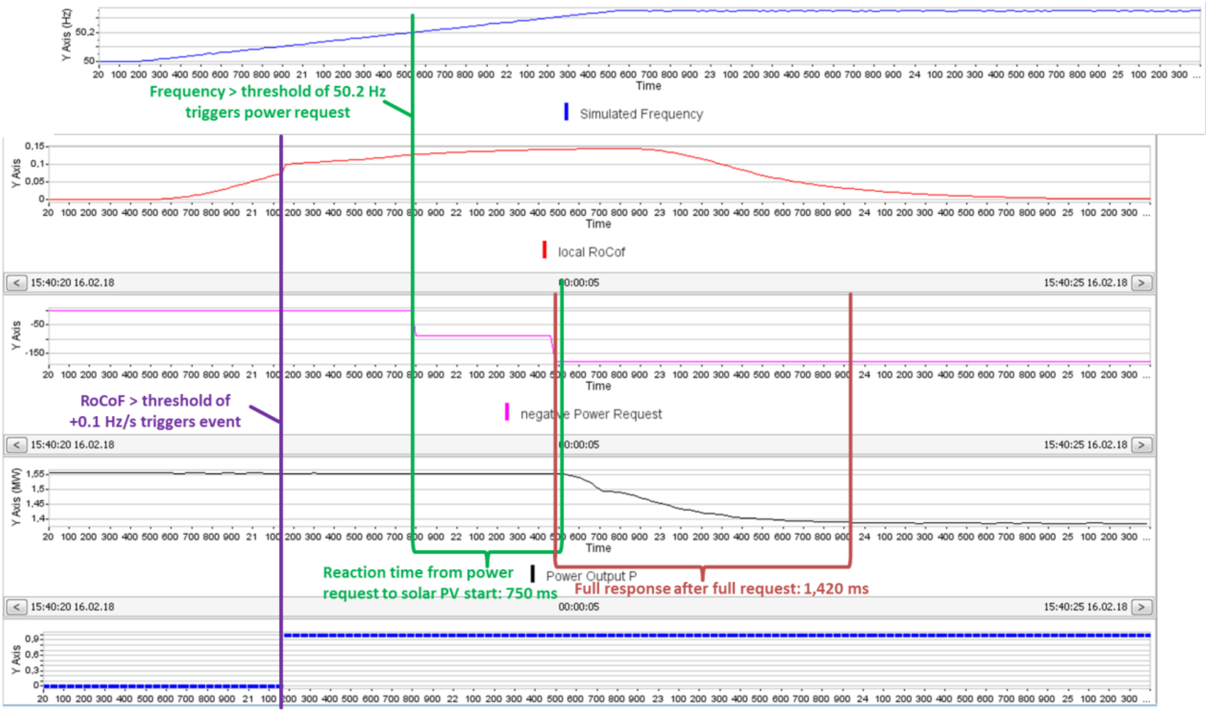


Figure 24: Exemplary Hardware in the Loop test. Simulated over-frequency event 50.35.

The RoCoF event detection limit was set at ±0.1 Hz/s and the event was successfully detected as the RoCoF reached +0.1 Hz/s. The power request was sent to the controller once the frequency reached the threshold of 50.2 Hz. Due to crossing of 2 thresholds after event detection i.e., 50.2 Hz and 50.3 Hz, the power request received by the BELECTRIC Hybrid Controller from the GE Local Controller was in two steps of 90 kW each, making the maximum power request to be 180 kW. Figure 24 shows the PMU display. The PV inverter's communication and internal logic response time was found to be ≈750 ms from the moment the Local Controller provided the power request to the start of the inverter ramp. It then took another 1.2 s to ramp down the requested 180 kW, thereby achieving a full response after the full request by the Local Controller after 1,420 ms.

The total ramp rate measured was found to be rather slow with 138 kW/s in average. It took Inverter 1.1 1.20 seconds to provide the full requested power of 180 kW. As the power request was divided in 2 steps the individual ramp rates measured were 214 kW/s for the initial 90 kW and 114 kW/s for the second ramp from 90 kW to 180 kW working point. As aforementioned, the previous ramp test concluded that the smaller the change in the working point the lower is the corresponding ramp rate. As the request was for a total of 180 kW, the ramp rate is less than we would expect it to be at such a large request. Nevertheless, it was a below average ramp rate compared to the ones we have seen in previous trials as outlined in section 6.1.B.

Curtailed PV power plant, simulated under-frequency event, 49 Hz, reaction time 210 ms

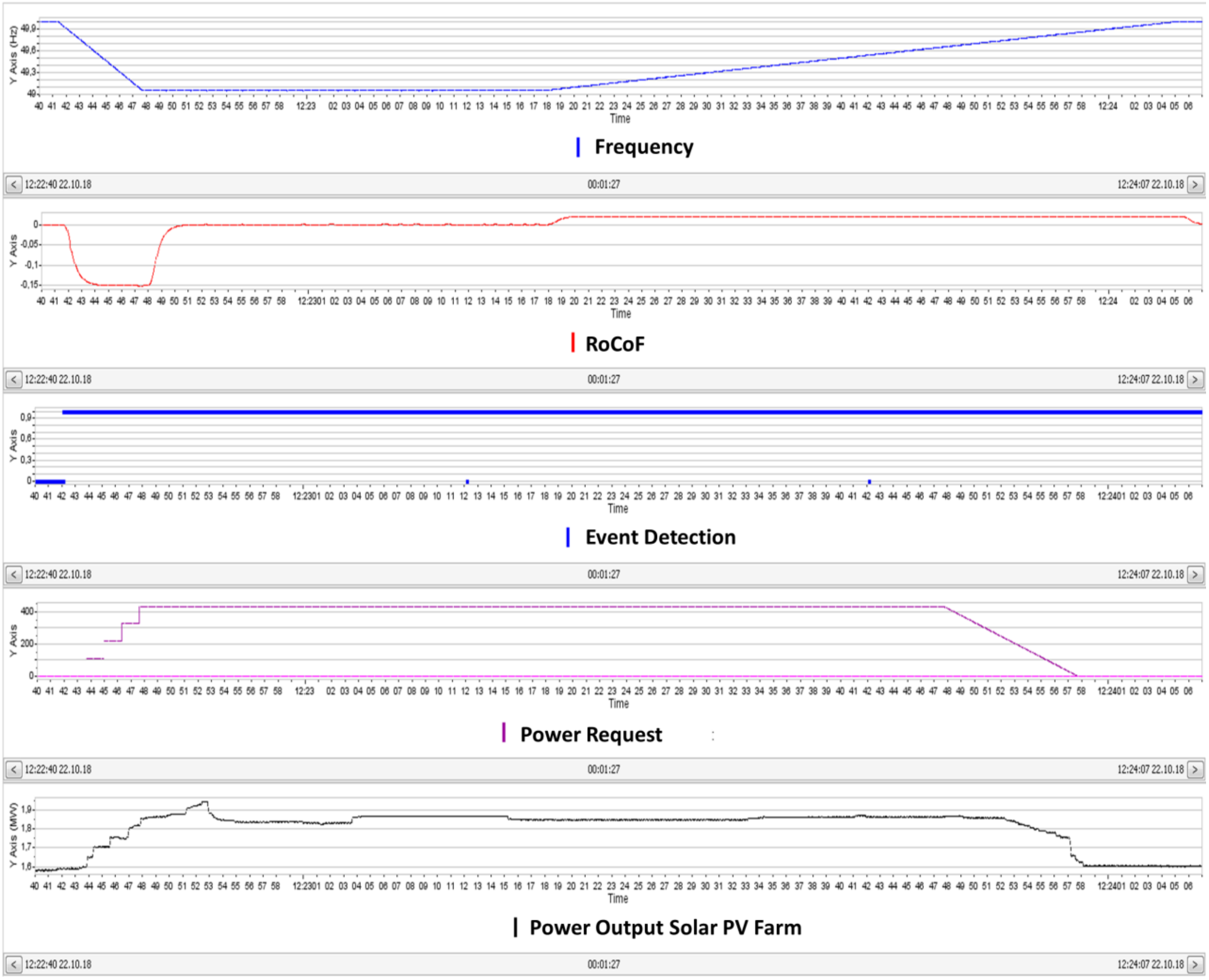


Figure 25: Exemplary Hardware in the Loop test. Simulated under-frequency event, 49 Hz, 400 kW power request in 4 steps, full view.

Inverter 1.1 and 1.2 are curtailed in this simulated HiL test shown in Figure 25. For this test, real positive and negative power availability is sent to the GE Local Controller by the BELECTRIC Hybrid Controller. On the other side was the GE PMU Simulator configured to inject a simulated event with a -0.15 Hz/s ramp down to 49 Hz.

The RoCoF event detection limit was set at ±0.04 Hz/s and the event was successfully detected as the RoCoF reached -0.04 Hz/s (Blue dotted line). The first power request was sent to the controller once the frequency reached the first threshold of 49.7 Hz. Due to crossing of 4 thresholds after event detection i.e., 49.7 Hz, 49.5 Hz, 49.3 Hz and 49 Hz, the power request received by the BELECTRIC Hybrid Controller from the GE Local Controller was in four steps of 100 kW each, making the maximum power request to be 400 kW.

The first step can be seen in more detailed in Figure 26. As RoCoF reaches the implemented limit of -0.04 Hz/s the event is detected and a power request of 100 kW is send as soon after frequency reaches the frequency threshold of 49.7 Hz. 210 ms later the inverter 1.1 is reacting to the request, joined by inverter 1.2 shortly afterwards to provide the full response for the first step in 680 ms after the full request by the Local Controller was received.

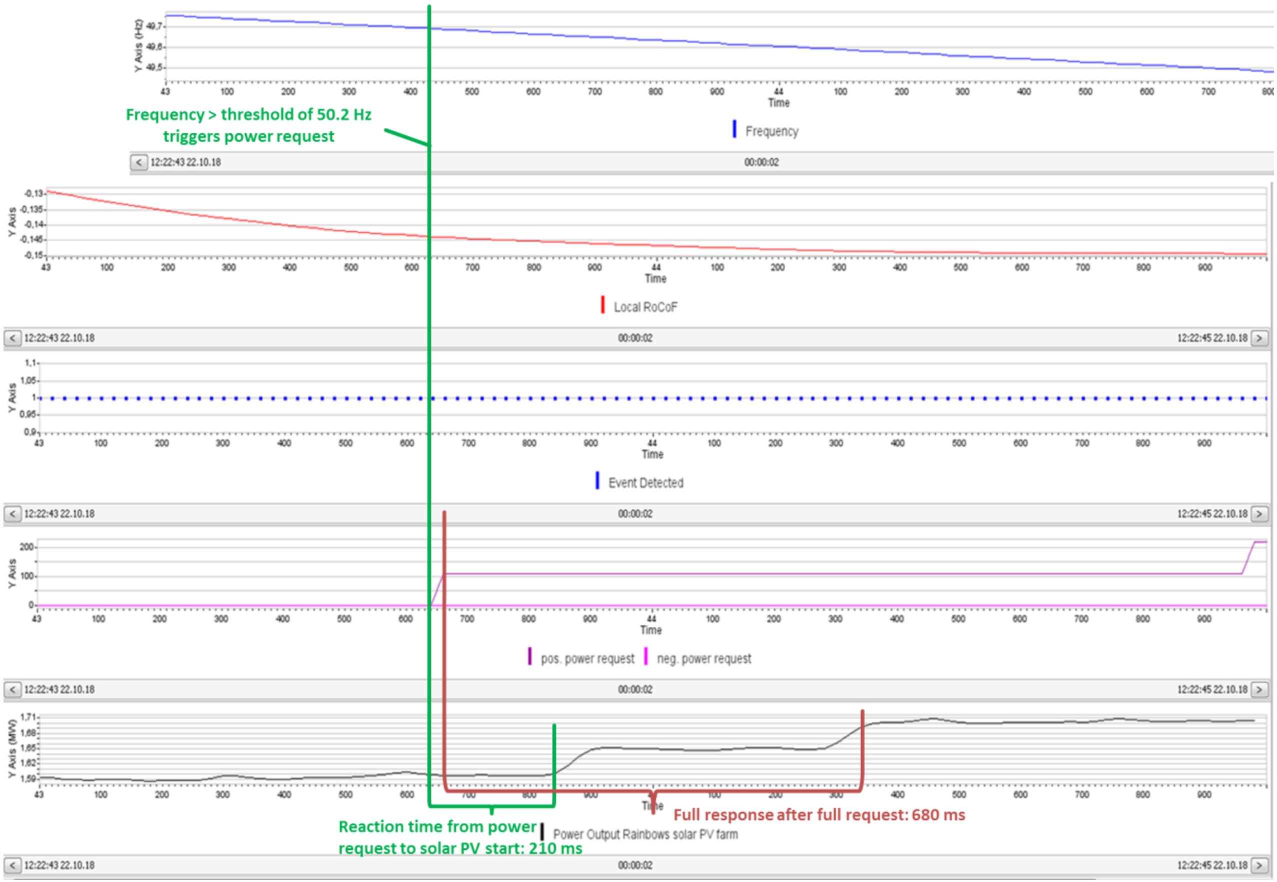


Figure 26: Exemplary Hardware in the Loop test. Simulated under-frequency event, 49 Hz, close-up to the first 100 kW step of 4 steps.

To provide a better ramp and consistent reaction performance, in a hybrid system trial with solar PV and battery, the first ramp will always be provided by the battery system which is configured to be faster than the PV inverter ramp rate.

Reaction times - summary

The average reaction time of the solar PV control version tested in 2018 was found to be 474 ms from ‘request send’ by the Local Controller to the first measurable reaction of the inverter.

Best case scenario was 120 ms, average 356 ms, worst case scenario 850 ms.

The reaction time of 850 ms is a rare occurrence. 83.3% of the tests showed reaction times below 500 ms and 58 % where below 300 ms, as shown in Figure 27.

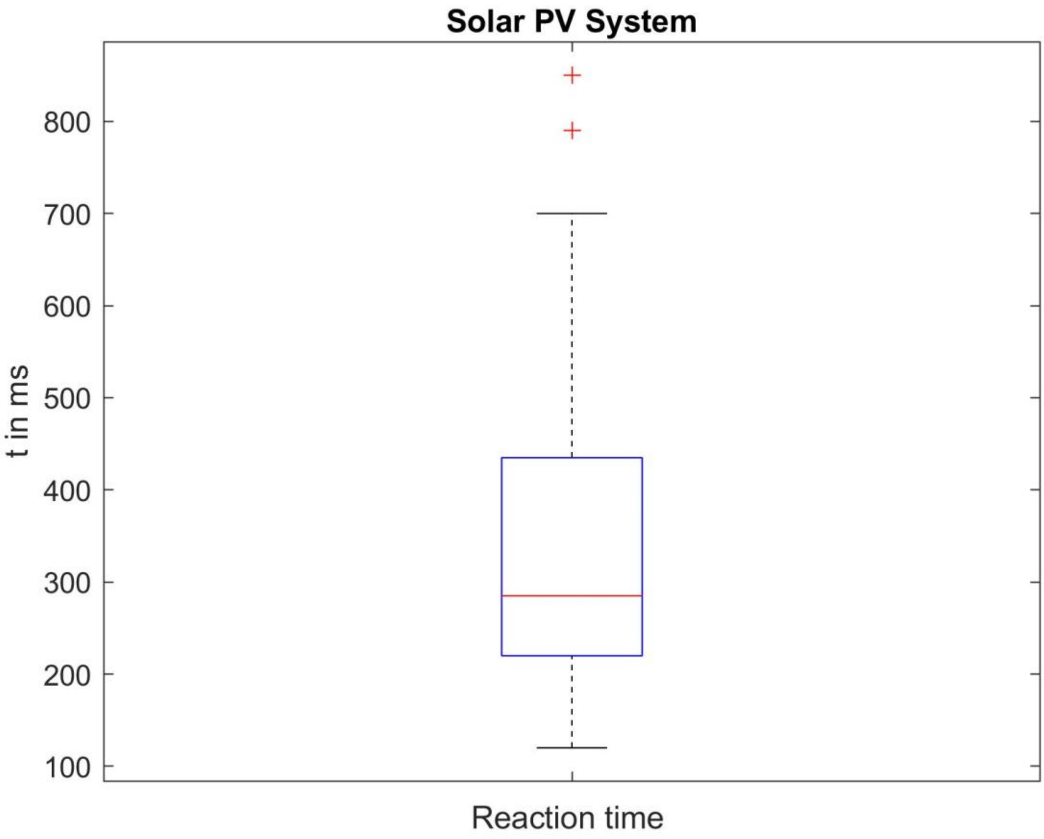


Figure 27: Box-Plot of the measured reaction times of the solar PV stand-alone Hardware in the Loop tests with simulated under- and over-frequencies. Median is at 280 ms. Average reaction time is 356 ms.

Figure 28 below captures the equipment, communication, and software parts included in the accumulation of the average reaction time of 356 ms.

In these 474 ms is included:

a. The time the GOOSE signal needs to reach the Belectric Hybrid Controller
b. The control mechanism in the Belectric Hybrid Controller (10 ms per cycle)
    i. To divide the request onto each connected and participating inverter
    ii. To calculate the new power set point of the inverters
    iii. To address and write on the specific register address of the inverters
c. Sending of the command via 1:N MODBUS TCP/IP communication protocol to the inverter (not deterministic; data point for ‘send’ only every 100 ms)
d. The reaction time within the internal inverter control and hardware response itself
e. Start of inverter response

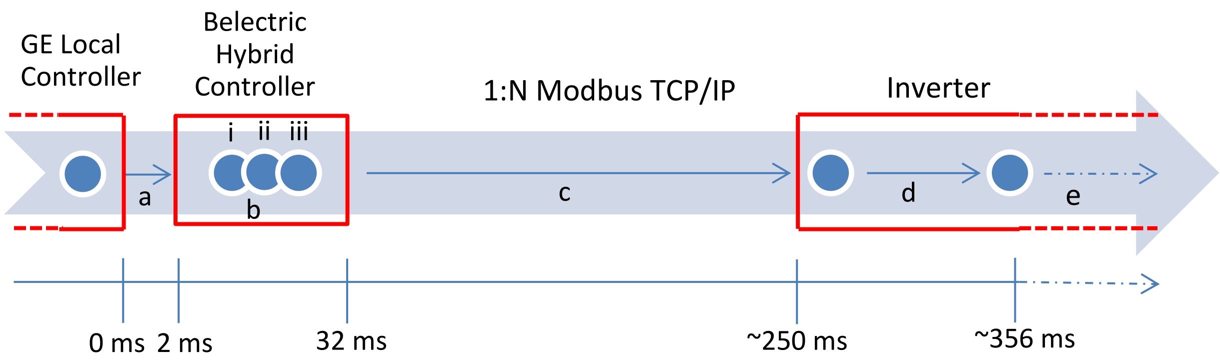


Figure 28: EFCC - PV reaction and response timeline after sending of a power request by GE Local Controller.

As shown, a major part of the reaction time is due to a) communication delays on the standard central inverter based solar PV farm networks based on 1:N Modbus infrastructure and b) internal inverter control mechanisms on the software side as well as being impacted by slow reacting low-frequency-filters commonly used in PV inverters on the hardware side of the inverters. PV inverters of this generation have not been built and designed to take part in fast frequency response without further updates.

Response time – Summary

The response time until full response is determined by the time the inverters take to fully provide the requested power after receiving the full power request.

Best case scenario was 120 ms, average 808 ms, worst case scenario 2,140 ms.

A full response in less than 500 ms was measured in 46% of the tests cases. A similar percentage goes for full response time above 1,000 ms which happened to be measured in 33% of the cases. Only a minority of the samples are in-between those two clusters. That means the time from full power request received to full power response by the inverters is either quite fast (below 500 ms) or quite slow (above 1,000 ms).

This can also be seen in the box plot of the response time in Figure 29 which is not as concentrated as the reaction time box plot in Figure 27.

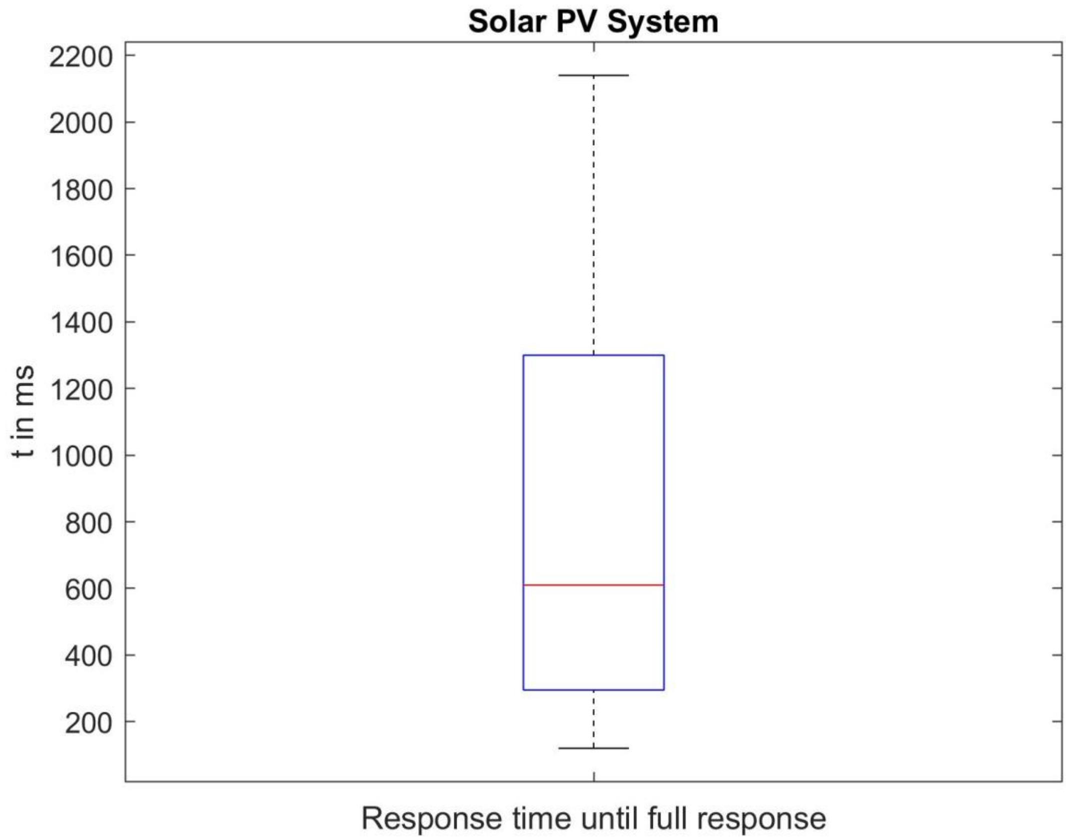


Figure 29: Box-Plot of the measured times until full inverter response of the solar PV stand-alone Hardware in the Loop tests with simulated under- and over-frequencies. Median is at 630 ms. Average response time until full response is 808 ms.

B. Real Frequency Event

The RoCoF threshold settings were changed for the real frequency event tests. As it has been ±0.1 Hz/s in the simulated tests it was lowered to ±0.04 Hz/s for real frequency events to cover for the rarity of such large frequency events. The first frequency thresholds remained at 50.2 Hz / 49.7 Hz.

The system in Great Britain experienced a frequency event on 07.03.2018 at 13:04 (CET). A RoCoF of -0.06 Hz/s with frequency nadir below 49.7 Hz but greater than 49.5 Hz was measured by the PMU at the solar PV grid connection point. As the RoCoF limit for event detection during this test was set at -0.04 Hz/s the event detection was triggered once this threshold was reached. This was followed by a power request of +7 kW (≈20% of available power).

During this week, the inverter hardware was configured to run at MPP without any curtailment thus the inverter should only had the capability to provide a negative power response by reducing the power during the event. A positive power request shouldn’t have been possible at that moment.

To investigate the reason for the 7 kW positive power request generation, PADCON PV web portal was used. It was found that during the moment of the event the output of the reference inverter 2.1

was 793 kW while inverter 1.1 output measured was 759 kW. Because of that difference the Local Controller received positive power availability of 34 kW thus a power request of 20% of positive power availability was sent.

The possible reason for different power production by each inverter is due to different number of modules connected to the inverters as well as due to cloud movement across the plant which is evident as each inverter power went downwards by more than 100 kW within the next 30 seconds. Figure 30 shows the snapshot of PMU where the cloud movement can be observed by looking at the plants total output which got reduced by 400 kW in total. This was found to be correct after observing the PADCON PV Web portal where each inverter reduced its power by 100 kW in a successive time scale thus confirming a small cloud moment across the PV plant.

As the inverter has a minimum power resolution of 8 kW (Section 6.1, sub-section C), the power request of 7 kW would not have been processed anyway by the inverter hardware. To prevent such situations to happen again an extra condition was added where the PV resource is set to be available only when 20% of resource availability is greater than 16 kW which corresponds to 2 % set point change.

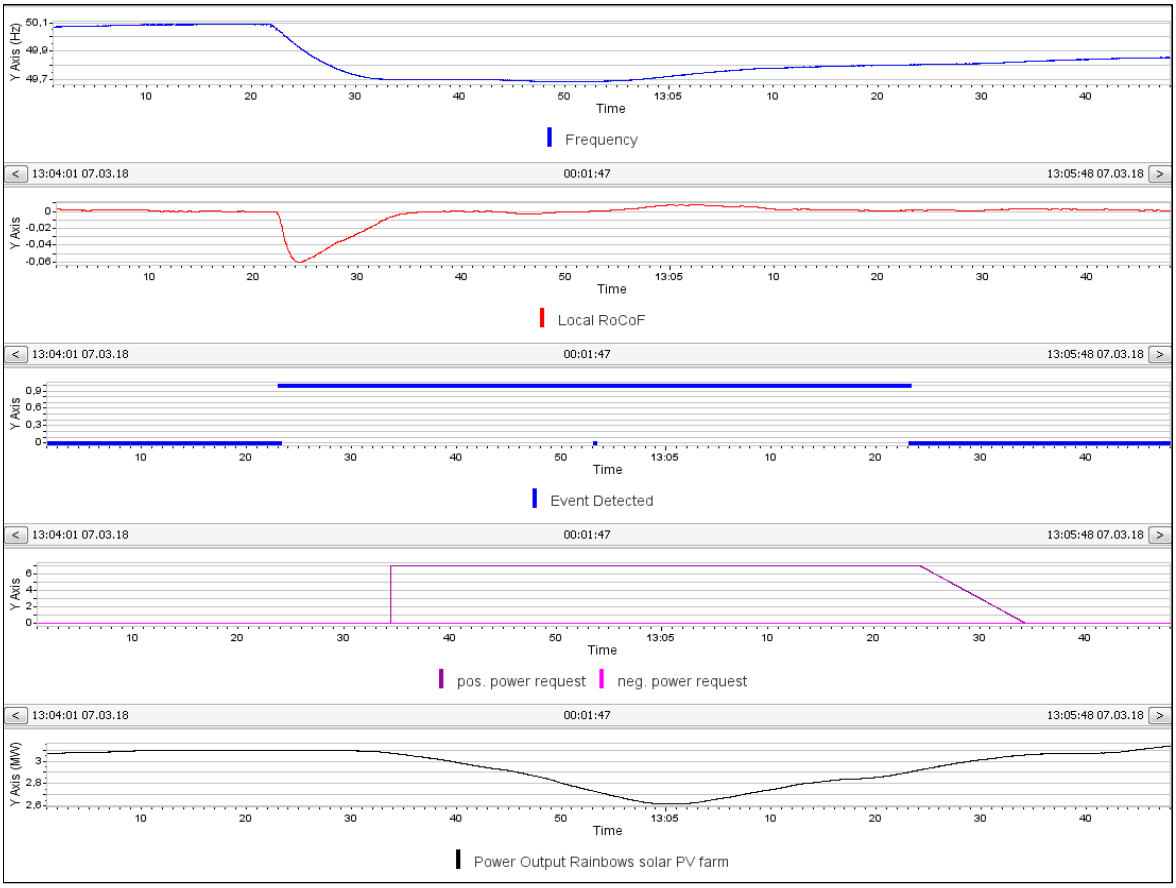


Figure 30: EFCC Scheme PMU display after event on 7th March 2018 at 13:05 (Central European Time).

Inverter 1.1 was curtailed for several months to 50 % of the reference inverter to provide positive power response during an under frequency event during March and April, August, September and October 2018. During an over frequency event Inverter 1.1 and Inverter 1.2 will provide the negative power response. Power requests received by the GE Local Controller during a frequency event are divided between the two inverters according to the individual power production at that instant.

Date	Time	max. RoCoF [Hz/s]	Freq nadir [Hz]	pwrRqst [kW]
Friday 23.02.	03:29	-0,094 Hz/s	49,62 Hz	
Saturday 24.02.	15:15	-0,049 Hz/s	49,78 Hz	
Thursday 01.03.	16:16	-0,056 Hz/s	49,89 Hz	
Sunday 04.03.	05:56	-0,057 Hz/s	49,81 Hz	
Tuesday 06.03.	12:25	-0,062 Hz/s	49,78 Hz	
Wednesday 07.03.	12:01	-0,060 Hz/s	49,69 Hz	7 kW
Thursday 08.03.	05:31	-0,045 Hz/s	49,83 Hz	
Tuesday 03.04.	03:09	-0,094 Hz/s	49,91 Hz	
Friday 20.04.	20:57	-0,039 Hz/s	49,70 Hz	
Tuesday 01.05.	11:24	-0,049 Hz/s	49,73 Hz	
Wednesday 02.05.	02:42	-0,080 Hz/s	49,75 Hz	
Friday 04.05.	09:00	-0,040 Hz/s	49,89 Hz	
Friday 01.06.	10:02	-0,070 Hz/s	49,68 Hz	30 kW
Tuesday 12.06.	05:09	-0,065 Hz/s	49,76 Hz	
Monday 18.06.	13:36	-0,045 Hz/s	49,90 Hz	
Wednesday 04.07.	00:32	-0,058 Hz/s	49,70 Hz	
Saturday 07.07.	18:25	-0,052 Hz/s	49,78 Hz	
Thursday 12.07.	13:25	-0,066 Hz/s	49,69 Hz	62 kW
Friday 27.07.	20:11	-0,042 Hz/s	49,80 Hz	
Sunday 12.08.	20:23	-0,053 Hz/s	49,68 Hz	
Tuesday 21.08.	03:58	-0,064 Hz/s	49,73 Hz	
Thursday 04.10.	01:07	-0,044 Hz/s	49,81 Hz	
Thursday 04.10.	12:12	-0,046 Hz/s	49,80 Hz	
Tuesday 08.10.	23:11	-0,058 Hz/s	49,87 Hz	
Thursday 11.10.	16:58	-0,060 Hz/s	49,69 Hz	2 kW
Thursday 11.10.	19:48	-0,057 Hz/s	49,60 Hz	

Table 9: Measured frequency events at Rainbows solar PV farm, Willersey, with RoCoF, frequency nadir and power request. Largest RoCoF measured was -0.094 H/z. No over-frequency event was measured. Lowest frequency nadir was 49.596 Hz. Of 26 measured events four triggered a power request, fulfilling the three conditions of reaching the RoCoF threshold as well as the frequency threshold while having power available.

In the month of March and April, August, September and October Inverter 1.1 was constantly curtailed to provide positive response in case of an under frequency event. During this trial period a few frequency events had happened in the GB grid that triggered the previously mentioned RoCoF threshold as shown in Figure 32 and Table 9. Of these events two triggered a power request as they reached the additional condition of going below the frequency threshold. But both events occurred at times with very low available power during sun set (on 11.10., power request of 1.8 kW which is too low to trigger an inverter response as working point shifts have to be around 8 kW minimum) or when the PV resource availability was falsely given as positive because a of difference between response delivering inverter and reference inverter (on 07.03., explained earlier in the section).

During May, June and July of 2018, the curtailment was simulated. In these three months 9 events where measured that triggered an event (all under frequency events, RoCoF below -0.04 Hz/s). 5 of these 9 events happened during daylight (marked in yellow in Table 9) and two of these 5 events reached the frequency threshold of 49.7 Hz. In both of these two events a positive power request was send in accordance of the actual available power of the solar PV farm of 30 kW and 60 kW each. As the curtailment was only simulated based on the actual power output of the PV farm no inverter reaction has happened. The system was again curtailed since August to provide both positive and negative response in case of a real event happening.

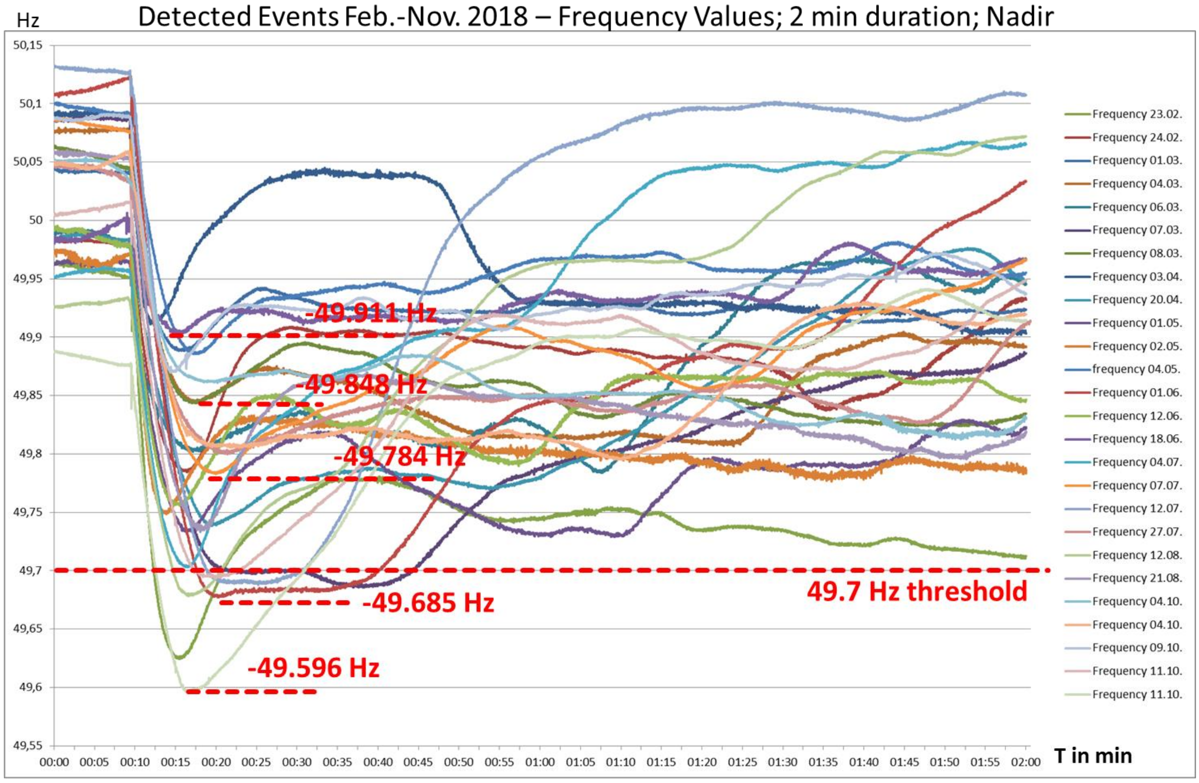


Figure 31: Detected Frequency Events on site in Willersey; February – November 2018, 2 min duration.

None of the 26 measured and triggered events since February 2018 have been over frequency events (see Figure 31) and no positive RoCoFs above +0.04 Hz/s have been measured on site in Willersey – see Figure 32. Therefore, no negative power request has been observed yet and no fast frequency response by the solar PV farm occurred for real events.

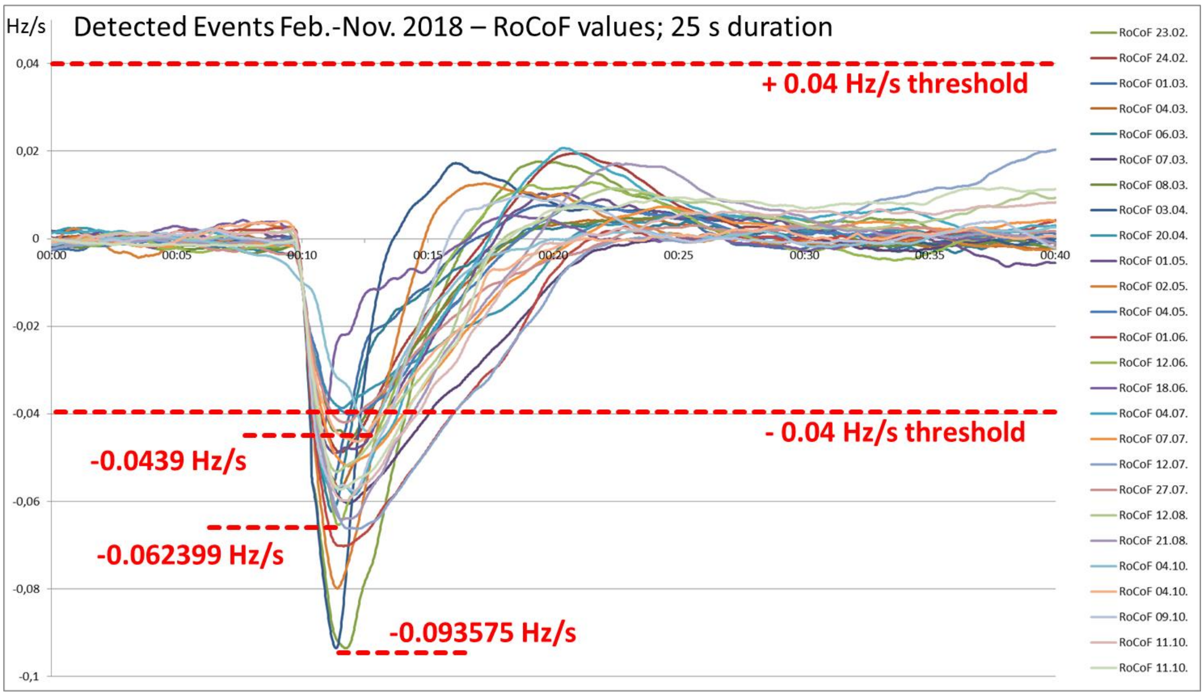


Figure 32: Detected Events - RoCoFs measured on site in Willersey; February – November 2018; 25s duration.

7 Testing Limitations

This section condenses the testing limitation experienced due to hardware setup, communication delays or communication losses during the EFCC Scheme development and test trials.

7.1 Precursor Tests

A. Real Frequency Event

Accurate measurement of inverter ramp rate is not possible with the current hardware and measurement setup. The total ramp rate results have some extent of uncertainty. This uncertainty in the measurement could be resolved by a SCADA measurement system in the PV plant which could measure the inverter parameters with a higher data resolution thus allowing accessing the power change in each inverter individually. The section below mentioned the uncertainty introduced in the ramp measurement test.

a. Absence of high resolution inverter output measurement system.

In the current hardware setup PADCON PV Web portal with minimum data granularity of 1 second allows BELECTRIC to see the output power of each individual inverter. To measure the ramp rate of an inverter, the PMU installed at the GCP was used. At the GCP the PMU measured the total power of the PV plant, meaning that the ramp rate of the inverter under test was evaluated by looking at the total output power from Rainbows PV Power Plant.
To minimize the impact of fluctuations in the total power due to the three non-participating inverters, this test was executed during the time of high and comparatively stable irradiance.

b. Inexplicit ramp end time-stamp

Although the ramp tests were executed during high and stable irradiance, small fluctuations in the pyrometer readings were still observed. This small variation in the irradiance introduced four times variation in the power due to four inverters which made it harder to find the time when the ramp ends. Figures 33, 33(a), 33(b), 33(c) explain the situation with an example of how a slight deviation in estimation of ramp end timing creates an impact on the total ramp rate. It can be observed that the start time and end time for inverter *fast ramp* is easily noticeable. While for the *correction ramp* even a small change in the ramp end time affects the inverters total ramp rate adversely.

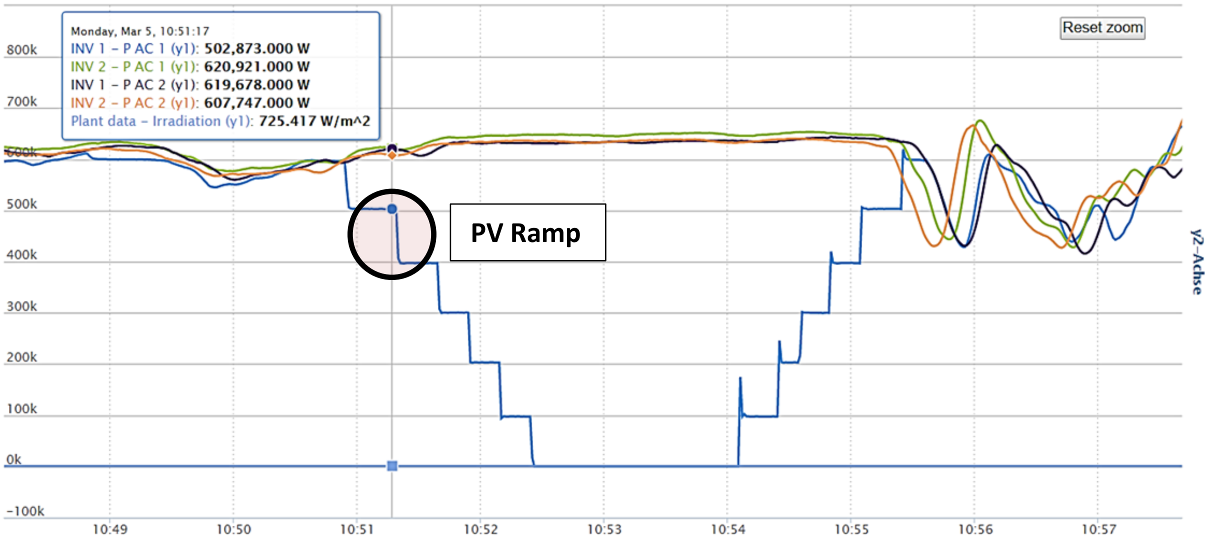


Figure 33: PADCON PV Web Portal Ramp Test Results.

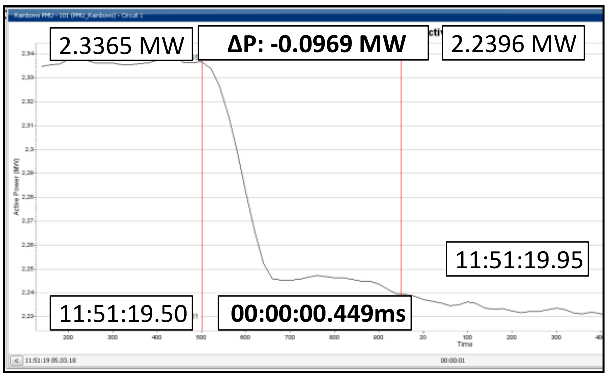


Figure 33(a): Total Ramp Rate measured - 215 kW/s (PMU).

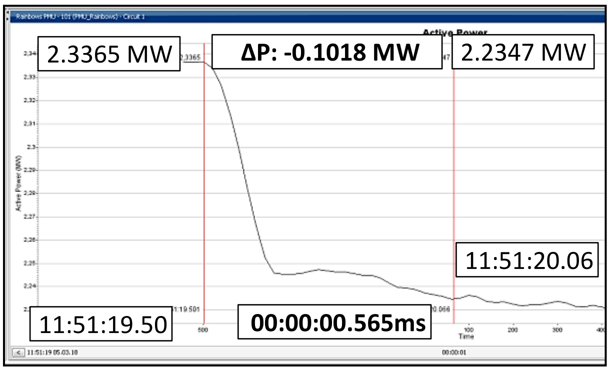


Figure 33(b): Total Ramp Rate measured - 180 kW/s (PMU).

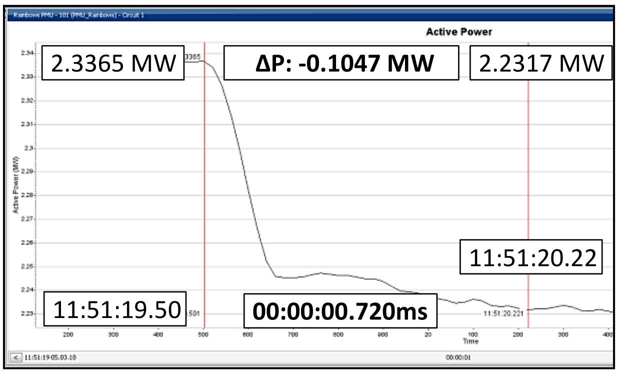


Figure 33(c): Total Ramp Rate measured - 144 kW/s (PMU).

B. Curtailment Test

The inverters AC output power is curtailed by giving a percentage value of its nominal power as a working point. The SMA inverter at Rainbows solar PV plants nominal power is 880 kW each; this limits the curtailment power resolution to 8.8 kW per step. In the current control implementation, during a power request, BELECTRIC provides the AC power of the magnitude of the lowest integral value which is a multiple of 8.8 kW and tries not to exceed the power above the requested kW.

C. PV Matlab model and inverter response

BELECTRIC used an in-house PV Matlab model and a sky imager cloud camera to provide 15 minute of forecasted power. The sky imager cloud camera assess the cloud movement and estimates (Probability value, P40 values) the global horizontal irradiance available in the next 15 minutes, which is given to the PV model along with other environmental factors as the temperature for example to find the MPP which will be produced at that particular irradiance by each inverter. Figure 34 shows the communication setup and the PV Matlab model running at the background of the BELECTRIC Hybrid Controller.

The PV Matlab model accuracy was tested by giving pyranometer reading and comparing the calculated power with the actual plants power output. The PV Matlab model was – in average – underestimating the output power by 5%. Investigating the sky camera it was found that the system introduced a high uncertainty into the forecasted values especially during days with broken clouds. Therefore BELECTRIC did not use or investigate it further.

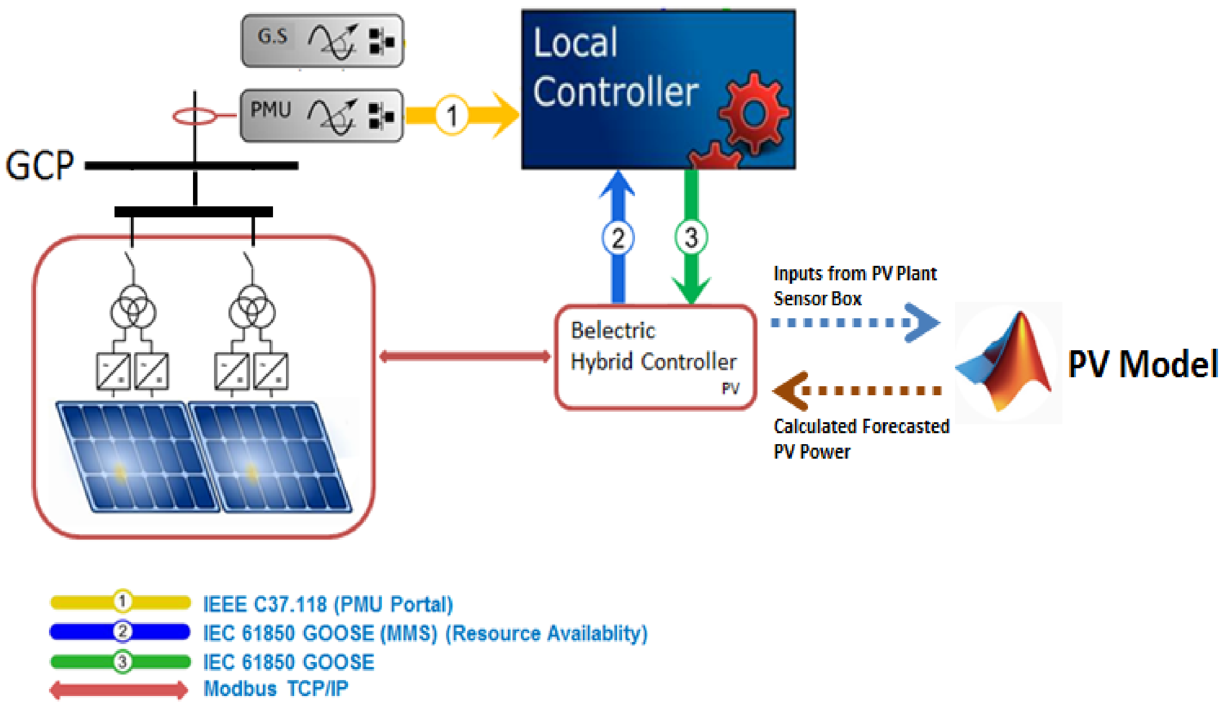


Figure 34: EFCC communication setup with PV Matlab model.

7.2 Open Loop Test

- Matlab, which is an interpreter, is comparatively slower than a compiler. The PV Matlab model running at the background of the BELECTRIC Hybrid Controller introduced processing delays thus directly affecting the hardware response time.
- Due to high error margin in the forecasted irradiance with the sky imager, the whole purpose of working with the PV Matlab model was lost thus PV Matlab model and the sky imager were successfully deactivated which brought down the hardware response time from 14 seconds in the range of under 750 ms (together with other measurements and actions that took place after the evaluation of the first trials as i.e. introduction of inverter toggling, see chapter 8.). Further development and optimization in the code has been made to reduce the reaction time of the inverter down to 120 ms (best case).
- Currently BELECTRIC uses a self-developed, probabilistic underestimating forecasting model. This could introduce errors in the power availability. The error quantification takes place by running the forecasting model against a real irradiance curve to see if the model estimates correctly the upcoming lowest available power over the next period. The error margin is reduced by larger safety margins to achieve an error rate that is similar low as the combination of PV model and sky camera error percentage.

7.3 Hardware in the Loop Test

- The occurrence of a frequency event that reaches both the RoCoF and Frequency threshold, especially during daylight, is very rare.
- Loss of GOOSE connection between GE PMU and the BELECTRIC Hybrid Controller was found to be a reoccurring issue. The reason for the communication break is still unknown and needs further investigation. To cope up with this situation a work around with soft system restarts was carried out by BELECTRIC.

8. Response Enhancement Summary

During the EFCC PV Stand Alone trials the communication process and inverter hardware control state played a major role in inverter response time. During the initial precursor test the inverter response times were observed to be slightly higher than 14 seconds. When sending the continuous requests for power curtailment the inverter response time was found to be that high only for the first power request. To reduce the response the control system was implemented to always send a set point to the inverter every 30 ms. This constant toggling of the inverter settings further reduced to response time to less than 4 seconds.

Due to lower accuracy of steadyEye sky imager camera, the hardware along with PV Matlab Model were deactivated from the communication system as mentioned in chapter 3 which further brought down the total response time of the inverter to.

At present the response time of the inverters is in the best case 120 ms, and 380 ms in average, which was achieved by implementing a new optimised control strategy and after deactivating the data input of the sensor box which measured the Inverter temperature, PV module temperature, wind speed at the location etc. for power forecasting calculation. The parameters from the sensor box were excluded only from the EFCC Control scheme, on request they can be made available from the PADCON PV Web Portal.

9. Conclusions & Learning Outcomes

After the EFCC PV Trial test results, it can be said that central inverter based large scale solar PV plants can be implemented into the EFCC scheme.

The Rainbows Solar PV plant was successfully configured to behave as a local resource in the National Grid NIC EFCC scheme. The system responded successfully to the power requests received from the GE Local Controller during the frequency events in the GB grid, measured by a PMU.

However there are several limitations and conditions to this statement which are outlined in this report, as comparably slow response and low ramp rates, the latter being different for ramp up and down. However these limitations can be easily addressed in the control scheme if the response service is to be implemented.

While each large scale (central inverter based) solar PV plant is somewhat different from each other, the majority of them would face similar issues in providing a fast frequency response services. Especially the response time of the inverters and potential delays in the communication set-up will be reoccurring factors. In addition, the ramp rates of PV inverters out in the field may be different but will generally be rather slow as the early generation of PV inverters were not build to be fast in the first place, but rather to be very resistant and stable towards oscillations inside a PV solar farm. That said, retrofitting these plants is an option as well as taking above learnings into account when designing new PV solar farms. Fast communication infrastructure as well as the possibility of the inverters for quick reaction is the key to provide fast frequency response.

A fast communication infrastructure is one of the key factors to provide fast frequency response. One of the restricting factors in case of the Rainbows solar PV farm is the MODBUS TCP/IP connection from the BELECTRIC Hybrid Controller to the inverters. The communication setup was designed as a 1:N connection bus with multiple clients participating, reading and writing simultaneously. As Modbus TCP isn't deterministic the response time differs and cannot be stated as a fix value. Determinism is a term that is used here to describe the ability of the communication protocol to guarantee that a message is sent or received in a finite and predictable amount of time. Modbus TCP with several devices and clients connected to the communication bus is not predictable and therefore non-deterministic. During the trials, delays of up to 13 seconds were recorded which has been addressed with improved controlling mechanisms.

Improving the response time can be done by reducing the 1:N connections of the Modbus to 1:1 connections. Since there is only one device connected to a port of a switch, there is no chance of collisions occurrence. A good network design with fast switches, and bridges where necessary, would raise the determinism of the network and reduce the communication delay.

Another response delay because of the MODBUS connection occurs due to the use of the TCP protocol. TCP provides reliable, ordered, and error-checked delivery of a stream of bytes between the devices running on hosts communicating by an IP network. But TCP requires a hand shake between sender and recipient. It checks if all data packages which have been send are fully received which takes extra time. UDP protocols may be more effective in this case but it has limitations in others ways.

Implementing a communication based on 1:1 connections and real time protocols improves the response time and make it deterministic. Retrofitting a PV power plant network in such ways is possible as well.

10. Suggested Future Work

One research topic in future projects is combining several non-local resources for frequency response under WAMS in EFCC scheme.

To prevent communication delays in provision of fast frequency response focus needs to be laid on the design of new PV farm topologies to achieve quicker response times and higher ramp rates.

By combining solar PV farms with battery storage behind the same grid connection point a systematic synergy can be accomplished in which battery may provide the fast reaction part of the overall frequency response.

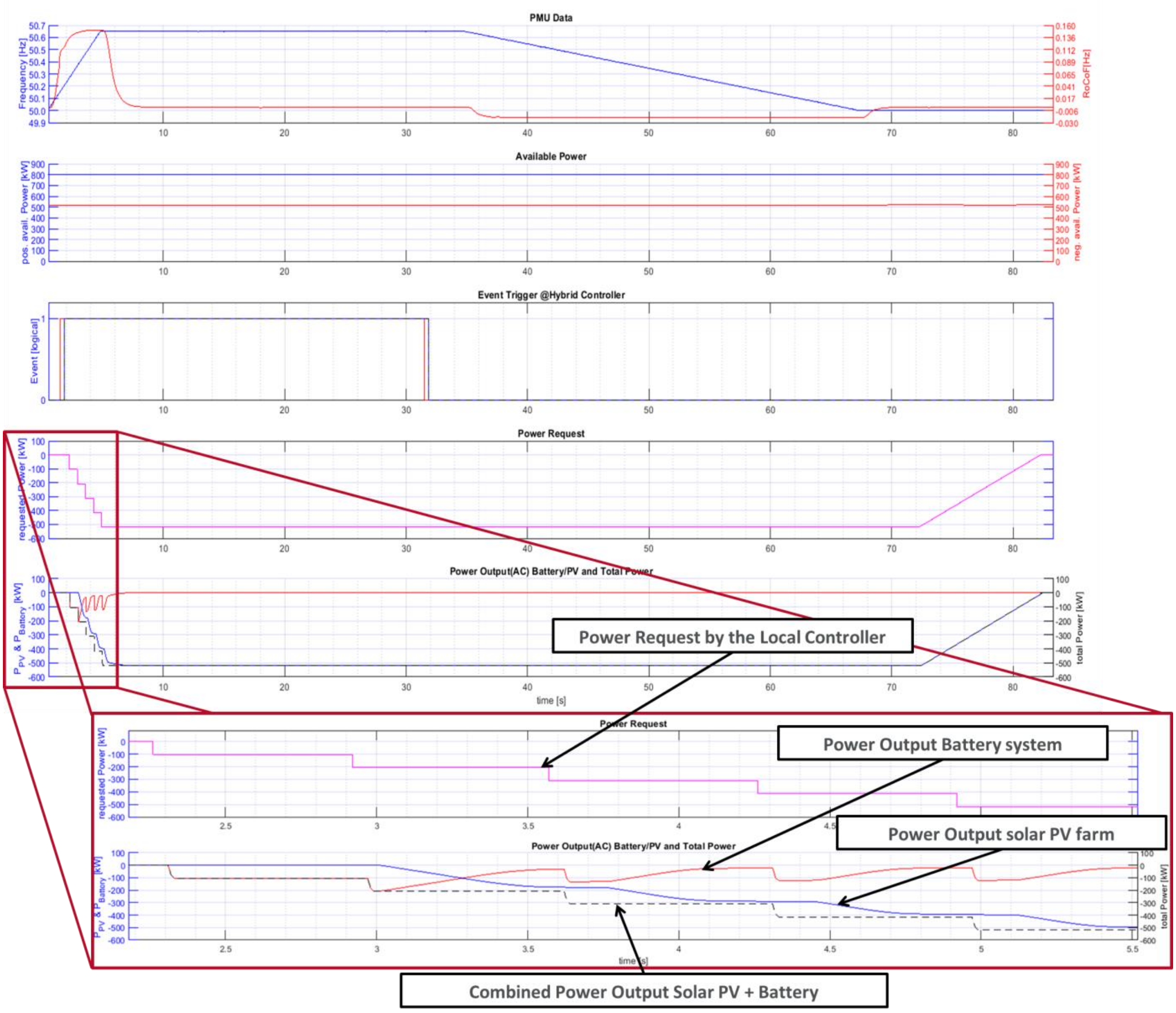


Figure 35: Simulated response of the combined solar PV and battery storage resource for an over frequency event. The battery system always provides the first ramp while the slower reacting PV system responds later. When the PV starts to ramp down, the battery reduces its power ramp back to 0 kW/s in accordance with the PV ramp. The combined power response of the Hybrid system follows the power request of the Local Controller closely.

This scheme will be established in a separate project phase where the Rainbows Solar PV Farm and a 1 MW / 1 MWh battery storage system will be acting as a single EFCC resource. This will enlarge the substantial available power in both response directions and could also limit the necessity of updating and retrofitting the communication structure and inverters of already constructed solar PV farms. The results of these tests and trials will be published under the NIA DESERT project.

Also, inverters may be programmed to behave like a synchronous machine, 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.

Another option for future research projects in this research area is the provision of black start service from non-synchronous generation and storage assets.

11. References

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Appendix 1– Test List

Tests	Result Status
Precursor Test	
• Inverter Control	PASS
• Curtailment Test	PASS
• Ramp Test	PASS
Open Loop Test	
• Simulated Frequency Event	PASS
• Real Frequency Event	PASS
Hardware in the Loop Test	
• Simulated Frequency Event	PASS
• Real Frequency Event	On Going

Table 10: EFCC Test plan status.

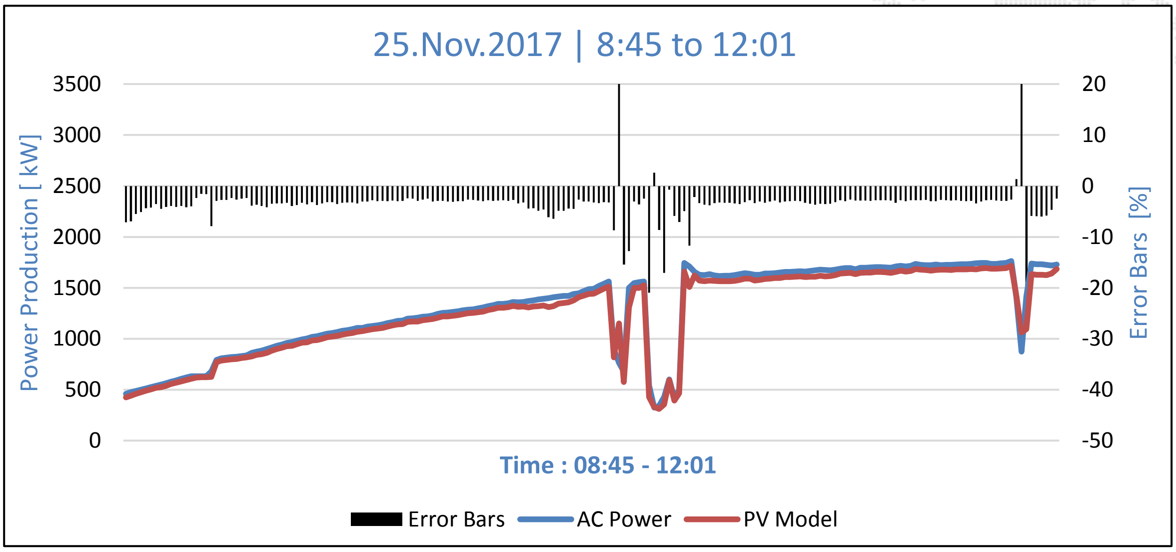
Appendix 2 – Test Data

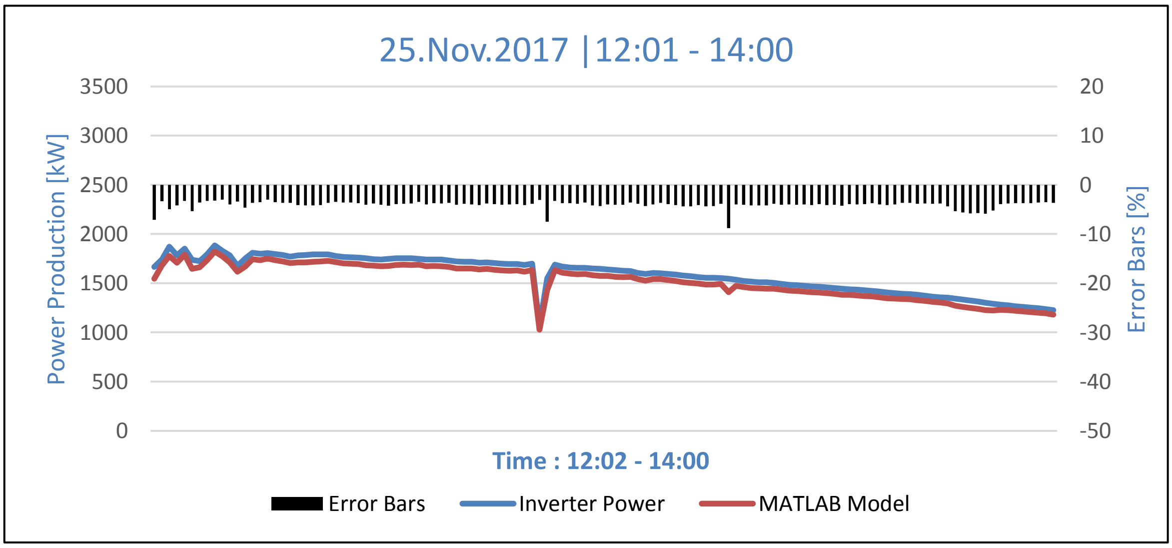
A. PV MATALAB Model Accuracy Test

For accuracy test the PV Model was given input from the installed pyranometer which measures the live irradiance. The graph shows the plot for the calculated power by the PV Model and the real AC power production by the Rainbows PV Plant. The PV Model is underestimating in nature with an average error of 5%. An under estimating PV Model can be used in EFCC Scheme. If it would overestimate the available power, the system may receive a power request by the GE Local Controller that it just cannot fulfil as the actual power availability is less. Table 10 shows the results observed after running an accuracy test for a week. To simplify the test, 1 minute data granularity was considered.

DAY	DATE	PADCON: ENERGY [MWH]	PV-MODEL:ENERGY [MWH]	ERROR
1	24.Nov.2017	453.93	435.712	- 04.01 %
2	25.Nov.2017	444.85	427.60	- 03.87 %
3	26.Nov.2017	276.69	262.39	- 05.16 %
4	27.Nov.2017	118.03	104.17	- 11.74%
5	28.Nov.2017	343.40	323.58	- 05.74 %
6	29.Nov.2017	160.46	146.33	- 08.80 %
7	30.Nov.2017	449.95	430.89	- 04.23 %
	TOTAL	2247.33 MWh	2130.70 MWh	
	DEVIATION	(-) 116.63 | Underestimated PV Model		
	% ENERGY ERROR	5.18 %		

Table 11: In-house PV Model - one week accuracy test.





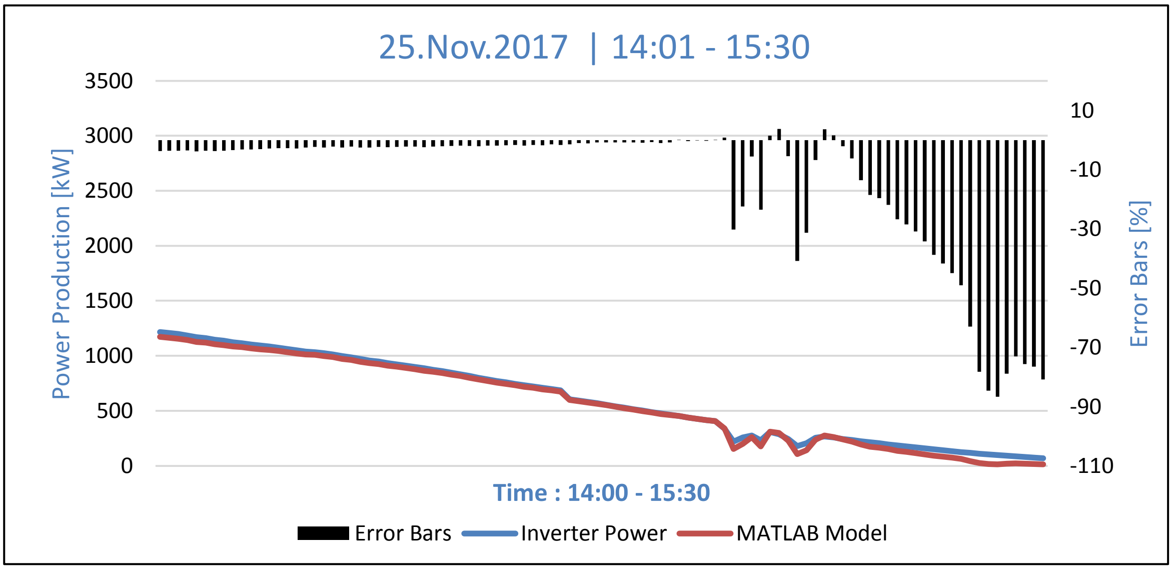


Figure 36: PV Model accuracy test plots.

Sudden spikes in the error margin are observed during sudden change in the power output of the PV plant. This is due to position of pyranometer and measurement of irradiance at one single point. The calculation is done by assuming the irradiance measured by the pyranometer to be uniformly distributed over the whole PV plant whereas during a cloud movement the irradiance in the whole area is non-uniform and gradually changes. This error can be filtered and reduced by installing more pyranometer and using average irradiance for calculation. During the time of low irradiance, i.e. during sun rise and sets, huge margin of errors were observed due to low power production therefore even a small difference in the two powers produced huge error margins.

B. Sky Imager Accuracy Test

The sky imager captures the cloud movement and provides a probabilistic 15 minute forecasted global horizontal irradiance value. In Willersey, the installed pyranometer measures irradiance at plane of array (20°). For this situation BELECTRIC's PV Model has a sophisticated GHI to POA converter which converts the 15 minutes forecasted global horizontal irradiance values from the sky imager to plane of array (20°) before starting the calculation.

During the accuracy test, the 15 minute forecasted GHI values from the sky imager were plotted against the live pyranometer plane of array irradiance after the desirable time shift between the two data points. The magnitude of the two data set points cannot be compared for accuracy due to different angle of inclination and also due to the probabilistic factor in the forecasted irradiance values. As a result, the change of pattern between the forecasted values and live pyranometer readings were investigated.

Figure 37 shows the plot between the cloud camera's 15 minute forecasted GHI values starting from t=0 against the pyranometers live POA irradiance starting from t=15.

Sky imager 15 minute forecasted GHI values at t=0 were expected to match with the pyranometer irradiance at t=15 but instead matches with pyranometer irradiance at t=-4 (Figure 38). The camera system actually forecasted what happened 4 minutes ago.

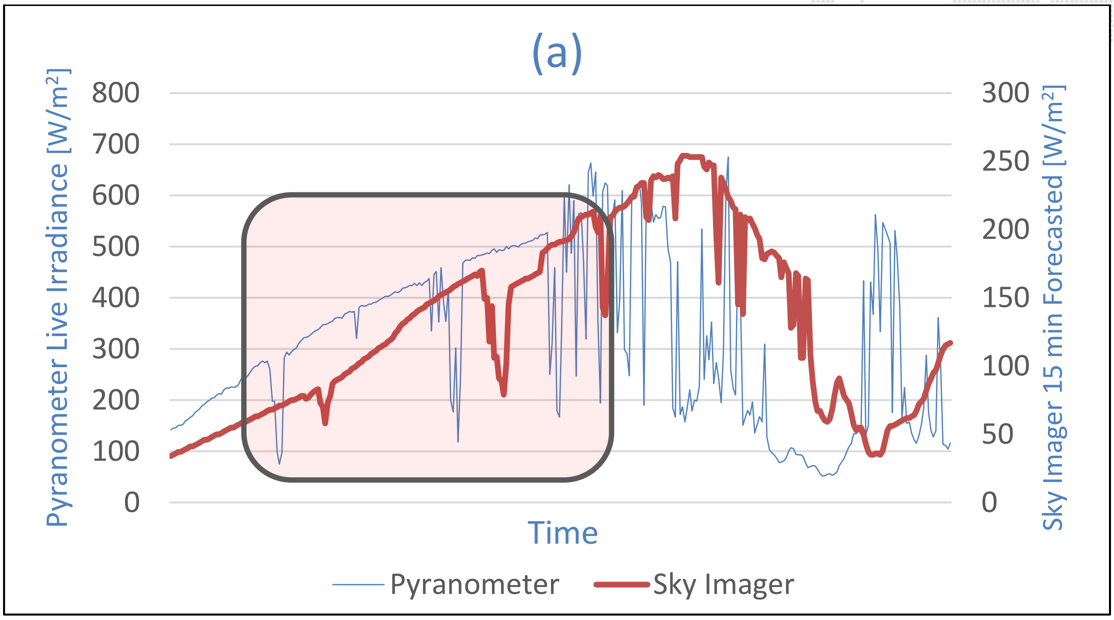


Figure 37: Pyranometer measurement [T=15] vs. Sky-imager [T=0]; 15 Minute forecasting.

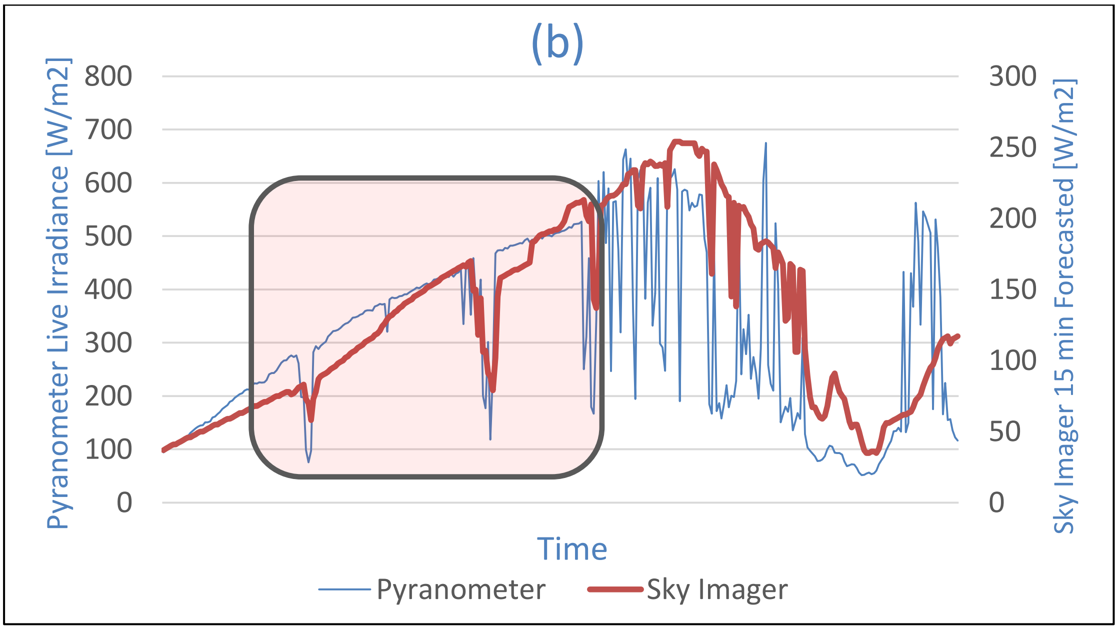


Figure 38: Pyranometer measurement [T=-4] vs. Sky-imager [T=0]; 15 Minute forecasting.

C. Ramp Rate Test

Test 1 Description:

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

SNO	AVERAGE RAMP (KW/SEC)	FAST RAMP		SLOW RAMP (KW/SEC)	RAMP STATUS
		Ramp kW/sec)	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

Average Fast Ramp up 737.5 kW/sec (Average Power % - 100%)

Average fast Ramp Down 722.6 kW/sec (Average Power % - 78%)

Test 2 Description:

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

SNO	AVERAGE RAMP (KW/SEC)	FAST RAMP		SLOW RAMP (KW/SEC)	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.

Average Fast Ramp up 556 kW/sec (Average Power % - 80%)

Average fast Ramp Down 497 kW/sec (Average Power % - 77%)

Test 3 Description:

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

SNO	AVERAGE RAMP (KW/SEC)	FAST RAMP		SLOW RAMP (KW/SEC)	RAMP STATUS
		Ramp kW/sec)	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.

Average Fast Ramp up 663 kW/sec (Average Power % - 86%)

Average fast Ramp Down 648 kW/sec (Average Power % - 80%)

Test 4 Description:

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

SNO	AVERAGE RAMP (KW/SEC)	FAST RAMP		SLOW RAMP (KW/SEC)	RAMP STATUS
		Ramp kW/sec)	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 15: Ramp Test 4.

Average Fast Ramp up 695 kW/sec (Average Power % - 88%)

Average fast Ramp Down 717 kW/sec (Average Power % - 87%)

Test 5 Description:

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

Average Fast Ramp up 788 kW/sec (Average Power % - 80%)

Average fast Ramp Down 779 kW/sec (Average Power % - 81%)

Test 6 Description:

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

SNO	AVERAGE RAMP (KW/SEC)	FAST RAMP		SLOW RAMP (KW/SEC)	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 16: Ramp Test 6.

Average Fast Ramp up 784 kW/sec (Average Power % - 108%)

Average fast Ramp Down 772 kW/sec (Average Power % - 87%)

Test 7 Description:

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

SNO	AVERAGE RAMP (KW/SEC)	FAST RAMP		SLOW RAMP (KW/SEC)	RAMP STATUS
		Ramp kW/sec)	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 17: Ramp Test 7.

Average Fast Ramp up 1000 kW/sec (Average Power % - 93%)

Average fast Ramp Down 835 kW/sec (Average Power % - 78%)

Fast Ramp up: Average % Power 89%

Fast Ramp down: Average % Power 80%

D. Open Loop Test | Real Power Availability

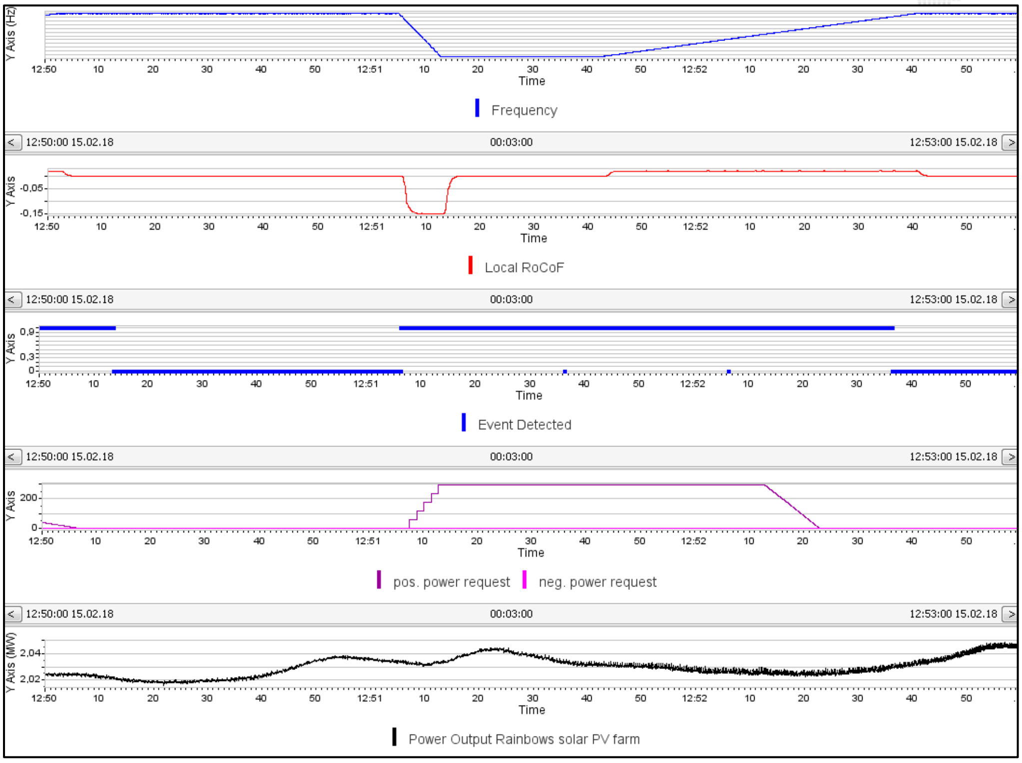


Figure 39: Under Frequency Event (48.85 Hz) | Power Availability ±300 kW | Power Request -293 kW.

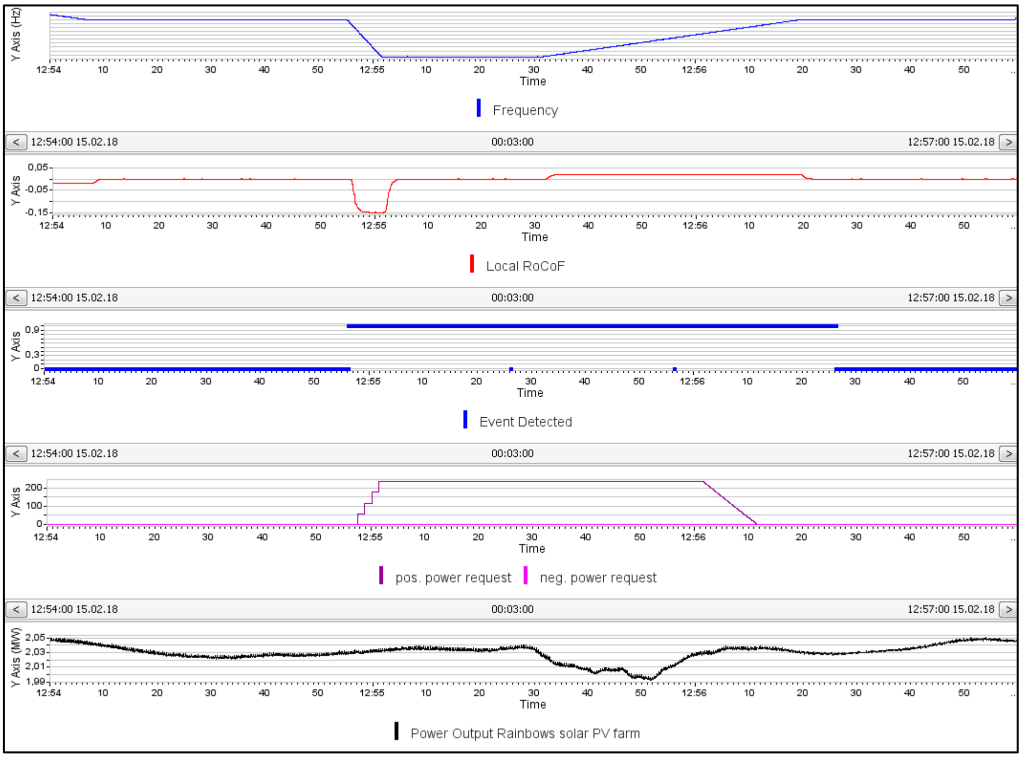


Figure 40: Under Frequency Event (49.05 Hz) | Power Availability ±300 kW | Power Request -234 kW.

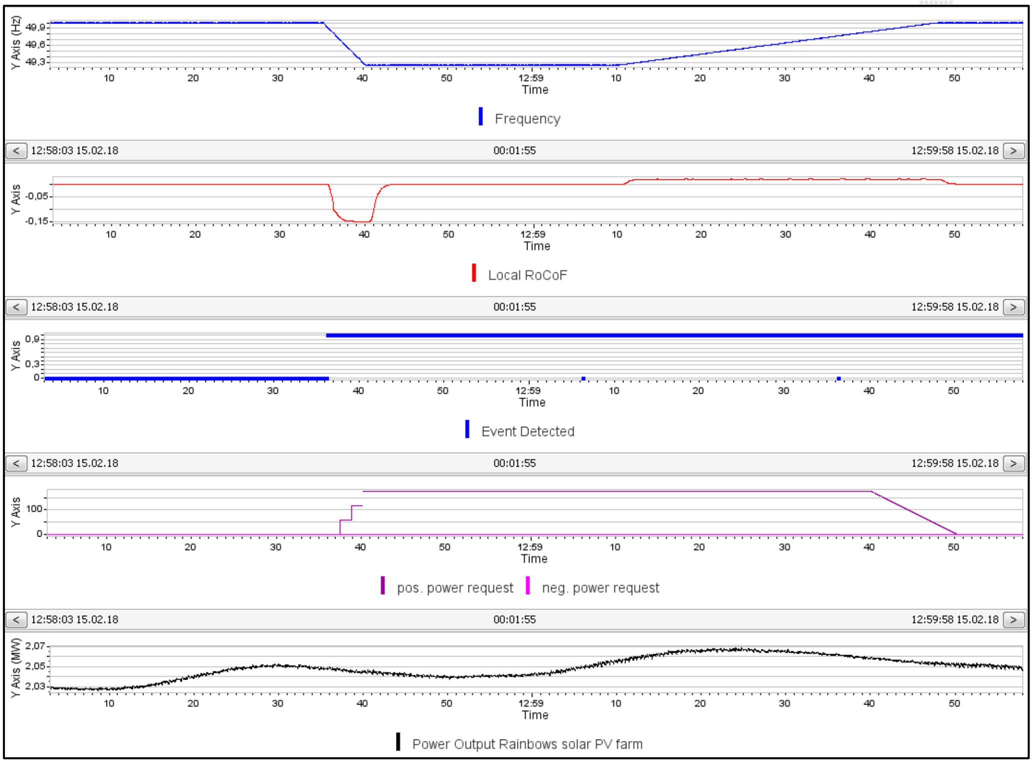


Figure 41: Under Frequency Event (49.25 Hz) | Power Availability ±300 kW | Power Request -175 kW.

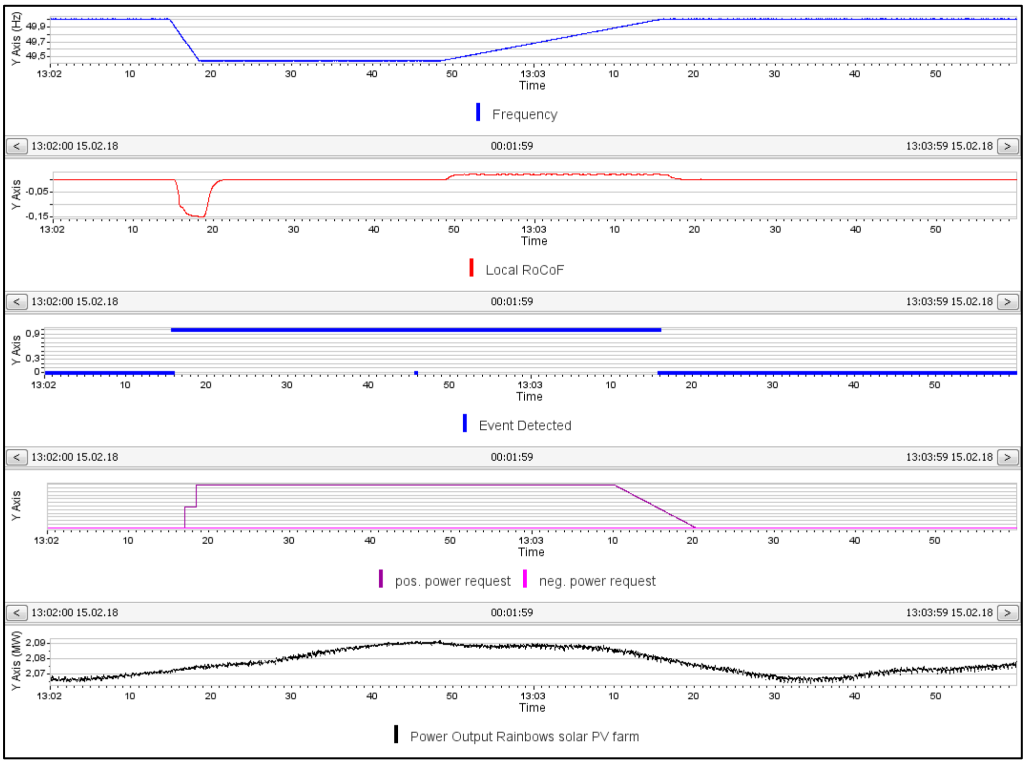


Figure 42: Under Frequency Event (49.45 Hz) | Power Availability ±300 kW | Power Request -117 kW.

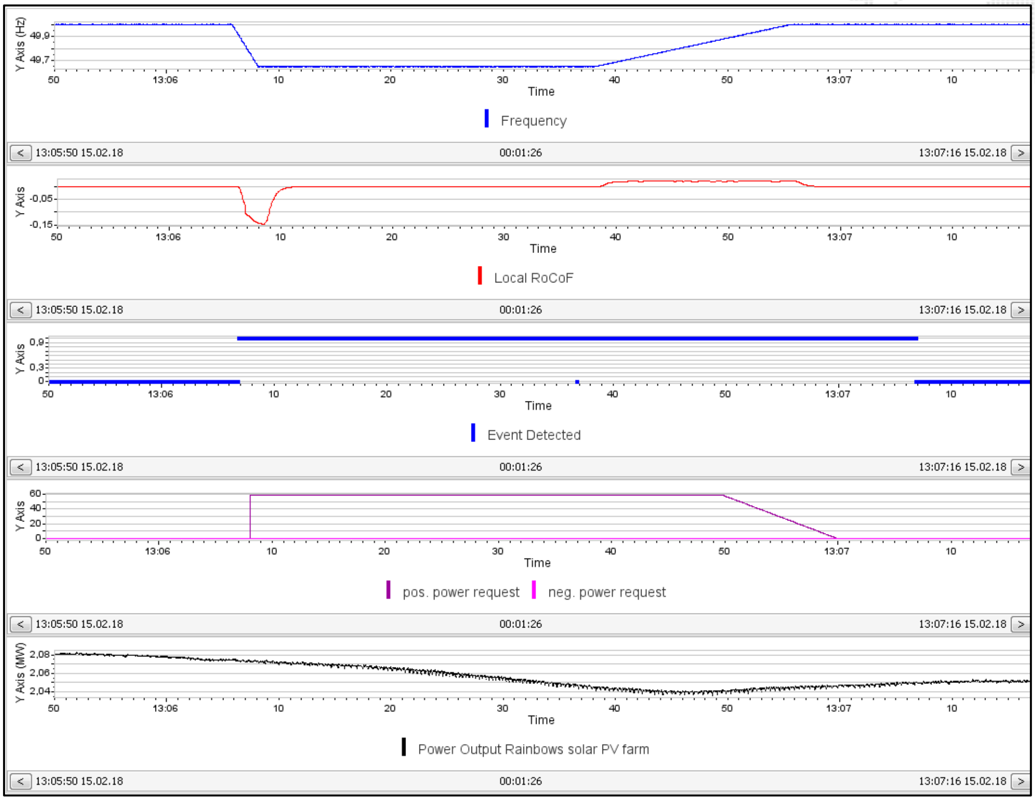


Figure 43: Under Frequency Event (49.65 Hz) | Power Availability ±300 kW | Power Request -58.6 kW.

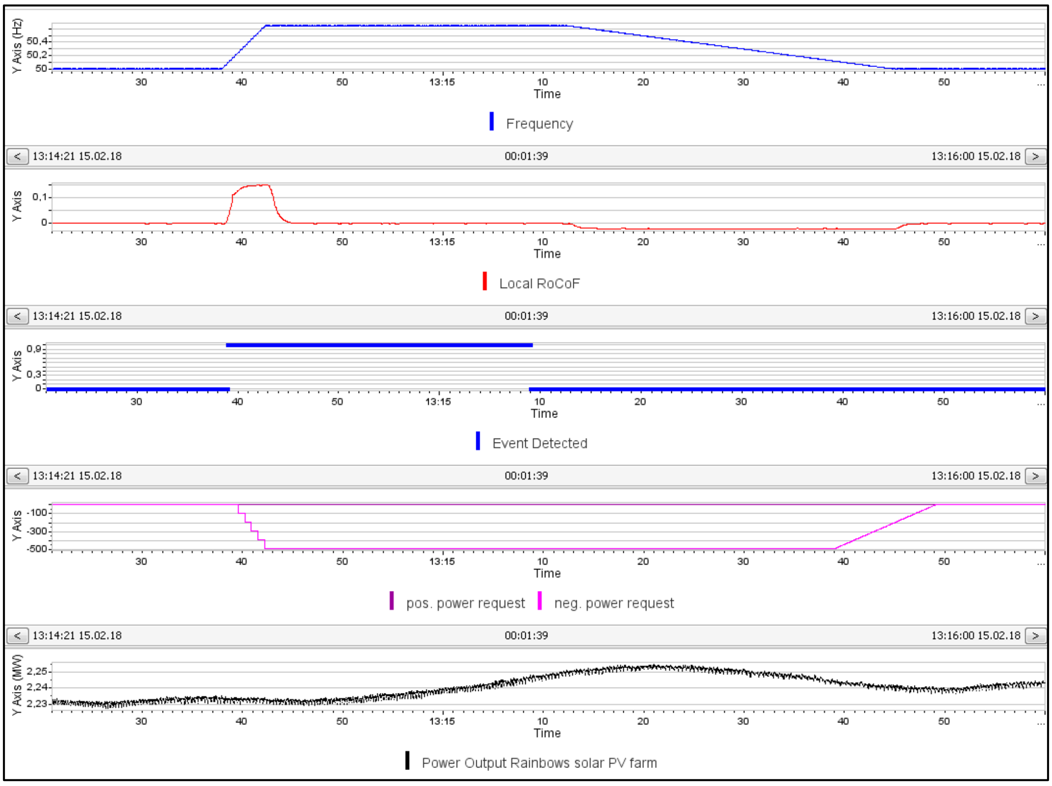


Figure 44: Under Frequency Event (48.85 Hz) | Power Availability ±300 kW | Power Request -489 kW.

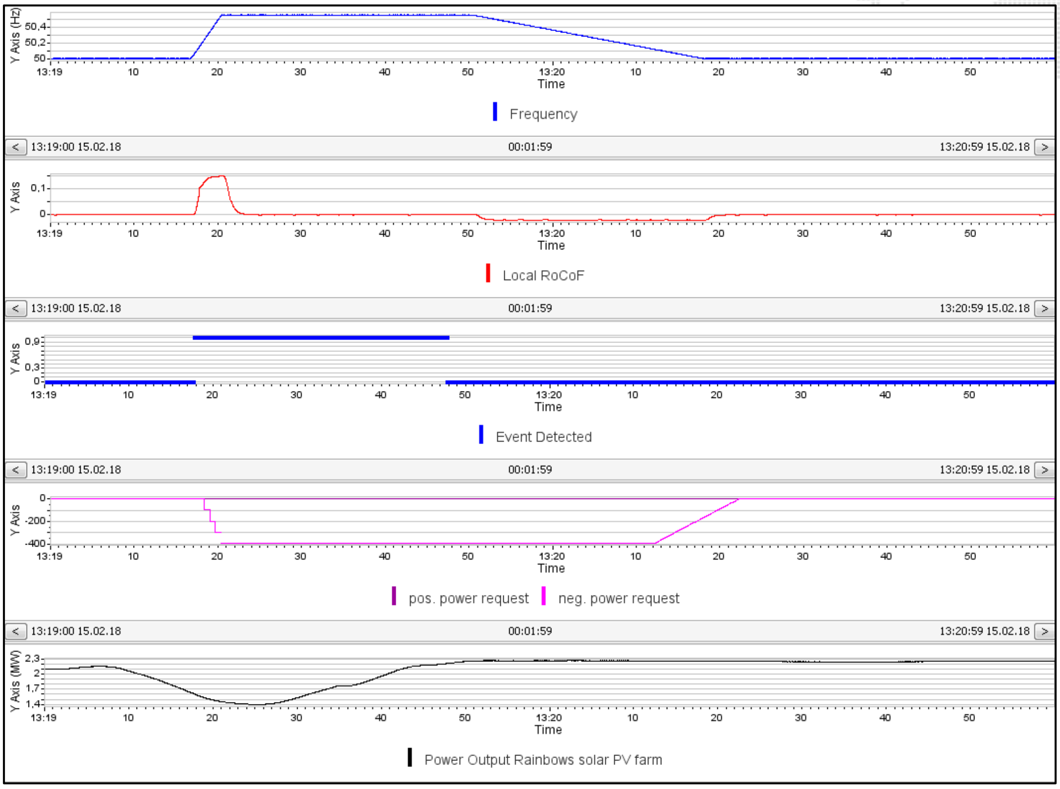


Figure 45: Over Frequency Event (49.05 Hz) | Power Availability ±492 kW | Power Request -391 kW.

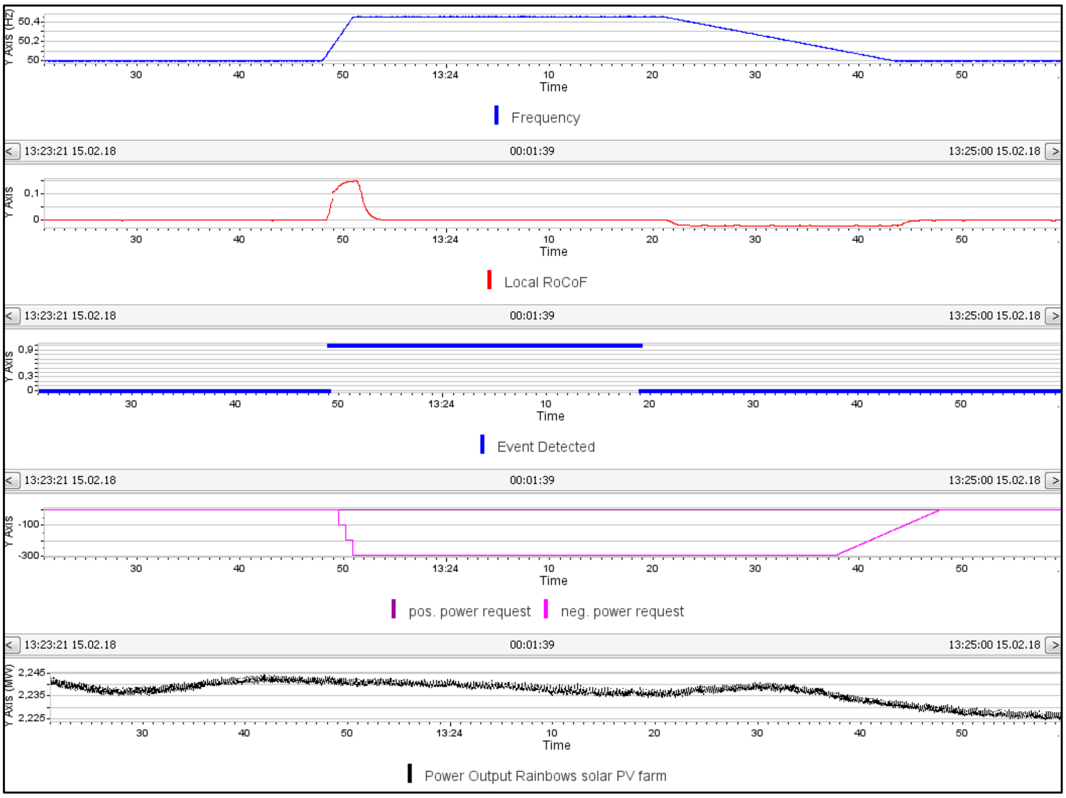


Figure 46: Over Frequency Event (49.25 Hz) | Power Availability ±492 kW | Power Request -293 kW.

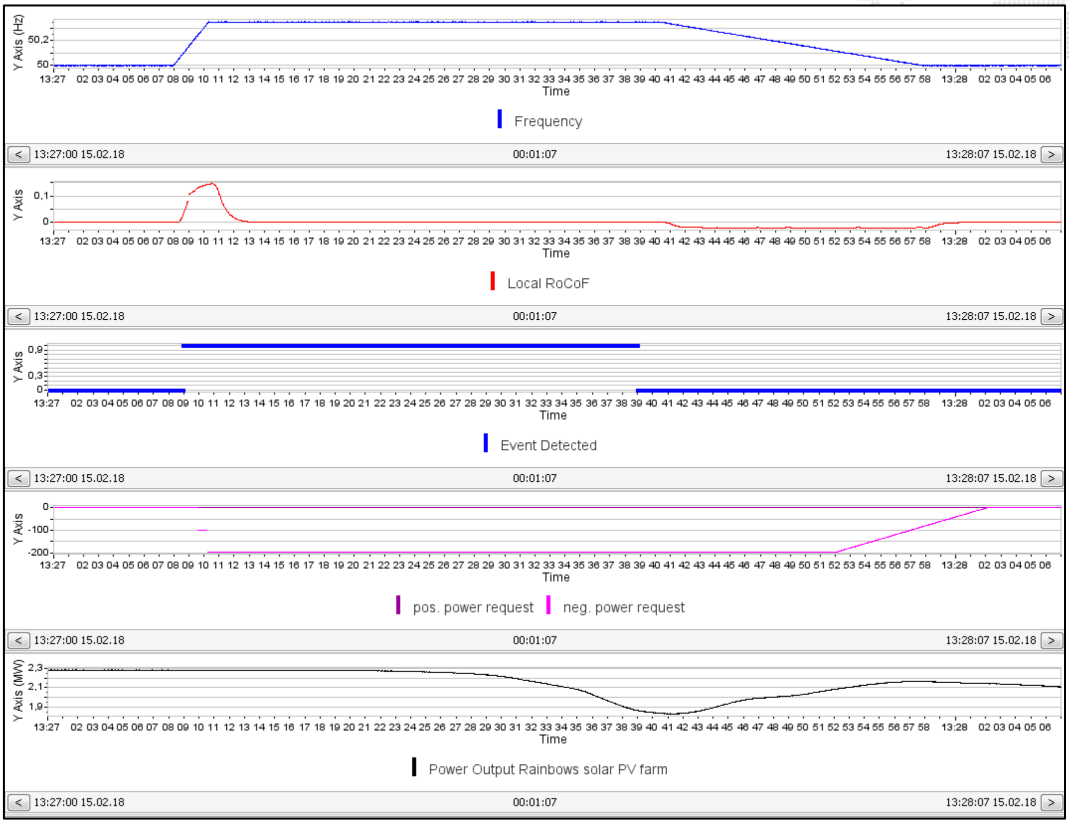


Figure 47: Over Frequency Event (49.45Hz) | Power Availability ±489 kW | Power Request -195 kW.

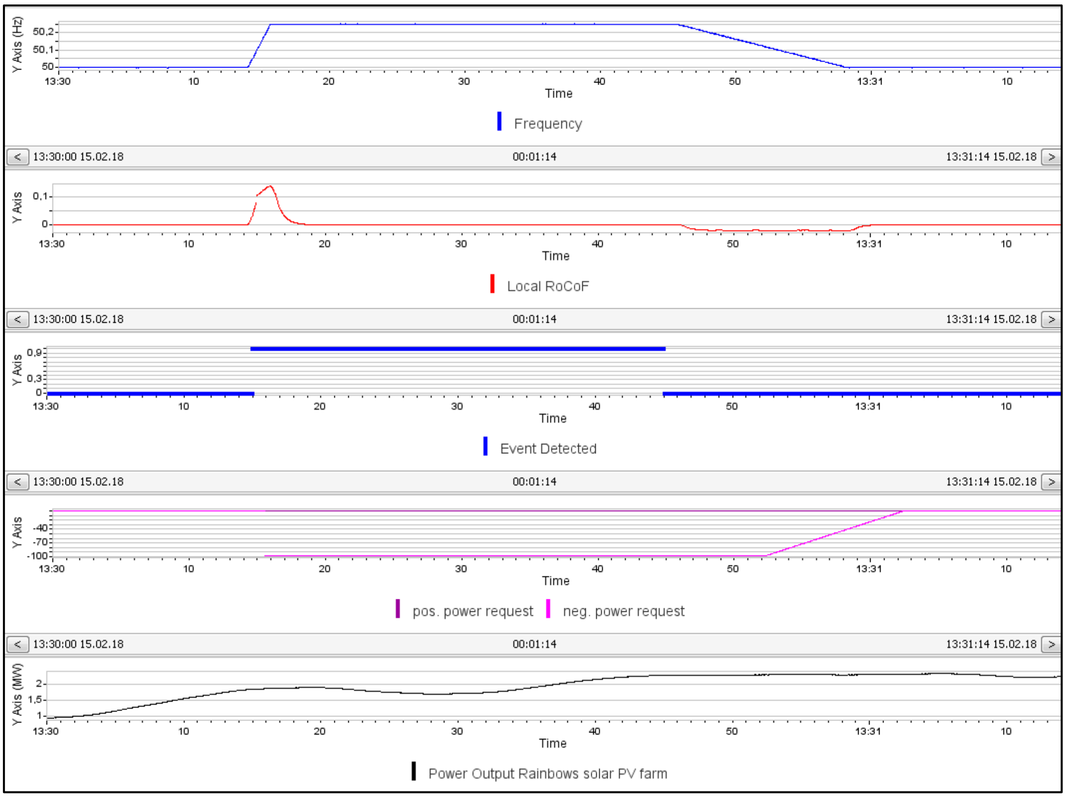


Figure 48: Over Frequency Event (49.65Hz) | Power Availability ±488 kW | Power Request -97 kW.

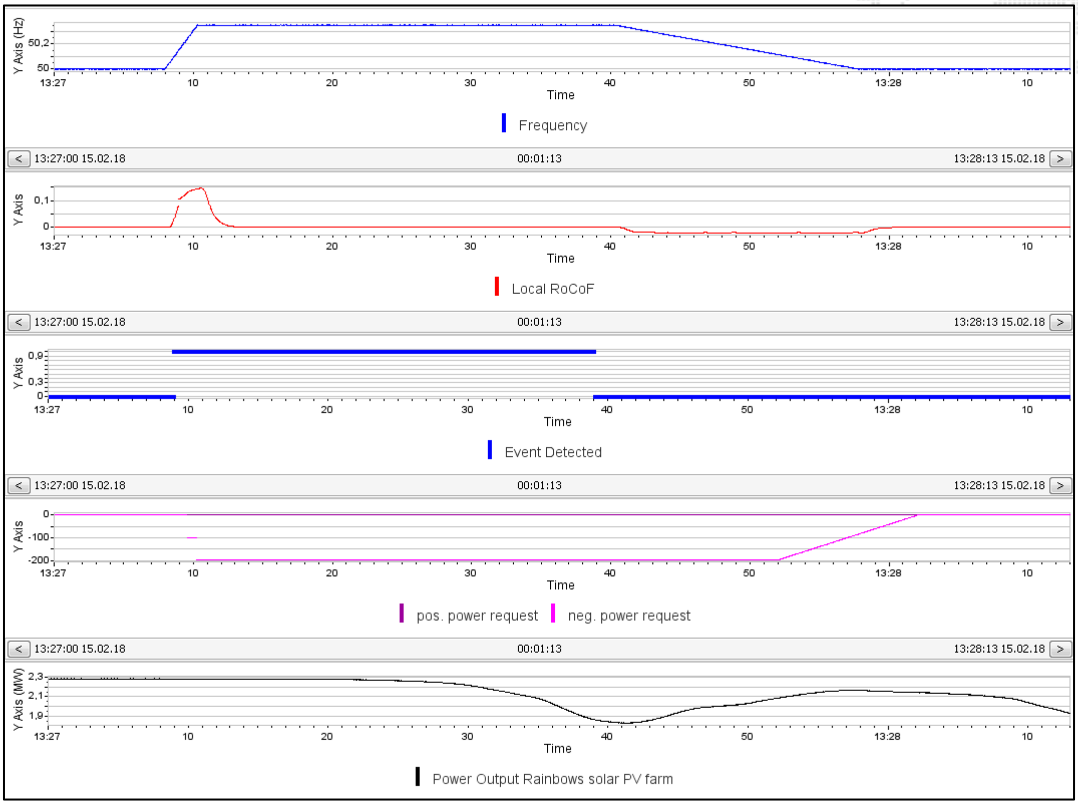


Figure 49: Over Frequency Event (49.65 Hz) | Power Availability ±300 kW | Power Request -58.6 kW.