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Testing of the Enhanced Frequency Control Capability (EFCC) Scheme: Part 1 - Local Operational Mode

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Version No.:	1.0	
Prepared By:	Dr Qiteng Hong	
Reviewed By:	Dr Ibrahim Abdulhadi	Prof Campbell Booth
Authorised By	David Rutherford	
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EXECUTIVE SUMMARY

This report presents the methods and results relating to tests conducted at the Power Network Demonstration Centre (PNDC) at the University of Strathclyde (UoS) for validating the Enhanced Frequency Control Capability (EFCC) scheme. This work is part of the EFCC project led by National Grid under Ofgem's Network Innovation Competition (NIC) funding framework.

The EFCC scheme has two main operational modes: wide-area mode, used when wide-area communication links are available and with sufficiently good quality; local mode, when the wide-area communication links are lost or have relatively poor quality. The Local Controller (LC) within the scheme can also be intentionally set to operate in local mode if required. The test activities at the PNDC have been conducted in two main stages, corresponding to the two operational modes mentioned earlier. The first stage is focused on testing the local mode, while the second stage concentrates on testing the wide-area operational mode using a Power-Hardware-in-the-Loop (P-HiL) test setup, which was established and configured specifically for the EFCC testing regime. For the wide-area mode tests, the impact of communication performance on the EFCC scheme's operation was also evaluated. Therefore, the final test report contains three main parts, i.e. local mode tests, wide-area mode tests (with ideal communication network conditions), and communication impact tests.

This document constitutes the first part of the overall final test report and presents the results from the first stage of tests concerned with evaluating EFCC performance when operating in local mode. In this mode, the LC does not have access to wide-area measurement signals (or it neglects those signals if the controller has been intentionally set to operate in local mode). Test results for the EFCC system's performance in wide-area mode and the impact of communication performance on EFCC will be reported in separate documents.

In the tests, analogue voltage signals from RTDS simulations are used to control the 1 MW-rated Motor-Generator (MG) set at the PNDC to emulate various frequency events on the physical test network. A physical PMU is connected to the PNDC's physical network to measure and pass local measurement data as input to the EFCC LC. A controllable 100 kW load bank is used as the resource under the control of the LC; this control is effected through communications using the Modbus protocol. The operation of the LC is tested under a variety of system conditions: under-frequency (with different overall magnitudes of frequency dips and rates-of-change), over-frequency (with different overall magnitudes of frequency rises and rates-of-change) and fault events (with varying durations and voltage depressions) for a range of different EFCC configurations and under conditions that reflect a range of different resource availabilities. These tests are used to understand the operation of the scheme and to de-risk it (through modifications and remedial interventions to the EFCC hardware and software) prior to its deployment in the field. The tests also contribute greatly to the understanding of the EFCC scheme's operation, its effectiveness and its impact on system operation, and provide information that is being, and will continue to be, used in dissemination exercises and by the project partner GE in modifying and enhancing the functionality of the EFCC scheme.

During the tests, several instances of non-optimal, and in some cases undesirable, EFCC system behaviour were identified and observed (e.g. failure to automatically switch to local mode when required, non-operation during certain frequency disturbances, etc.), which have been reported to GE. GE has worked to update the system in response to these observations and multiple upgraded versions of the system have been released during the test programme to address the identified issues and improve certain aspects of the system's operation. As mentioned earlier, this has also provided useful learning relating to the practical applications of the EFCC scheme and de-risking it in advance of field trials and adoption in business as usual.

The results presented in this report relate to the latest version of the controller and show that the LC is capable of successfully detecting both under- and over-frequency events and deploying the required amount of resource as appropriate. Various levels of delay in event detection and resource allocation have been observed. During fault events, all physical faults applied in the PNDC network have been successfully detected and no resource has been incorrectly deployed. A delay of approximately 0.5 s in fault detection has been observed following the fault voltage threshold being violated. It was advised by GE that such behaviour is expected and the delay is caused by the low pass filter implemented in the controllers.

This report also highlights a number of aspects of the scheme which do not affect the fundamental operation, but could potentially be improved. Recommendations for such improvements and a summary of the experience gained that could be useful for rolling out the system are also presented.

LIST ABBREVIATIONS

CS	Central Supervisor
EFCC	Enhanced Frequency Control Capability
LC	Local Controller
NG	National Grid
NIC	Network Innovation Competition
PMU	Phasor Measurement Unit
PNDC	Power Networks Demonstration Centre
RA	Regional Aggregator
SAT	Site Acceptance Test
UoM	University of Manchester
UoS	University of Strathclyde

Contents

1 INTRODUCTION

The role of the UoS within the EFCC project is to provide a realistic testbed using the facilities at the PNDC and conduct comprehensive validation of the scheme against its design specifications. The test activities present a complementary stage of validation to the tests conducted at the University of Manchester (UoM), where a Hardware-in-the-Loop (HiL) configuration has been established to evaluate the EFCC's performance within a purely simulation-based environment. At PNDC, the EFCC controllers are interfaced with a physical load bank and receive measurements from a physical PMU measuring the physical network voltage, offering a highly realistic test environment prior to field trials and grid deployments. The test activities have been defined in the test proposal document [1], which was developed by UoS, UoM, NG and GE.

The EFCC scheme has two main operational modes, wide-area and local mode. The wide-area mode is considered as the normal operational mode and is used when wide-area measurement signals are available and with sufficiently good quality, while the local mode is used when the wide-area communication links are lost or the wide-area data quality is too poor for making reliable system wide decisions. The LC can also be intentionally set to operate in local mode if required. Therefore, the test activities have been conducted in two main stages corresponding to both of the LC's operational modes.

The first stage aims to verify the controller's response to various events to test its dependability and security when operating in local mode. The LC's responses are compared to the expected responses defined by GE. The tests use network models in the RTDS to conduct a wide range of simulations, where the associated signals are used to control the MG set to drive the network to emulate a wide range of under and over-frequency events. Faults are also applied in simulation and in the PNDC physical network to test the security of the LC under its local mode, i.e. the capability to remain stable for events that do not require frequency response.

The second stage will incorporate wider-ranging closed-loop tests for testing the wide area operational mode of the scheme, including two LCs and three Regional Aggregators (RAs). An emulated Central Supervisor (CS) is used to supply resource information to the LCs. The EFCC scheme will also be assessed from the perspective of dependability under a range of frequency events and from the perspective of security under non-frequency events. By closing the loop, the effectiveness of the control actions from the LCs to restore the frequency will also be examined. Furthermore, the impact of the communications system's latency and jitter upon the performance of the EFCC scheme will also be evaluated in this stage of test.

This test report presents test activities and results of the first stage test of test for validating the LC's local mode. The test results for the second stage wide area mode tests will be presented in a separate report.

This document is organised as follows: in Section 2, the objectives for the tests are defined; the test configuration is described in Section 3; the limitations of the tests are described in Section 4; the test results for under-frequency events are presented in Section 5, for over-frequency events in Section 6, and for fault events in Section 7. Conclusions of the tests and recommendations for potential improvements of the EFCC scheme and future work are provided in Section 8.

2 OBJECTIVES

According to the EFCC user manual produced by GE [2], it is known that in local mode, the LCs operate purely based on the local PMU measurements. The LCs will automatically switch to this mode when the wide-area measurement signals become unavailable (or the quality of the data received is not sufficiently high for wide-area operation[1]). Alternatively, the LCs can also be intentionally configured to operate in the local mode through settings, where the wide-area signals will be ignored even when they are available and with good quality.

In the local mode, the LCs will control the resource to provide response in five stages, each stage operates according to a frequency and RoCoF threshold in the resource allocation block. The use of RoCoF thresholds is optional and they can be enabled or disabled with a dedicated setting. When the RoCoF thresholds are disabled, LCs only use the measured frequency for decision making and when the frequency exceeds each of the five pre-defined thresholds, 20% of available resource will be deployed. When the RoCoF thresholds are enabled, LCs evaluate both measured frequency and RoCoF values using the associated thresholds, and only when the frequency and RoCoF thresholds are both violated, 20% of available resources will be deployed at each stage. It should be noted that in the event detection block, there are also a frequency and a RoCoF threshold, but they are only used for detecting whether there is a frequency disturbance and not for determining the amount of the resource to be deployed. More details about the frequency and RoCoF thresholds are available in the EFCC user manual [2].

The LCs are also equipped with a fault detector for the local mode to identify disturbances caused by electrical faults in the network, thereby blocking the event being detected as a frequency event (i.e. mismatch of demand and generation) and resource being deployed unnecessarily.

The objectives of the tests presented in this report are to perform comprehensive validation of the LCs' functions in the local mode as described above, and they are described in more detail in the following subsections.

2.1 Validation of the communication interfaces between the EFCC controllers and the physical PMU with the PNDC facilities

At PNDC, five EFCC controllers (three RAs and two LCs) and one physical PMU were received for the testing. During the Site Acceptance Test (SAT), initial validation of the communication interface was conducted, i.e. it was demonstrated that the devices can successfully communicate with each other and also with the PNDC facilities, e.g. the RTDS, the PC hosting PhasorPoint (Phasor Data Concentrator), the PC with Straton (a software platform for LC and RA configuration), the load bank, etc. However, there are a number of aspects that were not validated during the SAT:

- the local PMU was previously connected to an Omicron amplifier as opposed to the physical network, so an appropriate connection point in the Low Voltage (LV) test bay at PNDC should be identified and a voltage transformer with appropriate specification is required to interface the PMU with the LV test bay connection point.
- the communication switch used during the SAT was from GE, but the actual switch used for testing is from Cisco (IE4010), where different configuration is required.
- the configuration of the data being communicated was not validated, e.g. the conversion of positive response command from the LC need to be specifically configured so as to provide meaningful input to the load bank to adjust the load level; the PMU need to be properly configured to reflect the actual voltage level of physical network and the installed VT ratio.

The issues listed above were not addressed during the SAT and are covered in this set of tests to avoid any undesirable behaviours of the EFCC scheme resulting from inappropriate setup of the scheme and the testbed.

[1] More detail on how the quality of the received data will affect the operation of the EFCC scheme is provided in the report " Testing of the Enhanced Frequency Control Capability (EFCC) Scheme: Part 3 - Communication Tests ".

2.2 Evaluation of the dependability of the EFCC controllers

Dependability is originally defined for evaluating the capability of protection systems to operate for faults that require protection action. In this project, this term is used to evaluate the EFCC scheme's capability to react to frequency events (i.e. events leading to power imbalance in the system) that require control actions (i.e. frequency response). It measures the sensitivity of the EFCC scheme to detect frequency events and send control commands.

In this set of tests, the dependability of the EFCC scheme under its local mode will be comprehensively tested through evaluating its behaviour in a wide range of under- and over-frequency disturbances with different settings and resource availability conditions.

2.3 Evaluation of the security of the EFCC controllers

Security is a term that is also originally used in protection systems to indicate the capability to stay stable (i.e. non-operation) in non-fault situations. In this work, the term is used to represent the capability of the EFCC scheme to remain stable during non-frequency events that do not require frequency response (e.g. faults), i.e. the EFCC scheme should not detect faults as frequency events and should not deploy a frequency response.

In this set of tests, different types of faults are applied in the physical network. These faults will lead to different levels of voltage dip and frequency deviation, which allows the comprehensive testing of the EFCC scheme's behaviour under different scenarios.

3 TEST CONFIGRUATION

Figure 1 shows the test configuration at the PNDC for testing the LC's local mode. A network model was created in RTDS, where different network disturbance scenarios can be emulated. The frequency signal from the emulated events is used as the input to the specially-designed frequency controller, which controls the MG set to precisely follow the frequency command signals. The design of this dedicated controller is described in detail in [3]. The controlled MG set drives the PNDC physical network, which contains both HV (11 kV) and LV (400V) voltage levels. A physical PMU is connected to the LV network bay collecting the local measurement for the LC using the IEEE C37.118.2 standard [4]. The load bank is also connected to the LV network, acting as the resource to be controlled by the LC. Local resource availability information is encoded in the Straton workstation. When a frequency event occurs, the LC will make decisions purely based on the local PMU measurement and the resource availability information. If frequency response is required, a command will be sent from the LC to the load bank using the Modbus protocol [5].

Figure 2 shows a number of other facilities and software packages used in the tests. The PC running RSCAD is used to configure the RTDS network model and triggering various disturbance events. The Straton PC allows the configuration of the logics among various EFCC functional blocks and the visualisation of values of the associated variables being used by the functional blocks [2]. The PhasorPoint PC hosts Phasor Data Concentrator (PDC), i.e. the server that captures all the IEEE C37.118.2 PMU streams, which also includes a set of inputs and outputs from the LCs and RAs. The PhasorPoint PC and the PC running RSCAD are the main devices for capturing test data.

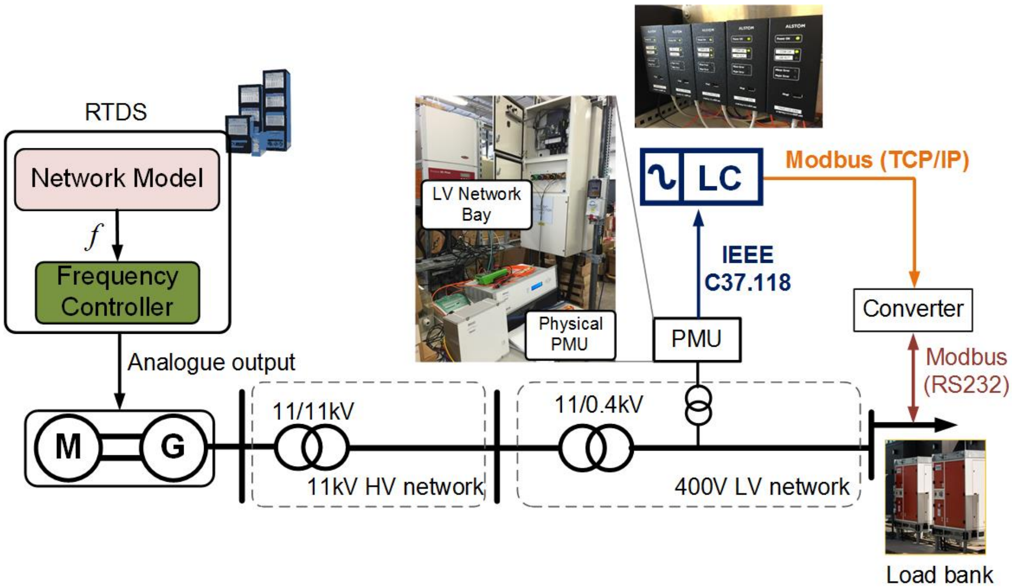

Figure 1. Schematic of the first stage local mode test configuration

Figure 2. (a) PC running RSCAD; (b) PCs hosting Straton and PhasorPoint

4 TEST LIMITATIONS AND ASSUMPTIONS

Although the test environment has been specifically designed and implemented to be realistic, there are a number of limitations that are unavoidable compared to an actual environment where the controllers are ultimately installed. These limitations are listed as follows:

- When testing the RoCoF and frequency thresholds in the LC that govern the event detection and resource allocation, events are emulated to be above and below the thresholds to test whether the system would react or not respectively. The marginal error in RoCoF and frequency measurements violating specified thresholds and triggering an LC response are only partly evaluated in these tests.
- Although the tests are carried out on a physical network, which is more realistic than simulation-based tests, it is anticipated that the system's behaviour will not always match that of a real grid. For example, during fault tests, the network is driven by an MG set which has relatively small inertia, whereas in a real environment, the LC could be installed in a distribution network connected fed from a strong grid, so the frequency, RoCoF and voltage dynamics could be different from what was observed in the tests.

While the fundamental working mechanism of the EFCC scheme was explained by GE via training sessions and the user manual, it should be noted that the implementation of the algorithms of the scheme are not transparent to PNDC, so the nature of the tests conducted are black-box tests and will therefore requires some input from GE to interpret the test results.

5 UNDER-FREQUENCY TESTS

In this set of tests, events that lead to different frequencies below nominal levels and RoCoF values will be emulated in the PNDC physical network for testing the LC's performance during under-frequency events. The following two main scenarios will be tested:

- LC only uses frequency thresholds, with RoCoF thresholds disabled
- LC uses both frequency and RoCoF thresholds for resource allocation

The first scenario allows the test of the LC's functionality of the five frequency thresholds, while the second scenario allows further validation of the RoCoF thresholds. In the tests presented in this section, the LC is commanded to operate in local mode through the dedicated setting with all the RAs connected and streaming data. The LC is expected to ignore all the wide-area signals and only use local measurement for decision making. Additional tests are reported in Appendix A, where wide area communication channels are intentionally disconnected, thus validating the LC's function to switch from wide area mode to local mode.

In all of the tests presented in this section, the resource availability information is listed in Table 1. It should be noted that

Table 1. Resource availability information of the load bank

Parameter	Value
Availability	True
Positive available power	50 kW
Negative available power	50 kW
Positive power response time	1 s
Negative power response time	1 s
Power ramp up rate	30 kW/s
Power ramp down rate	30 kW/s
Positive power max duration	10 s
Negative power max duration	10 s

5.1 LC only uses frequency thresholds for resource allocation with RoCoF thresholds disabled

In the following tests, the RoCoF thresholds are disabled, i.e. the LC will make decisions based only on the measured frequency values. The associated settings for the tests are listed in Table 2. The LC is still connected to the RAs but it is intentionally set to local mode through its setting, so the wide-area monitoring signals are expected to be neglected and only local measurements will be used for decision making.

Table 2. Settings in the LC for Test UF-1

Logical node: EvDeTFRC1 (Event Detection)	
Under-frequency RoCoF threshold (sUnFreqRCFThr)	0.12 Hz/s
Under-frequency threshold (sUnFreqThr)	0.6% (0.3 Hz)
Local mode status (sLocCtrl)	True

Logical node: RsrcAIGAPC1 (Resource Allocation)	
RoCoF thresholds status (sUseRCFLims)	False
Frequency thresholds (Hz, sFrqLThr)	49.7, 49.6, 49.5, 49.4, 49.3
Local mode status (sLocCtrl)	True

5.1.1 Test UF-1.1: frequency nadir does not violate any under-frequency thresholds

In this test, a loss of generation event that results in frequency nadir above all the under-frequency thresholds is triggered, i.e. no frequency threshold is violated, **so no resource should be dispatched**.

The test results are shown in Figure 3. The first plot is the frequency in the physical network measured using the RTDS virtual PMU and the physical PMU (data from PhasorPoint). The second plot is the RoCoF value measured by the LC and retrieved from PhasorPoint. The third plot shows the event detection flag signal recorded in PhasorPoint; the fourth plot shows the positive and negative response commands from the LC recorded in PhasorPoint; the fifth plot shows the active power output from the MG set recorded in the RTDS; and the last plot is the voltage measurement at the MG set terminal in the HV network using the RTDS PMU and the LV network (load bank connection point) using the physical PMU respectively. It can be seen that the data has been collected from two sources, i.e. RTDS and PhasorPoint – this is because the PhasorPoint does not have access to the MG set terminal measurements, so the power output from the MG set needs to be recorded in RTDS[2]. In the rest of the section, the same plot arrangement will be used for presenting test results, so the meaning of each plot will not be repeated. Key points in time are heighted using dashed lines and a number.

Table 3 provides a list of key observations during the tests. The event occurs at 1.50 s (T_1), following which the frequency starts to decrease. At around 3.70 s (T_2), the RoCoF value measured by the LC violated the event detection threshold 0.12 Hz/s and the event detection flag becomes true. The frequency drops to its nadir 49.73 Hz at around 5.80s (T_3), which is above the first frequency threshold. From the fourth plot, it can be seen that no resource is deployed, which is as expected. During the frequency disturbance, the voltage level (shown in the last plot) measured at the HV and the LV point experienced a level of disturbance as well, which results in the change in measured demand level at the MG set output. However, it is clear that no change to the load level was instructed by the LC.

In this test, the LC was not expected to provide any response and from the test results, it can be seen that the LC has successfully behaved as required.

[2] The presented data has been processed so that the time of the recorded data set from two sources is aligned. The frequency signal recorded in RTDS and the physical PMU has been used for aligning the data.

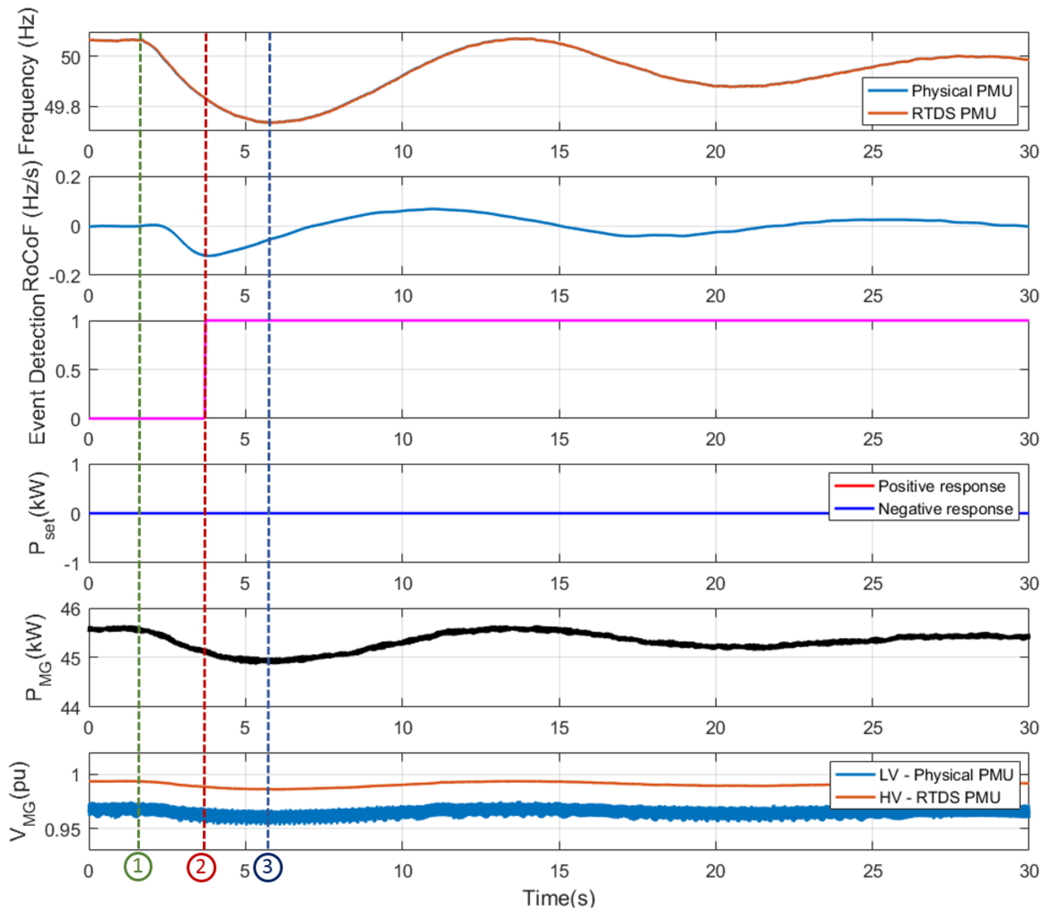

Figure 3. Results for Test UF-1.1

Table 3. Key observations from Test UF-1.1

Time	Observations
1.50 s (T_1)	Event occurs
3.70 s (T_2)	RoCoF drops below -0.12 Hz/s and event detection flag becomes high
5.85 s (T_3)	Frequency drops down to the nadir of 49.73 Hz

5.1.2 Test UF-1.2: validation of the first under-frequency threshold

In this test, the LC is tested in an under-frequency event that leads to a frequency nadir between 49.6 Hz and 49.7 Hz. The frequency nadir is below the setting of the first under-frequency threshold but above all the other thresholds, **so it is expected that only 20% of the resource should be deployed**.

The test results are shown in Figure 4 and key observations are listed in Table 4. The event occurs at 1.50 s (T_1), which leads to the largest RoCoF of around 0.1 Hz/s at 3.80 s (T_2). This is still below the event detection RoCoF threshold, so the event detection flag remains low. The frequency drops below 49.7 Hz at 4.80 s, which violates the event detection frequency threshold and also the first stage resource allocation under frequency threshold.

The event is detected at 5.92s (T_3) with 20% of the resource deploy at the same time. Following the command, the load starts to drop from 44.48 kW to 36.20 kW at around 6.57s (T_4). The resource deployment command remains at 10 kW until 11.38 s when the frequency recovers above 49.7 Hz and the resource command starts to ramp down.

The LC has successfully performed its function in this test. However, an approximate delay of 0.65 s between the command signal change and the actual change in the load level was observed.

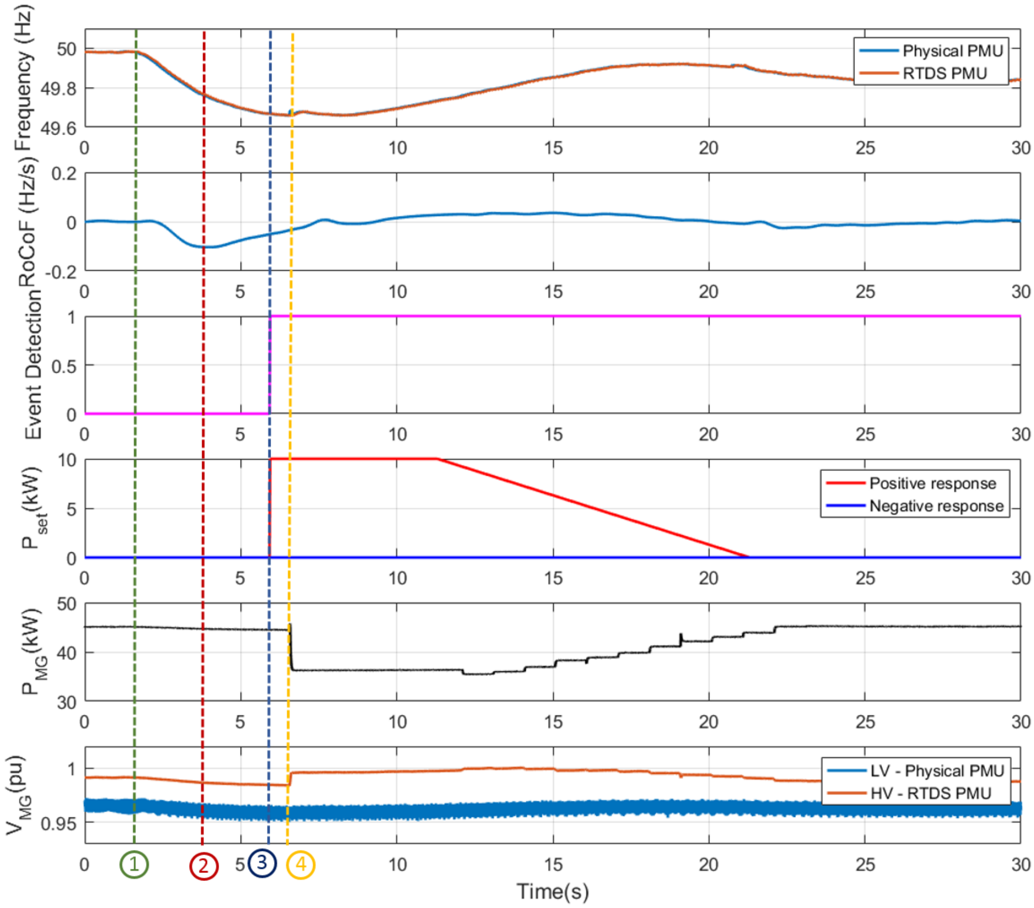

Figure 4. Results for Test UF-1.2

Table 4. Key observations from Test UF-1.2

Time	Observations
1.50 s (T_1)	Event occurs
3.80 s (T_2)	RoCoF drops to its minimum value of -0.1 Hz/s
4.80 s	Frequency drops below 49.7 Hz
5.92 s (T_3)	The event detection flag becomes high and 10kW (20%) of positive response requested by the controller
6.57 s (T_4)	Load drops from 44.48 kW to 36.20 kW
11.38 s	LC starts to ramp down positive response request
13.09 s	Load starts to ramp up

5.1.3 Test UF-1.3: validation of the second under-frequency threshold

In this test, the LC will be tested in an under-frequency event that leads to a frequency nadir between 49.5 Hz and 49.6 Hz. The frequency nadir is below the setting of the first two under-frequency thresholds but above the other thresholds, **so it is expected that a total of 40% of the resource should be deployed.**

The test results for Test UF-1.3 are shown in Figure 5 and key observations are listed in Table 5. The event occurs at 1.50s (T_1), which leads to the RoCoF violating the event detection threshold -0.12 Hz/s and the event detection flag becoming high at 3.70 s (T_2).

The event leads to a frequency nadir of 49.56 Hz, which violates the first two frequency thresholds, i.e. 49.7 Hz at 4.26 s and 49.6 Hz at 6.45 s. The LC correctly dispatched 20% of negative response at each step of frequency violation with an average delay of 0.35 s. Following on each positive response request command, the load bank successfully reduced its demand with an average delay of 0.74 s

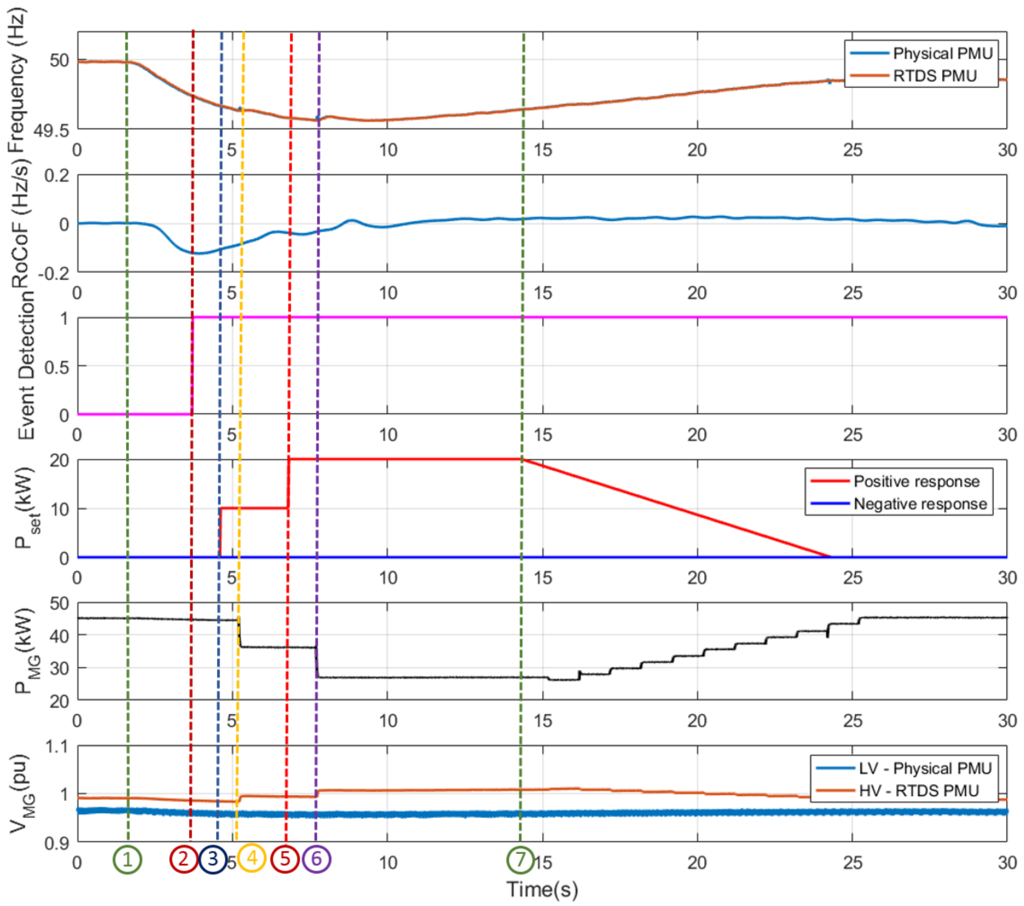

Figure 5. Results for Test UF-1.3

Table 5. Key observations from Test UF-1.3

Time	Observations
1.50 s (T_1)	Event occurs
3.70 s (T_2)	RoCoF drops below -0.12 Hz/s and event detection flag becomes high
4.26 s	Frequency drops below 49.7 Hz
4.60 s (T_3)	10kW (20%) of positive response requested by the controller
5.19 s (T_4)	Load drops from 44.45 kW to 36.20 kW
6.45 s	Frequency drops below 49.6 Hz
6.80 s (T_5)	Positive response request increases from 10kW to 20kW by the controller
7.69 s (T_6)	Load drops from 36.20 kW to 27.00 kW

12.50 s	Frequency recovers above 49.6 Hz
14.35 s (T_7)	LC starts to ramp down positive response request
15.18s	Load starts to ramp up

5.1.4 Test UF-1.4: validation of the third under-frequency threshold

In this test, an under-frequency event that leads to a frequency nadir between 49.4 Hz and 49.5 Hz will be emulated in the PNDC network. The frequency nadir is below the setting of the first three under-frequency thresholds but above the other thresholds, **so it is expected that a total of 60% of the resource should be deployed, with every 20% of the resource being dispatched when a frequency threshold is violated**.

The event results in a frequency nadir of approximately 49.44 Hz. The first three frequency thresholds are violated at 3.65 s, 6.38 s and 6.78s respectively. The LC correctly dispatched 20% of positive response at each step of frequency violation with an average delay of 0.47 s. Following on each positive response request command, the load bank successfully reduced its demand with an average delay of 0.54 s.

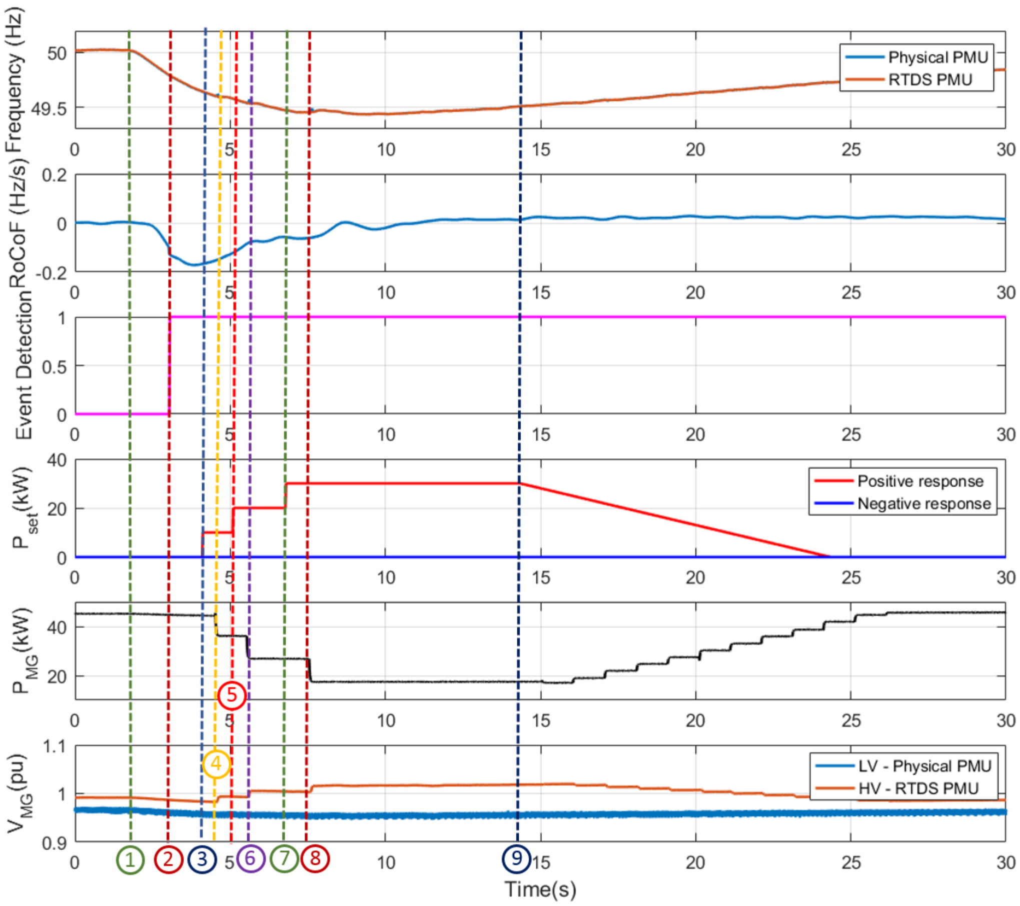

Figure 6. Results for Test UF-1.4

Table 6. Key observations from Test UF-1.4

Time	Observations
1.50 s (T_1)	Event occurs
3.03 s (T_2)	RoCoF drops below -0.12 Hz/s and event detection flag becomes high
3.65 s	Frequency drops below 49.7 Hz
4.10 s (T_3)	10 kW (20%) of positive response requested by the controller
4.51 s (T_4)	Load drops from 44.37 kW to 36.15 kW
4.55 s	Frequency drops below 49.6 Hz
5.08 s (T_5)	Positive response request increases from 10kW to 20kW by the controller
5.53 s (T_6)	Load drops from 36.10 kW to 26.86 kW
6.38 s	Frequency drops below 49.5Hz
6.78 s (T_7)	Positive response request increases from 20 kW to 30 kW by the controller
7.54 s (T_8)	Load drops from 26.81 kW to 17.37 kW
14.35 s (T_9)	LC starts to ramp down positive response request
15.04 s	Load starts to ramp up

5.1.5 Test UF-1.5: validation of the fourth under-frequency threshold

In this test, an under-frequency event that led to a frequency nadir between 49.3 Hz and 49.4 Hz was emulated in the PNDC network. The frequency nadir is below the setting of the first four under-frequency thresholds but above the last threshold, so it is expected that a total of 80% of the resource should be deployed, with every 20% of resource being dispatched when each frequency threshold is violated.

The test results for Test UF-1.5 are shown in Figure 7 and the key observations are listed in Table 7. The event occurs at 1.50s (T_1), which leads to the RoCoF violating the event detection threshold -0.12 Hz/s and the event detection flag becoming high at 2.94 s (T_2).

The event results in the frequency drops to just above 49.3 Hz. The first four frequency thresholds are violated at 3.38 s, 3.92s, 4.83s and 6.35s respectively. The LC correctly dispatched 20% of positive response at each step of frequency violation with an average delay of 0.525 s. Following on each positive response request command, the load bank successfully reduced its demand with an average delay of 0.9 s.

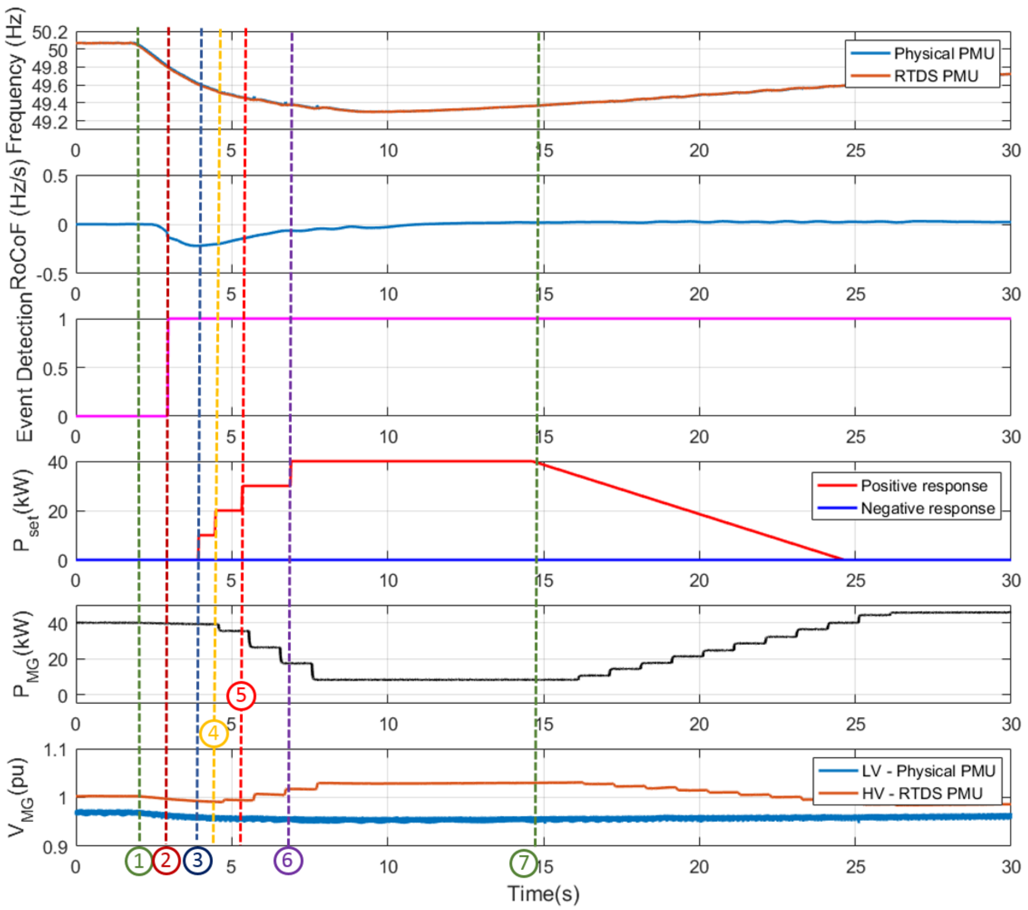

Figure 7. Results for Test UF-1.5

Table 7. Key observations from Test UF-1.5

Time	Observations
1.50 s (T_1)	Event occurs
2.94 s (T_2)	RoCoF drops below -0.12 Hz/s and event detection flag becomes high
3.38 s	Frequency drops below 49.7 Hz
3.92 s (T_3)	10 kW (20%) of positive response requested by the controller
4.56 s	Load drops from 39.24 kW to 35.5 kW
3.92 s	Frequency drops below 49.6 Hz
4.46 s (T_4)	Positive response request increases from 10 kW to 20 kW by the controller
5.52 s	Load drops from 35.43 kW to 26.44 kW
4.83 s	Frequency drops below 49.5 Hz
5.32s (T_5)	Positive response request increases from 20 kW to 30 kW by the controller
6.54 s	Load drops from 26.27 kW to 17.45 kW
6.35 s	Frequency drops below 49.4 Hz

6.88 s (T_6)	Positive response request increases from 30 kW to 40 kW by the controller
7.56 s	Load drops from 17.40 kW to 8.28 kW
14.66 s (T_7)	LC starts to ramp down positive response request
16.10 s	Load starts to ramp up

5.1.6 Test UF-1.6: validation of the fifth under-frequency threshold

In this test, an under-frequency event that leads to a frequency nadir below 49.3 Hz will be emulated in the PNDC network. The frequency nadir violates all of the resource allocation frequency thresholds, so it is expected that a 100% of the resource should be deployed, with every 20% of resource being dispatched when each frequency threshold is violated.

The test results for Test UF-1.6 are shown in Figure 8 and the key observations are listed in Table 8. The event occurs at 1.50 s (T_1), which leads to the RoCoF violating the event detection threshold -0.12 Hz/s and the event detection flag becoming high at 2.84 s (T_2).

The event results in the frequency dropping to just above 49.3 Hz. All of the five frequency thresholds are violated at 3.28 s, 3.80 s, 4.44 s, 5.45 and 7.22 s respectively. The LC correctly dispatched 20% of positive response at each step of frequency violation with an average delay of 0.46 s. Following on each positive response request command, the load bank successfully reduced its demand with an average delay of 1.2 s.

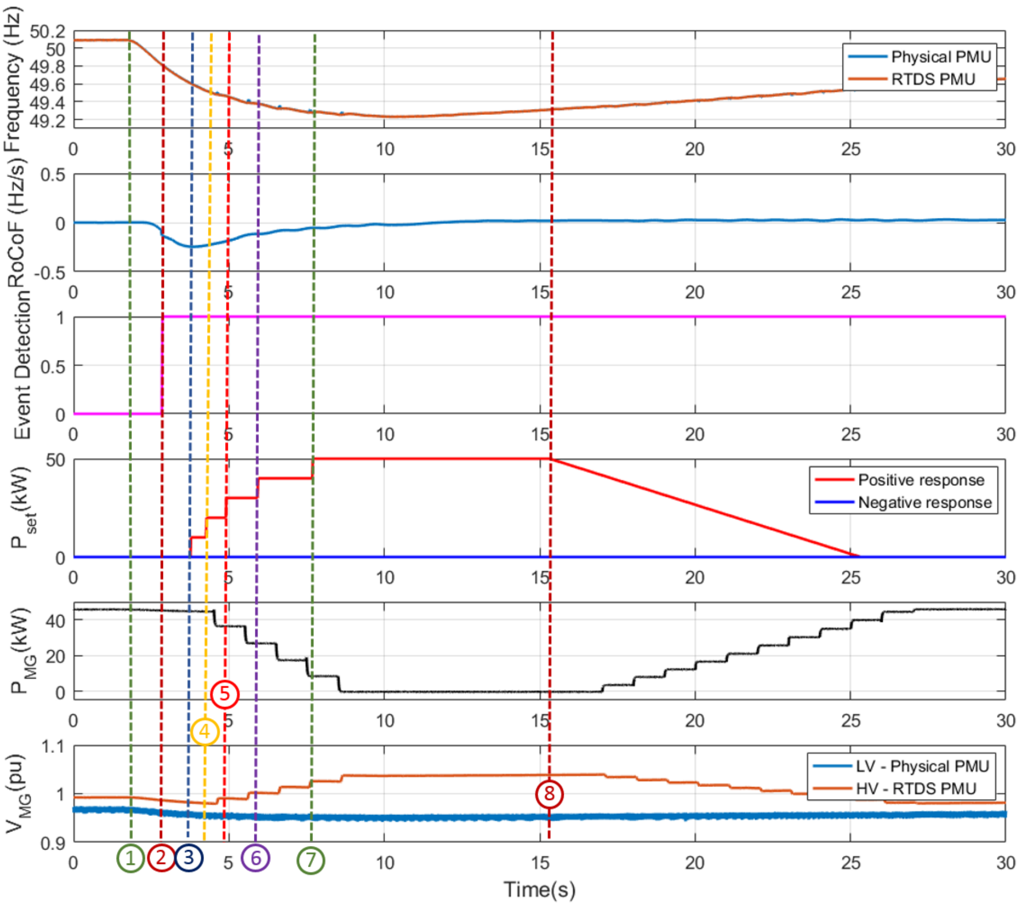

Figure 8. Results for Test UF-1.6

Table 8. Key observations from Test UF-1.6

Time	Observations
1.5 s (T_1)	Event occurs
2.84 s (T_2)	RoCoF drops below -0.12 Hz/s and event detection flag becomes high
3.28 s	Frequency drops below 49.7Hz
3.76 s (T_3)	10 kW (20%) of positive response requested by the controller
4.51 s	Load drops from 44.6 kW to 36.4 kW
3.80 s	Frequency drops below 49.6 Hz
4.26 s (T_4)	Positive response request increases from 10 kW to 20 kW by the controller
5.51 s	Load drops from 36.56 kW to 26.83 kW
4.44 s	Frequency drops below 49.5Hz
4.90 s (T_5)	Positive response request increases from 20 kW to 30 kW by the controller
6.51 s	Load drops from 26.71 kW to 17.33 kW
5.45 s	Frequency drops below 49.4 Hz
5.92 s (T_6)	Positive response request increases from 30 kW to 40 kW by the controller
7.49 s	Load drops from 17.33 kW to 8.38 kW
7.22 s	Frequency drops below 49.3 Hz
7.68 s (T_7)	Positive response request increases from 40 kW to 50kW by the controller
8.48 s	Load drops from 8.40kW to 0kW
15.32 s (T_8)	LC starts to ramp down positive response request
17.03 s	Load starts to ramp up

5.1.7 Summary of the under-frequency tests of LC's local mode with the RoCoF thresholds disabled

In this set of tests, the functionality of the LC when operating in local mode with RoCoF thresholds disabled has been tested under a range of frequency events that results in different levels of frequency nadirs.

The test results shows that the LC has successfully detected the events and deployed the required amount of resources based on the associated settings and design specification. However, various levels of delays have been observed:

- T_{d1}: time delay between the time when the frequency threshold being violated and the time a command is issued to deploy the resource
- T_{d2}: the delay between the time a command is issued to deploy the resource and the time the the load bank actually changes its load level.

The recorded T_{d1} from this set of tests are listed in Table 9 and plotted Figure 9 respectively. The overall average delay is approximately 0.58 s. As it can be seen from Figure 9, Test UF-1.2 has a relatively larger delay (>1 s) than others, while in the other tests the delay level is in the range of 0.3 - 0.6 s. It was commented by GE that that the larger delay is because the event detection is triggered by frequency not RoCoF in this test.

Table 9. T_{d1}: time delay in command issuing following frequency violation

	Test UF-1.1	Test UF-1.2	Test UF-1.3	Test UF-1.4	Test UF-1.5	Test UF-1.6	
Stage 1	-	1.12 s	0.34 s	0.48 s	0.54 s	0.48 s	
Stage 2	-	-	0.35 s	0.53 s	0.54 s	0.46 s	
Stage 3	-	-	-	0.40 s	0.49 s	0.46 s	
Stage 4	-	-	-	-	0.53 s	0.45 s	
Stage 5	-	-	-	-	-	0.46 s	
Average	-	1.12 s	0.35 s	0.47 s	0.53 s	0.46 s	0.58 s

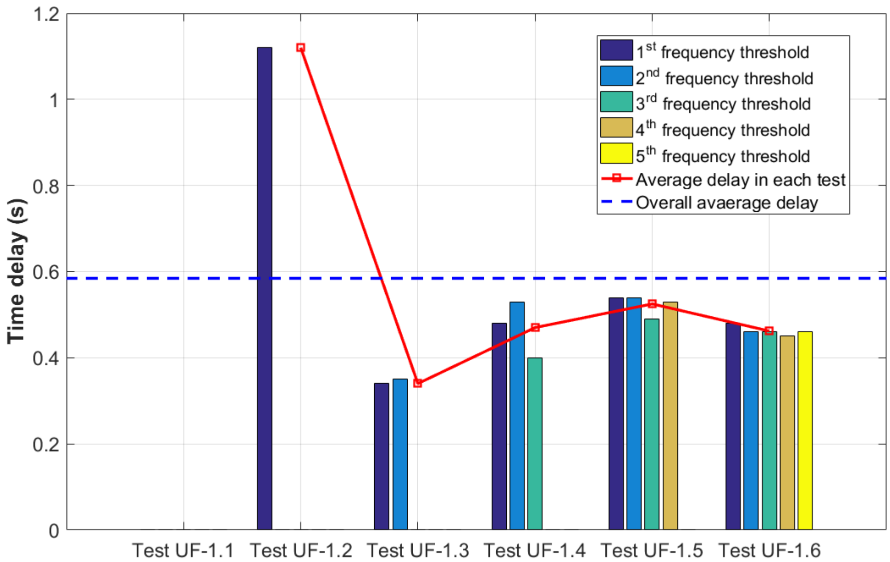

Figure 9. T_{d1}: time delay in command issuing following frequency violation

The recorded T_{d2} from this set of tests are listed in Table 10 and plotted Figure 10 respectively. The overall average delay is approximately 0.788 s. It is considered that this is caused by the way the load bank changes its load level following a command. As shown in Figure 11, when the load bank receives a command, it will change load level and hold that for around 1 s before it will change the load level again. This could be relating to the capability of the load bank in terms of how fast it can achieve the targeted power. The large variation in delay is considered to be caused by the time at the cycle when the LC sends the command.

Table 10. T_{d2}: delay between time when the command is issued to deploy resource and the time when the load bank actually changes its load level

	Test UF-1.1	Test UF-1.2	Test UF-1.3	Test UF-1.4	Test UF-1.5	Test UF-1.6
Stage 1	-	0.56 s	0.59 s	0.41 s	0.64 s	0.75 s
Stage 2	-	-	0.89 s	0.45 s	1.06 s	1.25 s
Stage 3	-	-	-	0.76 s	1.22 s	1.61 s
Stage 4	-	-	-	-	0.68 s	1.59 s
Stage 5	-	-	-	-	-	0.8 s
Average	-	0.56 s	0.74 s	0.54 s	0.9 s	1.2 s
Overall average: 0.788 s						

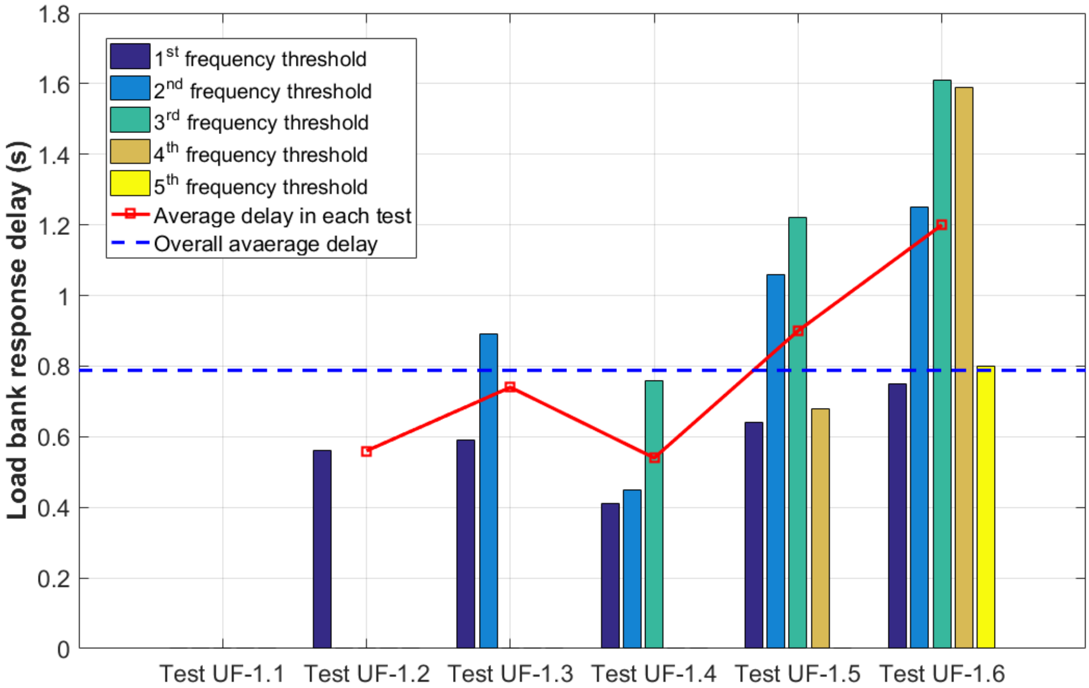

Figure 10. T_{d2}: delay between time when the command is issued to deploy resource and the time when the load bank actually changes its load level

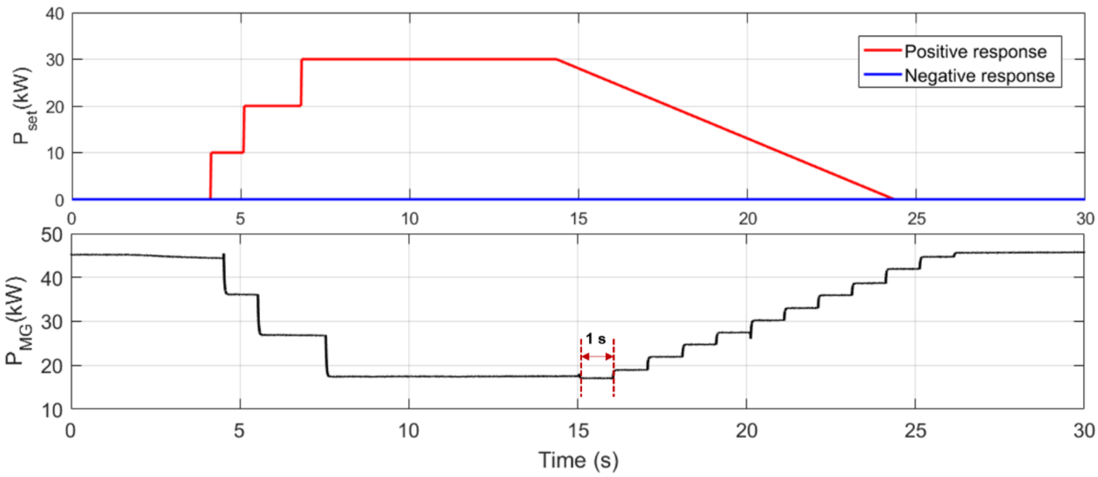

Figure 11. Load bank periodically changing its load level following the commands

5.2 LC uses both frequency and RoCoF thresholds for resource allocation

In this set of tests, the RoCoF thresholds are enabled in the local mode, i.e. the LC will make decisions based on both the measured frequency and RoCoF values. There are five RoCoF thresholds in the LC's resource allocation block, corresponding to five under-frequency thresholds. According to [2], the resource deployment will also be conducted in five stages with the RoCoF thresholds enabled. In each stage, only when both frequency and RoCoF violate the corresponding thresholds, 20% of the response will be deployed. It should be noted that the five frequency and five RoCoF thresholds being tested are in the resource allocation block and there is separate frequency and RoCoF thresholds in the event detection block. The resource deployment will only be triggered when both event detection and corresponding resource allocation thresholds are violated.

The validation of frequency thresholds has been conducted in Section 5.1. In this section, the operation of RoCoF thresholds are undertaken. Under-frequency events will be emulated in the PNDC network, which result in the violation of frequency thresholds, and the RoCoF thresholds are configured to be above and below the measured RoCoF to test LC's performance under both scenarios[3].

Table 11. Settings in the LC for Test UF-2

Logical node: EvDeTFRC1 (Event Detection)	
Under-frequency RoCoF threshold (sUnFreqRCFThr)	0.12 Hz/s
Under-frequency threshold (sUnFreqThr)	0.6% (0.3 Hz)
Local mode status (sLocCtrl)	True
Logical node: RsrcAlGAPC1 (Resource Allocation)	
RoCoF thresholds status (sUseRCFLims)	True
Local mode status (sLocCtrl)	True

[3] There is an alternative method for conducting these tests, where the RoCoF thresholds are kept unchanged and the disturbance events are chosen so that it leads to RoCoF above and below the thresholds. However, this could be difficult to implement as having an event causing different RoCoF will require a change of the event sizes (with the same overall inertial level) and when the event size is changed, the frequency nadir will also change, which makes the tests less comparable.

5.2.1 Test UF-2.1: validation of the first RoCoF threshold

In this subsection, an under-frequency event that leads to a frequency nadir between 49.6 Hz and 49.7 Hz will be emulated in the PNDC network to test the first RoCoF threshold in the resource allocation function block. Two tests will be conducted using the same frequency event (i.e. same loss of generation size and location), which will lead to the violation of the first frequency threshold (i.e. 49.7 Hz). In these two tests, the first RoCoF threshold is configured to be 0.1 Hz/s then 0.04 Hz/s, which corresponds to the cases where the measured RoCoF is above and below the RoCoF threshold.

5.2.1.1 Test UF-2.1a: the event violates the first frequency threshold, but does not violate the first RoCoF threshold

In this test, the frequency event will violate the first frequency threshold 49.7 Hz, but not the first RoCoF threshold 0.1 Hz/s, so the LC is expected to remain stable and not request any response from the resource. The detailed settings for the frequency and RoCoF thresholds are listed in Table 12.

The test results for Test UF-2.1a are shown in Figure 12 and the key observations from the test are listed in Table 13. The event occurs at 1.50 s (T_1), which leads to the largest RoCoF magnitude of 0.1 Hz/s at 3.56 s (T_2). From the settings shown in Table 13, it is know that this is within the event detection RoCoF threshold 0.12 Hz/s, so the event detection flag remains low at this point. The frequency continues to decrease to below 49.7 Hz at 4.96 s, which violates the event detection frequency threshold and the first resource allocation frequency threshold. The event detection flag becomes high at 5.90 s (T_3). No resource was requested.

From the test results, it can be seen that the LC has successfully detect the event, but did not request the resource to be deployed as required. However, there is a delay of approximately 0.94 s in event detection after the frequency threshold is violated. In the tests, it was observed that for the same event when the frequency drops to 49.7 Hz (i.e. the first frequency threshold), the magnitude of RoCoF value measured by the LC can vary approximately between 0.05-0.08 Hz/s. This is because even with the same loss of generation event, it is difficult to replicate the exact operating condition when the event occurs. During the test, the first RoCoF threshold setting was firstly chosen as 0.1 Hz/s and then decreased with a step of 0.01 Hz/s to 0.04 Hz/s, at which point the LC requested resource deployment.

Table 12. Resource allocation threshold settings for Test UF-2.1a

Thresholds	Frequency (sFrqLThr)	RoCoF (sRCFLims)
1	49.7 Hz	0.1 Hz/s
2	49.6 Hz	0 Hz/s
3	49.5 Hz	0 Hz/s
4	49.4 Hz	0 Hz/s
5	49.3 Hz	0 Hz/s

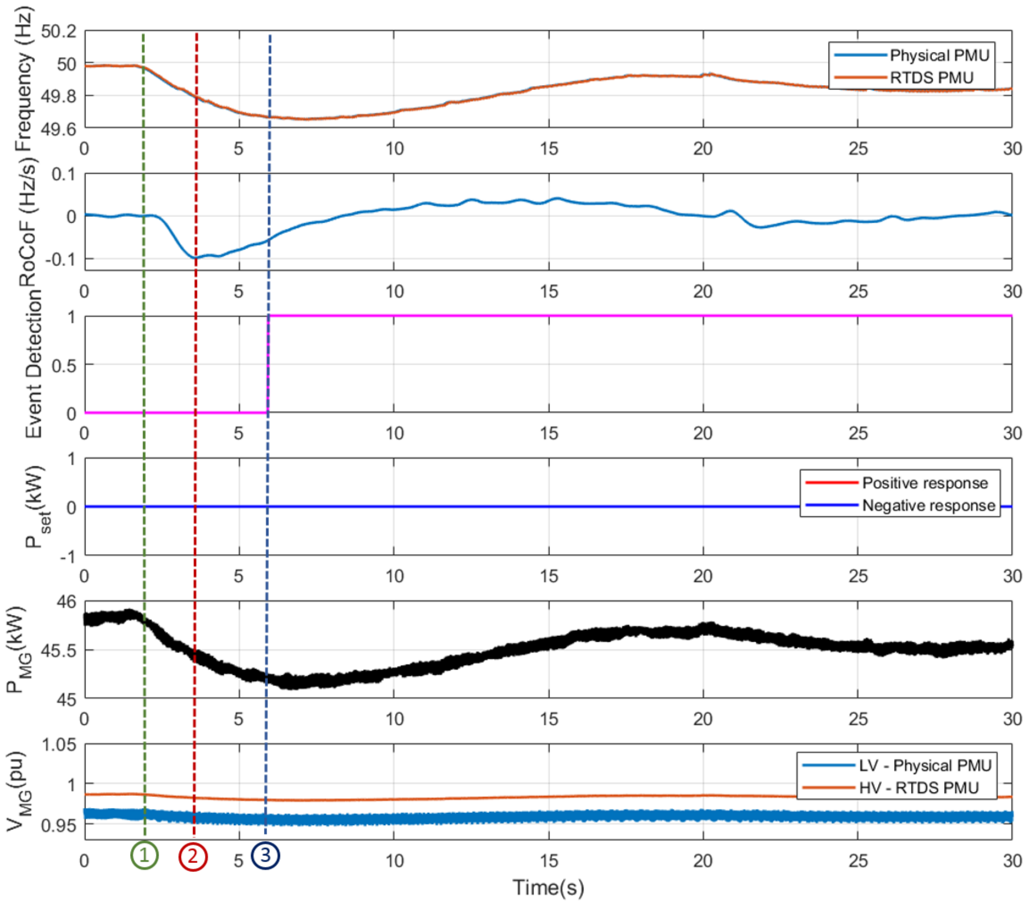

Figure 12. Results of Test UF-2.1a

Table 13. Key observations from Test OF-2.1a

Time	Observations
1.50 s (T_1)	Event occurs
3.56 s (T_2)	RoCoF drops to its minimum value of -0.10Hz/s
4.96 s	Frequency drops below 49.7Hz
5.90 s (T_3)	Event detection flag becomes high

5.2.1.2 Test UF-2.1b: both first frequency and RoCoF thresholds are violated

In this test, the same event as in Test UF-2.1a is re-played in the network. However, the first RoCoF threshold is now configured as 0.04 Hz/s as shown in Table 14, which means the event will violate both of the first frequency threshold and the first RoCoF threshold, so the LC is expected to request 20% of the resource to respond to the event.

The test results for Test UF-2.1b are shown in Figure 13 and the key observations from the test are listed in Table 15. The event occurs at 1.50 s (T_1), which leads to the largest RoCoF magnitude of 0.11 Hz/s at 3.92 s (T_2), which is less than the event detection RoCoF threshold 0.12 Hz/s, so the event detection flag remains low at this point. The frequency continues to decrease to below 49.7 Hz at 4.97 s, which is the event detection frequency threshold and the first resource allocation frequency threshold. The RoCoF magnitude at this point is 0.05 Hz/s, which is beyond the corresponding threshold. The event detection flag becomes high at 5.96 s (T_3) and 20% of the resource is requested as required at the same time.

From the test results, it can be seen that the LC has successfully detected the event and requested correct amount of resource. However, there is a delay of approximately 0.99 s in event detection after the frequency threshold is violated. No obvious delay in sending the command following the frequency and RoCoF threshold violation was observed, while a delay of about 0.84 s in load change following the command was observed.

Table 14. Resource allocation threshold setting for Test UF-2.1b

Thresholds	Frequency (sFrqLThr)	RoCoF (sRCFLims)
1	49.7 Hz	0.04 Hz/s
2	49.6 Hz	0 Hz/s
3	49.5 Hz	0 Hz/s
4	49.4 Hz	0 Hz/s
5	49.3 Hz	0 Hz/s

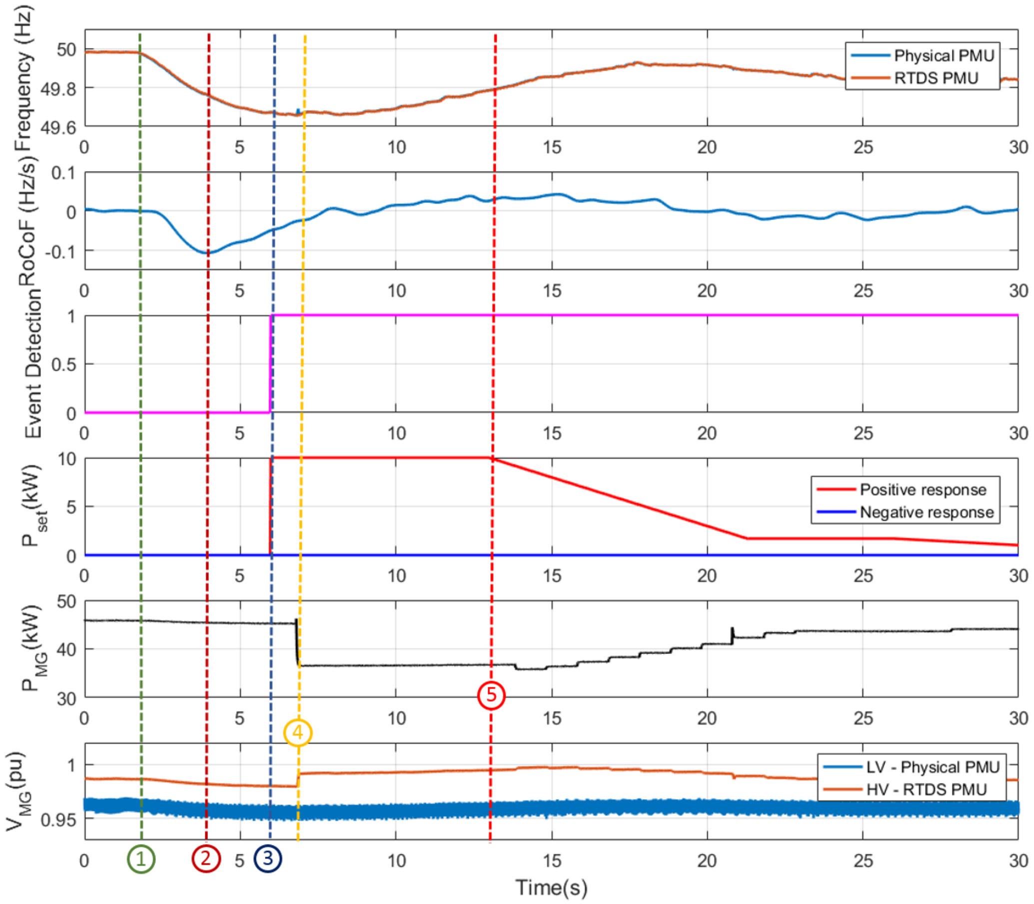

Figure 13. Results of Test UF-2.1b

Table 15. Key observation of Test UF-2.1b

Time	Observations
1.50 s (T_1)	Event occurs
3.92 s (T_2)	RoCoF drops to its minimum value of -0.11 Hz/s
4.97 s	Frequency drops below 49.7 Hz
5.96 s (T_3)	Event detection frequency threshold is violated and its flag becomes high. The RoCoF value at this point is -0.05 Hz/s. 10 kW (20%) of positive response requested by the controller.
6.80 s (T_4)	Load drops from 45 kW to 36.55 kW
13.00 s(T_5)	LC starts to ramp down positive response request
13.80 s	Load starts to ramp up

5.2.2 Test UF-2.2: validation of the second RoCoF threshold

In this subsection, an under-frequency event that leads to a frequency nadir between 49.5 Hz and 49.6 Hz will be emulated in the network to test the second RoCoF threshold in the resource allocation block. Two tests will be conducted using the same frequency event, which will lead to the violation of the second frequency threshold (i.e. 49.6 Hz). In these two tests, the second RoCoF threshold is configured to be 0.06 Hz/s and 0.04 Hz/s, which corresponds to the cases where the measured RoCoF is above and below the RoCoF setting.

5.2.2.1 Test UF-2.2a: the frequency violates the second threshold, but does not violate the second RoCoF threshold

In this test, the frequency event will violate the second frequency threshold 49.6 Hz, but not the second RoCoF threshold 0.06 Hz/s, so the LC is expected to request only 20% of power due to the violation of the first frequency and RoCoF thresholds. The detailed settings for the frequency and RoCoF thresholds are listed in Table 16.

The test results for Test UF-2.2a are shown in Figure 14 and the key observations from the test are listed in Table 17. The event occurs at 1.50s (T_1), which leads to RoCoF dropping below -0.12 Hz/s at 3.47 s (T_2), which is event detection RoCoF threshold, so the event detection flag becomes high at 3.48 s. The frequency continues to drop and violate the first frequency and RoCoF thresholds, which results in 20% of the resource be requested and deployed. At 6.37 s, the frequency decreases below 49.6 Hz, which is the second resource allocation frequency threshold with a RoCoF of -0.036 Hz/s, i.e. the corresponding RoCoF threshold is not violated, so no additional resource is requested.

From the test results, it can be seen that the LC has successfully detected the event and deployed 20% of the resource. However, there is a delay of approximately 0.01 s in event detection after the event detection RoCoF threshold is violated. The delay between the threshold violation and the issuing of the command is approximately 0.48 s; and the delay between the command and the load change is approximately 0.45 s.

Table 16. Resource allocation threshold setting for Test UF-2.2a

Thresholds	Frequency (sFrqLThr)	RoCoF (sRCFLims)
1	49.7 Hz	0.08 Hz/s
2	49.6 Hz	0.06 Hz/s
3	49.5 Hz	0 Hz/s
4	49.4 Hz	0 Hz/s
5	49.3 Hz	0 Hz/s

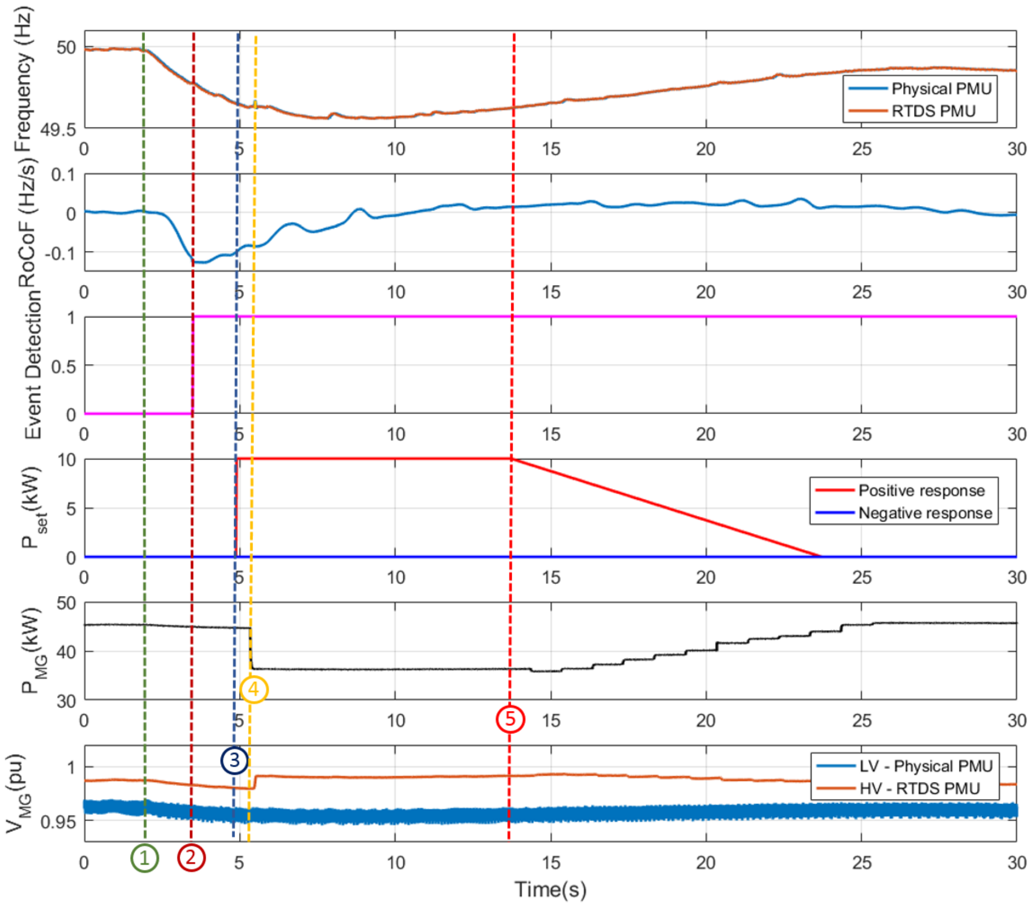

Figure 14. Results of Test UF-2.2a

Table 17. Key observation of Test UF-2.2a

Time	Observations
1.50 s (T_1)	Event occurs
3.47 s (T_2)	RoCoF drops to below -0.12 Hz/s
3.48 s	Event detection flag becomes high
4.40 s	Frequency drops below 49.7Hz with RoCoF of -0.11Hz/s
4.88 s (T_3)	10 kW (20%) of positive response requested by the controller.

5.33 s (T_4)	Load drops from 44.62 kW to 36.47 kW
6.37 s	Frequency drops below 49.6 Hz with RoCoF of -0.036 Hz/s
13.74 s (T_5)	LC starts to ramp down positive response request
14.33 s	Load starts to ramp up

5.2.2.2 Test UF-2.2b: both second frequency and RoCoF thresholds are violated

In this test, the frequency event will violate both of the second frequency (i.e. 49.6 Hz) and RoCoF thresholds (i.e. 0.04 Hz/s), so the LC is expected to request 40% of power due to the violation of first two frequency and RoCoF thresholds. The detailed settings for the frequency and RoCoF thresholds are listed in Table 18.

The test results for Test UF-2.2b are shown in Figure 15 and the key observations from the test are listed in Table 19. The event occurs at 1.50s (T_1), which leads to the RoCoF dropping below -0.12 Hz/s at 3.92 s (T_2), which is the event detection RoCoF threshold, so the event detection flag becomes high at 3.94 s.

The frequency continues to drop and violate the first frequency and RoCoF thresholds, which results in 20% of the resource be requested and deployed. At 6.74 s, the frequency decreases to 49.58 Hz, which is below the second resource allocation frequency threshold with a RoCoF of -0.04 Hz/s, so the RoCoF threshold is also violated. Therefore, a further 20% of resource is requested.

From the test results, it can be seen that the LC has successfully detect the event and deploy 40% of the resource. However, there is a delay of approximately 0.02 s in event detection after the event detection RoCoF threshold is violated. It suggested by GE that that the delay is caused by the data refreshing rate in the LC, which is every 20 ms. The average delay between the threshold violation and the controller issuing a command is approximately 0.23 s; and the average delay between the issuing of the command and the load change is approximately 0.575 s.

Table 18. Resource allocation threshold setting for Test UF-2.2b

Thresholds	Frequency (sFrqLThr)	RoCoF (sRCFLims)
1	49.7 Hz	0.08 Hz/s
2	49.6 Hz	0.04 Hz/s
3	49.5 Hz	0 Hz/s
4	49.4 Hz	0 Hz/s
5	49.3 Hz	0 Hz/s

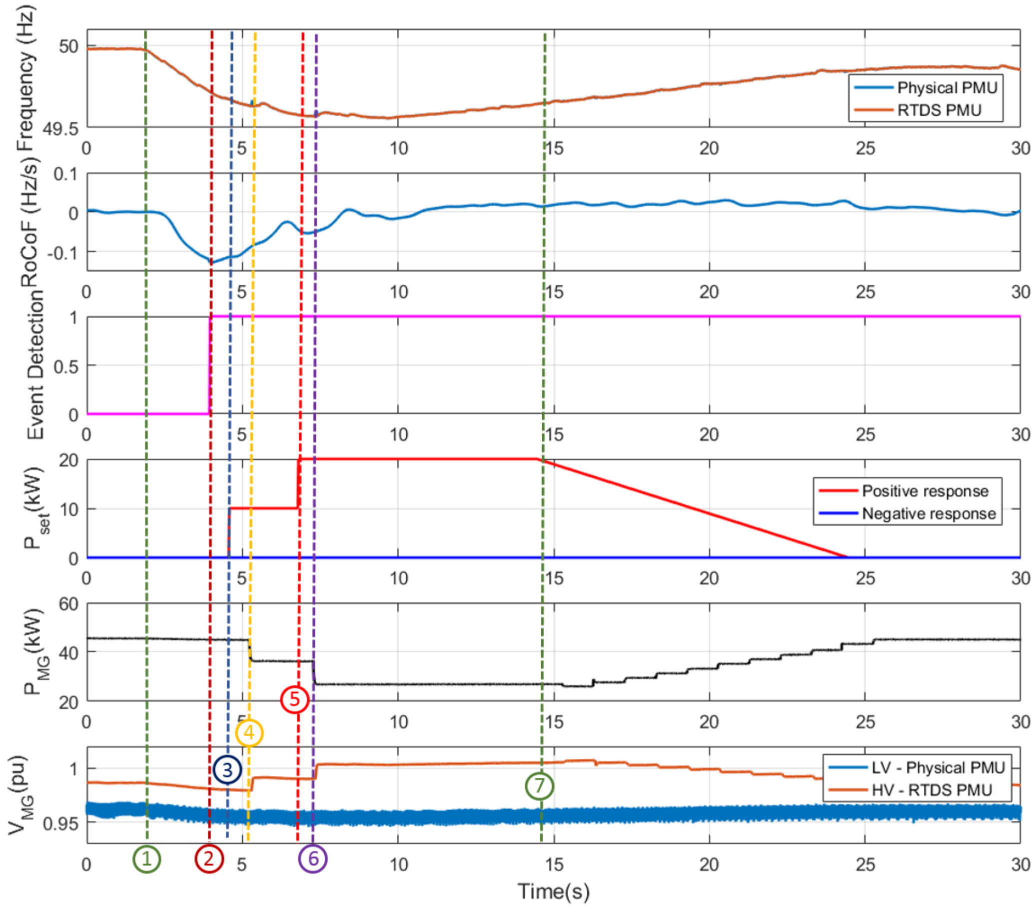

Figure 15. Results of Test UF-2.2b

Table 19. Key observation of Test UF-2.2b

Time	Observations
1.50 s (T_1)	Event occurs
3.92 s (T_2)	RoCoF drops to below -0.12 Hz/s
3.94 s	Event detection flag becomes high
4.14 s	Frequency drops below 49.7Hz with RoCoF of -0.125 Hz/s
4.56 s (T_3)	10kW (20%) of positive response requested by the controller.
5.22 s (T_4)	Load drops from 44.86 kW to 36.34 kW
6.25 s	Frequency drops below 49.6 Hz with RoCoF of -0.032 Hz/s
6.74 s	Frequency drops down to 49.58 Hz with RoCoF of -0.04 Hz/s
6.78 s (T_5)	Positive response request increases from 10 kW to 20 kW by the
7.27 s (T_6)	Load drops from 36.37 kW to 26.86 kW
14.46 s (T_7)	LC starts to ramp down positive response request
15.27 s	Load starts to ramp up

5.2.3 Test UF-2.3: validation of the third RoCoF threshold

In this subsection, an under-frequency event that leads to a frequency nadir between 49.4 Hz and 49.5 Hz will be emulated in the network to test the third RoCoF threshold in the resource allocation block. Two tests will be conducted using the same frequency event, which will lead to the violation of the third frequency threshold (i.e. 49.5 Hz). In these two tests, the third RoCoF threshold is configured to be 0.07 Hz/s and 0.05 Hz/s, which corresponds to the cases where the measured RoCoF is above and below the RoCoF setting.

5.2.3.1 Test UF-2.3a: the frequency violates the third threshold, but does not violate the third RoCoF threshold

In this test, the frequency event will violate the third frequency threshold of 49.6 Hz, but not the third RoCoF threshold 0.07 Hz/s, so the LC is expected to only request 40% of power due to the violation of first two frequency and RoCoF thresholds. The detailed settings for the frequency and RoCoF thresholds are listed in Table 20.

The test results for Test UF-2.3a are shown in Figure 16 and the key observations from the test are listed in Table 21. The event occurs at 1.50 s (T_1), which leads to the RoCoF dropping below -0.12 Hz/s at 3.07 s (T_2), i.e. the event detection RoCoF threshold, so the event detection flag become high at 3.08 s. The frequency continues to drop and violate the first two frequency and RoCoF thresholds, which results in 40% of the resource be requested and deployed. At 6.58 s, the frequency decreases below 49.5 Hz, which is the third resource allocation frequency threshold with RoCoF of -0.058 Hz/s, so the RoCoF threshold is not violated, so no further resource is requested.

From the test results, it can be seen that the LC has successfully detected the event and deployed 40% of the resource. However, there is a delay of approximately 0.01 s in event detection after the event detection RoCoF threshold is violated. It is considered that the delay is caused by the data refreshing rate in the LC, which is every 20 ms. The average delay between the threshold violation and the command is approximately 0.42 s; and the delay between the command and the load change is around 0.92 s.

Table 20. Resource allocation threshold setting for Test UF-2.3a

Thresholds	Frequency (sFrqLThr)	RoCoF (sRCFLims)
1	49.7 Hz	0.1 Hz/s
2	49.6 Hz	0.08 Hz/s
3	49.5 Hz	0.07 Hz/s
4	49.4 Hz	0 Hz/s
5	49.3 Hz	0 Hz/s

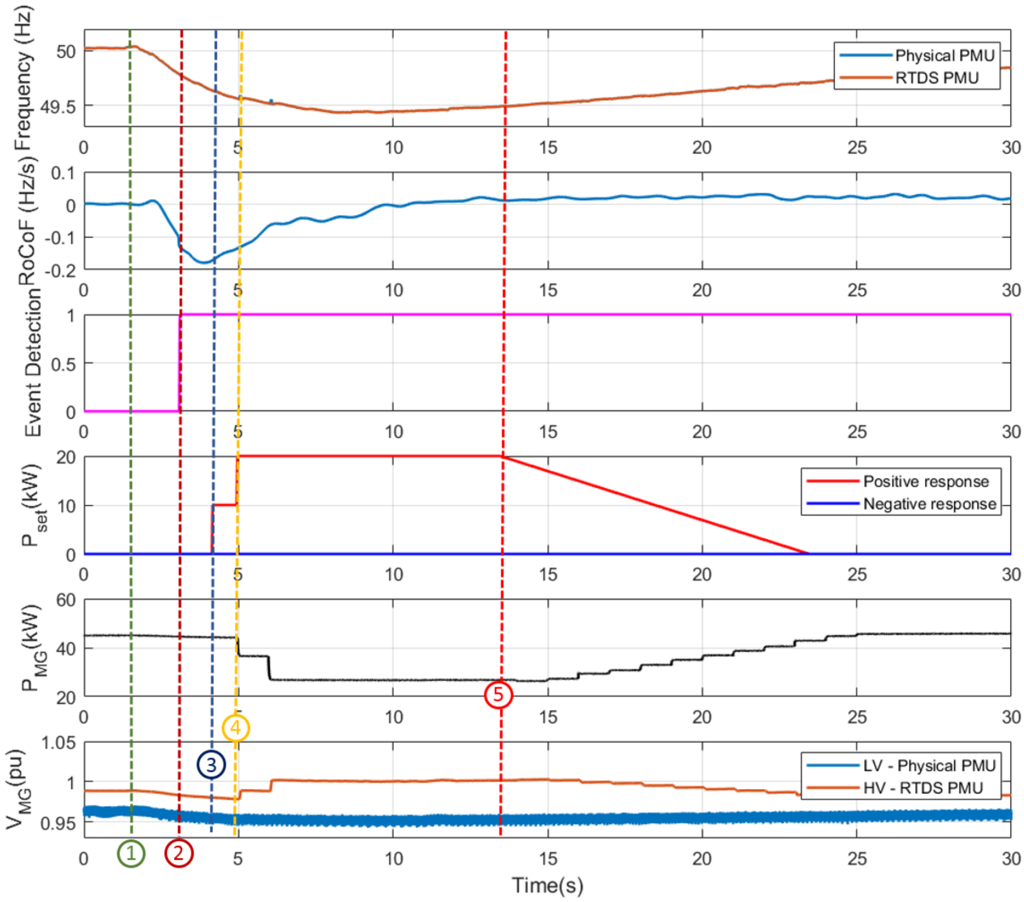

Figure 16. Results of Test UF-2.3a

Table 21. Key observation of Test UF-2.3a

Time	Observations
1.50 s (T_1)	Event occurs
3.07 s	RoCoF drops to below -0.12 Hz/s
3.08 s (T_2)	Event detection flag becomes high
3.72 s	Frequency drops below 49.7 Hz with RoCoF of 0.176 Hz/s
4.14 s (T_3)	10 kW (20%) of positive response requested by the controller.
4.96 s (T_4)	Load drops from 44.15 kW to 36.66 kW
4.52 s	Frequency drops below 49.6 Hz with RoCoF of -0.15 Hz/s
4.94 s (T_5)	Positive response request increases from 10kW to 20kW by the controller
5.96 s (T_6)	Load drops from 36.38 kW to 26.92 kW
6.58 s	Frequency drops below 49.5 Hz with RoCoF of -0.058 Hz/s
13.46 s (T_7)	LC starts to ramp down positive response request
13.97 s	Load starts to ramp up

5.2.3.2 Test UF-2.3b: both third frequency and RoCoF thresholds are violated

In this test, the frequency event will violate both of the third frequency (i.e. 49.5 Hz) and RoCoF threshold (i.e. 0.05 Hz/s), so the LC is expected to request 60% of power due to the violation of first three frequency and RoCoF thresholds. The detailed settings for the frequency and RoCoF thresholds are listed in Table 22.

The test results for Test UF-2.3b are shown in Figure 17 and the key observations from the test are listed in Table 23. The event occurs at 1.50 s (T1), which leads to the RoCoF dropping below the event detection RoCoF threshold of -0.12 Hz/s at 3.05 s (T_2), so the event detection flag become high at 3.06 s.

From the test results, it can be seen that the LC has successfully detect the event and deploys 60% of the resource. However, there is a delay of approximately 0.01 s in event detection after the event detection RoCoF threshold is violated. It is considered that the delay is caused by the data refreshing rate in the LC, which is every 20 ms. The average delay between the threshold violation and the power request command sending time is approximately 0.43 s; and the average delay between the command sending and the load change is approximately 0.55 s.

Table 22. Resource allocation threshold setting for Test UF-2.3b

Thresholds	Frequency (sFrqLThr)	RoCoF (sRCFLims)
1	49.7 Hz	0.1 Hz/s
2	49.6 Hz	0.08 Hz/s
3	49.5 Hz	0.05 Hz/s
4	49.4 Hz	0 Hz/s
5	49.3 Hz	0 Hz/s

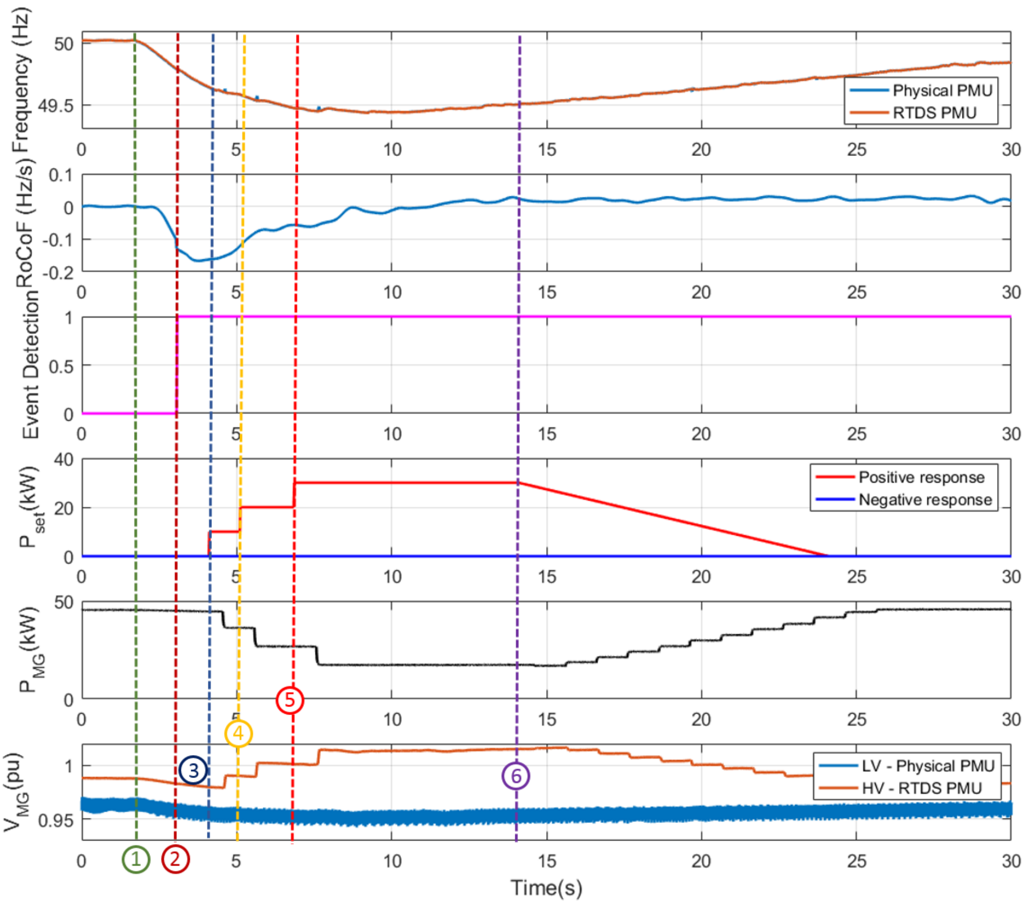

Figure 17. Results of Test UF-2.3b

Table 23. Key observation of Test UF-2.3b

Time	Observations
1.50 s (T_1)	Event occurs
3.05 s (T_2)	RoCoF drops to below -0.12 Hz/s
3.06 s	Event detection flag becomes high
3.67 s	Frequency drops below 49.7 Hz with RoCoF of -0.166 Hz/s
4.10 s	10kW (20%) of positive response requested by the controller.
4.55 s	Load drops from 44.39 kW to 36.33 kW
4.65 s	Frequency drops below 49.6 Hz with RoCoF of -0.145 Hz/s
5.10 s (T_3)	Positive response request increases from 10kW to 20kW by the
5.57 s	Load drops from 36.27 kW to 26.82kW
6.42 s	Frequency drops below 49.5 Hz with RoCoF of -0.067 Hz/s
6.84 s (T_4)	Positive response request increases from 20kW to 30 kW by the
7.57 s	Load drops from 26.77 kW to 17.38 kW
14.10 s (T_5)	LC starts to ramp down positive response request
14.60 s (T_6)	Load starts to ramp up

5.2.4 Test UF-2.4: validation of the fourth RoCoF threshold

In this subsection, an under-frequency event that leads to a frequency nadir between 49.3 Hz and 49.4 Hz will be emulated in the network to test the fourth RoCoF threshold in the resource allocation block. Two tests will be conducted using the same frequency event, which will lead to the violation of the third frequency threshold (i.e. 49.4 Hz). In these two tests, the third RoCoF threshold is configured to be 0.07 Hz/s and 0.06 Hz/s, which corresponds to the cases where the measured RoCoF is above and below the RoCoF setting.

5.2.4.1 Test UF-2.4a: the frequency violates the fourth threshold, but does not violate the fourth RoCoF threshold

In this test, the frequency event will violate the fourth frequency threshold 49.4 Hz, but not the fourth RoCoF threshold 0.07 Hz/s, so the LC is expected to only request 60% of power due to the violation of the first three frequency and RoCoF thresholds. The detailed settings for the frequency and RoCoF thresholds are listed in Table 24.

The test results for Test UF-2.4a are shown in Figure 18 and the key observations from the test are listed in Table 25. The event occurs at 1.50 s (T_1), which leads to the RoCoF dropping below -0.12 Hz/s, i.e. the event detection RoCoF threshold, and the event detection flag becomes high at 2.90 s. The frequency continues to drop and violate the first three frequency and RoCoF thresholds, which results in 60% of the resource to be requested and deployed. At 7.05 s, the frequency decreases below 49.4 Hz, which is the fourth resource allocation frequency threshold with RoCoF of -0.072 Hz/s, **i.e. the RoCoF threshold is also violated**. However, no further resource is requested.

From the test results, it can be seen that the LC has successfully detected the event and deploy 40% of the resource. However, no delay has been observed after the event detection RoCoF threshold is violated. The average delay between the threshold violation and the command is approximately 0.423 s; and the delay between the command and the load change is around 0.88 s. It should be noted that the fourth RoCoF threshold has also been violated, however, the fourth step of response is not requested. It is thought that the RoCoF value should be beyond the threshold for a certain period time for the LC to request response. In this test, the frequency and RoCoF violates threshold for approximately 120 ms, but the resource is still not deployed.

Table 24. Resource allocation threshold setting for Test UF-2.4a

Thresholds	Frequency (sFrqLThr)	RoCoF (sRCFLims)
1	49.7 Hz	0.12 Hz/s
2	49.6 Hz	0.10 Hz/s
3	49.5 Hz	0.08 Hz/s
4	49.4 Hz	0.07 Hz/s
5	49.3 Hz	0 Hz/s

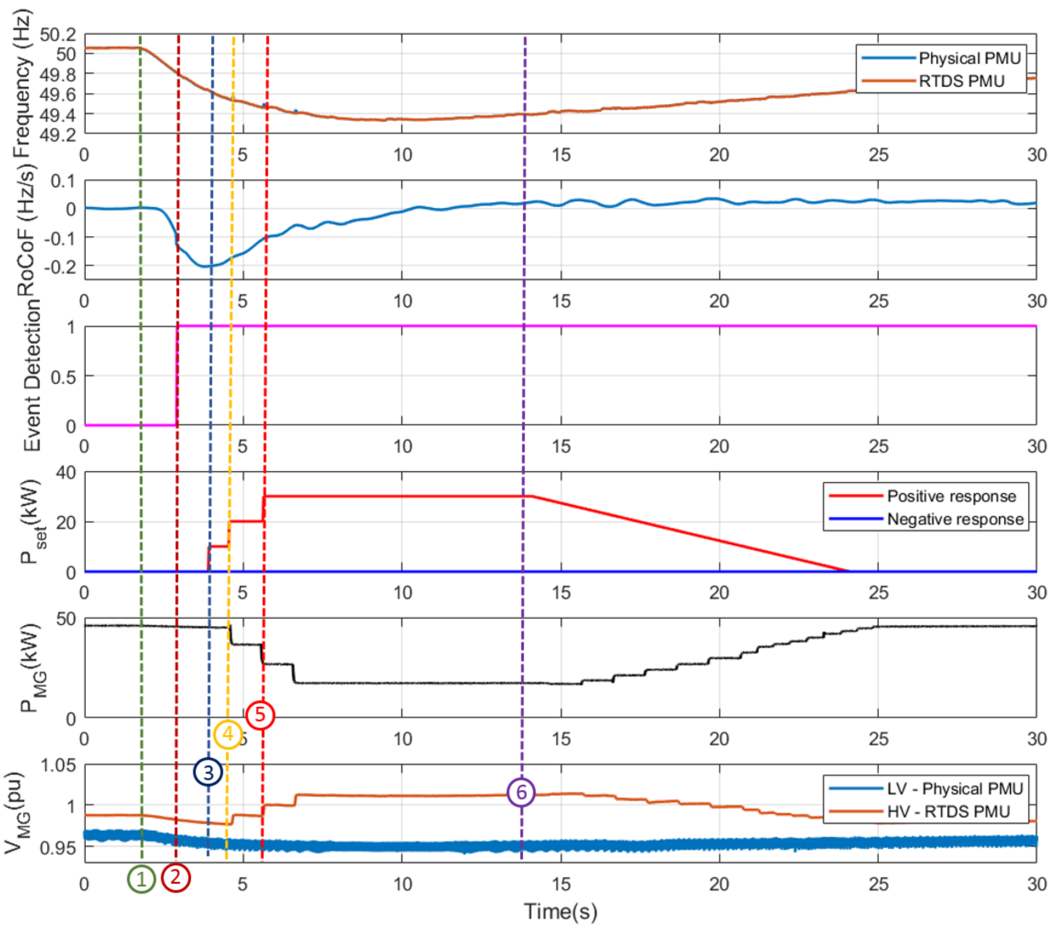

Figure 18. Results of Test UF-2.4a

Table 25. Key observation of Test UF-2.4a

Time	Observations
1.50 s (T_1)	Event occurs
2.90 s (T_2)	RoCoF drops to below -0.12 Hz/s and event detection flag becomes high
3.47 s	Frequency drops below 49.7 Hz with RoCoF of -0.190 Hz/s
3.90 s (T_3)	10 kW (20%) of positive response requested by the controller.
4.58 s	Load drops from 45.15 kW to 36.61 kW
4.13 s	Frequency drops below 49.6 Hz with RoCoF of -0.198 Hz/s
4.54 s (T_4)	Positive response request increases from 10 kW to 20 kW by the controller
5.56 s	Load drops from 36.51 kW to 26.80 kW
5.19 s	Frequency drops below 49.5 Hz with RoCoF of -0.144Hz/s
5.62 s (T_5)	Positive response request increases from 20 kW to 30 kW by the controller
6.56 s	Load drops from 26.66 kW to 17.31 kW
7.05 s	Frequency drops below 49.4 Hz with RoCoF of -0.072 Hz/s
14.12 s (T_6)	LC starts to ramp down positive response request
14.62 s	Load starts to ramp up

5.2.4.2 Test UF-2.4b: both fourth frequency and RoCoF thresholds are violated

In this test, the frequency event will violate both of the third frequency (i.e. 49.4 Hz) and RoCoF threshold (i.e. 0.06 Hz/s), so the LC is expected to request 80% of power due to the violation of first four frequency and RoCoF thresholds. The detailed settings for the frequency and RoCoF thresholds are listed in Table 26.

The test results for Test UF-2.4b are shown in Figure 19 and the key observations from the test are listed in Table 27. The event occurs at 1.50 s (T_1), which leads to the RoCoF dropping below the event detection RoCoF threshold -0.12 Hz/s and the event detection flag become high at 2.96 s (T_2).

The frequency continues to drop and violate the first three frequency and RoCoF thresholds, which results in 60% of the resource be requested and deployed. At 6.98 s, the frequency decreases below 49.4 Hz, which is the fourth resource allocation frequency threshold with RoCoF of -0.06 Hz/s, so the RoCoF threshold is also violated. Therefore, a further 20% of resource is requested.

From the test results, it can be seen that the LC has successfully detected the event and deployed 80% of the resource. No delay of has been observed in event detection. The average delay between the threshold violation and the power request command sending time is approximately 0.42 s; and the average delay between the command sending and the load change is approximately 0.853 s.

Table 26. Resource allocation threshold setting for Test UF-2.4b

Thresholds	Frequency (sFrqLThr)	RoCoF (sRCFLims)
1	49.7 Hz	0.12 Hz/s
2	49.6 Hz	0.10 Hz/s
3	49.5 Hz	0.08 Hz/s
4	49.4 Hz	0.06 Hz/s
5	49.3 Hz	0 Hz/s

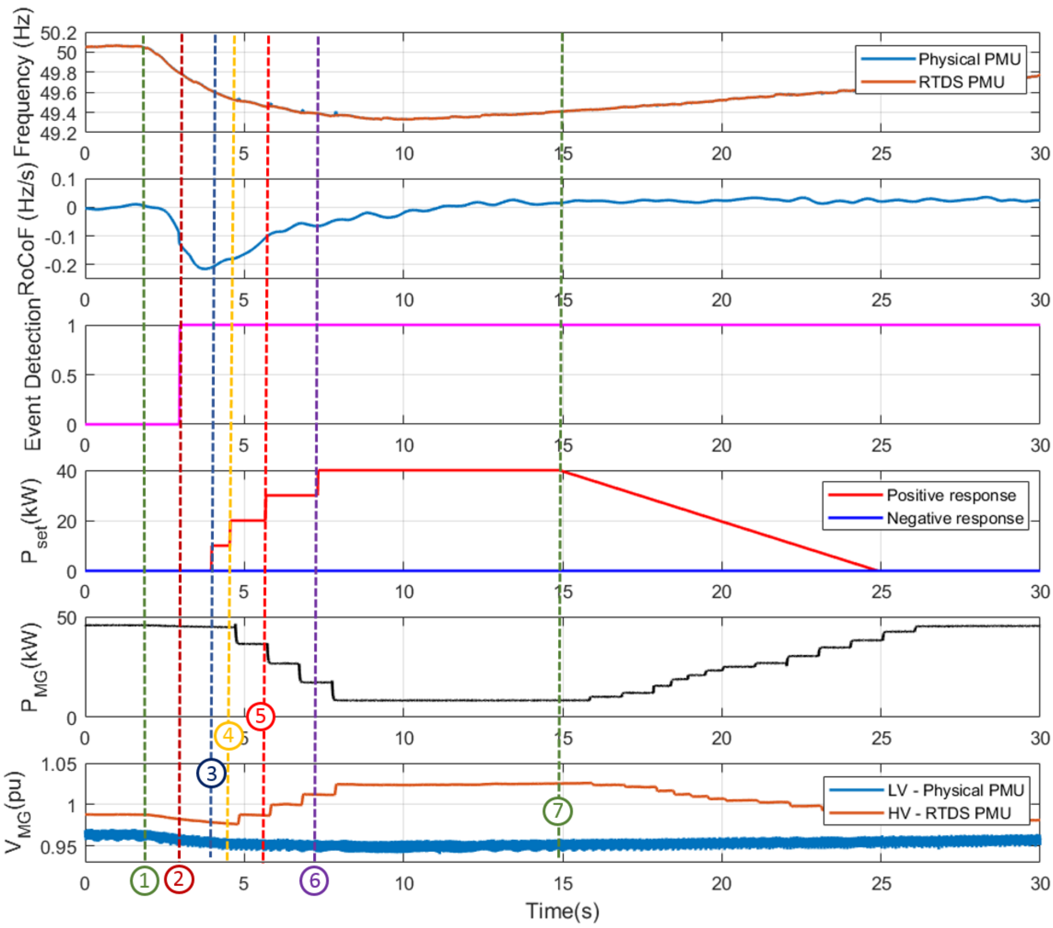

Figure 19 Results of Test UF-2.4b

Table 27. Key observation of Test UF-2.4b

Time	Observations
1.50 s (T_1)	Event occurs
2.96 s (T_2)	RoCoF drops to below -0.12 Hz/s and event detection flag becomes high
3.51 s	Frequency drops below 49.7 Hz with RoCoF of -0.204 Hz/s
3.96 s (T_3)	10kW (20%) of positive response requested by the controller.
4.70 s	Load drops from 44.69 kW to 36.48 kW
4.08 s	Frequency drops below 49.6 Hz with RoCoF of -0.203 Hz/s

4.54 s (T_4)	Positive response request increases from 10 kW to 20 kW by the controller
5.71 s	Load drops from 36.4 kW to 26.74 kW
5.21 s	Frequency drops below 49.5 Hz with RoCoF of -0.150 Hz/s
5.66 s (T_5)	Positive response request increases from 20 kW to 30 kW by the controller
6.71 s	Load drops from 26.66 kW to 17.34 kW
6.75 s	Frequency drops below 49.4 Hz with RoCoF of -0.056 Hz/s
6.98 s	Frequency drops below 49.395 Hz with RoCoF of -0.06 Hz/s
7.30 s (T_6)	Positive response request increases from 30 kW to 40 kW by the
7.75 s (T_7)	Load drops from 17.41 kW to 8.40 kW
14.92 s	LC starts to ramp down positive response request
15.84 s	Load starts to ramp up

5.2.5 Test UF-2.5: validation of the fifth RoCoF threshold

In this subsection, an under-frequency event that leads to a frequency nadir between 49.2 Hz and 49.3 Hz will be emulated in the network to test the fifth RoCoF threshold in the resource allocation block. Two tests will be conducted using the same frequency event, which will lead to the violation of the fifth frequency threshold (i.e. 49.3 Hz). In these two tests, the fifth RoCoF threshold is configured to be 0.04 Hz/s and 1 Hz/s, which corresponds to the cases where the measured RoCoF is above and below the RoCoF setting. During the tests, the fifth RoCoF threshold did not appear to contribute to the decision making, so the latter setting of 1 Hz/s is intentionally chosen to be significantly larger than the measured RoCoF to verify whether the fifth RoCoF setting is ignored by the resource allocation. This will be demonstrated by the results in Test UF-2.5b.

5.2.5.1 Test UF-2.5a: both fifth frequency and RoCoF thresholds are violated

In this test, the frequency event will violate the fifth frequency threshold of 49.3 Hz and the fifth RoCoF threshold 0.04 Hz/s, so the LC is expected to request 100% of power due to the violation of all frequency and RoCoF thresholds. The detailed settings for the frequency and RoCoF thresholds are listed in Table 28.

The test results for Test UF-2.5a are shown in Figure 20 and the key observations from the test are listed in Table 29. The event occurs at 1.50 s (T_1), which leads to the RoCoF dropping below -0.12 Hz/s, i.e. the event detection RoCoF threshold, and the event detection flag becomes high at 2.80 s (T_2). The frequency continues to drop and violate the first four frequency and RoCoF thresholds, which results in 80% of the resource to be requested and deployed. At 7.23 s, the frequency decreases below 49.3 Hz, which is the fifth resource allocation frequency threshold with RoCoF of -0.066 Hz/s, which also violates the corresponding RoCoF threshold. Therefore, a further 20% of resource is requested.

From the test results, it can be seen that the LC has successfully deployed 100% of resource as required. During this test, no delay was observed in event detection. The average delay between the threshold violation and the command is approximately 0.47 s; and the delay between the command and the load change is around 1.068 s. The LC's performance in this test is as expected.

Table 28. Resource allocation threshold setting for Test UF-2.5a

Thresholds	Frequency (sFrqLThr)	RoCoF (sRCFLims)
1	49.7 Hz	0.12 Hz/s
2	49.6 Hz	0.10 Hz/s
3	49.5 Hz	0.08 Hz/s
4	49.4 Hz	0.06 Hz/s
5	49.3 Hz	0.04 Hz/s

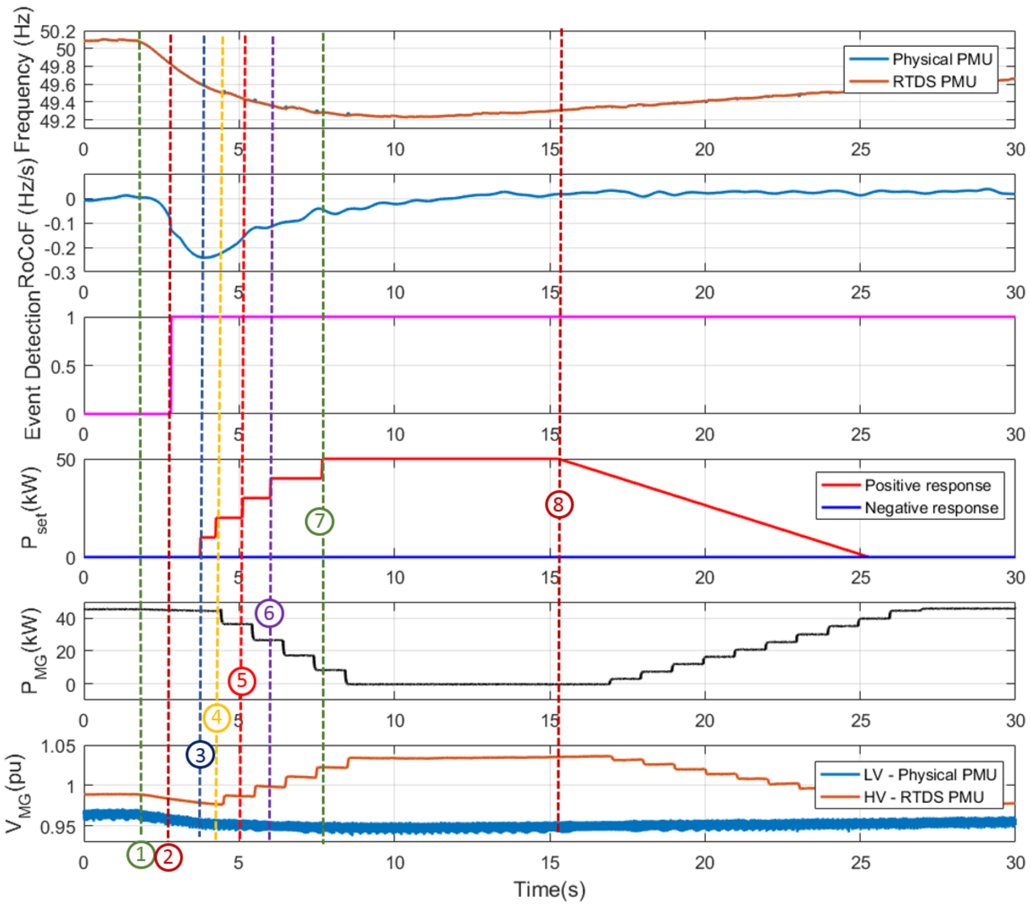

Figure 20 Results of Test UF-2.5a

Table 29. Key observation of Test UF-2.5a

Time	Observations
1.50 s (T_1)	Event occurs
2.80 s (T_2)	RoCoF drops to below -0.12 Hz/s and event detection flag becomes high
3.30 s	Frequency drops below 49.7 Hz with RoCoF of -1.980 Hz/s
3.74 s (T_3)	10 kW (20%) of positive response requested by the controller.
4.41 s	Load drops from 44.49kW to 36.42kW

3.80 s	Frequency drops below 49.6 Hz with RoCoF of -0.241 Hz/s
4.24 s (T_4)	Positive response request increases from 10kW to 20kW by the controller
5.41 s	Load drops from 36.48 kW to 26.63 kW
4.46 s	Frequency drops below 49.5 Hz with RoCoF of -2.221 Hz/s
5.10 s (T_5)	Positive response request increases from 20 kW to 30 kW by the controller
6.41 s	Load drops from 26.59 kW to 17.22 kW
5.56 s	Frequency drops below 49.4 Hz with RoCoF of -0.118 Hz/s
5.98 s (T_6)	Positive response request increases from 30 kW to 40 kW by the
7.40 s	Load drops from 17.25 kW to 8.34 kW
7.23 s	Frequency drops below 49.3 Hz with RoCoF of -0.066 Hz/s
7.64 s (T_7)	Positive response request increases from 40 kW to 50 kW by the
8.41 s	Load drops from 8.38 kW to 0 kW
15.30 s (T_8)	LC starts to ramp down positive response request
16.93 s	Load starts to ramp up

5.2.5.2 Test UF-2.5b: the frequency violates the fifth threshold, but does not violate the fifth RoCoF threshold

In this test, the frequency event will violate the fifth frequency threshold 49.3 Hz, but not the fifth RoCoF threshold 1 Hz/s, so the LC is expected to only request 80% of power due to the violation of first four frequency and RoCoF thresholds. The detailed settings for the frequency and RoCoF thresholds are listed in Table 30. The setting of fifth RoCoF threshold at 1 Hz/s is chosen to be significantly larger than the measured RoCoF. During the test, it is observed that no matter how big the fifth RoCoF threshold is, the fifth step of response will always be requested as long as the fifth frequency threshold is violated. This test is an example where the RoCoF threshold is significantly larger than the measured RoCoF, but the response is still requested.

The test results for Test UF-2.5b are shown in Figure 21 and the key observations from the test are listed in Table 31. The event occurs at 1.50 s (T_1), which leads to the RoCoF dropping below -0.12 Hz/s, i.e. the event detection RoCoF threshold, and the event detection flag becomes high at 2.84 s. The frequency continues to drop and violate the first four frequency and RoCoF thresholds, which results in 80% of the resource to be requested and deployed. At 7.30 s, the frequency decreases below 49.3 Hz, which is the fifth resource allocation frequency threshold with RoCoF of -0.075 Hz/s, **which has a magnitude that is far lower than the corresponding threshold of 1 Hz/s. However, a further 20% of resource is requested**.

From the test results, it can be seen that the LC has successfully detected the event and deploys 100% of the resource. No delay has been observed after the event detection RoCoF threshold is violated. The average delay between the threshold violation and the command is approximately 0.47 s; and the delay between the command and the load change is around 1.068 s. The LC's performance in this test is as expected.

Table 30. Resource allocation threshold setting for Test UF-2.5b

Thresholds	Frequency (sFrqLThr)	RoCoF (sRCFLims)
1	49.7 Hz	0.12 Hz/s

2	49.6 Hz	0.10 Hz/s
3	49.5 Hz	0.08 Hz/s
4	49.4 Hz	0.06 Hz/s
5	49.3 Hz	1 Hz/s

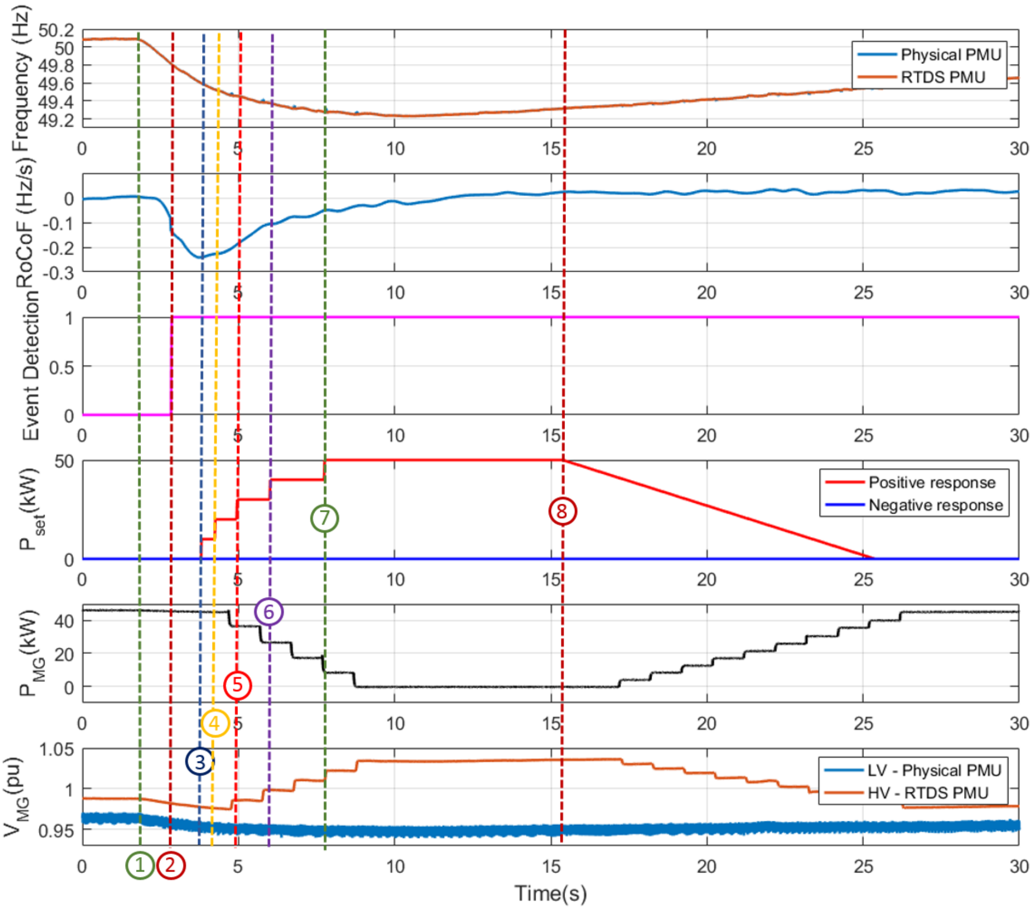

Figure 21. Results of Test UF-2.5b

Table 31. Key observation of Test UF-2.5b

Time	Observations
1.50 s (T_1)	Event occurs
2.84 s (T_2)	RoCoF drops to below -0.12 Hz/s and event detection flag becomes high
3.35 s	Frequency drops below 49.7 Hz with RoCoF of 0.206 Hz/s
3.80 s (T_3)	10 kW (20%) of positive response requested by the controller.
4.67 s	Load drops from 45.07 kW to 36.52 kW
3.80 s	Frequency drops below 49.6 Hz with RoCoF of 0.241 Hz/s
4.24 s (T_4)	Positive response request increases from 10 kW to 20 kW by the controller

5.68 s	Load drops from 36.42 kW to 26.69 kW
4.49 s	Frequency drops below 49.5 Hz with RoCoF of 0.222 Hz/s
4.94 s (T_5)	Positive response request increases from 20 kW to 30 kW by the
6.68 s	Load drops from 26.61 kW to 17.21 kW
5.55 s	Frequency drops below 49.4Hz with RoCoF of 0.135 Hz/s
6.00 s (T_6)	Positive response request increases from 30 kW to 40 kW by the controller
7.67 s	Load drops from 17.27 kW to 8.31 kW
7.30 s	Frequency drops below 49.3 Hz with RoCoF of 0.075 Hz/s
7.74 s (T_7)	Positive response request increases from 40 kW to 50 kW by the controller
8.68 s	Load drops from 8.36 kW to 0 kW
15.40 s (T_8)	LC starts to ramp down positive response request
17.19 s	Load starts to ramp up

5.2.1 Summary of the under-frequency tests of LC's local mode with the RoCoF thresholds enabled

In this set of tests, the functionality of the LC when operating in local mode with RoCoF thresholds enabled has been tested under a range of under-frequency events that results to different levels of frequency nadirs.

The test results shows that the LC has successfully detected the events in all cases. The first four RoCoF thresholds have been used to provide an extra layer of checking in addition to the frequency thresholds for resource deployment and from the results, it was show that the first four thresholds have successfully performed their function and deployed the required amount of resources based on the associated settings and design specification.

It was also observed that the RoCoF threshold needs to be violated for a certain period of time for the resource to be requested. This is evident in Test UF-2.4a, Test OF 2.2a and Test OF 2.4a (in Section 5.2).

For the fifth RoCoF threshold, it was found that this threshold is not used for decision making, i.e. when the frequency drops below the fifth frequency threshold, the resource will be deployed regardless of the measured RoCoF value. It is suggested by GE that this is intentionally designed so that the LC will respond in a severe frequency event (i.e. events with frequency violating the first four thresholds). However, this makes the setting meaningless for the scheme and will therefore not be required. Potentially, there could be two options for improvement:

- Remove the fifth RoCoF threshold as it is not used by the scheme to avoid causing any confusion
- Retaining the fifth RoCoF threshold, but give options to engineers regarding whether to enable it for decision making. If the users requires that the fifth RoCoF threshold to not to take effect, it can be disabled. This gives the engineers options to configure the system to achieve the behaviour they want.

During the tests, various levels of delays have been observed at different stages. There are three main delays observed.

- Delay in event detection when RoCoF threshold is violated – this delay typically ranges from 0-20 ms, which, as suggested by GE, is caused by the reporting rate of the LC, which is very 20 ms.
- T_{d1}: time delay between the time when the frequency threshold being violated and the time a command is issued to deploy resource.
- T_{d2}: the delay between the time when a command is issued to deploy the resource and the time the load bank actually changes its load level.

The recorded T_{d1} value from this set of tests are listed in Table 32 and plotted in Figure 22 respectively. The overall average delay is approximately 0.41 s. As it can be seen from Figure 22, most of the observed delay is around 0.4 s.

Table 32. T_{d1}: time delay in command issuing following frequency violation

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Average
Test UF-2.1a	-	-	-	-	-	-
Test UF-2.1b	0 s	-	-	-	-	0 s
Test UF-2.2a	0.48 s	-	-	-	-	0.48 s
Test UF-2.2b	0.42 s	0.04 s	-	-	-	0.23 s
Test UF-2.3a	0.42 s	0.42 s	-	-	-	0.42 s
Test UF-2.3b	0.43 s	0.45 s	0.42 s	-	-	0.433 s
Test UF-2.4a	0.43 s	0.41 s	0.43 s	-	-	0.423 s
Test UF-2.4b	0.45 s	0.46 s	0.45 s	0.32 s	-	0.42 s
Test UF-2.5a	0.44 s	0.44 s	0.64 s	0.42 s	0.41 s	0.47 s
Test UF-2.5b	0.45 s	0.44 s	0.45 s	0.45 s	0.44 s	0.446 s
Overall average delay: 0.41 s						

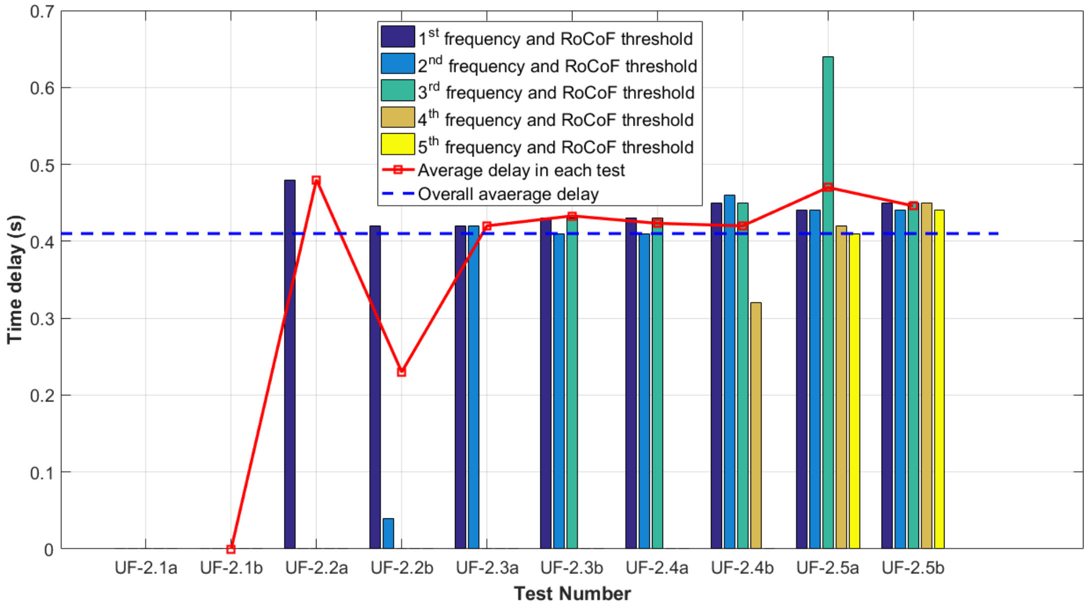

Figure 22. T_{d1}: time delay in command issuing following frequency violation

The recorded T_{d2} values from this set of tests are listed in Table 32 and plotted Figure 23 respectively. The overall average delay is approximately 0.92 s. It is considered that this is caused by the way the load bank change its load level following a command. As shown in Figure 11, when the load bank receives a command, it will change load level and hold that for around 1 s before it will change the load level again. This could be relating to the capability of the load bank in terms of how fast it can achieve the targeted power. The large variation in delay is considered to be caused by the time within the cycle at which the LC sends the command.

Table 33. T_{d2}: delay between time when the command is issued to deploy resource and the time when the load bank actually changes its load level

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Average
Test UF-2.1a	-	-	-	-	-	-
Test UF-2.1b	0.84 s	-	-	-	-	0.84 s
Test UF-2.2a	0.45 s	-	-	-	-	0.45 s
Test UF-2.2b	0.66 s	0.49 s	-	-	-	0.575 s
Test UF-2.3a	0.82 s	1.03 s	-	-	-	0.925 s
Test UF-2.3b	0.45 s	0.47 s	0.73 s	-	-	0.55 s
Test UF-2.4a	0.68 s	1.02 s	0.94 s	-	-	0.88 s
Test UF-2.4b	0.74 s	1.17 s	1.05 s	0.45 s	-	0.8525 s
Test UF-2.5a	0.67 s	1.17 s	1.31 s	1.42 s	0.77 s	1.068 s
Test UF-2.5b	0.87 s	1.44 s	1.74 s	1.67 s	0.94 s	1.332 s
Overall average delay: 0.92 s						

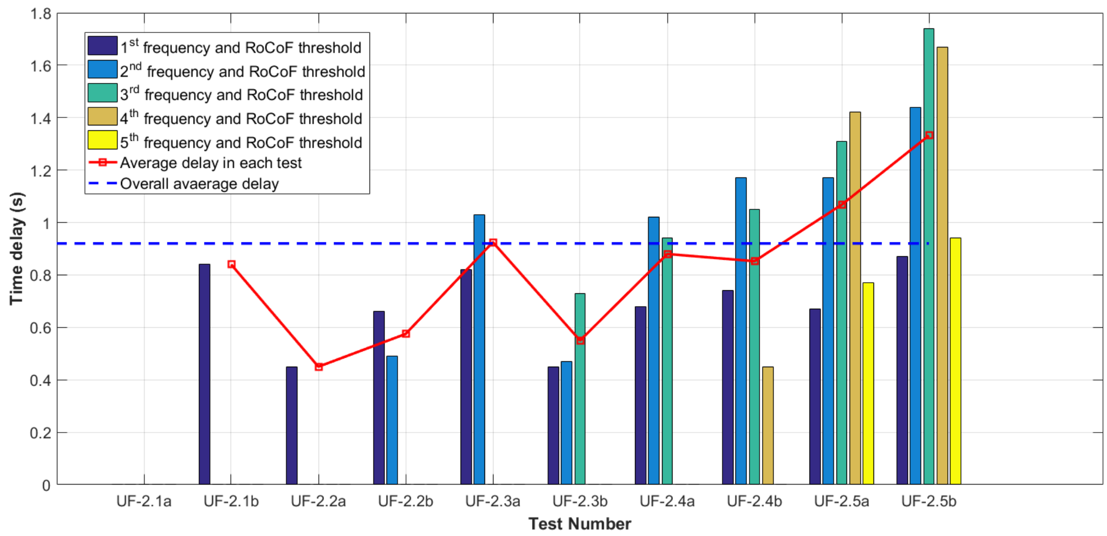

Figure 23. T_{d2}: delay between time when the command is issued to deploy resource and the time when the load bank actually changes its load level

6 OVER-FREQUENCY TESTS

In this set of tests, the performance of the LC's local mode will be tested in over-frequency events. Similar to the tests presented in Section 5, the following two main scenarios will be tested:

- LC only uses frequency thresholds, with RoCoF thresholds disabled.
- LC uses both frequency and RoCoF thresholds for resource allocation.

The first scenario allows the test of the LC's functionality for the five over-frequency thresholds, while the second scenario allows further validation of the RoCoF thresholds. In the tests presented in this section, the LC is configured to operate in local mode through the dedicated setting with all the RAs connected. The LC is expected to ignore all the wide-area signals and only use local measurements for decision making. In Appendix A, wide area communication channels are intentionally disconnected, thus validating the LC's function to switch from wide area mode to local mode.

In all of the tests presented in this section, the resource availability information provided in Table 34. During the tests, the base load is set to 20 kW, where the load bank can be controlled to increase demand to provide negative frequency response.

Table 34. Resource availability information for over-frequency tests

Parameter	Value
Availability	50kW
Positive available power	30kW
Negative available power	1 s
Positive power response time	1 s
Negative power response time	30kW/s
Power ramp up rate	30kW/s
Power ramp down rate	10 s
Positive power max duration	10 s
Negative power max duration	50kW

6.1 LC only uses frequency thresholds for resource allocation with RoCoF thresholds disabled

In the following tests, the RoCoF thresholds are disabled, i.e. the LC will make decisions only based on the measured frequency values. The LC is still connected to the RAs but it is intentionally set to local mode through its setting, so the wide-area monitoring signals are expected to be neglected and only local measurements will be used for decision making.

Table 35. Settings in the LC for Test OF-1

Logical node: EvDeTFRC1 (Event Detection)	
Over-frequency RoCoF threshold (sOvFreqRCFThr)	0.1 Hz/s
Under-frequency threshold (sOvFreqThr)	0.6% (0.3 Hz)
Local mode status (sLocCtrl)	True

Logical node: RsrcAIGAPC1 (Resource Allocation)	
RoCoF thresholds status (sUseRCFLims)	False
Frequency thresholds (Hz, sFrqLThr)	50.3, 50.4, 50.5, 50.6, 50.7
Local mode status (sLocCtrl)	True

6.1.1 Test OF-1.1: frequency peak does not violate any over-frequency thresholds

In this test, an over-frequency event via sudden load disconnection will be emulated in the PNDC network. During the event, the frequency remains below the over-frequency thresholds in the resource allocation block is violated. Therefore, no resource should be dispatched according to the design specification.

The test results for Test OF-1.1 are shown in Figure 24 and the key observations are listed in Table 36. The event occurs at 1.50 s (T_1), which leads to the largest RoCoF of 0.097 Hz/s at 4.06 s (T_2). As the maximum RoCoF value is lower than the event detection RoCoF threshold, the disturbance is not detected as an event. The frequency reaches the maximum value of 50.28 Hz at 5.80 s (T_3), which does not violate any frequency threshold, so no resource has been dispatched.

In this test, the LC remained stable to the over-frequency disturbance as expected.

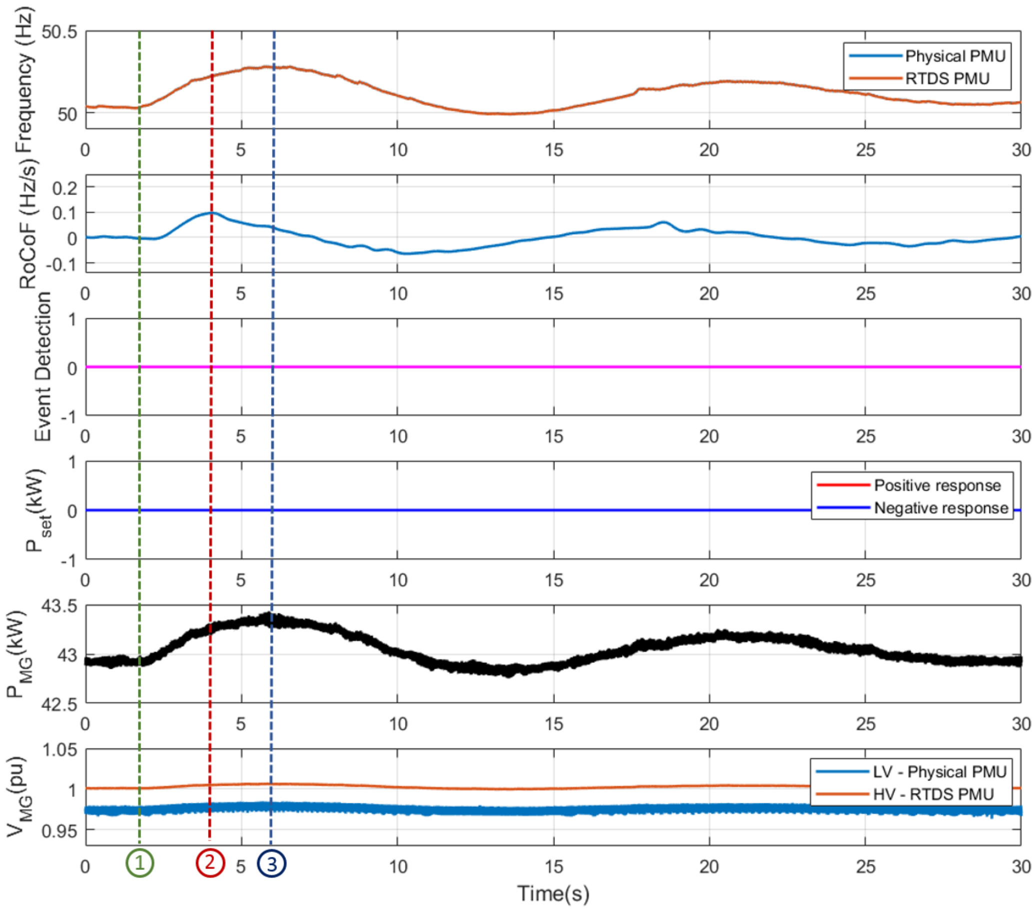

Figure 24. Results for Test OF-1.1

Table 36. Key observations from Test OF-1.1

Time	Observations
1.50 s (T_1)	Event occurs
4.06 s (T_2)	RoCoF reaches its maximum value of 0.097Hz/s
5.80 s (T_3)	Frequency increased to its maximum value of below 50.28 Hz

6.1.2 Test OF-1.2: validation of the first over-frequency threshold

In this test, an over-frequency event that leads to a maximum frequency between 50.3 Hz and 50.4 Hz will be emulated in the PNDC network. The maximum frequency violates the setting of the first over-frequency threshold but below the other four thresholds, so it is expected that 20% of the negative response should be deployed.

The test results for Test OF-1.2 are shown in Figure 25 and the key observations are listed in Table 37. The event occurs at 1.50s (T_1), which leads to the RoCoF violating the event detection threshold 0.1 Hz/s and the event detection flag becoming high at 3.54 s (T_2).

The event results in the frequency increasing to its maximum value of 50.34 Hz and the first frequency threshold being violated at 4.50 s. The LC correctly dispatches 20% of negative response following the frequency violation with a delay of 0.5 s. Following from the negative response request command, the load bank successfully reduced its demand with a delay of 0.42 s.

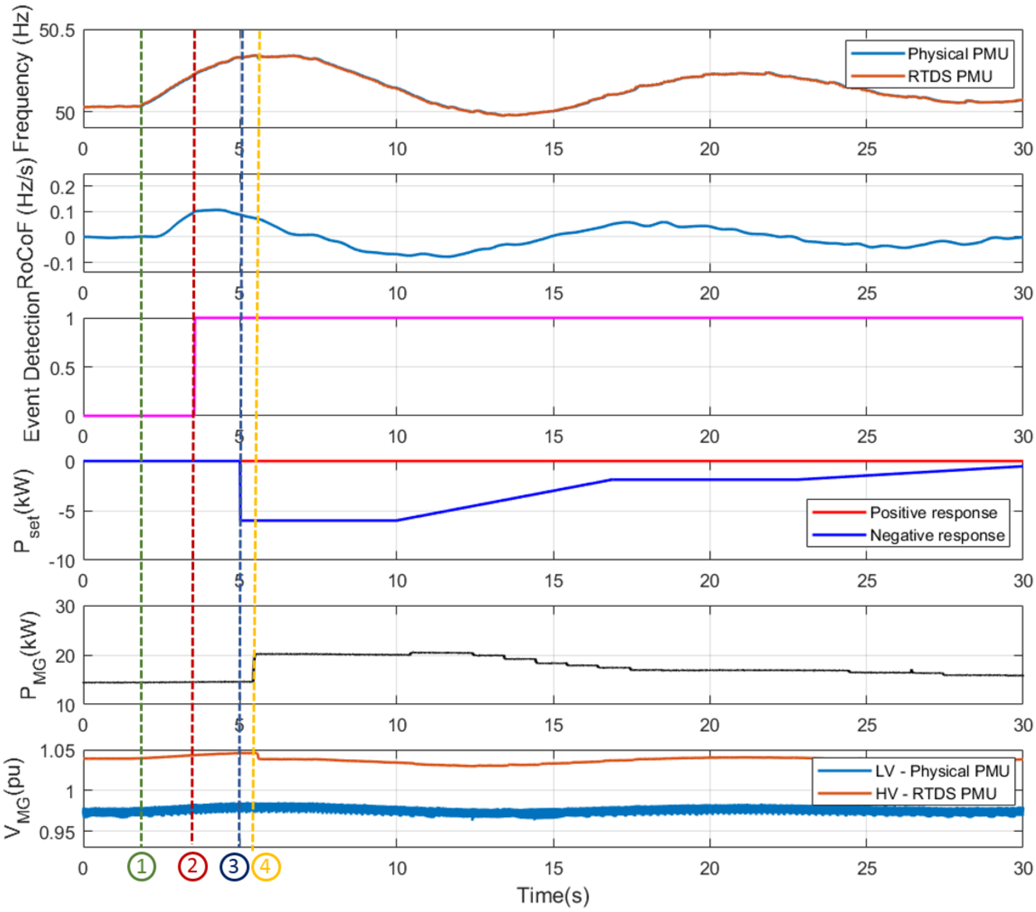

Figure 25. Results for Test OF-1.2

Table 37. Key observations from Test OF-1.2

Time	Observations
1.50 s (T_1)	Event occurs
3.54 s (T_2)	RoCoF increase to 0.1 Hz/s and the event detection flag becomes high
4.50 s	Frequency violates the first frequency threshold 50.3 Hz
5.00 s (T_3)	6 kW (20%) of negative response requested by the controller.
5.42 s	Load increases from 14.62 kW to 20.15 kW
10.00 s	LC starts to decrease negative response request
10.43 s	Load starts to ramp down

6.1.3 Test OF-1.3: validation of the second over-frequency threshold

In this test, an over-frequency event that leads to a maximum frequency between 50.4 Hz and 50.5 Hz will be emulated in the PNDC network. The event violates the first two over-frequency thresholds, so it is expected that 40% of the negative response should be deployed.

The test results for Test OF-1.3 are shown in Figure 26 and the key observations are listed in Table 38. The event occurs at 1.50 s (T_1), which leads to the RoCoF violating the event detection threshold 0.1 Hz/s and the event detection flag becoming high at 3.06 s (T_2).

The event results in the frequency increasing to its maximum value of 50.44 Hz and violating the first two frequency thresholds 3.58 s and 4.60 s respectively. The LC correctly dispatched 20% of negative response at each step of frequency violation with an average delay of 0.46 s. Following from the negative response request command, the load bank successfully increased its demand with an average delay of 0.81 s.

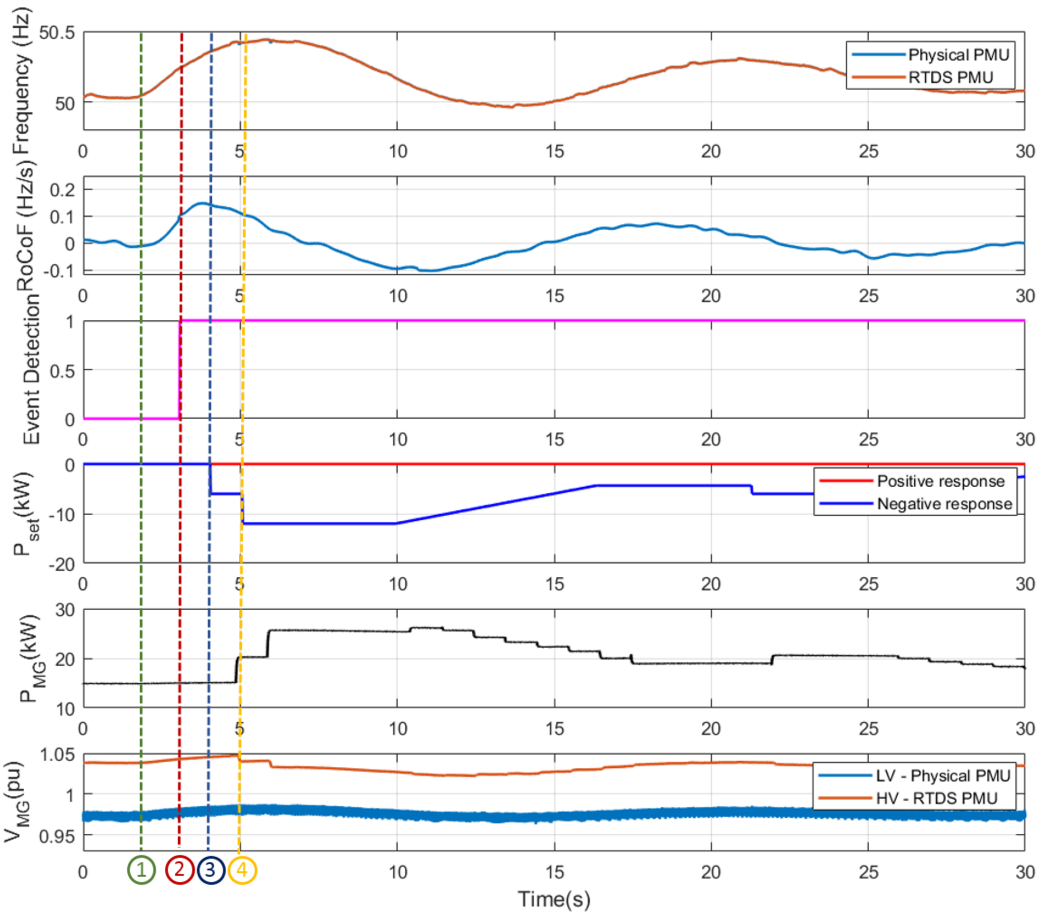

Figure 26. Results for Test OF-1.3

Table 38. Key observations from Test OF-1.3

Time	Observations
1.50 s (T_1)	Event occurs
3.06 s (T_2)	RoCoF increase to 0.1 Hz/s and the event detection flag becomes high
3.58 s	Frequency violates the first frequency threshold 50.3 Hz
4.04 s (T_3)	6 kW (20%) of negative response requested by the controller
4.86 s	Load increases from 15.10 kW to 20.23 kW
4.60 s	Frequency violates the second frequency threshold 50.4 Hz
5.06 s (T_4)	12 kW (40%) of negative response requested by the controller
5.86 s	Load increases from 20.26 kW to 25.62 kW
9.96 s	LC starts to decrease negative response request
10.40 s	Load starts to ramp down

6.1.4 Test OF-1.4: validation of the third over-frequency threshold

In this test, an over-frequency event that leads to a maximum frequency between 50.5 Hz and 50.6 Hz will be emulated in the PNDC network. The maximum frequency violates the setting of the first three over-frequency thresholds but below the other two thresholds, so it is expected that 60% of the negative response should be deployed, with every 20% of resource being requested when the corresponding frequency threshold is violated.

The test results for Test OF-1.4 are shown in Figure 27 and the key observations are listed in Table 39. The event occurs at 1.50 s (T_1), which leads to the RoCoF violating the event detection threshold 0.1 Hz/s and the event detection flag becoming high at 2.86 s (T_2).

The event results in the frequency increasing to its maximum value of 50.54 Hz and the first three frequency thresholds are violated at 3.17 s, 3.78 s and 4.92 s respectively. The LC correctly dispatched 20% of negative response at each step of frequency violation with an average delay of 0.44 s. Following from the negative response request command, the load bank successfully reduced its demand with an average delay of 0.9 s.

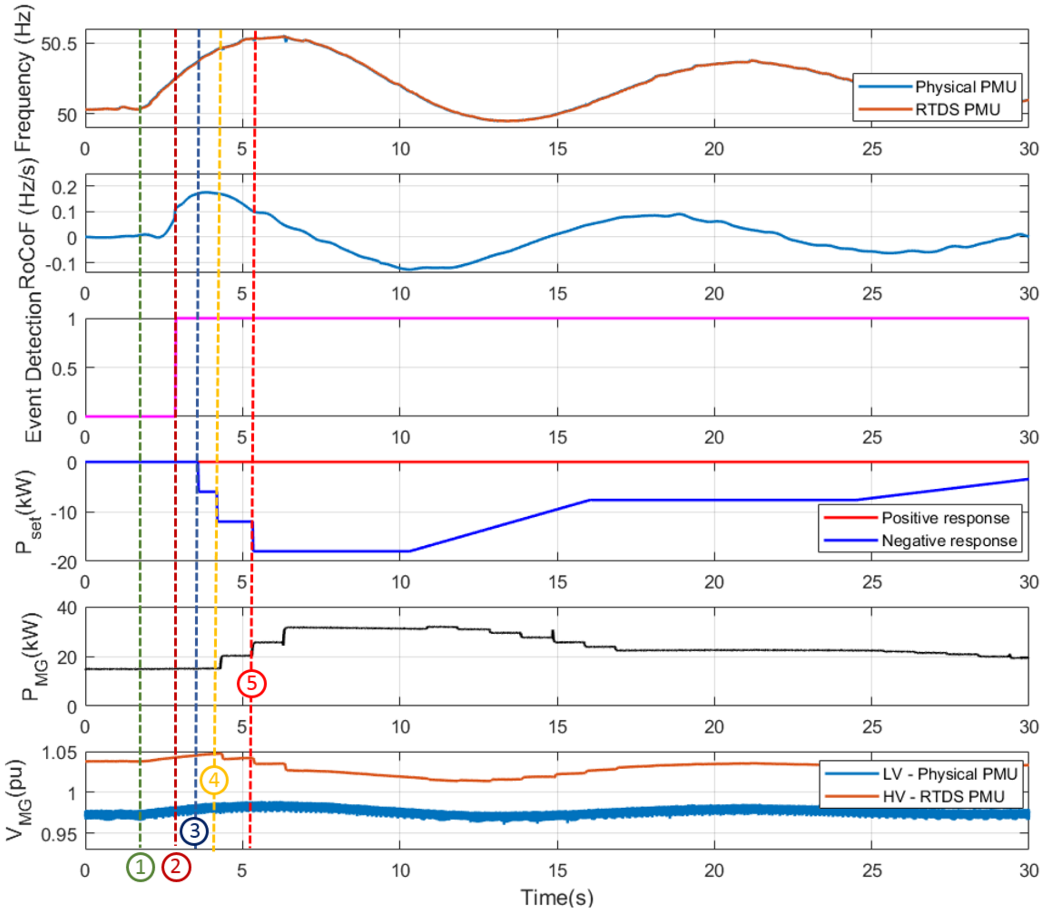

Figure 27. Results for Test OF-1.4

Table 39. Key observations from Test OF-1.4

Time	Observations
1.50 s (T_1)	Event occurs
2.86 s (T_2)	RoCoF increase to 0.1 Hz/s and the event detection flag becomes high
3.17 s	Frequency violates the first frequency threshold 50.3 Hz
3.62 s (T_3)	6kW (20%) of negative response requested by the controller

4.30 s	Load increases from 15.12 kW to 20.22 kW
3.78 s	Frequency violates the second frequency threshold 50.4 Hz
4.22 s (T_4)	12 kW (40%) of negative response requested by the controller
5.30 s	Load increases from 20.31 kW to 25.63 kW
4.92 s	Frequency violates the third frequency threshold 50.5 Hz
5.36 s (T_5)	18 kW (60%) of negative response requested by the controller
6.30 s	Load increases from 25.63 kW to 31.65 kW
10.34 s	LC starts to decrease negative response request
10.83 s	Load starts to ramp down

6.1.5 Test OF-1.5: validation of the fourth over-frequency threshold

In this test, an over-frequency event that leads to a maximum frequency between 50.6 Hz and 50.7 Hz will be emulated in the PNDC network. The maximum frequency violates the setting of the first four over-frequency thresholds but below the last threshold, so it is expected that 80% of the negative response should be deployed, with every 20% of resource being requested when the corresponding frequency threshold is violated.

The test results for Test OF-1.5 are shown in Figure 28 and the key observations are listed in Table 40. The event occurs at 1.50 s (T_1), which leads to the RoCoF violating the event detection threshold 0.1 Hz/s and the event detection flag becoming high at 2.82 s (T_2).

The event results in the frequency increasing to its maximum value of 50.67 Hz and the first four frequency thresholds are violated at 2.91 s, 3.32 s, 3.92 s and 4.71 s respectively. The LC correctly dispatched 20% of negative response at each step of frequency violation with an average delay of 0.45 s. Following from the negative response request commands, the load bank successfully reduced its demand with an average delay of 1.13 s.

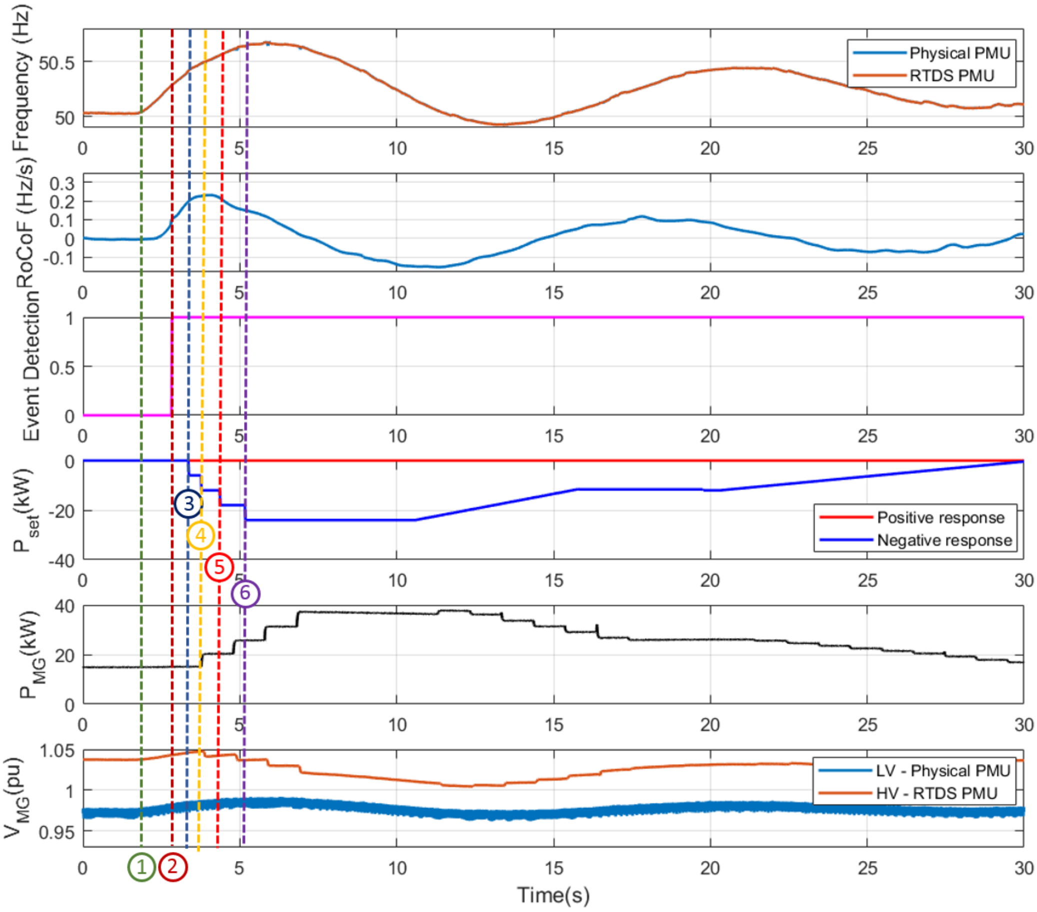

Figure 28. Results for Test OF-1.5

Table 40. Key observations from Test OF-1.5

Time	Observations
1.50 s (T_1)	Event occurs
2.82 s (T_2)	RoCoF increase to 0.1 Hz/s and the event detection flag becomes high
2.91 s	Frequency violates the first frequency threshold 50.3 Hz
3.36 s (T_3)	6kW (20%) of negative response requested by the controller
3.77 s	Load increases from 15.09 kW to 20.26 kW
3.32 s	Frequency violates the second frequency threshold 50.4 Hz
3.76 s (T_4)	12 kW (40%) of negative response requested by the controller
4.79 s	Load increases from 20.32 kW to 25.68 kW
3.92 s	Frequency violates the third frequency threshold 50.5 Hz
4.36 s (T_5)	18 kW (60%) of negative response requested by the controller
5.79 s	Load increases from 25.78 kW to 31.29 kW

4.71 s	Frequency violates the fourth frequency threshold 50.6 Hz
5.16 s (T_6)	24 kW (80%) of negative response requested by the controller
6.82 s	Load increases from 31.25 kW to 37.20 kW
10.60 s	LC starts to decrease negative response request
11.31 s	Load starts to ramp down

6.1.6 Test OF-1.6: validation of the fifth over-frequency threshold

In this test, an over-frequency event that leads to a maximum frequency between 50.7 Hz and 50.8 Hz will be emulated in the PNDC network. The maximum frequency violates the setting of all frequency thresholds, so it is expected that 100% of the negative response should be deployed, with every 20% of resource being requested when the corresponding frequency threshold is violated.

The test results for Test OF-1.6 are shown in Figure 29 and the key observations are listed in Table 41. The event occurs at 1.50 s (T_1), which leads to the RoCoF violating the event detection threshold 0.1 Hz/s and the event detection flag becoming high at 2.80 s (T_2).

The event results in the frequency increasing to its maximum value of 50.78 Hz and the five frequency thresholds are violated at 2.82 s, 3.15 s, 3.52 s, 4.08 s and 4.69 s respectively. The LC correctly dispatched 20% of negative response at each step of frequency violation with an average delay of 0.44 s. Following from the negative response request command, the load bank successfully increased its demand with an average delay of 1.19 s.

It worth noting that the load bank increases demand by approximately 40% at 5.69 s, which is thought to be a result of accumulated response requests from T_5 and T_6. The load bank appears to have a window of approximately 1 s between the changes in demand in response to consecutive control signals. Therefore, if multiple setpoint requests are issued within the window, it will take effect after the 1 s has elapsed.

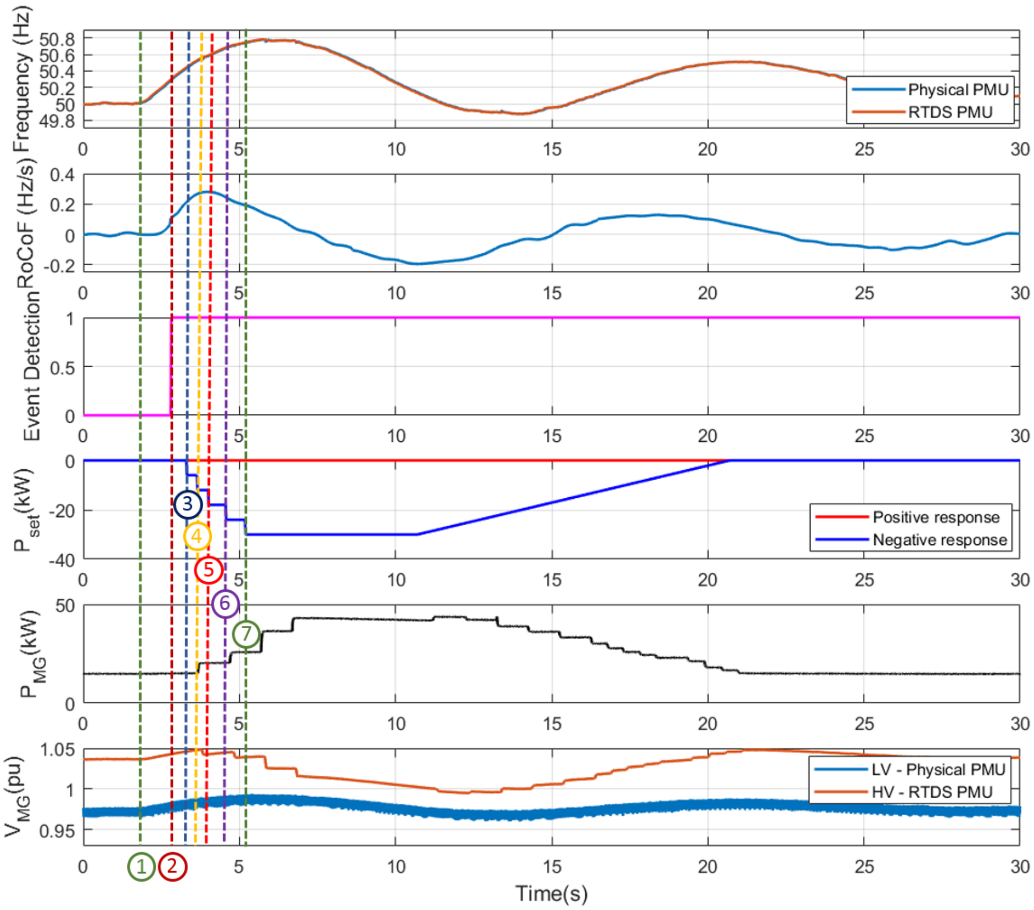

Figure 29. Results for Test OF-1.6

Table 41. Key observations from Test OF-1.6

Time	Observations
1.50 s (T_1)	Event occurs
2.80 s (T_2)	RoCoF increase to 0.1 Hz/s and the event detection flag becomes high
2.82 s	Frequency violates the first frequency threshold 50.3 Hz
3.26 s (T_3)	6 kW (20%) of negative response requested by the controller
3.67 s	Load increases from 15.11 kW to 20.33 kW
3.15 s	Frequency violates the second frequency threshold 50.4 Hz
3.60 s (T_4)	12kW (40%) of negative response requested by the controller
4.70 s	Load increases from 20.33 kW to 25.78 kW
3.52 s	Frequency violates the third frequency threshold 50.5 Hz
3.96 s (T_5)	18kW (60%) of negative response requested by the controller
4.08 s	Frequency violates the fourth frequency threshold 50.6 Hz

4.52 s (T_6)	24 kW (80%) of negative response requested by the controller
5.69 s	Load increases from 25.83 kW to 36.46 kW (40% increase)
4.69 s (T_7)	Frequency violates the fifth frequency threshold 50.7 Hz
5.14 s	30 kW (100%) of negative response requested by the controller
6.69 s	Load increases from 36.42 kW to 42.96 kW
10.66 s	LC starts to decrease negative response request
11.20 s	Load starts to ramp down

6.1.7 Summary of the over-frequency tests of LC's local mode with the RoCoF thresholds disabled

In this set of tests, the functionality of the LC when operating local mode with RoCoF thresholds disabled has been tested under a range of frequency events, which resulted in different levels of frequency peaks.

The test results show that the LC has successfully detected the events and deployed the required amount of resources based on the associated settings and design specification. However, various delays have been observed:

- T_{d1}: time delay between the time when the frequency threshold being violated and the time a command is issued to deploy the resource
- T_{d2}: the delay between when command is issued to deploy the resource and the time the load bank actually changes its load level.

The recorded T_{d1} from this set of tests are listed in Table 32 and plotted in Figure 30. The variation in the delay in various tests is relatively small and the overall average delay is approximately 0.45 s.

Table 42. T_{d1}: time delay in command issuing following frequency violation

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Average
Test OF-1.1	-	-	-	-	-	-
Test OF-1.2	0.5 s	-	-	-	-	0.5 s
Test OF-1.3	0.46 s	0.46 s	-	-	-	0.46 s
Test OF-1.4	0.45 s	0.44 s	0.44 s	-	-	0.433 s
Test OF-1.5	0.45 s	0.44 s	0.44 s	0.45 s	-	0.445 s
Test OF-1.6	0.44 s	0.45 s	0.44 s	0.44 s	0.45 s	0.444 s
Overall average delay: 0.45 s						

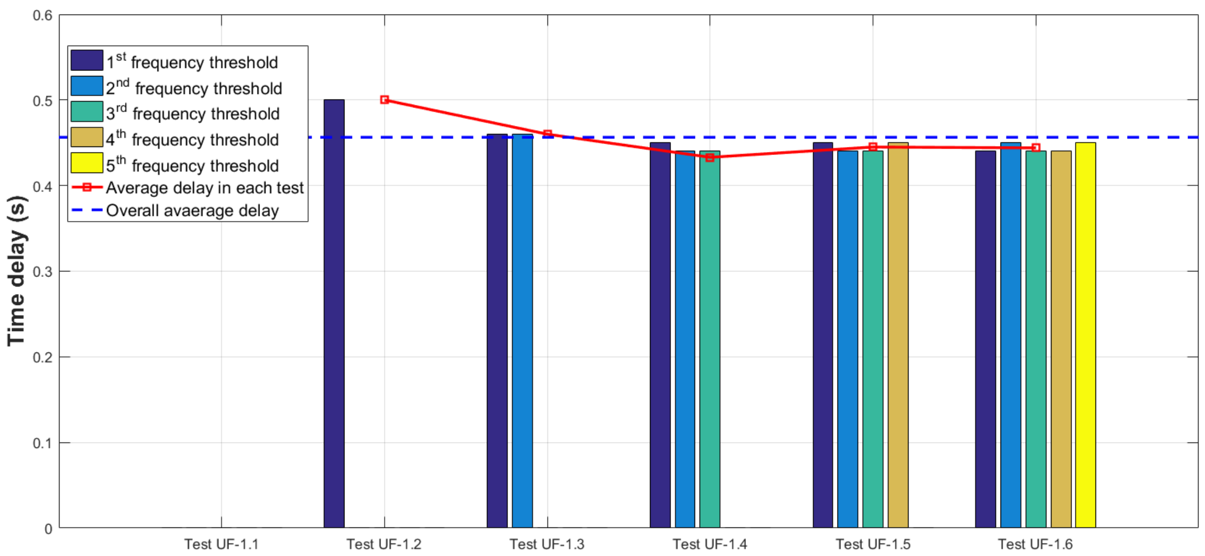

Figure 30. T_{d1}: time delay in command issuing following frequency violation

The recorded T_{d2} from this set of tests are listed in Table 33 and plotted in Figure 31. The overall average delay is approximately 1.02 s. It is thought that this is caused by the load bank's controller and its capability to change power in response to a set point change. The load bank can only periodically update its output and this period is around 1 s. if there are multiple setpoint requests in a test, the delay may accumulate, therefore the overall average delay tends to be higher

Table 43. T_{d2}: delay between command issued to deploy the resource and the time the load bank actually changes its load level

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Average
Test OF-1.1	-	-	-	-	-	-
Test OF-1.2	0.42 s	-	-	-	-	0.42 s
Test OF-1.3	0.82 s	0.8 s	-	-	-	0.81 s
Test OF-1.4	0.68 s	1.08 s	0.94 s	-	-	0.9 s
Test OF-1.5	0.41 s	1.03 s	1.43 s	1.66 s	-	1.133 s
Test OF-1.6	0.41 s	1.1 s	1.73 s	1.17 s	1.55 s	1.192 s
Overall average delay: 1.02 s						

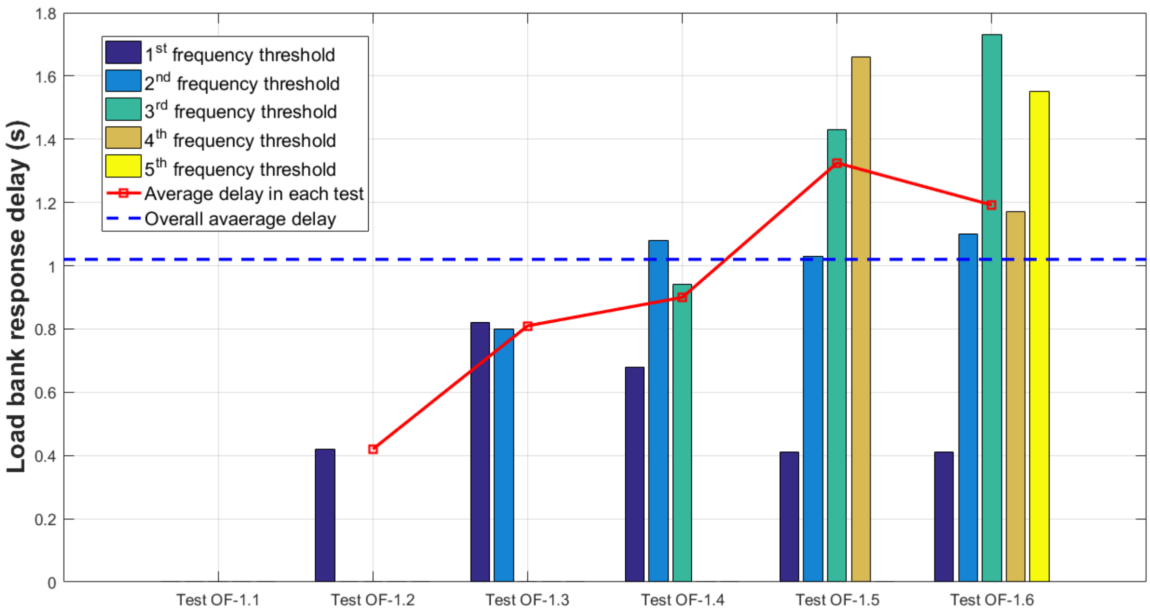

Figure 31. T_{d2}: delay between command issued to deploy the resource and the time the load bank actually changes its load level

6.2 LC uses both frequency and RoCoF thresholds for resource allocation

In this set of tests, the RoCoF thresholds are enabled in the local mode, i.e. the LC will make decisions based on both the measured frequency and RoCoF values, for testing the performance of the LC in over-frequency events. The LC is still connected to the RAs but it is intentionally set to local mode through its setting, so the wide-area monitoring signals are expected to be neglected and only local measurements will be used for decision making.

The validation of over-frequency thresholds have been conducted in Section 6.1. In this section, the operation of RoCoF thresholds are undertaken. Over-frequency events will be emulated in the PNDC network which result in the violation of frequency thresholds, and the RoCoF thresholds are set to be above and below the measured RoCoF to test LC's performance under both scenarios.

Table 44. Settings in the LC for Test OF-2

Logical node: EvDeTFRC1 (Event Detection)	
Over-frequency RoCoF threshold (sOvFreqRCFThr)	0.1 Hz/s
Over-frequency threshold (sOVFreqThr)	0.6% (0.3 Hz)
Local mode status (sLocCtrl)	True
Logical node: RsrcAlGAPC1 (Resource Allocation)	
RoCoF thresholds status (sUseRCFLims)	Ture
Frequency thresholds (Hz, sFrqHThr)	50.3, 50.4, 50.5, 50.6, 50.7
Local mode status (sLocCtrl)	True

6.2.1 Test OF-2.1: validation of the first RoCoF threshold

In this subsection, an over-frequency event that leads to a maximum frequency between 50.3 Hz and 50.4 Hz will be emulated in the network to test the first RoCoF threshold in the resource allocation block. Two tests were be conducted using the same frequency event (i.e. same loss of load size and location), which led to the violation of the first over-frequency threshold (i.e. 50.3 Hz). In these two tests, the first RoCoF threshold is configured to be 0.12 Hz/s and 0.10 Hz/s respectively, which corresponds to the cases where the measured RoCoF is above and below the RoCoF threshold.

6.2.1.1 Test OF-2.1a: the event violates the first threshold, but does not violate the first RoCoF threshold

In this test, the frequency event will violate the first frequency threshold 50.3 Hz, but not the first RoCoF threshold 0.12 Hz/s, so it is expected that the LC should not request any response from the resource due to the RoCoF threshold not being violated. The detailed settings for the frequency and RoCoF thresholds are listed in Table 45.

The test results for Test OF-2.1a are shown in Figure 32 and the key observations from the test are listed in Table 46. The event occurs at 1.50 s (T_1), which leads to the RoCoF reaching 0.1 Hz/s and the event detection flag becomes high at 3.36 s. The frequency continues to increase and violate the first frequency at 4.07 s with a RoCoF of 0.119 Hz/s, which is below the RoCoF threshold, so no resource is requested.

From the test results, it can be seen that the LC has successfully detected the event and did not request a resource response as required. No delay is observed in event detection.

Table 45. Resource allocation threshold setting for Test OF-2.1a

Thresholds	Frequency (sFrqLThr)	RoCoF (sRCFLims)
1	50.3 Hz	0.12 Hz/s
2	50.4 Hz	0 Hz/s
3	50.5 Hz	0 Hz/s
4	50.6 Hz	0 Hz/s
5	50.7 Hz	0 Hz/s

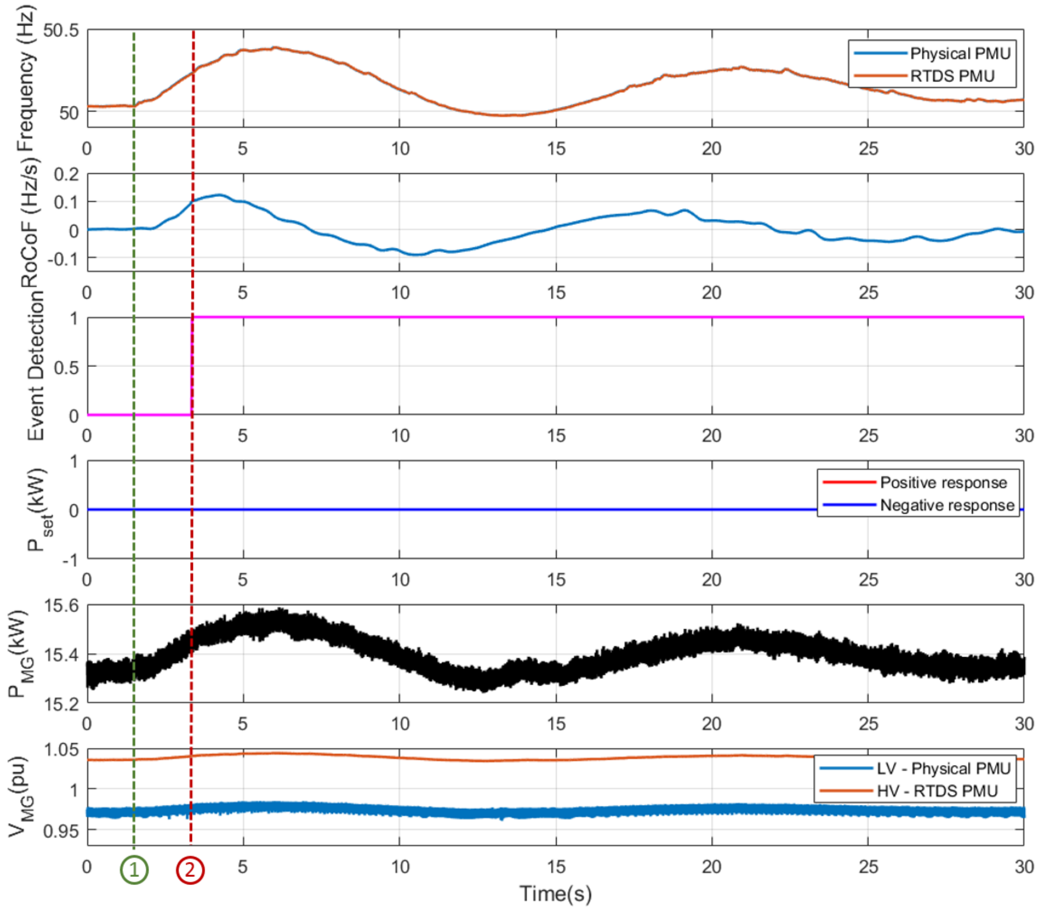

Figure 32. Results of Test OF-2.1a

Table 46. Key observation of Test OF-2.1a

Time	Observations
1.50 s (T_1)	Event occurs
3.36 s (T_2)	RoCoF increase to 0.1 Hz/s and the event detection flag becomes high
4.07 s	Frequency increase to 50.3 Hz with RoCoF of 0.119 Hz/s

6.2.1.2 Test OF-2.1b: both first frequency and RoCoF thresholds are violated

In this test, the same event as in Test OF-2.1a is re-played in the network. However, the first RoCoF threshold is configured as 0.1 Hz/s as shown in Table 47, and the frequency event will violate both of the first frequency and RoCoF thresholds, so the LC is expected to request 20% of the resource to respond to the event.

The test results for Test UF-2.1b are shown in Figure 33 and the key observations from the test are listed in Table 48. The event occurs at 1.50 s (T_1), which leads to the RoCoF increasing to 0.1 Hz/s and the event detection flag becoming high at 3.08 s. The frequency continues to increase and violates the first frequency threshold at 4.03 s with a RoCoF of 0.112 Hz/s, which is above the corresponding RoCoF threshold. Consequently, 20% of the resource is requested.

From the test results, it can be seen that the LC has successfully detected the event and requested the correct amount of resource. No delay has been observed in event detection. However, there is a delay of approximately 0.45 s in issuing the power request command following the frequency and RoCoF threshold violation and a delay of about 0.6 s in load change after the command is sent to the load bank.

Table 47. Resource allocation threshold setting for Test OF-2.1b

Thresholds	Frequency (sFrqLThr)	RoCoF (sRCFLims)
1	50.3 Hz	0.1 Hz/s
2	50.4 Hz	0 Hz/s
3	50.5 Hz	0 Hz/s
4	50.6 Hz	0 Hz/s
5	50.7 Hz	0 Hz/s

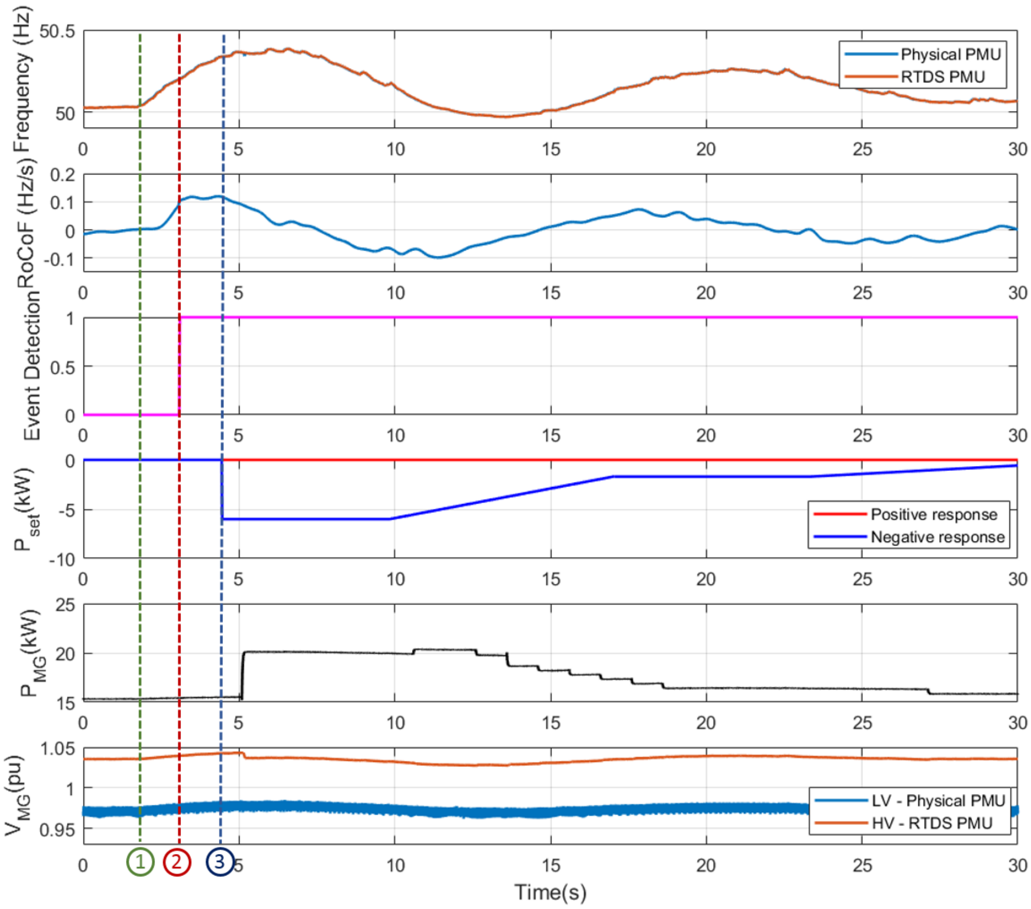

Figure 33. Results of Test OF-2.1b

Table 48. Key observation of Test OF-2.1b

Time	Observations
1.50 s (T_1)	Event occurs
3.08 s (T_2)	RoCoF increases above 0.1 Hz/s and the event detection flag becomes high
4.03 s	Frequency increase to 50.3 Hz with RoCoF of 0.112 Hz/s

4.48 s (T_3)	6 kW (20%) of negative response requested by the controller
5.08 s	Load increases from 15.53 kW to 20.10 kW
9.88 s	LC starts to decrease negative response request
10.59 s	Load starts to ramp down

6.2.2 Test OF-2.2: validation of the second RoCoF threshold

In this subsection, an over-frequency event that leads to a maximum frequency between 50.4 Hz and 50.5 Hz will be emulated in the network to test the second RoCoF threshold in the resource allocation block. In the following two tests, the second RoCoF threshold is configured to be 0.12 Hz/s and 0.1 Hz/s, which corresponds to the cases where the measured RoCoF during the event is above and below the RoCoF threshold.

6.2.2.1 Test OF-2.2a: LC detects the violation of second frequency threshold but not the second RoCoF threshold

In this test, the frequency event will violate the second frequency threshold 50.4 Hz and the RoCoF threshold 0.12 Hz/s, but the LC does not consider the RoCoF has violated the threshold. The LC is expected to request 40% of power due to the violation of first two frequency and RoCoF thresholds. The detailed settings for the frequency and RoCoF thresholds are listed in Table 49.

The test results for Test OF-2.2a are shown in Figure 34 and the key observations from the test are listed in Table 50. The event occurs at 1.50 s (T_1), which leads to the RoCoF reaching 0.10 Hz/s, i.e. the event detection RoCoF threshold, and the event detection flag becoming high at 3.08 s (T_2). The frequency continues to increase and violate the first frequency and RoCoF thresholds, which results in 20% of the resource being requested and deployed. At 6.37 s, the frequency increases above the second resource allocation frequency threshold 50.4 Hz with a RoCoF of 0.134 Hz/s, i.e. the RoCoF threshold **is also violated**. However, no further resource is requested.

From the test results, it can be seen that the LC has successfully detect the event and deployed the first 20% of the resource. It should be noted that the second RoCoF is also violated, however, the second step of response is not requested. It was suggested by GE that it was because the RoCoF value should be beyond the threshold for a certain period time for the LC to request response. In this test, the frequency and RoCoF violates threshold for approximately 270 ms (4.47 s to 4.74 s), but the resource is still not deployed.

No obvious delay has been observed after the event detection RoCoF threshold is violated. The delay between the threshold violation and the command is approximately 0.44 s; and the delay between the command and the load change is around 0.81 s.

Table 49. Resource allocation threshold setting for Test OF-2.2a

Thresholds	Frequency (sFrqLThr)	RoCoF (sRCFLims)
1	50.3 Hz	0.13 Hz/s
2	50.4 Hz	0.12 Hz/s
3	50.5 Hz	0 Hz/s
4	50.6 Hz	0 Hz/s
5	50.7 Hz	0 Hz/s

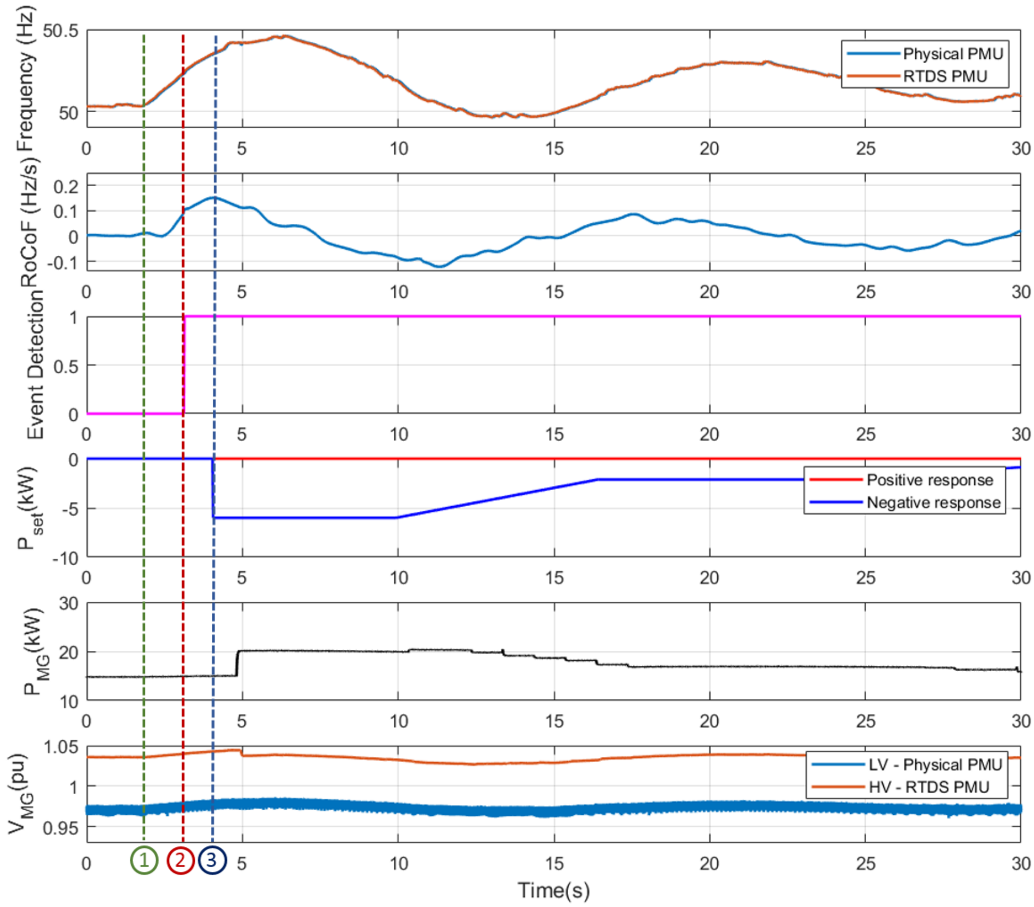

Figure 34. Results of Test OF-2.2a

Table 50. Key observation of Test OF-2.2a

Time	Observations
1.50 s (T_1)	Event occurs
3.08 s (T_2)	RoCoF increase to 0.1 Hz/s and the event detection flag becomes high
3.55 s	Frequency increases above 50.3 Hz with RoCoF of 0.129 Hz/s
3.56 s	Frequency increases above 50.302 Hz with RoCoF of 0.13 Hz/s
4.00 s (T_3)	6 kW (20%) of negative response requested by the controller
4.81 s	Load increases from 15.08 kW to 20.12 kW
4.47 s	Frequency increases above 50.4 Hz with RoCoF of 0.134 Hz/s
9.90 s	LC starts to decrease negative response request
10.33 s	Load starts to ramp down

6.2.2.2 Test OF-2.2b: both second frequency and RoCoF thresholds are violated

In this test, the frequency event will violate both of the second frequency (50.4 Hz) and RoCoF thresholds 0.1 Hz/s, so the LC is expected to request 40% of power. The detailed settings for the frequency and RoCoF thresholds are listed in Table 51.

The test results for Test OF-2.2b are shown in Figure 35 and the key observations from the test are listed in Table 52. The event occurs at 1.50 s (T_1), which leads to the RoCoF increasing to 0.1 Hz/s and the event detection flag becoming high at 3.02 s (T_2). The frequency continues to increase and violates the first frequency and RoCoF thresholds, which results in 20% of the resource being requested and deployed. At 4.60 s, the frequency increases above 50.4 Hz, which is the second resource allocation frequency threshold, with a RoCoF value of 0.127 Hz/s, so the RoCoF threshold is also violated. Therefore, a further 20% of resource is requested.

From the test results, it can be seen that the LC has successfully detected the event and deployed 40% of the resource. No delay has been observed in event detection. The average delay between the threshold violation and the command is approximately 0.445 s; and the average delay between the command and the load change is around 0.72 s.

Table 51. Resource allocation threshold setting for Test OF-2.2b

Thresholds	Frequency (sFrqLThr)	RoCoF (sRCFLims)
1	50.3 Hz	0.13 Hz/s
2	50.4 Hz	0.1 Hz/s
3	50.5 Hz	0 Hz/s
4	50.6 Hz	0 Hz/s
5	50.7 Hz	0 Hz/s

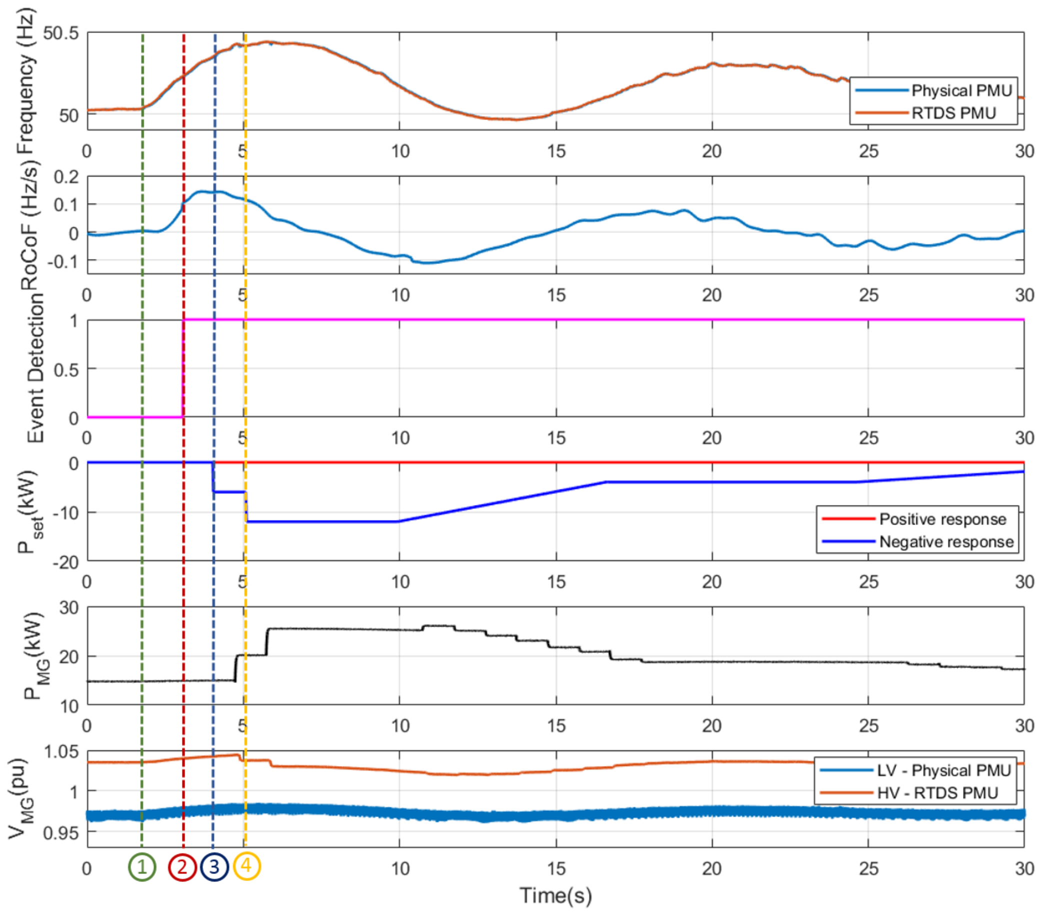

Figure 35. Results of Test OF-2.2b

Table 52. Key observation of Test OF-2.2b

Time	Observations
1.50 s (T_1)	Event occurs
3.02 s	RoCoF increases above 0.1 Hz/s and the event detection flag becomes high
3.53 s	Frequency increases above 50.3 Hz with RoCoF of 0.142 Hz/s
3.98 s (T_2)	6 kW (20%) of negative response requested by the controller
4.73 s	Load increases from 15.02 kW to 20.10 kW
4.60 s	Frequency increases above 50.4 Hz with RoCoF of 0.127 Hz/s
5.04 s (T_3)	12 kW (40%) of negative response requested by the controller
5.73 s	Load increases from 20.14 kW to 20.50 kW
9.90 s	LC starts to decrease negative response request
10.73 s	Load starts to ramp down

6.2.3 Test OF-2.3: validation of the third RoCoF threshold

In this subsection, an over-frequency event that leads to a maximum frequency between 50.5 Hz and 50.6 Hz will be emulated in the network to test the third RoCoF threshold in the resource allocation block. In the following two tests, the third RoCoF threshold is configured to be 0.15 Hz/s and 0.09 Hz/s, which corresponds to the cases where the measured RoCoF is above and below the RoCoF threshold.

6.2.3.1 Test OF-2.3a: the event violates the third threshold, but does not violate the third RoCoF threshold

In this test, the frequency event will violate the third frequency threshold 50.5 Hz but not the corresponding RoCoF threshold 0.15 Hz/s. The LC is expected to only request 40% of power due to the violation of first two frequency and RoCoF thresholds. The detailed settings for the frequency and RoCoF thresholds are listed in Table 53.

The test results for Test OF-2.3a are shown in Figure 36 and the key observations from the test are listed in Table 54. The event occurs at 1.50 s (T_1), which leads to the RoCoF increasing to 0.1 Hz/s and the event detection flag becoming high at 2.94 s (T_2). The frequency continues to increase and violates the first two frequency and RoCoF thresholds, which results in 40% of the resource be requested and deployed. At 4.93 s, the frequency increases above 50.5 Hz, which is the second resource allocation frequency threshold, with a RoCoF value of 0.143 Hz/s, i.e. the third RoCoF threshold is not violated, so no further resource is requested.

From the test results, it can be seen that the LC has successfully detected the event and deploy 40% of the resource. No obvious delay has been observed after the event detection RoCoF threshold is violated. The average delay between the threshold violation and the command is approximately 0.26 s; and the average delay between the command and the load change is around 0.755 s.

Table 53. Resource allocation threshold setting for Test OF-2.3a

Thresholds	Frequency (sFrqLThr)	RoCoF (sRCFLims)
1	50.3 Hz	0.18 Hz/s
2	50.4 Hz	0.16 Hz/s

3	50.5 Hz	0.15 Hz/s
4	50.6 Hz	0 Hz/s
5	50.7 Hz	0 Hz/s

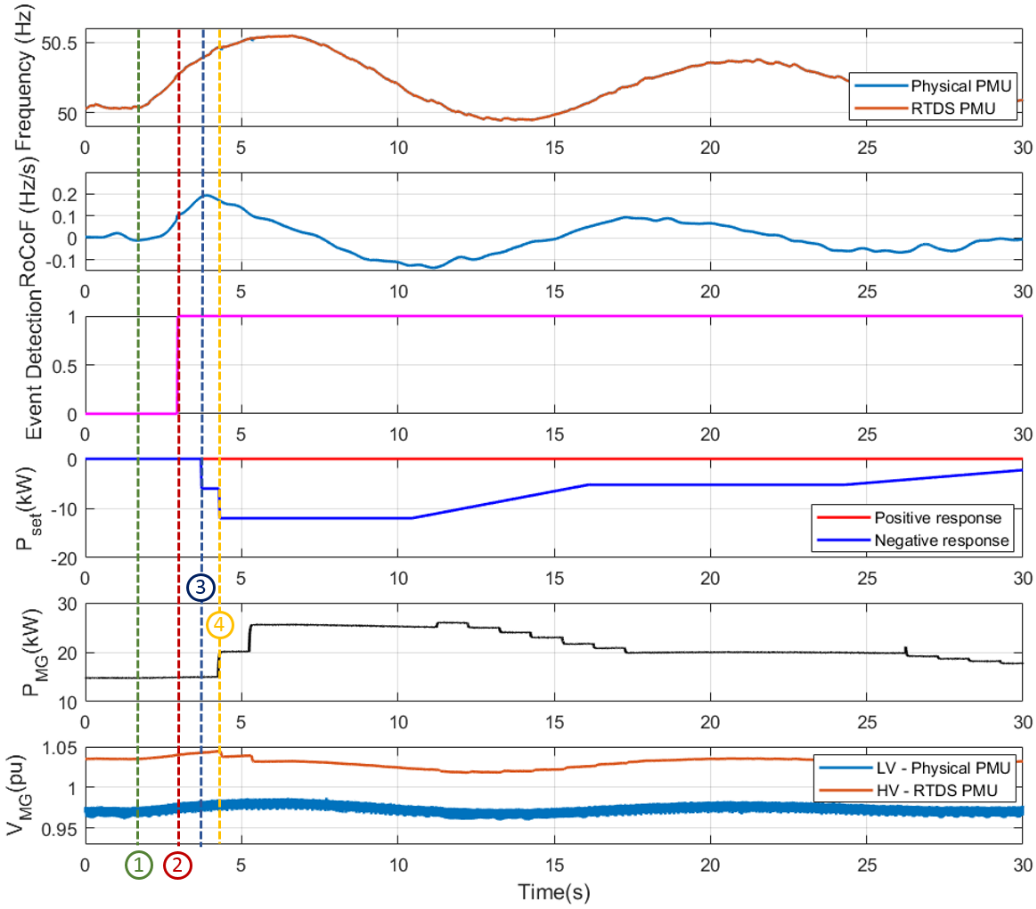

Figure 36. Results of Test OF-2.3a

Table 54. Key observation of Test OF-2.3a

Time	Observations
1.50 s (T_1)	Event occurs
2.94 s (T_2)	RoCoF increases above 0.1 Hz/s and the event detection flag becomes high
3.14 s	Frequency increases below 50.3 Hz with RoCoF of 0.114 Hz/s
3.64 s	Frequency increases above 50.38 Hz with RoCoF of 0.18 Hz/s
3.70 s (T_3)	6 kW (20%) of negative response requested by the controller
4.25 s	Load increases from 15.00 kW to 20.10 kW
3.82 s	Frequency increases above 50.4 Hz with RoCoF of 0.193 Hz/s
4.28 s (T_4)	12 kW (40%) of negative response requested by the controller
5.24 s	Load increases from 20.14 kW to 25.59 kW
4.93 s	Frequency increases to 50.5 Hz with RoCoF of 0.143 Hz/s

10.46 s	LC starts to decrease negative response request
11.24 s	Load starts to ramp down

6.2.3.2 Test OF-2.3b: both third frequency and RoCoF thresholds are violated

In this test, the frequency event violated both the third frequency (50.5 Hz) and RoCoF (0.09 Hz/s) thresholds, so the LC is expected to request 60% of power due to the violation of first three frequency and RoCoF thresholds. The detailed settings for the frequency and RoCoF thresholds are listed in Table 55.

The test results for Test OF-2.3b are shown in Figure 37 and the key observations from the test are listed in Table 56. The event occurs at 1.50 s (T_1), which leads to the RoCoF increasing to 0.1 Hz/s and the event detection flag becoming high at 2.98 s. The frequency continues to increase and violate the first two frequency and RoCoF thresholds, which results in 40% of the resource to be requested and deployed. At 4.92 s, the frequency increases above 50.5 Hz, which is the third resource allocation frequency threshold with a RoCoF value of 0.132 Hz/s, so the RoCoF threshold is also violated. Therefore, a further 20% of resource is requested.

From the test results, it can be seen that the LC has successfully detected the event and deployed 60% of the resource. No delay has been observed in event detection. The average delay between the threshold violation and the command is approximately 0.32 s; and the average delay between the command and the load change is around 0.753 s. **It should be noted that during the tests, the settings of 0.13 Hz/s and 0.11 Hz/s for the third RoCoF threshold were also tested, but no resource was requested when these are applied. This is further evidence showing that the measured RoCoF need to be beyond the threshold for certain period of time before it can be can considered to have violated the threshold.**

Table 55. Resource allocation threshold setting for Test OF-2.3b

Thresholds	Frequency (sFrqLThr)	RoCoF (sRCFLims)
1	50.3 Hz	0.18 Hz/s
2	50.4 Hz	0.16 Hz/s
3	50.5 Hz	0.09 Hz/s (setting of 0.13 Hz/s and 0.11 Hz/s also tested)
4	50.6 Hz	0 Hz/s
5	50.7 Hz	0 Hz/s

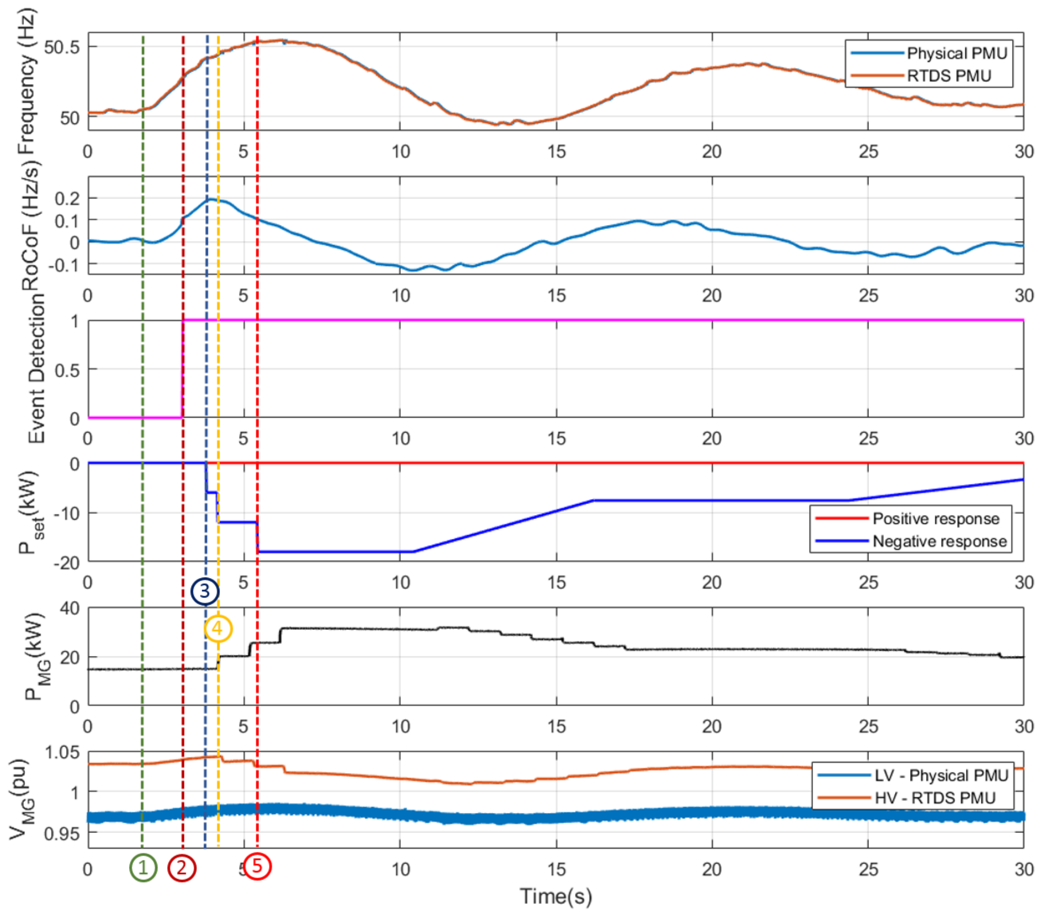

Figure 37. Results of Test OF-2.3b

Table 56. Key observation of Test OF-2.3b

Time	Observations
1.50 s (T_1)	Event occurs
2.98 s (T_2)	RoCoF exceeds 0.1 Hz/s and the event detection flag becomes high
3.10 s	Frequency increases above 50.3 Hz with RoCoF of 0.116 Hz/s
3.69 s	Frequency increases above 50.41 Hz with RoCoF of 0.18 Hz/s
3.74 s (T_3)	6 kW (20%) of negative response requested by the controller
4.16 s	Load increases from 14.97 kW to 20.03 kW
3.66 s	Frequency increases above 50.4 Hz with RoCoF of 0.177 Hz/s
4.10 s (T_4)	12 kW (40%) of negative response requested by the controller
5.17 s	Load increases from 20.08 kW to 25.48 kW
4.92 s	Frequency increases above 50.5 Hz with RoCoF of 0.132 Hz/s
5.38 s (T_5)	18 kW (60%) of negative response requested by the controller
6.15 s	Load increases from 25.46 kW to 31.34 kW
10.38 s	LC starts to decrease negative response request

11.19 s	Load starts to ramp down

6.2.4 Test OF-2.4: validation of the fourth RoCoF threshold

In this subsection, an over-frequency event that leads to a maximum frequency between 50.6 Hz and 50.7 Hz will be emulated in the network to test the fourth RoCoF threshold in the resource allocation block. In the following two tests, the fourth RoCoF threshold is configured to be 0.15 Hz/s and 0.13 Hz/s, which corresponds to the cases where the LC considers the measured RoCoF has not and has violated the corresponding RoCoF thresholds respectively.

6.2.4.1 Test OF-2.4a: LC detects the violation of fourth frequency threshold but not the fourth RoCoF threshold

In this test, the frequency event will violate the fourth frequency threshold 50.6 Hz and the RoCoF threshold 0.15 Hz/s, but the LC does not consider the RoCoF has been violated. The LC is expected to only request 40% of power due to the violation of first two frequency and RoCoF thresholds. The detailed settings for the frequency and RoCoF thresholds are listed in Table 57.

The test results for Test OF-2.4a are shown in Figure 38 and the key observations from the test are listed in Table 58. The event occurs at 1.50 s (T_1), which leads to the RoCoF exceeds 0.1 Hz/s, i.e. the event detection RoCoF threshold, and the event detection flag becoming high at 2.88 s (T_2). The frequency continues to increase and violate the first three frequency and RoCoF thresholds, which results in 60% of the resource to be requested and deployed. At 4.73 s, the frequency increases above 50.6 Hz, which is the fourth resource allocation frequency threshold with a RoCoF value of 0.184 Hz/s, i.e. the RoCoF threshold **is also violated**. However, no further resource is requested.

From the test results, it can be seen that the LC has successfully detected the event and deployed 40% of the resource. It should be noted that the fourth RoCoF threshold is also violated, however the fourth step of response is not requested. It was suggested by GE that the RoCoF value should be beyond the threshold for a certain period time for the LC to request response. In this test, the frequency and RoCoF violates the threshold for approximately 320 ms (4.73s to 5.05s), but the resource is still not deployed. **Input from GE is required to clarify this observation.**

No delay has been observed after the event detection RoCoF threshold is violated. The delay between the threshold violation and the command is approximately 0.31 s; and the delay between the command and the load change is around 1.16 s.

Table 57. Resource allocation threshold setting for Test OF-2.4a

Thresholds	Frequency (sFrqLThr)	RoCoF (sRCFLims)
1	50.3 Hz	0.18 Hz/s
2	50.4 Hz	0.17 Hz/s
3	50.5 Hz	0.16 Hz/s
4	50.6 Hz	0.15 Hz/s
5	50.7 Hz	0 Hz/s

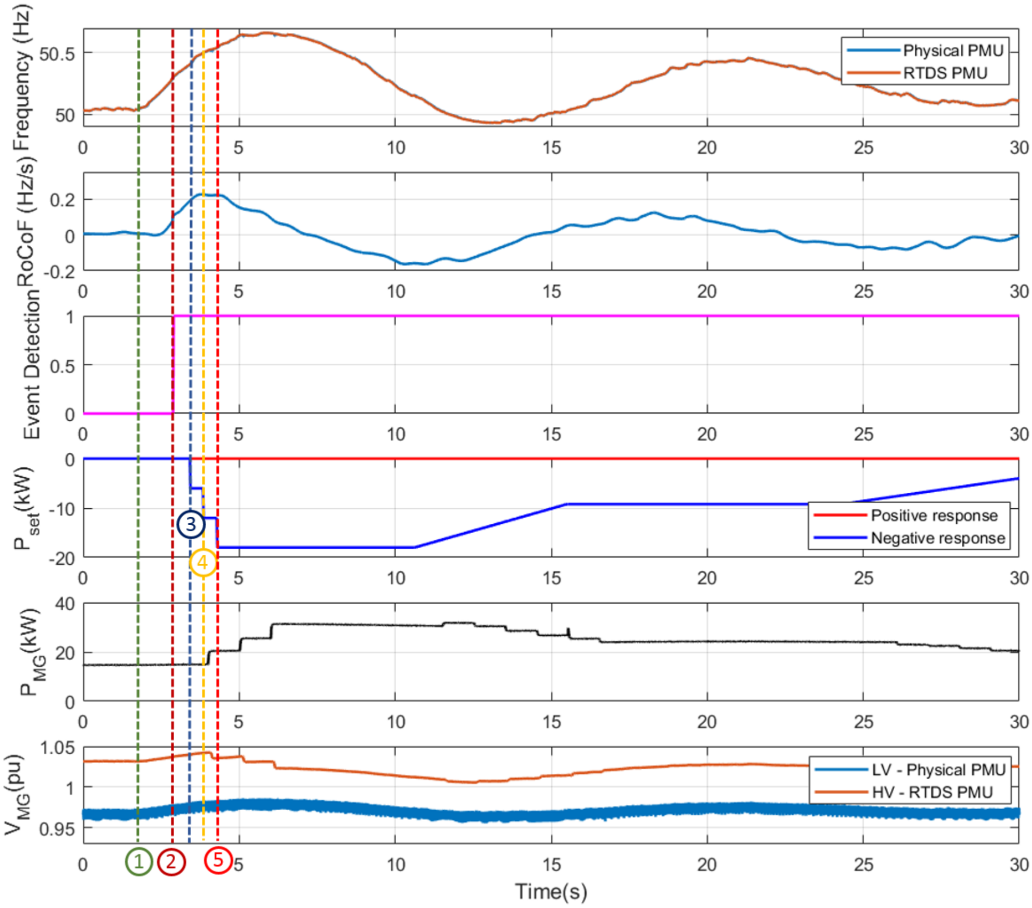

Figure 38. Results of Test OF-2.4a

Table 58. Key observation of Test OF-2.4a

Time	Observations
1.50 s (T_1)	Event occurs
2.88 s (T_2)	RoCoF increases above 0.1 Hz/s and the event detection flag becomes high
2.88 s	Frequency increases above 50.3 Hz with RoCoF of 0.1 Hz/s
3.37 s	Frequency increases above 50.395 Hz with RoCoF of 0.18 Hz/s
3.42 s (T_3)	6 kW (20%) of negative response requested by the controller
4.00 s	Load increases from 14.90 kW to 20.39 kW
3.40 s	Frequency increases above 50.4 Hz with RoCoF of 0.186 Hz/s
3.84 s (T_4)	12 kW (40%) of negative response requested by the controller
5.02 s	Load increases from 20.51 kW to 25.47 kW
3.84 s	Frequency increases above 50.5 Hz with RoCoF of 0.226 Hz/s
4.28 s (T_5)	18 kW (60%) of negative response requested by the controller
4.73 s	Frequency increases above 50.6 Hz with RoCoF of 0.184 Hz/s
6.02 s	Load increases from 25.44 kW to 31.29 kW

10.62 s	LC starts to decrease negative response request
11.52 s	Load starts to ramp down

6.2.4.2 Test OF-2.4b: both fourth frequency and RoCoF thresholds are violated

In this test, the frequency event violated both the fourth frequency (50.6 Hz) and RoCoF thresholds 0.13 Hz/s, so the LC is expected to request 80% of power due to the violation of first four frequency and RoCoF thresholds. The detailed settings for the frequency and RoCoF thresholds are listed in Table 59.

The test results for Test OF-2.4b are shown in Figure 39 and the key observations from the test are listed in Table 60. The event occurs at 1.50 s (T_1), which leads to the RoCoF increasing to 0.1 Hz/s and the event detection flag becoming high at 2.94 s. The frequency continues to increase and violates the first three frequency and RoCoF thresholds, which results in 60% of the resource to be requested and deployed. At 4.65 s, the frequency increases above 50.6 Hz, which is the third resource allocation frequency threshold with RoCoF of 0.182 Hz/s, so the RoCoF threshold is also violated. Therefore, a further 20% of resource is requested.

From the test results, it can be seen that the LC has successfully detected the event and deployed 80% of the resource. No delay has been observed in event detection. The average delay between the threshold violation and the command is approximately 0.36 s; and the average delay between the command and the load change is around 1.18 s.

Table 59. Resource allocation threshold setting for Test OF-2.4b

Thresholds	Frequency (sFrqLThr)	RoCoF (sRCFLims)
1	50.3 Hz	0.18 Hz/s
2	50.4 Hz	0.17 Hz/s
3	50.5 Hz	0.16 Hz/s
4	50.6 Hz	0.13 Hz/s
5	50.7 Hz	0 Hz/s

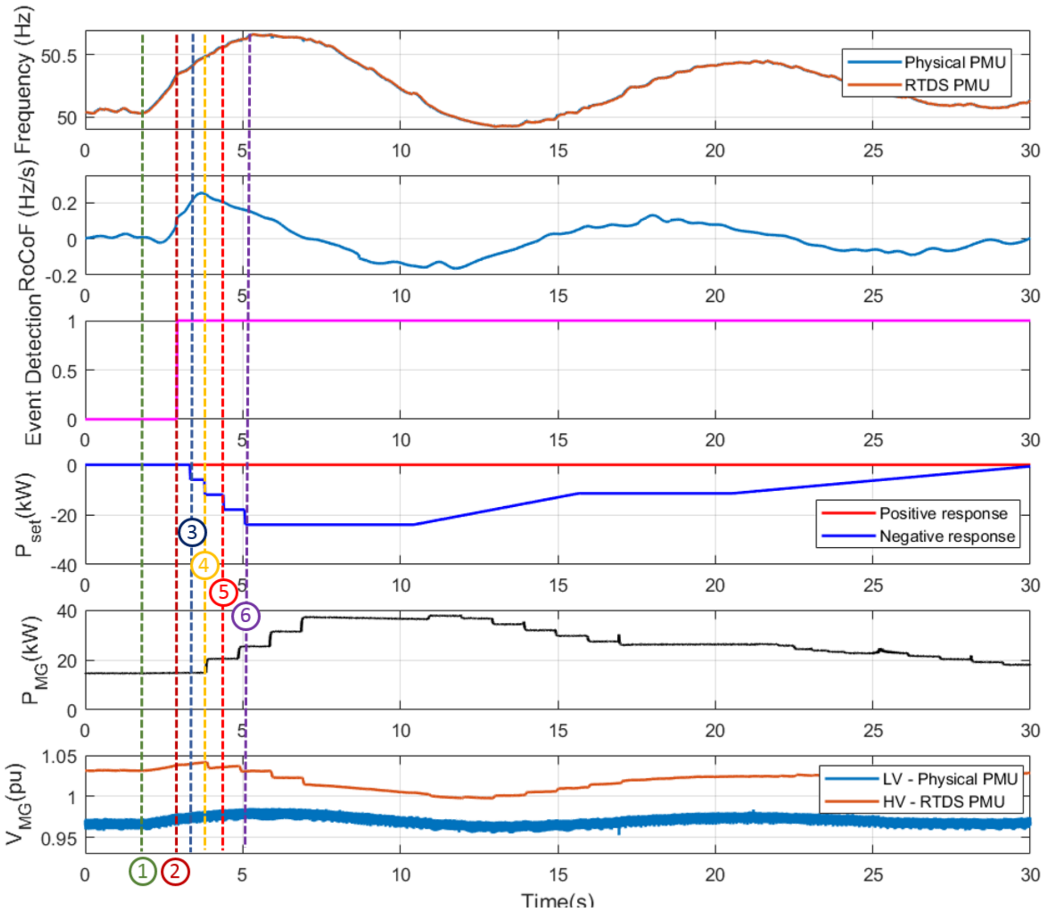

Figure 39. Results of Test OF-2.4b

Table 60. Key observation of Test OF-2.4b

Time	Observations
1.50 s (T_1)	Event occurs
2.94 s (T_2)	RoCoF increases above 0.1 Hz/s and the event detection flag becomes high
2.85 s	Frequency increases above 50.3 Hz with RoCoF of 0.046 Hz/s
3.28 s	Frequency increases to 50.385 Hz with RoCoF of 0.18 Hz/s
3.36 s (T_3)	6 kW (20%) of negative response requested by the controller
3.83 s	Load increases from 14.92 kW to 20.48 kW
3.37 s	Frequency increases above 50.4 Hz with RoCoF of 0.195 Hz/s
3.82 s (T_4)	12 kW (40%) of negative response requested by the controller
4.86 s	Load increases from 20.50 kW to 25.44 kW
3.97 s	Frequency increases above 50.5 Hz with RoCoF of 0.232 Hz/s
4.42 s (T_5)	18 kW (60%) of negative response requested by the controller
5.86 s	Load increases from 25.43 kW to 31.37 kW
4.65 s	Frequency increases above 50.6 Hz with RoCoF of 0.182 Hz/s

5.10 s (T_5)	24 kW (80%) of negative response requested by the controller
6.86 s	Load increases from 31.40 kW to 37.11 kW
10.48 s	LC starts to decrease negative response request
10.89 s	Load starts to ramp down

6.2.5 Test OF-2.5: validation of the fifth RoCoF threshold

In this subsection, an over-frequency event that leads to a maximum frequency above 50.7 Hz will be emulated in the network to test the fifth RoCoF threshold in the resource allocation block. During the tests, it was observed that no matter how large the fifth RoCoF threshold is set, the final step of resource will always be requested as long as the frequency violates the fifth frequency threshold.

In the following two tests, two values have been used for the fifth RoCoF threshold: one is 0.15 Hz/s which is relatively small and the latter one will be 1 Hz/s, which is much larger than the measured RoCoF at 50.7 Hz.

6.2.5.1 Test OF-2.5a: both fifth frequency and RoCoF thresholds are violated

In this test, the frequency event will violate the fifth frequency threshold 50.7 Hz and the fifth RoCoF threshold 0.15 Hz/s, so the LC is expected to request 100% of power due to the violation of all frequency and RoCoF thresholds. The detailed settings for the frequency and RoCoF thresholds are listed in Table 62.

The test results for Test OF-2.5a are shown in Figure 40 and the key observations from the test are listed in Table 62. The event occurs at 1.50 s (T_1), which leads to the RoCoF increasing to 0.1 Hz/s and the event detection becoming high at 2.80 s. The frequency continues to increase and violate the first four frequency and RoCoF thresholds, which results in 80% of the resource to be requested. At 4.56 s, the frequency increases above 50.7 Hz, which is the fifth resource allocation frequency threshold with a RoCoF of 0.258 Hz/s, which is larger than the corresponding threshold of 0.15 Hz/s, so a further 20% of resource is requested.

From the test results, it can be seen that the LC has successfully deployed 100% of resource as required. During this test, no delay has been observed for event detection. The average delay between the threshold violation and the command is approximately 0.364 s; and the delay between the command and the load change is around 1.168 s. It was observed that the load bank increases 40% of power in a single step at 5.00 s – it is deemed that this is caused by two consecutive setpoint changes being sent relatively close to each other in time. Consequently, when the load bank changes the output, it used the latter power requested value which combines two steps of 20% power request.

Table 61. Resource allocation threshold setting for Test OF-2.5a

Thresholds	Frequency (sFrqLThr)	RoCoF (sRCFLims)
1	50.3 Hz	0.2 Hz/s
2	50.4 Hz	0.19 Hz/s
3	50.5 Hz	0.18 Hz/s
4	50.6 Hz	0.17 Hz/s
5	50.7 Hz	0.15 Hz/s

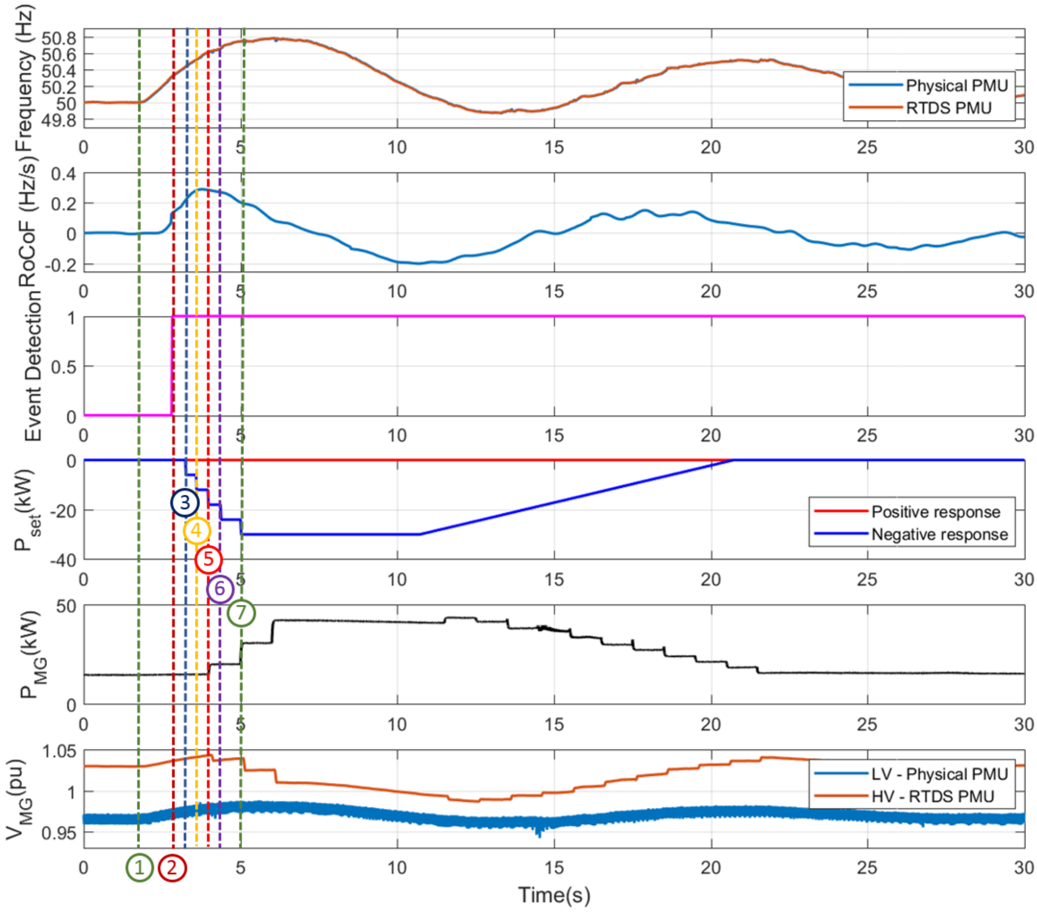

Figure 40. Results of Test OF-2.5a

Table 62. Key observation of Test OF-2.5a

Time	Observations
1.50 s (T_1)	Event occurs
2.80 s (T_2)	RoCoF increases above 0.1 Hz/s and the event detection flag becomes high
2.76 s	Frequency increases above 50.3 Hz with RoCoF of 0.062 Hz/s
3.19 s	Frequency increases above 50.4 Hz with RoCoF of 0.20Hz/s
3.24 s (T_3)	6 kW (20%) of negative response requested by the controller
3.98 s	Load increases from 15.06 kW to 20.20 kW
3.13 s	Frequency increase to 50.4 Hz with RoCoF of 0.183 Hz/s
3.16 s	Frequency increase to 50.402 Hz with RoCoF of 0.19 Hz/s
3.58 s (T_4)	12 kW (40%) of negative response requested by the controller
3.50 s	Frequency increase to 50.5 Hz with RoCoF of 0.27 Hz/s
3.96 s (T_5)	18 kW (60%) of negative response requested by the controller
5.00 s	Load increases from 20.34 kW to 31.00kW

3.91 s	Frequency increase to 50.6 Hz with RoCoF of 0.285 Hz/s
4.36 s (T_6)	24 kW (80%) of negative response requested by the controller
4.56 s	Frequency increase to 50.7 Hz with RoCoF of 0.258 Hz/s
5.00 s (T_7)	30 kW (100%) of negative response requested by the controller
6.00 s	Load increases from 31.07 kW to 42.18 kW
10.72 s	LC starts to decrease negative response request
11.50 s	Load starts to ramp down

6.2.5.2 Test OF-2.5b: the frequency violates the fifth threshold, but does not violate the fifth RoCoF threshold

In this test, the frequency event will violate the fifth frequency threshold of 50.7 Hz, but not the fifth RoCoF threshold of 1 Hz/s, so the LC is expected to only request 80% of power due to the violation of the first four frequency and RoCoF thresholds. The detailed settings for the frequency and RoCoF thresholds are listed in Table 63. The setting of fifth RoCoF threshold at 1 Hz/s is chosen to be significantly larger than the measured RoCoF. During the test, it was observed that no matter how large the fifth RoCoF threshold is, the fifth step of response will always be requested as long as the fifth frequency threshold is violated. The same behaviour was observed in Test UF-2.5b as presented in Section 6.2.5.2.

The test results for Test OF-2.5b are shown in Figure 41 and the key observations from the test are listed in Table 64. The event occurs at 1.50 s (T_1), which leads to the RoCoF increasing to 0.10 Hz/s, i.e. the event detection RoCoF threshold, and the event detection flag becoming high at 2.76 s. The frequency continues to increase and violate the first four frequency and RoCoF thresholds, which results in 80% of the resource to be requested and deployed. At 4.62 s, the frequency increases above 50.7 Hz, which is the fifth resource allocation frequency threshold with a RoCoF of 0.231 Hz/s. The measured RoCoF is much lower than the corresponding threshold 1 Hz/s. However, a further 20% of resource is requested.

From the test results, it can be seen that the LC will always deploy 100% of resource as long as the fifth frequency threshold is violated. It is suggested by GE that this is intentionally designed so that the LC will respond in a severe frequency events (e.g. when first four frequency thresholds are violated). However, this leads to the fifth RoCoF threshold not being used in the controller, thus not necessary.

During this test, no delay has been observed in event detection. The average delay between the threshold violation and the command is approximately 0.374 s; and the delay between the command and the load change is around 1.126 s. It is observed that the load bank changed 40% of its power output in a single step (second and third power request at 3.58 s and 4.00 s respectively) – this is caused by the two requests that are sent relatively close to each other. When the load bank changes its output, it used the latter power requested value which combines two steps of 20% power request.

Table 63. Resource allocation threshold setting for Test OF-2.5b

Thresholds	Frequency (sFrqLThr)	RoCoF (sRCFLims)
1	50.3 Hz	0.2 Hz/s
2	50.4 Hz	0.19 Hz/s
3	50.5 Hz	0.18 Hz/s
4	50.6 Hz	0.17 Hz/s
5	50.7 Hz	1 Hz/s

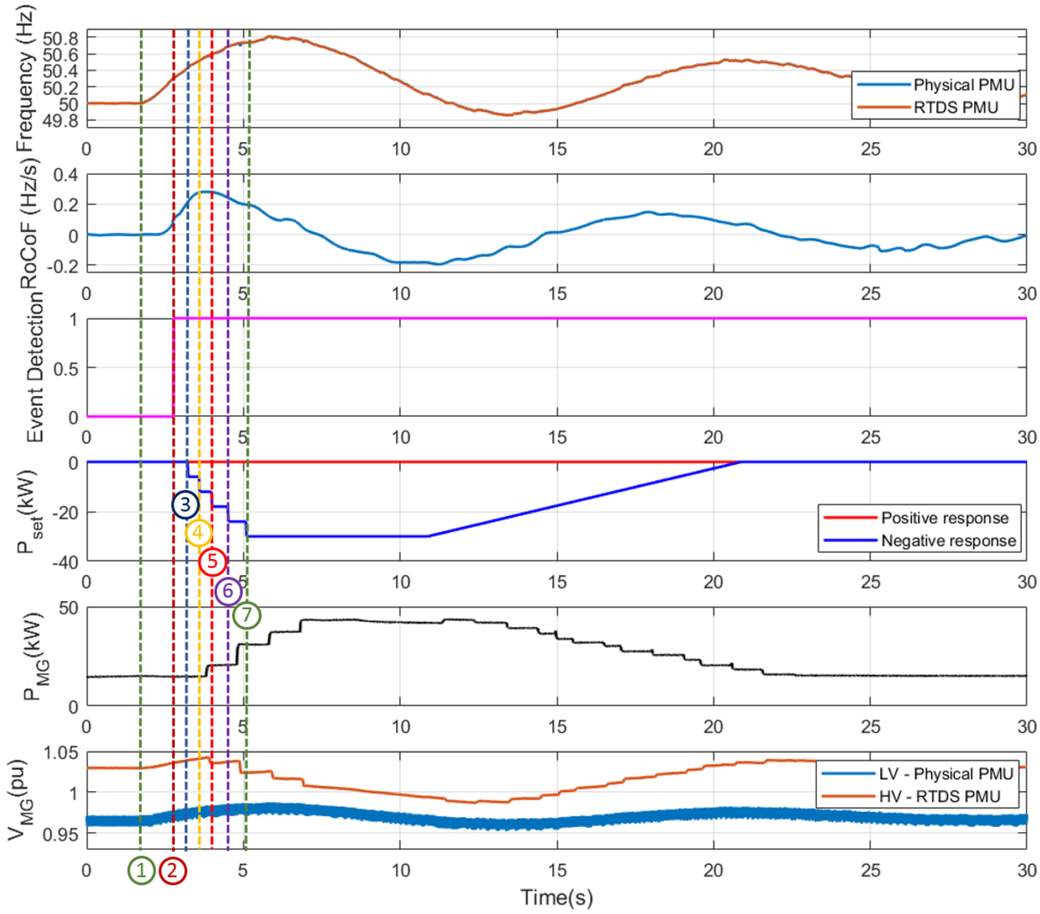

Figure 41. Results of Test OF-2.5b

Table 64. Key observation of Test OF-2.5b

Time	Observations
1.50 s (T_1)	Event occurs
2.76 s	RoCoF increases above 0.1 Hz/s and the event detection flag becomes high
2.75 s	Frequency increases above 50.3 Hz with RoCoF of 0.09 Hz/s
3.18 s	Frequency increases to 50.414 Hz with RoCoF of 0.2 Hz/s
3.22 s (T_2)	6 kW (20%) of negative response requested by the controller
3.81 s	Load increases from 14.85 kW to 20.51 kW
3.14 s	Frequency increases above 50.4 Hz with RoCoF of 0.189 Hz/s
3.15 s	Frequency increases above 50.403 Hz with RoCoF of 0.19Hz/s
3.58 s (T_3)	12 kW (40%) of negative response requested by the controller
3.52 s	Frequency increases above 50.5 Hz with RoCoF of 0.271Hz/s
4.00 s (T_4)	18 kW (60%) of negative response requested by the controller
4.79 s	Load increases from 20.56 kW to 30.93kW
4.04 s	Frequency increases above 50.6 Hz with RoCoF of 0.277 Hz/s

4.50 s (T_5)	24 kW (80%) of negative response requested by the controller
5.81 s	Load increases from 30.93 kW to 37.21kW
4.62 s	Frequency increase to 50.7 Hz with RoCoF of 0.231Hz/s
5.08 s (T_6)	30 kW (100%) of negative response requested by the controller
6.81 s	Load increases from 37.27 kW to 42.94 kW
10.88 s	LC starts to decrease negative response request
11.35 s	Load starts to ramp down

6.2.6 Summary of the over-frequency tests of LC's local mode with the RoCoF thresholds enabled

In this set of tests, the functionality of the LC when operating in local mode with RoCoF thresholds enabled has been tested under a range of over-frequency events.

The test results show that the LC has successfully detected the events in all cases. The first four RoCoF thresholds have been used to provide an extra layer of checking for resource deployment. From the results, it was shown that the first four thresholds have successfully performed their functions and deployed the required amount of resources based on the associated settings and design specification.

It was also found that the RoCoF threshold needs to be violated for a certain period of time for the resource to be requested. This is evident in Test UF-2.4a (in Section 5.2.4), Test OF 2.2a and Test OF 2.4a.

It was found that the fifth RoCoF threshold is not used for decision making, i.e. when the frequency drops below the fifth frequency threshold, the resource will be deployed regardless of the measured RoCoF value. The same observation was made for Test UF-2 in Section 5.2. It was suggested by GE that this is intentionally designed so that the LC will respond in severe frequency disturbance where the first four thresholds are violated. Recommendations for potential improvements to this was discussed in Section 5.2.1.

During the tests, various delays have been observed at different stages. Three main delays have been observed:

- Delay in event detection when the RoCoF threshold is violated – this delay typically ranges from 0-20 ms, which is thought to be caused by the reporting rate of the LC, which is very 20 ms.
- T_{d1}: time delay between the time when the frequency threshold being violated and the time a command is issued to deploy the resource
- T_{d2}: the delay between the time when a command is issued to deploy the resource and the time the load bank actually changes its load level.

The recorded Td1 from this set of tests are listed in Table 65 and plotted in Figure 42. The overall average value of Td1 is approximately 0.36 s.

Table 65. T_{d1}: time delay in command issuing following frequency violation

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Average
Test OF-2.1a	-	-	-	-	-	-
Test OF-2.1b	0.45 s	-	-	-	-	0.45 s

Test OF-2.2a	0.44 s	-	-	-	-	0.44 s
Test OF-2.2b	0.45 s	0.44 s	-	-	-	0.445 s
Test OF-2.3a	0.06 s	0.46 s	-	-	-	0.26 s
Test OF-2.3b	0.05 s	0.44 s	0.46 s	-	-	0.32 s
Test OF-2.4a	0.05 s	0.44 s	0.44 s	-	-	0.31 s
Test OF-2.4b	0.08 s	0.45 s	0.45 s	0.45 s	-	0.36 s
Test OF-2.5a	0.05 s	0.42 s	0.46 s	0.45 s	0.44 s	0.36 s
Test OF-2.5b	0.04 s	0.43 s	0.48 s	0.46 s	0.46 s	0.37 s
Overall average delay: 0.36 s						

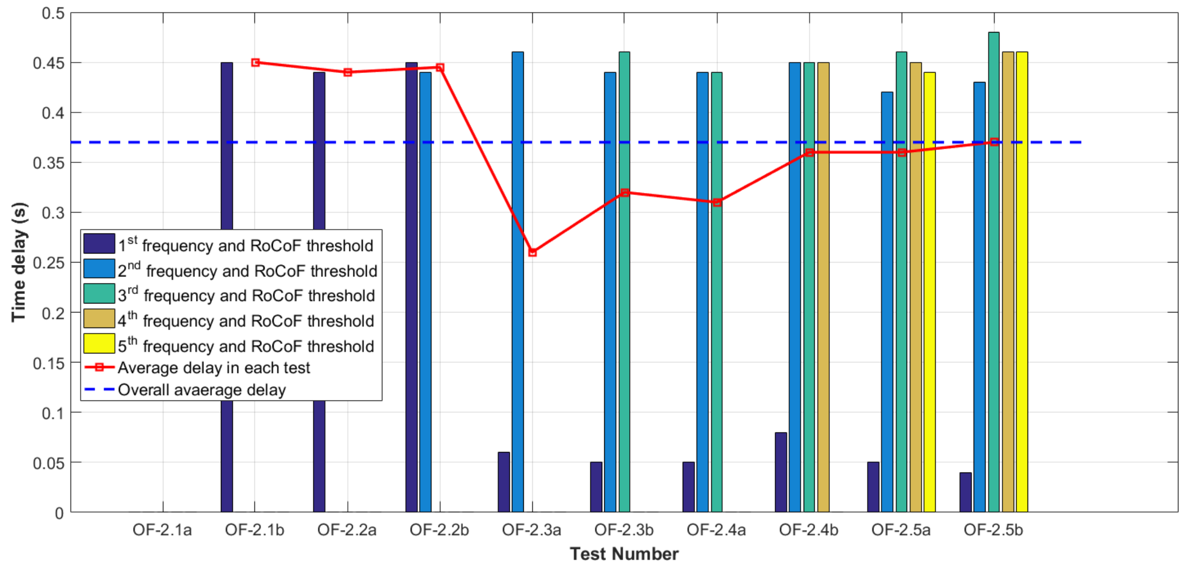

Figure 42. T_{d1}: time delay in command issuing following frequency violation

The recorded T_{d2} from this set of tests are listed in Table 66 and plotted in Figure 43. The overall average delay is approximately 1.01 s. It is considered that this is caused by the way the load bank change its load level following a command. As shown in Figure 43, when the load bank receives a command, it will change its load level and hold that for around 1 s before it will change the load level again. This may be related to the capability of the load bank in terms of how fast it can achieve the targeted power. The large variation in delay is thought to be caused by the point in time within the load bank's output refreshing cycle when the LC send the command.

Table 66. T_{d2}: command is issued to deploy resource and the time the load bank actually changes its load level

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Average
Test OF-2.1a	-	-	-	-	-	-
Test OF-2.1b	0.60 s	-	-	-	-	0.60 s
Test OF-2.2a	0.81 s	-	-	-	-	0.81 s

Test OF-2.2b	0.75 s	0.69 s	-	-	-	0.72 s
Test OF-2.3a	0.55 s	0.96 s	-	-	-	0.76 s
Test OF-2.3b	0.42 s	1.07 s	0.77s	-	-	0.75 s
Test OF-2.4a	0.58 s	1.18 s	1.74 s	-	-	1.17 s
Test OF-2.4b	0.47 s	1.04 s	1.44 s	1.76 s	-	1.18 s
Test OF-2.5a	0.74 s	1.42 s	1.04 s	1.64 s	1.00 s	1.17 s
Test OF-2.5b	0.59 s	1.21 s	0.79 s	1.31 s	1.73 s	1.13 s
Overall average delay: 1.01 s						

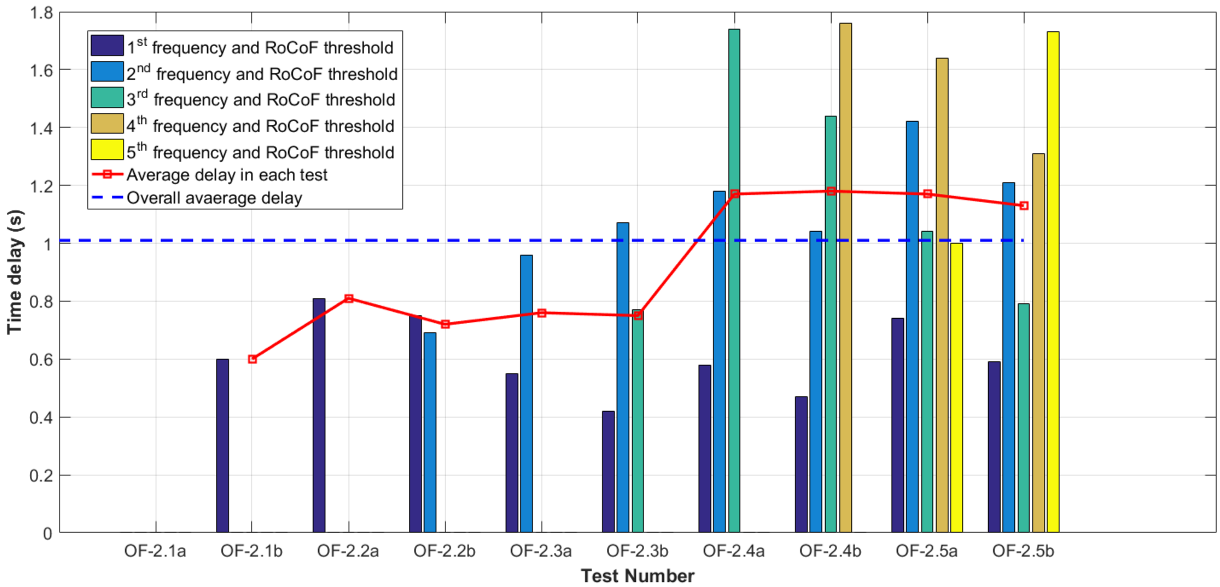

Figure 43. T_{d2}: delay between command issued to deploy resource and the time the load bank actually changes its load level

7 FAULT EVENTS

7.1 Overview of the fault tests

This section presents the results of the tests to evaluate the LC's performance under its local mode during fault events. The LC is expected to detect faults in the local mode and remain stable to these events by blocking the event detection and resource deployment. The capability of the LC to do so will be verified.

Different types of solid faults, which are the most severe fault conditions, have been applied in the PNDC network to test the security of the system. The test configuration is shown in Figure 44. The MG set supplies the PNDC HV (11 kV) and LV (400 V) networks; the faults are applied in the LV network, where the physical PMU and the load banks are installed. The faults were applied using a dedicated fault thrower, which controls the fault duration to last for around 150 ms. The types of faults applied are: Phase-Earth (Ph-E), Phase-Phase (Ph-Ph), Phase-Phase-Earth (Ph-Ph-E) and Three-Phase-Earth (3Ph-E) faults.

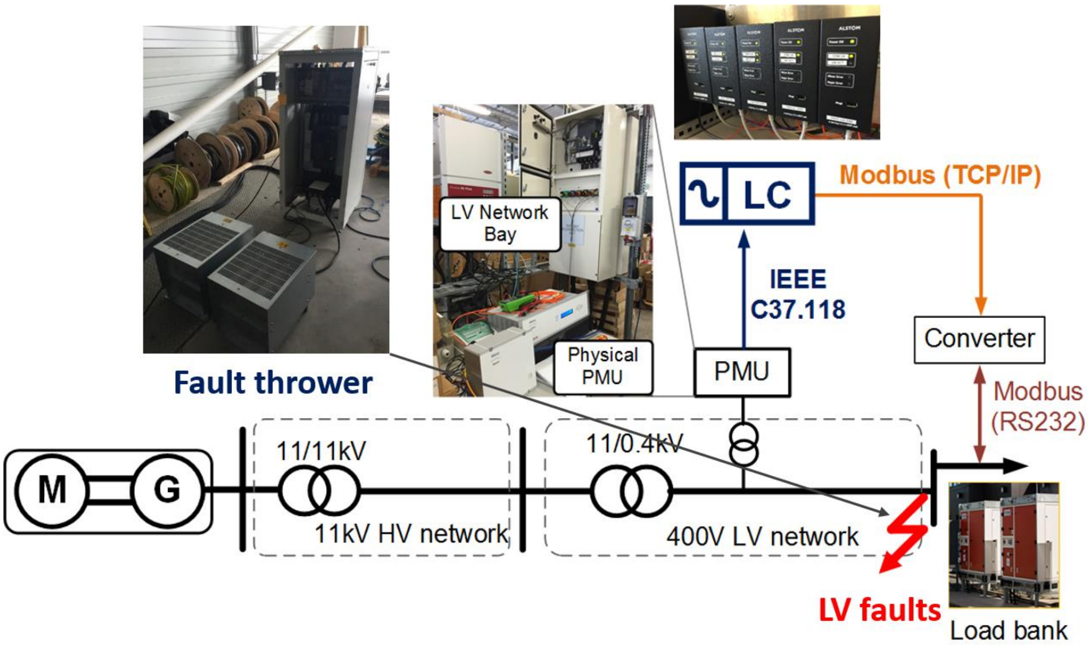

Figure 44. Fault test configuration

7.2 Settings of the LC

In these tests, the following settings relating to the fault detection function were used. The RAs remained connected to the switch, but the LC is set to operate in local mode, therefore the wide area signal is not used for decision making.

Table 67. Settings in the LC for fault tests

Logical node: EvDeTFRC1 (Event Detection)	
Under-frequency RoCoF threshold (sUnFreqRCFThr)	0.1 Hz/s
Under-frequency threshold (sUnFreqThr)	0.6% (0.3Hz)
Over-frequency RoCoF threshold (sOvFreqRCFThr)	0.1 Hz/s
Over-frequency threshold (sOvFreqThr)	0.6% (0.3Hz)
Local mode status (sLocCtrl)	True

Logical node: RsrcAIGAPC1 (Resource Allocation)	
RoCoF thresholds status (sUseRCFLims)	False
Low frequency thresholds (Hz, sFrqLThr)	49.7, 49.6, 49.5, 49.4, 49.3
High frequency thresholds (Hz, sFrqHThr)	50.7, 50.6, 50.5, 50.4, 50.3
Local mode status (sLocCtrl)	True
Logical node: fault/dead-line detection	
Hysteresis for "Fault Off" Condition (s, sFltOffHyst)	0.12
Nominal Voltage Values (V, sNomV)	230000
Fault Level Pick-Up Threshold (sFltLvlThr)	80%

7.3 Test F-1: 3Ph-E fault test

In this test, a 3Ph-E fault is applied to the network. The recorded data in PhasorPoint is shown in Figure 45 and the key observations are listed in Table 68. The fault is applied at 24.90 s (T_1), which leads to the voltage dropping below the fault detection voltage threshold, i.e. 80% of the nominal value, at 24.92 s (T_2). During the fault, the minimum voltage observed is around 0.2 pu. Such a large level of voltage dip is expected since the applied fault is bolted.

The fault also leads to a significant frequency disturbance with the largest frequency deviation observed to be greater than 1 Hz (frequency dropping below 49 Hz). This violates the event detection under frequency threshold of 49.7 Hz at 24.95s (T_3). The fault is successfully detected by the LC at 25.32 s (T_4), which is a delay of around 0.42 s after the fault inception. The fault detection flag remains high for approximately 160 ms. The output from the event detection block remains low as required.

The zoom-in view of the measured frequency and RoCoF from LC and PMU is shown in Figure 46, where it can be seen that that the RoCoF data recorded from the output of the LC does not appear to align with frequency change. This is, as suggested by GE, is caused by the filter implemented in the LC for minimising the RoCoF measurement noise. While the filter is essential to minimise the risk of wrongly detecting a normal operation condition as an event due to measurement issues. From the test results, it can be seen that this may comprise the LC's ability to capture the RoCoF changes in the network in a timely manner.

Furthermore, from the RoCoF and fault detection plots in Figure 45, it can be seen that, the measured RoCoF is forced to a value of zero just before the fault detection flag becomes high. This could be an internal blocking function implemented in LC. However, this is not described the user manual and will therefore require interpretation from GE.

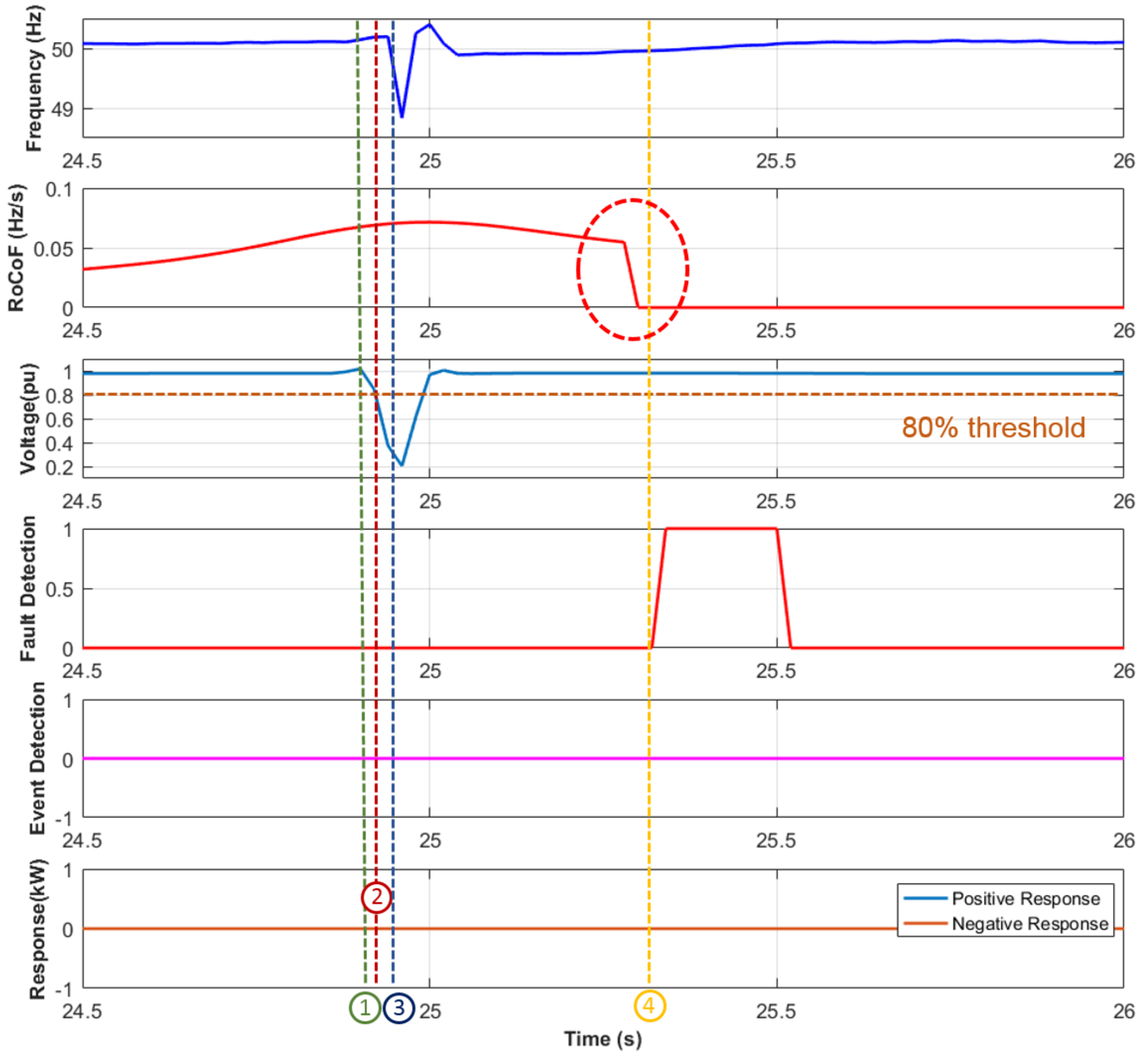

Figure 45. Results of Test F-1

Table 68. Key observations of Test F-1

Time	Observations
24.90 s (T_1)	Fault event occurs
24.92 s (T_2)	Voltage magnitude drops below 80% of the nominal value, i.e. fault detection voltage threshold.
24.95 s (T_3)	Frequency drops between 49.7 Hz, i.e. the event detection frequency threshold.
25.32 s (T_4)	Fault detected

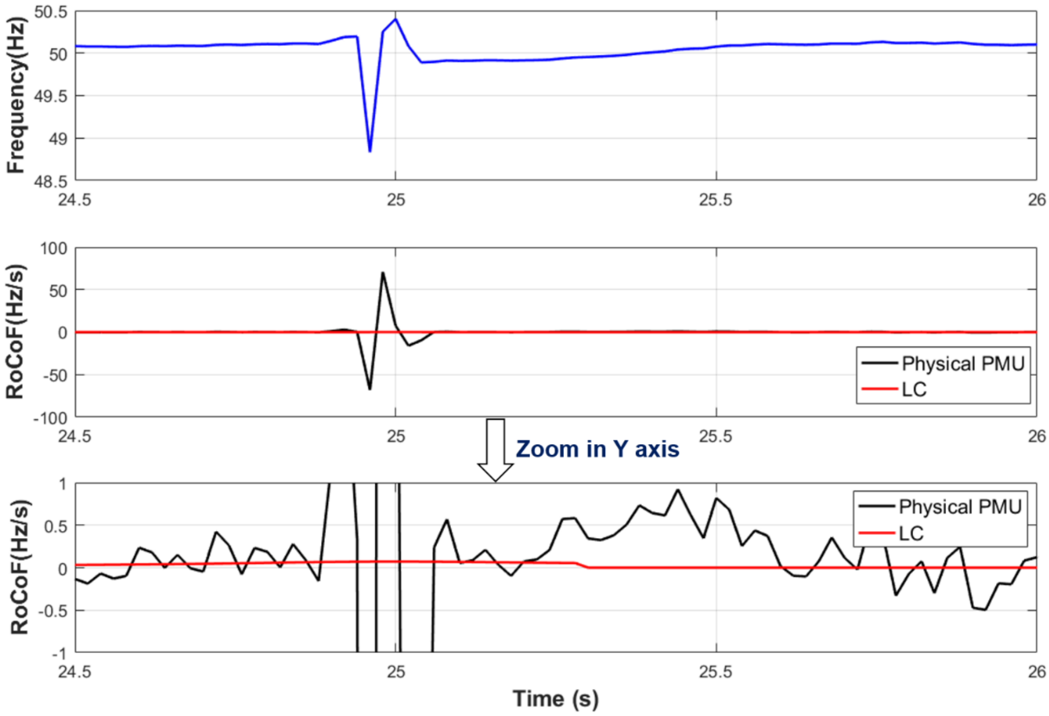

Figure 46. Frequency and RoCoF measurement in Test F-1

7.4 Test F-2: Ph-Ph fault test

In this test, a Ph-Ph fault is applied in the network. The test results are shown in Figure 47 and the key observations are listed in Table 69. The fault event occurs at around 40.54 s (T_1), which leads to the voltage dropping below the 80% fault detection voltage threshold at 40.56 s (T_3). During the fault, the minimum voltage observed is around 0.58 pu.

In the frequency profile, the frequency drops below the event detection frequency threshold of 49.7 Hz at 40.55 s (T_2). This LC does not detect such deviation as a frequency event as required, and the fault is successfully detected by the LC at 40.94 s (T_4), which is around 0.4 s after the fault inception. The fault detection flag remains high for approximately 160 ms.

The RoCoF value measured by the LC is within the event detection RoCoF threshold during the whole process, so it won't lead to the fault being detected as a frequency event using the RoCoF measurement. Similar to the case in Test F-1, the measurement RoCoF is filtered by the LC so it does not effectively reflect the frequency change in the network. Furthermore, from the RoCoF and fault detection plots in Figure 47, similar to the previous test, it can be seen that, the measured RoCoF is forced to a value of zero when the fault detection flag becomes high. This was confirmed by GE to be expected behaviour of the functional block, where the RoCoF value is forced to be 0 when the LC considers there is a fault in the network.

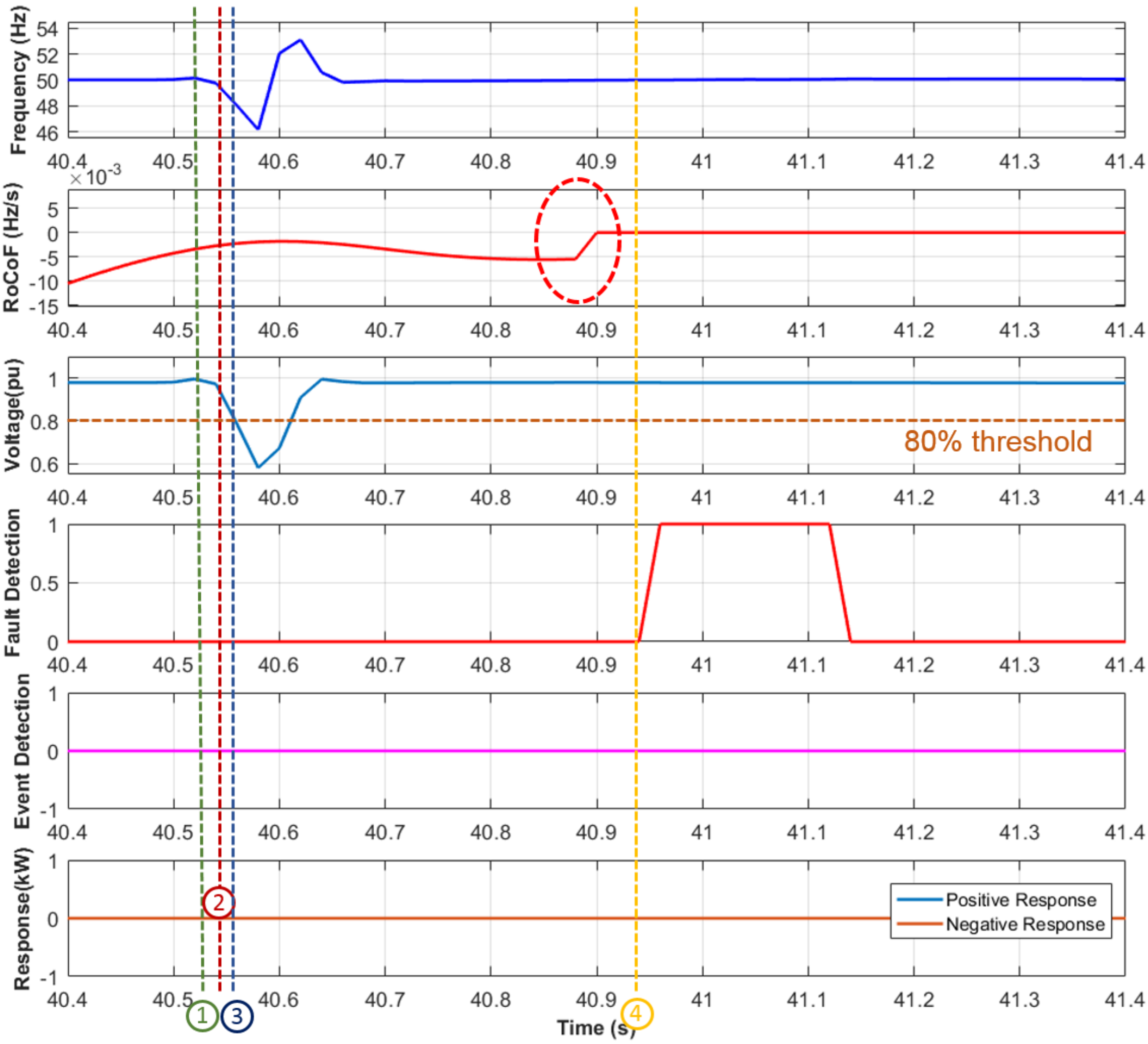

Figure 47. Results of Test F-2

Table 69. Key observations of Test F-2

Time	Observations
40.54 s (T_1)	Fault event occurs
40.55 s (T_2)	Frequency drops between 49.7 Hz, i.e. the event detection frequency threshold.
40.56 s (T_3)	Voltage magnitude drops below 80% of the nominal value, i.e. fault detection voltage threshold.
40.94 s (T_4)	Fault detected

7.5 Test F-3: Ph-Ph-E fault test

In this test, a Ph-Ph-E fault is applied to the network. The test results are shown in Figure 48 and the key observations are listed in Table 70. The fault event occurs at around 33.22 s (T_1), which leads to the voltage dropping below the 80% fault detection voltage threshold at 33.25 s (T_2). During the fault, the minimum voltage observed is around 0.49 pu.

In the frequency profile, the frequency drops below the event detection frequency threshold of 49.7 Hz at 33.27 s (T_3). The event detection successfully remains low, and the fault is successfully detected by the LC at 33.64 s (T_4), which is around 0.42s after the fault inception. The fault detection flag remains high for approximately 160 ms.

The RoCoF value measured by the LC is within the event detection RoCoF threshold during the whole process, so it won't lead to the fault being detected as a frequency event. Similar to the cases in previous fault tests, the measured RoCoF is filtered by the LC so does not effectively reflect the frequency change in the network. Furthermore, from the RoCoF and fault detection plots in Figure 48, similar to the previous test, it can be seen that, the measured RoCoF is forced to a value of zero just before the fault detection flag becomes high.

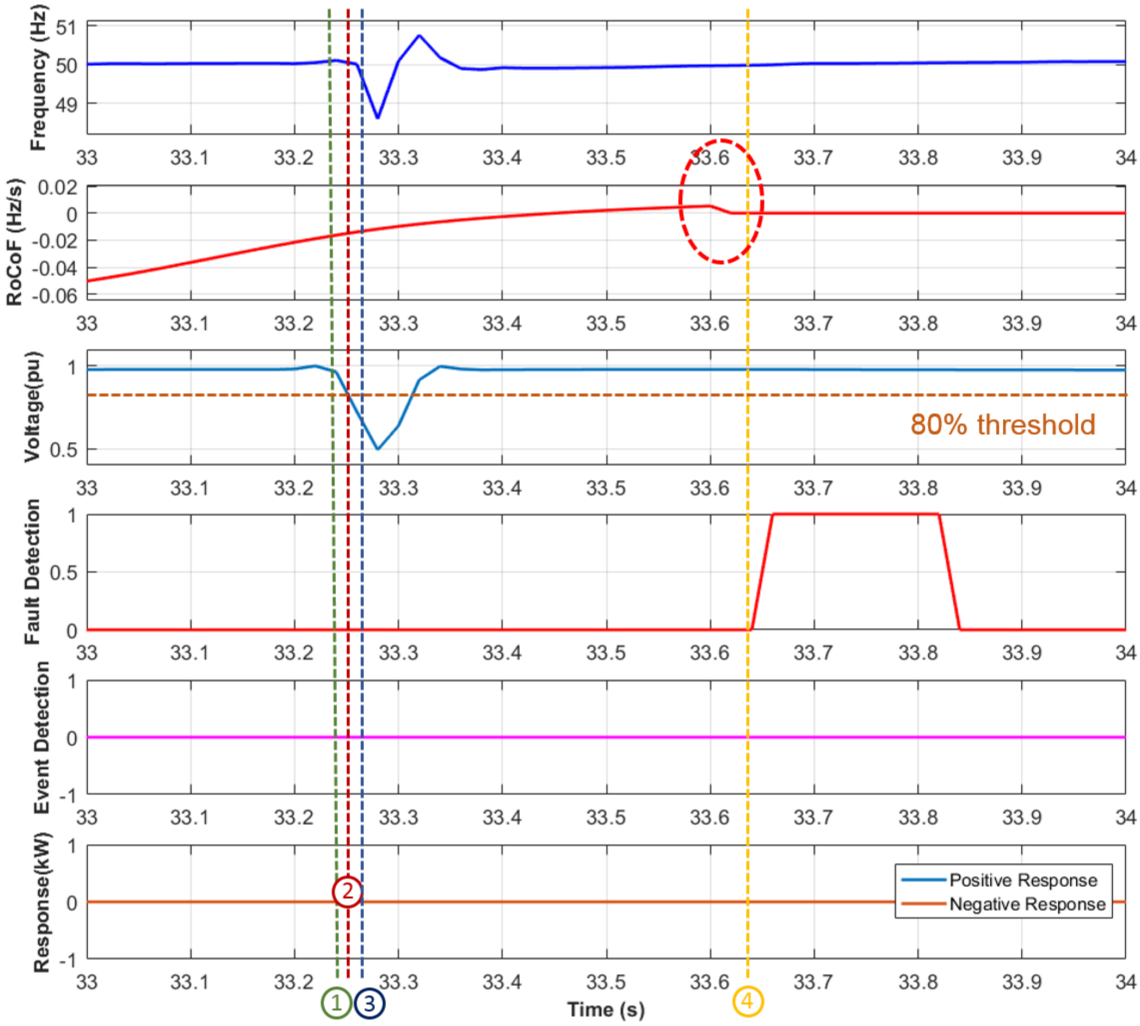

Figure 48. Results of Test F-3

Table 70. Key observations of Test F-3

Time	Observations
33.22 s (T_1)	Fault event occurs
33.25 s (T_2)	Voltage magnitude drops below 80% of the nominal value, i.e. fault detection voltage threshold.
33.27 s (T_3)	Frequency drops between 49.7 Hz, i.e. the event detection frequency threshold.
33.64 s (T_4)	Fault detected

7.6 Test F-4: Ph-E fault test

In this test, a Ph-E fault is applied to the network. The test results are shown in Figure 49 and the key observations are listed in Table 71. The fault event occurs at around 27.84 s (T_1), which leads to the voltage dropping below the 80% fault detection voltage threshold at 27.89 s (T_2). During the fault, the minimum voltage observed is around 0.75pu.

The fault does not cause a significant disturbance to frequency and RoCoF - neither of the frequency or RoCoF exceed the corresponding event detection thresholds, so the event detection block does not detect the fault as a frequency event. Similar to the previous tests, it can be seen from the RoCoF and fault detection plots in Figure 48, that, the measured RoCoF is forced to a value of zero just before the fault detection flag becomes high.

The fault is successfully detected by the LC at 28.26 s (T_3), which is around 0.42 s after the fault occurs. The fault detection flag remain high for approximately 160 ms.

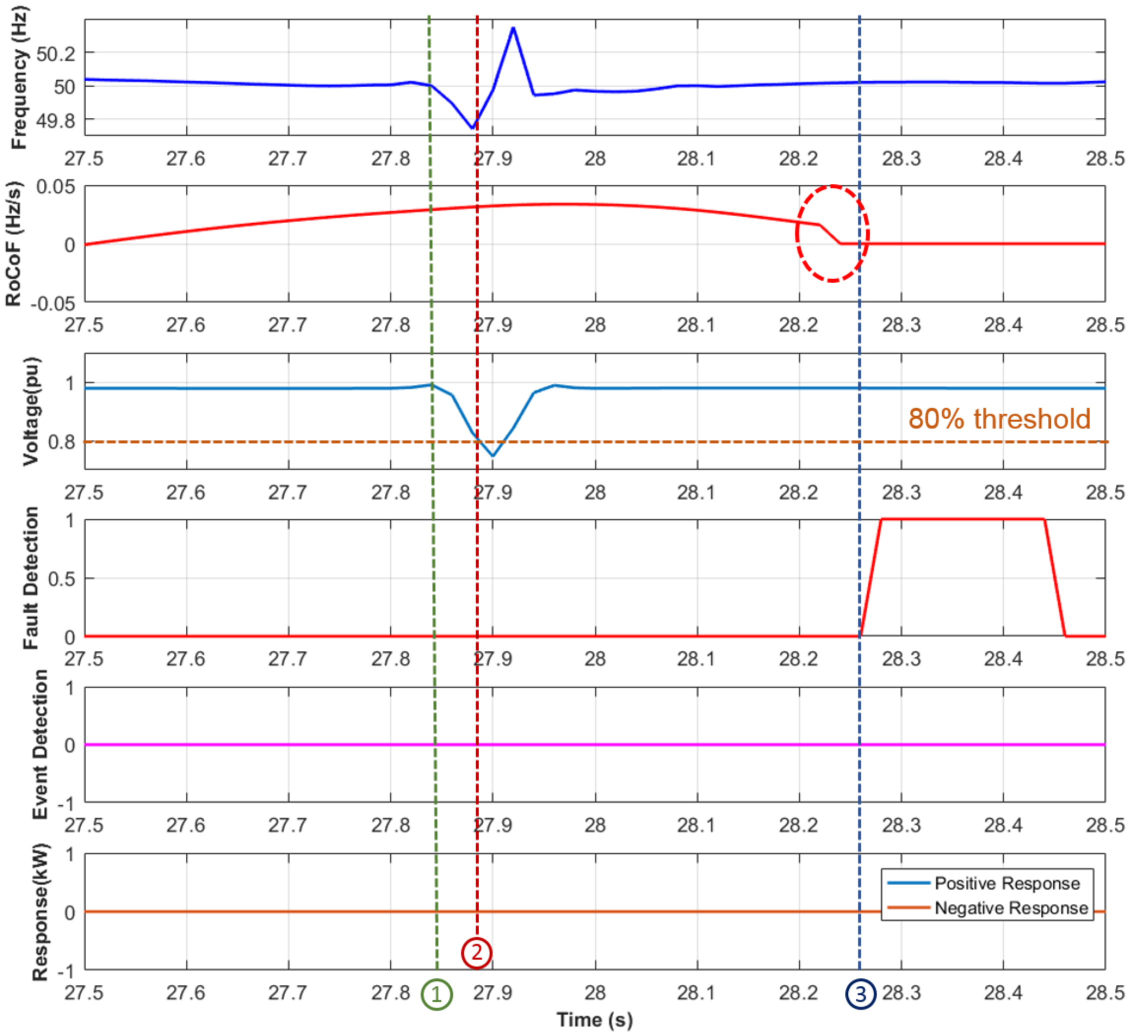

Figure 49. Results of Test F-4

Table 71. Key observations of Test F-4

Time	Observations
27.84 s (T_1)	Fault event occurs
27.89 s (T_2)	Voltage magnitude drops below 80% of the nominal value, i.e. fault detection voltage threshold.

28.26 s (T_3)	Fault detected

7.7 Summary of fault event tests

In this section, the results of tests for evaluating the security of the LC's local mode have been presented, where various types of solid faults have been applied in the PNDC network. All faults except Ph-E fault cause a significant frequency disturbance, leading to the event detection threshold being violated. The LC successfully remains stable, i.e. non-detection of these fault as frequency events in all fault events applied. In the Ph-E faults during the tests, the frequency and RoCoF do not violate any event detection thresholds, so they are not expected to lead to any actions on the event detection block even without fault blocking function.

In the tested fault events, the LC successfully detected all fault events, with the fault flag becoming high for approximately 160 ms. However, a delay of around 0.42 s in fault detection was observed in all the tests. It was also observed that the filter implemented in the LC, while necessary to tackling the measurement noise, it can significantly compromise the RoCoF measurement in accurately reflecting the frequency changes in the network. It was also observed that the measured RoCoF is forced to a value of zero just before the fault detection flag becomes high. This could be an internal blocking function implemented in LC. Input from GE will be required to interpret these observations.

8 KEY FINDINGS AND CONCLUSIONS

This report presented the results from the tests conducted at PNDC for evaluating the EFCC system's performance while operating in local mode. The response of the LC has been tested in response to under-frequency, over-frequency and fault events using different settings and resource availability information.

The tests using under- and over-frequency events were conducted for evaluating the sensitivity of the LC to frequency events, i.e. the capability to correctly detect an event when required and deploy the correct amount of resource to respond to the event. The LC was tested under two scenarios – that is when the RoCoF thresholds were disabled and enabled. The former case was used to validate the frequency thresholds, while the latter case tests were used to validate the RoCoF thresholds.

The fault event tests evaluated the stability of the LC, i.e. the capability of the LC to detect faults and remain stable (not request resource deployment) to these non-frequency events.

8.1 Summary of overall functional performance

During the tests, a number of undesirable behaviours relating to the response of the EFCC scheme were identified. These have been reported to GE and multiple versions of the system have been released throughout the testing programme to tackle the identified issues and improve certain aspects of the system's operation. The results presented in this report are from the latest version of the controller and the results show that the LC is now capable of successfully detecting both under- and over-frequency events and deploying the required amount of resource. Various levels of delays in event detection and resource allocation have been observed. During fault events, all physical faults applied in the PNDC network have been successfully detected as such and no resource has been deployed (as required).

8.2 Observed delays in LC response and their cause

In several of the dependability and security tests, delays in the EFCC system's decision making and resource deployment instructions were observed.

In the dependability tests, i.e. under- and over-frequency tests, there are three main types of delay, which are summarised as follows:

1. **Delay in event detection**
   - **Description:** when the event detection frequency or RoCoF thresholds are violated, there is a delay before the event detection flag becoming high.
   - **Range of delay:** when the event detection is trigged by the violation of the RoCoF threshold, the delay is typically within 20 ms, while when the event detection is trigged by the violation of the frequency threshold, the delay is approximately 1 s (see the test results in Test UF-1.2 and Test UF-2.1)
   - **Cause of the delay:** As suggested by GE, the delay associated with the frequency threshold for event detection is intentionally introduced by the scheme to minimise the risk of mal-detection of frequency events. The delay observed using the RoCoF threshold for event detection is thought to be caused by the 20 ms of the controllers reporting interval.

2. **Delay in resource allocation**
   - **Description:** when the associated frequency (and RoCoF) thresholds are violated, there is a delay in issuing a power request command from the resource.
   - **Range of delay:** This delay typically ranges from 0.3 s – 0.5 s, and it is relatively consistent across various tests. The overall average delay for all tests is 0.451 s.
   - **Cause of the delay:** GE suggested that the delay was intentionally introduced by the scheme to avoid mal-detection of non-frequency events.

3. **Delay in resource response**
   - **Description:** when a change in power request is sent to the load bank, there is a delay in the load bank's response.

- **Range of delay:** These delays have a relatively large range from less than 0.5 s to more than 1.5 s, but mostly lie around the 1 s mark. The overall average delay for all tests is 0.935 s. If a test involved multiple steps of power request, the average delay tends to increase.
- **Cause of the delay:** It is thought that this is caused by the load bank's controller and its capability to change power rapidly. The load bank can only periodically change its output power and this period is around 1 s. If there are multiple power output change requests issued from the LC within 1 s, the delay may accumulate, therefore the overall average delay tends to be higher. Any controlled resource will have an inherent delay in changing/ramp rate, and this should be considered further in the wider context of the applicability and effectiveness of the EFCC scheme.

During the security tests where faults were applied, an approximate average delay of 0.42 s in fault detection after the voltage threshold being violated is observed across all tests. It is considered that this is caused by internal function blocks that intentionally introduce delays to avoid incorrect frequency event detection.

8.3 Additional identified issues and recommendations for potential improvement

The main issues identified in the test are listed in Table 72. It is considered that these issues can potentially have a major impact on the operation of the LC during its local mode. These have been remedied with new versions of the scheme released by GE. A more detailed description of the issues and the associated versions of the system released is provided in Appendix B.

Table 72. Main issues identified during the local mode tests

	Issue description	Status
1	Failure in switching from wide-area mode to local mode when the communication links are lost.	Resolved
2	Failure in resource allocation function when thresholds are violated	Resolved
3	Failure in fault detection and event blocking	Resolved

There are also a number of other aspects of behaviour observed during the test programme, which do not fundamentally affect the performance of the scheme, but may be considered for as possible improvements in the future. These observations are described below, along with recommendations for potential improvements and actions.

1. The fifth RoCoF threshold in the resource allocation block

- **Description:** When the RoCoF thresholds are enabled, they are used along with the frequency thresholds to determine whether a response should be instructed. It is expected that only when both the frequency and RoCoF thresholds are violated, these resources will be deployed. During the test, it was found that, unlike the first four RoCoF thresholds, which are used along with the first four frequency thresholds for decision making as described in the user manual, the fifth RoCoF threshold is not used for resource allocation, i.e. when the frequency drops below the fifth frequency threshold, the resource will be deployed regardless of the measured RoCoF value. It is suggested by GE that this is intentionally designed so that the LC will always respond in situation where frequency is severely disturbed. However, this means the fifth RoCoF threshold is not used by the scheme in any cases.
- **Recommendation:** There could be two options for improvement: 1) remove the fifth RoCoF threshold as it is not used by the scheme to avoid causing any confusion; 2) retaining the fifth RoCoF threshold, but give options to engineers regarding whether to enable it for decision

making. If the users requires that the fifth RoCoF threshold to not to take effect, it can be disabled. This gives the engineers options to configure the system to achieve the behaviour they want.

2. RoCoF measurement during fault events

- **Description:** during fault tests, the RoCoF data recorded from the output of the LC does not appear to align closely with the frequency change. This is thought to be caused by the filter implemented in the LC for minimising the RoCoF measurement noise. While the filter is essential to minimise the risk of mistakenly detecting a normal operation condition as an event due to measurement issues, the test results show that this may comprise the LC's ability to capture the RoCoF changes in the network in a timely manner.
- **Recommendation:** a study should be conducted to derive the optimal parameters for the implemented filters.

3. Settings of the scheme

Description: the settings in the EFCC controllers can be categorised into two main types: one type is mainly associated with power system parameters, e.g. frequency and RoCoF thresholds and the other type is associated with the algorithm itself, e.g. time constant of the filters, detection moving window, etc. The power system type of settings can be chosen based the system studies. However, the algorithm type of settings are directly associated with the design of the EFCC system itself and setting of these parameters can be difficult. As there is no guideline for setting this type of parameters provided, the default values are used during the tests. It was found that the default values do not always give desirable performance. For the same frequency and RoCoF thresholds in the event detection and resource allocation block, the default value of algorithm type of settings may need to be tuned to give the required performance. Examples of such settings include "sSusRspTm", which is used to control the maximum time that the resource response can be sustained, "sFrqChgThr" which is the event detection frequency change threshold, etc.

- **Recommendation:** a study should be conducted to derive the most appropriate settings for the full range of adjustable parameters and a guidance documentation should be developed for future reference if the scheme is to be rolled out for deployment.

4. Various delays in event detection and resource allocation

- **Description:** the delay in event detection and resource allocation can affect the speed of response of the resource, and this could therefore have an impact on the effectiveness of the overall action of the EFCC system and the restoration of system frequency following an event. From the tests, the event detection, resource allocation and fault detection delays have been evaluated, however, the delay from resource response only covers the load bank in the tests.
- **Recommendation:** the response delay from all resources that may be under the control of the EFCC system should be characterised and taken into account during the frequency restoration study. The main delay that could be caused by the physical capability of the resource to respond to a command and the delay in the resource's individual controller and any associated communications equipment.

This report has presented the results and findings from the first stage tests of the overall validation programme for evaluating the performance of the EFCC scheme. The evaluation of the EFCC scheme's wide-area mode and the impact of the communication performance on the operation of the scheme will be detailed in separate reports.

APPENDIX A: ADDITIONAL TESTS: LC SWITCHING FROM WIDE-AREA TO LOCAL MODE

In Sections 5 to 6, the LC is configured (through the setting " sLocCtrl") to operate in local mode. In practice, it is also possible that the LC would operate in local mode if the wide area communication links are lost or the communication data is not of sufficiently good quality for wide-area operation. In this section, tests are conducted to validate the LC's capability to automatically switch to local mode when the communication delay is longer than the required specification. Furthermore, the resource availability condition for the tests in this section is provided in Table 73. The resource information has been intentionally chosen to be different from the case in the tests in Section 5 to further test the performance of the LC in different resource availability scenarios. The settings for the tests presented in this section are provided in Table 74.

Table 73. Resource availability information

Availability	True
Positive available power	60 kW
Negative available power	60 kW
Positive power response time	1 s
Negative power response time	1 s
Power ramp up rate	30 kW/s
Power ramp down rate	30 kW/s
Positive power max duration	60 s
Negative power max duration	60 s

Table 74. Settings in the LC in the additional tests

Logical node: EvDeTFRC1 (Event Detection)	
Under-frequency RoCoF threshold (sUnFreqRCFThr)	0.12Hz/s
Under-frequency threshold (sUnFreqThr)	0.6% (0.3Hz)
Local mode status (sLocCtrl)	False
sSusRspTm	60 s
sSusRspRsFrq	0.04
sWa2LocSwdl	2
Logical node: RsrcAlGAPC1 (Resource Allocation)	
RoCoF thresholds status (sUseRCFLims)	False

Frequency thresholds (Hz, sFrqLThr)	49.7, 49.6, 49.5, 49.4, 49.3
Local mode status (sLocCtrl)	False

In these tests, the same setup is used as in the tests presented in Section 5. The RAs are connected, but the latency between the RAs to the LC is configured to be 300 ms using the communication emulator, which is beyond the size of the buffering window (i.e. 200 ms). Therefore, the LC is expected to switch automatically from wide-area mode to local mode. Figure 50 shows the confidence level observed in the LC being tested when the 300 ms latency is introduced to between the three RAs and LC1 in sequence. The confidence level is a value used by the LC to indicate whether the communication packets have been successfully received from the RAs. If all the packets from all three RAs are successfully received, then the confidence level will be 100%. If one of the three RAs fails to send the packets to the LC or the packets arrives too late, the confidence level will drop by 1/3. As it can be seen from Figure 50, in this case the confidence level drops gradually and eventually becomes zero.

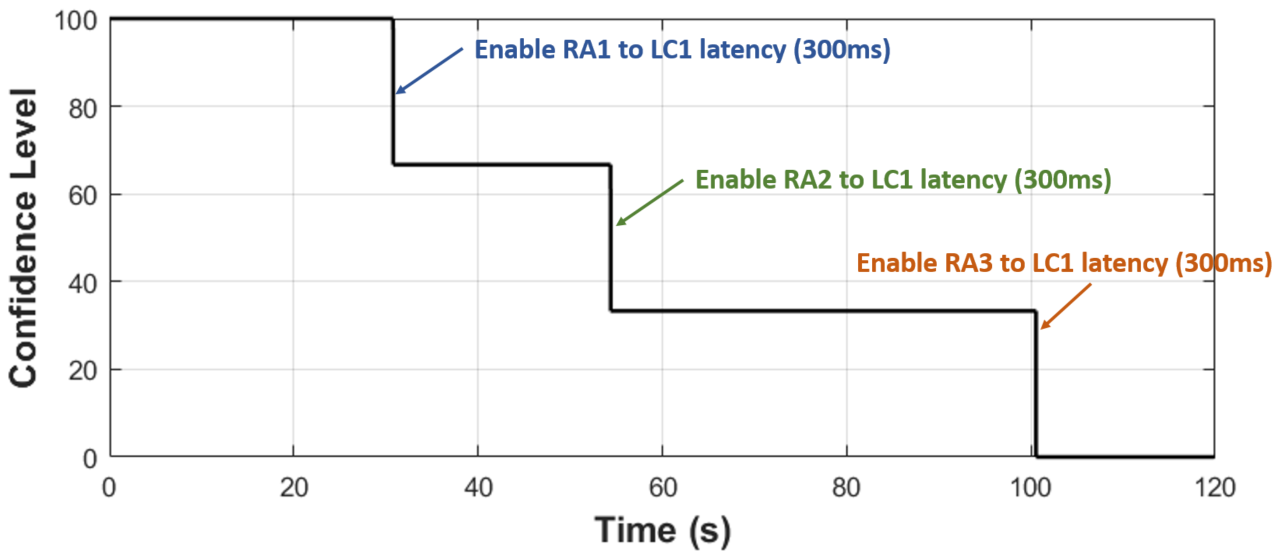

Figure 50. Confidence level when the communication latency is enabled using the communication emulator

A.1. Test AD-1: testing of the LC's function in switching to local mode from wide area mode when the communication performance is beyond the acceptable limits

An under-frequency event is emulated in the PNDC network, which results in the frequency nadir being between 49.2 Hz and 49.3 Hz. The settings in Test UF 1.1-1.6 provided in Section 5.1 are used for this test. If the LC had successfully switched to the local mode, it is expected that the LC would deploy 100% of the resource in 5 steps, with each step a 20% of power is request when one of the frequency thresholds is violated.

The results are shown in Figure 51, where it can be seen that the resource is deployed in 5 steps, which each step requesting 20% of the resource when a frequency threshold is violated. This means the LC has successfully switched to local mode because in wide-area mode the request of power instructed by the LC would not use these under-frequency thresholds.

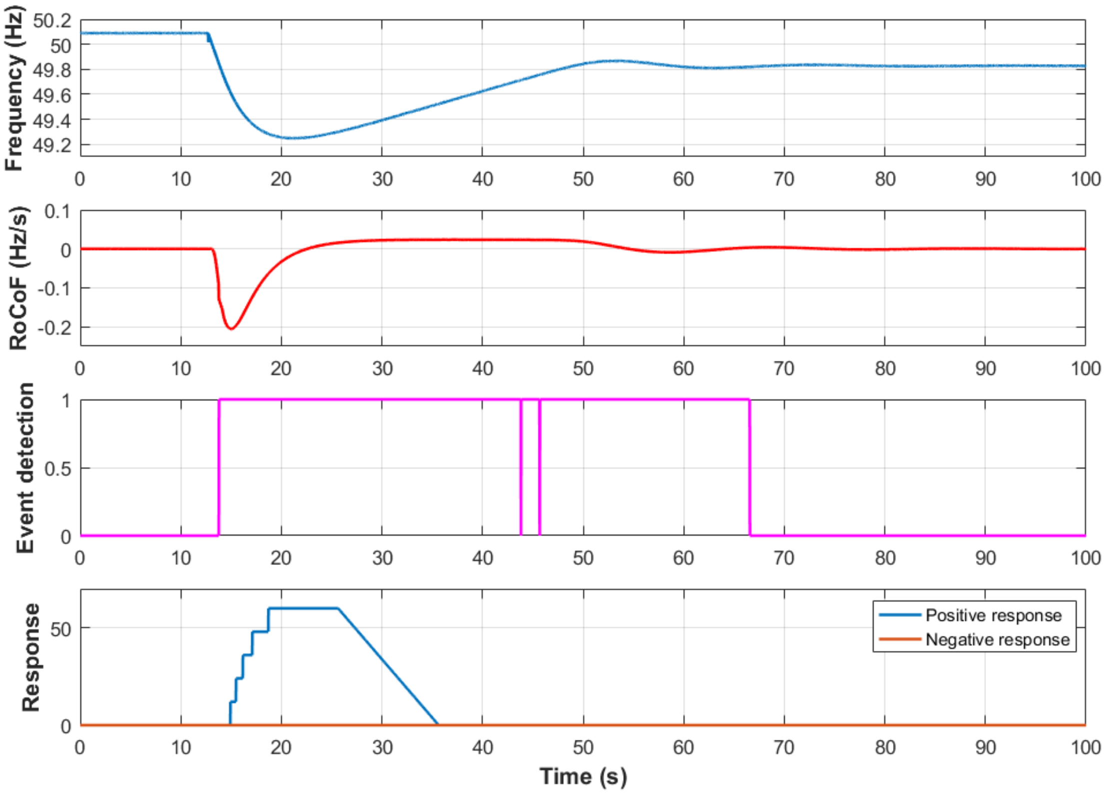

Figure 51. Test results for Test AD-1

A.2 Test AD-2: validation of the LC's performance in local mode when the local resource is disabled

In this test, the local resource is set to be unavailable. The LC is therefore expected not to request any power even when the associated thresholds are violated. The resource information of this test is listed in Table 75, which shows that the availability of the resource has been set as "false".

An under-frequency event with a frequency nadir below 49.3 Hz is emulated in the network, which violates all the five frequency thresholds. The test results are shown in Figure 52. It can be seen that, while the event is detected by the LC, no resource is deployed. This means the LC has successfully blocked the power request due to the resource being unavailable.

Table 75. Resource availability information

Availability	False
Positive available power	60 kW
Negative available power	60 kW
Positive power response time	1 s
Negative power response time	1 s
Power ramp up rate	30 kW/s
Power ramp down rate	30 kW/s
Positive power max duration	60 s
Negative power max duration	60 s

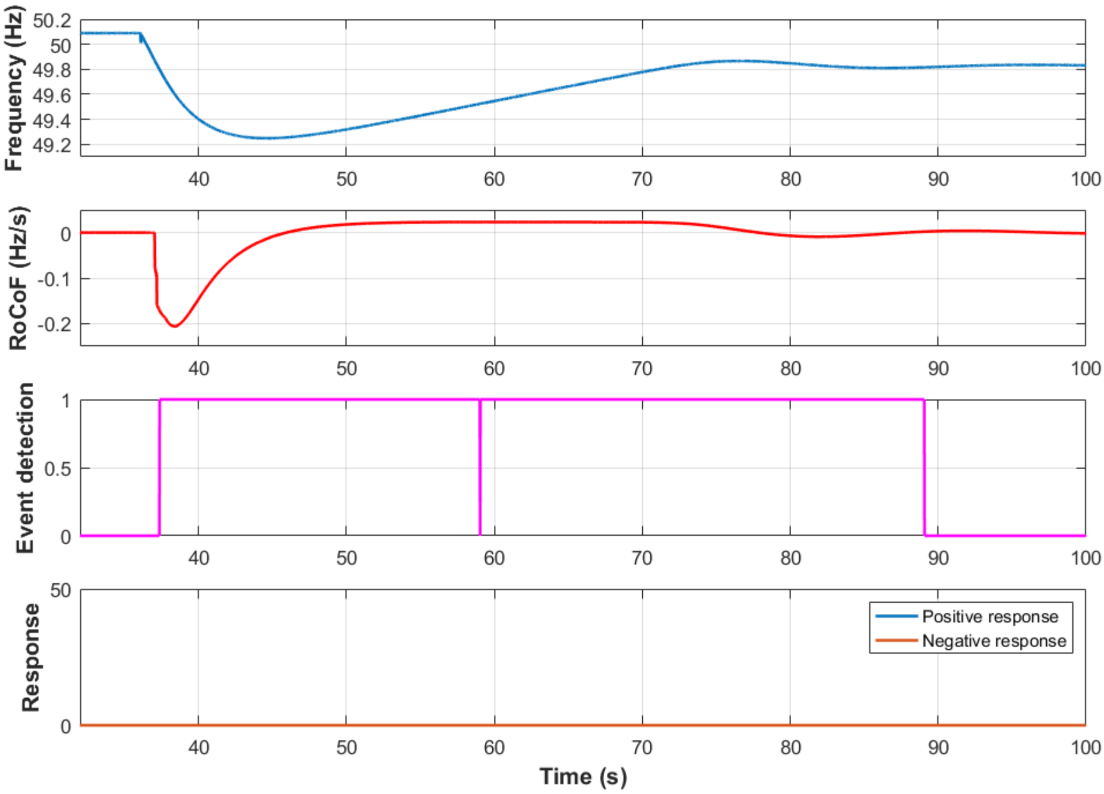

Figure 52. Results of Test AD-2

APPENDIX B: LOG OF ISSUES IDENTIFIED DURING THE LOCAL MODE TESTS AND THE VERSIONS OF THE TESTED LC ALGORITHM

This section presents the log of the issues identified during the tests at the University of Strathclyde for validating the EFCC's performance is its local mode.

	Issues identified	GE's fixed versions and the progress details
1	**Failure in switching from wide-area mode to local mode.** When the links between the LC and the RAs are disconnected, the LC failed to switch from the wide-area mode to local mode, resulting in failure in providing the required event detection and resource allocation function.	1. On 19-06-2017, GE confirmed that this was an internal issue of the controller. 2. The issue has been fixed in the version that GE sent on 07-07-2017
2	**Issue with resource allocation function (local mode)** When the LC operates in its local mode, events can be successfully detected, but there is no resource instructed to be deployed by the LC. This has been tested under all the following conditions: different event detection RoCoF threshold settings, local mode through RAs disconnection and the "use local mode" setting parameter, with "use RoCoF" setting enabled and disabled, different frequency and RoCoF threshold settings, etc. GE confirmed that this is due to an issue within the resource allocation block.	1. On 20-06-2017, GE commented UoM experienced similar issues and a fixed version of the PLC file had been sent to fix the problem, but the resource deployment problem persisted for the system at PNDC. 2. On 29-06-2017: GE sent a further version, and it was tested on 07-07-2017, but the LC stopped working with the new block. Two LED lights were not on. GE thought this might be the problem with library and firmware in the LC being out of date. 3. On 07-07-2017, GE sent a further version to address the library problem. This version fixed the resource allocation problem.
3	**Undesirable response to fault events** In some cases, e.g. three-phase-ground faults, the LC detected the fault events as over-frequency events and instructed negative response.	1. On 12-07-2017, GE suggested that this might be due to an inappropriate setting of the sFltOffHyst parameter within the OpnLnPTU block. 2. On 19-07-2017, retested with the updated settings as suggested by GE – the problem was still not resolved. 3. On 20-07-2017, GE suggested to try different settings for sOvFreqThr and sUnFreqThr. 4. On 24-07-2017, retested using new values for sOvFreqThr and sUnFreqThr (also with the nominal voltage updated), the problem was still not resolved. All associated data was sent to GE

		5. On 26-07-2017: GE would look into this issue. 6. A new version of the firmware was released on 08/08/2017 7. Physical faults have been applied in the network to test the fault detector on 11/09/2017 – the local fault flag was not setup in PhasorPoint 8. GE engineers visited PNDC to configure the fault flag on 14/09/2017 9. Fault retested on 16/10/2017, 17/10/2017, 23/10/2017 with different settings recommended by GE. The fault flag still does not function properly 10. 09/11/2017 – it was detected that the fault detector signal in the PLC was not configured properly, resulting in the data failing to send to PhasorPoint. The issue was fixed and the fault detector is retested.
4	Issue with 5th step of RoCoF threshold in local mode When the RoCoF thresholds are enabled in local mode, the 5th threshold is neglected in under-frequency events but is used in over-frequency events.	1. On 21-07-2017, tests of under frequency events in local mode with RoCoF thresholds enabled were conducted. For the first four RoCoF thresholds, only when the frequency AND RoCoF thresholds are violated, the resource were deployed, which is expected. However, when testing the fifth RoCoF threshold, it seems this threshold is not used by the algorithm for decision making. Even with a large RoCoF threshold, whenever the frequency threshold was violated, the resource was still deployed. 2. On 25/07/2017, GE suggested that this was intentionally designed so that the resource could be fully deployed in severe frequency events (i.e. when the first four frequency thretholds are all violated). 3. On 26/07/2017, the LC was tested for over-frequency events, where the resource was not deployed entirely when the 5th frequency threshold was violated. This is inconsistent with the previous point raised by GE. 4. On 26/07/2017: GE confirmed that there is an element missing in the over-frequency part, so it should deploy all resource as long as the 5th frequency threshold was violated, but there is a piece of code missing in the algorithm. The issue has been revolved and rested in the new firmware version.

5	**Complete firmware upgrade where some other issues are fixed (10/08/2017)**	1. GE issued a new firmware that replaces all the functional block in the previous version of the system on 08/08/2017, and there were a few issues during the upgrade process and the firmware is successfully upgraded on 10/08/2017. 2. Tests conducted in local mode had to be repeated to validate the new version of the system.
6	**New event detection block is issued on 15/08/2017**	1. When the block was issued, the under-frequency tests have been completed. 2. The block was uploaded to the controller on 17/08/2017, but it does not give any response but events are successfully detected 3. Attempted to switch to the old event detection block (from Seán) and the controller stopped working 4. 21/08/2017 resolved the start-up issue with Andreas – reinstalled the firmware from 08/08/2017 5. The old version of the event detector from firmware upgrade has been used for the over frequency tests. The issue was fixed on 14/09/2017 and the system has been retested

9 REFERENCES

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