UNIVERSITY of STRATHCLYDE
POWER NETWORKS
DEMONSTRATION CENTRE

Testing of the Enhanced Frequency Control Capability (EFCC) Scheme: Part 2 - Wide Area Mode Tests

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EXECUTIVE SUMMARY

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

This report is Part 2 of a set of total 3 reports. The tests presented in this report focus on the evaluation of the performance of the EFCC scheme when operating in its wide-area mode, where all communication links are enabled and possess sufficiently good quality. The other two reports focus on the testing of the EFCC scheme's local operational mode (Part 1) and upon the evaluation of the impact of communication performance on the wide-area operation of the scheme (Part 3).

The EFCC scheme's wide-area operational mode has been tested for the following performance criteria: (1) its **dependability** during under- and over-frequency disturbances, where the scheme is expected to detect and deploy fast frequency responses to enhance the frequency restoration; (2) its **security** during non-frequency disturbances (i.e. faults), where it is expected to remain stable (i.e. non-operational); (3) its **capability to react correctly during cascading events** (i.e. frequency disturbances following fault events), where it is expected to detect both fault events and the frequency disturbances and correctly deploy frequency response as required.

During the frequency disturbances tests for evaluating the **dependability** of the EFCC scheme, it was found that, for the same amount of power imbalance, both of the resources and events' locations will affect the speed of the EFCC response, thereby the effectiveness of the control actions. If the EFCC resources are located in the same region where the event occurs, the EFCC responses will be deployed faster and are more effective than the resources in other regions, which aligns with the design specifications. During the tests, the frequency was successfully controlled between 49.5 Hz to 50.5 Hz for a 1 GW loss of generation in a low-inertia system (i.e. 82 GVAs) when there are resources available in the same region as the event. In the case where the EFCC resources are located different regions from the event, it was observed that the EFCC scheme delayed the response by 2 s, which is by design to avoid causing system stability issues. However, the inclusion of this delay within the EFCC scheme should be considered as, in some cases, it can reduce the effectiveness of the scheme in containing frequency excursions.

The impact of the capacity of the resources has also been investigated and it was found that a larger EFCC resource capacity did not necessarily mean a better frequency restoration performance. It was found that when the LCs have excessive capacity, they will only deploy the amount that is required to contain the frequency and the rest of the capacity might not be used. Therefore, there is a potential that the capacities of the EFCC resources could be optimised so that they can contain the frequency deviation at the required limited while minimising the reserved power.

In the fault event tests for evaluating the EFCC's **security**, it was found that the EFCC scheme successfully detected all faults as required and did not deploy any resource in all test cases, which aligned with the design specifications.

In the **cascading event tests**, the EFCC scheme has successfully detected all faults and the subsequent frequency events. Frequency responses were also triggered, which successfully contained the frequency deviation at the required level in all tests. However, compared to the tests with only under-frequency events (i.e. no faults), it was found that the EFCC scheme could be affected by the faults and trigger different control actions (e.g. triggering fast response to events locating in other regions from the resources) and different types of faults could also lead to different control actions from the EFCC controllers. While from the tested scenarios, the different behaviours of EFCC scheme due to the faults did not appear to affect the frequency being contained at the required limit, it was considered that the impact of such different behaviours need to be further investigated.

LIST OF ABBREVIATIONS

CS	Central Supervisor
EFCC	Enhanced Frequency Control Capability
GB	Great Britain
LC	Local Controller
MG	Motor-Generator
NG	National Grid
NIC	Network Innovation Competition
NSG	Non-Synchronous Generator
P-HiL	Power-Hardware-in-the-Loop
Ph-E	Phase-Earth
Ph-Ph	Phase-Phase
PMU	Phasor Measurement Unit
PNDC	Power Networks Demonstration Centre
RA	Regional Aggregator
RoCoF	Rate of Change of Frequency
RTDS	Real-Time Digital Simulator
SG	Synchronous Generator
3Ph-E	Three-Phase-Earth
UoS	University of Strathclyde

Contents

1 INTRODUCTION

The role of the UoS within the EFCC project is to develop and provide a realistic testbed using the facilities at the PNDC and conduct comprehensive testing and validation of the scheme against its design specifications. The tests presented in this report focus on the evaluation of EFCC scheme's performance while it is operating in the wide-area mode. This report is Part 2 of a set of total 3 reports, the other two reports focus on the testing of the EFCC scheme's local mode of operation (Part 1) and the impact of communication performance and degradation on the EFCC scheme performance respectively (Part 3).

The EFCC scheme's wide-area operational mode has been tested with respect to the following three main aspects: its dependability during under- and over-frequency disturbances, where the scheme is expected to detect and deploy fast frequency responses to enhance the frequency restoration; its security during non-frequency disturbances (i.e. faults), where it is expected to remain stable (i.e. non-operational); and its capability to react correctly to "cascading events", that is where, for example, frequency disturbances occur following fault events, where the scheme is expected to detect both the fault events and the subsequent frequency disturbances and correctly inhibit and deploy frequency response as required as the event progresses. This report will present the test results and the analysis of the results from all of the aforementioned tests, and key findings will also be concluded.

This document is organised as follows: Section 2 describes the test objectives for validating the EFCC's performance in the wide-area mode; Section 3 presents the configuration of the established testbed; in Section 4, the potential limitations of the tests are described; Section 5 presents the test results for evaluating the dependability of the EFCC during frequency disturbances; Section 6 presents the results from the tests for evaluating the security of the EFCC during faults; Section 7 presents results of the tests for evaluating the EFCC's performance during cascading events; finally, Section 8 highlights the key findings and conclusions.

2 TEST OBJECTIVE

The key objective of this set of tests are to comprehensively evaluate the performance of the EFCC scheme in its wide-area mode under a wide range of system operating conditions and disturbances. The detailed objectives are summarised in the following subsections.

2.1 Validation of the dependability of the EFCC scheme during frequency disturbances

During frequency disturbances (i.e. power imbalance events), the EFCC scheme is required to be sensitive enough to promptly detect the events and deploy the correct amount of resources to enhance the frequency restoration. This is referred to as the dependability of the scheme during frequency events. In these tests, the EFCC scheme's dependability will be evaluated during both under- and over-frequency disturbances with different levels of power imbalance while the events and controlled resources being placed in different locations and with different capacities.

2.2 Validation of the security of the EFCC scheme during faults

Fault events that do not result in the disconnection of any loads or generation are not considered as frequency events in the system (although large generators' rotors may "swing" in the period during and immediately after the fault). Therefore, during such fault events, the EFCC scheme is not required to deploy any response. However, faults could potentially cause a large temporary variation in frequency *measured*, so it is important for the EFCC scheme to distinguish between a fault event and a frequency disturbance. The capability of the EFCC scheme to remain stable and non-operational during faults is referred to as the security of the scheme during faults. This set of tests also aims to evaluate the EFCC scheme's security during different types of faults at different network locations.

2.3 Evaluation of the performance of the EFCC scheme during cascading events

Another objective of this set of tests is to evaluate the performance of the EFCC scheme when cascading events occur. In these tests, the cascading events mainly refer to frequency disturbances following on from and caused by fault events, which would typically occur when there is a fault in the system and the subsequent protection operation results in a loss of generation or load from the system. The tests will evaluate the EFCC's capability in detecting faults and inhibiting response during the fault event, subsequently identifying the frequency disturbance and deploying frequency response to assist the frequency restoration.

3 OVERVIEW OF THE TESTBED

3.1 Test Configuration

The experimental setup for testing the EFCC's wide-area operational mode is shown in Figure 1. In this setup, three Regional Aggregators (RAs) and two Local Controllers (LCs) were tested. The function of the Central Supervisor (CS) was emulated using a dedicated software block. The functionality of the EFCC controllers (i.e. CS, RAs and LCs) is described in detail in [1]. The testbed contains two main parts: a reduced GB transmission network simulated in a Real-Time Digital Simulator (RTDS) and an 11 kV physical network with load banks connected. The simulated GB transmission network model is coupled with the 11 kV physical network through a Power-Hardware-in-the-Loop (P-HiL) setup using a MW-scale Motor-Generator (MG) set [2]. The physical communication network setup for this test configuration is provided in Appendix A.

The simulated network model in RTDS, as illustrated in Figure 2 and with detailed information about the model provide in Appendix B, is divided into three regions, where each region has two P-Class PMU models installed in the locations shown in the figure, streaming real-time synchrophasor data to the three RAs (e.g. PMU-R1-1 and PMU-R1-2 are the two PMUs streaming data to RA1 in Region 1). The three RAs receive and process real-time measurements from the RTDS virtual PMUs and send data to the two LCs. One LC (i.e. LC1) controls an energy storage resource modelled in the RTDS and the other LC (i.e. LC2) controls a physical load bank at PNDC acting as a demand side response. In addition to the PMUs installed across the network as shown in Figure 2, each LC is equipped with one local PMU for local measurement (e.g. PMU-LC1 is a local PMU for LC1), which is used in case of failure in receiving good quality wide-area monitoring signals. The local PMU used by LC2 is a physical PMU installed at a bus in the PNDC network that is synchronised with a bus in the RTDS simulation, while LC1 uses a modelled P-Class PMU in RTDS. It should be noted that the locations of LC1 and LC2 in Figure 2 are for illustration only and the exact locations might be different in different tests, which will be specified later in the report.

The emulated CS has knowledge of the resource availability and characteristics from two resources controlled by LC1 and LC2 and it sends the information to the two LCs, which is used to determine the amount of resource required during a frequency disturbance.

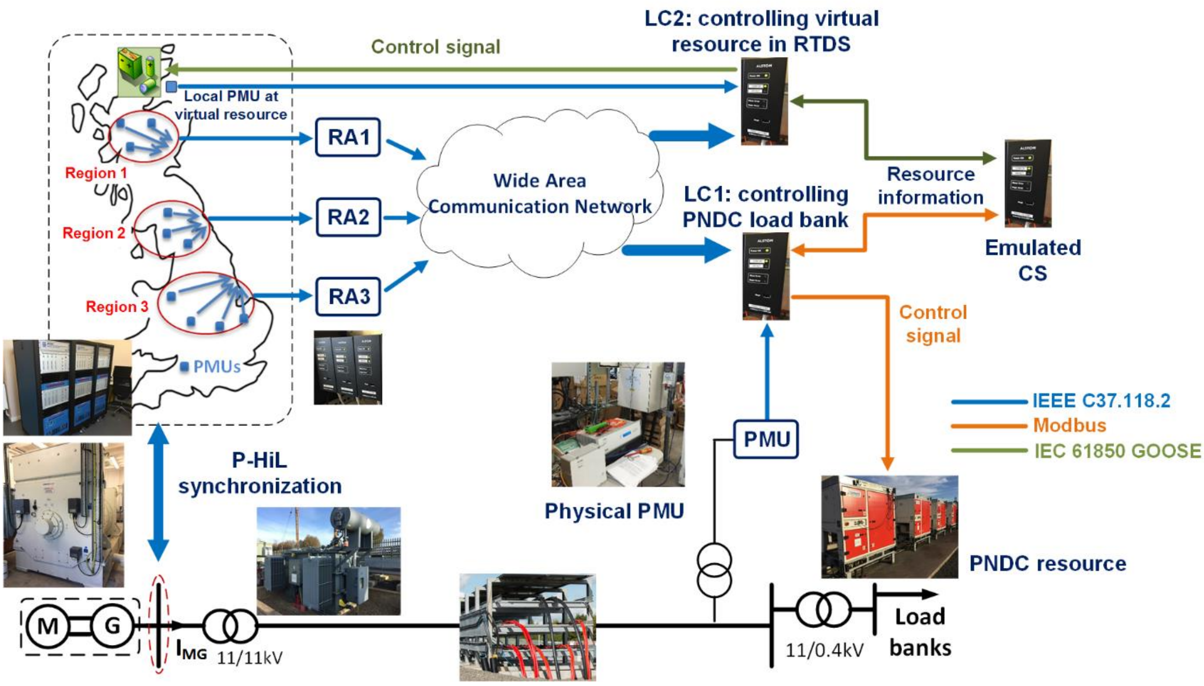

Figure 1. P-HiL testbed for testing EFCC's wide area operational mode

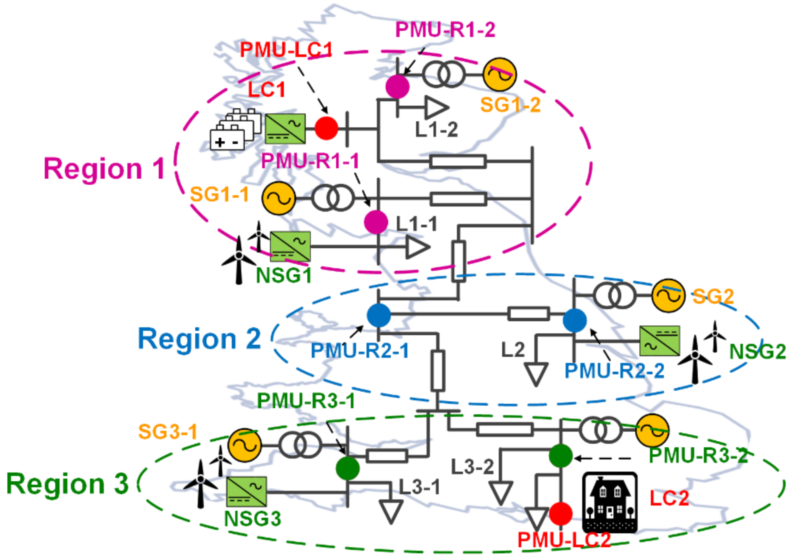

Figure 2. Schematic of the reduced GB transmission network model in RTDS

3.2 Data recording

In the tests presented in this report, test results are recorded in PhasorPoint and RTDS's dedicated software package RSCAD. The data captured from each component of the EFCC scheme is listed as follows:

- **LCs:** system frequency, local frequency, system Rate of Change of Frequency (RoCoF), local RoCoF, positive power request command, negative power request command, confidence level, event detection, fault detection flag and system RoCoF quality.
- **RAs:** aggregated regional angle, aggregated regional angle's confidence level, aggregated regional frequency, aggregated regional frequency's confidence level and fault detection flag.
- **PMUs:** frequency, RoCoF, voltage magnitude and angle.
- **RSCAD (RTDS software platform):** frequency in each region of the simulated network, frequency and voltage of the PNDC network, power change in the modelled RTDS resource controlled by LC1, and power change at the demand controlled by LC2.

4 TEST LIMITATIONS

While the test setup has been established to be as realistic as possible to emulate the real operating environment for the EFCC controllers, there are a number of inevitable limitations, which are summarised as follows:

- The synchronisation between the RTDS simulation and the 11 kV physical network has been successfully achieved using the MG set. When a frequency disturbance occurs, the MG set controller time response limits can cause a frequency deviation between simulation and the physical network. Depending on the severity of the simulated frequency disturbance, the error is typically between 0.02 Hz - 0.04 Hz. Nevertheless, according to GE, the EFCC scheme only uses measurements from RAs for decision making in its wide-area mode, so this should not have significant impacts on the operation of the EFCC scheme
- The CS function is performed using an emulated software block, i.e. the real-time interaction between the CS and the LCs have not been validated in these tests.

5 EVALUATION OF THE DEPENDABILITY OF THE EFCC SCHEME

5.1 Overview of the tests conducted

The list of the tests conducted for evaluating the EFCC's dependability is provided in Table 1. Each of the tests includes the evaluation of the EFCC's performance in both under- and over-frequency events. In the table, R1-3 refer to Region 1-3 in the network. The tests have been defined so that the EFCC scheme is tested under: different types of frequency disturbances (i.e. under- and over-frequency events); events with different sizes (i.e. different amounts of power imbalance); events at different locations of the network; and resources with different capacities and locations. The comparison of the tests listed in Table 1 for evaluating the impact of the aforementioned various factors on the performance of the EFCC scheme is further explained as follows:

- Test 1, 2 and 3: for evaluating the impact of the locations of the frequency disturbances.
- Test 1, 4 and 6: for evaluating the impact of the capacities of the EFCC resources on the overall frequency restoration performance (i.e. the capacities of the resources were increased from 300 MW to 1 GW). Test 3, 5 and 7 are also defined for the same purpose, but with the disturbance located in a different region.
- Test 1, 8 and 10: for evaluating the impact of the EFCC resources when having different distribution of capacities (i.e. LC1 and LC2 have equal amount of capacity in Test 1; LC2 has a larger capacity in Test 8; and LC1 has a larger capacity in Test 10). Test 3, 9 and 11 are defined for the same purpose, but with the disturbance located in a different region.
- Test 6 and 12: for evaluating the impact of the size of the power imbalance (i.e. the power imbalance was increased from 1 GW to 1.32 GW). Test 7 and 13 are defined for the same purpose, but with the disturbance located in a different region.
- Test 1, 14 and 15: for evaluating the impact of the locations of the resources (i.e. LC1 and LC2 were placed in R1 and R3 respectively in Test 1; LC1 was moved to R2 with LC2 remained unchanged in Test 14; and both LC1 and LC2 were located in R3 in Test 15).

Under-frequency events were triggered by disconnecting infeeds to the network, while over-frequency events were triggered by disconnecting demands. It should be noted that the resource capacities for LC1 and LC2, ranging from 300 MW - 1000 MW, were chosen for evaluating the functionality of the EFCC scheme and investigating how the sizes of the available resource power will affect the overall control effectiveness. In some cases, there is not enough resource power under the control of EFCC to fully address the event – other power would be required via other forms of response in such cases. However, in such cases, benefits are still considerable. The values chosen do not represent the actual EFCC resource capacities that will be required in the GB transmission network, which is not within the scope of the tests.

The test results from the listed tests will be analysed and compared in Section 5.3 to evaluate how the locations and sizes of the resources and the events will affect the EFCC operation and the effectiveness of the corresponding control actions. The system inertia level in all the test was set as 82 GVAs, which is based on the anticipated lowest inertia level in 2020/2021 as reported in the System Operability Framework [3]. The settings of the LCs and the resource availability information for all of the tests are provided in Appendix C.

Table 1. List of tests conducted for evaluating EFCC's dependability

Tests	Event Size	Event Location	LC1 Location	LC1 Resource	LC2 Location	LC2 Resource
1	1 GW	R3	R1	300 MW	R3	300 MW
2	1 GW	R2	R1	300 MW	R3	300 MW
3	1 GW	R1	R1	300 MW	R3	300 MW
4	1 GW	R3	R1	600 MW	R3	600 MW
5	1 GW	R1	R1	600 MW	R3	600 MW
6	1 GW	R3	R1	1 GW	R3	1 GW

7	1 GW	R1	R1	1 GW	R3	1 GW
8	1 GW	R3	R1	300 MW	R3	1 GW
9	1 GW	R1	R1	300 MW	R3	1 GW
10	1 GW	R3	R1	1 GW	R3	300 MW
11	1 GW	R1	R1	1 GW	R3	300 MW
12	1.32 GW	R3	R1	1 GW	R3	1 GW
13	1.32 GW	R1	R1	1 GW	R3	1 GW
14	1 GW	R1	R2	300 MW	R3	300 MW
15	1 GW	R1	R3	300 MW	R3	300 MW

5.2 Tests results for evaluating EFCC's dependability in frequency disturbances

5.2.1 Test 1: 1 GW event in Region 3; LC1: 300 MW in Region 1; LC2: 300 MW in Region 3

In Test 1, the arrangement of the resources and the events is shown in Figure 3, where it can be seen that both of LC1 and LC2 resources have 300 MW positive and negative response available respectively, and LC1 is placed in Region 1, while LC2 is placed in Region 3.

An under-frequency and an over-frequency event with 1 GW power imbalance were triggered in Region 3.

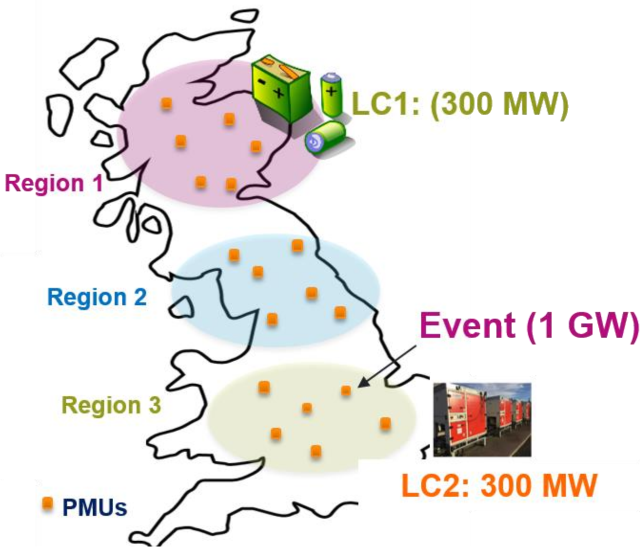

Figure 3. Resource and event location for Test 1

5.2.1.1 Under-frequency event in Test 1

An under-frequency event was trigged by disconnecting 1 GW infeed in Region 3. The test results are shown in Figure 4 and the key observations are listed in Table 2. In Figure 4, the first plot shows the system frequency measured by the LCs with and without the EFCC response. The second plot shows the system and local RoCoF values measured by LC1 and LC2. The third plot shows the event detection signal from the LCs. The fourth plot presents the resource deployment command from the LCs. The last plot shows the actual power changes in the two resources being controlled. For the resource controlled by LC2, the power level shown is the value that has been amplified and fed back to the RTDS.

In this test, LC2 is located in the region where the event occurred. From the test results, it can be seen that LC2 deployed the full 300 MW positive response available immediately when the event is detected, while LC1 deployed 120 MW response 2 s later. Compared to the case where there is no EFCC response, the frequency nadir was improved from 49.31 Hz to 49.54 Hz, i.e. the frequency deviation was successfully contained in the required level. From the training and the user manual provided by GE, it is considered that the 2 s delay in LC1 was intentionally introduced for resources that are not located in the region where the event occurs and it is configurable via the associated setting “sWa2LocSwDl”.

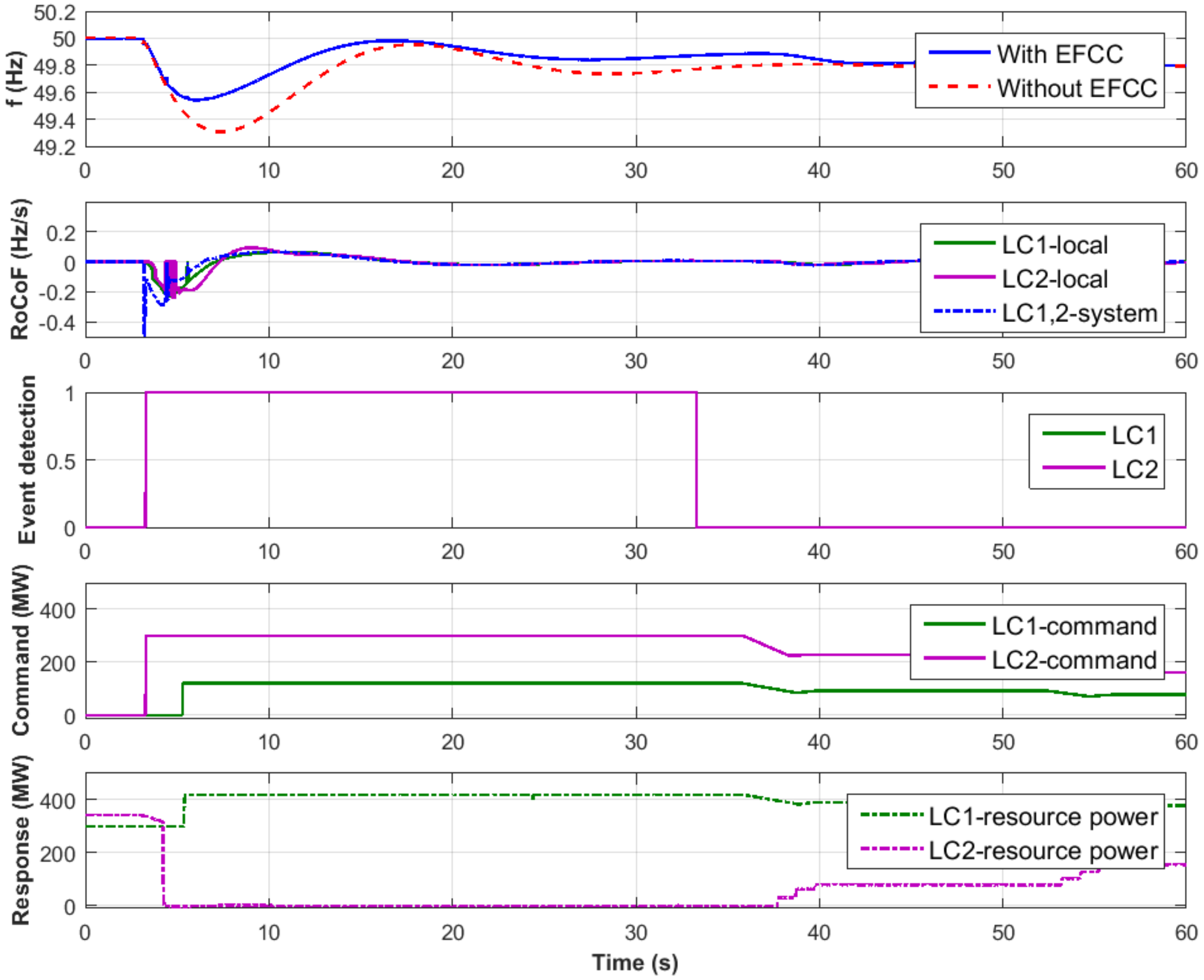

Figure 4. Test 1: under-frequency event test results from LCs

Table 2. Key observations in the under-frequency event in Test 1

Time	Observations
3.08 s	Event occurred
3.20 s	Event detected and LC2 commanded 300 MW positive power
5.20 s	LC1 commanded 120 MW positive power
4.21 s	LC2 reduced 319 MW demand (from 319 MW to 0 MW)
5.36 s	LC1 increased 120 MW output (from 299 MW to 419 MW)
6.30 s	Frequency reaches nadir : 49.54 Hz (49.31 Hz if no EFCC response)

5.2.1.2 Over-frequency event in Test 1

In this test, an over-frequency event was trigged by disconnecting 1 GW load in Region 3. The test results are shown in Figure 5 and the key observations are listed in Table 3.

LC2 is located in the region where the event occurred, and it successfully commanded 300 MW negative power immediately when the event was detected and there was no significant contribution for LC1 during the event. The frequency peak is 50.51 Hz, which is 0.19 Hz improvement compared to the case where there is no EFCC response, where the frequency peak is 50.70 Hz. In this test, EFCC has successfully performed its function, i.e. correctly sent command to the load bank at the required time, but the frequency is slightly over the 50.50 Hz limit is due to the delay (approximately 0.84 s) in the response of the load bank to the command.

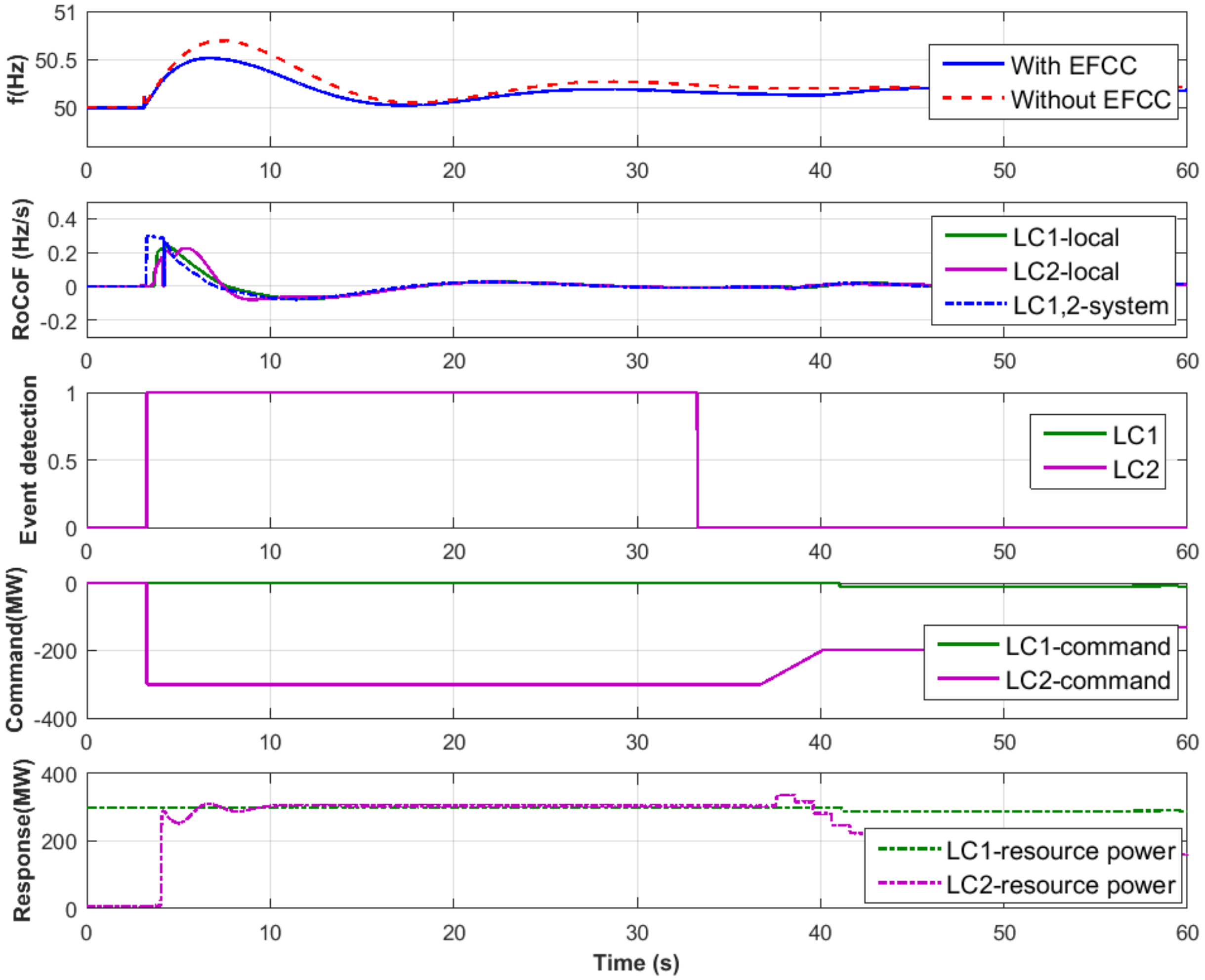

Figure 5. Test 1: over-frequency event test results from LCs

Table 3. Key observations in the over-frequency event in Test 1

Time	Observations
3.06 s	Event occurred
3.20 s	Event detected and LC2 commanded 300 MW negative power
4.04 s	LC2 increased 299 MW demand (from 9 MW to 305 MW)
6.60 s	Frequency reaches peak : 50.51 Hz (50.70 Hz if no EFCC response)

5.2.2 Test 2: 1 GW event in Region 2; LC1: 300 MW in Region 1; LC2: 300 MW in Region 3

In this test, the arrangement of the resources and the event is as shown in Figure 6, where it can be seen that both of LC1 and LC2 have the same locations and same resource capacities as Test 1, but the events were triggered in Region 2.

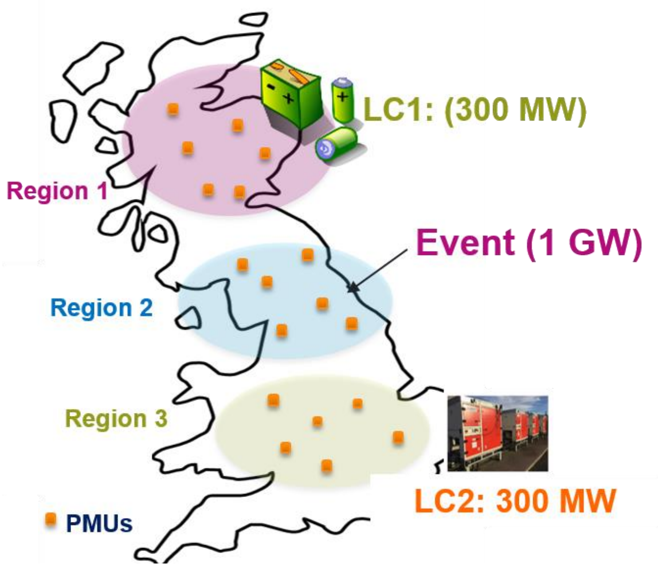

Figure 6. Resource and event location for Test 2

5.2.2.1 Under-frequency event in Test 2

In this test, an under-frequency event was trigged by disconnecting 1 GW infeed in Region 2. The test results are shown in Figure 7 and the key observations are listed in Table 4.

In this test, the event occurred in a region that is different from the regions where the two LCs were located. From the test results, it can be seen that LC1 and LC2 commanded 180 MW and 240 MW positive responses respectively at 5.28 s, which is 2 s after the event was detected. Regarding the frequency behaviour, the frequency nadir is 49.42 Hz, which has 0.11 Hz improvement compared to the case where there is no EFCC response. Based on the design specifications of the EFCC scheme, this performance is expected, as the LCs are required to remain inactive for the first 2 s for events that are not located in the same region as the resources.

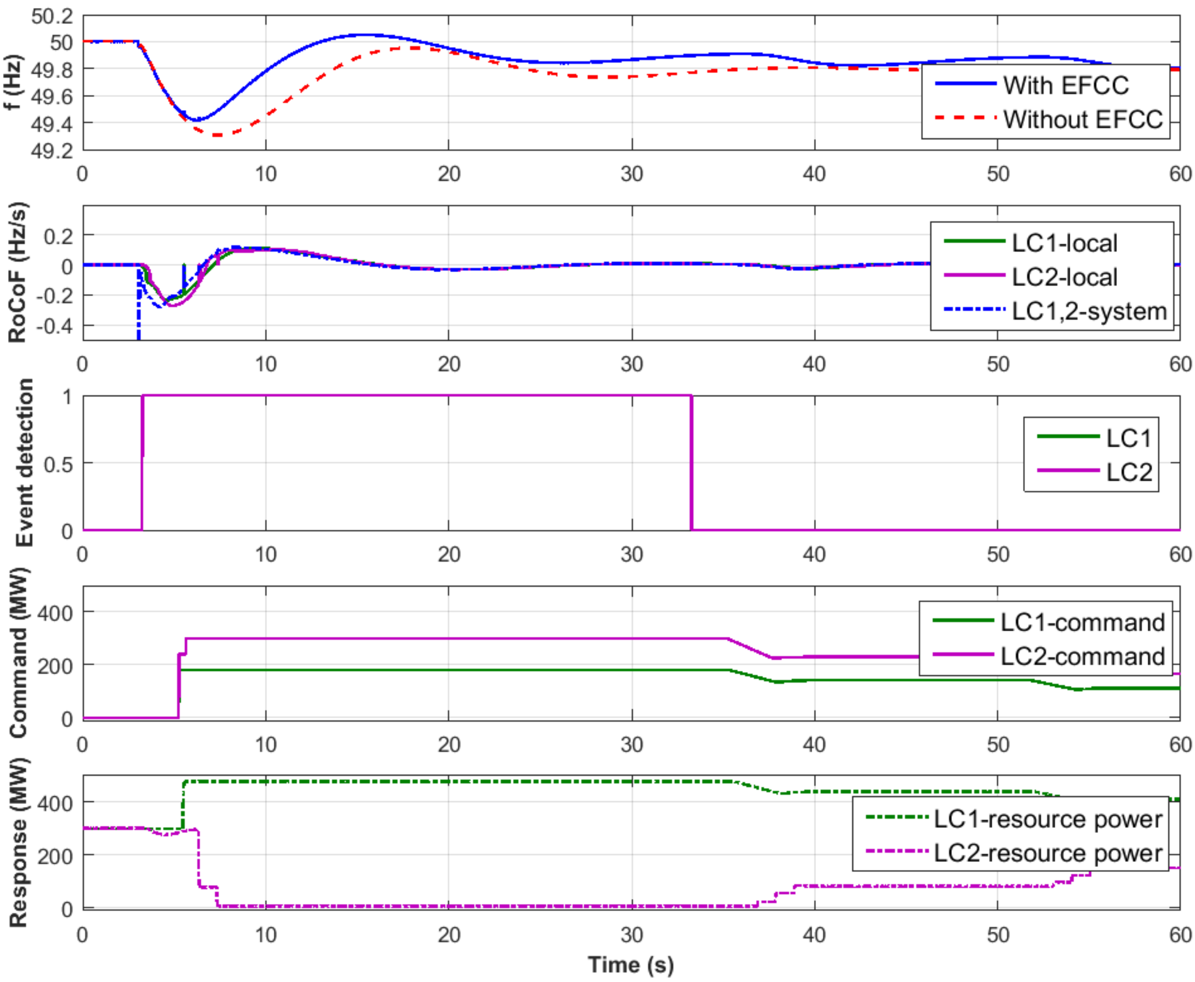

Figure 7. Test 2: under-frequency event test results from LCs

Table 4. Key observations in the under-frequency event in Test 2

Time	Observations
3.06 s	Event occurred
3.28 s	Event detected
5.28 s	LC1 commanded 180 MW positive power; LC2 initially commanded 240 MW and then 300 MW positive power.
5.47 s	LC1 increased 180 MW output (from 299 MW to 479 MW)
6.31 s	LC2 reduced 218 MW demand and then further reduced 70 MW (from 297 MW 80 MW and then to 9 MW)
6.34 s	Frequency reaches nadir : 49.42 Hz (49.31 Hz if no EFCC response)

5.2.2.2 Over-frequency event in Test 2

In this test, an over-frequency event was trigged by disconnecting 1 GW load in Region 2. The test results are shown in Figure 8 and the key observations are listed in Table 5.

From the test results, it can be seen that LC1 and LC2 commanded 157 MW and 245 MW negative responses respectively at 5.20 s, which is 2 s after the event was detected. Compared to the case without EFCC response, the frequency peak was reduced from 50.59 Hz to 50.56 Hz. Similar to the under-frequency case presented in Section 5.2.2.1, the performance of EFCC scheme in this test aligns with the expectation.

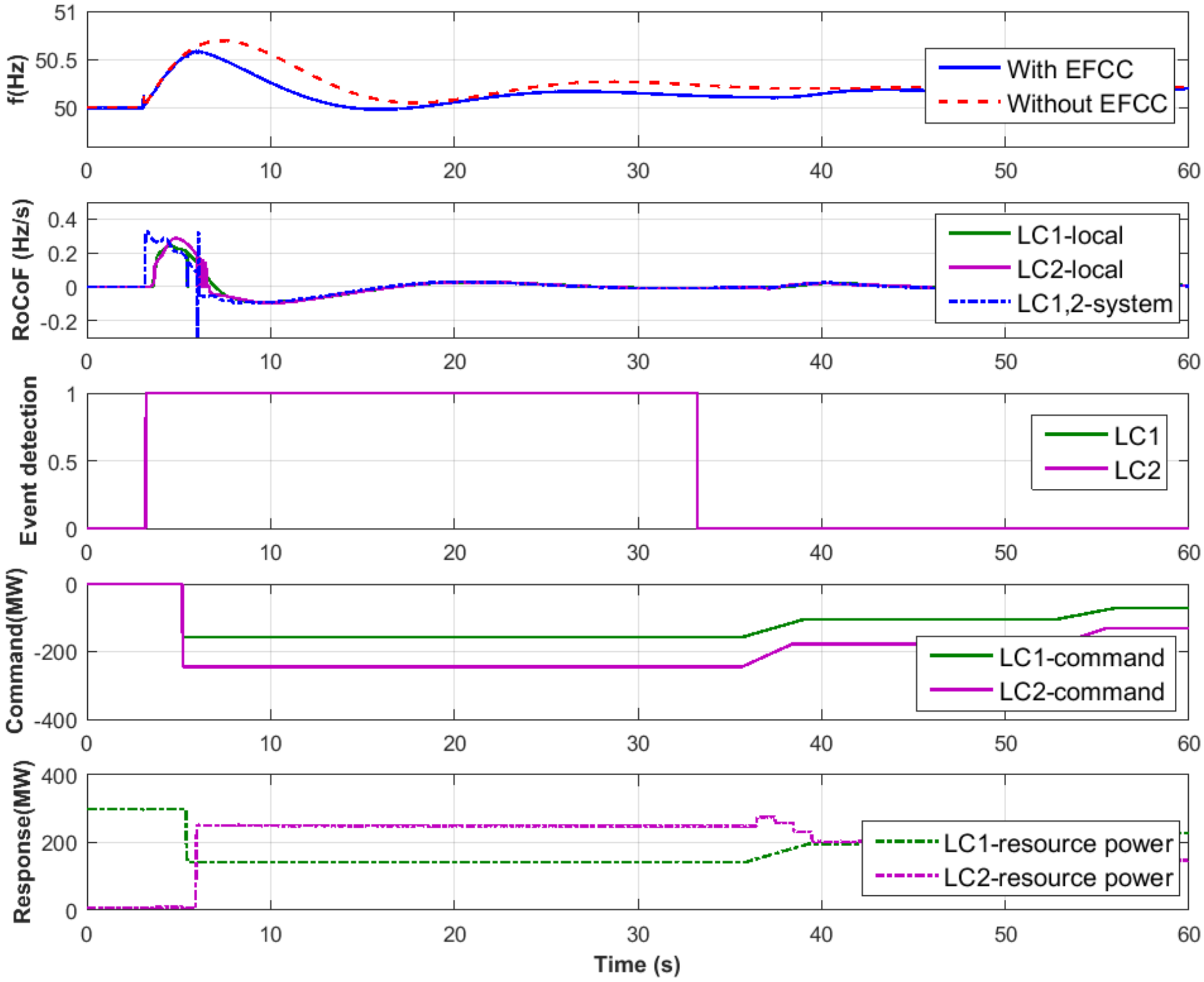

Figure 8. Test 2: over-frequency event test results from LCs

Table 5. Key observations in the over-frequency event in Test 2

Time	Observations
3.06 s	Event occurred
3.20 s	Event detected
5.20 s	LC1 commanded 157 MW negative power and LC2 commanded 245 MW negative power
5.40 s	LC1 decreased 156 MW output (from 299 MW to 143 MW)
5.93 s	LC2 increased 244 MW demand (from 7 MW to 251 MW)
5.98 s	Frequency reaches peak : 50.59 Hz (50.70 Hz if no EFCC response)

5.2.3 Test 3: 1 GW event in Region 1; LC1: 300 MW in Region 1; LC2: 300 MW in Region 3

In this test, the arrangement of the resources and the event is shown in Figure 9. The location and resource capacity of LC1 and LC2 remained the same as previous tests, but the events were triggered in Region 1.

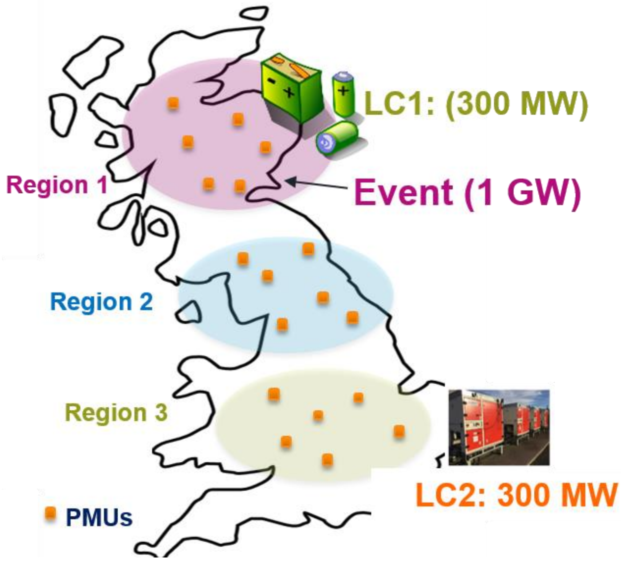

Figure 9. Resource and event location for Test 3

5.2.3.1 Under-frequency event in Test 3

In this test, an under-frequency event was trigged by disconnecting 1 GW infeed in Region 1. The test results are shown in Figure 10 and the key observations are listed in Table 6.

In this test, the event occurred in a region where LC1 is located. From the test results, it can be seen that LC1 commanded 298 MW immediately when the event is detected, while LC2 commanded 180 MW after 2 s of the event being detected. Due to the fast response from LC1, the frequency nadir was improved from 49.31 Hz to 49.56 Hz, which successfully maintain the frequency within the statuary limit.

It is important to emphasise that the frequency restoration in this case and Test 1 are significantly more effective compared to the under-frequency event Test 2 with similar amount of resources being deployed, largely due to the elimination of the 2 s delay in response that is evident in the earlier test results. This shows that EFCC scheme will respond differently to events at different locations and a faster response to the frequency disturbance can significantly improve the frequency behaviour.

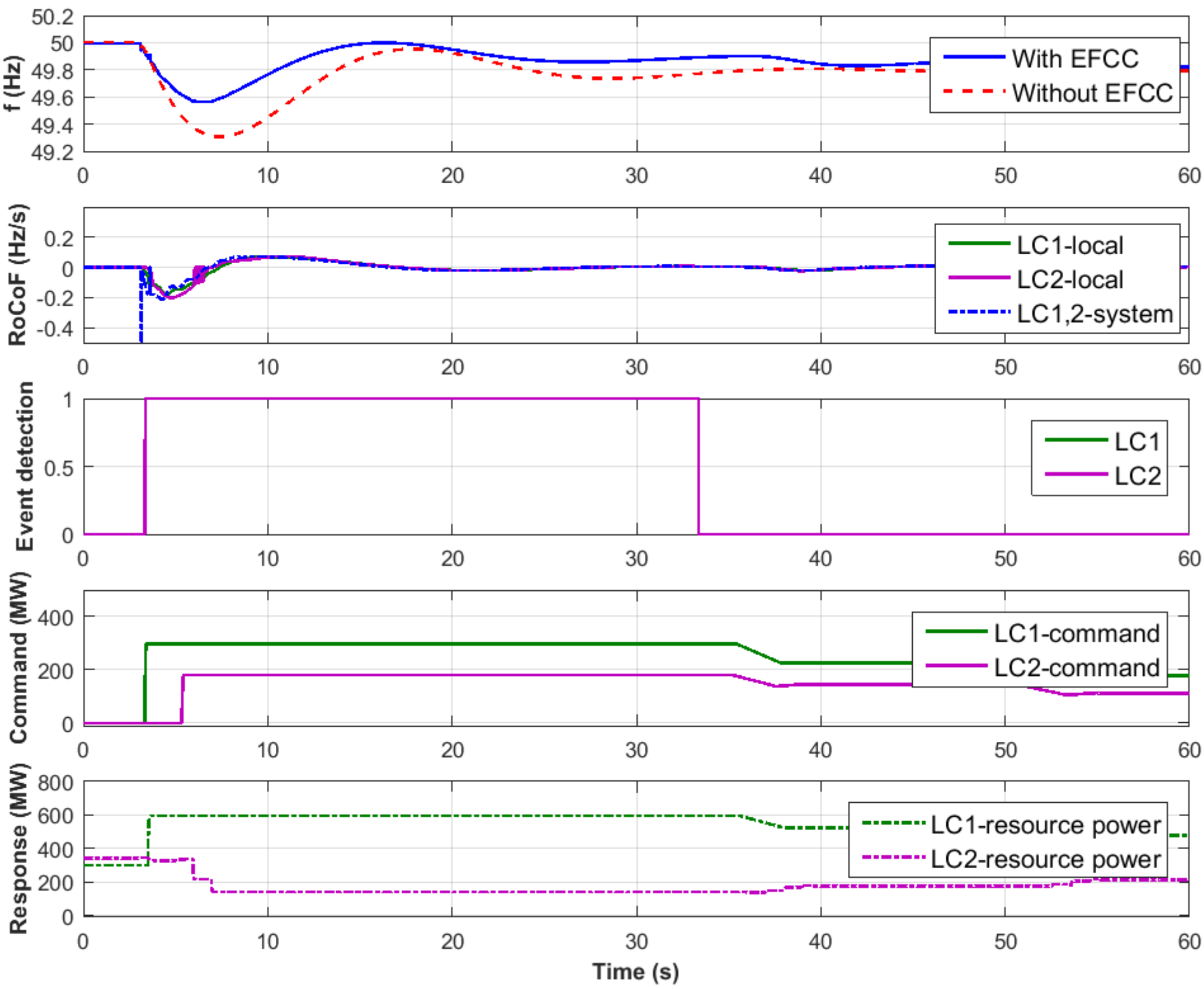

Figure 10. Test 3: under-frequency event test results from LCs

Table 6. Key observations in the under-frequency event in Test 3

Time	Observations
3.08 s	Event occurred
3.34 s	Event detected and LC1 commanded 298 MW positive power
5.34 s	LC2 commanded 180 MW positive power
3.50 s	LC1 increased 296 MW output (from 299 MW to 595 MW)
5.94 s	LC2 reduced 197 MW demand (from 339 MW to 214 MW and then 142 MW)
6.70 s	Frequency reaches nadir : 49.56 Hz (49.31 Hz if no EFCC response)

5.2.3.2 Over-frequency event in Test 3

In this test, an over-frequency event was trigged by disconnecting 1 GW load in Region 1. The test results are shown in Figure 11 and the key observations are listed in Table 7.

In this test, the event occurred in a region where LC1 is located. From the test results, it can be seen that LC1 commanded 300 MW negative power immediately when the event is detected, while LC2 commanded 120 MW after 2 s of the event being detected. Similar to the under-frequency test presented in Section 5.2.3.1, the LC1's fast reaction to the event results in much more effective frequency control compared to the case in Test 2. In this case, the frequency peak was controlled at 50.43 Hz, while the value would be 50.70 Hz if there is no EFCC response.

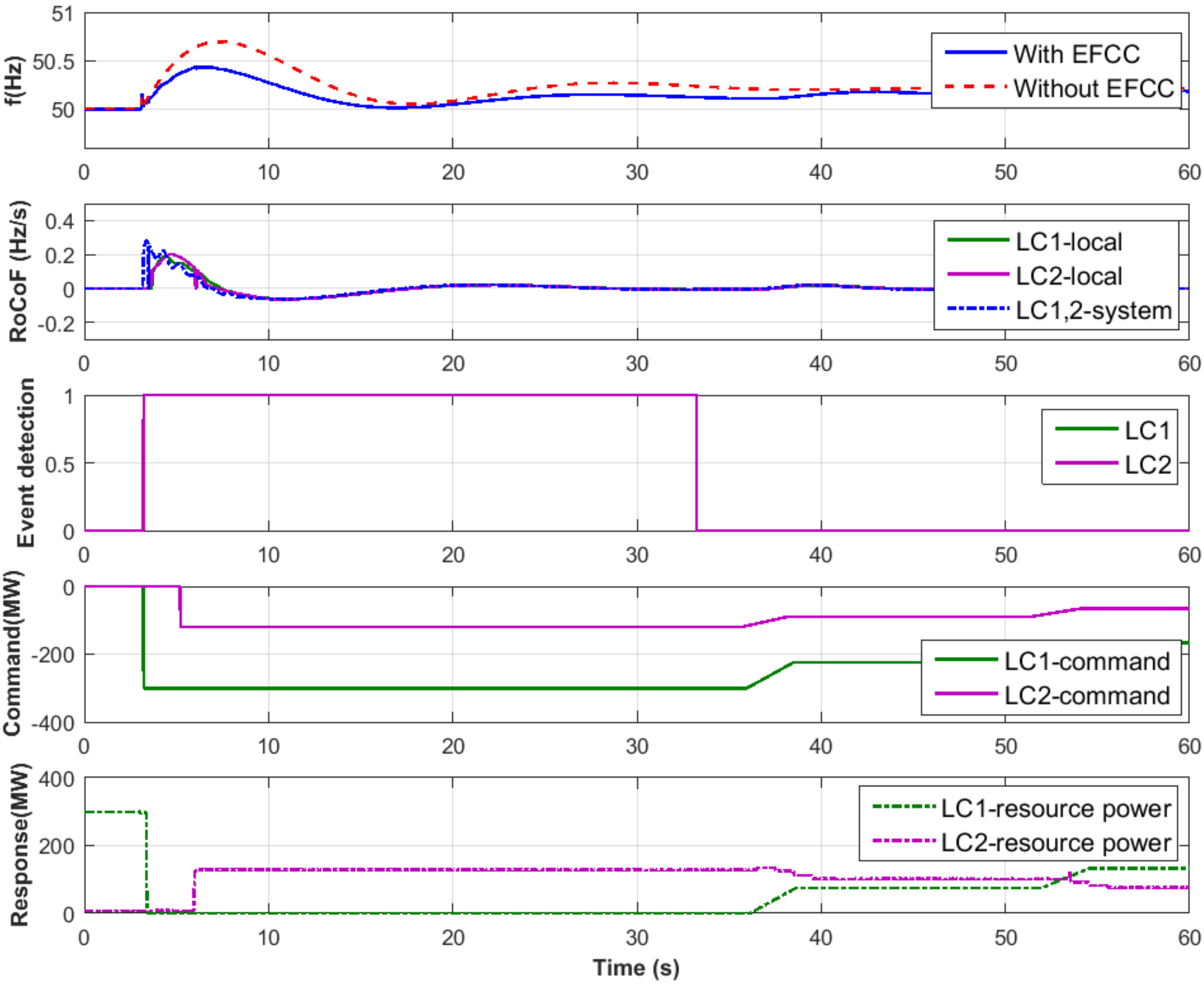

Figure 11. Test 3: over-frequency event test results from LCs

Table 7. Key observations in the over-frequency event in Test 3

Time	Observations
3.06 s	Event occurred
3.20 s	Event detected and LC1 commanded 300 MW negative power
5.20 s	LC2 commanded 120 MW negative power
3.36 s	LC1 resource decreased 299 MW output (from 299 MW to 0 MW)
5.95 s	LC2 increased 122 MW demand (from 7 MW to 129 MW)
6.12 s	Frequency reaches peak : 50.43 Hz (50.70 Hz if no EFCC response)

5.2.4 Test 4: 1 GW event in Region 3; LC1: 600 MW in Region 1; LC2: 600 MW in Region 3

In this test, the arrangement of the resources and the event is as shown in Figure 12. Both of LC1 and LC2 resources have 600 MW positive and negative response available, and LC1 is placed in Region 1, while LC2 is placed in Region 3. An under-frequency event and an over-frequency event with 1 GW power imbalance were triggered in Region 3. This is the same arrangement as Test 1 but with both of the resources' capacities increased from 300 MW to 600 MW.

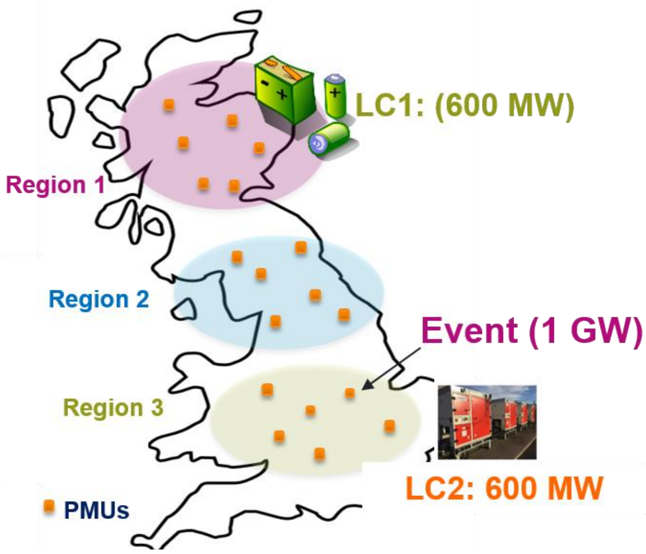

Figure 12. Resource and event location for Test 4

5.2.4.1 Under-frequency event in Test 4

In this test, an under-frequency event was trigged by disconnecting 1 GW infeed in Region 3. The test results are shown in Figure 13 and the key observations are listed in Table 8.

In this test, LC2 is located in the region where the event occurred. From the test results, it can be seen that LC2 deployed the 535 MW positive response available immediately when the event is detected, while LC1 deployed 240 MW response 2 s later. Compared to the case where there is no EFCC response, the frequency nadir was improved from 49.31 Hz to 49.51 Hz, i.e. the frequency deviation was successfully contained in the required level.

Comparing this test with the under-frequency test in Test 1 (Section 5.2.1.1), it can be seen that the increase in capacity does not necessarily result in better performance in frequency restoration.

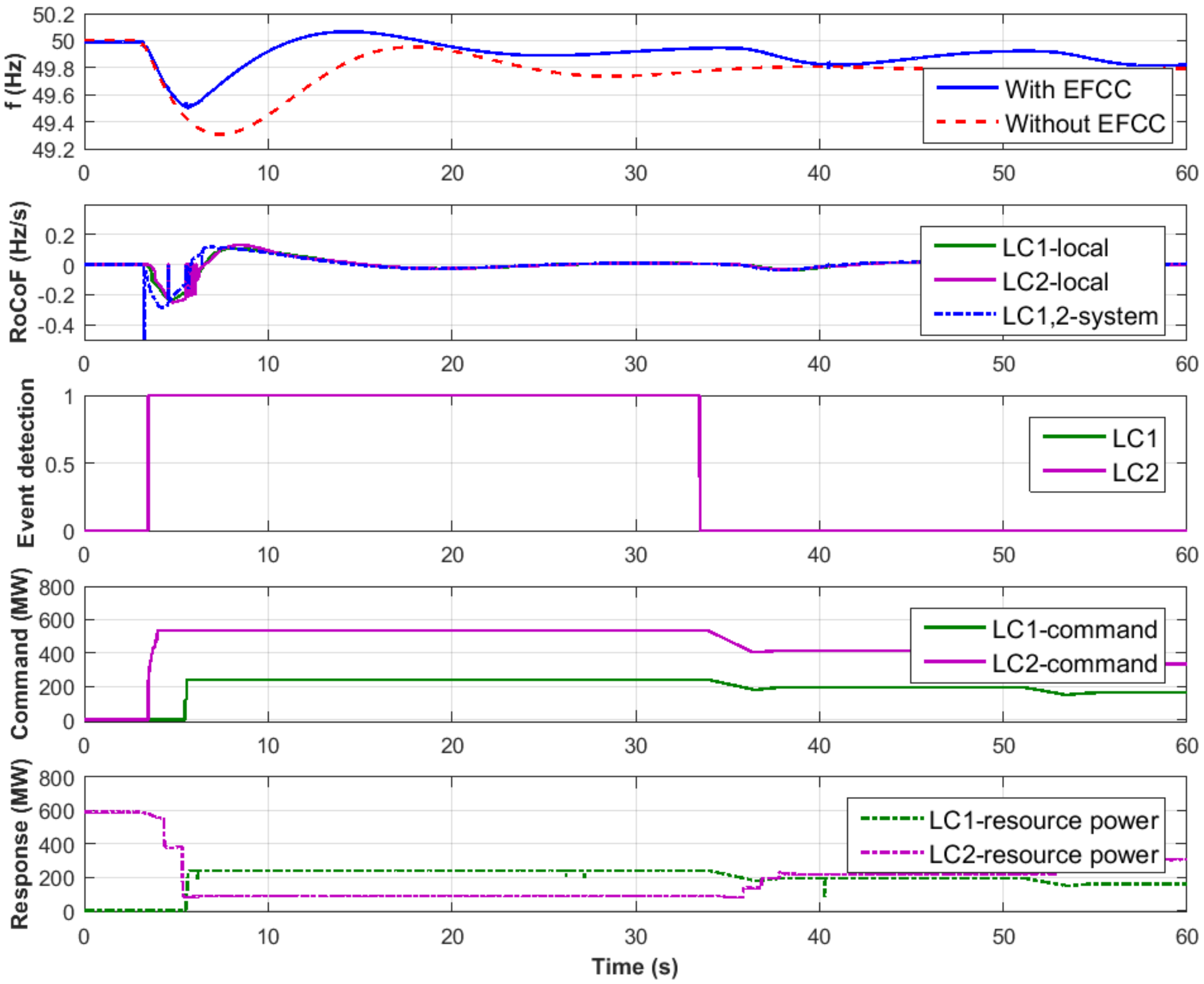

Figure 13. Test 4: under-frequency event test results from LCs

Table 8. Key observations in the under-frequency event in Test 4

Time	Observations
3.06 s	Event occurred
3.36 s	Event detected and LC2 commanded 535 MW positive power
5.36 s	LC1 commanded 240 MW
4.32 s	LC2 resource reduced 470 MW demand (from 550 MW to 380 MW, and then to 80 MW)
5.52 s	LC1 resource increased 240 MW output (from 0 MW to 240 MW)
5.61 s	Frequency reaches nadir : 49.51 Hz (49.31 Hz if no EFCC response)

5.2.4.2 Over-frequency event in Test 4

In this test, an over-frequency event was trigged by disconnecting 1 GW of load in Region 3. The test results are shown in Figure 14 and the key observations are listed in Table 9.

The event occurred in a region where LC2 is located. From the test results, it can be seen that LC2 successfully commanded 535 MW immediately when the event was detected, while there was no significant power dispatched by LC1. The frequency peak is 50.41 Hz, which is 0.29 Hz improvement compared to the frequency peak 50.70 Hz in the case without EFCC response. The behaviour of EFCC scheme in the test was desirable and aligned with the design specifications.

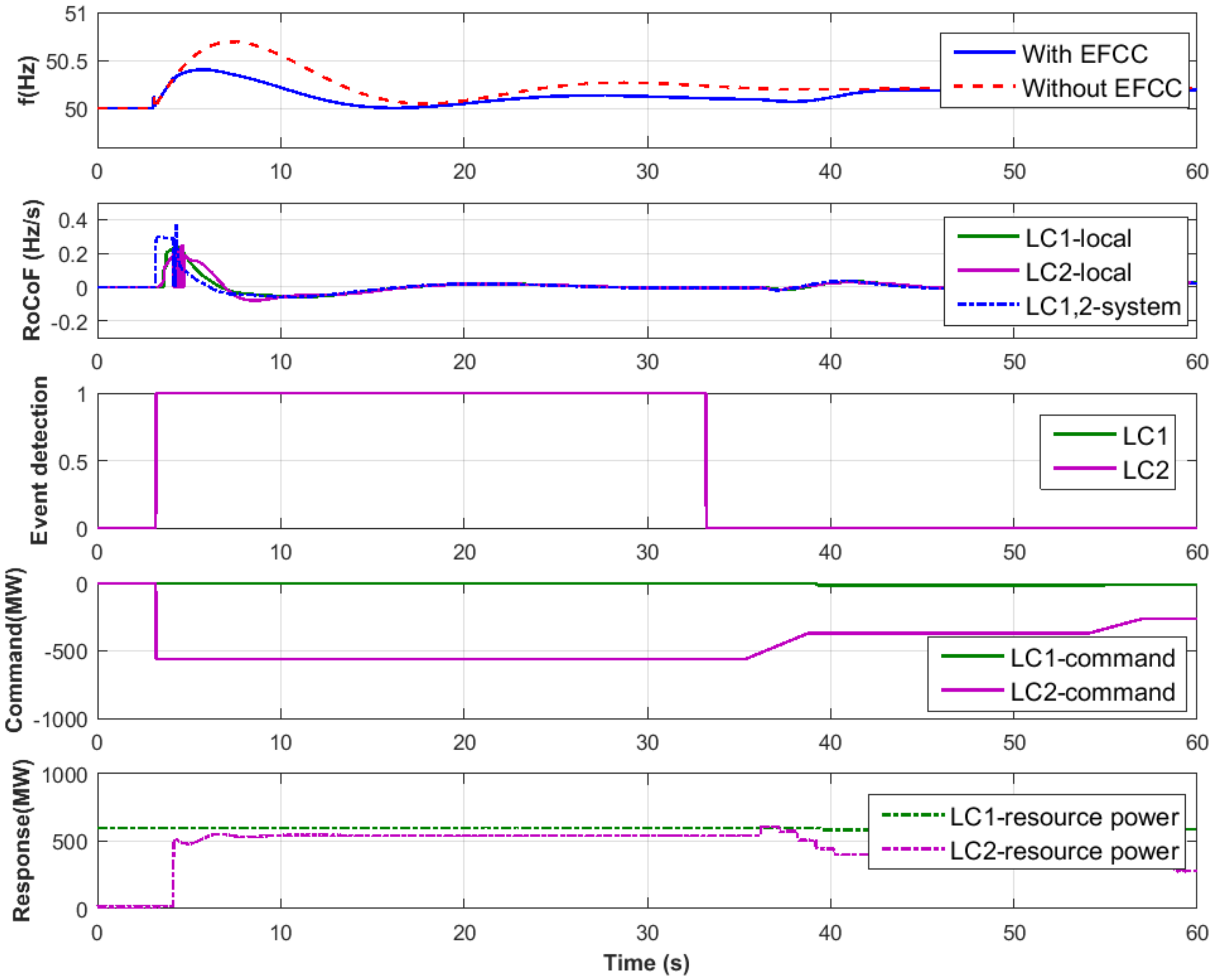

Figure 14. Test 4: over-frequency event test results from LCs

Table 9. Key observations in the over-frequency event in Test 4

Time	Observations
3.06 s	Event occurred
3.18 s	Event detected and LC2 commanded 560 MW negative power
4.12 s	LC2 increased 529 MW demand (from 20 MW to 549 MW)
5.80 s	Frequency reaches peak : 50.41 Hz (50.70 Hz if no EFCC response)

5.2.5 Test 5: 1 GW event in Region 1; LC1: 600 MW in Region 1; LC2: 600 MW in Region 3

In Test 5, the arrangement of the resources and the event are shown in Figure 12, where it can be seen that the resource capacities and locations are the same as in Test 4, but the events are triggered in Region 1 as opposed to Region 3.

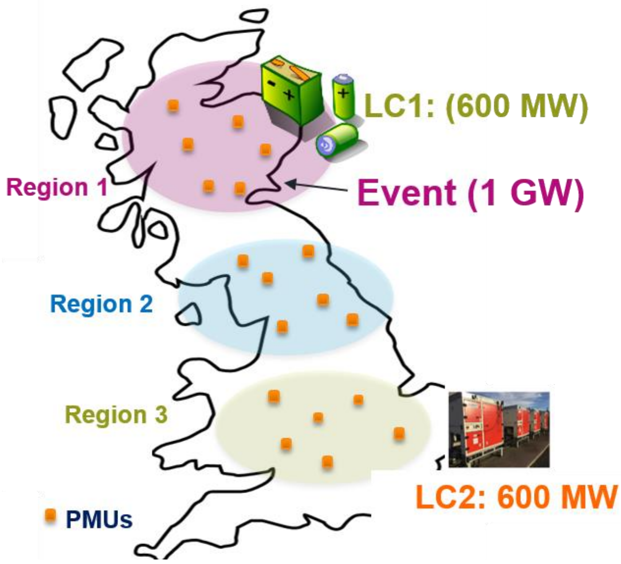

Figure 15. Resource and event location for Test 5

5.2.5.1 Under-frequency event in Test 5

In this test, an under-frequency event was trigged by disconnecting 1 GW infeed in Region 1. The test results are shown in Figure 16 and the key observations are listed in Table 10.

LC1, located in the same region where the event occurred, commanded 400 MW in total out of 600 MW positive power immediately after the event is detected, while LC2, located in Region 3, delayed 2 s in resource deployment with 240 MW power in total requested. The fast action of LC1 is very effective in restoring the frequency, where the nadir is successfully controlled above 49.50 Hz at 49.61 Hz as opposed to 49.31 Hz in the case where there is no EFCC response.

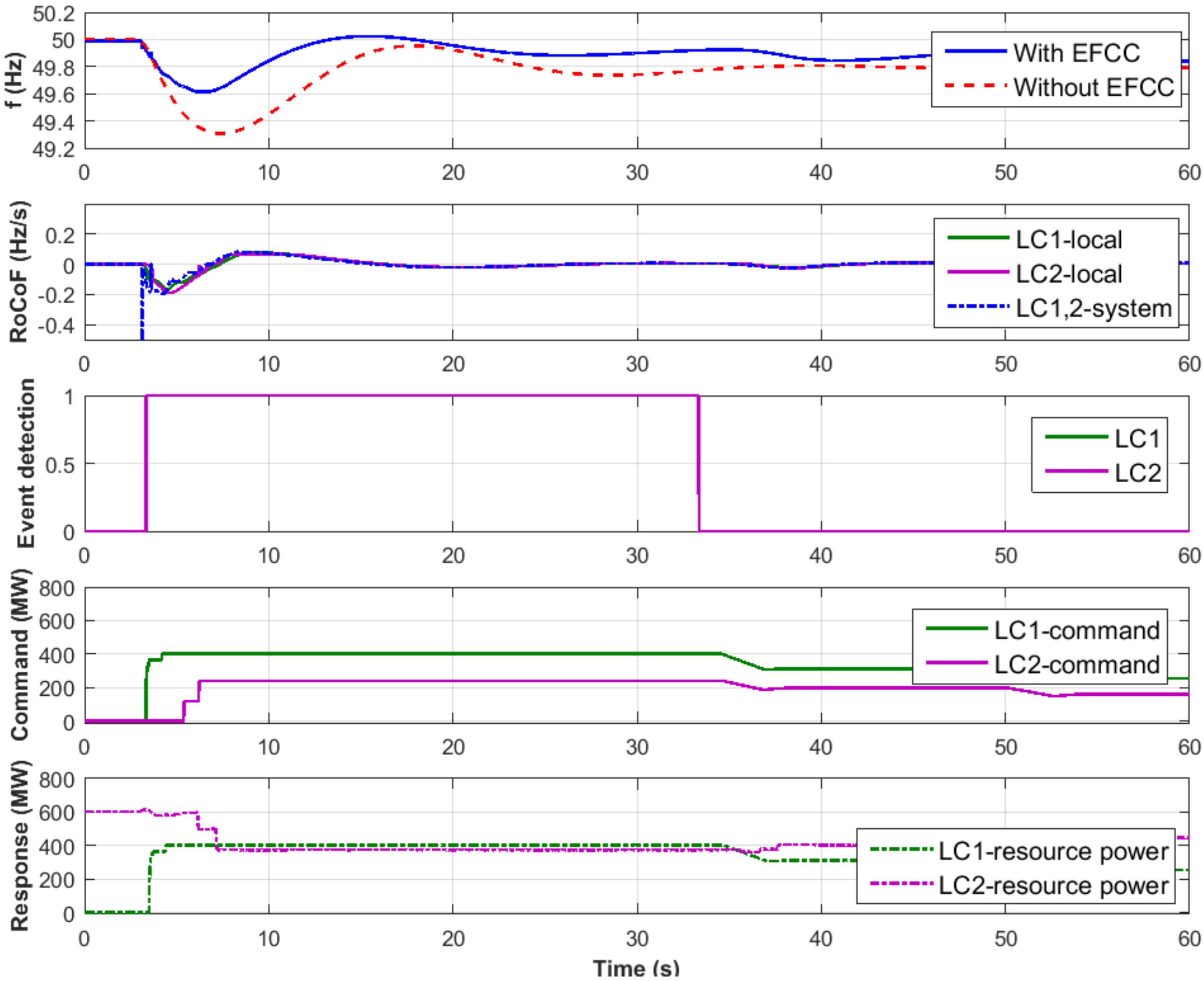

Figure 16. Test 5: under-frequency event test results from LCs

Table 10. Key observations in the under-frequency event in Test 5

Time	Observations
3.08 s	Event occurred
3.32 s	Event detected LC1 commanded 366 MW and then 400 MW positive power
5.38 s	LC2 commanded 120 MW and then 240 MW positive power
3.50 s	LC1 resource increased 400 MW output (from 0 MW to 364 MW and then 400 MW)
6.14 s	LC2 resource reduced 225 MW demand (600 MW to 500 and then 375 MW)
6.20 s	Frequency reaches nadir : 49.61 Hz (49.31 Hz if no EFCC response)

5.2.5.2 Over-frequency event in Test 5

In this test, an over-frequency event was trigged by disconnecting 1 GW load in Region 1. The test results are shown in Figure 17 and the key observations are listed in Table 11.

Similar to the previous case of under-frequency event in the same location, LC1 deployed response immediately after the event is detected. LC1 deployed all of its 600 MW negative response, while LC2 also commanded 600 MW negative power after 2 s. The frequency peak was effectively controlled at 50.27 Hz as opposed to 50.70 Hz in the case of no EFCC response.

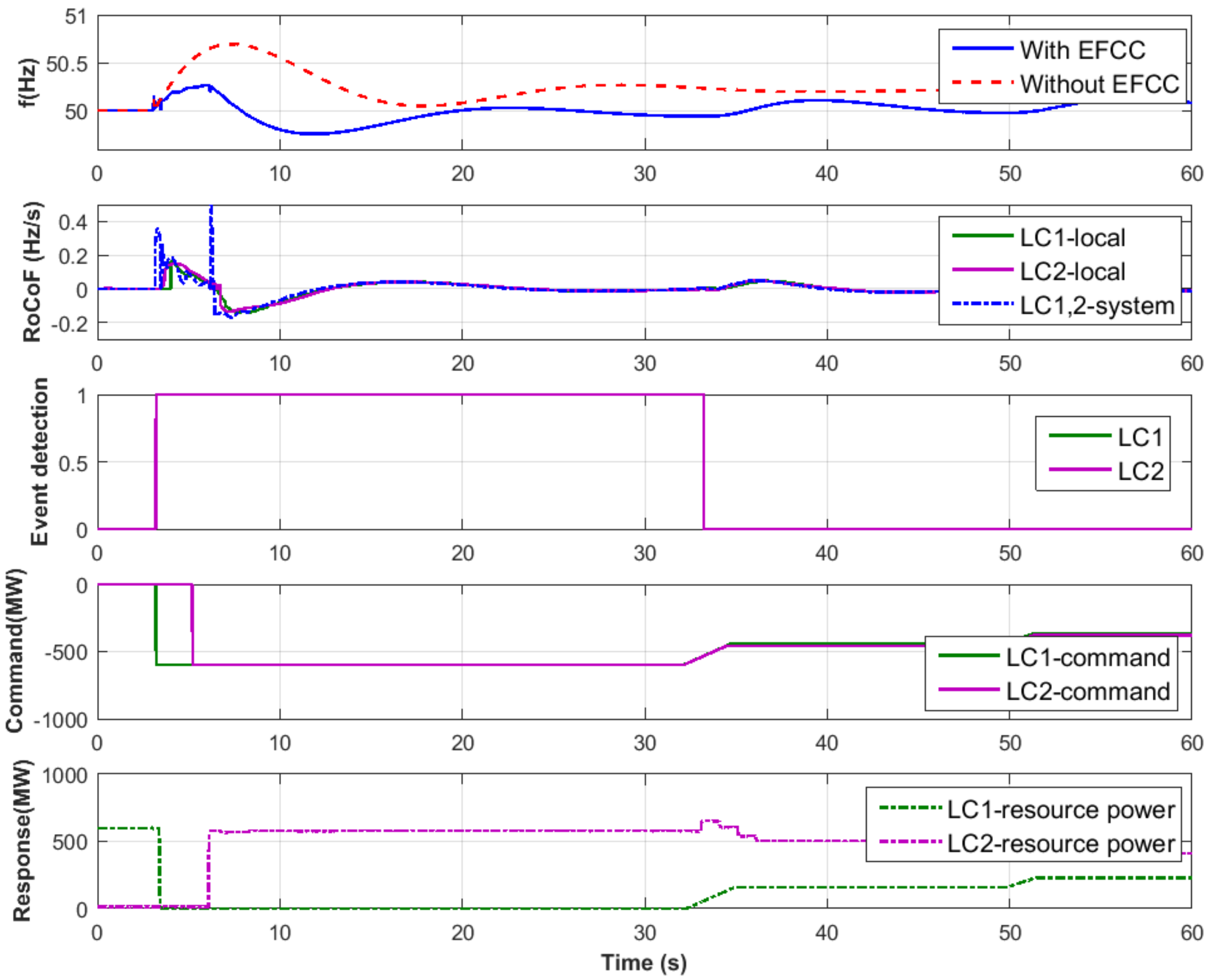

Figure 17. Test 5: over-frequency event test results from LCs

Table 11. Key observations in the over-frequency event in Test 5

Time	Observations
3.08 s	Event occurred
3.20 s	Event detected and LC1 commanded 600 MW negative power
5.20 s	LC2 commanded 600 MW negative power
3.38 s	LC1 resource decreased 600 MW output (from 600 MW to 0 MW)
21.45 s	LC2 resource increased 566 MW output (from 14 MW to 580 MW)
6.14 s	Frequency reaches peak : 50.27 Hz (50.70 Hz if no EFCC response)

5.2.6 Test 6: 1 GW event in Region 3; LC1: 1GW in Region 1; LC2: 1 GW in Region 3

In Test 6, the arrangement of the resources and the event are shown in Figure 18. The capacities of the resource controlled by LC1 and LC2 are increased to 1 GW, and the events are triggered in Region 3.

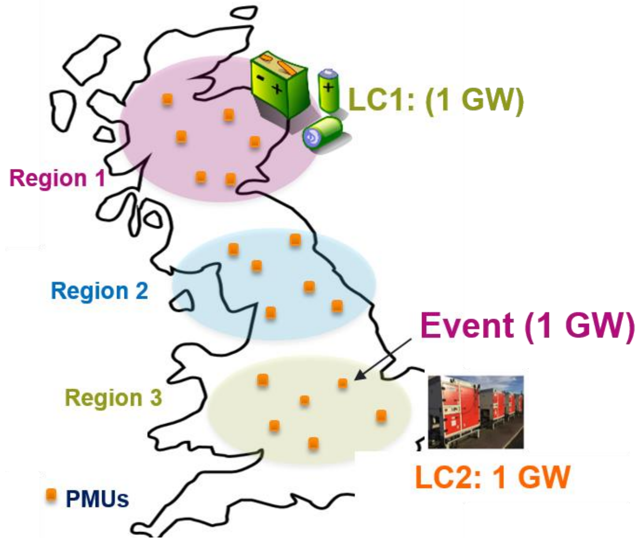

Figure 18. Resource and event location for Test 6

5.2.6.1 Under-frequency event in Test 6

In this test, an under-frequency event was trigged by disconnecting 1 GW infeed in Region 3. The test results are shown in Figure 19 and the key observations are listed in Table 12.

From the presented results, it can be seen that LC2, locating in the same region where the event occurred, commanded 800 MW positive power in total to the event immediately when it was detected, while LC1, locating in another region (Region 1) had about 2 s of delay in deploying the resource. The frequency was successfully contained at 49.51 Hz as opposed to 49.31 Hz in the case where there is no EFCC response. The EFCC's response in this test aligns with the design specifications.

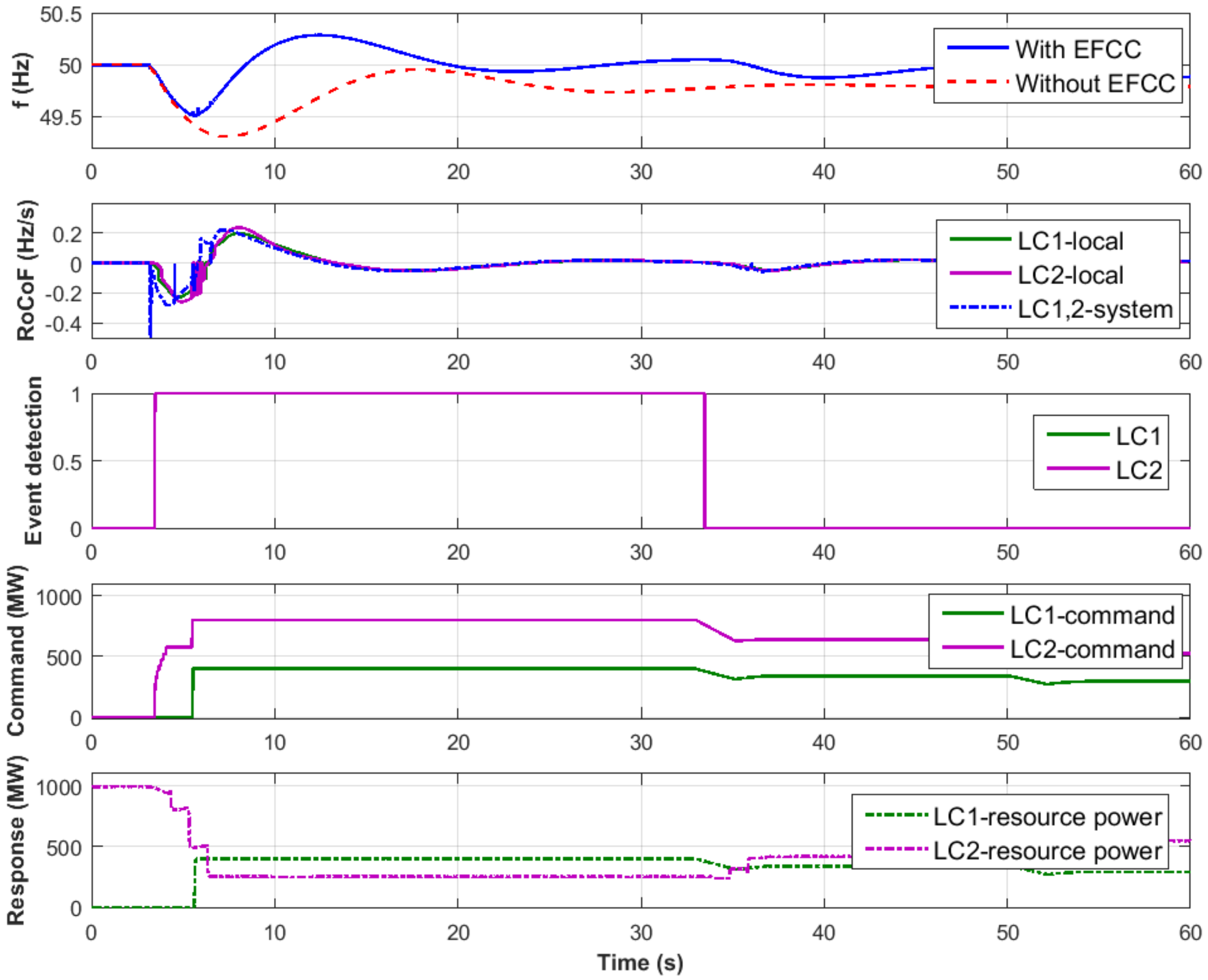

Figure 19. Test 6: under-frequency event test results from LCs

Table 12. Key observations in the under-frequency event in Test 6

Time	Observations
3.08 s	Event occurred
3.34 s	Event detected and LC2 commanded 675 MW and then 800 MW positive power
5.40 s	LC1 commanded 400 MW positive power
4.30 s	LC2 reduced 690 MW demand (from 940 MW to 250 MW in three steps, i.e. 805 MW, 487 MW and 250 MW, with approximately 1 s interval).
5.55 s	LC1 increased 400 MW output (from 0 MW to 200 MW)
5.68 s	Frequency reaches to nadir : 49.51 Hz (49.31 Hz if no EFCC response)

5.2.6.2 Over-frequency event in Test 6

In this test, an over-frequency event was trigged by disconnecting 1 GW of load in Region 3. The test results are shown in Figure 20 and the key observations are listed in Table 13.

Similar to the under-frequency test in Test 6, LC2 responded to the event immediately when it was detected, while LC1 held for 2 s after the event was detected. The frequency was successfully contained at 50.40 Hz with EFCC as opposed to 50.70 Hz in the case without EFCC response. The EFCC's performance in this tests alilgns with the design specifications.

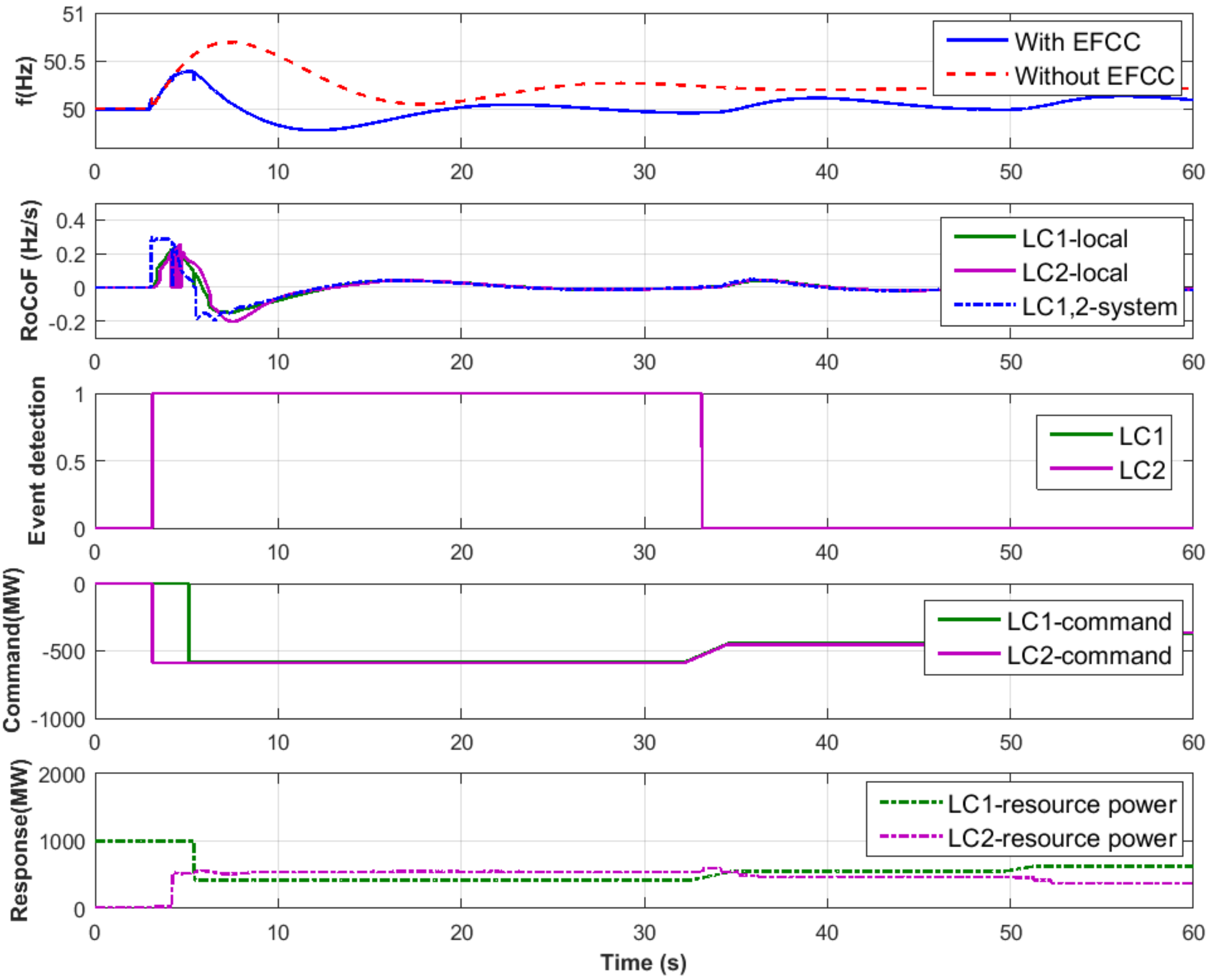

Figure 20. Test 6: over-frequency event test results from LCs

Table 13. Key observations in the over-frequency event in Test 6

Time	Observations
3.08 s	Event occurred
3.20 s	Event detected and LC2 commanded 587 MW negative power
5.20 s	LC1 commanded 580 MW negative power
4.20 s	LC2 resource increased 508 MW output (from 22 MW to 530 MW)
5.38 s	LC1 resource decreased 578 MW output (from 998 MW to 420 MW)
5.44 s	Frequency reaches peak : 50.40 Hz (50.70 Hz if no EFCC response)

5.2.7 Test 7: 1 GW event in Region 1; LC1: 1 GW in Region 1; LC2: 1 GW in Region 3

In Test 7, the arrangement of the resources and the event are shown in Figure 21. The capacities and locations of the resources controlled by LC1 and LC2 remained the same as in Test 6, but the events were triggered in Region 1.

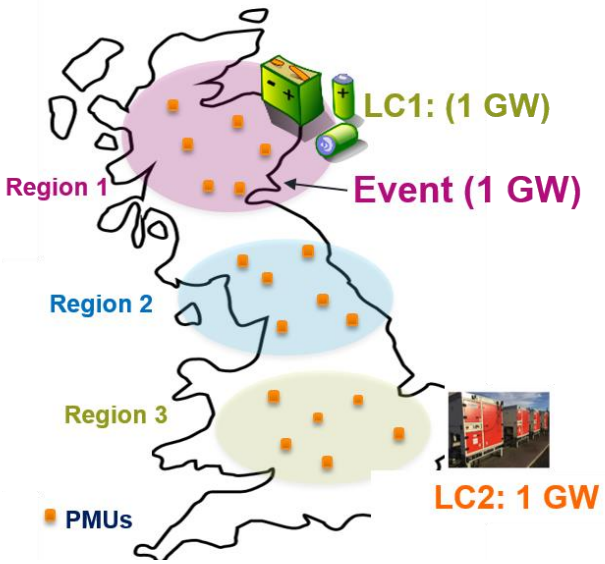

Figure 21. Resource and event location for Test 7

5.2.7.1 Under-frequency event in Test 7

In this test, an under-frequency event was trigged by disconnecting 1 GW infeed in Region 1. The test results are shown in Figure 22 and the key observations are listed in Table 14.

From the test results, it can be seen that LC1 deployed its response immediately after the event was detected and the frequency was successfully contained at 49.60 Hz. The amount of power deployed was only around 375 MW (out of 1000 MW available power).

Comparing this test with the under-frequency test in Test 6 (presented in Section 5.2.6.1), where the frequency was contained at 49.51 Hz with 690 MW response from LC2 and 400 MW from LC1, the test used much less power but more effectively controlled the frequency deviation. This is due to the fact that the load bank is relatively slow in responding to the command. This shows that the faster of the response, potentially the fewer amount of EFCC-type of response will be required to contain the frequency the required level.

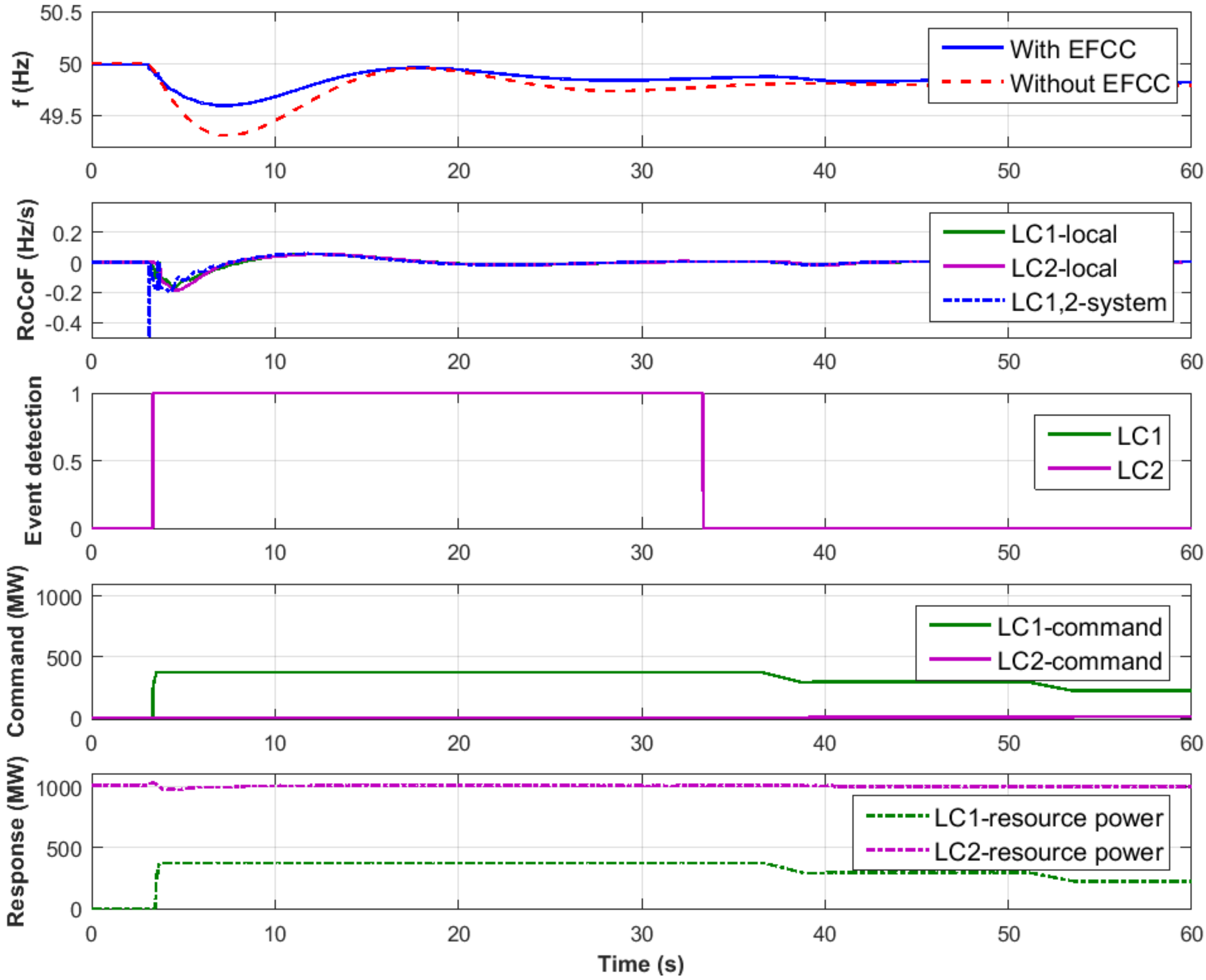

Figure 22. Test 7: under-frequency event test results from LCs

Table 14. Key observations in the under-frequency event in Test 7

Time	Observations
3.08 s	Event occurred
3.32 s	Event detected and LC1 commanded 376 MW positive power
3.48 s	LC1 resource increased 375 MW output (from 0 MW to 375 MW)
7.60 s	Frequency reaches to nadir : 49.60 Hz (49.31 Hz if no EFCC response)

5.2.7.2 Over-frequency event in Test 7

In this test, an over-frequency event was trigged by disconnecting 1 GW of load in Region 1. The test results are shown in Figure 23 and the key observations are listed in Table 15.

Similar to the test results in an under-frequency event in Test 7, the fast action from LC1 with deployed power close to the power imbalance, the frequency was controlled effectively with the frequency peak being 50.27 Hz as opposed to 50.70 Hz in the case without EFCC response.

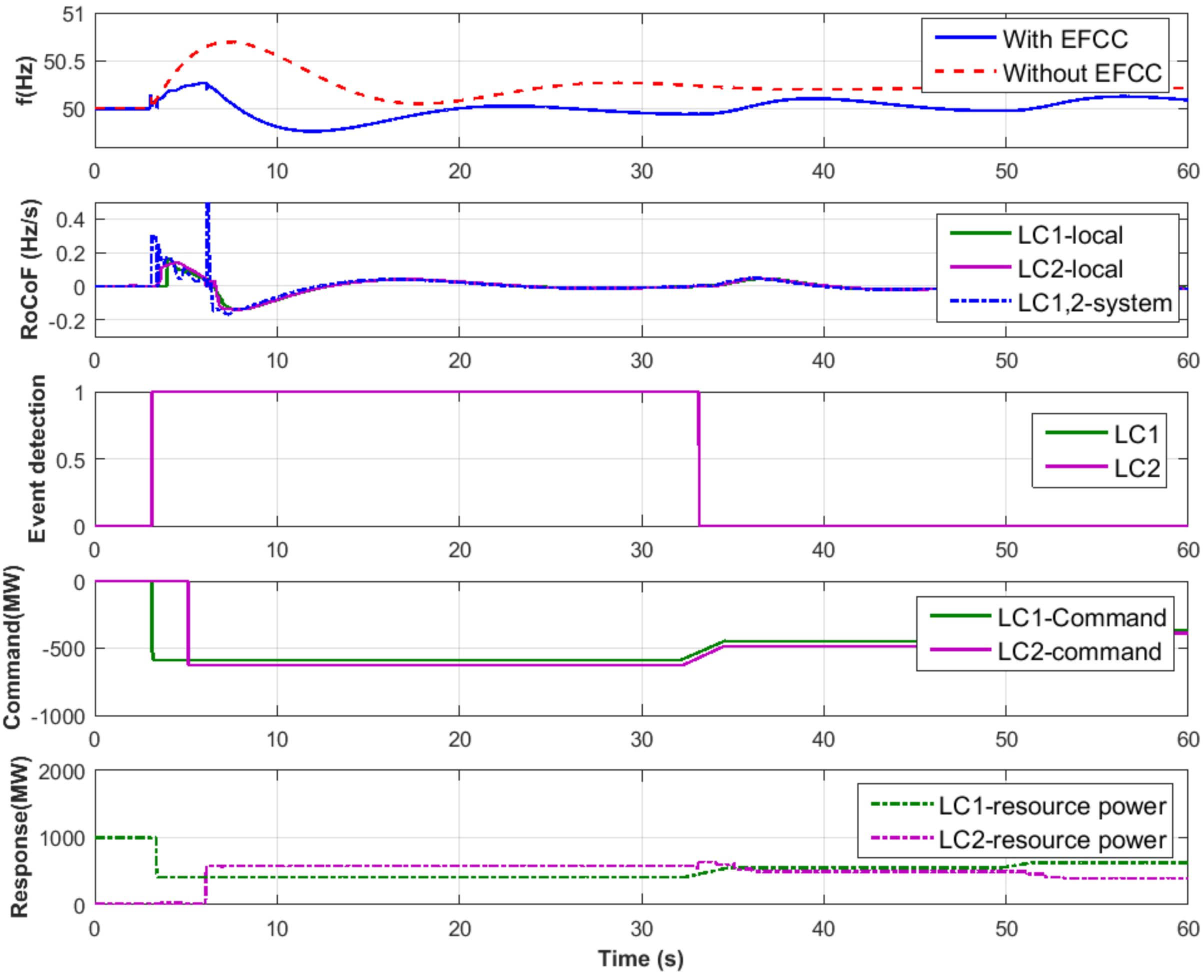

Figure 23. Test 7: over-frequency event test results from LCs

Table 15. Key observations in the over-frequency event in Test 7

Time	Observations
3.08 s	Event occurred
3.16 s	Event detected and LC2 commanded 587 MW negative power
5.16 s	LC2 commanded 628 MW negative power
3.36 s	LC1 resource decreased 588 MW output (from 1000 MW to 412 MW)
6.07 s	LC2 resource increased 562 MW output (from 20 MW to 582 MW)
6.14 s	Frequency reaches to peak : 50.27 Hz (50.70 Hz if no EFCC response)

5.2.8 Test 8: 1 GW event in Region 3; LC1: 300 MW in Region 1; LC2: 1 GW in Region 3

In Test 8, the arrangement of the resources and the events are shown in Figure 24. The resources controlled by LC1 and LC2 were located in region 1 and 3 respectively with different capacities – LC1 controlling 300 MW resource while LC2 controlling 1 GW resource. This will investigate the impact of different sizes of resources at different locations on the frequency restoration performance.

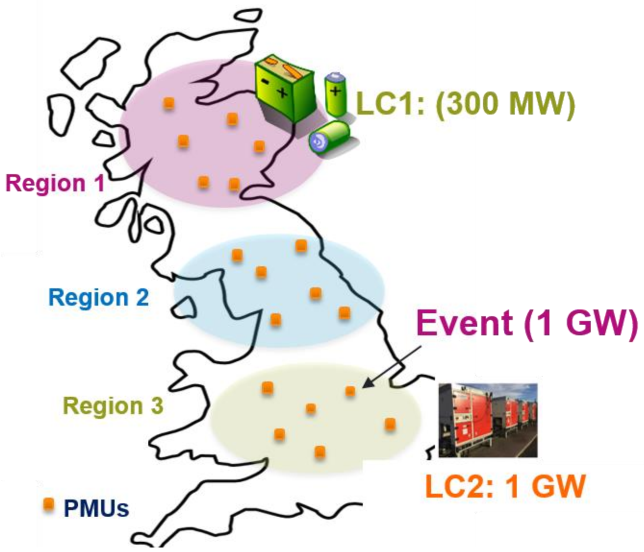

Figure 24. Resource and event location for Test 8

5.2.8.1 Under-frequency event in Test 8

In this test, an under-frequency event was trigged by disconnecting 1 GW infeed in Region 3. The test results are shown in Figure 25 and the key observations are listed in Table 16.

From the test results, it can be seen that LC2, locating in the same region as the event, commanded 526 MW power immediately after the event occurred, while LC1 commanded 120 MW after 2 s. The frequency nadir was successfully contained at 49.54 Hz as appose to 49.31 Hz in the case with EFCC response. The EFCC's performance in this test aligns with the design specifications.

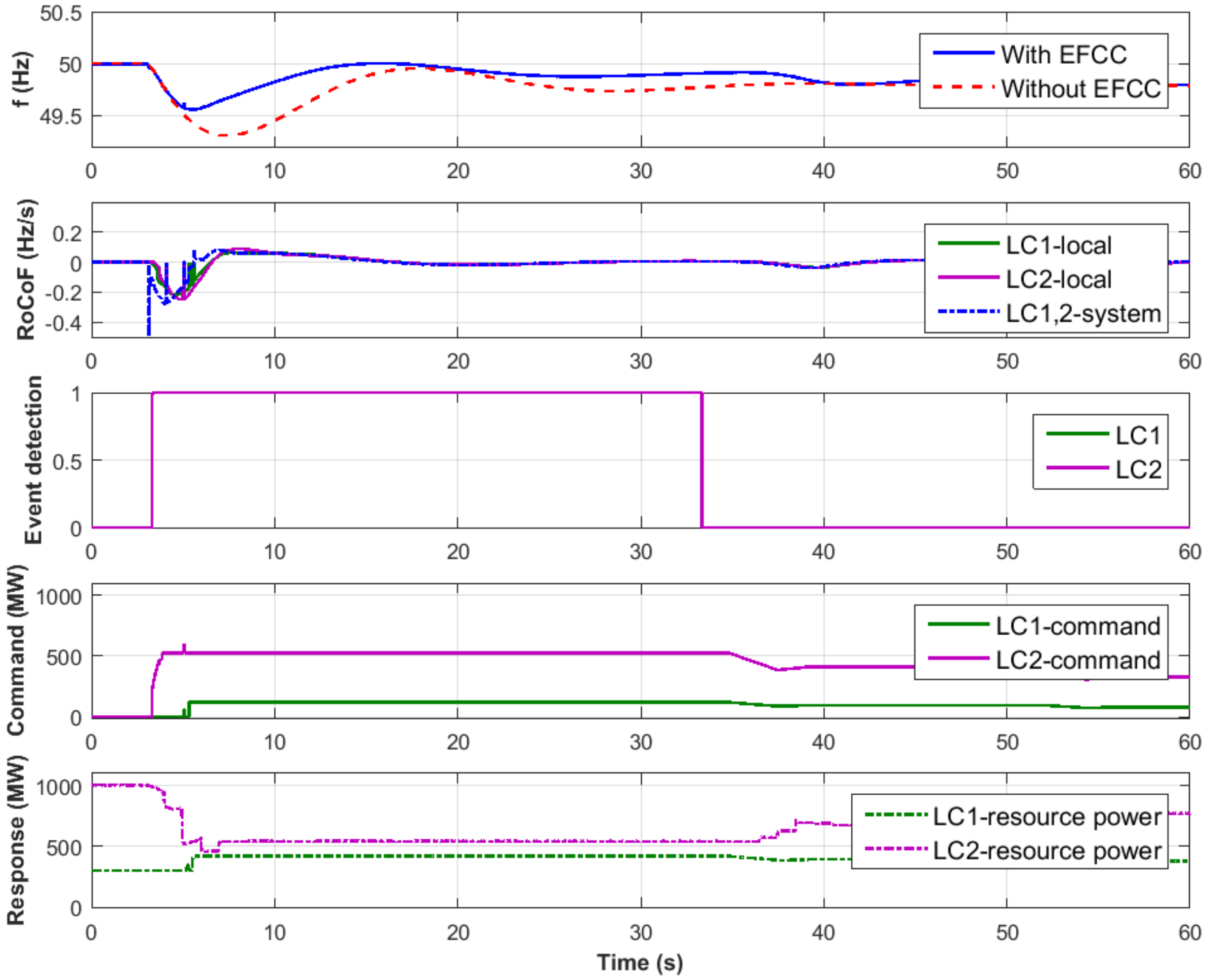

Figure 25. Test 8: under-frequency event test results from LCs

Table 16. Key observations in the under-frequency event in Test 8

Time	Observations
3.08 s	Event occurred
3.30 s	Event detected and LC2 commanded 526 MW positive power
5.32 s	LC1 commanded 120 MW
3.95 s	LC2 reduced 405 MW demand in a number of steps (from 945 MW to 540 MW)
5.49 s	LC1 increased 120 MW output (from 300 MW to 420 MW)
5.40 s	Frequency reaches to nadir : 49.54 Hz (49.31 Hz if no EFCC response)

5.2.8.2 Over-frequency event in Test 8

In this test, an over-frequency event was trigged by disconnecting 1 GW load in Region 3, where undesirable response from EFCC was observed. Positive response was deployed for the over-frequency event. The results are shown in Figure 26, where it can be seen that LC2 deployed positive 550 MW to the over-frequency event, and the frequency peak was successfully controlled at 50.37 Hz. The EFCC's performance in this test aligns with the design specifications.

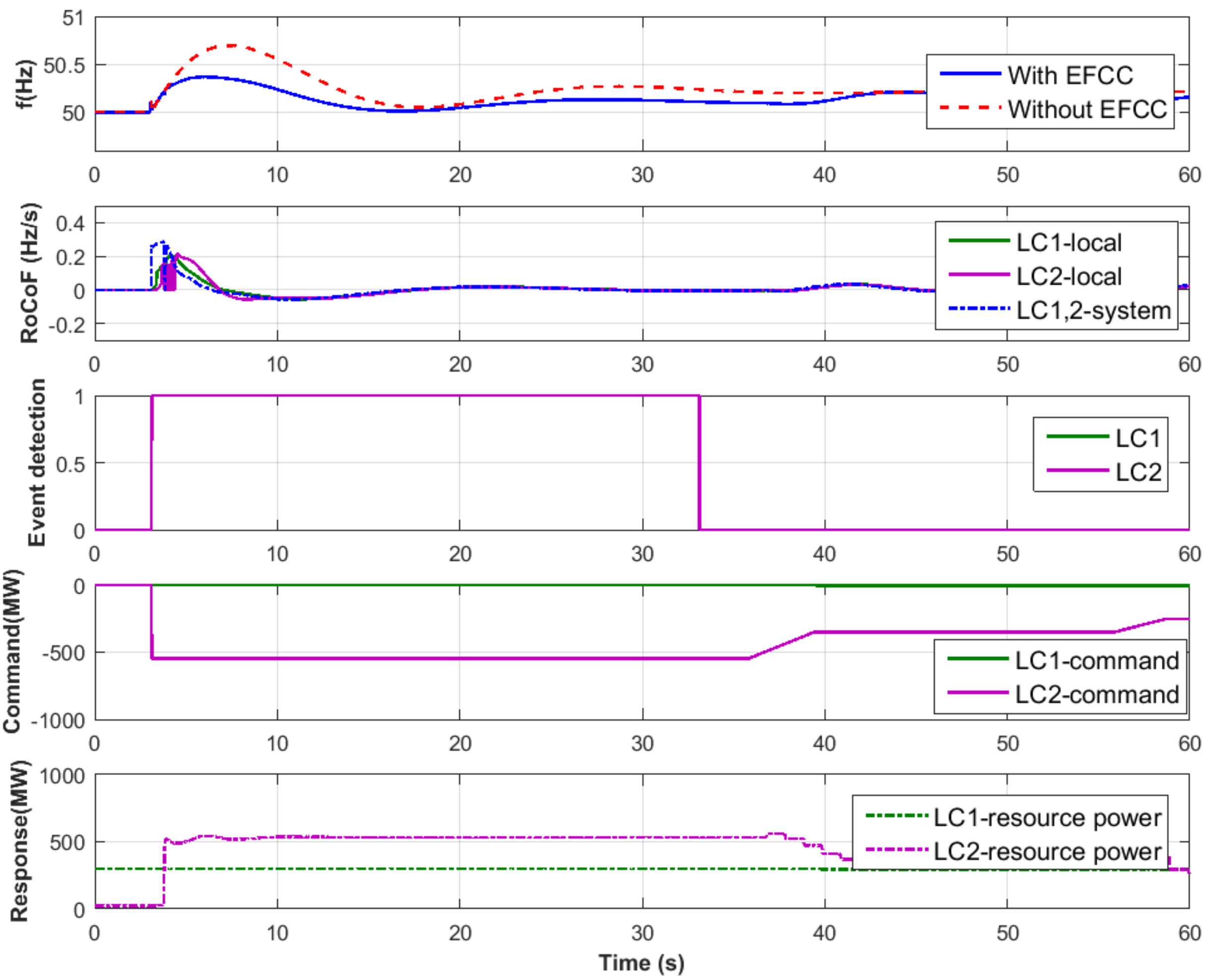

Figure 26. Test 8: over-frequency event test results from LCs

Table 17. Key observations in the over-frequency event in Test 8 with LCs expected responses

Time	Observations
3.10 s	Event occurred
3.14 s	Event detected and LC2 commanded 550 MW negative power.
3.79 s	LC2 resource increased 493 MW demand (from 27 MW to 520 MW)
6.10 s	Frequency reaches peak : 50.37 Hz (50.70 Hz if no EFCC response)

5.2.9 Test 9: 1 GW event in Region 1; LC1: 300 MW in Region 1; LC2: 1 GW in Region 3

In Test 9, the arrangement of the resources and the events are shown in Figure 27. The resources' capacities and locations were the same as in Test 8, but the events were triggered in Region 1.

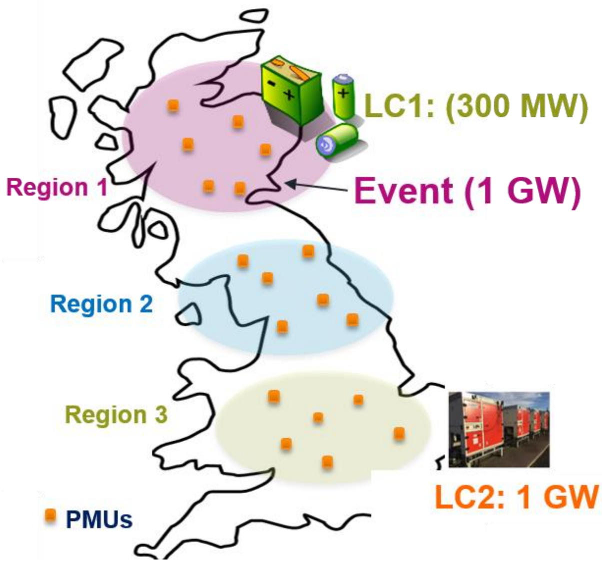

Figure 27. Resource and event location for Test 9

5.2.9.1 Under-frequency event in Test 9

In this test, an under-frequency event was trigged by disconnecting 1 GW infeed in Region 1. The test results are shown in Figure 28 and the key observations are listed in Table 18.

From the test results, it can be seen that LC1 responded 273 MW positive power to the event immediately after the event was detected, while LC2 responded 2 s later following LC1's command. The response from EFCC successfully maintained the frequency above 49.50 Hz.

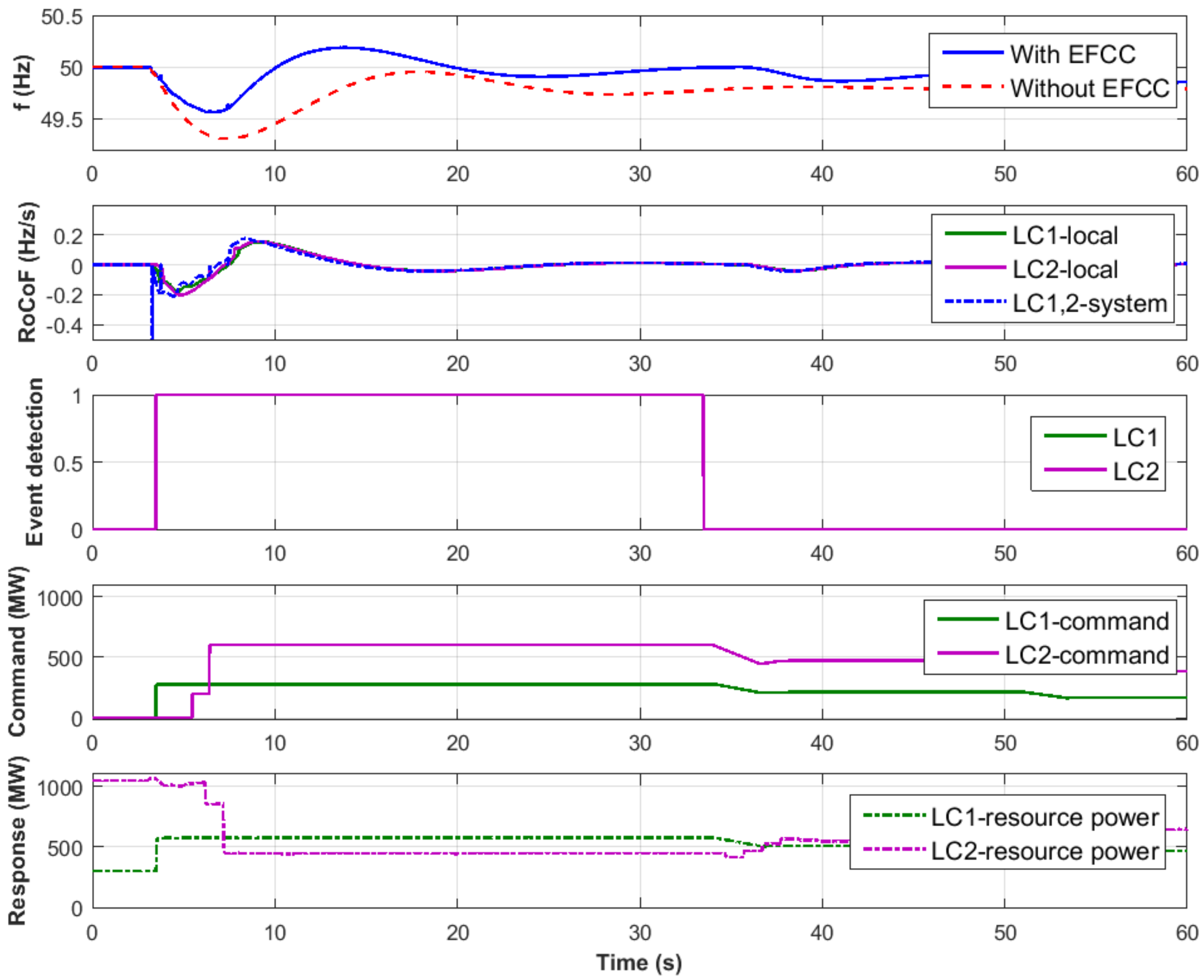

Figure 28. Test 9: under-frequency event test results from LCs

Table 18. Key observations in the under-frequency event in Test 9

Time	Observations
3.08 s	Event occurred
3.20 s	Event detected and LC1 commanded 276 MW positive power
5.32 s	LC2 commanded 600 MW positive power (from 0 MW to 200 MW and then 600 MW)
3.49 s	LC1 increased 273 MW output (from 300 MW to 573 MW)
6.16 s	LC2 reduced 580 MW demand in total (from 1030 MW to 850 and then 450 MW)
6.24 s	Frequency reaches nadir : 49.56 Hz (49.31 Hz if no EFCC response)

5.2.9.2 Over-frequency event in Test 9

In this test, an over-frequency event was trigged by disconnecting 1 GW load in Region 1. The test results are shown in Figure 29 and the key observations are listed in Table 19.

Similar to the under-frequency test in Test 9, LC1 responded faster than LC2 and the frequency was successfully controlled within 50.50 Hz.

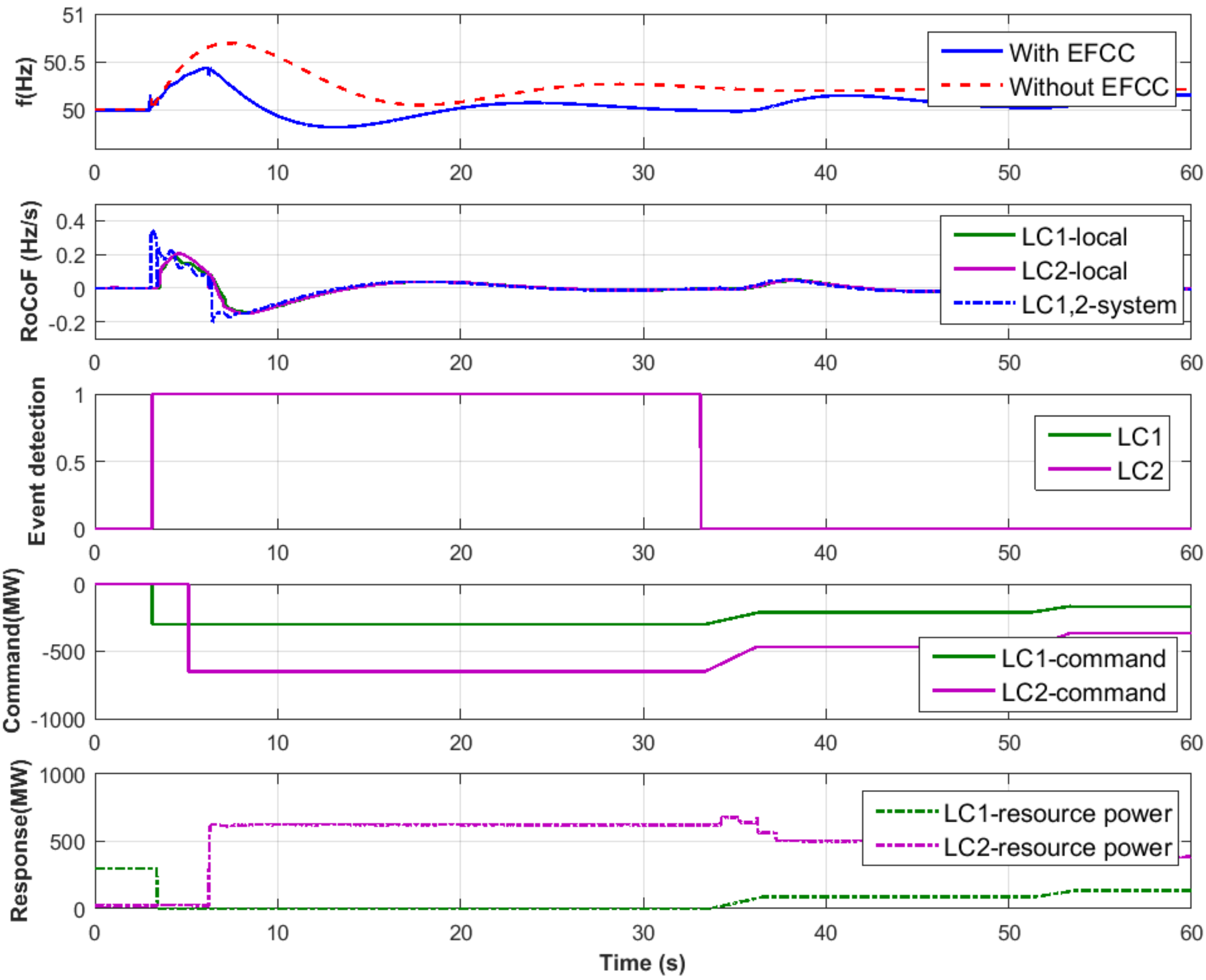

Figure 29. Test 9: over-frequency event test results from LCs

Table 19. Key observations in the over-frequency event in Test 9

Time	Observations
3.08 s	Event occurred
3.20 s	Event detected and LC1 commanded 300 MW negative power.
5.20 s	LC2 commanded 651 MW negative power
3.38 s	LC1 resource decreased 299 MW output (from 299 MW to 0 MW)
6.23 s	LC2 resource increased 604 MW demand (from 21 MW to 625 MW)
6.30 s	Frequency reaches to peak : 50.44 Hz (50.70 Hz if no EFCC response)

5.2.10 Test 10: 1 GW event in Region 3; LC1: 1 GW in Region 1; LC2: 300 MW in Region 3

In Test 10, the arrangement of the resources and the events are shown in Figure 30, where LC1 had a resource with a larger capacity than LC2. The events were triggered in Region 3.

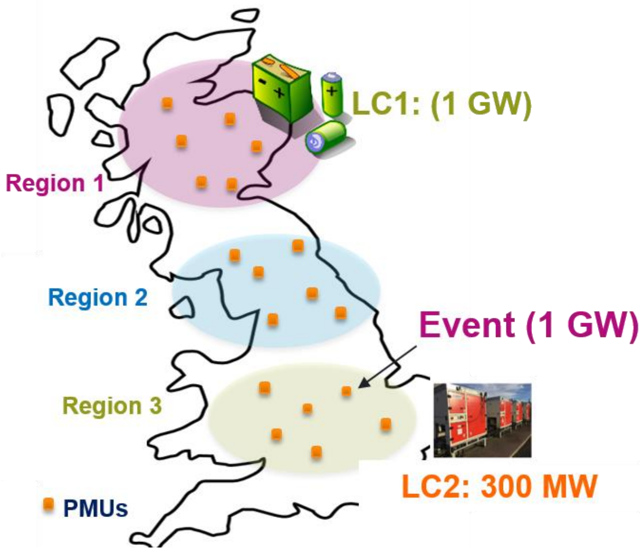

Figure 30. Resource and event location for Test 10

5.2.10.1 Under-frequency event in Test 10

In this test, an under-frequency event was trigged by disconnecting 1 GW infeed in Region 3. The test results are shown in Figure 31 and the key observations are listed in Table 20.

From the test results, it can be seen that LC2 responded to the event immediately when the event was detected, while LC1 responded 2 s later. The EFCC responses successfully raise the nadir from 49.31 Hz to 49.54 Hz, which his above the required limit 49.50 Hz.

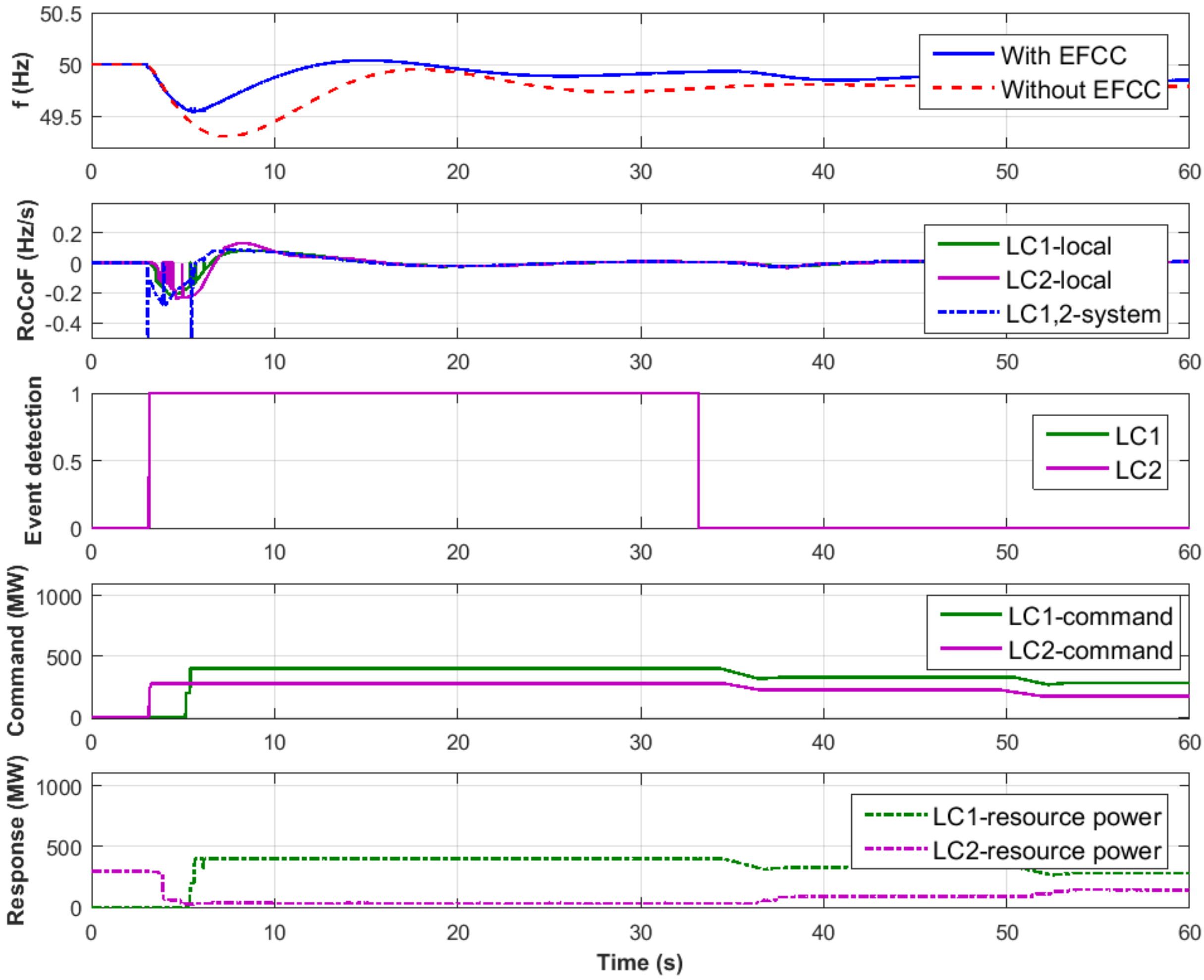

Figure 31. Test 10: under-frequency event test results from LCs

Table 20. Key observations in the under-frequency event in Test 10

Time	Observations
3.08 s	Event occurred
3.18 s	Event detected and LC2 commanded 274 MW positive power
5.18 s	LC1 commanded 400 MW in total (firstly 200 MW and then 400 MW)
3.87 s	LC2 reduced 254 MW demand (from 279 MW to 25 MW)
5.36 s	LC1 increased 400 MW output in total (from 0 MW to 200 MW and then to 400 MW)
5.64 s	Frequency reaches to nadir : 49.54 Hz (49.31 Hz if no EFCC response)

5.2.10.2 Over-frequency event in Test 10

In this test, an over-frequency event was trigged by disconnecting 1 GW of load in Region 3. The test results are shown in Figure 32 and the key observations are listed in Table 21.

Similar to the under-frequency case in Test 10, LC2 responded to the event immediately when the event was detected, while LC1 responded 2 s later. The EFCC responses successfully contained the frequency peak at 50.48 Hz as opposed to 50.57 Hz in the case without EFCC responses.

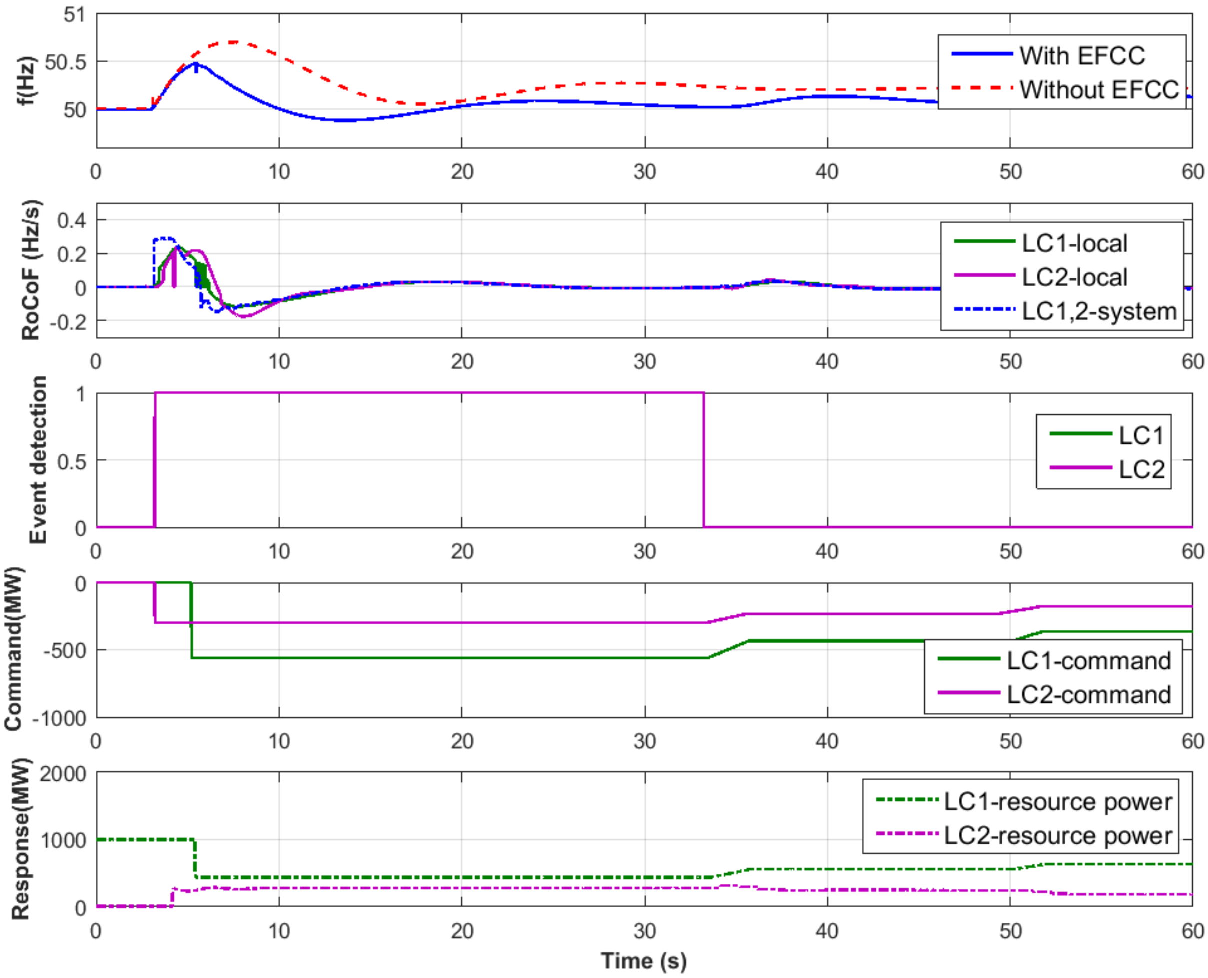

Figure 32. Test 10: over-frequency event test results from LCs

Table 21. Key observations in the over-frequency event in Test 10

Time	Observations
3.06 s	Event occurred
3.20 s	Event detected and LC2 commanded 300 MW negative power
5.20 s	LC1 commanded 560 MW negative power.
4.16 s	LC2 resource increased 259 MW demand (from 8 MW to 267 MW)
5.38 s	LC1 resource decreased 560 MW output (from 997 MW to 437 MW)
5.44 s	Frequency reaches peak : 50.48 Hz (50.70 Hz if no EFCC response)

5.2.11 Test 11: 1 GW event in Region 1; LC1: 1 GW in Region 1; LC2: 300 MW in Region 3

In Test 11, the arrangement of the resources and the events are shown in Figure 33. The resources' capacities and locations were the same as in Test 10, but the events were triggered in Region 1.

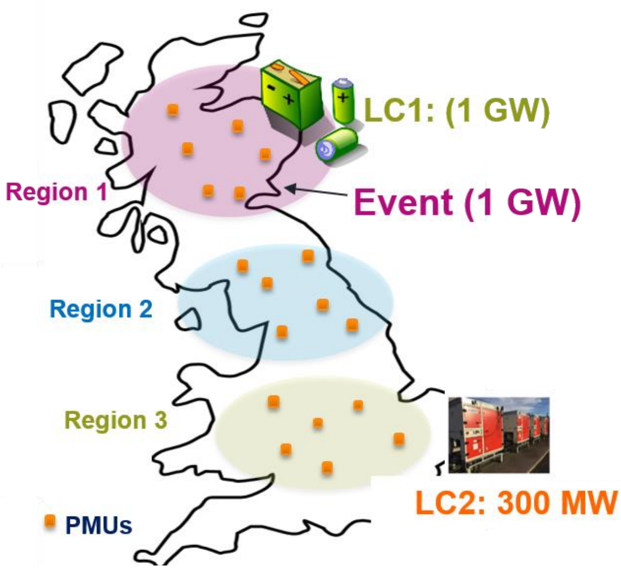

Figure 33. Resource and event location for Test 11

5.2.11.1 Under-frequency event in Test 11

In this test, an under-frequency event was trigged by disconnecting 1 GW infeed in Region 1. The test results are shown in Figure 34 and the key observations are listed in Table 23.

From the test results, it can be seen LC1 responded immediately to the event when it was detected, while LC2 is 2 s slower in commanding the response. LC1 only deployed 415 MW out of 1000 MW and the frequency was successfully maintained above 49.50 Hz.

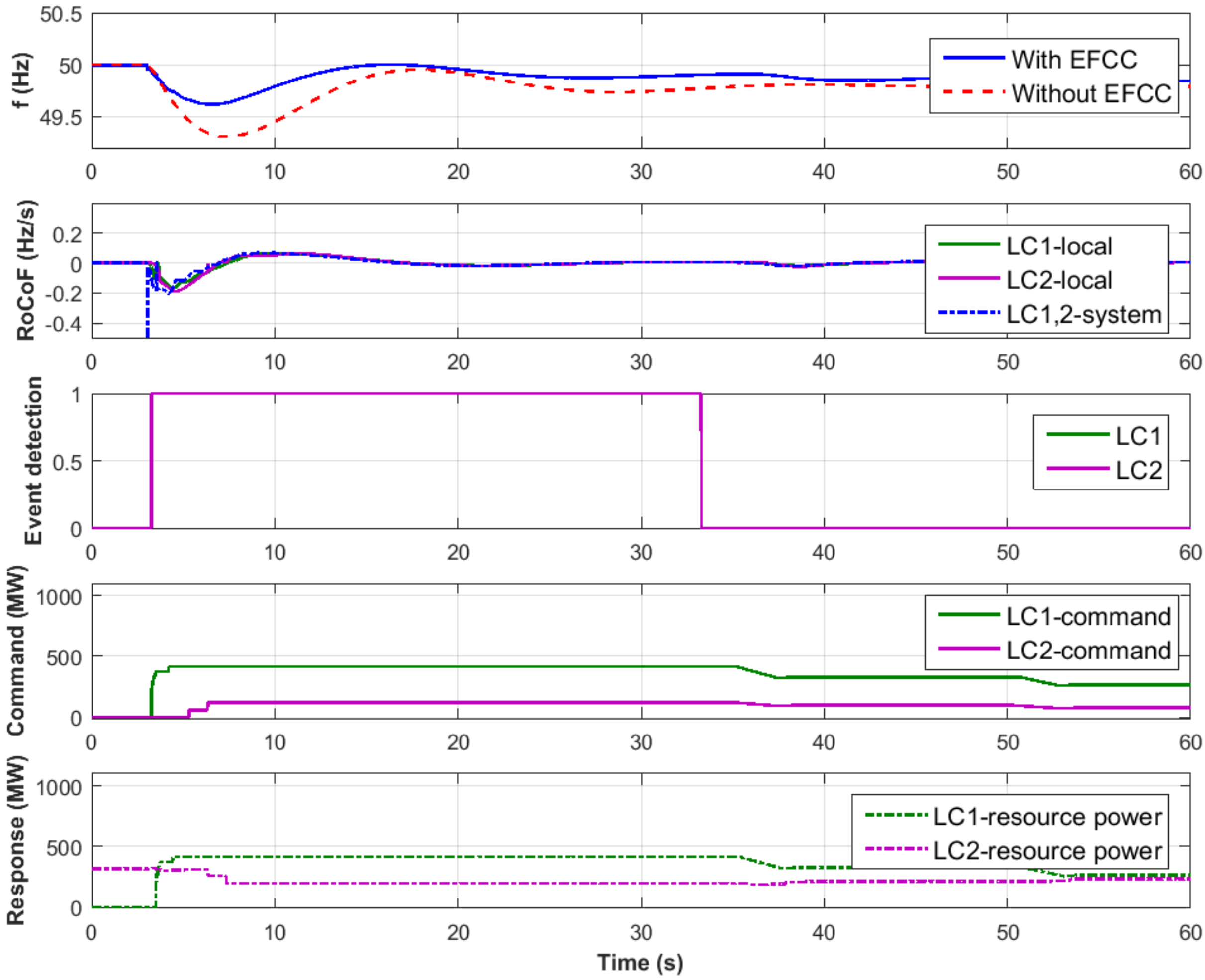

Figure 34. Test 11 under-frequency event test results from LCs

Table 22. Key observations in the under-frequency event in Test 11

Time	Observations
3.08 s	Event occurred
3.32 s	Event detected and LC1 commanded 415 MW positive power in total (firstly 375 MW and then 415 MW)
5.38 s	LC2 commanded 120 MW positive power in total (firstly 60 MW at 5.38 s and then 120 MW at 6.40 s)
3.49 s	LC1 increased 413 MW output (from 0 MW to 373 MW and then 413 MW)
6.34 s	LC2 reduced 116 MW demand in total (from 312 MW to 257 MW and then to 196 MW)
6.82 s	Frequency reaches nadir : 49.62 Hz (49.31 Hz if no EFCC response)

5.2.11.2 Over-frequency event in Test 11

In this test, an over-frequency event was trigged by disconnecting 1 GW load in Region 1. The test results are shown in Figure 35 and the key observations are listed in Table 23.

From the test results, it can be seen that LC1 commanded 667 MW positive power immediately when the event was detected, while the commanded response from LC2 was 300 MW and delayed for 2. The frequency peak was successfully controlled at 50.23 Hz, which is within the 50.50 Hz limit.

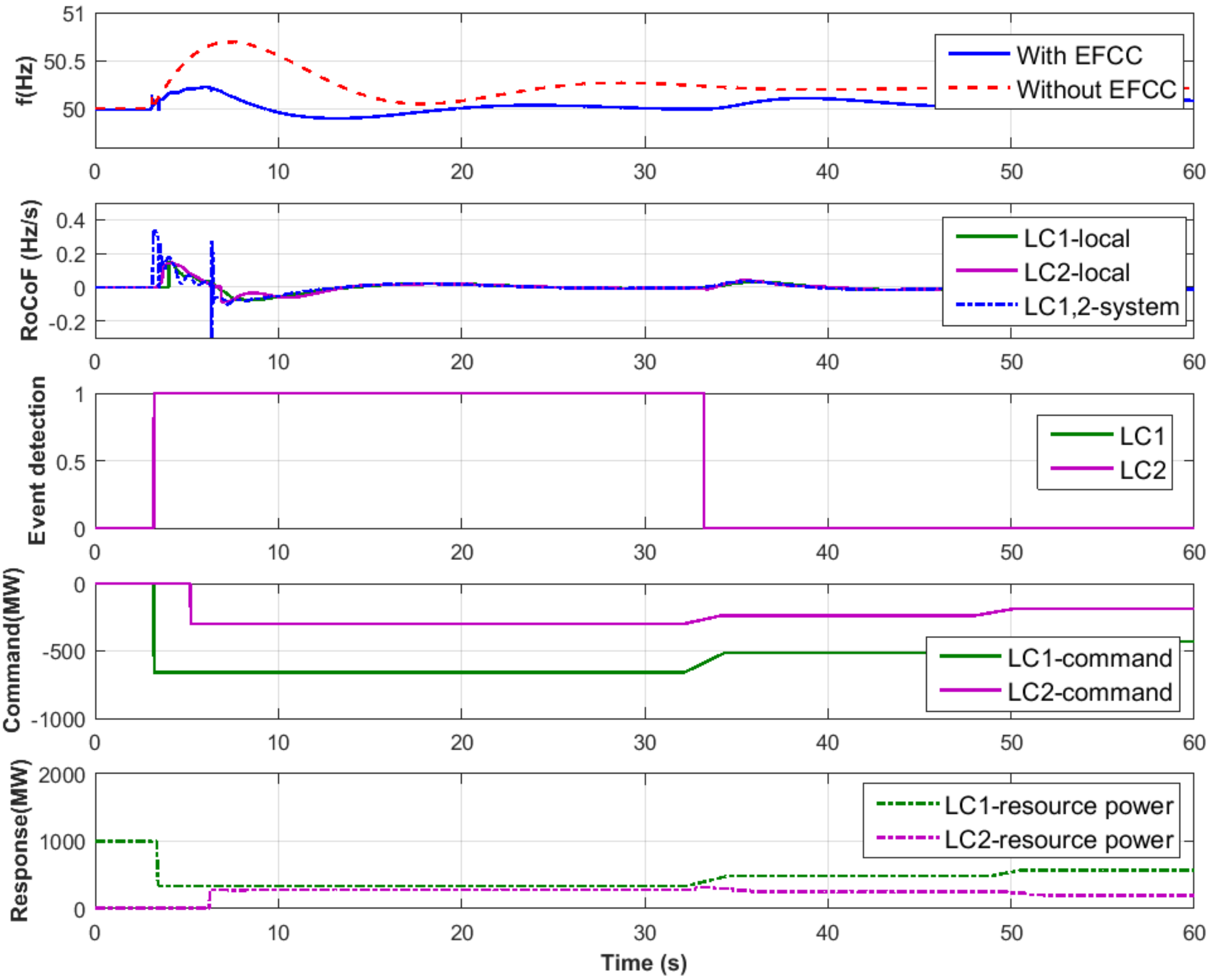

Figure 35. Test 11: over-frequency event test results from LCs

Table 23. Key observations in the over-frequency event in Test 11

Time	Observations
3.06 s	Event occurred
3.20 s	Event detected and LC1 commanded 661 MW negative power.
5.20 s	LC2 commanded 300 MW negative power.
3.38 s	LC1 resource decreased 657 MW output (from 996 MW to 339 MW)
6.23 s	LC2 resource increased 278 MW demand (from 6 MW to 284 MW)
6.00 s	Frequency reaches peak : 50.23 Hz (50.70 Hz if no EFCC response)

5.2.12 Test 12: 1.32 GW event in Region 3; LC1: 1 GW in Region 1; LC2: 1 GW in Region 3

In Test 12, the arrangement of the resources and the events are shown in Figure 36, where the size of the event was increased to 1.32 GW, which is assumed to be the largest generation loss in the GB system [4, 5].

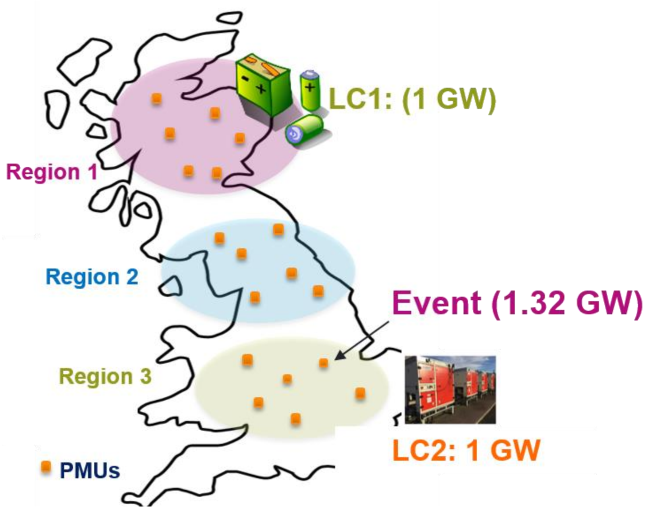

Figure 36. Resource and event location for Test 12

5.2.12.1 Under-frequency event in Test 12

In this test, an under-frequency event was trigged by disconnecting 1.32 GW infeed in Region 3. The test results are shown in Figure 37 and the key observations are listed in Table 24.

From the test results, it can be seen that the increase in the size of power imbalance caused a larger frequency disturbance, with frequency the nadir dropping to 49.08 Hz without EFCC. This violates the 49.2 Hz frequency containment limit.

In this test, LC2 responded to the event immediately when the event was detected, while LC1 responded 2 s later. The frequency nadir was controlled at 49.41 Hz, which is a significant improvement compared with the case without EFCC responses.

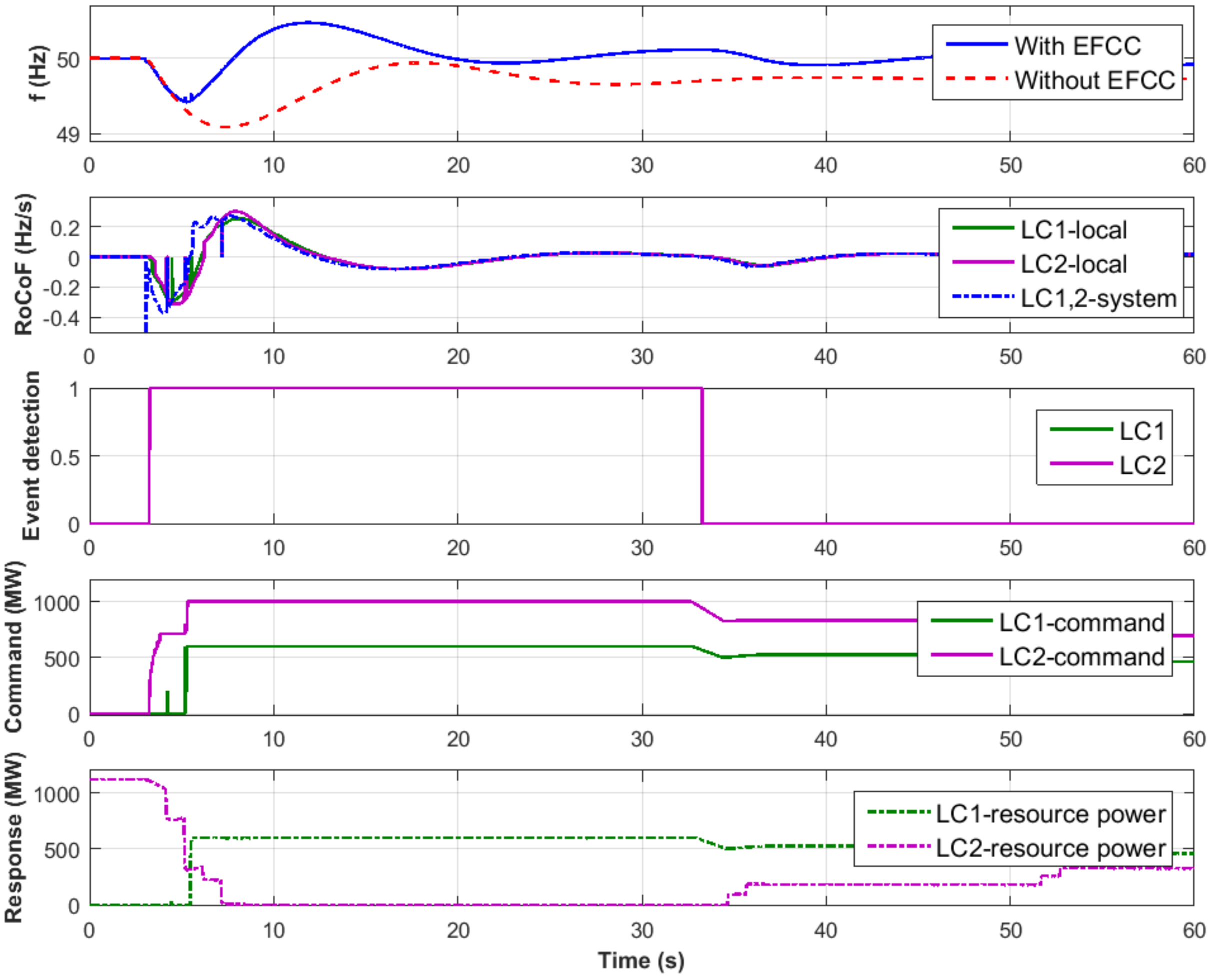

Figure 37. Test 12: under-frequency event test results from LCs

Table 24. Key observations in the under-frequency event in Test 12

Time	Observations
3.08 s	Event occurred
3.28 s	Event detected and LC2 commanded 1000 MW positive power in total (firstly 712 MW and then 1000 MW).
5.20 s	LC1 commanded 600 MW output.
4.13 s	LC2 reduced 1012 MW demand in a number of steps (from 1020 MW to 8 MW).
5.45 s	LC1 increased 600 MW output (from 0 MW to 600 MW)
5.28 s	Frequency reaches nadir : 49.41 Hz (49.08 Hz if no EFCC response)

5.2.12.2 Over-frequency event in Test 12

In this test, an over-frequency event was trigged by disconnecting 1.32 GW load in Region 3. The test results are shown in Figure 38 and the key observations are listed in Table 25.

In this test, LC1 responded immediately to the event when it was detected, while the response from LC2 is negligible. The frequency peak was successfully controlled at 50.49 Hz.

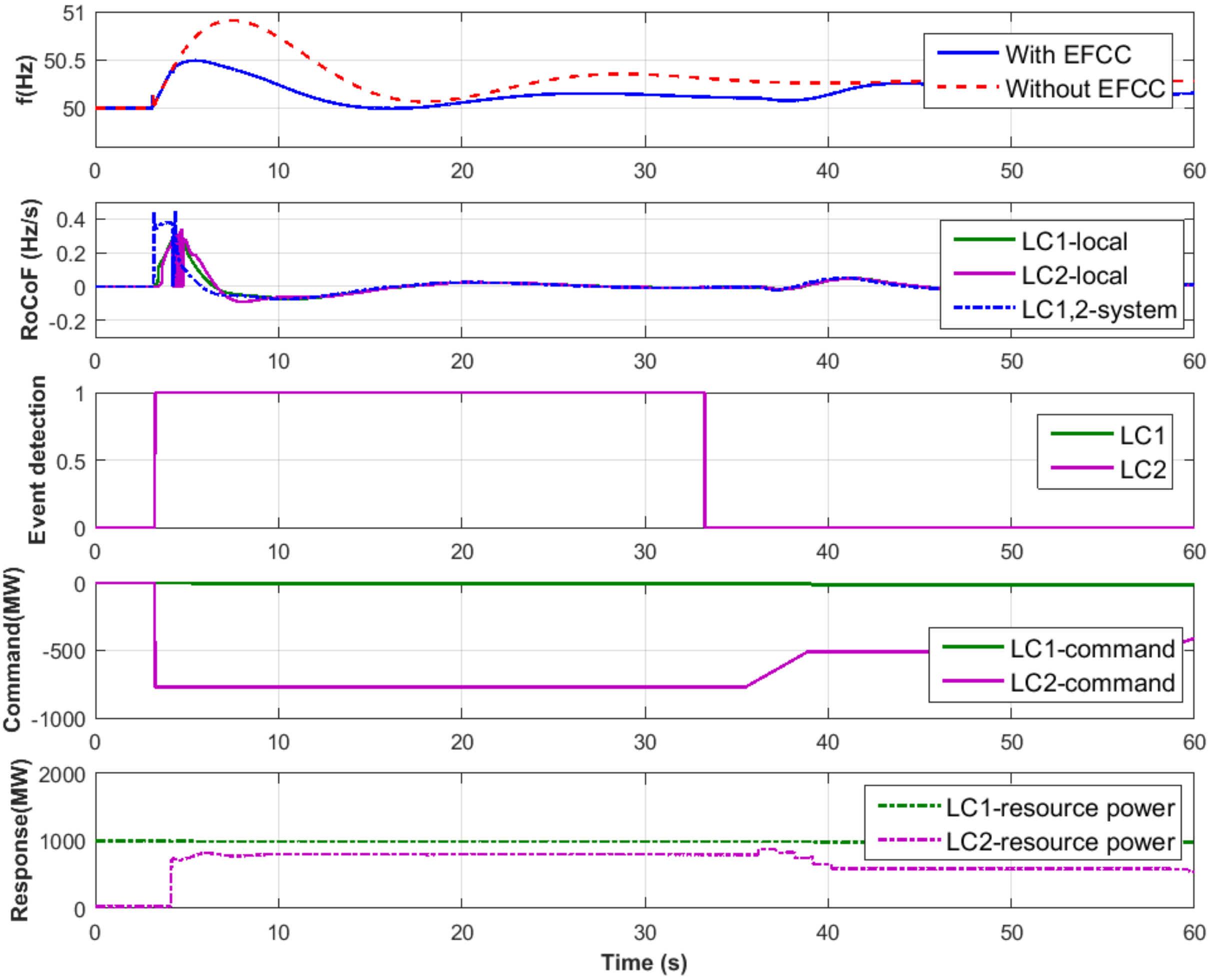

Figure 38. Test 12: over-frequency event test results from LCs

Table 25. Key observations in the over-frequency event in Test 12

Time	Observations
3.14 s	Event occurred
3.28 s	Event detected and LC2 commanded 771 MW negative power
4.11 s	LC2 increased 708 MW demand (from 32 MW to 740 MW)
5.50 s	Frequency reaches peak : 50.49 Hz (50.91 Hz if no EFCC response)

5.2.13 Test 13: 1.32 GW event in Region 1; LC1: 1 GW in Region 1; LC2: 1 GW in Region 3

In Test 13, the arrangement of the resources and the events are shown in Figure 39. The resources' capacities and locations were the same as in Test 12, but the events were triggered in Region 1.

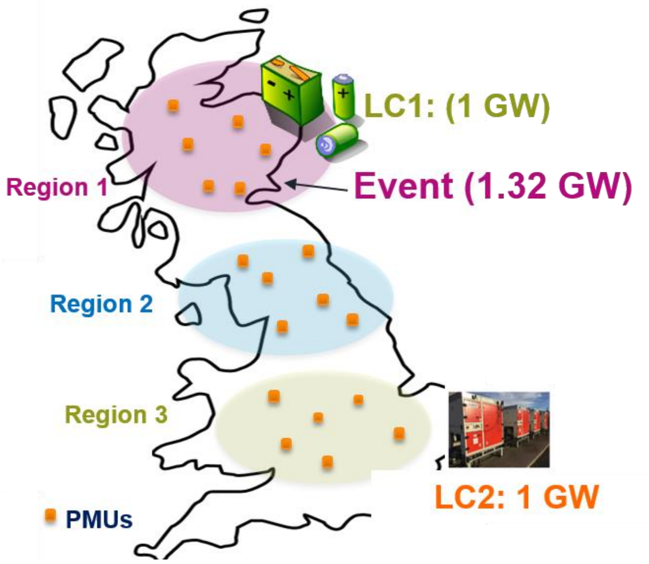

Figure 39. Resource and event location for Test 13

5.2.13.1 Under-frequency event in Test 13

In this test, an under-frequency event was trigged by disconnecting 1.32 GW infeed in Region 1. The test results are shown in Figure 40 and the key observations are listed in Table 26.

From the test results, it can be seen that LC1 responded immediately when the event was detected, while LC2 responded 2 s later. The EFCC response is very effective in controlling the frequency, where the frequency nadir is maintained at 49.51 Hz as opposed to 49.08 Hz in the case without EFCC response. This shows that with a sufficiently fast response and sufficient response capacity, the frequency can be very effectively controlled even during a very large frequency disturbance events in a system with very low inertia (i.e. 82 GVAs).

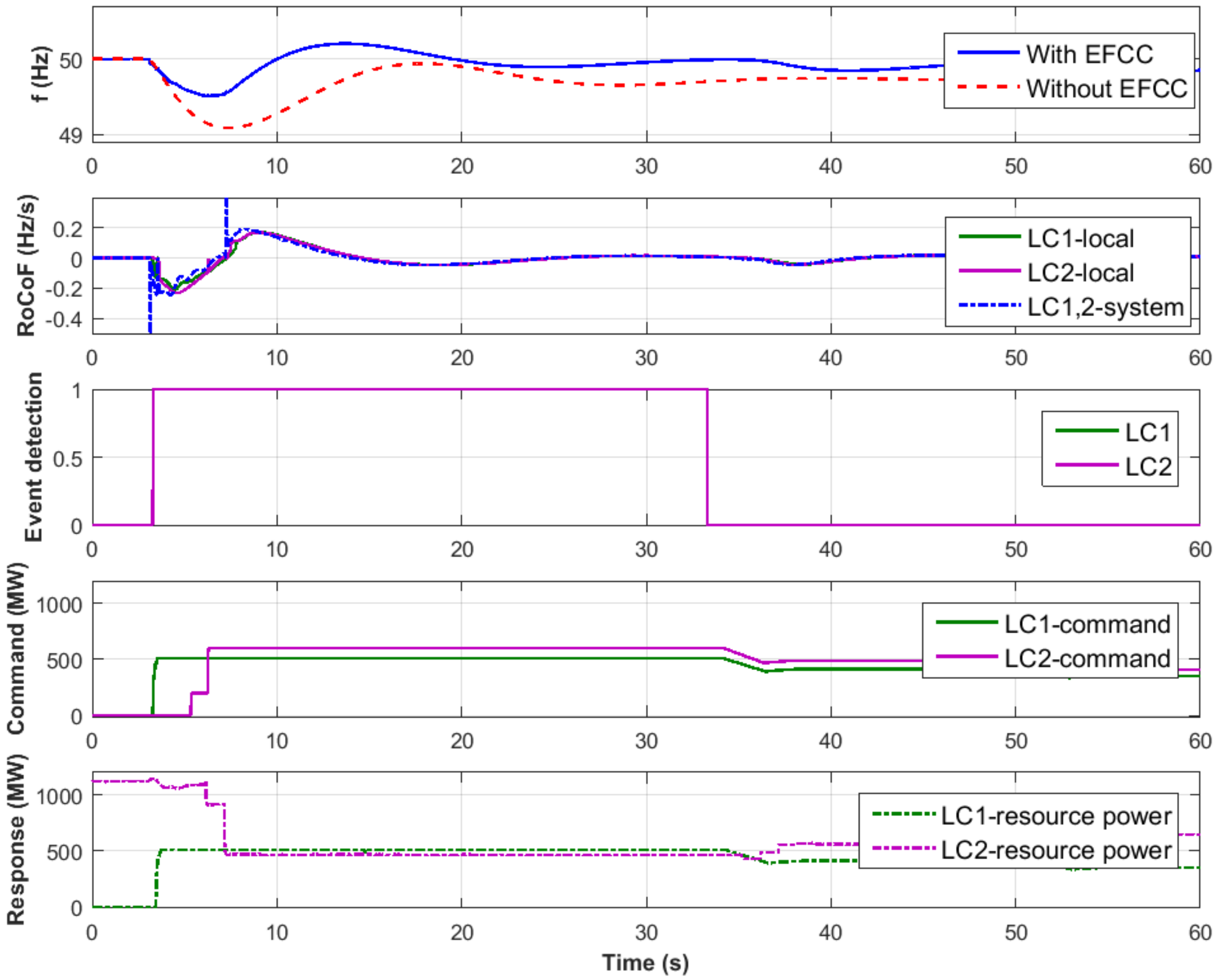

Figure 40. Test 13 under-frequency event test results from LCs

Table 26. Key observations in the under-frequency event in Test 13

Time	Observations
3.08 s	Event occurred
3.28 s	Event detected and LC1 commanded 512 MW positive power
5.34 s	LC2 commanded 600 MW positive power in total (firstly 200 MW and then 600 MW)
3.45 s	LC1 increased 510 MW output (from 0 MW to 510 MW)
6.14 s	LC2 resource decreased 628 MW demand in total (from 1095 MW to 910 MW and then to 467 MW)
5.22 s	Frequency reaches nadir: 49.51 Hz (49.08 Hz if no EFCC response)

5.2.13.2 Over-frequency event in Test 13

In this test, an over-frequency event was trigged by disconnecting 1.32 GW load in Region 1. The test results are shown in Figure 41 and the key observations are listed in Table 27.

Similar to the case in the under-frequency test in Test 13, the EFCC scheme effectively contained the frequency with the frequency peaking at 52.26 Hz as opposed to 50.91 Hz in the case without the EFCC response.

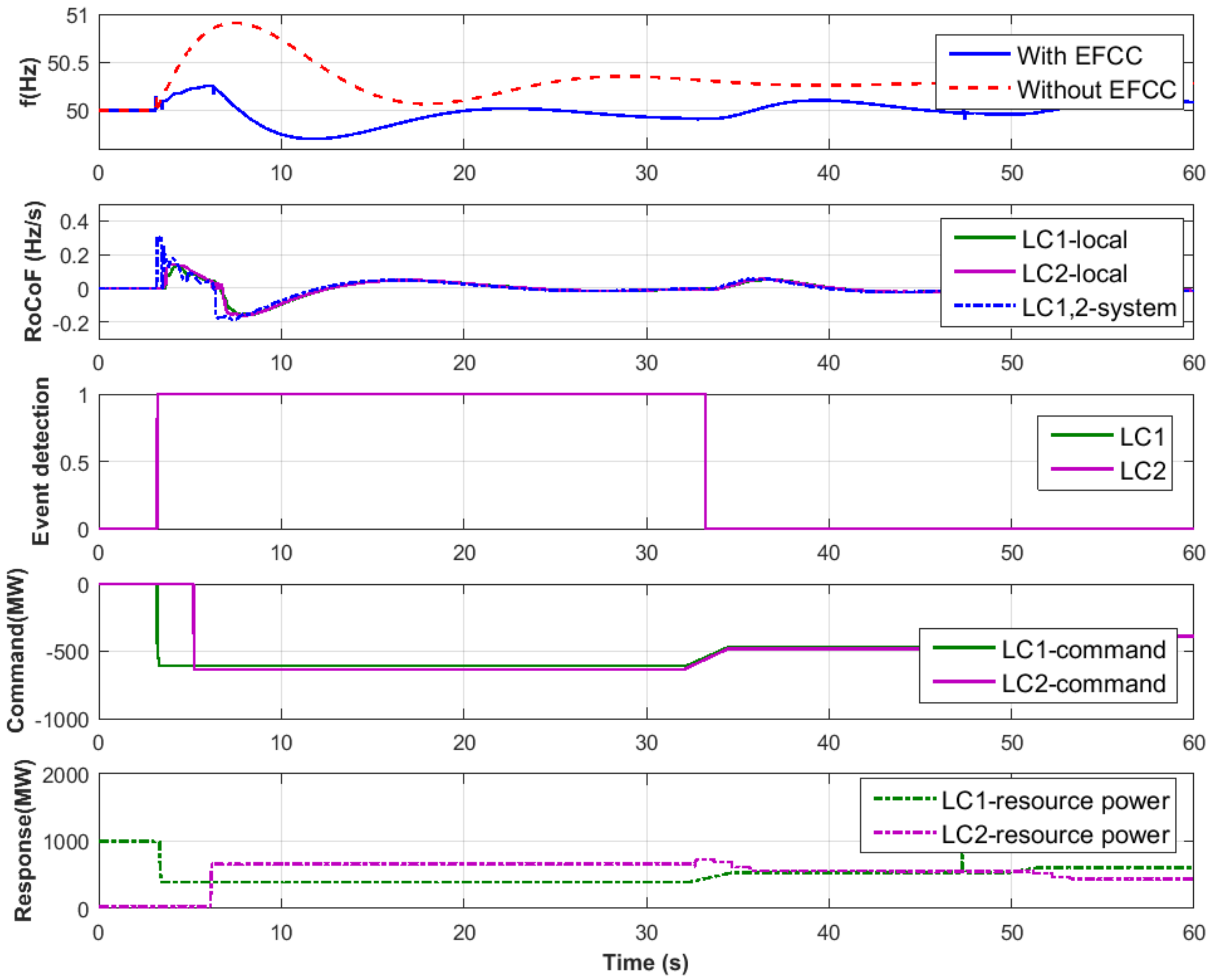

Figure 41. Test 13: over-frequency event test results from LCs

Table 27. Key observations in the over-frequency event in Test 13

Time	Observations
3.14 s	Event occurred
3.22 s	Event detected and LC1 commanded 608 MW negative power
5.22 s	LC2 commanded 634 MW negative power
3.33 s	LC1 resource decreased 605 MW output (from 996 MW to 391 MW)
6.13 s	LC2 resource increased 648 MW demand in total (from 22 MW to 670 MW)
6.22 s	Frequency reaches peak : 50.26 Hz (50.91 Hz if no EFCC response)

5.2.14 Test 14: 1 GW event in Region 1; LC1: 300 MW in Region 2; LC2: 300 MW in Region 3

In Test 14, the arrangement of the resources and the events are shown in Figure 42, where LC1's resource was located in Region 2 and LC2's resource remained in Region 3. The event was triggered in Region 1. This will investigate the impact of changes in resources locations in the EFCC scheme's response and performance.

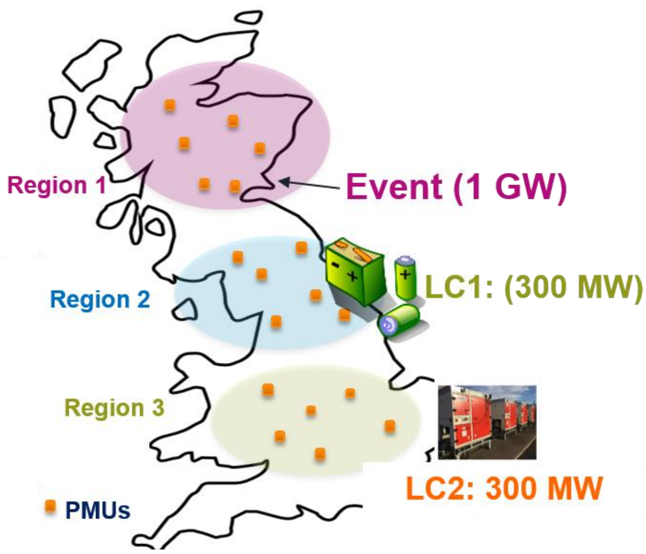

Figure 42. Resource and event location for Test 14

5.2.14.1 Under-frequency event in Test 14

In this test, an under-frequency event was trigged by disconnecting 1GW infeed in Region 1. The test results are shown in Figure 43 and the key observations are listed in Table 28.

In this case, both LC1 and LC2 were not located in the region where the event occurred and they both have 2 s of delay in responding to the event. As a result, the frequency nadir was controlled at 49.41 Hz, which is below the required 49.50 Hz limit. However, compared to the case without the EFCC responses, the frequency nadir was still raised by 0.1 Hz.

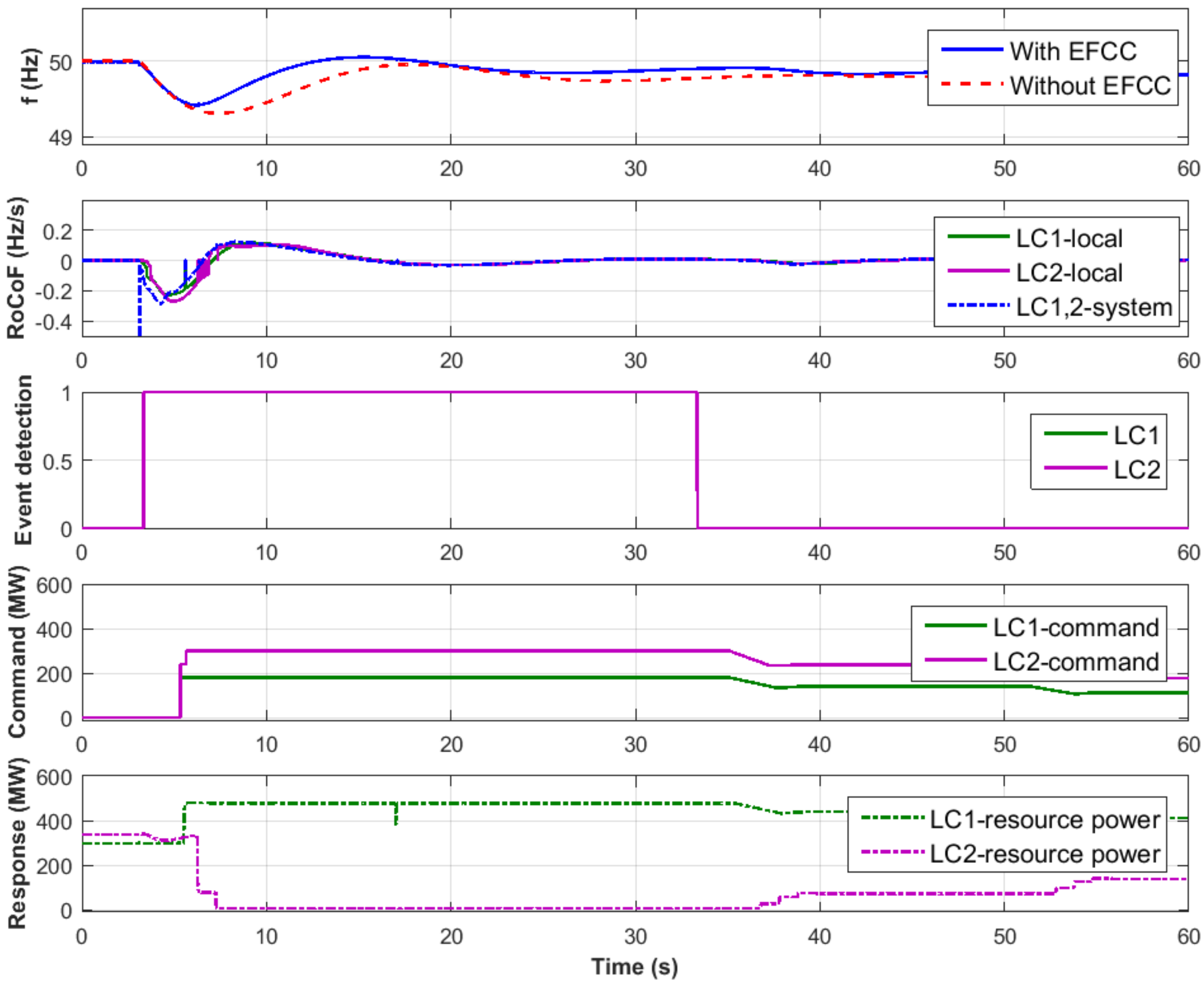

Figure 43. Test 14: under-frequency event test results from LCs

Table 28. Key observations in the under-frequency event in Test 14

Time	Observations
3.08 s	Event occurred
3.32 s	Event detected
5.32 s	LC1 commanded 180 MW positive power. LC2 commanded 240 MW positive power at 5.32 s and then 300 MW at 5.66 s
5.51 s	LC1 increased 180 MW output (from 299 MW to 479 MW)
6.24 s	LC2 reduced 325 MW demand (from 332 MW to 78 MW at 6.24 s and then 7 MW at 7.24 s)
6.30 s	Frequency reaches nadir : 49.41 Hz (49.31 Hz if no EFCC response)

5.2.14.2 Over-frequency event in Test 14

In this test, an over-frequency event was trigged by disconnecting 1 GW load in Region 1. The results and key observations are presented in Figure 44 and Table 29 respectively. Due to under-frequency test, LC1 and LC2 both delayed 2 s responding as they are not located in the region where the event occurred. As a results, the EFCC responses only controlled the frequency peak at 50.55 Hz. which is above the required 50.50 Hz limit. However, compared to the case without the EFCC responses, the frequency peak was still reduced by 0.15 Hz.

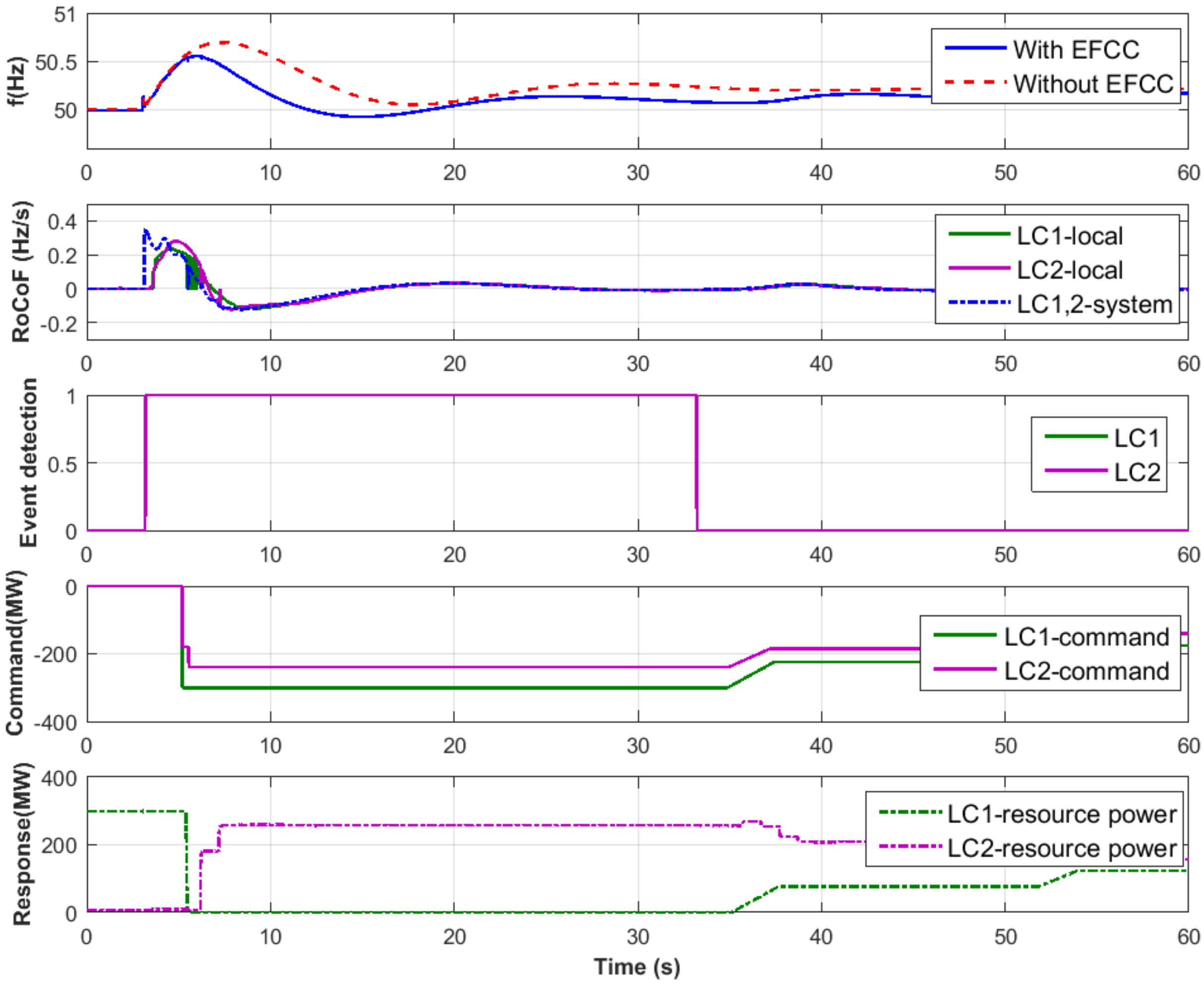

Figure 44. Test 14: over-frequency event test results from LCs

Table 29. Key observations in the over-frequency event in Test 14

Time	Observations
3.08 s	Event occurred
3.22 s	Event detected
5.22 s	LC1 commanded 300 MW and LC2 commanded 240 MW negative power
5.39 s	LC1 resource decreased 300 MW output (from 300 MW to 0 MW)
6.18 s	LC2 resource increased 252 MW demand (from 7 MW to 181 MW at 6.24 s and then 259 MW at 7.18 s)
6.06 s	Frequency reaches peak : 50.55 Hz (50.70 Hz if no EFCC response)

5.2.15 Test 15: 1 GW event in Region 1; LC1: 300 MW in Region 3; LC2: 300 MW in Region 3

In Test 15, the arrangement of the resources and the events are shown in Figure 46, where both LC1 and LC2's resources were located in Region 3. The event was triggered in Region 1. This also aims to investigate the impact of changes in resources locations on the EFCC scheme's response and performance.

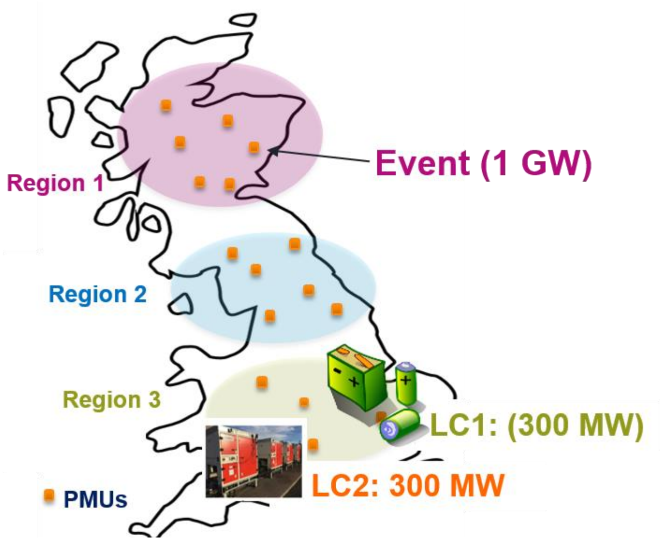

Figure 45. Resource and event location for Test 19

5.2.15.1 Under-frequency event in Test 15

In this test, an under-frequency event was trigged by disconnecting 1 GW infeed in Region 1. The test results are shown in Figure 46 and the key observations are listed in Table 30.

In this case, both LC1 and LC2 were not located in the region where the event occurred and they both have 2 s of delay in responding to the event. As a result, the frequency was not effectively contained and fell to 49.43 Hz, which is below the required 49.50 Hz limit. However, compared to the case without the EFCC responses, the frequency nadir was still raised by 0.12 Hz.

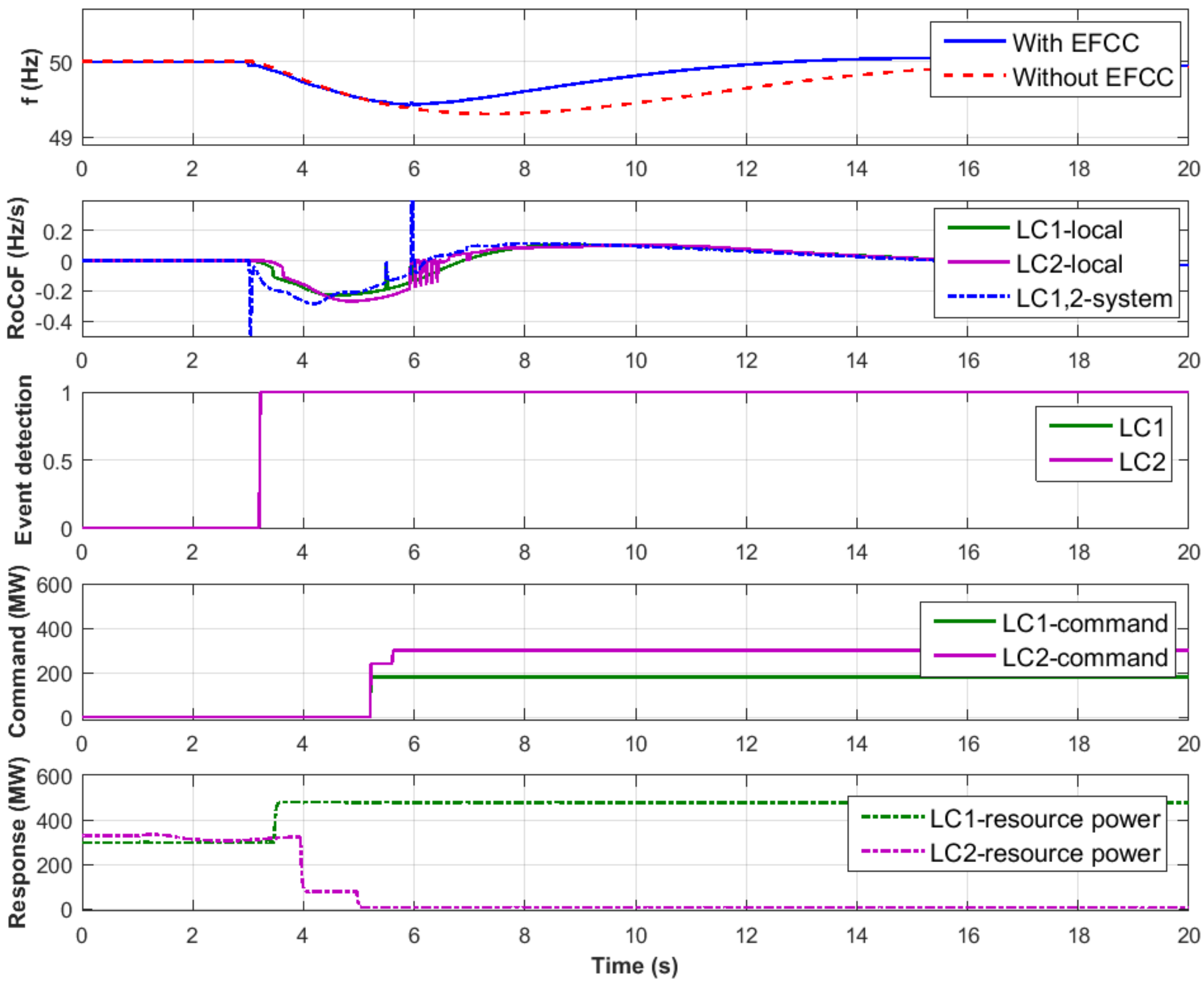

Figure 46. Test 15: under-frequency event test results from LCs

Table 30. Key observations in the under-frequency event in Test 15

Time	Observations
1.08 s	Event occurred
1.30 s	Event detected
3.30 s	LC1 commanded 180 MW positive power. LC2 commanded 240 MW positive power at 3.30 s and then 300 MW at 3.70 s
3.47 s	LC1 increased 179 MW output (from 300 MW to 479 MW)
3.94 s	LC2 reduced 297 MW demand (from 325 MW to 78 MW at 3.94 s and then 8 MW at 4.96 s)
4.02 s	Frequency reaches nadir : 49.43 Hz (49.31 Hz if no EFCC response)

5.2.15.2 Over-frequency event in Test 15

In this test, an over-frequency event was triggered by disconnecting 1 GW load in Region 1. The test results are shown in Figure 47 and the key observations are listed in Table 31.

Similar to the case in the under-frequency test in Test 15, both LCs were located in different regions from where the event occurred so they had 2 s delay in responding to the event. As a results, the EFCC responses only controlled the frequency peak at 50.55 Hz. which is above the required 50.50 Hz limit. However, compared to the case without the EFCC responses, the frequency peak was still reduced by 0.15 Hz.

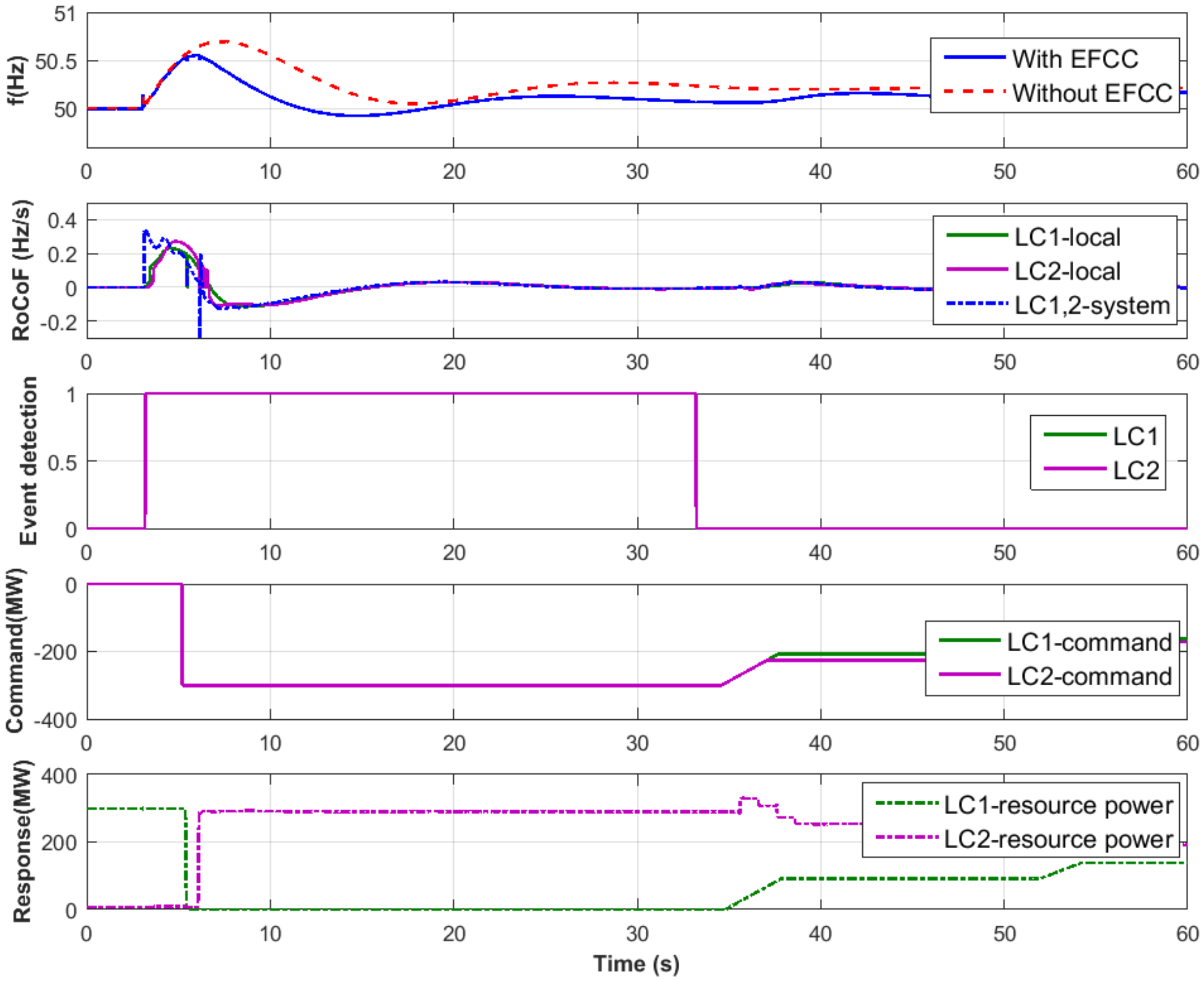

Figure 47. Test 15: over-frequency event test results from LCs

Table 31. Key observations in the over-frequency event in Test 15

Time	Observations
3.06 s	Event occurred
3.20 s	Event detected
5.20 s	LC1 and LC2 both commanded 300 MW negative power
5.38 s	LC1 resource decreased 299 MW output (from 299 MW to 0 MW)
6.07 s	LC2 resource increased 281 MW demand (from 7 MW to 290 MW)
6.05 s	Frequency reaches peak: 50.55 Hz (50.70 Hz if no EFCC response)

5.3 Analysis of the frequency test results

This subsection will analyse the test results presented in Section 5.2 to evaluate the impact of the event location on the EFCC scheme's behaviour; the impact of the resources' locations on the EFCC performance; and the capacities of the resources being controlled by the LCs on the effectiveness of frequency restoration.

5.3.1 Impact of the event location on the EFCC scheme's behaviour

In Test 1 and Test 3, LC1 and LC2 had the same resource locations and resource capacities but with events triggered in different regions. The resources and the events' information for these two tests are shown in Figure 48.

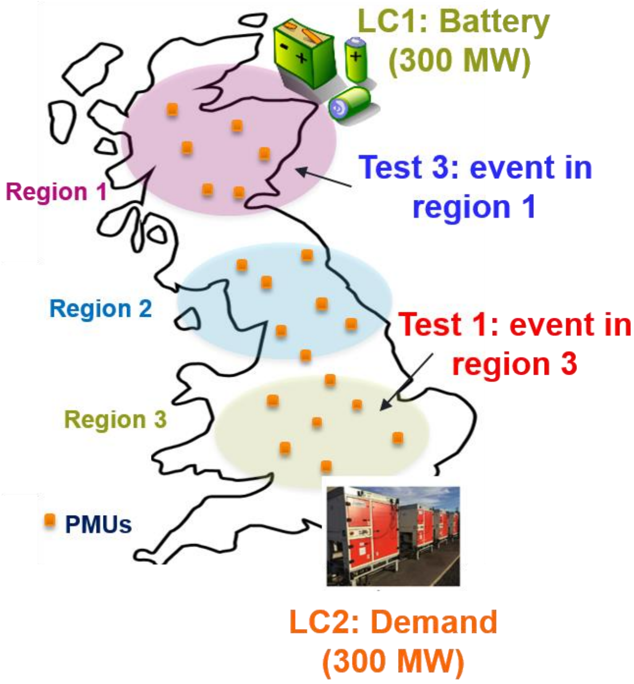

Figure 48. Resources and event information in Test 1 and Test 3

The comparison of the results from under-frequency tests is shown in Figure 49. It can be seen that, for the same amount of power imbalance, the EFCC scheme will react differently to the event if it is located in different regions of the network. The resource located in the region where the event occurred will responded faster than the resources located in other regions – in this test configuration, LC1 in Test 3 responded faster than LC2 in Test 1. This reveals the need to take the event locations into account when planning the EFCC resource locations.

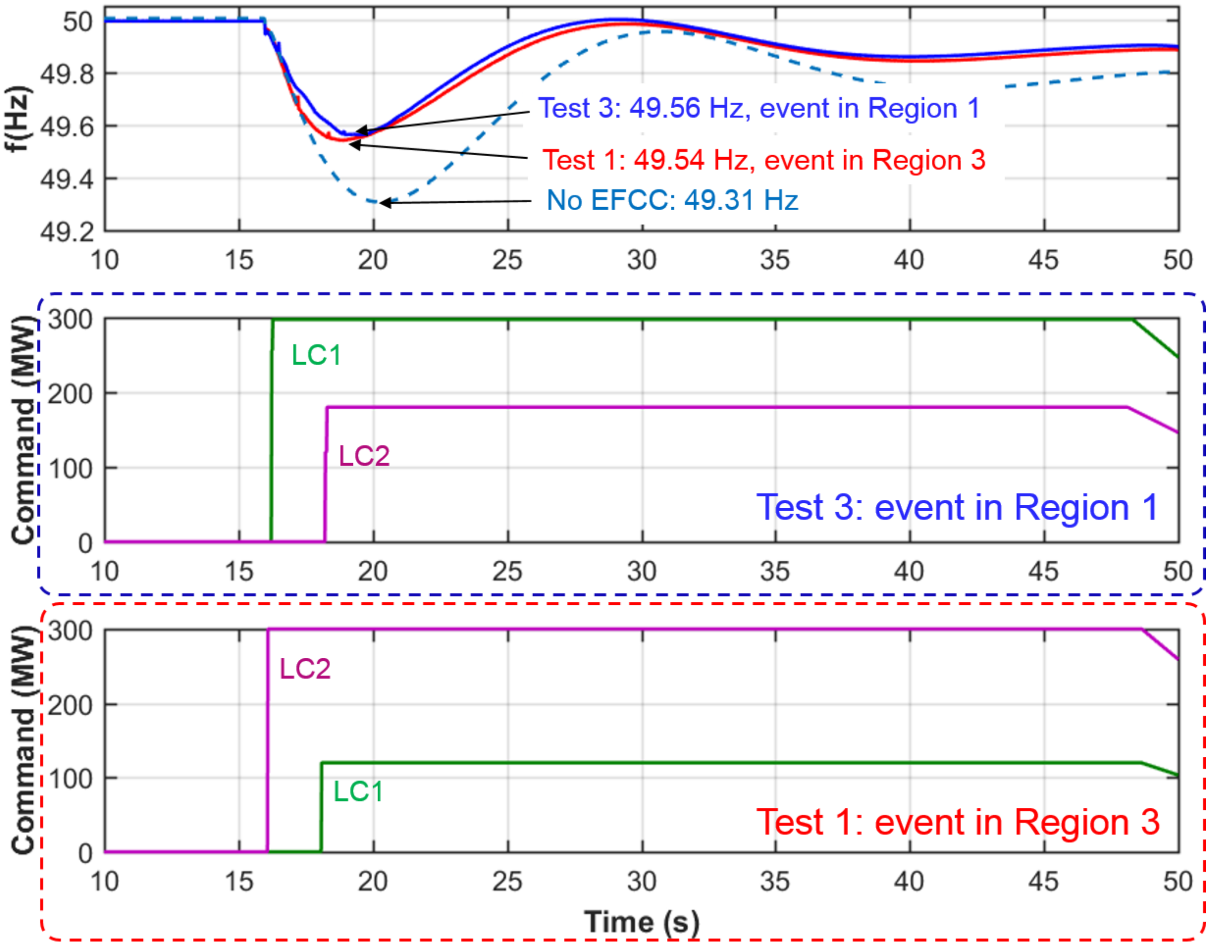

Figure 49. Comparison of under-frequency test results in Test 1 and Test 3

5.3.2 Impact of resource locations on EFCC's behaviour

In Test 5, 14 and 15, the same 1 GW loss of infeed event was triggered in Region 1 and LC 2 was kept in Region 3 in all three tests. However, as shown in Figure 50, LC1 and its resource was placed in Region 1, 2 and 3 respectively. This aims at investigating the resource locations' impact on the EFCC scheme's decision making and the associated frequency restoration performance.

The comparison of the under-frequency test results from these three tests are shown in Figure 51. It can be seen that, only in Test 5, there is a resource located in the region where the event occurred and LC1 responded immediately when the event was detected. In the other two tests, both resources delayed their response by 2 s. As a result, the frequency restoration is most effective in Test 5.

This shows that, for the same event, when the resources were placed in different regions, the decision made by EFCC will be different. According to the EFCC design specification [1], "*the scheme aims to distribute the response across a system targeting the regions most affected first before bringing in additional control from remaining regions if required*", therefore, the LC in the region where the event occurred (also the region most affected by the event) is expected to respond faster than the resources placed in other regions. From Test 5, 14 and 15, the results align well with the design specifications, i.e. LC1 in Region 1 responded first to the event occurred in the same region.

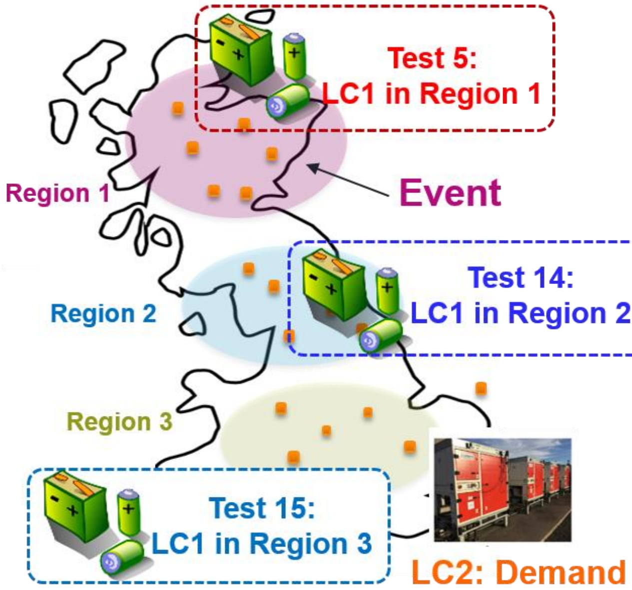

Figure 50. Resources and event information for Test 5, 14 and 15

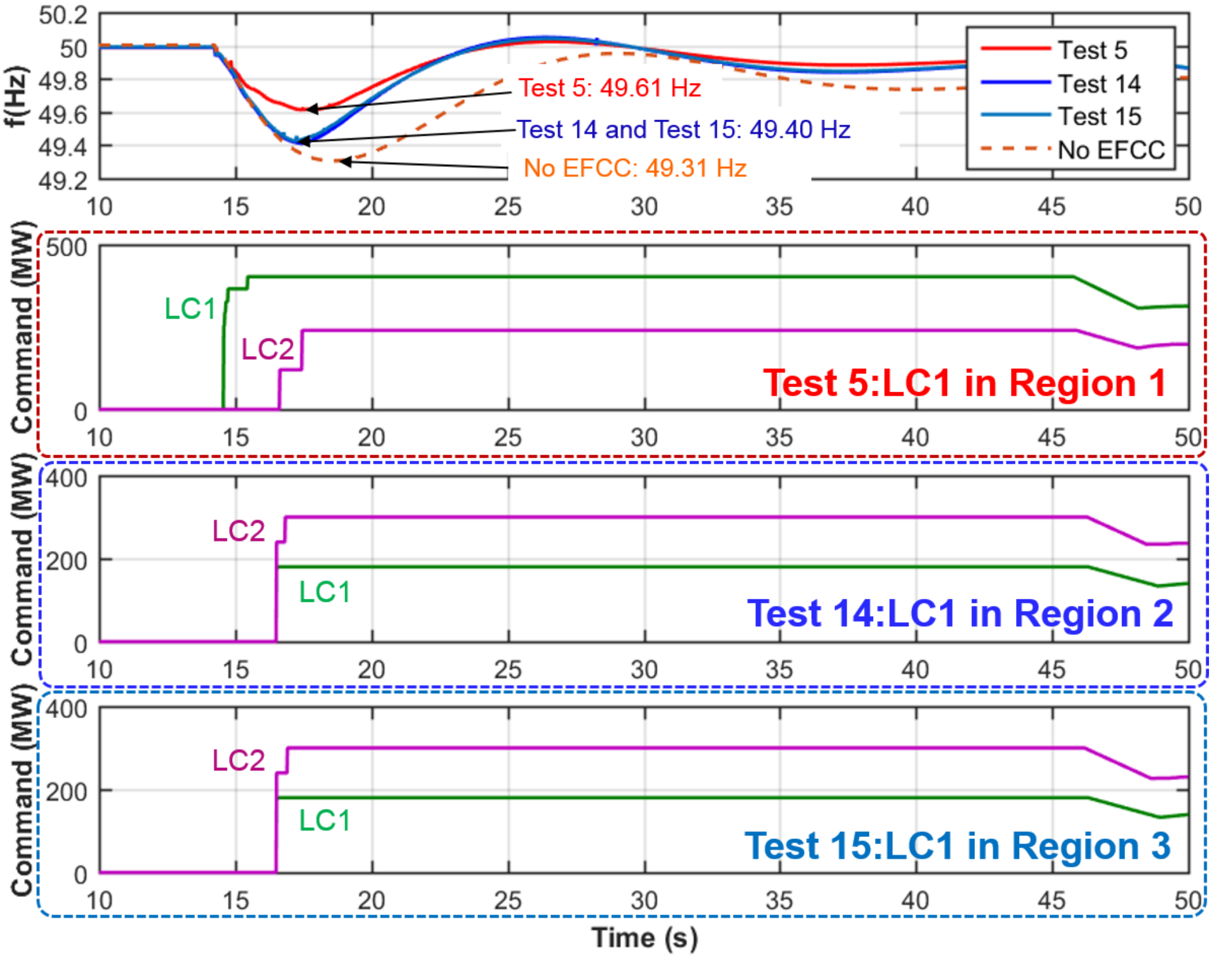

Figure 51. Comparison of under-frequency tests in Test 5, 14 and 15

5.3.3 Impact of resource capacities on the frequency restoration performance

In Test 3, 5 and 7, the same 1 GW loss of infeed event was triggered in Region 1 and the location of both resources were in regions 1 and 3 as shown in Figure 52. However, the capacities of the two resources were gradually increased to investigate how such changes will affect the EFCC scheme's decision making and the associated frequency restoration performance.

The comparison of the under-frequency test results from these three tests are shown in Figure 53. It can be seen that, the timings of the resource deployment from these two LCs did not have obvious change in these three tests. As the capacities increased from 300 MW to 1000 MW, the increase in the commanded power by LC1 (located in the same region as the event) was not significant (only increased by less than 200 MW). The frequency nadirs in these tests are all successfully maintained above 49.50 Hz, but did not have significant improvement with the increase of EFCC capacity. This shows that there is potential to optimise the amount of EFCC responses, so that they can effectively contain the frequency at the required level, while minimising the EFCC reserve power needed.

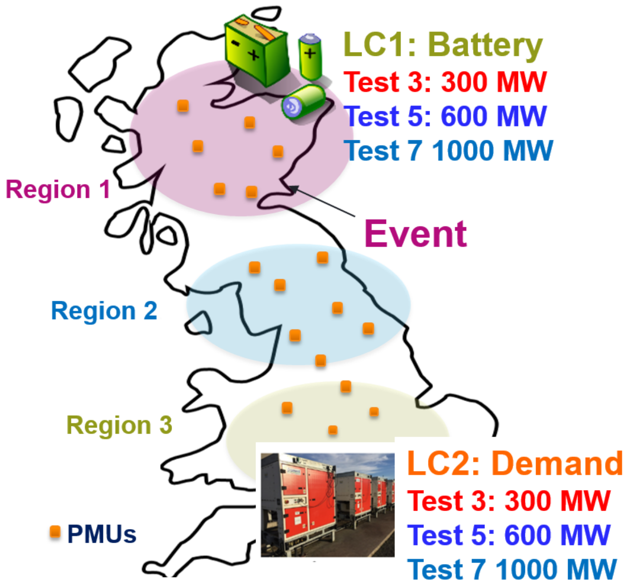

Figure 52. Resources and event information for Test 3, 5 and 7

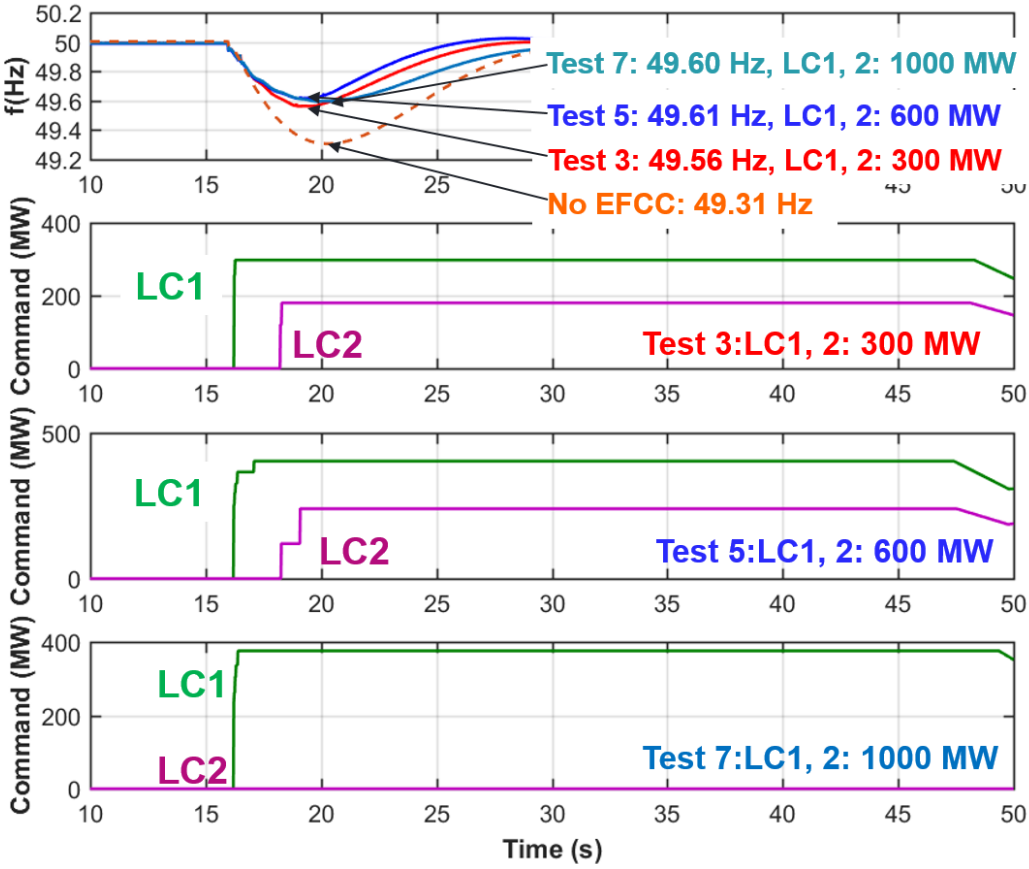

Figure 53. Comparison of under-frequency tests in Test 3, 5 and 7

6 EVALUATION OF THE SECURITY OF THE EFCC SCHEME

In this section, the results of the tests for evaluating the EFCC scheme's security during fault events will be presented. These tests are conducted while the system is operating in wide-area mode, so the fault detection function was performed by the RAs (whereas in local mode the fault detection function is carried out by the LCs), which receive real time measurements from virtual PMUs in the RTDS model. The faults are applied in simulation.

The faults are be applied in all three regions, and include Ph-E, Ph-Ph and 3Ph-E faults. The GB transmission network model in RTDS is a simplified model, so the impact of the fault on the equivalent lines in the network model is relatively large compared to a fault in an actual line in the real system. In these tests, the fault impedance and duration are chosen as 3 Ω and 80 ms respectively, which aim to emulate severe fault conditions while avoiding causing system instability. The fault detection voltage threshold (a setting in the RA) was set to 80% in all cases.

6.1 Tests results for faults in Region 1

In Region 1, the faults are applied at the location shown in Figure 54.

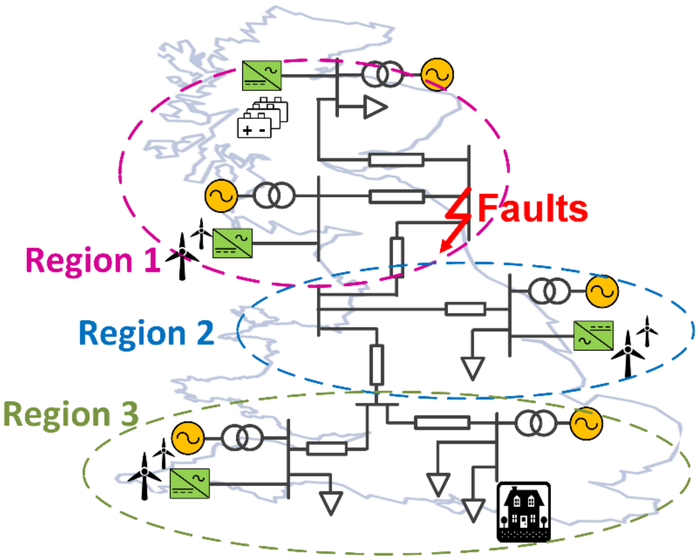

Figure 54. Location of faults in Region 1

6.1.1 Test Fault-R1-Ph-E: Ph-E fault in Region 1

In this test, a Ph-E fault was applied in Region 1 and the test results are shown in Figure 55. It can be seen that the fault caused significant variation in frequency. The fault was successfully detected by RA1 and RA2, while RA3 did not detect the fault as it was furthest away from Region 3 and did not violate the voltage threshold.

It should be noted that the event detection flag also became high at the same time when the fault was detected – this should not be the case. However, as specified, the LCs did not deploy any response.

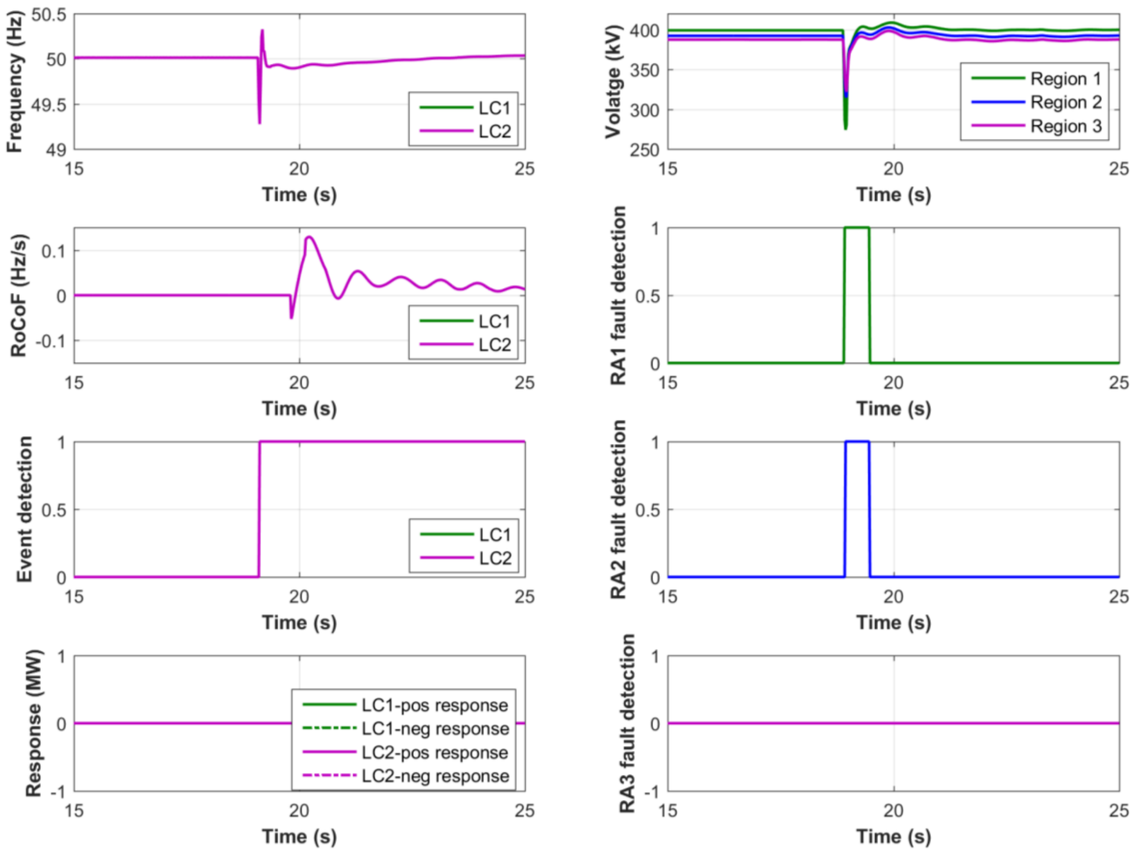

Figure 55. Test results for a Ph-E fault in Region 1

6.1.2 Test Fault-R1-Ph-Ph: Ph-Ph fault in Region 1

In this test, a Ph-Ph fault was applied in Region 1 and the test results are shown in Figure 56. The fault was successfully detected by all three RAs and the LCs did not detect the fault as an event and did not deploy any resource, which is in accordance with the design specification.

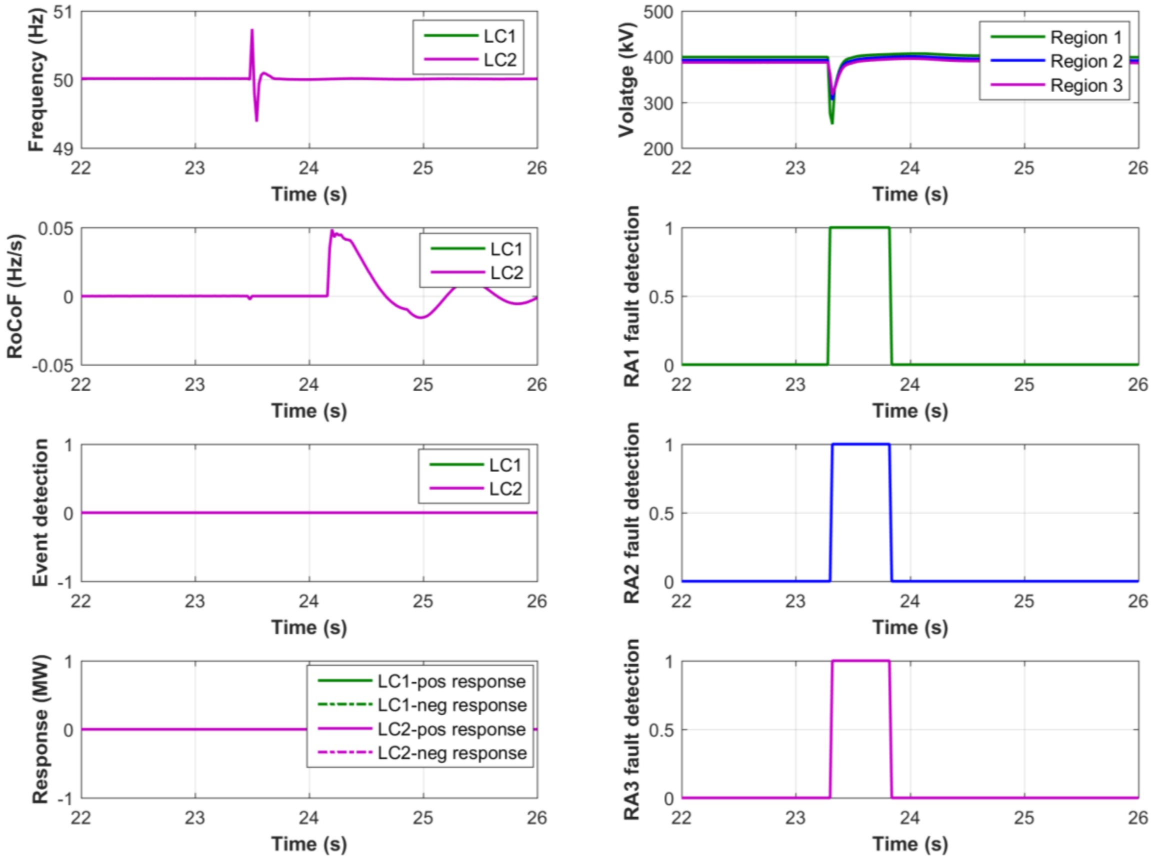

Figure 56. Test results for a Ph-Ph fault in Region 1

6.1.3 Test Fault-R1-3Ph-E: 3Ph-E fault in Region 1

In this test, a 3Ph-E fault was applied in Region 1 and the test results are shown in Figure 57. The fault was successfully detected by all three RAs, but the LCs also detected the fault as an event. No resources were deployed to respond to the fault, which is accordance with the design specification.

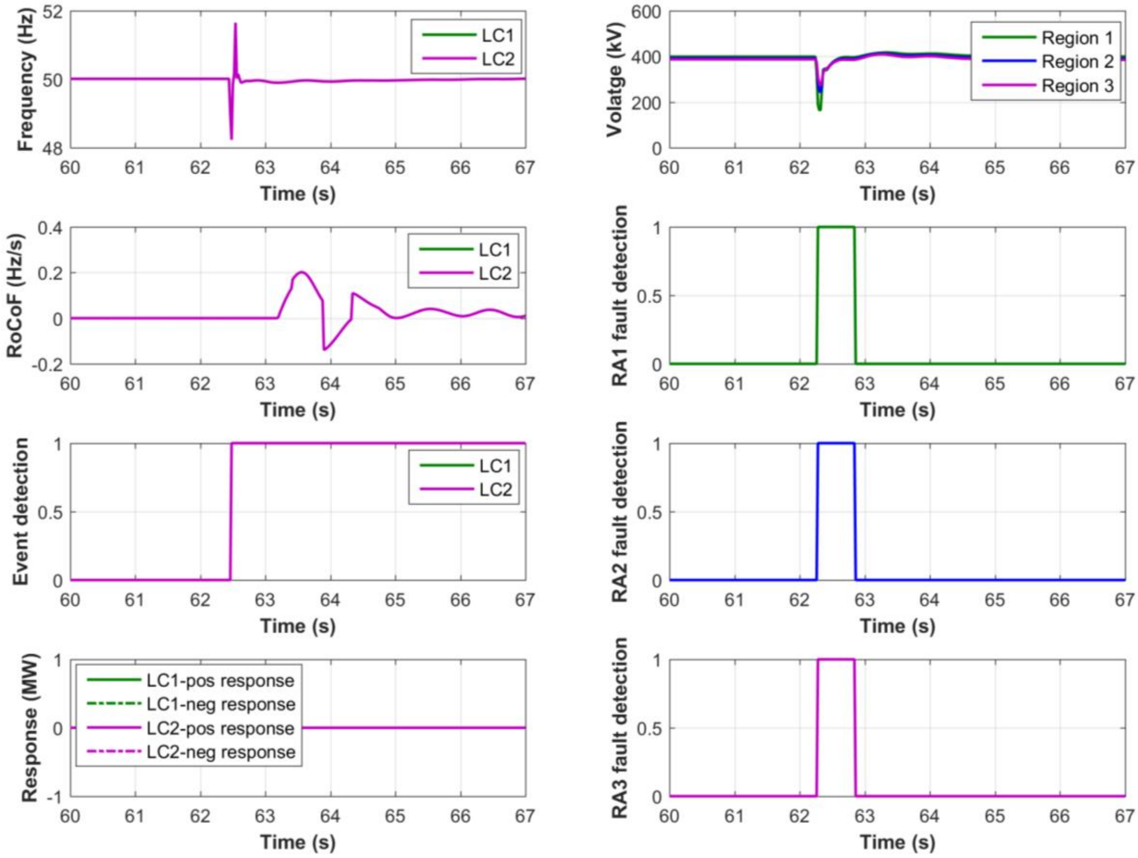

Figure 57. Test results for a 3Ph-E fault in Region 1

6.2 Tests results for faults in Region 2

In Region 2, the faults are applied at the location shown in Figure 58.

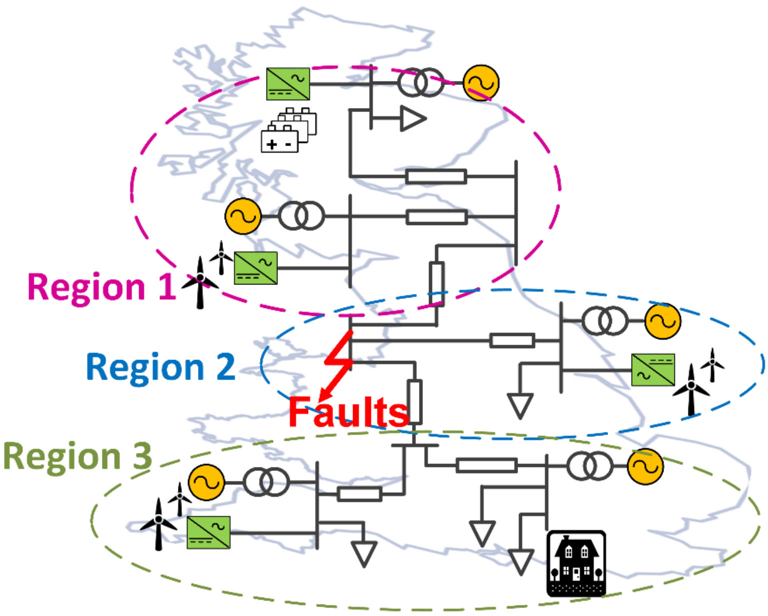

Figure 58. Location of faults in Region 2

6.2.1 Test Fault-R2-Ph-E: Ph-E fault in Region 2

In this test, a Ph-E fault was applied in Region 2 and the test results are shown in Figure 59. The fault was successfully detected by all three RAs and the fault was not detected as an event and no EFCC response was deployed. This followed the design specification.

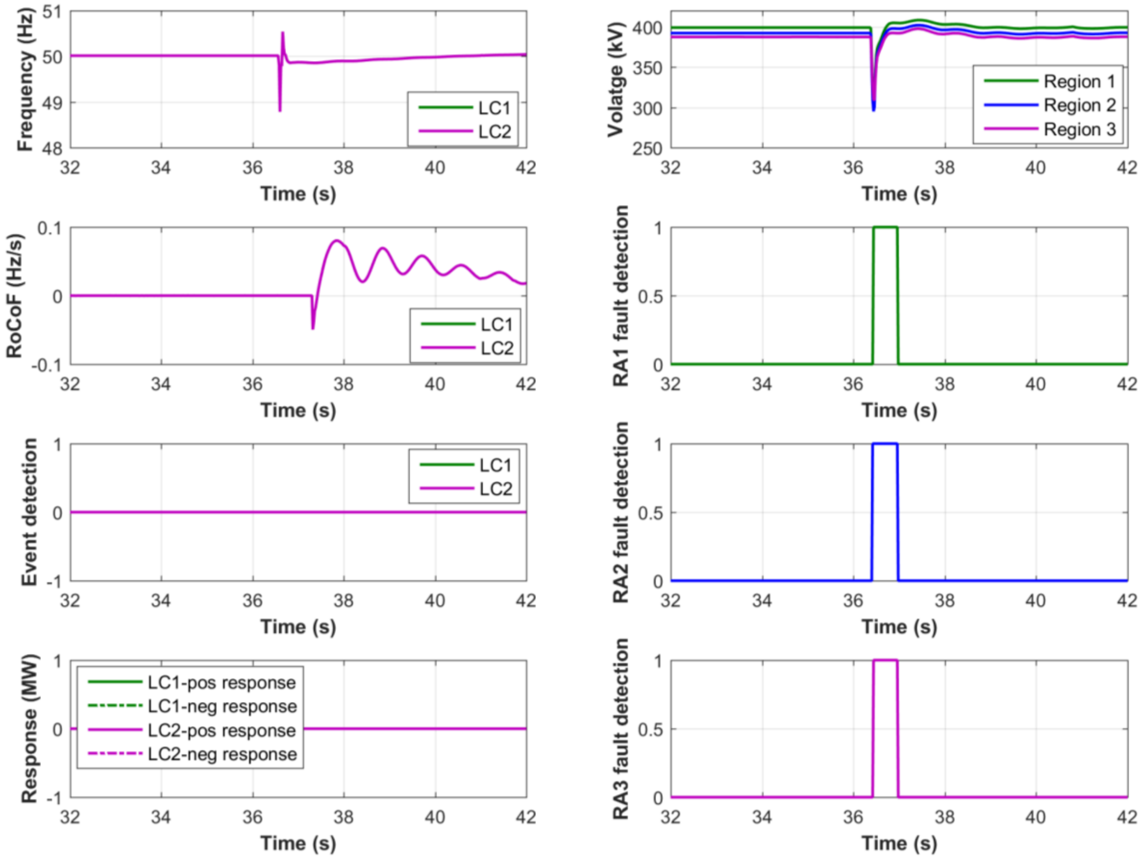

Figure 59. Test results for a Ph-E fault in Region 2

6.2.2 Test Fault-R2-Ph-Ph: Ph-Ph fault in Region 2

In this test, a Ph-Ph fault was applied in Region 2 and the test results are shown in Figure 60. The fault was successfully detected by all three RAs, but it was also detected as an event. No resources were deployed to respond to the fault, which is in accordance with the design specification.

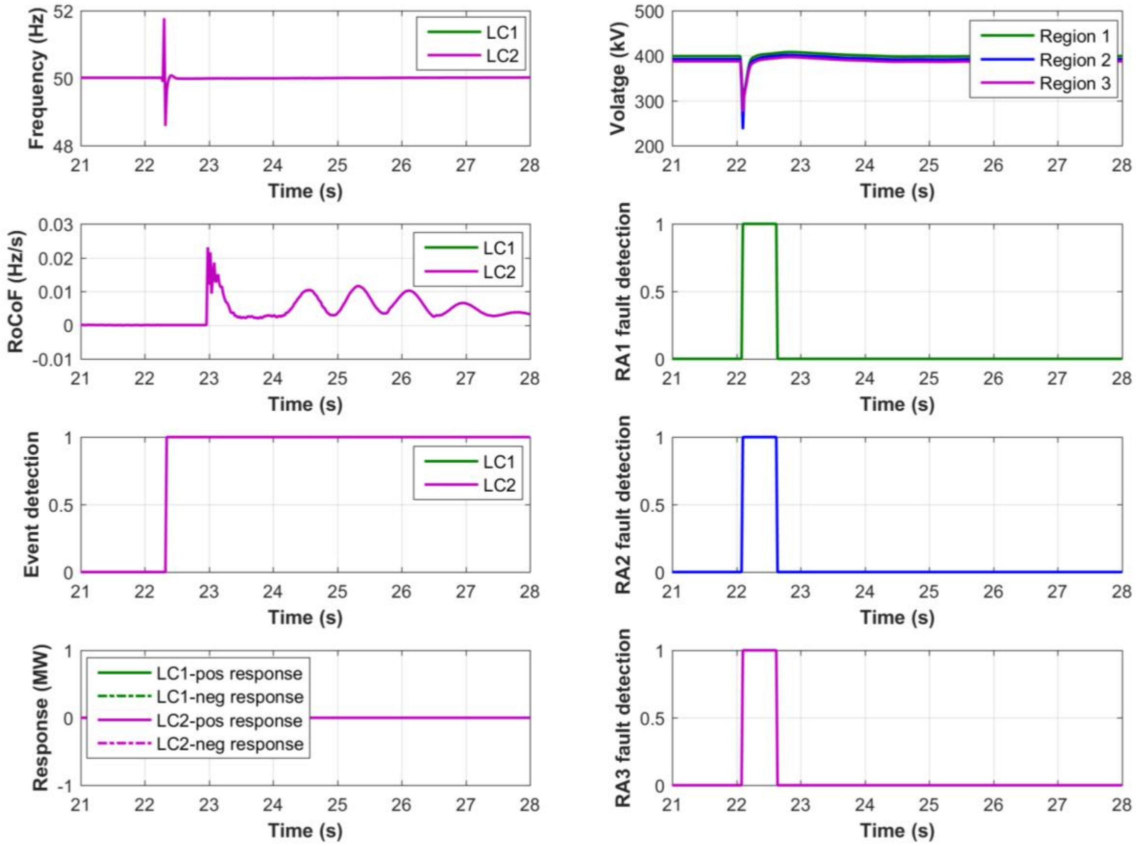

Figure 60. Test results for a Ph-Ph fault in Region 2

6.2.3 Test Fault-R2-3Ph-E: 3Ph-E fault in Region 2

In this test, a 3Ph-E fault was applied in Region 2 and the test results are shown in Figure 61. Similar results as in Ph-Ph fault test were observed, where the fault was successfully detected by all three RAs, but it was also unexpectedly detected as an event. No resources were deployed to respond to the fault, which is in accordance with the design specification.

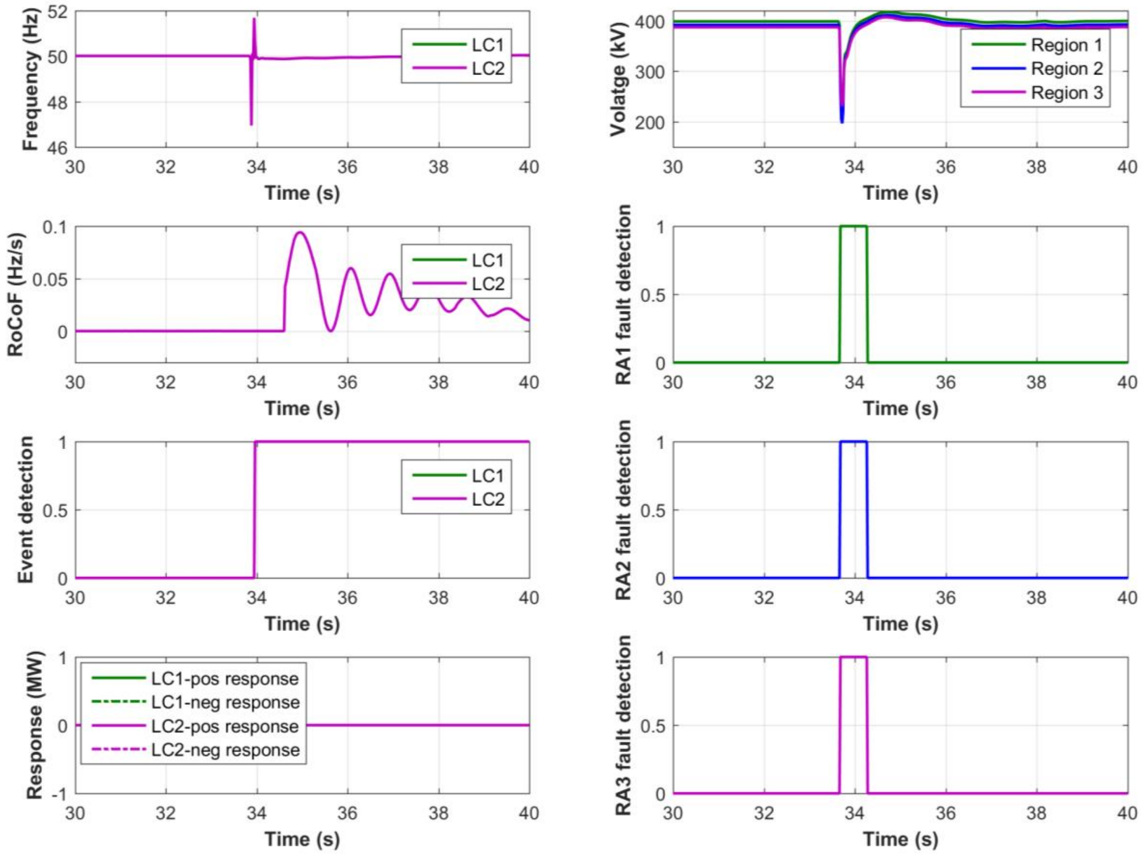

Figure 61. Test results for a 3Ph-E fault in Region 2

6.3 Tests results for faults in Region 3

In Region 3, the faults are applied at the location shown in Figure 62.

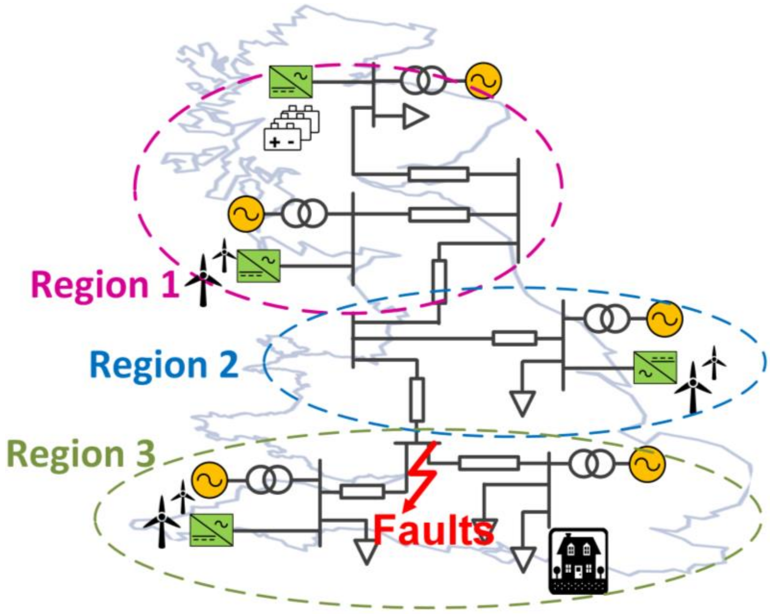

Figure 62. Location of faults in Region 3

6.3.1 Test Fault-R3-Ph-E: Ph-E fault in Region 3

In this test, a Ph-E fault was applied in Region 3 and the test results are shown in Figure 63. The fault was successfully detected by all three RAs and the fault was not detected as an event. No EFCC response was deployed. This follows the design specification.

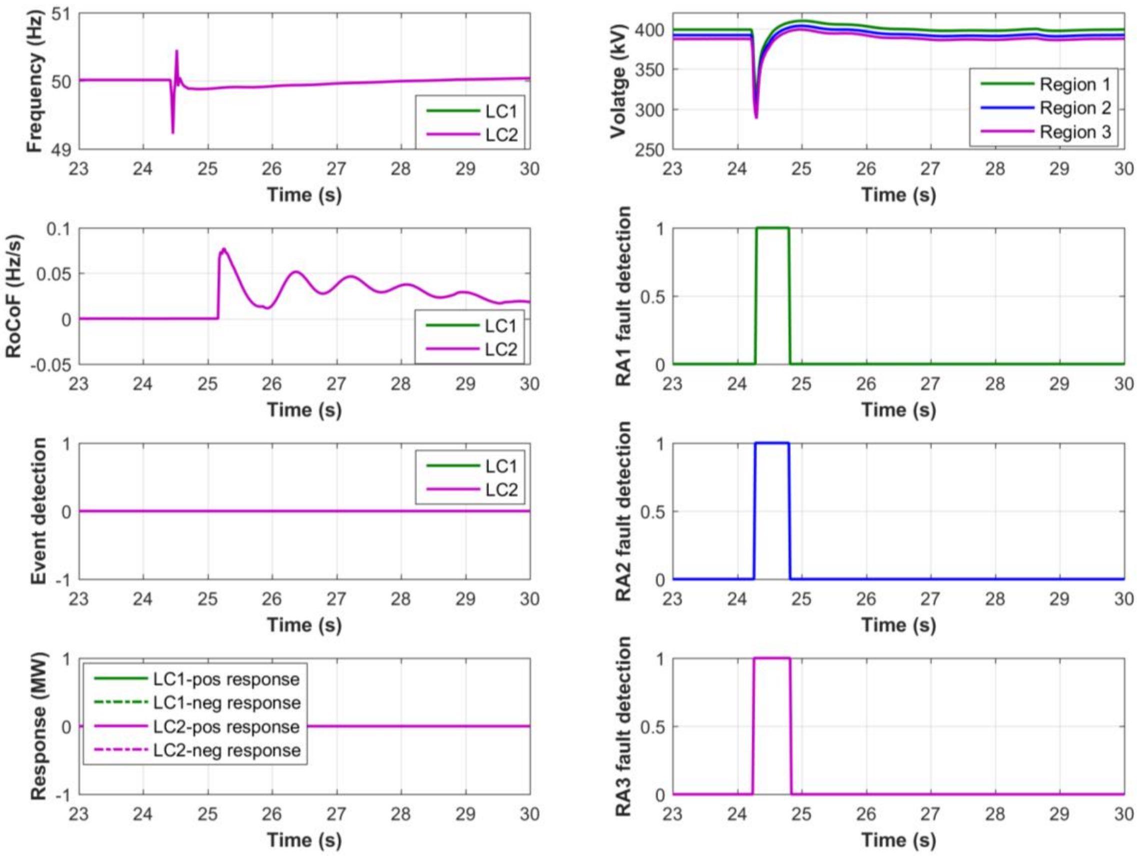

Figure 63. Test results for a Ph-E fault in Region 3

6.3.2 Test Fault-R3-Ph-Ph: Ph-Ph fault in Region 3

In this test, a Ph-Ph fault was applied in Region 3 and the test results are shown in Figure 64. The fault was successfully detected by all three RAs, but it was also unexpectedly detected as an event. No resources were deployed to respond to the fault, which is in accordance with the design specification.

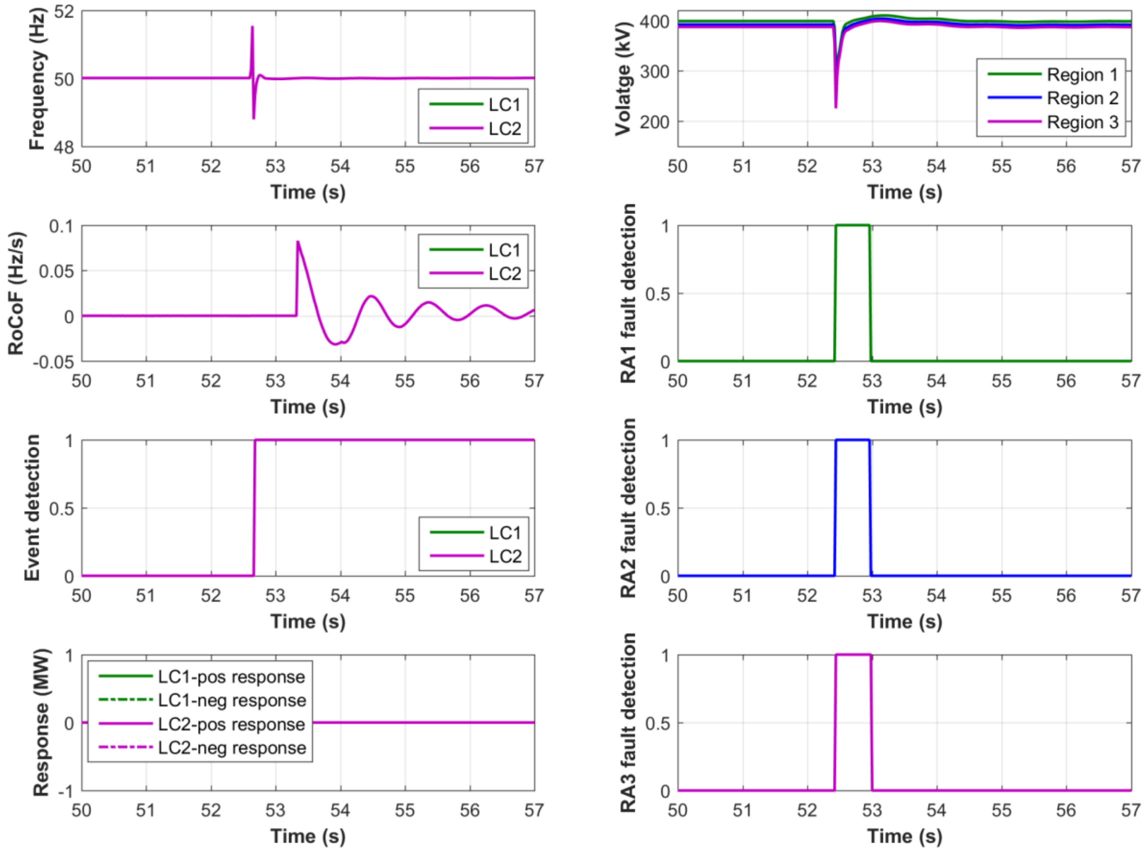

Figure 64. Test results for a Ph-Ph fault in Region 3

6.3.3 Test Fault-R3-3Ph-E: 3Ph-E fault in Region 3

In this test, a 3Ph-E fault was applied in Region 3 and the test results are shown in Figure 65. Similar results as in the Ph-Ph fault test were observed, where the fault was successfully detected by all three RAs, but it was also unexpectedly detected as an event. No resources were deployed to respond to the fault, which is in accordance with the design specification.

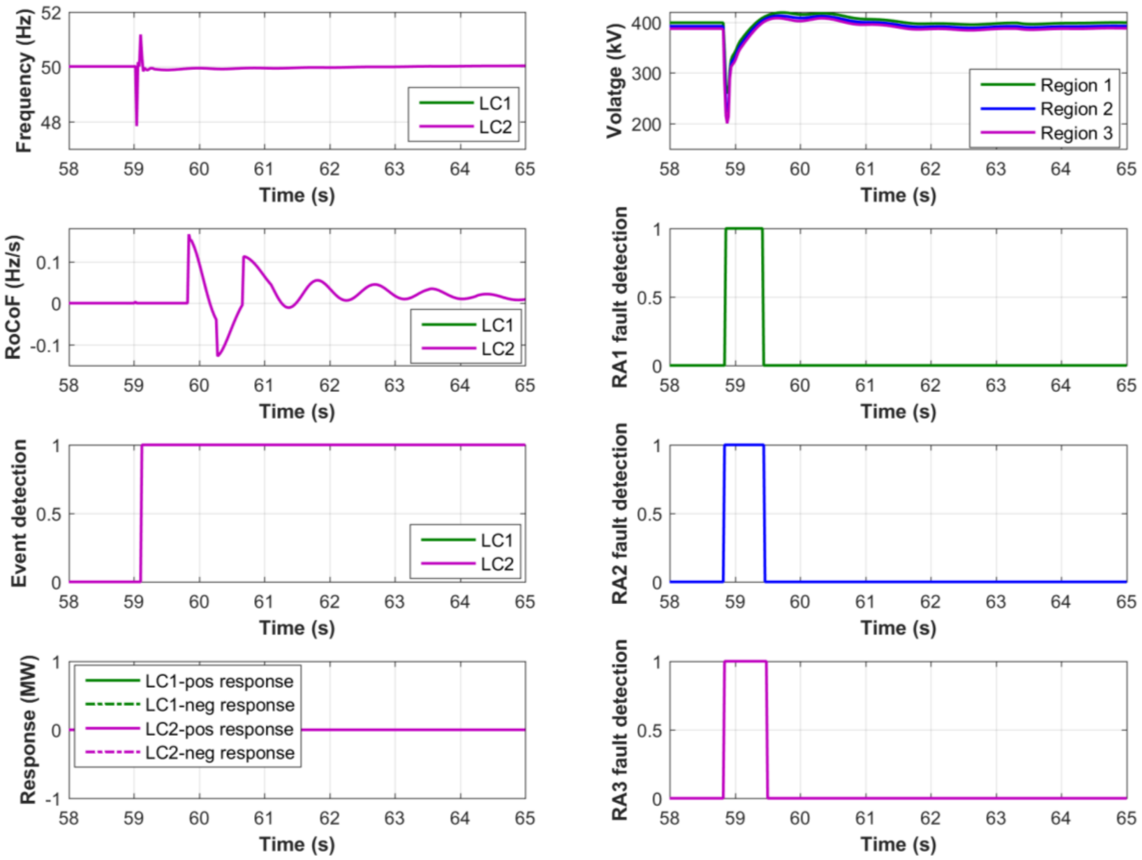

Figure 65. Test results for a 3Ph-E fault in Region 3

6.4 Summary of fault tests

In all the tests presented in this section, the RAs have successfully detected all faults as required and the EFCC scheme did not deploy and resources in all test cases, which also aligns with expectations.

In some cases (e.g. Ph-Ph and 3Ph-E faults), the faults were detected as events even when the fault flags were high and blocking the event detection signal. It was suggested by GE that this aligned with the design specifications and was caused by the violation of the event detection frequency threshold, which is set as 49.7 Hz in the tests. Although the existing setting could lead to a fault being detected as an event, based on the EFCC user manual, the resource is deployed based on measured RoCoF, which is blocked during the fault. Therefore, this should not cause unexpected deployment of resources during a fault, which is evident by the test results shown in this section.

7 EVALUATION OF THE EFCC'S PERFORMANCE DURING CASCADING EVENTS

This section presents the results from the tests for evaluating the performance of the EFCC scheme during cascading events, i.e. loss of generation frequency disturbances following on from faults.

Similar to the tests described in Section 6, faults are applied in all three regions and the fault resistance, duration and types are the same as the corresponding faults in Section 6, i.e. a Ph-E fault in Region 1 in these tests is the same fault as the Ph-E fault as applied in the tests presented in Section 6. However, in these tests, loss of infeed events were subsequently triggered in 100 ms following the fault occurrence to emulate the protection action in tripping one of the lines, leading to power imbalance events.

The size of the power imbalance event is 1 GW and the resource availability information for both LCs are the same as in Test 8 in Section 5.2 (and detailed in Appendix C), where both LCs' resources have 1000 MW of capacity.

7.1 Tests of generation loss following faults in Region 1

7.1.1 Loss of generation following a Ph-E fault in Region 1

In this test, a Ph-E fault was applied in Region 1, followed by a 1 GW loss of infeed. The test results are shown in Figure 66. The fault occurred at 16.56 s and it was successfully detected by all three RAs. The LCs also detected the under-frequency event at 17.44 s, with LC1 commanding 442 MW at 17.45 s, and LC2 commanding 255 MW at 17.46 s and then 400 MW at 19.44 s. Transient variations in the command from LC2 were observed. Compared to the case without the EFCC responses, the frequency nadir was raised from 49.31 Hz to 49.61 Hz, i.e. the frequency was successfully contained above the required 49.50 Hz limit.

It should be noted that this test has the same resource availability condition and triggered frequency event as Test 7 presented in Section 5.2.7.1. The only difference is that this test had a fault before the frequency event. Comparing the test results from these two tests, LC2 did not dispatch any response in Test 7, while LC2 deployed power immediately when the frequency event was detected in this test. Therefore, this shows that the control actions from the EFCC scheme could be affected by the occurrence of the fault even with the same power imbalance at the same location.

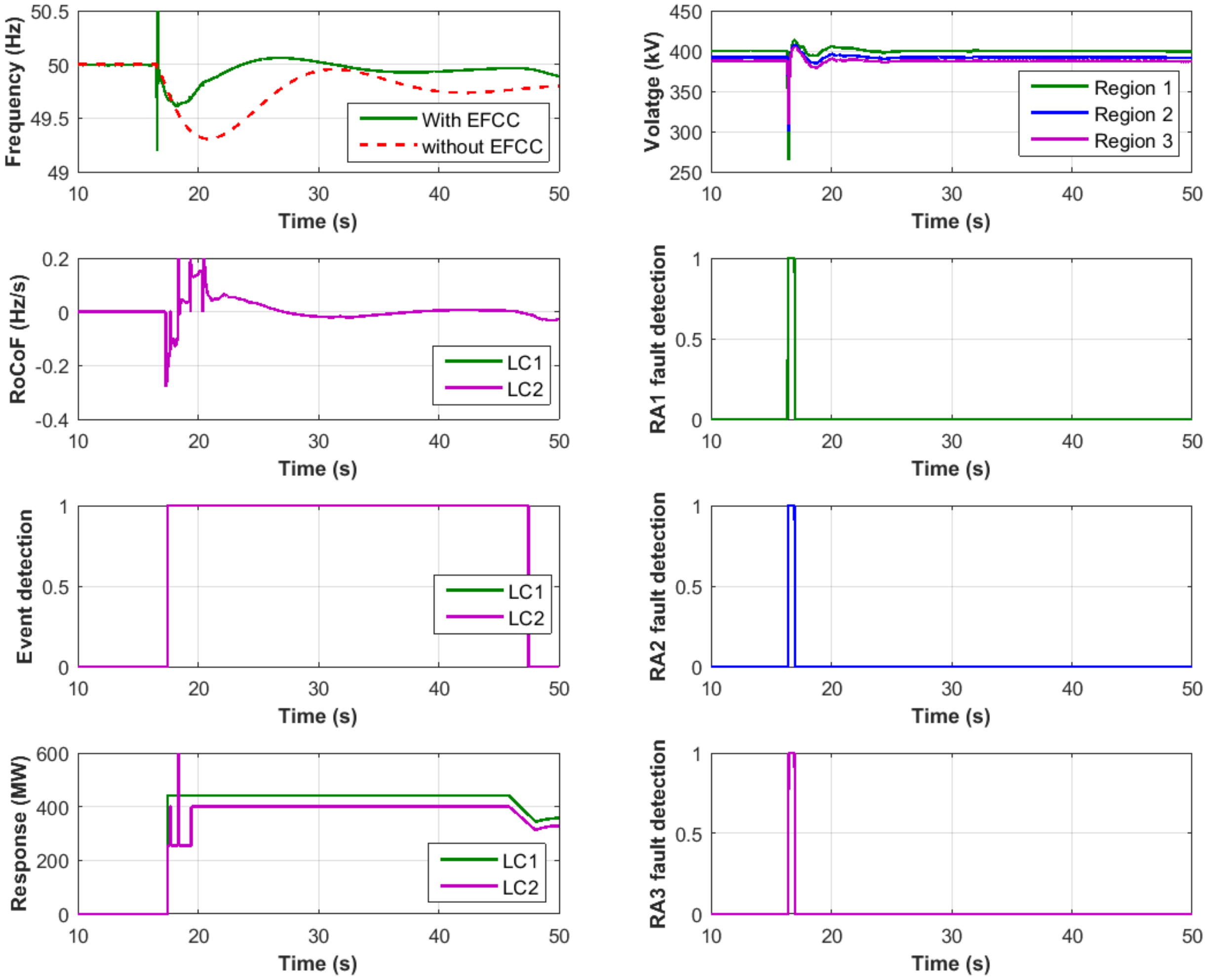

Figure 66. Test results for a loss of generation event following Ph-E fault in Region 1

7.1.2 Loss of generation following Ph-Ph fault in Region 1

In this test, a Ph-Ph fault was applied in Region 1, followed by a 1 GW loss of infeed. The test results are shown in Figure 67. The fault occurred at 18.88 s and it was successfully detected by all three RAs. The LCs also detected the under-frequency event at 17.44 s, with LC1 commanding 452 MW at 17.44 s, and no response from LC2 was commanded.

Compared to the case without the EFCC responses, the frequency nadir was raised from 49.31 Hz to 49.61 Hz, i.e. the frequency was successfully contained above the required 49.50 Hz limit.

It should be noted that, in this test, the control actions (amount and time of active power commanded) from the EFCC scheme were different from the previous test, where the fault was with the Ph-E type. This shows that the type of the fault during a cascading event also has an impact on the control actions from the EFCC scheme.

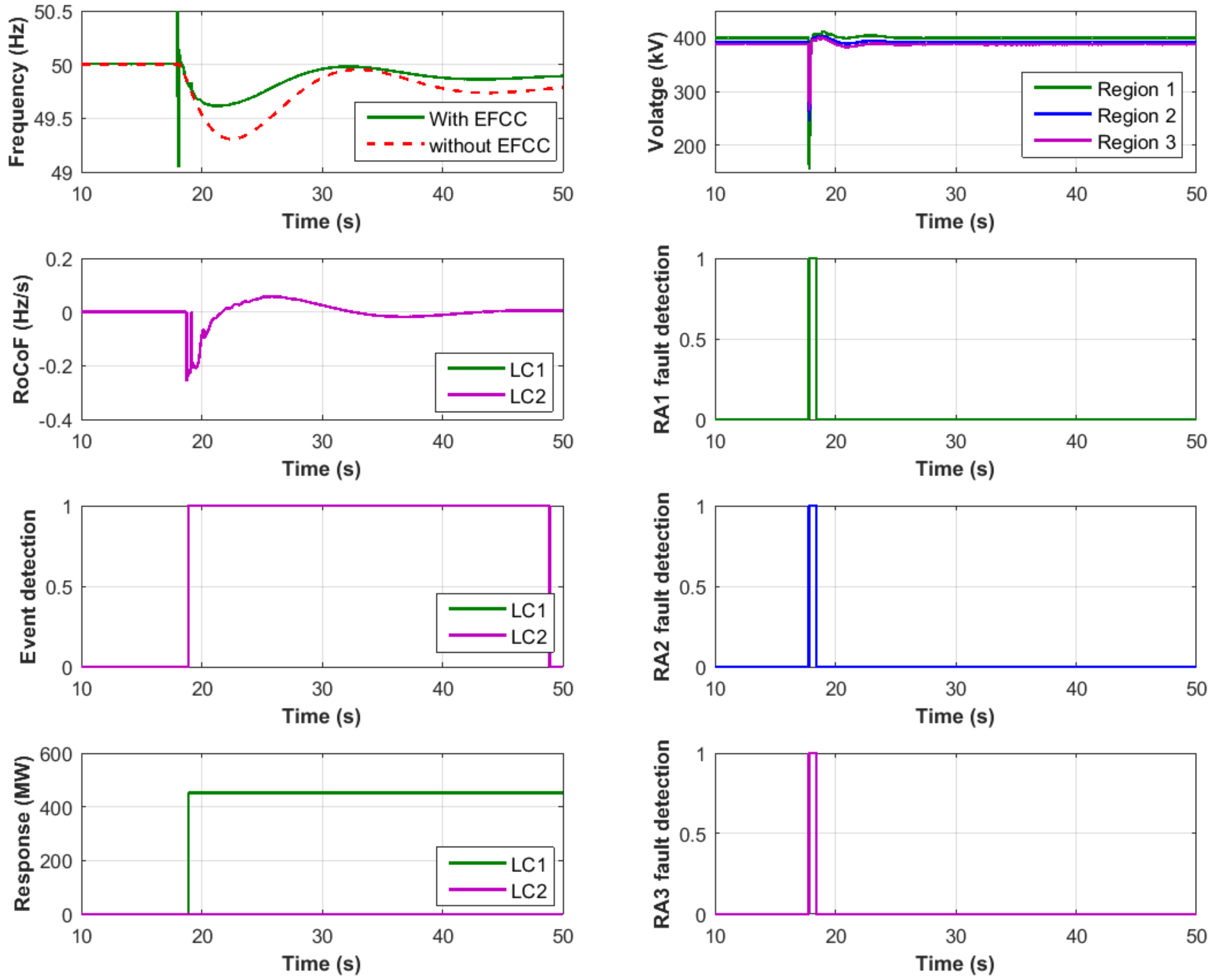

Figure 67. Test results for a loss of generation event following Ph-Ph fault in Region 1

7.1.3 Loss of generation following 3Ph-E fault in Region 1

In this test, a 3Ph-E fault was applied in Region 1, followed by a 1 GW loss of infeed. The test results are shown in Figure 68.

The test results are shown in Figure 67. The fault occurred at 14.12 s and it was successfully detected by all three RAs. The LCs also detected the under-frequency event at 15.06 s, with LC1 commanding 419 MW in total at 15.06 s, and LC2 commanding 600 MW at 17.14 s. Transient variations in the command from LC2 were observed. Compared to the case without the EFCC responses, the frequency nadir was raised from 49.31 Hz to 49.60 Hz, i.e. the frequency was successfully contained above the required 49.50 Hz limit.

Again, the control actions from the EFCC scheme were different from the previous two cases even with the frequency disturbances occurred in the same location and with same amount of power imbalance. These different behaviours in EFCC scheme due to different fault types were also observed in the following tests, and the description will not be repeated.

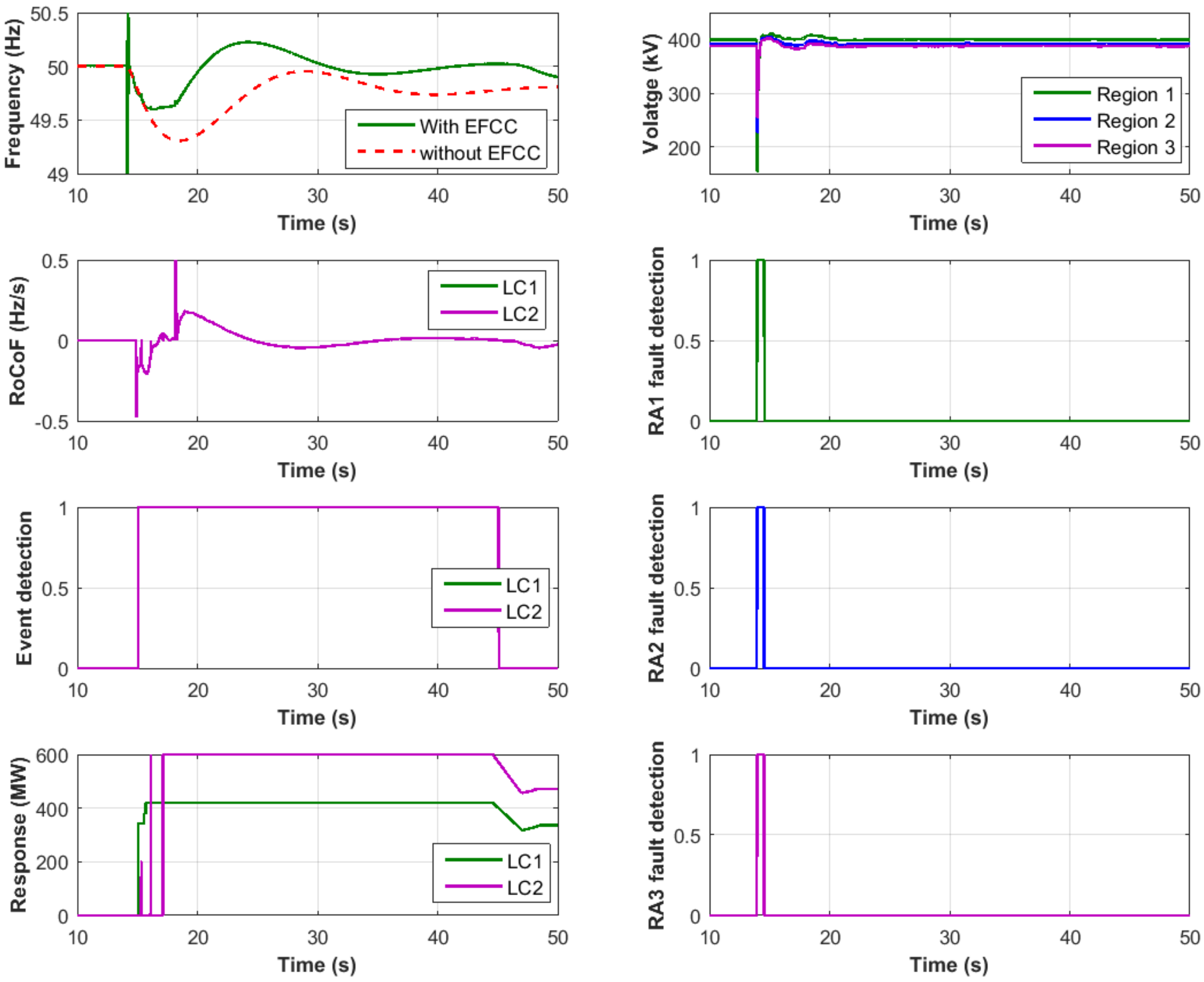

Figure 68. Test results for a loss of generation event following 3Ph-E fault in Region 1

7.2 Tests of generation loss following faults in Region 2

7.2.1 Loss of generation following Ph-E fault in Region 2

In this test, a Ph-E fault was applied in Region 2, followed by a 1 GW loss of infeed. The test results are shown in Figure 69. The fault occurred at 14.24 s and it was successfully detected by all three RAs. The LCs also detected the under-frequency event at 15.10 s, with LC2 commanding 476 MW at 15.12 s and then 600 MW at 17.26 s, and LC1 commanding 400 MW at 17.18 s. Transient variations in the commands from LC1 and LC2 were observed. Compared to the case without the EFCC responses, the frequency nadir was raised from 49.31 Hz to 49.50 Hz, i.e. the frequency was successfully contained at the required limit.

It should be noted that, the frequency disturbance is located in Region 2, which is different from the regions where LC1 and LC2 were located. From the tests (e.g. Test 2) presented in Section 5.2, both LC1 and LC2 by design will hold for 2 s before commanding power for events locating in other regions. In this test, LC2 commanded power immediately when the event was detected. This again shows the occurrence of fault will affect the control actions from the EFCC scheme.

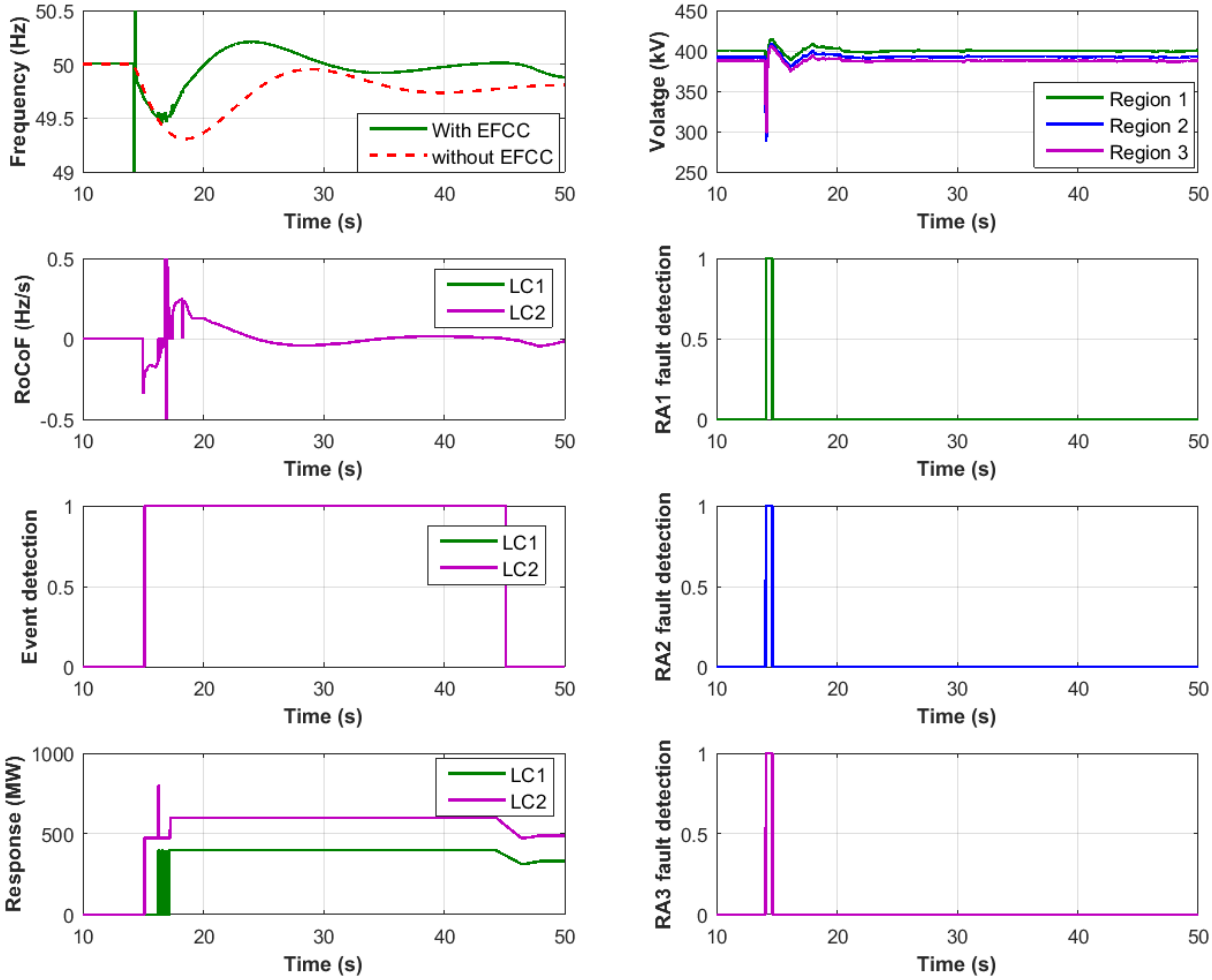

Figure 69. Test results for a loss of generation event following Ph-E fault in Region 2

7.2.2 Loss of generation following Ph-Ph fault in Region 2

In this test, a Ph-Ph fault was applied in Region 2, followed by a 1 GW loss of infeed. The test results are shown in Figure 70. The fault occurred at 15.06 s and it was successfully detected by all three RAs. The LCs also detected the under-frequency event at 15.96 s, with LC1 commanding 371 MW at 17.18 s.

Compared to the case without the EFCC responses, the frequency nadir was raised from 49.31 Hz to 49.56 Hz, i.e. the frequency was successfully contained at the required limit.

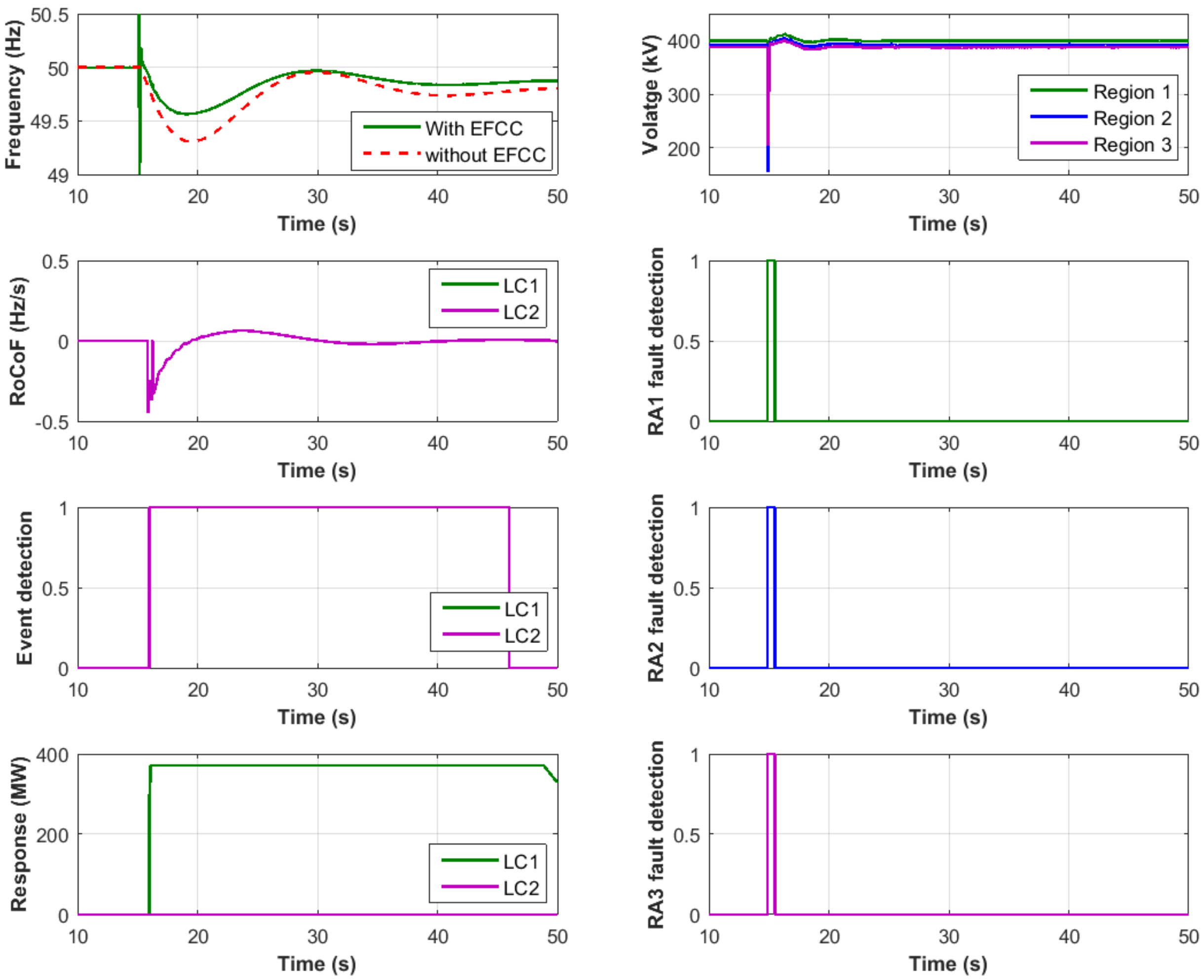

Figure 70. Test results for a loss of generation event following Ph-Ph fault in Region 2

7.2.3 Loss of generation following 3Ph-E fault in Region 2

In this test, a 3Ph-E fault was applied in Region 2, followed by a 1 GW loss of infeed. The test results are shown in Figure 71. The fault occurred at 14.60 s and it was successfully detected by all three RAs. The LCs also detected the under-frequency event at 15.50 s, with LC1 commanding 412 MW at 15.52 s and LC2 commanding 400 MW at 17.64 s. Transient variations in the command from LC2 were observed.

Compared to the case without the EFCC responses, the frequency nadir was raised from 49.31 Hz to 49.60 Hz, i.e. the frequency was successfully contained at the required 49.50 Hz limit.

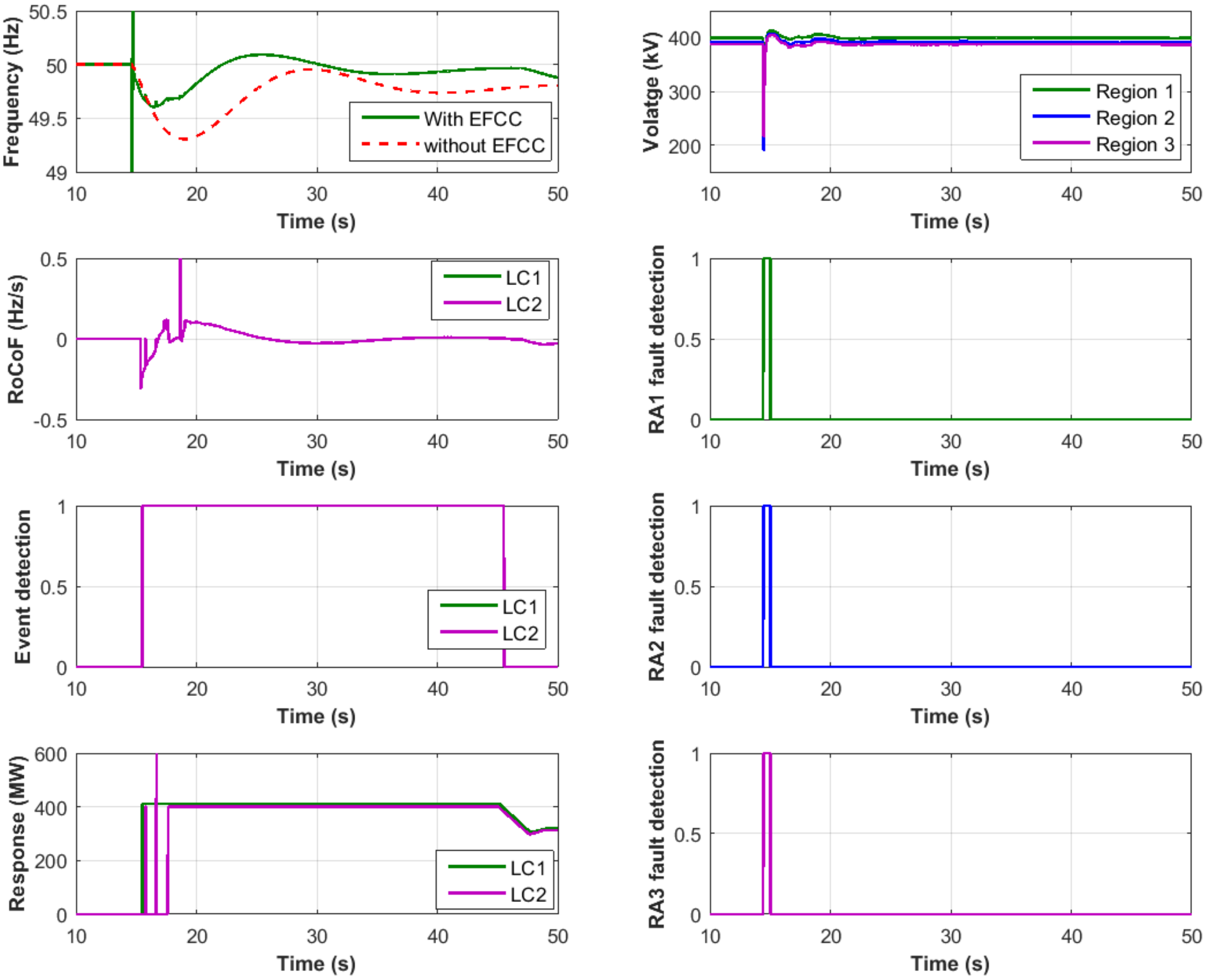

Figure 71. Test results for a loss of generation event following 3Ph-E fault in Region 2

7.3 Tests of generation loss following faults in Region 3

7.3.1 Loss of generation following Ph-E fault in Region 3

In this test, a Ph-E fault was applied in Region 3, followed by a 1 GW loss of infeed. The test results are shown in Figure 72. The fault occurred at 14.14 s and it was successfully detected by all three RAs. The LCs also detected the under-frequency event at 15.04 s, with LC1 commanding 407 MW at 15.04 s and LC2 commanding 400 MW at 17.06 s. Transient variations in the commands from LC2 were observed.

Compared to the case without the EFCC responses, the frequency nadir was raised from 49.31 Hz to 49.54 Hz, i.e. the frequency was successfully contained at the required limit.

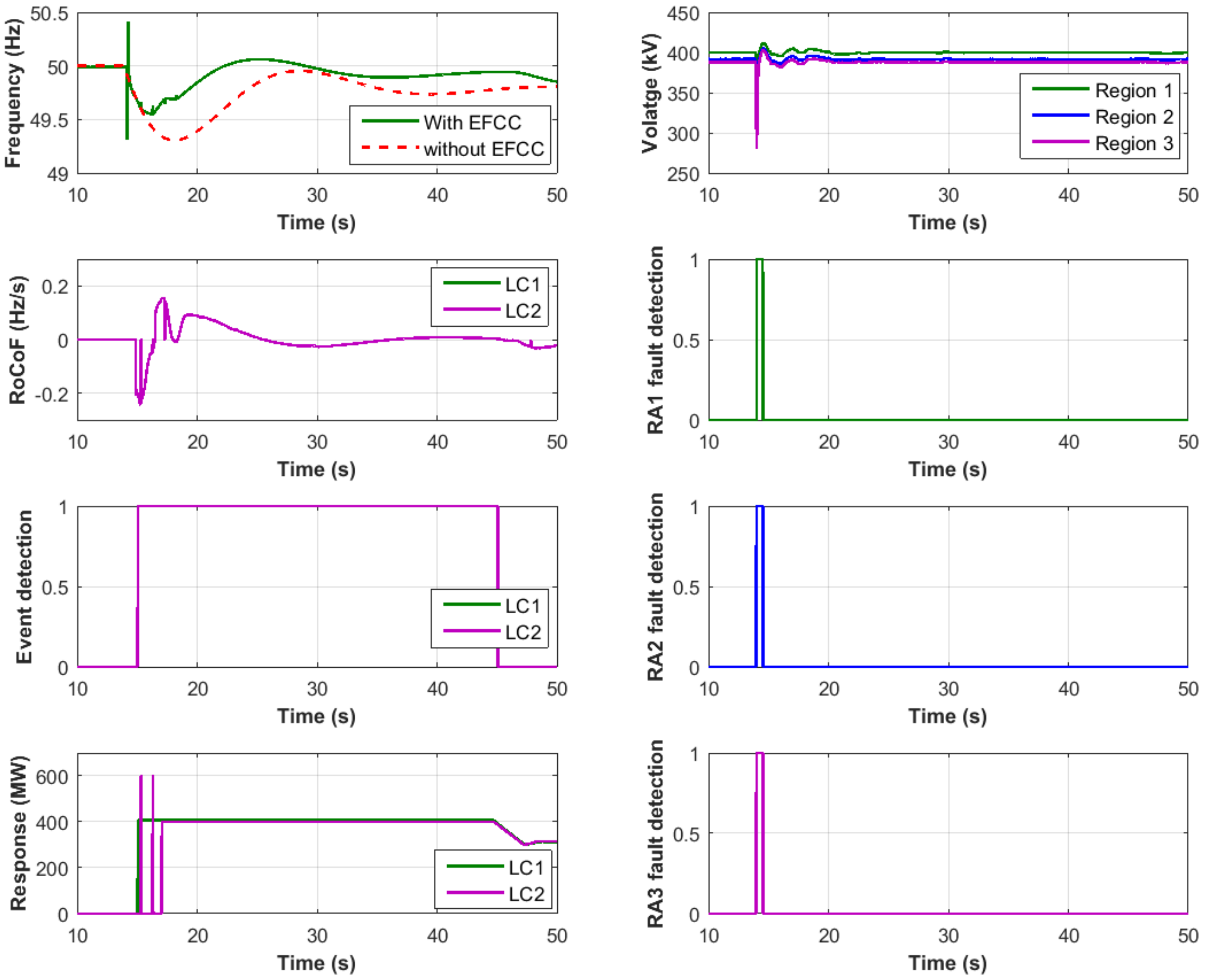

Figure 72. Test results for a loss of generation event following Ph-E fault in Region 3

7.3.2 Loss of generation following Ph-Ph fault in Region 3

In this test, a Ph-Ph fault was applied in Region 3, followed by a 1 GW loss of infeed. The test results are shown in Figure 73. The fault occurred at 15.06 s and it was successfully detected by all three RAs. The LCs also detected the under-frequency event at 16.04 s, with LC1 commanding 466 MW at 16.04 s.

Compared to the case without the EFCC responses, the frequency nadir was raised from 49.31 Hz to 49.58 Hz, i.e. the frequency was successfully contained at the required limit.

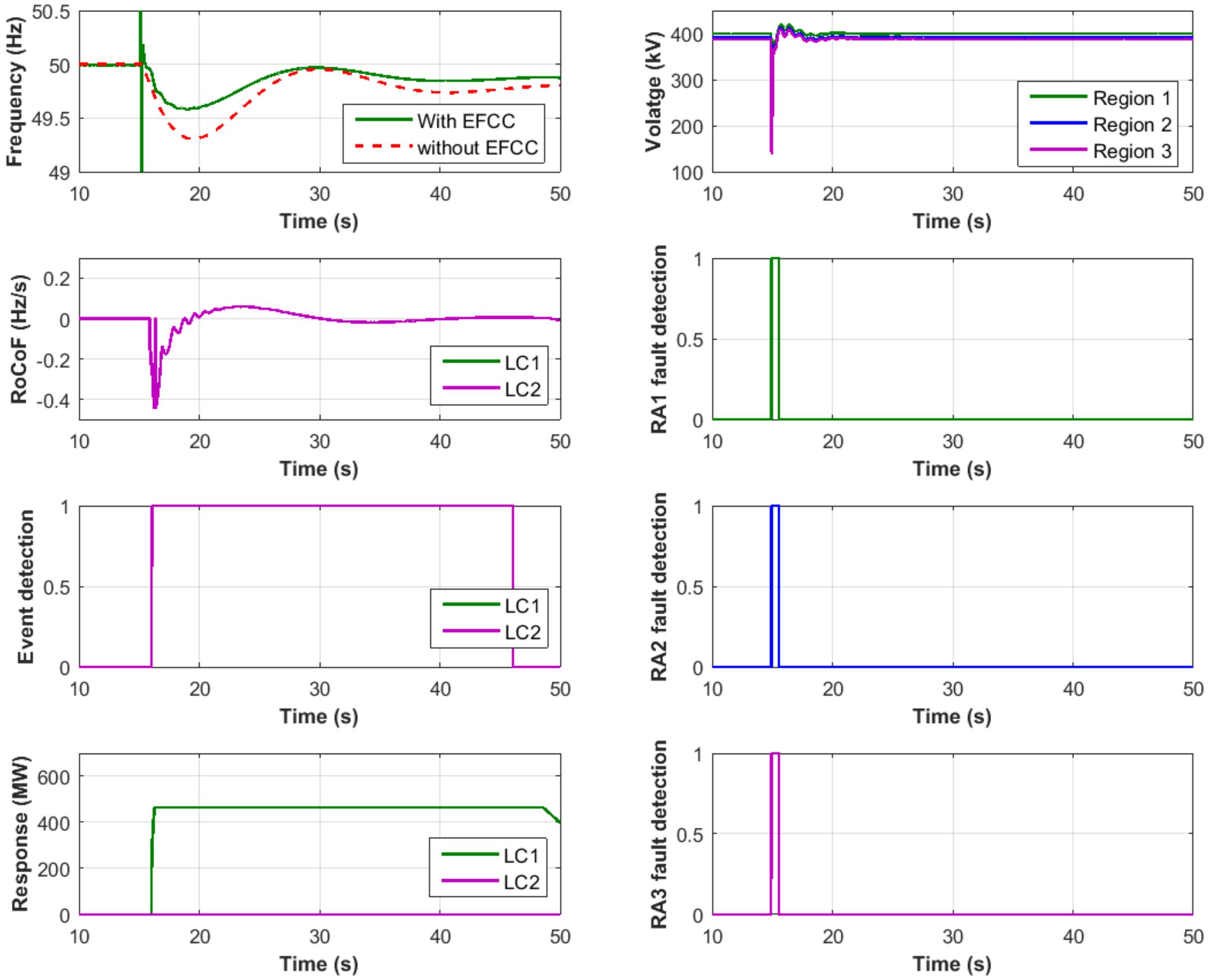

Figure 73. Test results for a loss of generation event following Ph-Ph fault in Region 3

7.3.3 Loss of generation following 3Ph-E fault in Region 3

In this test, a 3Ph-E fault was applied in Region 3, followed by a 1 GW loss of infeed. The test results are shown in Figure 74. The fault occurred at 15.18 s and it was successfully detected by all three RAs. The LCs also detected the under-frequency event at 16.14 s, with LC1 commanding 424 MW at 16.14 s and LC2 commanding 400 MW at 18.40 s. Transient variations in the command from LC2 were observed.

Compared to the case without the EFCC responses, the frequency nadir was raised from 49.31 Hz to 49.55 Hz, i.e. the frequency was successfully contained at the required 49.50 Hz limit.

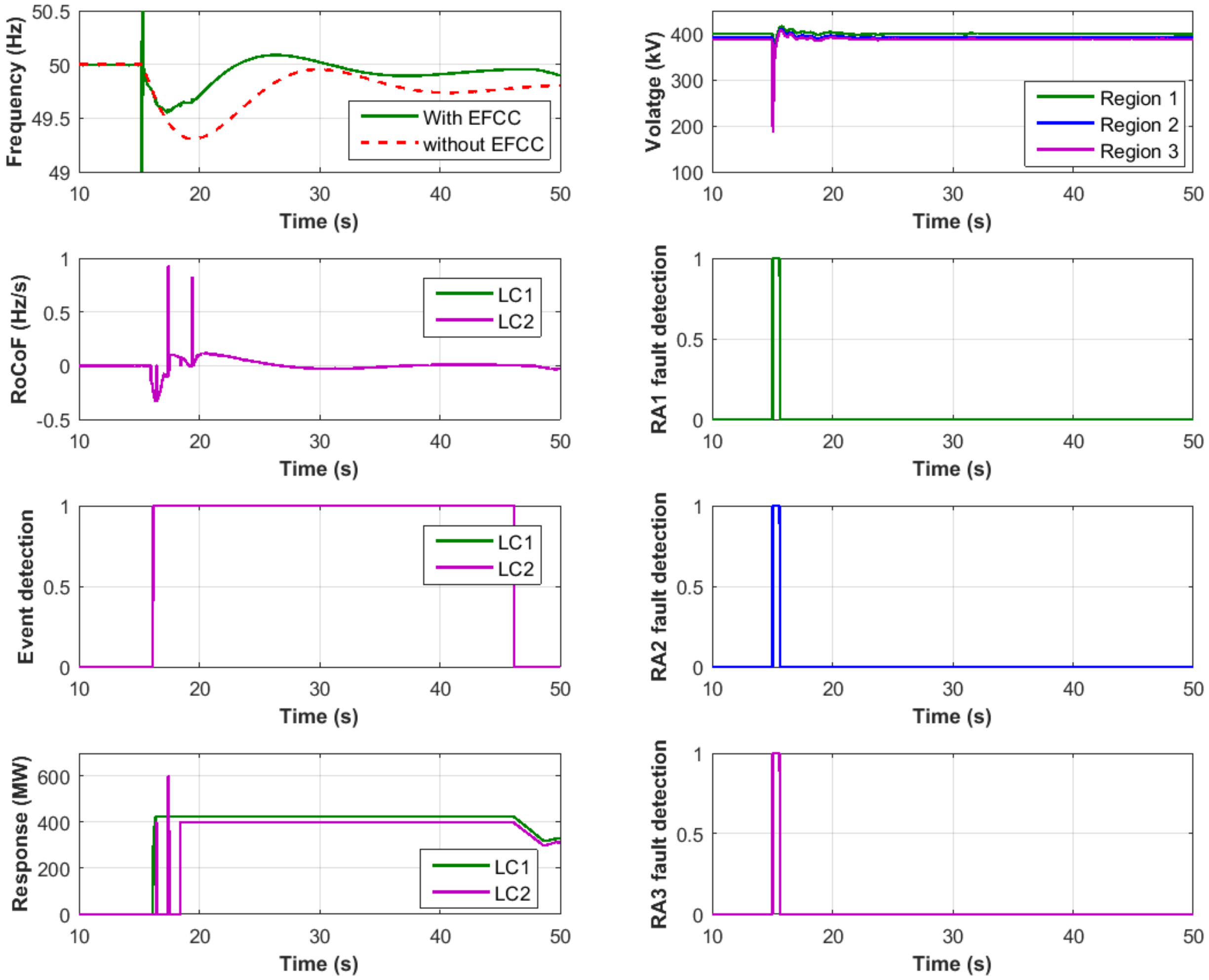

Figure 74. Test results for a loss of generation event following 3Ph-E fault in Region 3

7.4 Summary of cascading event tests

In the tests presented in this section, the RAs have successfully detected all faults and the LCs have also successfully detected all subsequent frequency events. The frequency was successfully contained above the required 49.50 Hz limit in all of the tested scenarios.

However, it was also found that, compared to the case there is no fault before the frequency event, the EFCC scheme can exhibit different behaviours. Furthermore, for the same fault and loss of generation locatation, different types of faults could also lead to different frequency responses from the EFCC controllers. While from the tested scenarios, the different behaviours of EFCC scheme due to the faults did not appear to affect the frequency being contained at the required limit, it was considered that the impact of such different behaviours due to faults need to be further investigated in detail.

8 KEY FINDINGS AND CONCLUSIONS

In this report, the test results for evaluating the EFCC's performance under its wide-area operational mode have been presented and analysed. The tests were conducted using the P-HiL testbed that has been established at the PNDC. The performance of the EFCC scheme has been evaluated with respect to its dependability during frequency disturbances; its security during non-frequency events (i.e. faults); and its behaviour during cascading events (loss of generation events following faults). The key findings are summarised in the following sections. There are also observations that require further investigation in order to understand the scheme behaviour. These observations are summarised in Section 8.4.

8.1 Findings from frequency disturbances tests for evaluating the dependability of the EFCC scheme

1. Impact of resources and event locations

It was found that, for the same amount of power imbalance, the EFCC will react differently if the event is located in different regions of the network. Similarly, if the resources and associated LCs were placed in different locations, they will also have different responses to the same event. Both of the resources and events' locations will affect the speed of response, thereby the effectiveness of the control actions. If the EFCC resources are located in the same region where the event occurs, the EFCC responses will be deployed faster and are more effective than the resources in other regions, which aligns with the design specifications. During the tests, if there are resources available in the same region as the event, the frequency was successfully controlled between 49.50 Hz to 50.50 Hz for a 1 GW loss of generation in a low-inertia system (i.e. 82 GVAs). In the case where the EFCC resources are located different regions from the event, it was also observed that the EFCC scheme delayed the response by 2 s, which is by design to avoid causing system stability issues. However, the inclusion of this delay within the EFCC scheme should be considered as, in some cases, it can reduce the effectiveness of the scheme in containing frequency excursions.

2. Impact of the resources' capacities

The impact of the capacity of the resource has also been investigated and it was found that, a larger EFCC resource capacity did not necessarily mean a better frequency restoration performance. It was found that if the LCs have excessive capacity, they will only deploy the amount that is required to contain the frequency and the rest of the capacity might not be used. Therefore, there is a potential that the capacity of the EFCC resources could be optimised so that they can contain the frequency deviation while minimising the reserved power required.

3. General findings

Overall, the dependability tests demonstrated that the frequency can be effectively controlled with fast frequency responses deployed by the EFCC scheme even in a very low inertia system (82 GVAs) if there are resource locating in the same region as the event and with suitable capacity. However, as mentioned in earlier in this document, while the EFCC resources were designed not to react immediately to events located in other regions and the test results align with the design specifications, it should be noted that the inclusion of intentional delay can reduce the effectiveness of the scheme in containing frequency excursions. It was suggested that further investigation should be conducted to investigate system operating conditions where such intentional delay could be eliminated without causing system wide stability issues.

8.2 Findings from fault event tests for evaluating the EFCC's security

It was found that the EFCC have successfully detected all faults as required and the EFCC scheme did not deploy and resources in all test cases, which align with design specifications. In some cases (e.g. Ph-Ph and 3Ph-E faults), the faults were detected as events even when the fault flags were high and blocking the event detection signal. It was suggested by GE that this aligned with the design specifications and was caused by the violation of the event detection frequency threshold and based on the user manual, this would not cause undesirable dispatch of resources, which is evident by the test results presented in this report.

8.3 Findings from cascading event tests

In all of the tested scenarios, the RAs successfully detected the faults and the LCs also successfully detected subsequent frequency events. The frequency was successfully contained above the required 49.50 Hz limit in all of the tested cases.

However, it was also found that, compared to the case there is no fault before the frequency event, the EFCC could exhibit different behaviours. Furthermore, for the same fault and loss of generation location, different types of faults could also lead to different frequency responses from EFCC controllers. While from the tested scenarios, the different behaviours of EFCC scheme due to the faults did not appear to affect the frequency being contained at the required limit, it was considered that the impact of such different behaviours due to faults need to be further investigated.

8.4 Summary of observations that require further investigation

1. There are cases (e.g. Test 2, 14 and 15 in Section 5.2), where the event occurred in the region outside the region where the LC was located, the LC delayed the resource deployment by 2 s. This led to the overall frequency response being less effective. While this aligns with the design specifications, it was considered that further investigation of whether and when the intentional 2 s delay should be included is required. Avoiding the 2 s delay when it is not required could potentially lead to more effective frequency restoration performance.
2. In some fault event tests (e.g. Test Fault-R3-Ph-Ph in Section 6.3.2 and Test Fault-R3-3Ph-E in Section 6.3.3), the event detection flag became high even when the fault flag was high. It was suggested by GE that the event detection frequency threshold setting should be desensitised to 48 Hz to avoid the unexpected detection of fault as an event. However, the usefulness of such a low frequency threshold (even as a failover mechanism) need to be further investigated.
3. In the cascading event tests, the occurrences of faults and different fault types will both affect the EFCC scheme's control actions. It was considered that the impact of such different behaviours due to faults need to be further investigated.

9 REFERENCES

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APPENDIX A: COMMUNICATION NETWORK ARRANGEMENT FOR THE TESTS

The complete communication interface connections and the associated protocols/standards are illustrated in Figure 75. The associated communication parameters of the devices shown in Figure 75 are provided in Table 32.

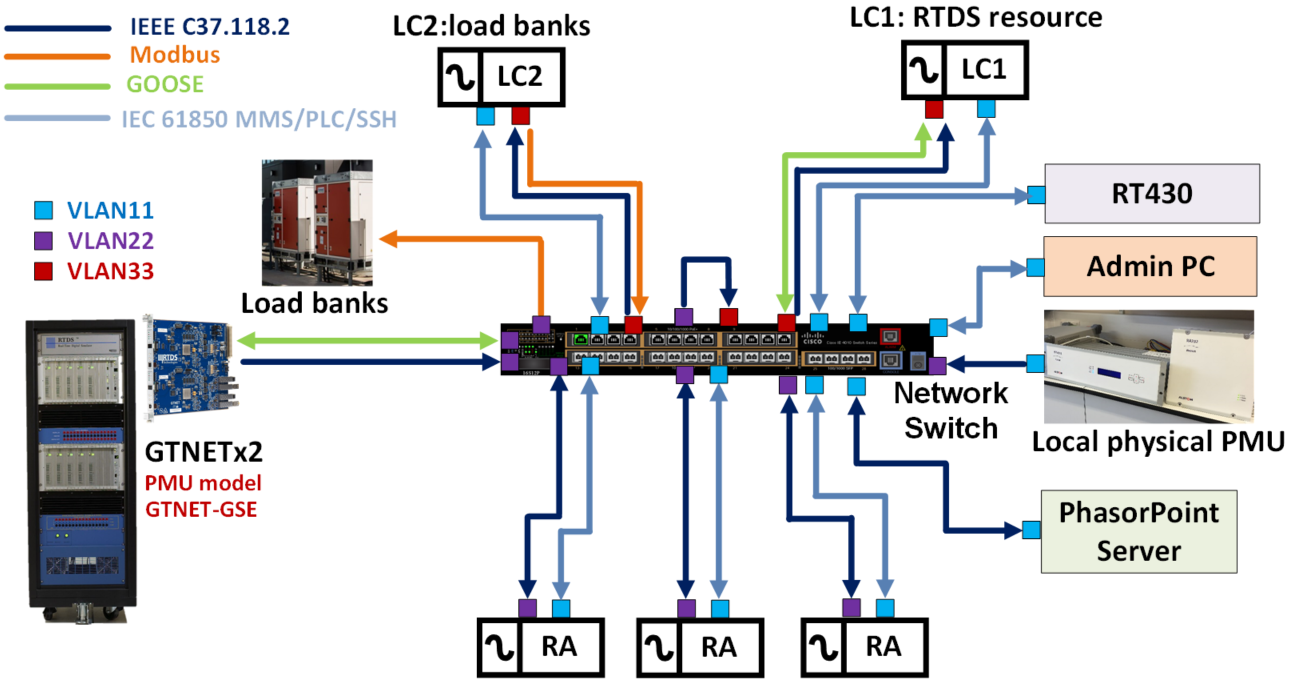

Figure 75. Setup of communication links

Table 32. Communication parameters of associated devices

Devices	VLAN ID	IP Address	MAC address	Port number
Communication switch	N/A	192.168.1.250	Not required	N/A
RA1	1	192.168.1.111	Not required	1
	22	192.168.22.242	80:B3:2A:94:00:14	13
RA2	1	192.168.1.112	Not required	2
	22	192.168.22.243	80:B3:2A:94:00:1C	14
RA3	1	192.168.1.113	Not required	3
	22	192.168.22.244	80:B3:2A:94:00:32	15
LC1 (RTDS)	1	192.168.1.110	Not required	4
	33	192.168.22.245	80:B3:2A:94:00:2E	16
LC2 (Load bank)	1	192.168.1.109	Not required	5
	33	192.168.22.246	80:B3:2A:94:00:2A	17

Physical PMU	33	192.168.22.200	Not required	12
PhasorPoint PC	1	192.168.1.106	Not required	10
	22	192.168.22.201	Not required	
Load bank	22	192.168.22.204	Not required	11
GPS clock	1	192.168.1.108	Not required	7
Straton PC	1	192.168.1.105	Not required	8
RTDS	22	192.168.22.202	Not required	18 (PMU)
	22	Not required	Not required	21 (GOOSE)
VLAN1-Admin	1	N/A	N/A	6
VLAN22-Admin	22	N/A	N/A	20
VLAN33-Admin	33	N/A	N/A	9

APPENDIX B: REDUCED GB TRANSMISSION NETWORK MODEL IN RTDS

The reduced GB transmission network model in RTDS is illustrated in Figure 76, with detailed dispatching information provided in Table 33. The model contains three regions: Region 1 represents the north part of the network containing two Synchronous Generators (SGs, i.e. SG1-1 and SG1-2), one Non-Synchronous Generator (NSG, i.e. NSG1), two loads (i.e. L1-1 and L1-2) and one energy storage resource controlled by LC1; Region 2 represents the middle part of the network containing one SG (i.e. SG2), one NGS (i.e. NSG2) and one load (i.e. L2); and Region 3 represents the south part of the network containing two SGs (SGs, i.e. SG3-1 and SG3-2), one NSG (i.e. NSG3); two loads (i.e. L3-1 and L3-2) and one demand-side resource controlled by LC2. NSGs (including the energy storage unit controlled by LC1) is modelled using controllable current sources.

When the model is dispatched according to the data presented in Table 33, the overall system will have an inertia level of approximately 82 GVAs. The model can be adjusted to represent different inertia levels by changing the capacities of the SGs and the values of their associated inertia constant (H).

The SGs are equipped with "IEEEG1" type governor [6, 7], providing primary response in addition to the EFCC response during frequency disturbance. The selected governor model aligns with the model used by the University of Manchester and was validated against the GB 36-bus model in PowerFactory. The schematics of the IEEEG1 governor and turbine models are presented in Figure 77 and Figure 78 respectively, and the detailed configurations of the models are provided in Table 34.

The excitation system model used in the SGs is with "IEEE ST1A" type [8], and the detailed schematic of the model and its configurations are presented in Figure 79 and Table 35 respectively.

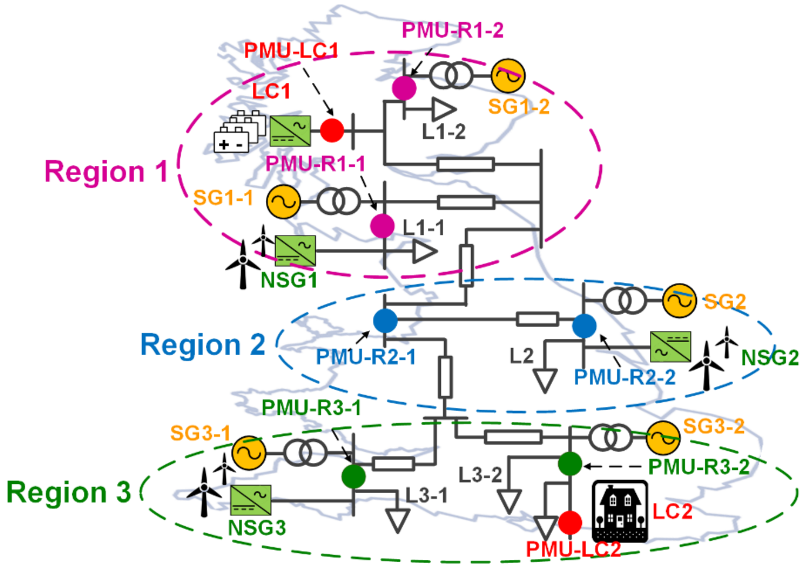

Figure 76. Schematic of the RTDS GB reduced transmission network model

Table 33. Dispatch of the GB transmission network model in RTDS

Region	Generation					Load		
		S (GVA)	P (GW)	Q (GVar)	H (s)		P (GW)	Q (GVar)
1	SG1-1	2	1.18	0.053	3	L1-1	2	0.4
	SG1-2	2	1.58	1.45	3	L1-2	2	1
	NSG1	N/A	3	0	N/A	-	-	-
2	SG2-1	4	3.16	0.42	4	L2	2.2	0.4
	NSG2	N/A	3	0	N/A	-	-	-
3	SG3-1	4	3.15	1.93	6	L3-1	3.2	0.6

	SG3-2	5	3.95	1.13	6	L3-2	11	2.2
	NSG3	N/A	3	0	N/A	-	-	-
Total	**-**	**-**	**22.02**	**4.98**	**-**	**-**	**20.4**	**4.3**

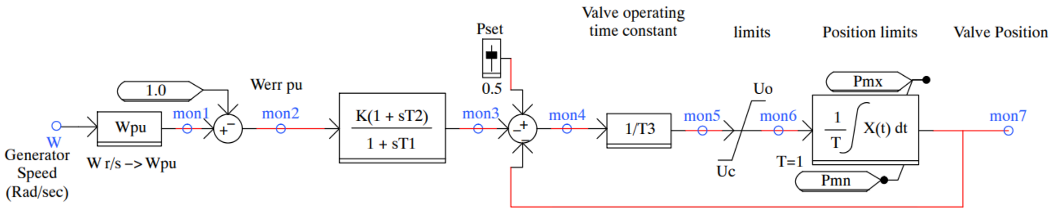

Figure 77. IEEEG1 speed governor model [7]

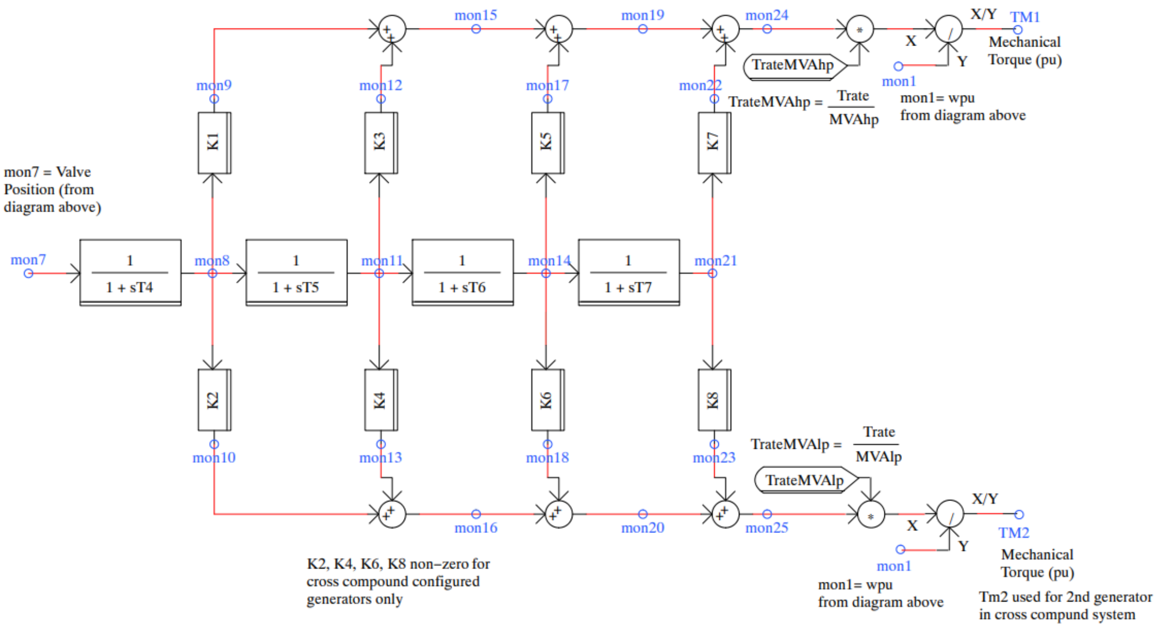

Figure 78. IEEEG1 steam turbine model [7]

Table 34. Parameters of the SGs' governor models in the RTDS GB transmission network model [7]

Name	Description	Value	Unit
K	Governor gain[1]	14	-
T_1	Governor lag time constant	1	s
T_2	Governor lead time constant	1	s

[1] It should be noted that the governor gain represents a droop value of 1/14=7.1%, which is higher than the typical droop value of 4% that is used in the actual GB system. When validating the RTDS model, it was noticed that the droop values used in the model need to be higher than the typical value of 4% in the actual system in order to make the model behave similarly to historical events. It is considered that this is due to the fact that in the actual system, not all SGs are equipped with droop control while all SGs in the RTDS model contain droop-type controllers, so the droop settings in the model need to be tuned less sensitive to frequency changes to compensate the differences between the model and the actual system.

T_3	Valve positioner time constant	0.5	s
U_o	Maximum valve opening velocity	0.1	pu/s
U_c	Minimum valve opening velocity	-10	pu/s
P_{mx}	Maximum valve opening	1.1	pu
P_{mn}	Minimum valve opening	0.4	pu
T_4	Inlet piping/steam bowl time constant	0.32	s
K_1	Fraction of high pressure shaft power after first boiler pass	0.25	-
K_2	Fraction of low pressure shaft power after first boiler pass	0	-
T_5	Time constant of second boiler pass	10	s
K_3	Fraction of high pressure shaft power after second boiler pass	0	-
K_4	Fraction of low pressure shaft power after second boiler pass	0	-
T_6	Time constant of third boiler pass	0.2	s
K_5	Fraction of high pressure shaft power after third boiler pass	0.2	-
K_6	Fraction of low pressure shaft power after third boiler pass	0	-
T_7	Time constant of fourth boiler pass	3	s
K_7	Fraction of high pressure shaft power after fourth boiler pass	0.55	-
K_8	Fraction of low pressure shaft power after fourth boiler pass	0	-

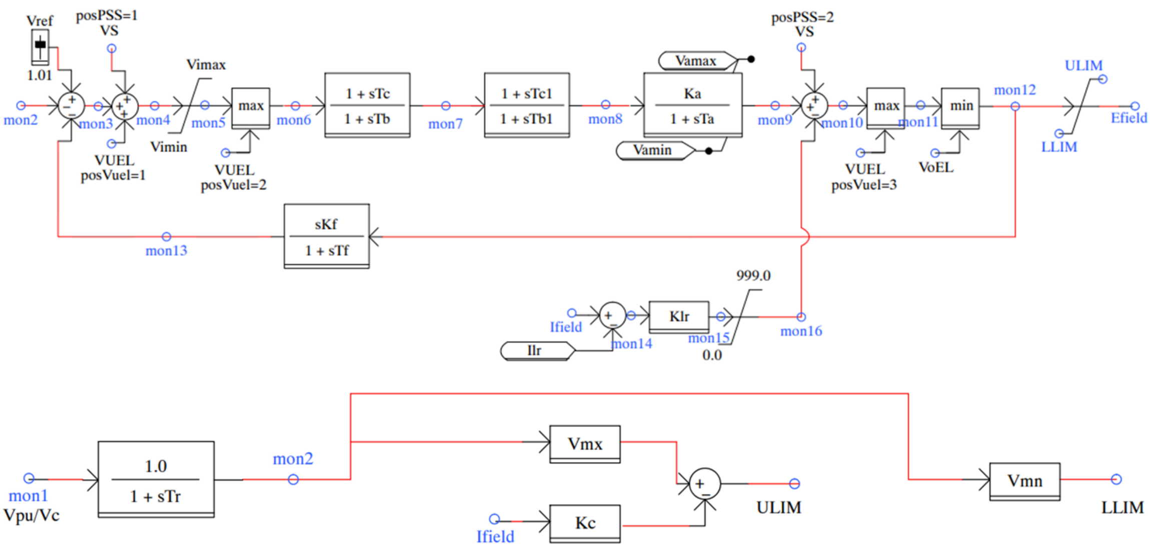

Figure 79. IEEE ST1A excitation system [9]

Table 35. Parameters of the SGs' excitation system models in the RTDS GB transmission network model [9]

Name	Description	Value	Unit

Tr	Voltage transducer time constant	0	s
V_{imx}	Maximum error limit	1	pu
V_{imn}	Minimum error limit	-1	pu
T_c	AVR lead time constant	1	s
T_b	AVR lag time constant	20	s
T_{c1}	AVR lead time constant	0	s
T_{b1}	AVR lag time constant	0	s
K_a	Voltage regulator gain	200	-
T_a	Voltage regulator time constant	0.02	s
V_{amx}	Maximum control element output	8	pu
V_{amn}	Minimum control element output	-8	pu
V_{rmx}	Maximum controller limit	5.7	pu
V_{rmn}	Minimum controller limit	-4.9	-
K_c	Excitation system regulation factor	0.175	-
K_f	Rate feedback gain	0	-
T_f	Rate feedback time constant	1	s
K_{lr}	Current limit reference gain	4.54	-
I_{lr}	Current limit reference	4.4	-

APPENDIX C: LC SETTINGS AND RESOURCE AVAILABILITY INFORMATION FOR ALL TESTS

Table 36. Settings in the LCs' event detection blocks

Setting Parameter	Description	Value
sOVFreqThr	Frequency threshold for over-frequency events	0.6% (0.3Hz)
sOvFreqRCFThr	RoCoF threshold for over-frequency events	0.1 Hz/s
sUnFreqThr	Frequency threshold for under-frequency events	0.6% (0.3Hz)
sUnFreqRCFThr	RoCoF threshold for under-frequency events	0.1 Hz/s
sLocCtrl	Enabling local mode	false

Table 37. Settings in the LCs' resource allocation blocks

Setting Parameter	Description	Value
sWa2LocSwDl	Switching time delay from wide area to local mode	10s
sSusRspTm	Timeout of sustained response	20s
sSusRspRsFrq	Frequency boundaries to release resource	0.06
sSusRspRsRCF	RoCoF boundary to release resource	0.05
sLocCtrl	Enabling local mode	false

Table 38. Resource availability information for Test 1, 2, 3, 4, 5, 14, and 15

	LC1	LC2
Resource type	1	1
Availability	true	true
Positive available power	300 MW	300 MW[2]
Negative available power	300 MW	300 MW
Positive power response time	0.1 s	0.1 s
Negative power response time	0.1 s	0.1 s
Power ramp up rate	1000MW/s	1000MW/s
Power ramp down rate	1000 MW/s	1000 MW/s
Positive power max duration	80s	80s
Negative power max duration	80s	80s

Table 39. Resource availability information for Test 6 and 7

	LC1	LC2
Resource type	1	1
Availability	true	true
Positive available power	600 MW	600 MW
Negative available power	600 MW	600 MW
Positive power response time	0.1 s	0.1 s
Negative power response time	0.1 s	0.1 s
Power ramp up rate	1000MW/s	1000MW/s
Power ramp down rate	1000 MW/s	1000 MW/s
Positive power max duration	80s	80s
Negative power max duration	80s	80s

[2] The total capacity of the load bank used in the physical network is 50 kW, but it was amplified to 300 MW in simulation via the P-HiL configuration as detailed in the paper [2]. The level of amplification is $(V_{grid}/V_{MG})\times G_i$, where V_{grid} =400 kV and it is the voltage level in simulation; V_{MG} =11 kV is the voltage level at MG set terminal; and G_i=165 is the current amplification factor.

Table 40. Resource availability information for Test 8, 9, 12 and 13

	LC1	LC2
Resource type	1	1
Availability	true	true
Positive available power	1000 MW	1000 MW
Negative available power	1000 MW	1000 MW
Positive power response time	0.1 s	0.1 s
Negative power response time	0.1 s	0.1 s
Power ramp up rate	1000MW/s	1000MW/s
Power ramp down rate	1000 MW/s	1000 MW/s
Positive power max duration	80s	80s
Negative power max duration	80s	80s

Table 41. Resource availability information for Test 10

	LC1	LC2
Resource type	1	1
Availability	true	true
Positive available power	300 MW	1000 MW
Negative available power	300 MW	1000 MW
Positive power response time	0.1 s	0.1 s
Negative power response time	0.1 s	0.1 s
Power ramp up rate	1000MW/s	1000MW/s
Power ramp down rate	1000 MW/s	1000 MW/s
Positive power max duration	80s	80s
Negative power max duration	80s	80s

Table 42. Resource availability information for Test 11

	LC1	LC2
Resource type	1	1
Availability	true	true
Positive available power	1000 MW	300 MW
Negative available power	1000 MW	300 MW
Positive power response time	0.1 s	0.1 s
Negative power response time	0.1 s	0.1 s
Power ramp up rate	1000MW/s	1000MW/s
Power ramp down rate	1000 MW/s	1000 MW/s
Positive power max duration	80s	80s
Negative power max duration	80s	80s

APPENDIX D: DATA RECORDED IN THE REGIONAL AGGREGATORS FOR UNDER-FREQUENCY TESTS IN SECTION 5

In this section, the regional frequency measured by the RAs along with the system frequency measured by the LCs in the under-frequency tests as reported in Section 5 are presented. In the following presented figures, the variations in the frequency in different regions of the network are shown. In some cases, the regional variation of frequency is relatively small (e.g. Figure 80), while in other cases, the regional variation can be relatively large (e.g. Figure 87). This is caused by the different regional inertia and the frequency disturbance locations.

In each of the figure, it can be seen that the system frequency lags the regional frequency by approximately 100 ms. This is due to the buffering window that was used to deal with communication latency and jitter, i.e. the LCs intentionally wait for 100 ms for the packets to arrive. More detail on the buffering window and the communication impact on the EFCC operation is presented in Part 3 of the test report (a separate document).

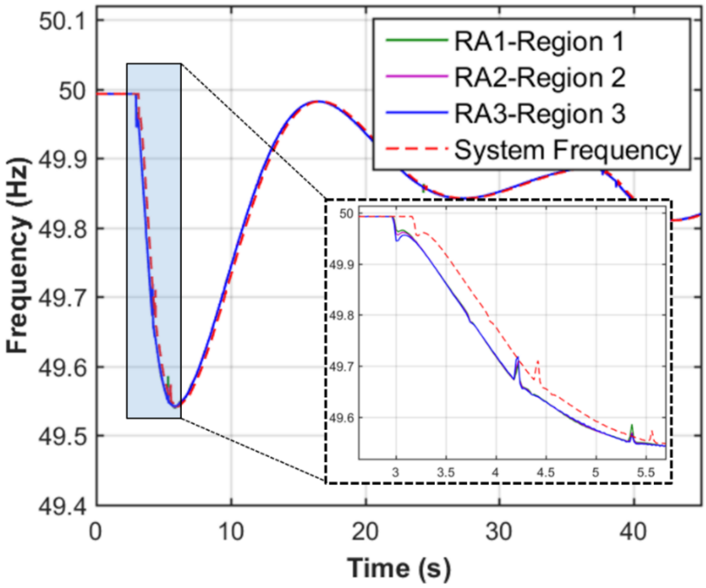

Figure 80. Data recorded in the RAs in the under-frequency test in Test 1

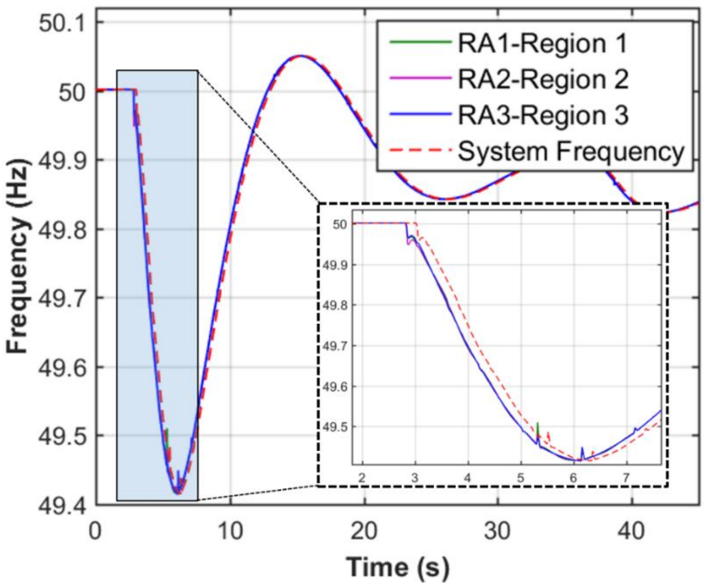

Figure 81. Data recorded in the RAs in the under-frequency test in Test 2

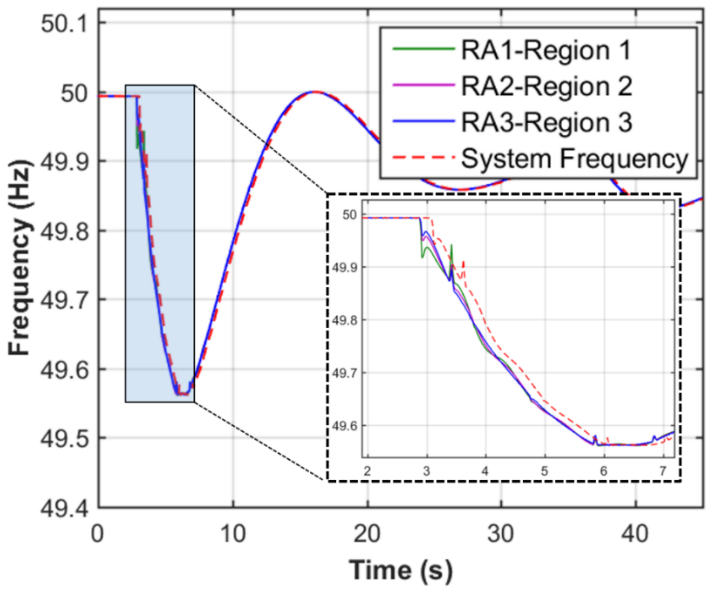

Figure 82. Data recorded in the RAs in the under-frequency test in Test 3

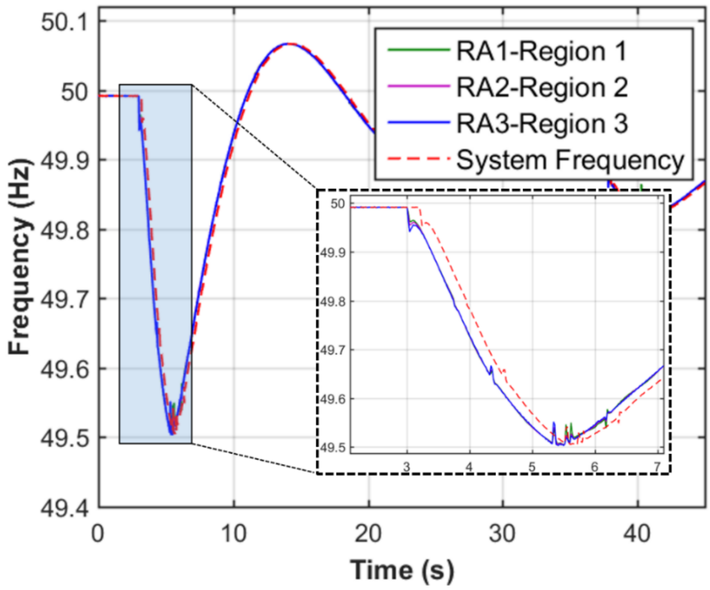

Figure 83. Data recorded in the RAs in the under-frequency test in Test 4

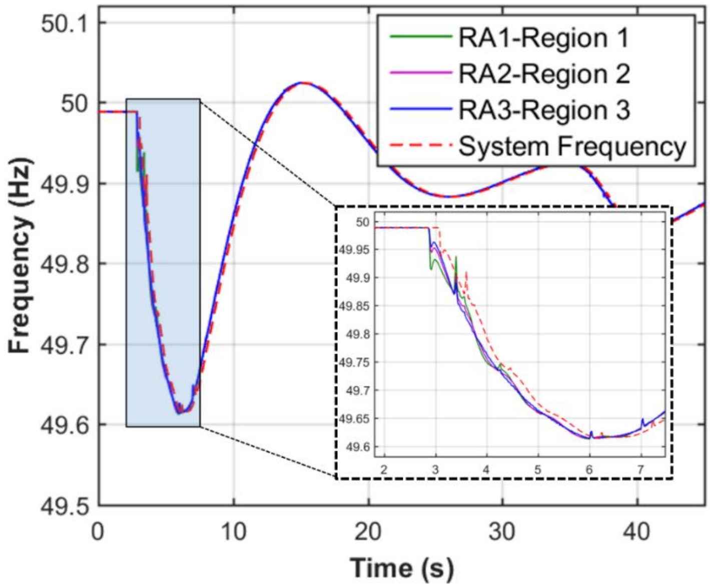

Figure 84. Data recorded in the RAs in the under-frequency test in Test 5

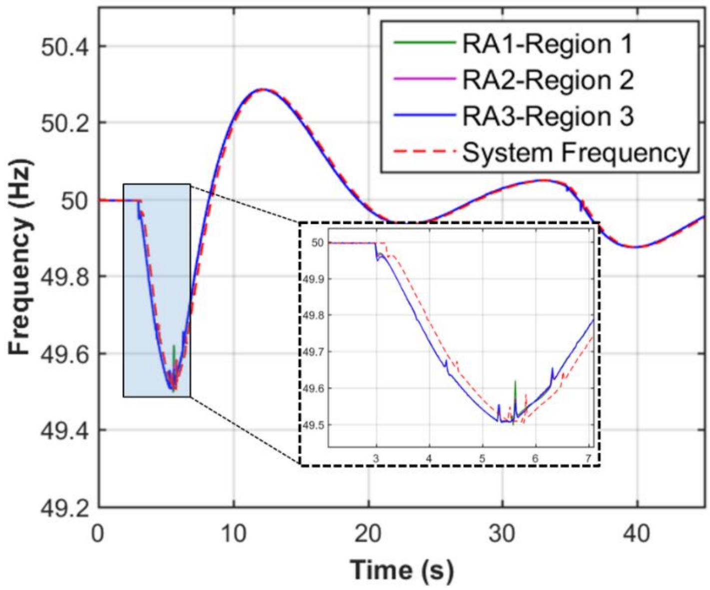

Figure 85. Data recorded in the RAs in the under-frequency test in Test 6

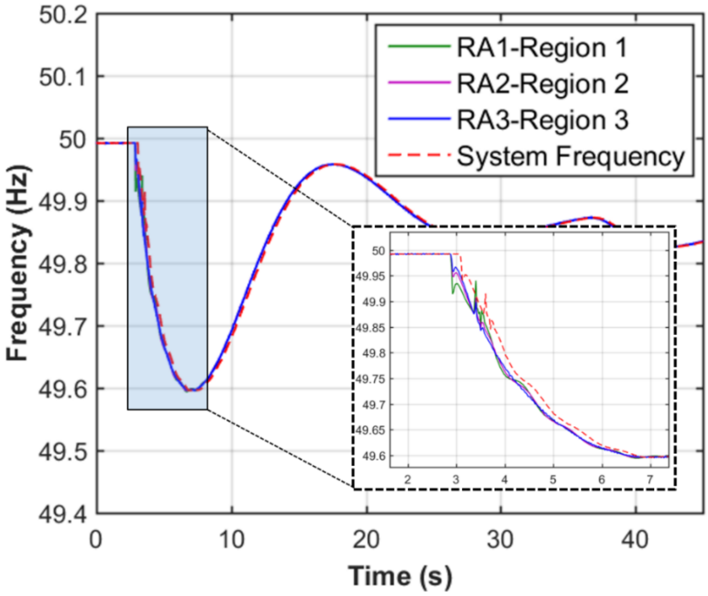

Figure 86. Data recorded in the RAs in the under-frequency test in Test 7

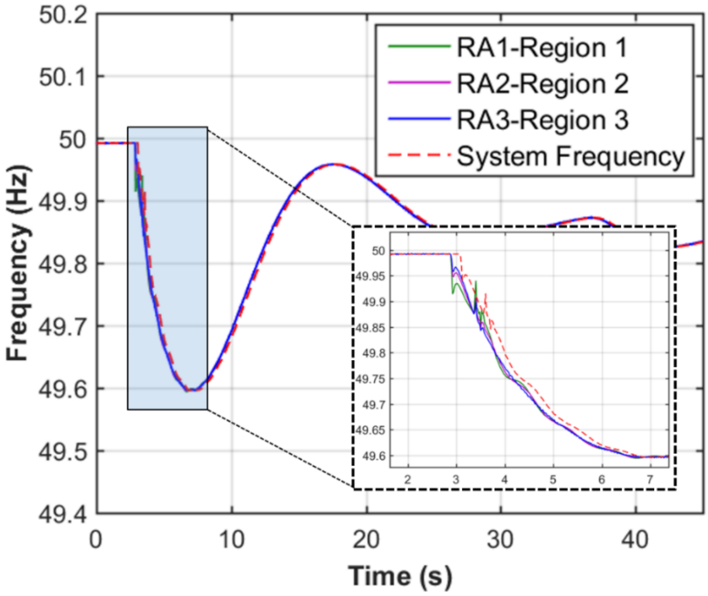

Figure 87. Data recorded in the RAs in the under-frequency test in Test 8

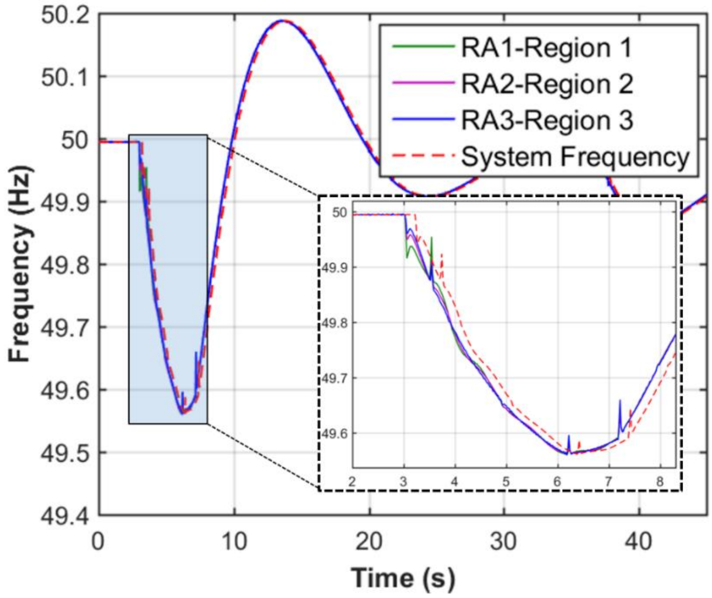

Figure 88. Data recorded in the RAs in the under-frequency test in Test 9

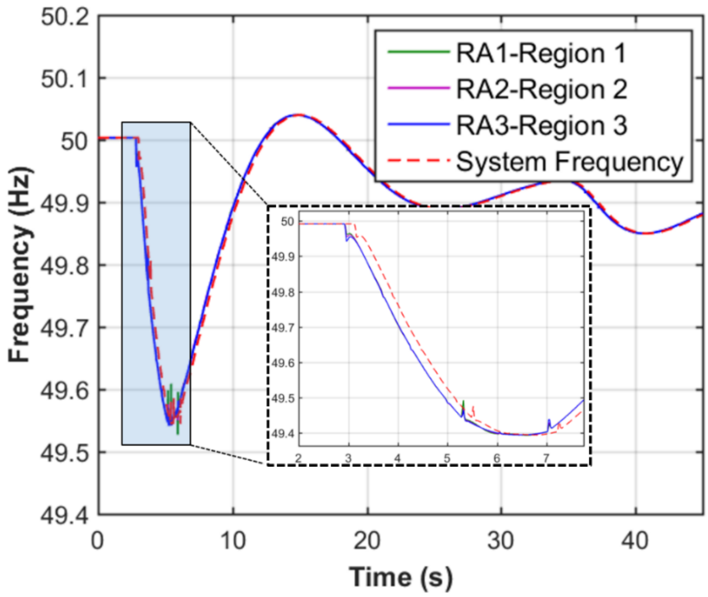

Figure 89. Data recorded in the RAs in the under-frequency test in Test 10

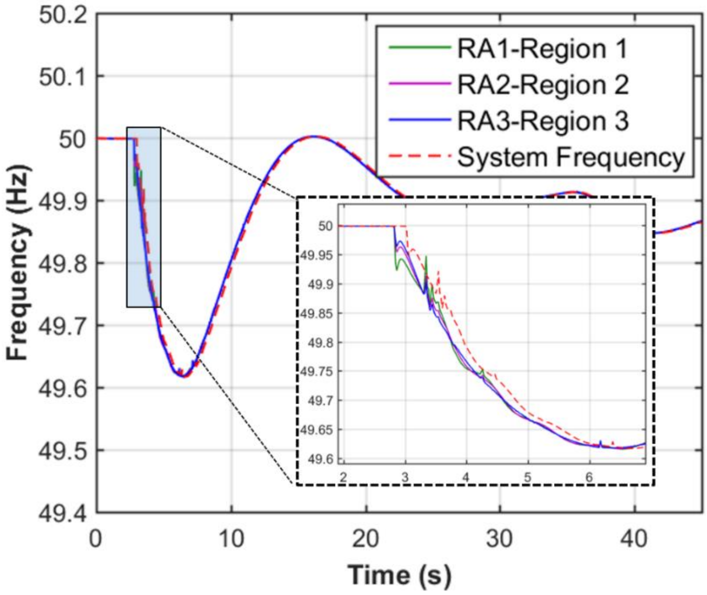

Figure 90. Data recorded in the RAs in the under-frequency test in Test 11

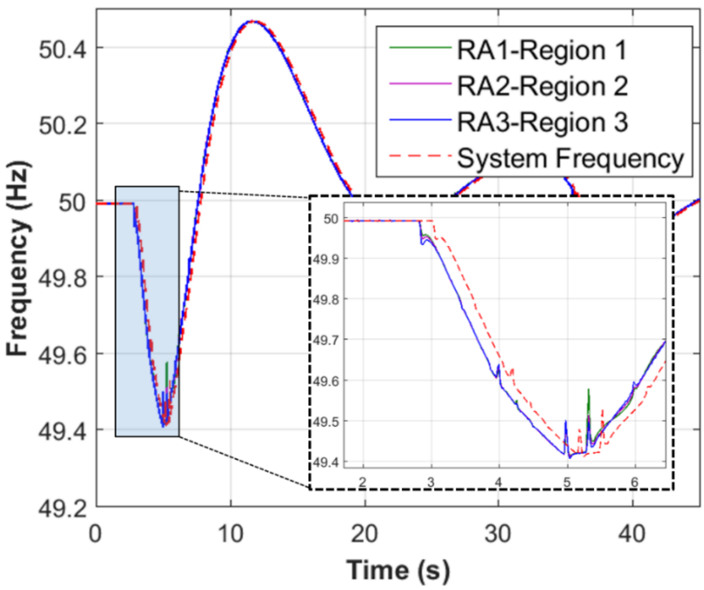

Figure 91. Data recorded in the RAs in the under-frequency test in Test 12

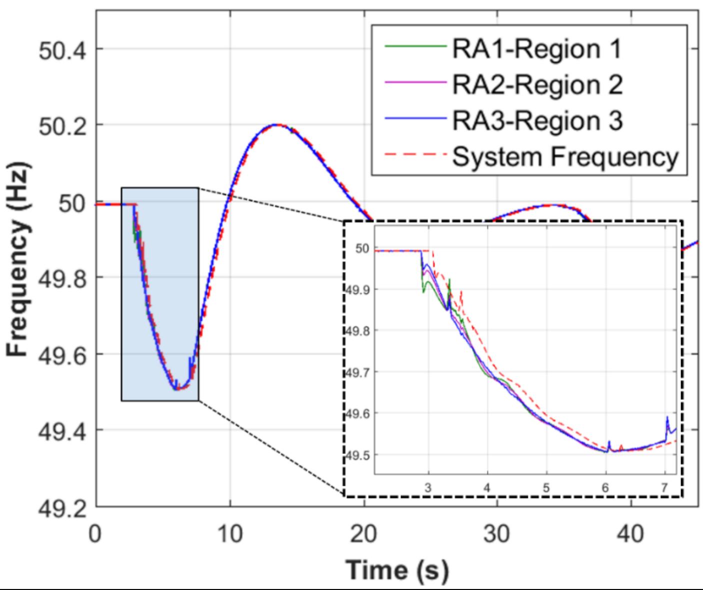

Figure 92. Data recorded in the RAs in the under-frequency test in Test 13

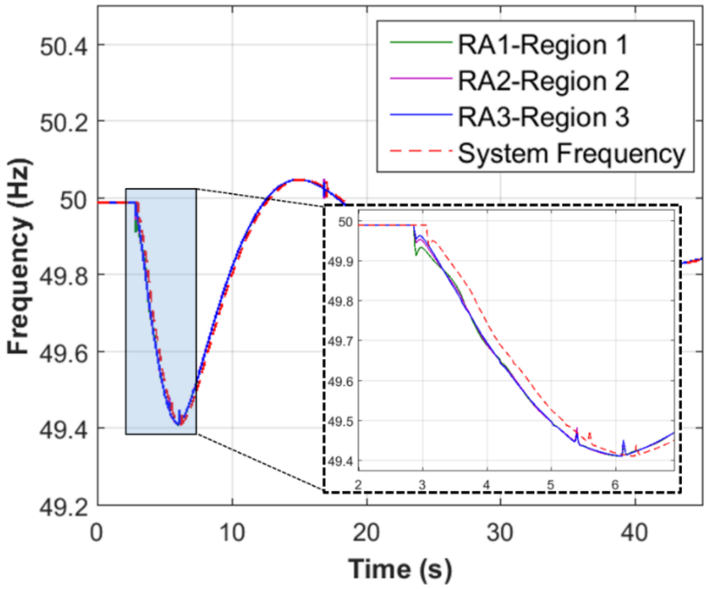

Figure 93. Data recorded in the RAs in the under-frequency test in Test 14

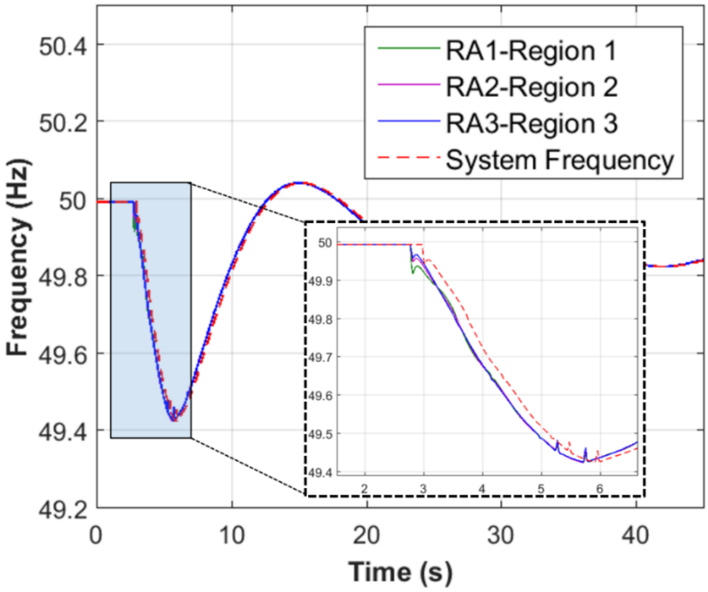

Figure 94. Data recorded in the RAs in the under-frequency test in Test 15