Testing of the Enhanced Frequency Control Capability (EFCC) Scheme: Additional Local Operational Mode Tests

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EXECUTIVE SUMMARY

This report presents further studies and tests conducted at the Power Networks Demonstration Centre (PNDC) for the investigation of the Enhanced Frequency Control Capability (EFCC) scheme's local operational mode and interim wide-area mode.

For the local operational mode studies, the impact of the signal filters implemented in the Local Controllers (LCs) for frequency and Rate of Change of Frequency (RoCoF) measurements have been investigated. It was found that the filters played an important role in removing noises in the original signals transmitted by the scheme’s PMUs, thus reducing the risk of undesirable operation of the LCs. However, the filtering of the signals will lead to delays in decision making. For frequency measurements, the delay is approximately 0.5 s, whereas for RoCoF measurements, there is a delay of approximately 2 s between the event occurrence and the time at which filtered RoCoF reaches its maximum magnitude. In addition to the delay in measurement, the filtered RoCoF measurements also have smaller magnitudes compared to the unfiltered measurements. These impacts from single filtering need to be taken into account when configuring the settings associated with the local mode of operation to ensure the response is triggered with sufficient speed.

Methods for calculating the appropriate LCs' settings so as to avoid Low Frequency Demand Disconnection (LFDD) operation have been developed, which take into account the filtering delay of the measurements, resource deployment delay, event sizes, etc. The developed setting methods and the calculated settings are validated against a range of different events with different resource capacities. It was found that the developed setting calculation methods were able to ensure the resources are successfully deployed before the frequency reaches the first stage LFDD threshold of 48.8 Hz. This is critical in order to avoid both LFDD disconnection of load and incorrect response from LCs to frequency events, which could introduce potential risks of cascade instability.

In this study, the quantification of the resource capacity required for avoiding LFDD operation with largest single generation loss of 1.8 GW at 82 GVAs and 67 GVAs inertia levels has also been conducted. The quantification of the resource capacity is based on the conservative assumption where only 20% of available resource is triggered with the settings calculated by the methods developed in this work. It was found that with a resource response delay of 0.5 s, for the 82 GVAs inertia level, the frequency and RoCoF thresholds need to be configured as 49.4 Hz and 0.30 Hz/s, and the EFCC response required is 200 MW (i.e. 1000 MW of capacity) to avoid LFDD operation. For the 67 GVAs inertia level, the frequency and RoCoF thresholds need to be configured as 49.5 Hz and 0.28 Hz/s, and the EFCC response required is 500 MW (i.e. 2500 MW of capacity) to avoid LFDD operation.

The report also evaluates the feasibility of using the interim wide-area mode as an alternative of the EFCC's wide-area operational mode. It was found that the key advantage of the interim wide-area mode is it avoids the need for real-time communication across different zones, while still being able to provide a level of regional consideration for resource deployment during frequency disturbances. The potential options for further development and implementation of the interim wide-area mode are presented, which include prototyping the scheme in real-time platforms and testing it using a real-time hardware-in-the-loop approach to further validate its performance.

LIST OF ABBREVIATIONS

CS	Central Supervisor
COI	Centre of Inertia
EFCC	Enhanced Frequency Control Capability
GE	General Electric
LC	Local Controller
LFDD	Low Frequency Demand Disconnection
NG	National Grid
NIC	Network Innovation Competition
PMU	Phasor Measurement Unit
PNDC	Power Networks Demonstration Centre
RA	Regional Aggregator
UoM	University of Manchester
UoS	University of Strathclyde

Contents

1 INTRODUCTION

This report presents further studies and tests conducted at the PNDC for the investigation of EFCC's local operational mode and interim wide-area mode as requested by National Grid.

The EFCC scheme, as developed by GE, has two main operational modes, wide-area and local mode. The wide-area mode is considered as the normal operational mode and is used when wide-area measurement signals are available and with sufficiently good quality, while the local mode is used when the wide-area communication links are lost or the wide-area data quality is of inadequate quality for making reliable system wide decisions. Comprehensive performance verification of these two operational modes has been conducted and the test results are presented in [1] and [2] respectively.

In the studies and tests presented in this report, the impact of the signal filters implemented in the LCs' local operational mode for frequency and RoCoF measurements is investigated. The methods for calculating appropriate settings (i.e. frequency and RoCoF thresholds in event detection and resource allocation functions) for LCs to avoid LFDD will be presented. The quantification of the EFCC's capacity required when there is only 20% of the resource deployed to avoid LFDD will also be discussed.

The interim wide-area mode has been developed by the University of Manchester (UoM) as an alternative approach to GE's wide-area operational mode and it attempts to provide regional responses with lower requirements on communication infrastructures than the GE developed wide-area mode [3]. In this report, the feasibility of using the interim wide-area mode as an alternative of the EFCC's wide-area operational mode is evaluated. The advantages of the interim wide-area mode will be discussed and the potential improvements and further developments for implementation in a real system are also investigated and presented. The potential options for implementing the interim wide-area mode in real-time platforms is investigated and the methods and arrangement for testing such a real-time system is also presented.

This report is organised as follows: in Section 2, the objectives for the tests and the studies are presented; the limitations and assumptions of the tests are discussed in Section 3; the test configuration is described in Section 4; Section 5 presents the studies for investigating the impact of the filters implemented in the LCs on the frequency and RoCoF measurements; Section 6 presents the methods developed for the configuration of the settings in LC's local operational mode and the test results for the validation of the calculated settings; Section 7 presents the quantification of the EFCC capacity required in its local operation mode to avoid LFDD; In Section 8, the interim wide-area mode operation will be evaluated in detail and further developments for its implementation in a real system are discussed. Section 9 summarises the key learnings and conclusions from the studies presented in this report.

2 OBJECTIVES

2.1 Objectives of local mode extra tests

For the extra tests of the EFCC's local operational mode, there are three main objectives:

- Evaluation of the impact of the filters implemented in LCs on both frequency and RoCoF measurements;
- Development of methods for calculating appropriate settings for frequency and RoCoF thresholds in order to avoid LFDD;
- Quantification of the EFCC response required in local mode to avoid LFDD when there is only 20% of the resource being deployed (this is considered as the worst-case scenario, where only one out of five stages of response deployment is triggered).

2.2 Objectives of the evaluation of the interim wide-area mode

For the evaluation of the interim wide-area mode, the objectives are:

- To evaluate the advantages and limitations of this approach, so as to gain a detailed understanding of its feasibility for practical deployment.
- To produce recommendations on the real-time implementation and testing options for this operational mode and potential improvements for its further development.

3 TEST LIMITATIONS AND ASSUMPTIONS

The main limitation for the test is associated with the uncertainty of the available primary reserve power, types of resources providing primary response and the characteristics and capability of the EFCC resources. This will impact the frequency behaviour during loss of generation events, thus affecting the selection of appropriate settings for the LCs.

To address this issue, this work has adopted the worst-case scenario where no primary response is triggered before the EFCC response in its local mode (more detail about this will be discussed in Section 6).

4 TEST CONFIGURATION

Figure 1 shows the test configuration for the local mode tests in this work. The GB transmission network model is simulated in RTDS and the instantaneous voltage signals measured at the LC location are output from the RTDS which is amplified. The amplified RTDS reference voltage signals are fed to physical PMU (110 V PMU input represent nominal 400 kV bus voltage). The PMU sends synchrophasor data to the LC using IEEEC37.118.2 [4]. The LC monitors these synchrophasor measurements and sends commands via GOOSE messaging to control a simulated resource in RTDS in accordance to its control logic. More detail about the simulated network model is available in [2].

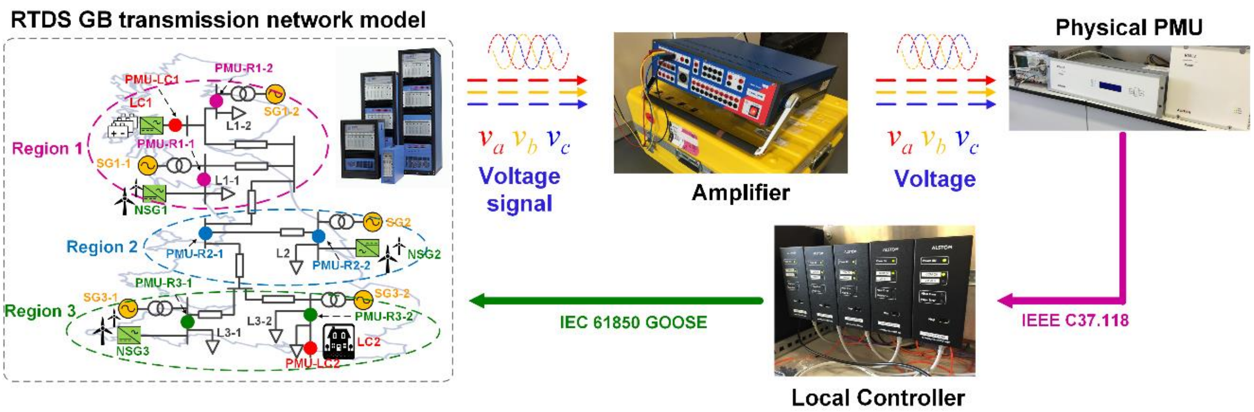

Figure 1. Schematic of the local mode test configuration

5 IMPACT OF FILTERING ON FREQUENCY AND ROCOF MEASUREMENT

This section investigates the impact of signal filtering on the frequency and RoCoF measurements in the LCs while in local operational mode. The filtering impact will be taken into account to determe appropriate settings for frequency and RoCoF thresholds in order to avoid LFDD, which is presented in Section 6.

5.1 Impact of filtering on frequency measurements

According to the EFCC user manual [5], during the local mode, the frequency measured by the local PMU will be filtered using a low-pass filter in the LC in order to remove inter-area oscillations and transient behaviours due to faults. The cut-off frequency (f_c) of the low-pass filter is 0.3 Hz, based on which the time constant (t_c) of the filter can be calculated as follows:

$$t_c = \frac{1}{2\pi f_c} = \frac{1}{2\pi \times 0.3} = 0.53s$$

This means that the frequency measurement will be delayed by approximately 0.53 s. Figure 2 shows the un-filtered frequency measured by a PMU and the filtered frequency measurement from a LC during a loss of generation event. A zoom-in view of Figure 2 is provided in Figure 3. It can be seen from Figure 3 that the frequency measured by the PMU decreased to 49.70 Hz at around 31.33 s, while the filtered frequency measurement reached 49.70 Hz at around 31.83 s, which delayed the PMU measurement for around 0.5 s. This aligns with GE's design specification regarding the low-pass filter in the LC.

In this example, 49.70 Hz is the first frequency setting threshold of the LC, which when violated, it was expected that the LC would deploy 20% of its available resource. From the results presented in Figure 2 and Figure 3, it can be seen that the LC used the filtered frequency as the base for determining whether the frequency threshold has been violated, which led to approximately 0.5 s of delay in decision making. This response characteristic will be taken into consideration for determining the settings of the frequency threshold, which is discussed in detail in Section 6.

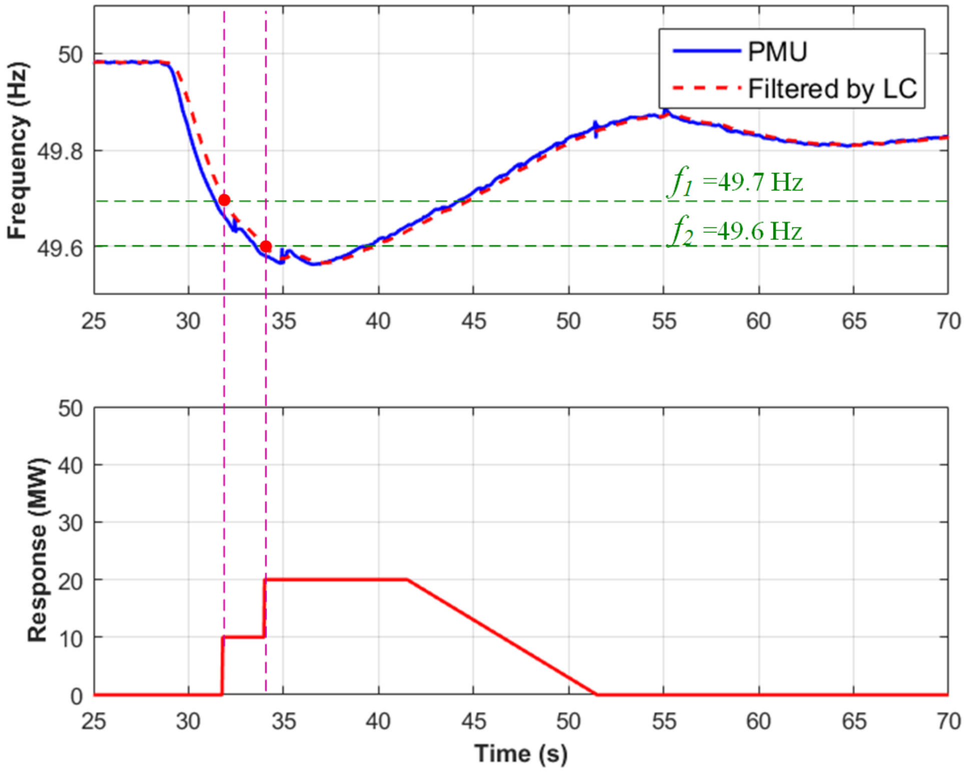

Figure 2. Un-filtered frequency measurement in a PMU and filtered frequency measurement in the LC during a loss of generation event

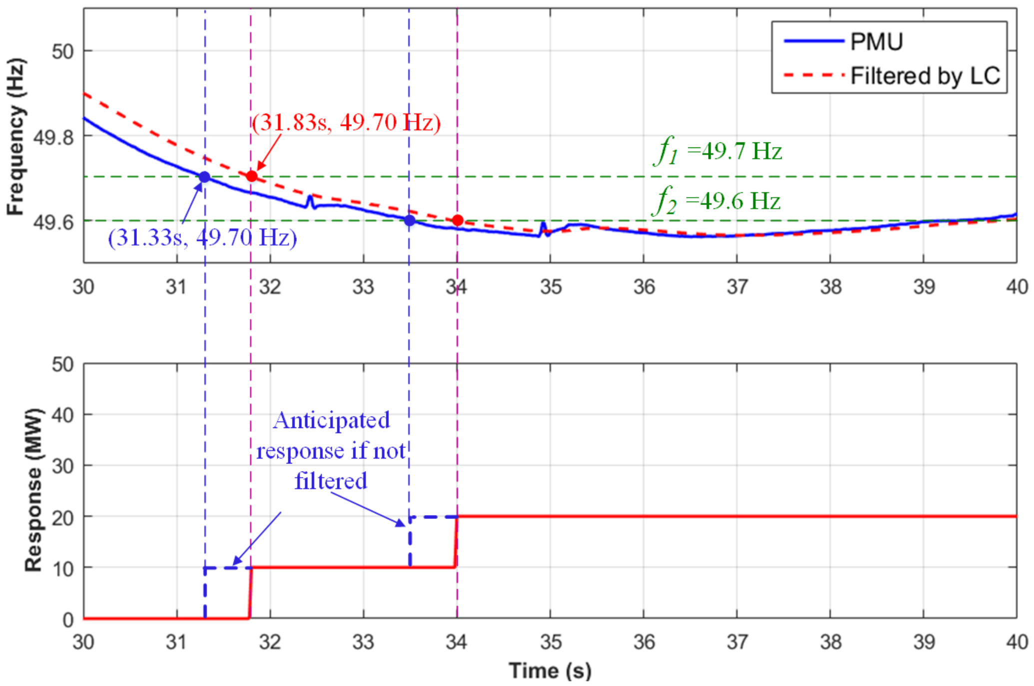

Figure 3. Zoom-in view of the un-filtered frequency measurement in a PMU and filtered frequency measurement in the LC in a loss of generation event

5.2 Impact of filtering on RoCoF measurement

The RoCoF measurement can be significantly different for different PMU models and manufacturers. In this section, the RoCoF measured by a GE physical PMU, a PMU model (P class) in RTDS, and the LC will be compared with the derivative of the machine speed during frequency disturbances.

Figure 4 shows the RoCoF measurements from an event with a loss of 1 GW generation in Region 2 and the measurement point located in Region 3. Figure 4.(b) is a zoom-in view of Figure 4.(a). It can be seen that the event occurred at around 1.49 s. Following the event, both the RTDS PMU model and the GE physical PMU produced very noisy RoCoF measurements, but the filtered RoCoF measured in the LC is much smoother and successfully removed the undesirable transient spikes. However, it should also be noted that the filtered RoCoF in the LC has a smaller RoCoF peak magnitude than all the other measurement methods. The machine speed measurement is taken from the simulated synchronous machines in the RTDS and it can be seen that its derivative reached the minimum value (i.e. maximum in magnitude) at around 1.84 s, while the filtered RoCoF reached its minimum at 3.40 s, which delayed the event occurrence for 3.40 s-1.49 s=1.91 s.

Similar observations were made in a number of other simulated events (with the measurement point remaining in Region 3): Figure 5 shows the RoCoF measurements from a loss of 1 GW event in Region 3, where the LC measured RoCoF delayed the event occurrence by 1.94 s; Figure 6 shows the RoCoF measurements from a loss of 1.8 GW event in Region 2, where the LC measured RoCoF delayed the event occurrence by 1.96 s; and Figure 7 shows the RoCoF measurements from a loss of 1.8 GW event in Region 3, where the LC measured RoCoF delay the event occurrence by 2.02 s.

From the test results, the following conclusions regarding the filtered RoCoF measurement in the LC can be made:

- The signal filter in the LC appeared to be effective in removing the undesirable noise and measurement spikes in the RoCoF signals compared with physical and simulated PMU measurements;
- There is an approximate delay of 2 s between the event occurrence and the time at which the filtered RoCoF reaches its maximum magnitude;
- The filtered RoCoF measurement has a smaller largest magnitude compared with the actual largest RoCoF magnitude based on machine speed (during a frequency event, the maximum

RoCoF magnitude occurs at the point when the event happens). From the test results, it was found that the measured maximum RoCoF is around 65% of the theoretical max RoCoF as calculated from the swing equation.

The above findings are taken into consideration when defining the suitable RoCoF settings to avoid LFDD as presented in Section 6.

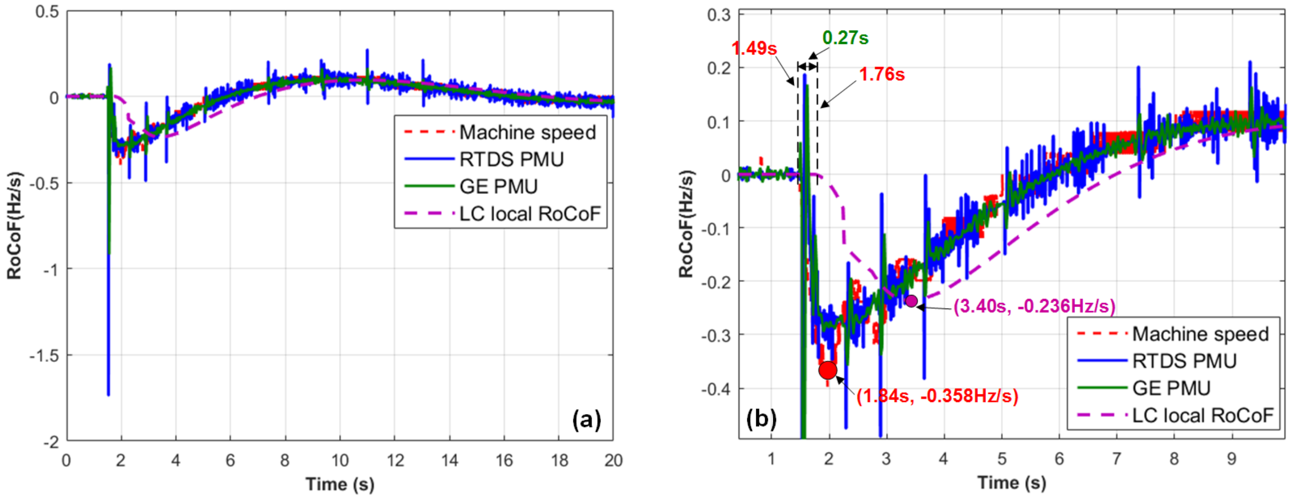

Figure 4. RoCoF measurements in a loss of 1 GW generation event (Region 2)

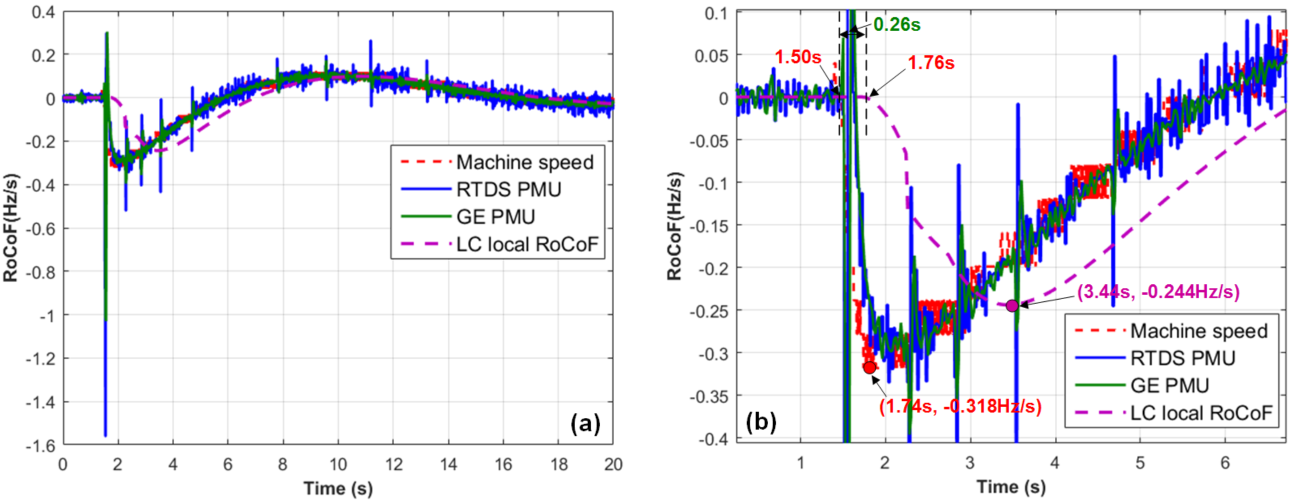

Figure 5. RoCoF measurements in a loss of 1 GW generation event (Region 3)

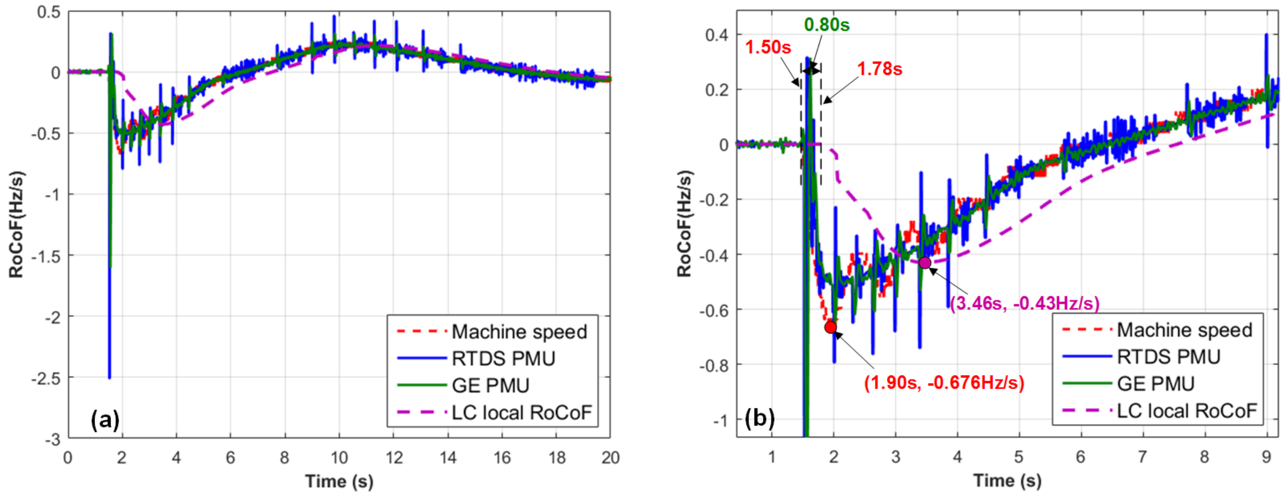

Figure 6. RoCoF measurements in a loss of 1.8 GW generation event (Region 2)

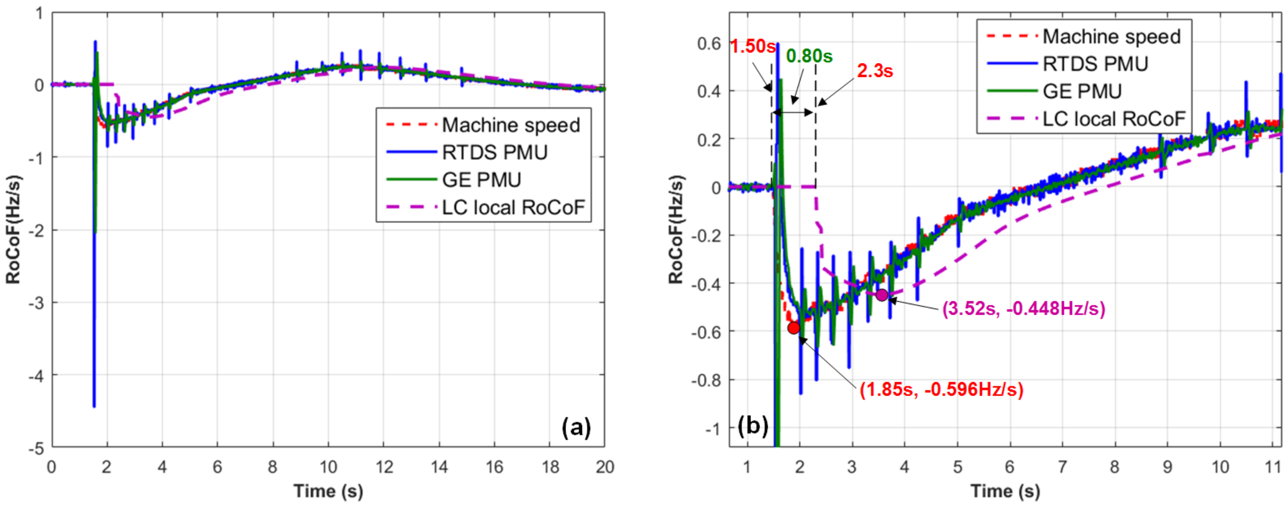

Figure 7. RoCoF measurements in a loss of 1.8 GW generation event (Region 3)

6 IDENTIFICATION OF APPROPRIATE SETTINGS FOR EFCC'S LOCAL OPERATIONAL MODE

6.1 Frequency and RoCoF thresholds in local operational mode

In EFCC's local operational mode, the detection of frequency events and the allocation of the amount of response to be deployed during the frequency disturbances are determined by the settings in the event detection and resource allocation blocks as shown in Table 1. A full description of the local mode operation is reported in [5]. However, a high level description is provided below.

In the event detection block, there is one frequency setting (f_{ED}) and one RoCoF setting ($RoCoF_{ED}$). A disturbance is considered as a frequency event when either of these two settings is violated.

In the resource allocation block, the resource is controlled to provide response in five stages. Each stage operates according to a frequency and RoCoF threshold. The use of RoCoF thresholds is optional and they can be enabled or disabled with a dedicated setting. When the RoCoF thresholds are disabled, LCs only use the measured frequency for decision making and when the frequency exceeds each of the five pre-defined thresholds, 20% of available resource will be deployed (this is currently a fixed feature in the EFCC scheme). When the RoCoF thresholds are enabled, LCs evaluate both measured frequency and RoCoF values using the associated thresholds, and only when the frequency and RoCoF thresholds are both violated, 20% of available resources will be deployed at each stage.

It should be noted that for any resource to be deployed, the disturbance has to be detected as an event, i.e. the frequency and/or the RoCoF need to violate the associated event detection thresholds.

In the following subsections, methods for determining the aforementioned frequency and RoCoF settings in event detection and resource allocation functions will be provided. As there is no unique solution for the settings, the methods established in this work will consider the most conservative settings, i.e. the settings will be configured in the manner that it will be sufficiently senstive to trigger 20% of the resource to avoid LFDD. This means, if an event can be contained by the settings calculated using the method from this work, any more sensitive settings will guarantee that the event will also be successfully contained above the LFDD threshold. Therefore, for the resource allocation block, only f_{UF1} and $RoCoF_{UF1}$ are considered as they are the thresholds determining whether the first 20% of resource should be deployed.

Table 1. Settings for decision making during under-frequency events in EFCC's local mode

Functional block	Settings	Description
Event Detection	f_{ED}	Frequency threshold setting
	$RoCoF_{ED}$	RoCoF threshold setting
Resource allocation	f_{UF1}	First frequency threshold
	$RoCoF_{UF1}$	First RoCoF threshold (optional)
	f_{UF2}	Second frequency threshold
	$RoCoF_{UF2}$	Second RoCoF threshold (optional)
	f_{UF3}	Third frequency threshold
	$RoCoF_{UF3}$	Third RoCoF threshold (optional)
	f_{UF4}	Fourth frequency threshold
	$RoCoF_{UF4}$	Fourth RoCoF threshold (optional)

	f_{UF5}	Fifth frequency threshold
	$RoCoF_{UF5}$	Fifth RoCoF threshold (optional)

This objectives of the settings calculation is to ensure:

- The disturbance that leads to LFDD (purely relying on primary response) should be detected, i.e. f_{ED} and $RoCoF_{ED}$ should be chosen to be sufficiently sensitive to allow the event to be detected at a time that allows the resources to have sufficient time to be deployed;
- f_{UF1}(and $RoCoF_{UF1}$in the case where the RoCoF thresholds are used for resource allocation) should be set sensitive enough so that when it was violated, there is sufficient time for the resource to be deployed.

In the following sections, the determination of the frequency and RoCoF settings will be discussed.

6.2 Method for calculating frequency settings

This subsection investigates possible frequency settings in order to avoid LFDD. As mentioned previously, the method will calculate conservative settings where only 20% of the resource is deployed before the frequency reaches the low frequency limit f_L, which is 48.80 Hz for the first stage LFDD. This means that f_{UF1} needs to be chosen to ensure the resource is triggered such that power will be injected to the system before it reaches f_L. As the resource will only be deployed when a disturbance is identified as a frequency event by the LC, so the event detection should also be triggered, i.e. either f_{ED} or $RoCoF_{ED}$ should be violated. This subsection will focus on the calculation of frequency thresholds f_{ED} and f_{UF1}.The RoCoF thresholds will be determined in the next subsection.

Figure 8 shows the critical timings to be considered for determining the suitable frequency thresholds. Table 2 provides a description of the parameters shown in Figure 8 and the ones used for the calculation of the RoCoF threshold presented later in the report.

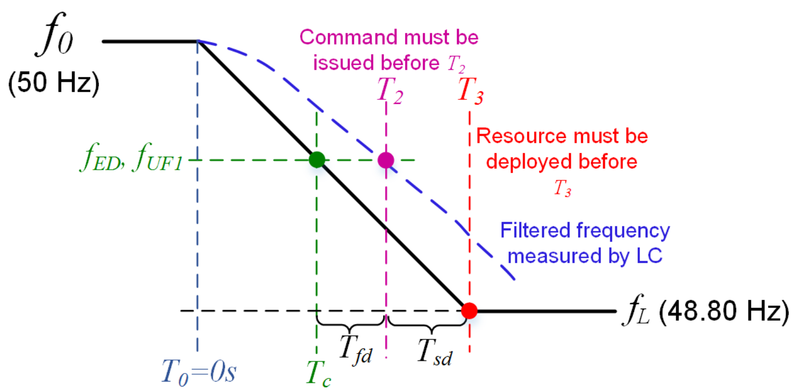

Figure 8. Critical timings for defining frequency thresholds in the resource allocation block

Table 2. Description of parameters used for the calculation of LC settings

I_s	System inertia level in GVAs
f_0	System nominal frequency (i.e. 50 Hz).
f_L	The low frequency limit in Hz. In this case, it is the LFDD frequency threshold 48.80 Hz.
ΔP	Size of the loss-of-generation event in GW
T_{fd}	Local frequency measurement delay in seconds

T_{rd}	Local RoCoF measurement delay in seconds
T_{sd}	Resource response delay in seconds

Based on the swing equation shown in (**1**), the initial $RoCoF_{Max}$ (Hz/s) following a frequency disturbance can be calculated:

$$RoCoF_{Max} = \frac{\Delta P}{2 \times I_s} f_0 \qquad (1)$$

Each resource will have a finite delay (T_{sd}) in responding to a power command from the LC. Therefore, as shown in Figure 8, in order to ensure the system frequency does not drop below f_L, a command needs to be sent to the resource by T_2, so that the response can be injected to the network by T_3, which is the time where the frequency will reach f_L without any response.

In Figure 8, a conservative assumption has been made, where it was assumed that the RoCoF will maintain its initial value during the frequency degradation. In reality, governor response may have triggered during this period, which will gradually reduce the RoCoF magnitude over time. However, the governor's actions will highly depend on the types of synchronous machines and the capability of the governors, therefore, the assumption made in this work represents the worst-case scenario, where the frequency decreases at the largest rate. This will ensure the calculated settings are sufficient to trigger the response under all different governor scenarios (including the absence of governor response).

Referring to Figure 8, the LC needs to be configured so that at T_2, the frequency measured by the LC will violate the both f_{ED} and f_{UF1}.

Since there is a filtering delay in measuring frequency, therefore, f_{ED} and f_{UF1} should be set as follows in order to allow sufficient time for the filtering and resource deployment delay.

$$f_{ED} = f_{UF1} = f_L + (T_{fd} + T_{sd}) \times RoCoF_{Max} \qquad (2)$$

The reason for f_{ED} and f_{UF1} to be set as the same value is that, for the resource to be deployed, by the time the event violates the resource allocation threshold, it should also violate the event detection threshold, so that both conditions of the resource deployment are met.

In (**2**), T_{fd} is associated with the frequency measurement delay and from Section 5.1, which has been found to be approximately 0.5 s; f_L is 48.80 Hz for the LFDD threshold; and T_{sd} is associated with the resource delay in response to the command. The information regarding the resource characteristics (e.g. response delay to a command) could be supplied by the service provider who owns the resource.

6.3 Method for calculating RoCoF settings

In order to ensure the command for resource deployment is sent by T_2 as shown in Figure 8, RoCoF thresholds, $RoCoF_{ED}$ (and $RoCoF_{UF1}$ when RoCoF thresholds are enabled in the resource allocation block), should be set so that the measured RoCoF will violate the thresholds by T_2.

The filtered and un-filtered RoCoF measurements during an event are illustrated in Figure 9, where T_2 is the same time point as T_2 in Figure 8.

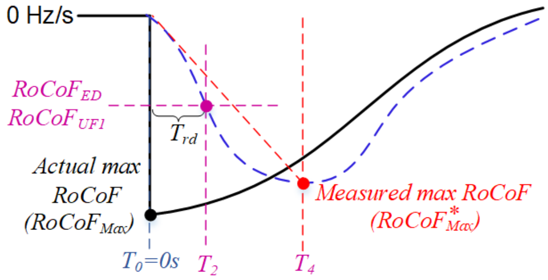

Figure 9. Critical timings for determining RoCoF settings

From Figure 8, it can be found that:

$$T_2 = T_3 - T_{sd}$$

Assuming the event occurrence time $T_0 = 0\ s$, the RoCoF measurement delay T_{rd} is:

$$T_{rd} = T_2 = T_3 - T_{sd}$$

Since:

$$T_3 = \frac{f_0 - f_L}{RoCoF_{Max}}$$

Therefore:

$$T_{rd} = \frac{f_0 - f_L}{RoCoF_{Max}} - T_{sd}$$

Therefore, $RoCoF_{ED}$ (and $RoCoF_{UF1}$) should be set so that the time for the measured RoCoF magnitude to increase from 0 to $RoCoF_{ED}$ (and $RoCoF_{UF1}$) should not exceed T_{rd}. An approximation has been made to represent how the measured RoCoF changes with time, where the measured RoCoF ($RoCoF^*$) is considered as a liner function of time:

$$RoCoF^* = Kt$$

Where

$$K = \frac{RoCoF^*_{Max}}{T_4 - T_0} = \frac{RoCoF^*_{Max}}{T_4}$$

Therefore, the RoCoF thresholds can be calculated as:

$$RoCoF_{ED} = RoCoF_{UF1} = \frac{RoCoF^*_{Max}}{T_4} \times T_{rd} \tag{3}$$

From the tests conducted in Section 5.2, T_4 is typically 2 s and $RoCoF^*_{Max}$ is around 65% of the theoretical largest RoCoF magnitude during a frequency disturbance, e.g. for the 82 GVAs inertia level and a loss of 1.8 GW, the theoretical calculated $RoCoF_{Max}$ is 0.549 Hz/s, then $RoCoF^*_{Max} = 0.549 \times 65\% = 0.357\ Hz/s$.

6.4 Examples for the calculation of frequency and RoCoF settings

This section provides an example of how the settings can be calculated for a certain resource and inertia level using the methods presented in Section 6.2 and 6.3.

The settings are configured to avoid the operation LFDD. Therefore, in the following example, the event size used for determining the settings is an event that leads to beaching the frequency the first stage LFDD threshold of 48.80 Hz. For 82 GVAs, this event size is around 1.71 GW. It should be noted that, this event size is subject to the capacity and the speed of generators providing primary response. These values of event sizes that lead to LFDD can be determined by running simulation of network models with the operating conditions that are of interest. The other associated parameters and their values are provided in Table 3.

Table 3: Values of parameters required for calculating frequency settings

I_s	82 GVAs	ΔP	1.71 GW
f_0	50 Hz	T_{fd}	0.5s
f_L	48.8 Hz	T_{sd}	0.5s

Using equation (1) and (2), the frequency threshold settings can be calculated:

$$RoCoF_{Max} = \frac{\Delta P}{2 \times I_s} f_0 = \frac{1.71\ GW}{2 \times 82\ GVAs} \times 50Hz = 0.521Hz/s$$

$$f_{ED} = f_{UF1} = f_L + (T_{fd} + T_{sd}) \times RoCoF_{Max} = 48.80Hz + (0.5s + 0.5s) \times 0.521Hz/s = 49.321\ Hz$$

In the LC, the minimum step size for the frequency setting is 0.1 Hz, so 49.4 Hz should be chosen to ensure sufficient sensitivity under the inertia level of 82 GVAs.

For RoCoF settings:

$$T_{rd} = \frac{f_0 - f_L}{RoCoF} - T_{sd} = \frac{50 - 48.80}{0.521} - 0.5 = 1.803s$$

$$RoCoF^*_{Max} = RoCoF_{Max} \times 65\% = 0.339Hz/s$$

$$RoCoF_{ED} = RoCoF_{UF1} = \frac{RoCoF^*_{Max}}{T_4} \times T_{rd} = \frac{0.339}{2} \times 1.803s = 0.306\ Hz/s$$

The minimum step in the LC for RoCoF setting is 0.01 Hz/s, so 0.30 Hz/s should be chosen to ensure sufficient sensitivity under the inertia level of 82 GVAs.

Using the same method, the settings for 67 GVAs can be calculated. A summary of setting for 82 GVAs and 67 GVAs to ensure the LC is capable to deploy resources for an event that leads to the frequency dropping to 48.80 Hz is provided in Table 4, and the detailed calculation process is provided in Appendix A.

Table 4. Calculated settings to contain events leading to LFDD threshold at 67 GVAs and 82 GVAs inertia level

Inertia level	82 GVAs	67 GVAs
Size of event leading to 48.80 Hz frequency nadir	1.71 GW	1.51 GW
f_{ED}	49.4 Hz	49.4 Hz
$RoCoF_{ED}$	0.30 Hz/s	0.29 Hz/s
f_{UF1}	49.4 Hz	49.4 Hz
$RoCoF_{UF1}$ (if enabled)	0.30 Hz/s	0.29 Hz/s

6.5 Validation of the calculated settings from tests

In this section, the settings calculated in Section 6.4 are applied to the LC and validated using the test setup as shown in Figure 1.

For the 82 GVAs inertia level, an event with a size of 1.71 GW will lead to the frequency dropping to 48.80 Hz if no EFCC response is introduced. The event was simulated in RTDS and the LC's performance is tested with the RoCoF thresholds in resource allocation block disabled and enabled.

Figure 10 shows the test results with RoCoF threshold disabled in the resource allocation block, i.e. the LC only used f_{ED} and $RoCoF_{ED}$ for event detection and only used f_{UF1} to determine the resource deployment. It can be seen that, if there is no EFCC response, the system frequency will drop to the LFDD threshold 48.80 Hz. With the EFCC response, the calculated settings, with consideration of resource response time and LC filtering delay, allowed the resource to be triggered and deployed before the frequency reached the LFDD threshold. Therefore, the calculated settings are valid to achieve the objective of deploying resource in time to avoid LFDD operation.

Figure 11 shows the test results with RoCoF threshold enabled in the resource allocation block, i.e. the LC will use f_{ED} and $RoCoF_{ED}$ for event detection and use f_{UF1} and $RoCoF_{UF1}$ to determine the resource deployment. Similar to the observation in Figure 10, the calculated settings successfully enabled the resource to be triggered and deployed before the frequency reached the LFDD threshold.

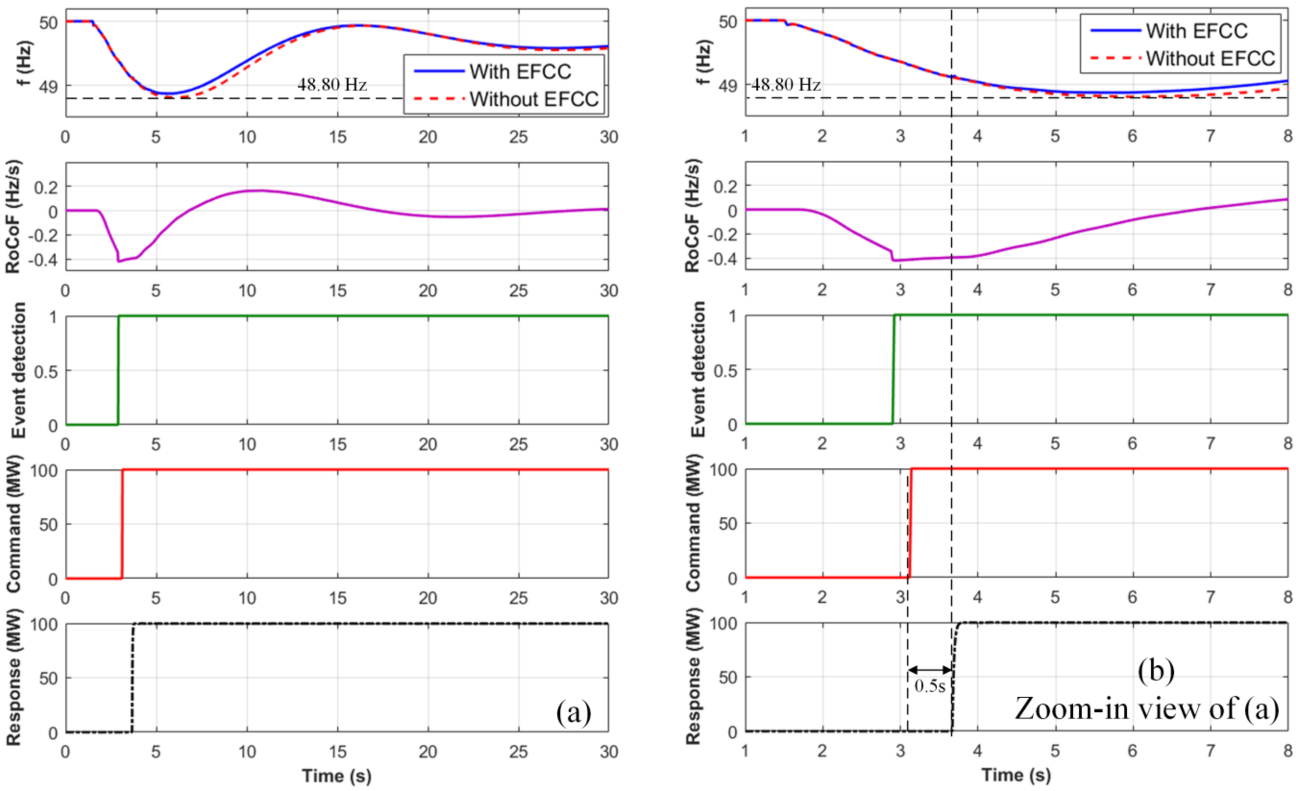

Figure 10. Test results with only frequency thresholds are enabled in resource allocation block - 82 GVAs

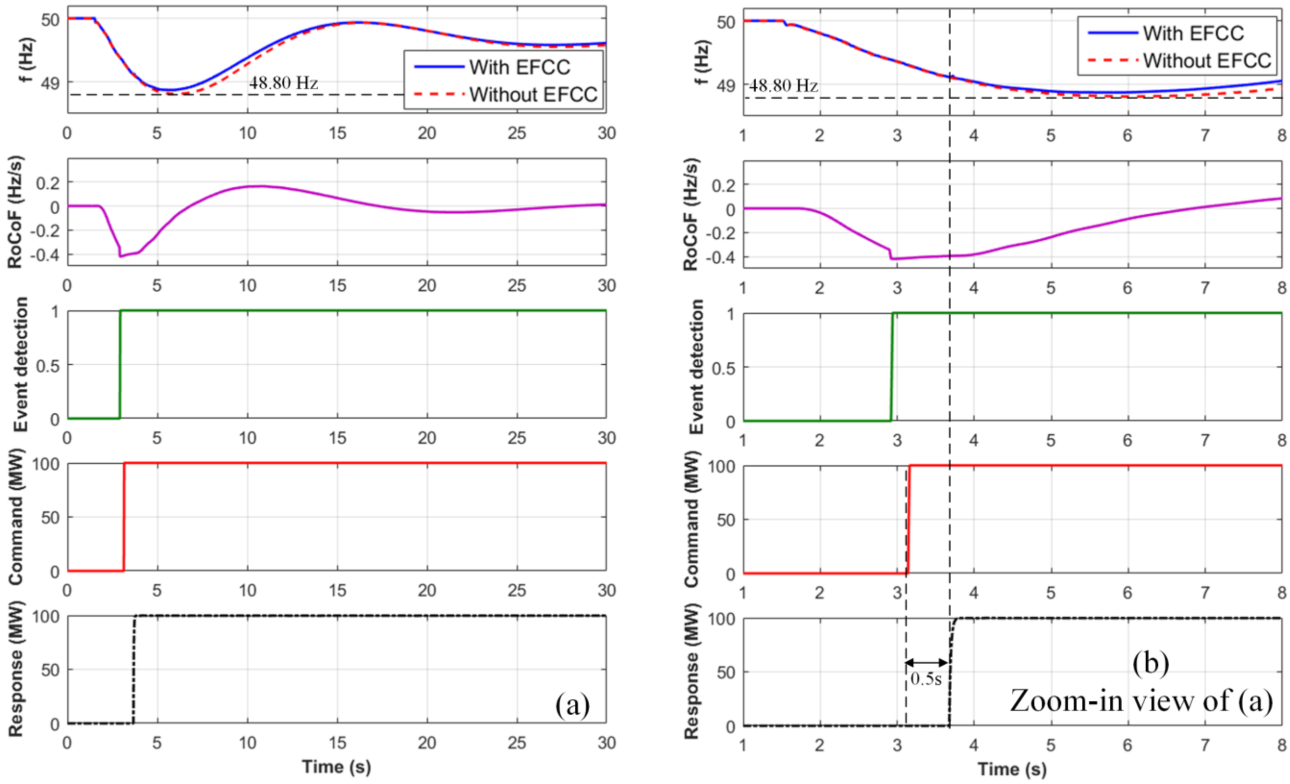

Figure 11. Test results with both frequency and RoCoF thresholds are enabled in resource allocation block – 82 GVAs

For the 67 GVAs inertia level, an event with a size of 1.51 GW will lead to the frequency dropping to 48.80 Hz if no EFCC response is introduced.

Figure 12 shows the test results with RoCoF threshold disabled in the resource allocation block. It can be seen that, with the EFCC response, the calculated settings allowed the resource to be triggered and deployed before the frequency reached the LFDD threshold, so they are valid to achieve the objective of deploying resource in time to avoid LFDD operation.

Figure 13 shows the test results with RoCoF threshold enabled in the resource allocation block, i.e. the LC will use f_{ED} and $RoCoF_{ED}$ for event detection and use f_{UF1} and $RoCoF_{UF1}$ to determine the resource deployment. Similar to the observation in Figure 12, the calculated settings successfully enabled the resource to be triggered and deployed before the frequency reached the LFDD threshold.

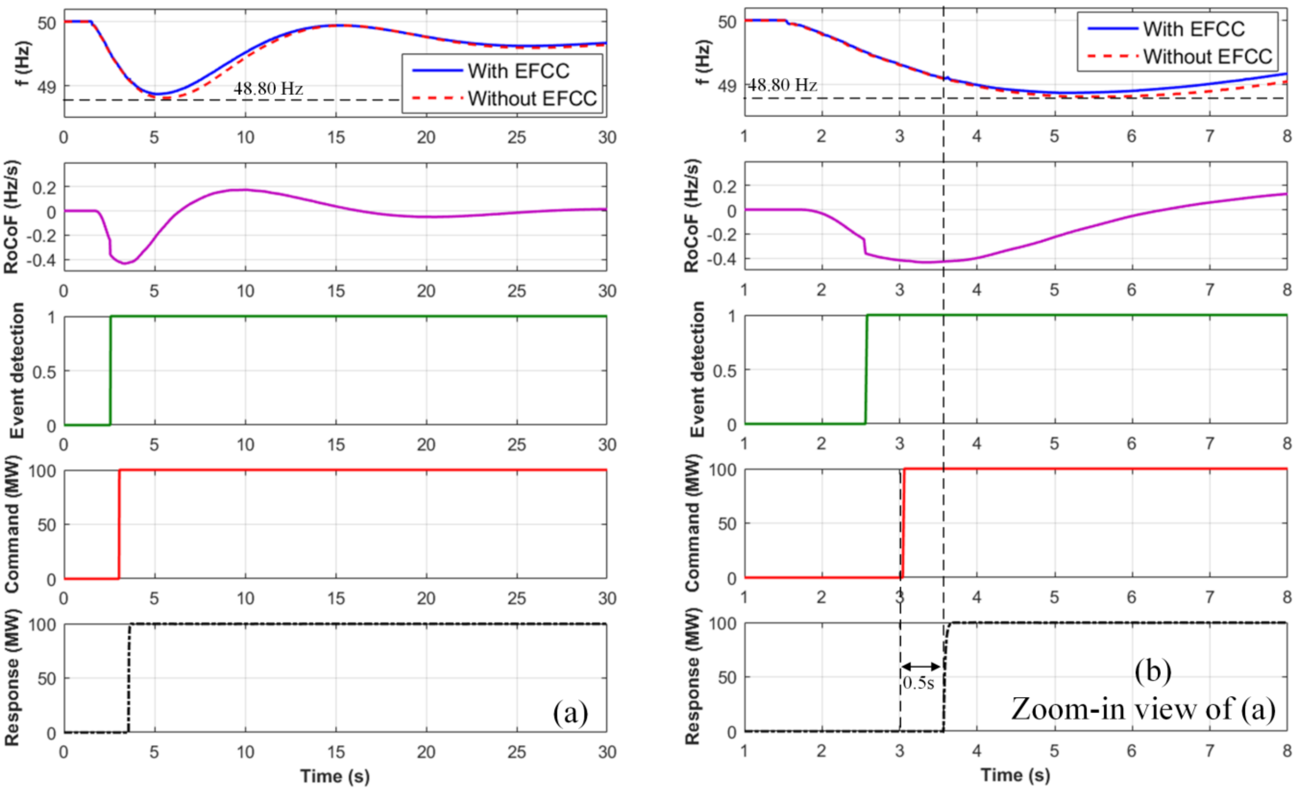

Figure 12. Test results with only frequency thresholds are enabled in resource allocation block - 67 GVAs

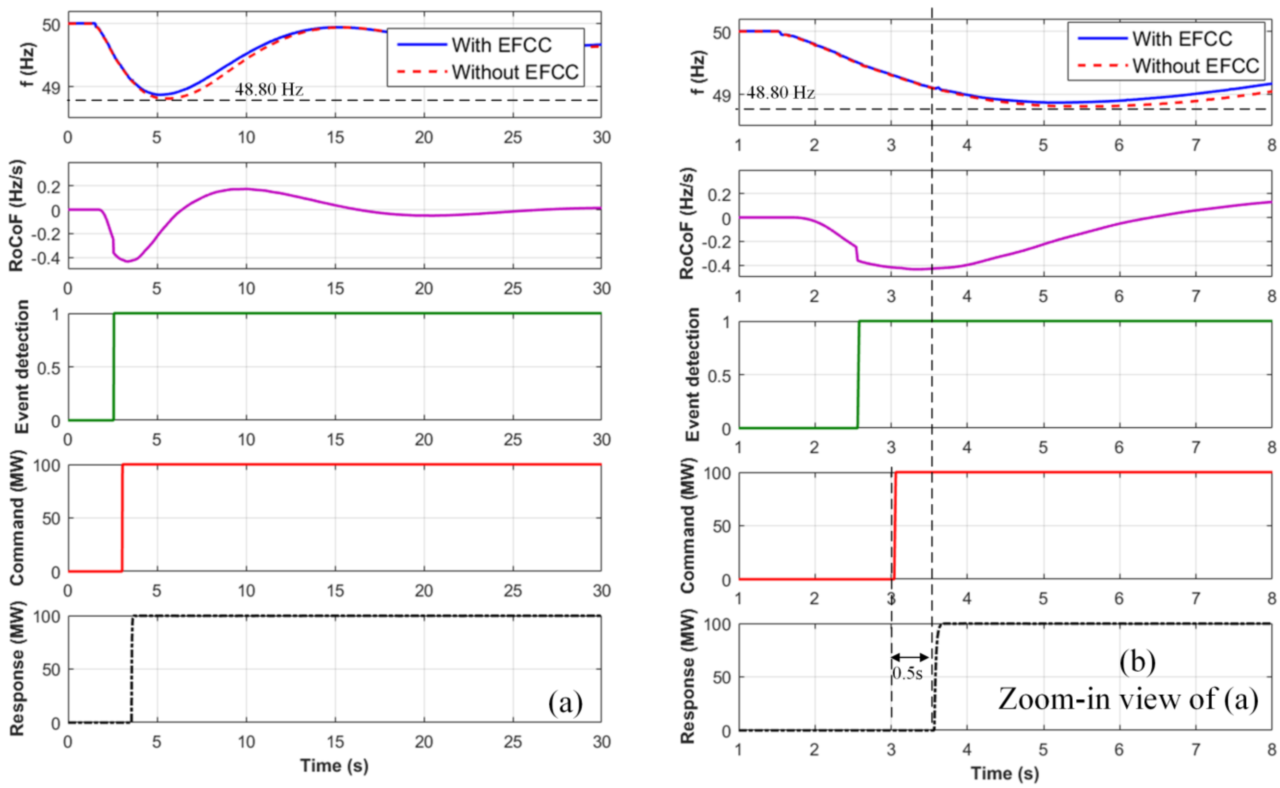

Figure 13. Test results with both frequency and RoCoF thresholds are enabled in resource allocation block – 67 GVAs

7 QUANTIFICATION OF THE REQUIRED EFCC RESOURCE UNDER LOCAL MODE OPERATION

It can be seen from the test results presented in Section 6.5 that for an event that leads to a frequency nadir at the LFDD threshold of 48.80 Hz, the calculated settings enabled the resource deployment before the frequency dropped to that nadir. i.e. as long as there is resource available, the calculated settings will ensure the frequency nadir is above 48.80 Hz, thus avoiding LFDD operation. The level of increase in frequency nadir depends on the amount of the resource available.

However, in reality, the maximum planned loss event is 1.8 GW in the GB transmission system [6], which is larger than the event sizes that led to the frequency nadir at 48.80 Hz for both 82 GVAs and 67 GVAs scenarios. Therefore, in this section, the target event will be chosen as 1.8 GW, i.e. the settings will be re-calculated, so that LFDD operation is avoided for the maximum 1.8 GW loss. As mentioned previously, suitable settings will only enable the resource deployment command to be triggered at the appropriate time. The level of improvement in frequency nadir will depend on the amount of resource available. In this section, the amount of EFCC resource required to avoid LFDD operation is determined for 82 GVAs and 67 GVAs inertia levels (as instructed by NG). The quantification of the required EFCC resource capacity will be based on the most conservative assumptions, where only the first stage of response (i.e. 20% of the resource) is deployed.

Using the setting calculation methods presented in Section 6, the settings for containing the frequency for a 1.8 GW generation loss event in 82 GVAs and 67 GVAs inertia levels can be calculated and are shown in Table 5. The detailed calculation process is provided in Appendix B and C respectively.

Table 5. Calculated settings to contain the frequency for 1.8 GW events at 67 GVAs and 82 GVAs inertia levels

Inertia level	82 GVAs	67 GVAs
Event size	1.8 GW	1.8 GW
f_{ED}	49.4 Hz	49.5 Hz
$RoCoF_{ED}$	0.30 Hz/s	0.28 Hz/s
f_{UF1}	49.4 Hz	49.5 Hz
$RoCoF_{UF1}$ (if enabled)	0.30 Hz/s	0.28 Hz/s

7.1 Quantification of EFCC response at the inertia level of 82 GVAs

The calculated settings, as presented in Table 5, were applied in the LC and tested for the inertia levels of 82 GVAs and 67 GVAs with 1.8 GW events. During the tests, the available resource sizes were gradually increased until the frequency was successfully contained above 48.80 Hz with only 20% of the available resource being deployed.

Figure 14 shows the test results with 100 MW (i.e. a total capacity of 500 MW) EFCC response deployed during the 1.8 GW event at the inertia level of 82 GVAs. It can be seen that, with the calculated settings, the resource was successfully deployed before the frequency reached 48.80 Hz, which further demonstrates the validity of the settings.

With 100 MW of resource being deployed, the frequency nadir was raised but still crossed the 48.80 Hz LFDD threshold. The resource capacity was then increased so that the deployed power is increased from 100 MW to 200 MW. As shown in Figure 15, the frequency nadir was above 48.80 Hz, thus avoiding LFDD operation. Therefore, at least a 200 MW resource will be required (i.e. 200MW/20% = 1000 MW EFCC capacity) for the calculated settings at the inertia level of 82 GVAs to contain a 1.8 GW events to avoid LFDD operation.

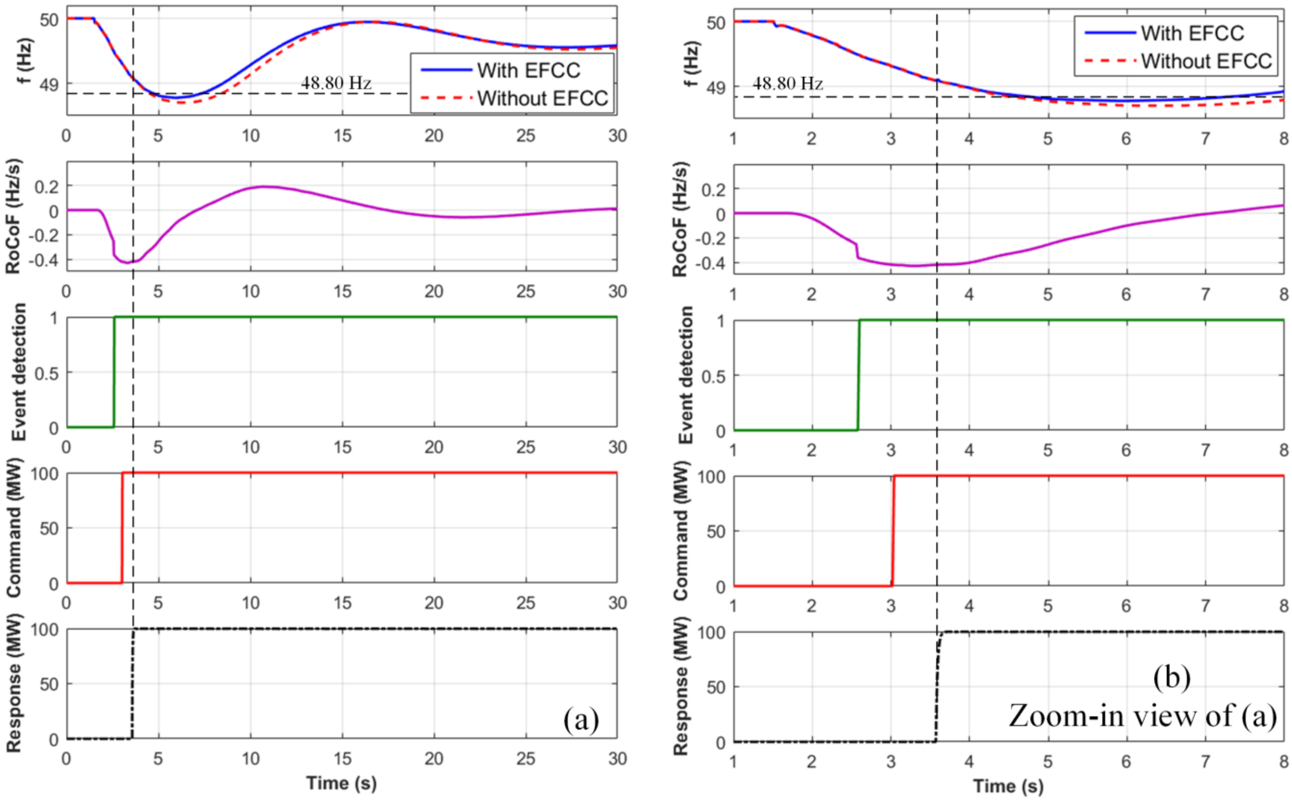

Figure 14. Test results for a 1.8 GW event at 82 GVAs with 100 MW EFCC response deployed

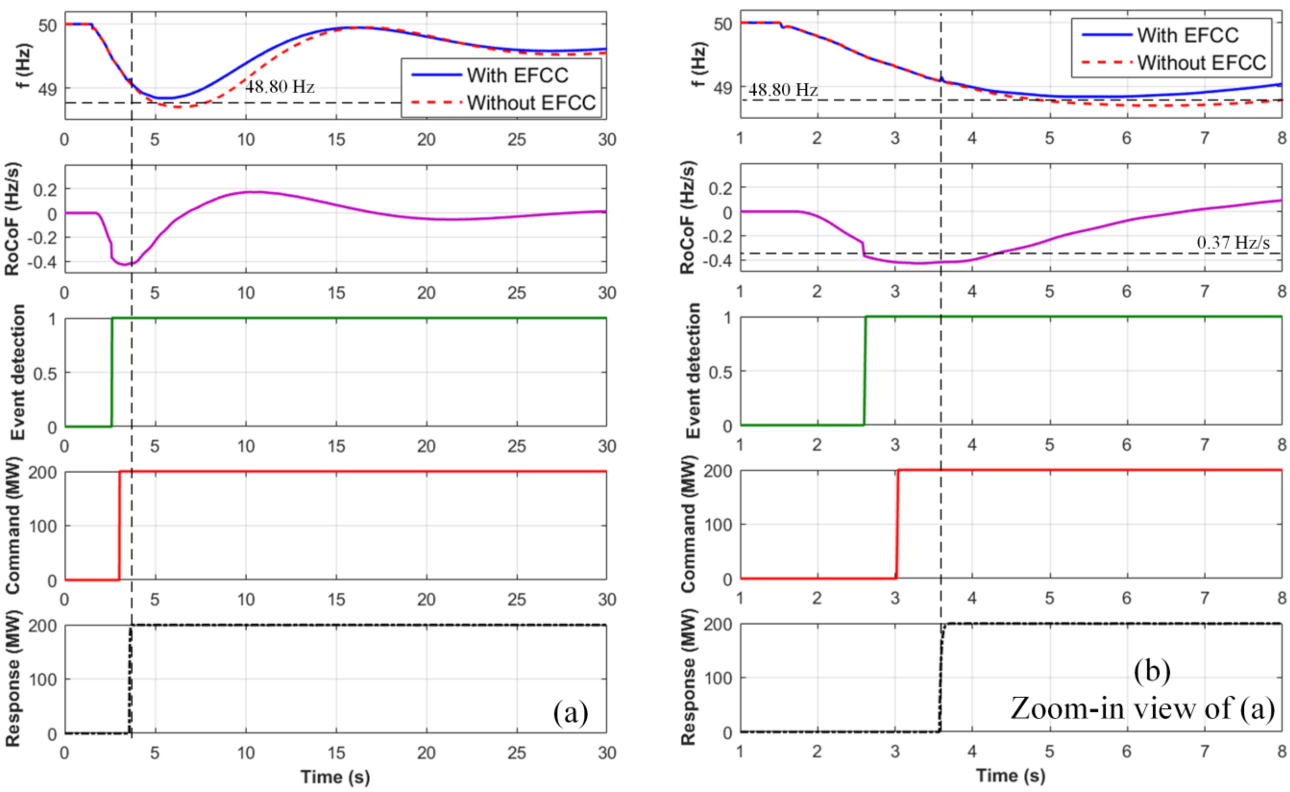

Figure 15. Test results for a 1.8 GW event at 82 GVAs with 200 MW EFCC resource deployed

7.2 Quantification of EFCC response at the inertia level of 67 GVAs

For the inertia level of 67 GVAs, similar to the tests presented in Section 7.1, the available resources sizes were gradually increased until the frequency was successfully contained above the 48.8 Hz LFDD threshold with only 20% of the resource deployed.

Figure 16 shows the test results with 400 MW EFCC response deployed (i.e. 2000 MW EFCC capacity) during the 1.8 GW event at the 67 GVAs inertia level. It can be seen that, with the calculated settings, the resource was successfully deployed before the frequency reached 48.80 Hz, which again further demonstrates the validity of the settings.

With the 400 MW of resource being deployed, the frequency nadir crossed the 48.80 Hz LFDD threshold. The resource capacity is thus increased so that the deployed power is increased from 400 MW to 500 MW as shown in Figure 17, which shows that the frequency nadir was successfully contained above 48.80 Hz, thus avoiding LFDD operation. Therefore, a 500 MW resource will be required (i.e. 500MW/20% = 2500MW EFCC capacity) for the calculated settings at the inertia level of 67 GVAs to contain 1.8 GW events to avoid LFDD operation.

It should be noted that the quantified EFCC response required are based on the most conservative settings. In a real system, the system operator could choose to set the scheme more sensitive, which will reduce the amount of the EFCC reserve required. However, since the local operational mode is considered as a backup mode, it is considered that the settings should not be configured to be too sensitive so that other LCs, who may still operate in wide-area mode would have the priority to contain the event. The scenario presented here is the most conservative scenarios.

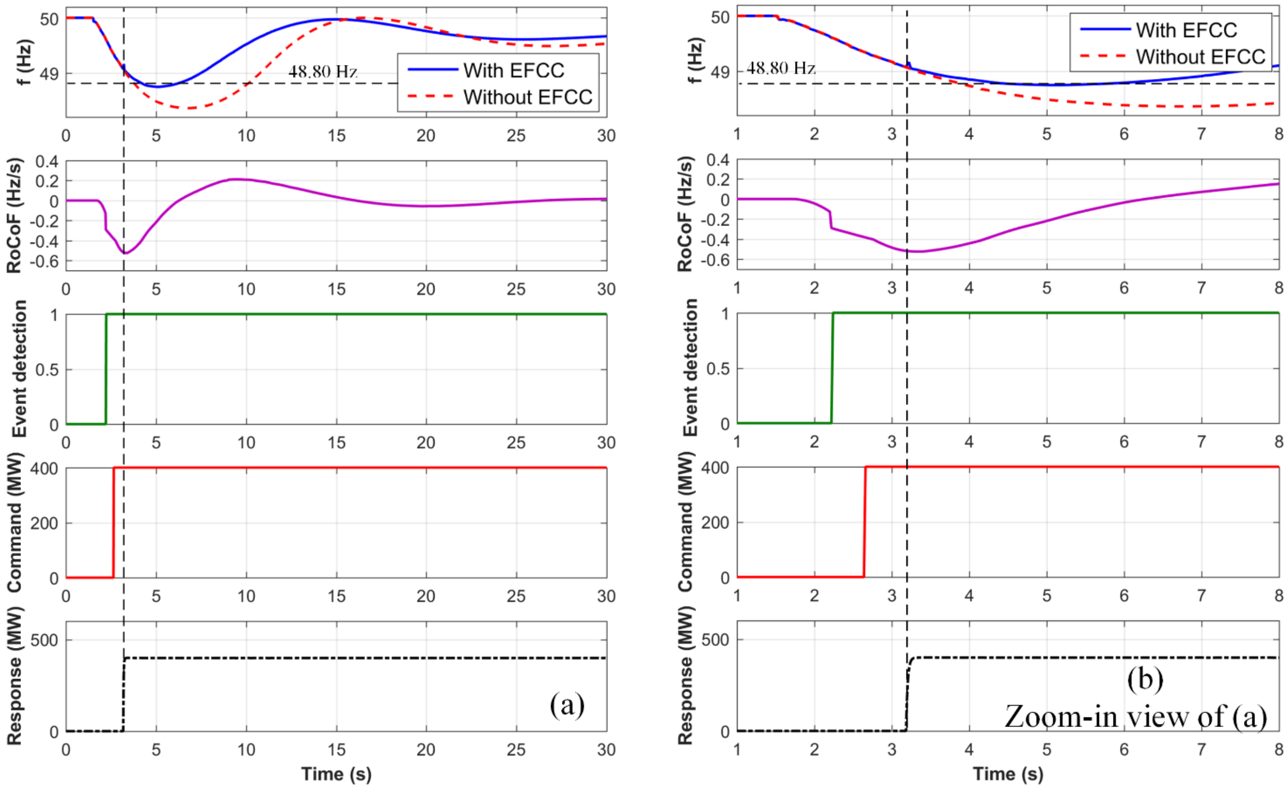

Figure 16. Test results from 1.8 GW at 67 GVAs with 400 MW EFCC resource deployed

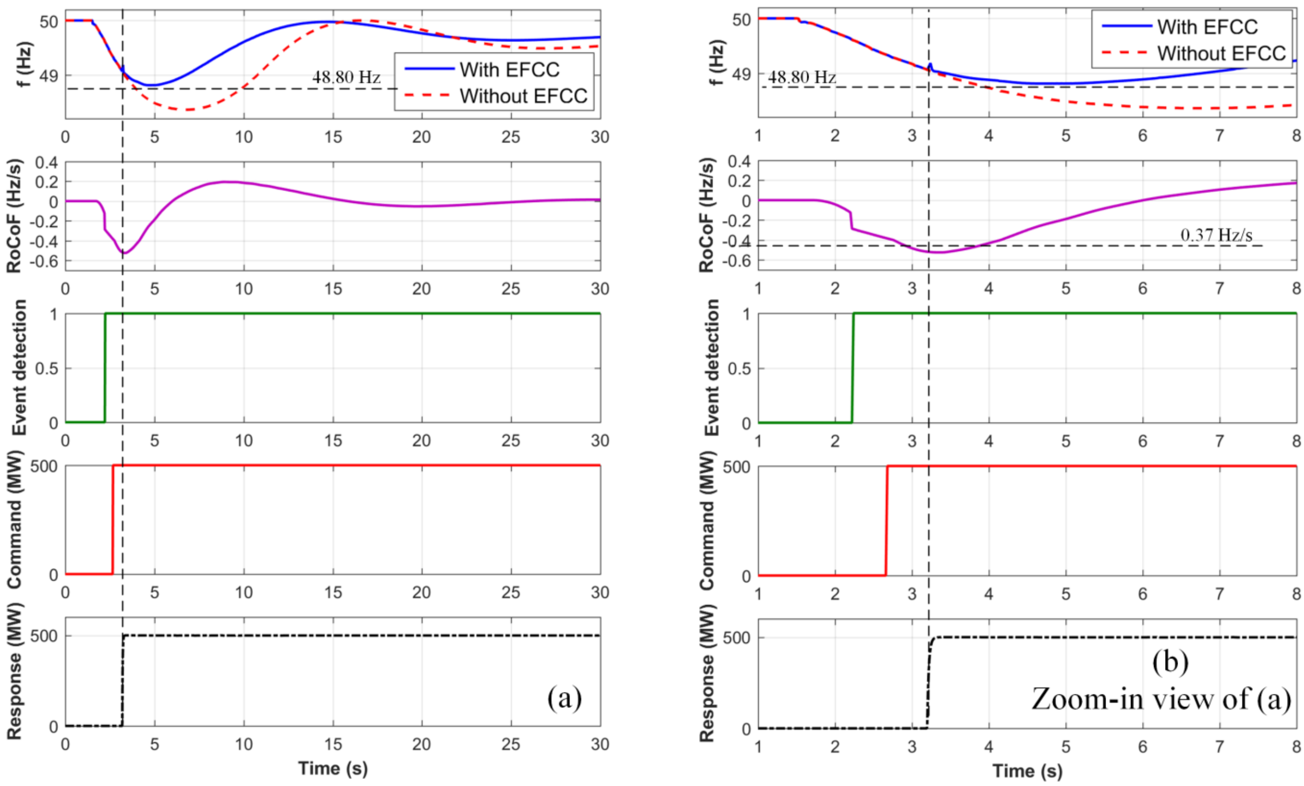

Figure 17. Test results from 1.8 GW at 67 GVAs with 500 MW EFCC resource deployed

8 INTERIM WIDE-AREA MODE

8.1 Overview of the interim wide-area mode

The EFCC's interim wide-area mode was developed as part of the EFCC project, with an attempt to reduce the requirement for communication infrastructure, while still taking into account the regional impact of frequency disturbances. A full description of the interim wide-area mode is available in [3]. In this section, a high-level overview of the interim wide-area mode is presented, along with an evaluation of the associated advantages, limitations, its feasibility for practical implementation, and suggestions for improvements and further developments.

A schematic diagram of the interim wide-area mode operation is provided in Figure 18. In this operational mode, the network is still divided into zones. In the studies conducted in [3], the GB transmission network was divided into 36 zones, corresponding to the 36 zones of the reduced GB transmission network model.

Each zone is equipped with one LC, which receives real-time measurements from PMUs installed within the corresponding zone. It was assumed that each synchronous generator in the zone will have a PMU installed, so the data transmitted from the PMUs include measured frequency and the inertia of the associated synchronous generators. For example, as shown in Figure 18, H_{36}^{i} and f_{36}^{i} are the inertia constant of the i^{th} synchronous generator and the frequency measured at the terminal of the i^{th} synchronous generator within zone 36. The LC will then take the information to calculate the zone centre of inertia (COI) and the zone average RoCoF (e.g.H_{36}^{COI} and $RoCoF_{36}^{COI}$ respectively). Based on this information, the power response required in the corresponding zone is calculated using the following equation:

$$\Delta P_k = 2 H_k^{COI} \times RoCoF_k^{COI} \quad (4)$$

Where ΔP_k is the calculated response required in zone *k*; H_k^{COI} is the equivalent inertia constant of zone *k*; and $RoCoF_k^{COI}$ is the equivalent RoCoF of zone *k.*

The resources being controlled are loads, so the calculated ΔP_k will lead to the same amount of load in the corresponding zone to be disconnected. In the developed version of the interim wide-area mode, it was assumed that there was always sufficient resource available within each zone to be deployed.

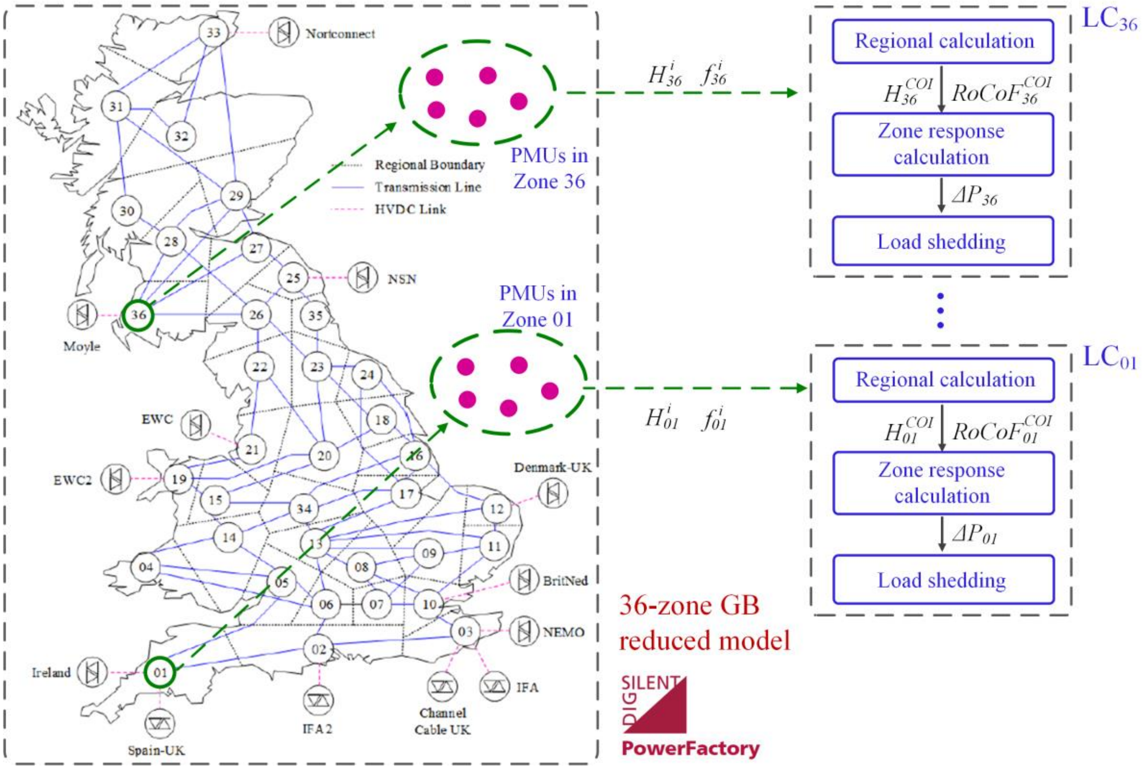

Figure 18. Schematic of the interim wide-area mode operation

8.2 Real-time prototyping and testing of the interim wide-area mode operation

Currently, the algorithms for the interim wide-area mode are implemented in PowerFactory. This allows the system to be conveniently tested using the 36-bus reduced GB transmission network model. However, the shortcoming is there is no direct way of exporting the algorithms and run them in a real-time platform for further validation of the system.

In order to run the algorithms in real time, one option is to develop the algorithms in Simulink. C code can then be generated from these algorithms, which can then be deployed in appropriate real-time platforms (e.g. Beckhoff industrial PCs [7], or even off the shelf PCs). Alternatively, it can be implemented in GE's LC hardware platform. The schematic for testing the interim wide-area mode in a real-time environment is shown in Figure 19, which is a simplified configuration compared with the wide-area model test platform as presented in [2].

The GB transmission network model in RTDS as used in [2] can still be used for the tests, with adjustments so that there are multiple synchronous machines in each zone and each synchronous machine is monitored using a PMU. Each zone will be equipped with a LC, which could either be a GE hardware platform (or equivalent) containing the interim wide-area mode algorithms. No CS is required in the system and the inertia of the synchronous machines will be communicated to the LC via the PMU streams using IEEE C37.118.2. The control signals from the LCs can use GOOSE messaging and the controllable resources could be various types, without being restricted to loads as the existing arrangement.

The impact of communication performance on the operation of this scheme can also be investigated by introducing various degraded communication conditions using dedicated communication emulators in the real-time communication links as shown in Figure 19.

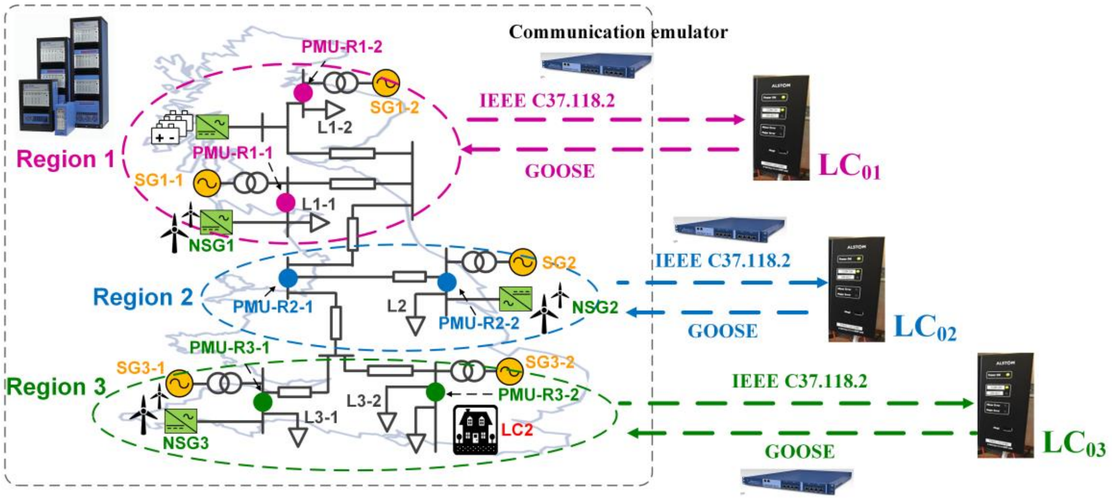

Figure 19. Real-time prototyping and testing of interim wide-area mode

8.3 Advantages of interim wide-area mode

The key advantage of the interim wide-area mode is that it does reduce the requirements for communication infrastructures compared to the wide-area mode of operation.

In the wide area mode, within each region, a communication network is required to transmit data from PMUs to the Regional Aggregators (RAs); and across regions, the RAs will also send all of the regional aggregated data to all LCs.

For the interim wide-area mode of operation, the first part of the real time communication within each zone, i.e. transmitting data from PMUs to create a regional representation, is still needed. However, the second part of the communication network for transferring regional data to other regions is not required. Furthermore, the inertia information of the synchronous generators can be transmitted using PMU streams, so no CS is required.

In terms of the regional variations influenced by the event, since the region that is mostly affected by the event will be reflected in the measured RoCoF, using the zone RoCoF to calculate the required response does take into account the regional variation of frequency disturbances.

8.4 Potential improvement and further development of the interim wide-area mode

From the discussions in the previous sections and the studies presented in [3], the interim wide-area mode could potentially be an option for future fast frequency response before the full deployment of the EFCC's wide-area mode of operation. However, the current version of the system is mainly a proof of concept, thus further improvements and developments will be required to comprehensively validate and de-risk the approach.

The limitations of the existing algorithm and the potential further improvements are summarised as follows:

1. Within each region, only one LC and one resource is considered. However, in reality, there could be multiple resources within one region. Depending on the resource types and availability, their capability of providing frequency response can vary significantly.
   Therefore, recommended improvements include:
   - Different resources with different capabilities and characteristics should be considered for the provision of frequency response.
   - A mechanism of coordinating multiple resources should be developed. This mechanism will play a similar optimisation role as the CS in the GE's wide area mode.

2. Once the resources are deployed, the interim wide-area mode it will permanently maintain the same output. While in reality, some resources might need to ramp down their power output after a period.
   Therefore, recommended improvements include:
   - Ramping down of resources should be included in the scheme.
   - Studies should be conducted to develop a smooth handover process between fast responding and other types of resources.

3. The approach assumes that there is always sufficient response available in each zone to deploy the calculated response. However, in reality, there might not be sufficient total response or the response could be too slow. There is a scaling factor available in the scheme that allows the control of the amount of load to be shed in percentage of the estimated event size, however, this scaling factor needs to be manually configured at the moment.
   Therefore, recommended improvements include:
   - Investigation of mechanisms to deal with scenarios where there is insufficient response or the characteristics of the response in the zone are not satisfactory should be conducted.
   - Where sufficient resources are available, an optimisation process should be included to ensure only resources with the most desirable characteristics are used and to avoid over-responding.
   - Following on from the previous point, an in-depth investigation of when a regional information is required to deploy the response should be performed. This will inform whether it is possible to use resources in other regions in the case where there is insufficient response available in the region affected by the disturbance.

4. In the existing approach, one PMU is required for each synchronous machine contributing to inertia. Practically, there could be difficulties associated with the ownership of the PMUs. If the service providers are expected to be the owners of the PMUs, then it will introduce additional cost for them. There will also be complexity in managing and maintenance of the facility, which might involve both the TSO and the generator owners.
   Therefore, further developments could consider broadcasting the inertia information from the control centre. The control centre has information about the connected synchronous generators readily available. This information could be broadcasted to the LCs. Although communication will be required between the control room and the resource site, such communication is not real time and this type of non-real-time communication will likely be required anyway for the control room to reach to the resource sites.

5. Currently, the response required from each region is calculated using equation (**4**). Although this approach takes into account the RoCoF measured in each zone, the calculated response also depends on the inertia of the corresponding zone. For a particular event, it is anticipated that if a zone has a relatively small inertia, the zone aggregated RoCoF will be larger. Based on (**4**), the smaller of H_k^{COI} means a smaller ΔP_k is needed but a larger RoCoF means a larger ΔP_k is needed. Figure 19 shows an example of the response from the interim wide-area mode from [3]. It can be seen that, even though the event is in zone 1, the responses were distributed across all zones with different responded power. In UoM's work, the effectiveness of a different locational strategy for deploying the response has been evaluated, but how regional response could be effective in avoiding the risk of system wide oscillation or separation has not been fully investigated.
   Therefore, for the further developments, more fundamental analysis of the approach for calculating the response in each zone will be required. It would also be useful to develop a systematic method to quantify the limit at which a regional response will be necessary to avoid system instability during frequency response.

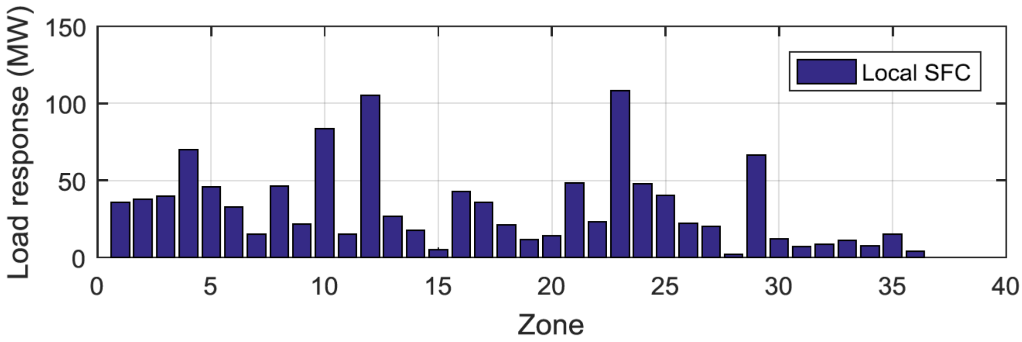

Figure 20. Load response triggered by the interim wide-area mode for a 1.56 GW event in Zone 1 [3]

9 KEY FINDINGS AND CONCLUSIONS

In this report, detailed studies and test results for investigating the impact of the filters used in LCs under their local operational mode and the methods for establishing the settings to avoid LFDD operation have been presented. Furthermore, using the methods developed for configuring the settings under the LCs' local operational mode, the capacity of the resource required to avoid LFDD operation is quantified. Finally, the feasibility of using the interim wide-area mode as an intermediate to EFCC's wide-area mode has been investigated and the recommendations for potential improvements and future studies have also been presented. Possible options and approaches for real-time prototyping and testing the interim wide-area mode have also been presented.

The key findings from the aforementioned various studies are summarised as follows:

1. **Impact of LC's signal filtering on decision making**
   From the studies, it was found that the filters implemented in the LC played an important role in filtering out undesirable noise in the original frequency and RoCoF measurements from the PMUs. The filtered signals will introduce delays in decision making. For frequency measurement, the delay is approximately 0.5 s, whereas for RoCoF measurement, there is an approximate delay of 2 s between the event occurrence and the time at which filtered RoCoF reaches its maximum magnitude.
   In addition to the delay in measurement, the filtered RoCoF measurements also have smaller magnitudes compared to the un-filtered measurements. From the test results, it was found that the measured maximum RoCoF by the LCs during frequency disturbances is around 65% of the theoretical maximum RoCoF.

2. **Findings from the development of methods for configuration the settings in local operational mode**
   It was found that the appropriate settings to avoid LFDD operation need to take into account the filtering delay of the measurements, delay in resource deployment, the maximum event sizes, etc. It was found that the developed setting calculation methods were able to ensure the resource is successfully deployed before the frequency reaches the lowest acceptable limit (i.e. the LFDD threshold of 48.80 Hz in this study). The calculated settings represent the most conservative requirements (i.e. only 20% of available resource is triggered) to achieve the objective of avoiding LFDD operation.

3. **Findings from the quantification of the EFCC resource required to avoid LFDD**
   In this study, the quantification of the resource capacity required for avoiding LFDD operation with largest planned generation loss of 1.8 GW at 82 GVAs and 67 GVAs inertia levels have been conducted. The quantification of the resource capacity is based on the conservative assumption where there only 20% of the resource capacity is triggered with the settings calculated by the methods developed in this work. It was found that with a resource response delay of 0.5 s, for the 82 GVAs inertia level, the frequency and RoCoF thresholds need to be configured as 49.4 Hz and 0.30 Hz/s, and the EFCC response required is 200 MW (i.e. 1000 MW of capacity) to avoid LFDD operation. For the 67 GVAs inertia level, the frequency and RoCoF thresholds need to be configured as 49.5 Hz and 0.28 Hz/s, and the EFCC response required is 500 MW (i.e. 2500 MW of capacity) to avoid LFDD operation.

4. **Findings from evaluation of the EFCC's interim wide-area mode of operation**
   It was found that the key advantage of the interim wide-area mode is that it does not require real-time communication across different zones, which is required by the wide-area mode of operation. However, using the interim wide-area mode in the real transmission grid requires further developments and studies. The key areas for further investigation of the interim wide-area mode include: (1) fundamental studies of the effectiveness of the approach for calculating the response power required in each zone (particularly focusing on how it can effectively support the suppression of inter-area oscillation or system separation). (2) Consideration of scenarios where there is varied distribution of resource capacities in different zones (3). The coordination and optimisation of multiple different resources within each zone.

APPENDIX A: CALCULATION OF SETTINGS FOR 67GVAS INERTIA LEVEL FOR AN EVENT FREQUENCY REACHING THE LFDD THRESHOLD

The event size used for determining the settings is the event that leads to the frequency nadir at the LFDD threshold of 48.80 Hz. For 67 GVAs, this event size if around 1.51 GW. It should be noted that this event size is subject to the capacity and the speed of generators providing primary response. However, by running simulations, this event size that leads to the LFDD threshold can be determined for different system operating conditions. The other associated parameters and their values are provided in Table 6.

Table 6: Values of parameters required for calculating frequency settings

I_s	67 GVAs	ΔP	1.51 GW
f_0	50 Hz	T_{fd}	0.5s
f_L	48.8 Hz	T_{sd}	0.5s

Using equation (1) and (2), the frequency threshold settings can be calculated:

$$RoCoF_{Max} = \frac{\Delta P}{2 \times I_s} f_0 = \frac{1.51\ GW}{2 \times 67\ GVAs} \times 50Hz = 0.563Hz/s$$

$$f_{ED} = f_{UF1} = f_L + \left(T_{fd} + T_{sd}\right) \times RoCoF = 48.80Hz + (0.5s + 0.5s) \times 0.563Hz/s = 49.363\ Hz$$

Since the LC minimum step size for the frequency setting is 0.1 Hz, 49.4 Hz should be chosen to ensure sufficient sensitivity with the inertia level of 67 GVAs.

For RoCoF settings:

$$T_{rd} = \frac{f_0 - f_L}{RoCoF} - T_{sd} = \frac{50 - 48.80}{0.563} - 0.5 = 1.631s$$

$$RoCoF^*_{Max} = RoCoF_{Max} \times 65\% = 0.365Hz/s$$

$$RoCoF_{ED} = RoCoF_{UF1} = \frac{RoCoF^*_{Max}}{T_4} \times T_{rd} = \frac{0.365}{2} \times 1.631s = 0.298\ Hz/s$$

Since the minimum step for the RoCoF setting is 0.01 Hz/s, so 0.29 Hz/s should be chosen to ensure sufficient sensitivity with the inertia level of 67 GVAs.

APPENDIX B: CALCULATION OF SETTINGS FOR THE 82 GVAS INERTIA LEVEL FOR A 1.8 GW LOSS EVENT

The event size used for determining the settings is the maximum loss event with a power deficit of 1.8 GW. The associated parameters and their values for the settings calculation are provided in Table 7.

Table 7: Values of parameters required for calculating settings - 82 GVAs with 1.8 GW loss

I_s	82 GVAs	ΔP	1.8 GW
f_0	50 Hz	T_{fd}	0.5 s
f_L	48.8 Hz	T_{sd}	0.5 s

Using equation (1) and (2), the frequency threshold settings can be calculated:

$$RoCoF_{Max} = \frac{\Delta P}{2 \times I_s} f_0 = \frac{1.8\ GW}{2 \times 82\ GVAs} \times 50\ Hz = 0.549\ Hz/s$$

$$f_{ED} = f_{UF1} = f_L + (T_{fd} + T_{sd}) \times RoCoF = 48.80Hz + (0.5\ s + 0.5\ s) \times 0.549\ Hz/s = 49.349\ Hz$$

The LC minimum step size for the frequency setting is 0.1 Hz, so the setting is chosen to be 49.40 Hz to ensure sufficient sensitivity with the inertia level of 82 GVAs.

For RoCoF settings:

$$T_{rd} = \frac{f_0 - f_L}{RoCoF} - T_{sd} = \frac{50 - 48.80}{0.549} - 0.5 = 1.686s$$

$$RoCoF^*_{Max} = RoCoF_{Max} \times 65\% = 0.357Hz/s$$

$$RoCoF_{ED} = RoCoF_{UF1} = \frac{RoCoF^*_{Max}}{T_4} \times T_{rd} = \frac{0.357}{2} \times 1.686s = 0.301\ Hz/s$$

The minimum step for RoCoF setting is 0.01 Hz/s, so the setting is chosen to be 0.30 Hz/s to ensure sufficient sensitivity with the inertia level of 82 GVAs.

APPENDIX C: CALCULATION OF SETTINGS FOR THE 67GVAS INERTIA LEVEL FOR A 1.8 GW LOSS EVENT

The event size used for determining the settings is the maximum loss event with a power deficit of 1.8 GW. The associated parameters and their values for settings calculation are provided in Table 8.

Table 8: Values of parameters required for calculating settings - 67 GVAs with 1.8 GW loss

I_s	82 GVAs	ΔP	1.8 GW
f_0	50 Hz	T_{fd}	0.5 s
f_L	48.8 Hz	T_{sd}	0.5 s

Using equation (1) and (2), the frequency threshold settings can be calculated:

$$RoCoF_{Max} = \frac{\Delta P}{2 \times I_s} f_0 = \frac{1.8\ GW}{2 \times 67\ GVAs} \times 50\ Hz = 0.672\ Hz/s$$

$$f_{ED} = f_{UF1} = f_L + \left(T_{fd} + T_{sd}\right) \times RoCoF_{Max} = 48.80\ Hz + (0.5s + 0.5s) \times 0.672\ Hz/s = 49.472\ Hz$$

The LC minimum step size for the frequency setting is 0.1 Hz, so the setting should be chosen as 49.5 Hz to ensure sufficient sensitivity with the inertia level of 67 GVAs.

For RoCoF settings:

$$T_{rd} = \frac{f_0 - f_L}{RoCoF} - T_{sd} = \frac{50 - 48.80}{0.672} - 0.5 = 1.286s$$

$$RoCoF^*_{Max} = RoCoF_{Max} \times 65\% = 0.437Hz/s$$

$$RoCoF_{ED} = RoCoF_{UF1} = \frac{RoCoF^*_{Max}}{T_4} \times T_{rd} = \frac{0.437}{2} \times 1.286s = 0.281\ Hz/s$$

The minimum step for RoCoF setting is 0.01 Hz/s, so the setting should be chosen as 0.28 Hz/s to ensure sufficient sensitivity with the inertia level of 67 GVAs.

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