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# Application of Wide-Area and Monitoring and Control Techniques for Fast Frequency Control in Power Systems with Low Inertia

**Q. HONG[1], S. NORRIS[2], M. SUN[3], O. BAGLEYBTER[2], D. WILSON[2], B. MARSHALL[4], V. TERZIJA[3], C. BOOTH[1]**

**[1]University of Strathclyde, [2] GE Grid Solutions, [3]University of Manchester, [4] The National HVDC Centre**

**United Kingdom**

## SUMMARY

The increasing penetration of renewable generation has led to a massive decrease of system inertia, which brings significant challenges for frequency control because less time is available to take control actions before the frequency deviates to an unacceptable level. As a result, network operators need to procure more reserve power to contain the frequency deviation, which will lead a significant increase of operational cost. Furthermore, renewable generation is often un-uniformly distributed in the system, so there are also differences in the inertia level in different parts of the network, resulting in regional variations of frequency during frequency disturbances. Therefore, future frequency response schemes not only need to be faster, but also need to consider the regional impact of frequency disturbances to avoid the response deployed from jeopardising the overall system stability.

This paper presents a novel wide-area monitoring and control scheme that is capable of dispatching fast and coordinated frequency response from a variety of distributed resources (e.g. wind, PV, energy storage, etc.). The proposed system, termed "Enhanced Frequency Control Capability (EFCC)", fully considers the regional impact of frequency disturbances and is capable of deploying much faster response compared with conventional primary response schemes (from a few seconds to within one second), thus enhancing the frequency control in future power systems with low inertia. The EFCC system has been developed under an innovation project via the UK's Network Innovation Competition framework. This paper presents the overall architecture of the EFCC system and the design of the key components within EFCC to realise the enhanced frequency control objectives. Case studies are presented, which demonstrate that the EFCC system is effective in containing the frequency deviation in a low inertia system while considering the regional impact; it can correctly distinguish frequency events from pure electrical faults to avoid unnecessary operation; and it is capable of effectively handling communication degradation to correctly provide frequency response when required.

## KEYWORDS

Fast frequency control, low inertia system, wide-area monitoring and control systems, PMUs.

Email: q.hong@strath.ac.uk

## 1. INTRODUCTION

The GB transmission system has set an ambitious plan to meet the objective of achieving zero carbon operation of the system by 2025 [1], and it has seen a significant increase of renewable generation in the past decade [2]. Renewable resources are typically interfaced with the power system via power-electronic converters, which do not naturally contribute inertia to the system. Therefore, the rapid increase of renewable generation has resulted in a significant reduction of the overall system inertia. One of the most notable challenges for operating low-inertia systems is the effective control of frequency during frequency events (e.g. loss of generation or demand) [3]. The decreased system inertia will lead to the system being more volatile to disturbances, i.e. for the same amount of power imbalance, the system will have a higher RoCoF, thus the frequency will deviate faster from the nominal value [4]. If no action is taken, these changes will lead to significant increase of operational cost by procuring more reserve power [2] in order to meet the frequency control requirements [5]. Therefore, faster frequency responses, capable of acting to frequency deviation in a sub-second time scale, will be required to effectively tackle the frequency control challenges [6].

In addition to the challenges associated with the speed of frequency response, the regional impact of power imbalance events is also considered as a critical issue that needs to be addressed for future frequency control [7]. The un-uniformly distributed system inertia has caused angle separation and frequency variations among regions during disturbances. Fast frequency responses that act within 0.5-2s of a disturbance will interact with the regional angles, frequency and RoCoF, increasing or decreasing the angle and frequency differences depending on where the response is relative to the disturbance. Therefore, fast response without proper consideration of the regional impact of the events can further stress the system and, in the worst-case scenario, lead to system separation [7-9].

This paper presents a novel wide-area monitoring and control scheme, termed “Enhanced Frequency Control Capability (EFCC)”, which is designed to address the aforementioned challenges associated with the need for faster frequency response and consideration of regional impact of frequency disturbances. The EFCC system uses real-time measurements from Phasor Measurement Units (PMUs) installed across the network to monitor the system condition and is capable of detecting frequency disturbances in a timely manner and dispatching fast and coordinated frequency response from a variety of distributed resources (from a few seconds to within one second), while considering the regional impact of frequency disturbances. The EFCC system has been developed under an innovation project via the UK’s Network Innovation Competition framework.

This paper is structured as follows: Section 2 presents the overall design of the EFCC system; Section 3 describes the key elements within the EFCC system; and Section 4 presents case studies to evaluate the EFCC’s performance during frequency events, faults and degraded communication conditions.

## 2. OVERALL DESIGN OF THE EFCC SYSTEM FOR FAST AND REGIONAL FREQUENCY RESPONSE

The fundamental principle of EFCC to enable faster and regional frequency response is based on the use of real-time wide-area measurements from PMUs for detecting and locating the events, and based on the resources available in each region and the event’s impact on the corresponding region, it will calculate the frequency response contribution from each individual resources. Figure 1 presents the overall system design and the key components in EFCC in order to achieve the aforementioned control objectives.

As shown in Figure 1, the GB transmission system is divided into a number of regions (based on coherent groups of generators) and each region contains a set of PMUs, which will send their real-time angle and frequency measurements to Regional Aggregators (RAs). The RAs will process the PMU measurements, where time alignment and averaging of measured quantifies are performed, and then broadcast the regional aggregated values to all of the Local Controllers (LCs) that are participating in wide area control. The LCs are located at the service providers’ sites, e.g. energy storage units, windfarms, demand resource aggregators’ sites. The data paths shown in yellow indicate fast streamed synchrophasor data at 20ms time interval (for a 50Hz system), and this data is used by the LCs to detect and trigger the resources within 0.5s of the disturbance occurring.

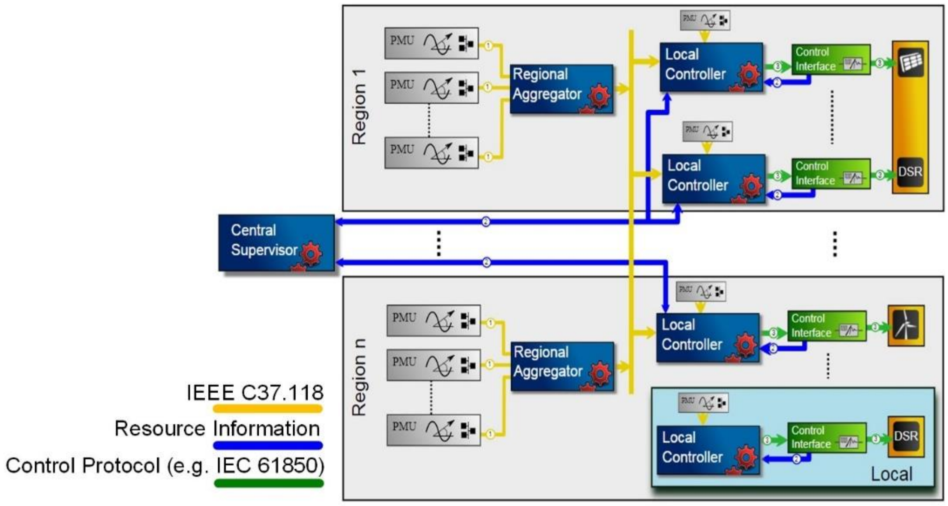


Figure 1. Design of the EFCC scheme [4]

The scheme also requires the monitoring of resource availability information, which is performed by the Central Supervisor (CS). Its key role is to monitor the available capacity of resources and their capability, distribute parameters such as regional inertia values and triggering thresholds, and to provide an interface for system operators. The communication between the CS and the LCs is slower than that of the frequency and angle data, with a typical update rate of 5 minutes. It is also important to note that the CS only supplies the resource available information and ranks their priority for deployment, but does not directly send control comments to resources, which are performed by the LCs. The distributed architecture was proposed as it offered more predictable communication latency, reduced bandwidth requirements for data and higher reliability.

## 3. DESIGN OF FUNCTIONS IN THE MAIN COMPONENTS IN THE EFCC SYSTEM

### 3.1. Local Controllers (LCs)

The LC is main element that performs control actions, and it contains three main functions, i.e. system aggregation, event detection, and resource allocation as shown in Figure 2. The data from the RAs is broadcasted across the network, where each LC receives the data from each of the RAs, therefore each LC performs system aggregation and event detection and are coordinated as they are driven from the same data.

**System Aggregation**

System Aggregation uses regionally aggregated signals from the RAs to produce a system equivalence to reduce the effects of inter-area oscillation. The aim is to represent the full system as a single equivalent machine in order to focus on system wide events. Additionally, comparison between the system and regional signals allows identification of the locations which are affected by the disturbance.

Both the regional and system levels of aggregation serve as a useful method in minimising the effects of local and inter-area modes of oscillation, where such modes of oscillations can impact the ability to detect true events or degrade the ability to respond to events. The oscillations can affect RoCoF values which may cause LCs to under or over-respond. Consider Figure 3 where all signals except the black dashed line are individual PMU frequency values. There is dispersion between the signals but the effects of the oscillations are also visible resulting in some signals to change from negative to positive RoCoF during backswings. This behaviour can lead to incorrect detection of frequency events and also impact on the calculation for required system response.

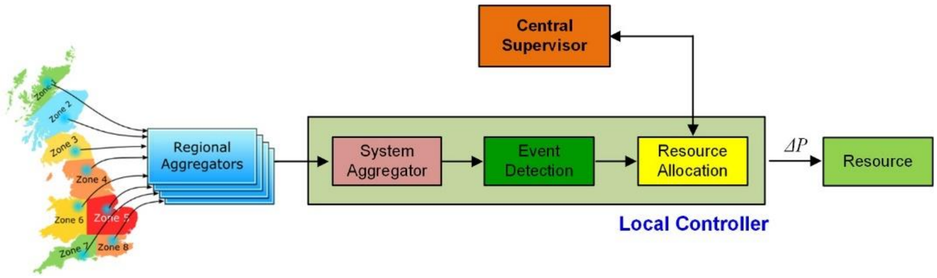


Figure 2. Architecture of the local controller

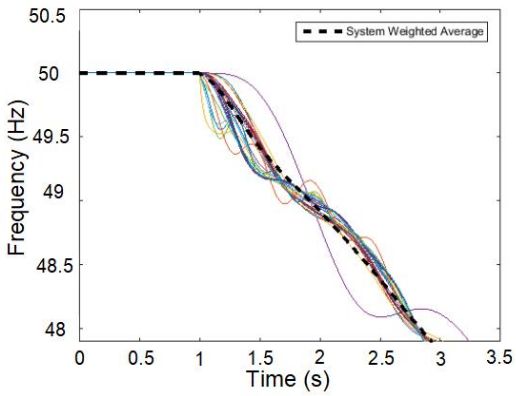


Figure 3: Frequency measured at PMUs and the system aggregated frequency based on the centre of inertia technique

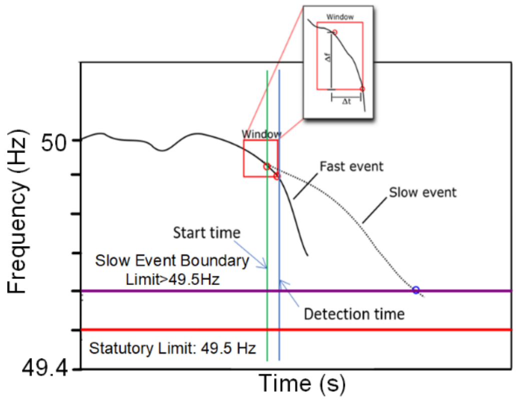


Figure 4: Event detection method

**Event detection**

A key requirement for the fast frequency control solution was enabling a response within 500ms, therefore a fast method of detecting a frequency event is required. When using wide-area signals, the impact of communication delays and the quality of data are critical. The EFCC scheme is designed to respond to system-wide events, i.e. those events which are observable at a system level, which is possible using the regional and system levels of aggregation. The need to retain the regional information is important for the locational discrimination required when deploying resource.

The method for event detection is shown in Figure 4. For the wide-area event detection, the algorithm uses a moving window across the frequency signal. The event detection algorithm is designed to detect events with large RoCoFs, and it does not require the full window to be filled in order to determine the RoCoF value. Instead, it uses a method that focuses on the events, therefore minimising the latency of detection. The algorithm also has the ability to detect larger RoCoF values faster than slower RoCoF values making it ideal for the fast frequency response applications. When a large RoCoF value is detected, a trigger signal is generated.

**Resource allocation**

The disturbances which the EFCC system is designed to operate for can be a loss of infeed (e.g. trip of generation or importing HVDC interconnection), or a loss of outfeed from the area. The purpose of the locational fast frequency response control mechanism is to deliver an overall response in proportion to the power that is lost or gained, in a timeframe and location that does not degrade the stability of the grid. The LCs combine the area angle and frequency signals from each of the areas to determine a system frequency value for the connected regions of the network. Estimated regional inertia values are used as weightings to derive real-time system angle and frequency values. It is also possible to consider islanding as part of the mechanism using the phasor measurements where islanded areas can be excluded from the aggregation. The overall system RoCoF is derived from the aggregated system frequency. The system RoCoF is a significantly smoother signal compared with individual local ROCOF values, and when combined with an inertia estimate, it can be used to determine the power imbalance in the system. The scheme will can then deploy an overall response in proportion to the power imbalance.

### 3.2. Regional Aggregators (RAs)

The RAs receive measurements from PMUs and aggregate the signals to form regional frequency and angle signals that are less influenced by the local variations seen in individual PMUs using the weighted averaging functions. Aggregation at a regional level as opposed a system-only level allows the reduction of the effects of local modes of oscillations and data bandwidth can be minimised which is another key design consideration when using wide-area communications networks. The regional aggregated signals are sent to each LC which calculates the resulting "system equivalent values" for further decision making.

Another key role of the RAs is to detect fault events, which on their own, do not require frequency response but can appear as a power imbalance event especially in the time range of a few hundred milliseconds. Faults can be characterised by low-voltage in the part of the network close to the fault. A fault in the system causes generators to accelerate where the degree of acceleration is dependent upon proximity to the fault and fault duration. When the fault is cleared, the generators should begin to stabilise back to nominal frequency assuming no load or generation was lost during the fault.

RAs continuously analyse the voltage phasors from the PMUs and evaluate whether there is any sudden and severe drop in voltage. If any of the PMUs connected to a region detect this behaviour, the aggregated signal from the regional aggregator continues but is combined with a "fault-on" signal as shown in Figure 5. When any of the signals coming into the system aggregator contains a "fault-on" signal, the event detection within the LC is blocked until such time that the fault has been cleared for a sufficient wait time to allow the system to stabilise. With this fault detection mechanism, the LCs will know to ignore the effects that the fault has, for example, a high RoCoF during a fault. When the fault has cleared, the flag will be removed, and LCs will know to start trusting subsequent RoCoF data, therefore will be able to detect any subsequent load or generation trips which occur after a fault. A trip during the fault period can also be detected as the degradation in frequency will continue after the fault has cleared and can be detected by the algorithm.

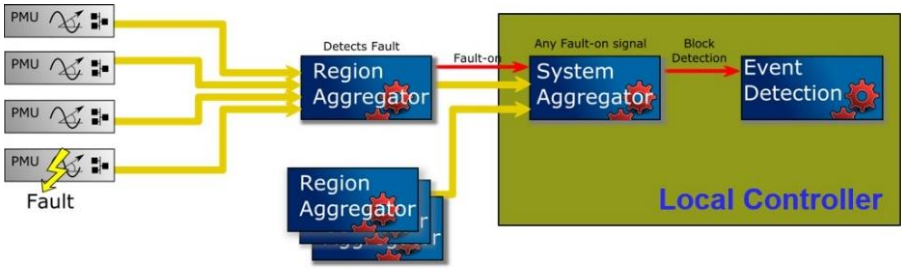


Figure 5: Control Scheme Behaviour during fault

### 3.3. Central Supervisor (CS)

One of the key design briefs for the EFCC scheme was it should have the ability to be resource agnostic, and enable many resources to take part in the rapidly transforming frequency ancillary service market. Therefore, there can be many resources available with different response profiles, where some resources may be able to respond very quickly but may have limited response duration, while others may have a slower response but much longer response duration. While the goal is to deploy fast response, using only fast response may be risky if the duration was not taken into account as the response may be deplete quickly leading which would simply serve to delay the same energy imbalance, hence negating any benefits of the fast frequency control. The overall response should therefore be both fast and capable of sustaining a response so to gracefully reduce while handing over to the conventional governor control. This can be achieved by selecting a mix of resources with the different characteristics of speed of response and duration.

A coordination element is essential to bring all this diversity and dispersion together, which is handled through the CS, while each LC is responsible for collecting resource specific information from its own connected resource and communicating this to the CS. Each LC in the scheme requires high-level knowledge of what other resources exist in the system and their shared region, which is communicated from the CS. Discrete response elements such as loads are controlled differently from continuous elements such as gas turbines, batteries etc. The scheme allows discrete elements to be tripped in a coordinated way with other discrete elements in the system.

During normal operation of the scheme, when a LC detects a change in its connected resource it will send an update to the CS. If the CS loses visibility of the LC, it will assume it is unavailable and if the LC loses connection to the CS, it will assume a local mode of operation. The local mode of operation is included so that some level of control is still available should a loss of communications event occur.

The CS performs an optimization function in order to achieve the optimal mix of resources within the region, assuming an abundance of resources which is currently on speed of response. The CS will compare each of the resources and assign them a priority based on their speed of response and their duration (ability to maintain that response). Faster resources are prioritized higher, but also the CS will mix static resource such as load with continuous resources to prevent scenarios where all deployment is simply load shedding. The results of the prioritisation are sent to every LC as an anonymised table, however each LC can identify itself within the table.

**Deployment of the regional resource**

Within a region, the LC will deploy power according to the priority table sent by the CS, based on which, each LC is able to recreate the profile as shown in Figure 6 and also knows its own position within the table. The table combines all the resources into different bands based on the optimisation, i.e. band 1 are the fastest and band 3 being the slowest. When an event occurs, the LC will then move through this list and deploy the appropriate resources starting from the optimal resources (fastest). As more resource is required, it will call upon more resource, band 2, band 3 etc. Each LC performs the same function, but will then compare its own unique identifier to the position in the table and will deploy if the resource required according to the table matches its own ID. There is a table for each of the regions. The benefit of using this approach is that all LCs are coordinated but do not need to identify the characteristics of others, potentially competing, resources in the market. Additionally, it prevents unnecessary delay in deployment during the event if each of the LCs had to coordinate between each other in order to deploy response. It is important to note that the CS does not take any decisions during an event, as the latency involved in centralised decision making would be prohibitive. Instead, this resource management and prioritisation is done continuously, but at a slower rate (e.g. 30s +). When an event is detected by the LCs, they will freeze the last set of results received from the CS and the scheme will deploy based on this.

### 3.4. Graceful degradation to handle degraded commination conditions

Wide-area control brings many benefits such as increased observability of the system and robustness through multiple data sources. However, a key component to the wide-area scheme is the communications network. Wide-area control system must be designed in a way that takes into account the effects of degraded communication conditions, such as latency, jitter, packet loss, etc. The ability of a control scheme to operate through these types of issues is referred to as graceful degradation, where the performance of the control scheme will be degraded in proportion to the impact of the issue. For example, in this scheme, there are multiple sources of data in the form of PMUs or RAs. Therefore, even with complete failure of one of these components, there is still data available from other sources allowing for a control decision. However, it may be less optimal than a decision based on full observability. Each of algorithms used in the wide-area scheme have been designed with graceful degradation in mind.

Unlike an analog signal, the algorithms within EFCC are designed with the expectation that data will not always be 100% available or reliable. Data can be lost, delayed, or corrupted while transported through the wide-area communications network, or may suffer from time issues e.g. GPS unlock. Therefore, the algorithms use a range of techniques such as interpolation, gap-filling etc. for data gaps and for sustained loss of data, such as a device failure, continue operation with the available measurements, to a limit. The key enabler for this graceful degradation is the use of quality metadata, where every signal used by the control scheme contains a set of quality metrics which determine how 'good' a signal is. The use of quality is a core component in IEC 61850, and is combined with the quality metrics contained in IEEE C37.118 synchrophasors. Every operation made by the control scheme will consider the values of a signal, but also the quality metrics, which will be propagated throughout the scheme. Therefore, when making the critical control decisions, the quality of the data being used is always assessed.

In the EFCC system, each LC has the ability to quantify the quality of the wide-area signals in the form of confidence levels, with 100% representing full confidence with the data. Insufficient confidence in the data obtained from the wide-area would force the controller to prefer locally available measurements and take control actions based on these measurements. While this action will be slower, to filter out local noise and oscillations, it means that a controller can still provide a useful resource to the grid at reduced performance (i.e. graceful degradation).

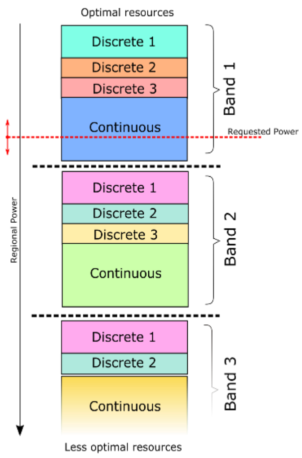


Figure 6. Coordination of responses

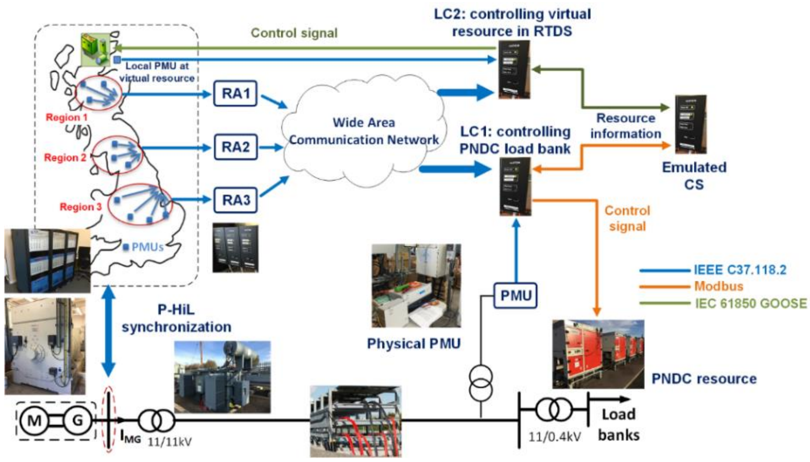


Figure 7. P-HiL test configuration for validating the EFCC performance

## 4. CASE STUDIES

In this section, case studies are presented to validate the performance of the EFCC scheme during frequency disturbances, fault events and when the communication system performance degraded.

### 4.1. The validation of the EFCC system with event at different locations

The test setup for evaluating the EFCC's performance during frequency events is shown in Figure 7. In this setup, three RAs and two LCs were tested. The function of the CS was emulated using a dedicated software block. 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, with details reported in [10]. The simulated network model in RTDS is divided into three regions, where each region has two P-Class PMU models installed, streaming real-time synchrophasor data to the three RAs. The three RAs receive and process synchrophasor data and send the regional aggregated 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. Each LC is also equipped with one local PMU for local measurement, 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 in the physical PNDC network, while LC1 uses a modelled PMU in RTDS. The emulated CS has knowledge of the resource availability and characteristics from the 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. The network model was configured to have an overall system inertia level of 82 GVAs, which is the estimated most common inertia level in the GB system in 2025-26 [2].

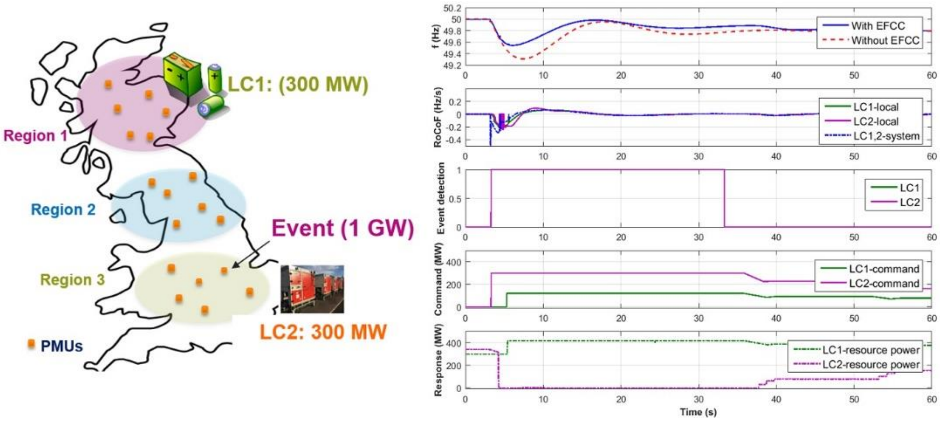


Figure 8. Case 1A test results

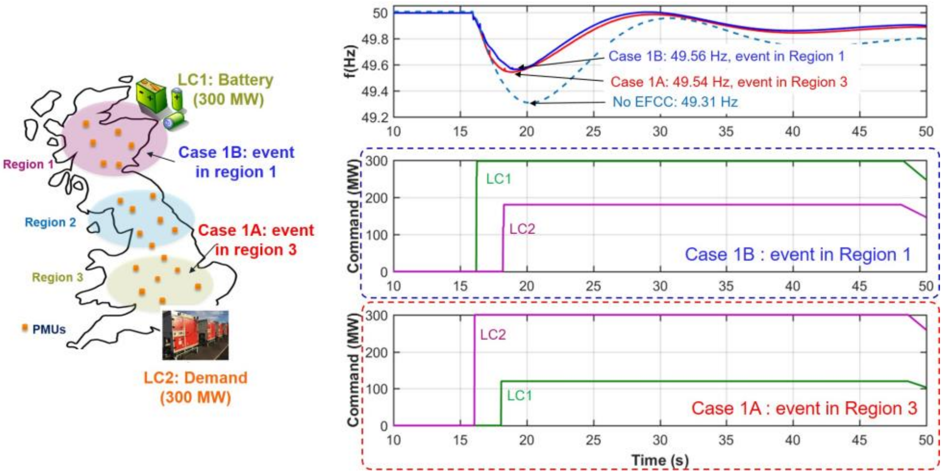


Figure 9. Comparison of the EFCC response with event locating in different regions

In the first test case, i.e. case 1A, the arrangement of the resources and the event are shown in Figure 8. It can be seen that both of LC1 and LC2 resources have 300 MW reserve available, and LC1 is located in Region 1, while LC2 is located in Region 3.  An under-frequency event was trigged by disconnecting 1 GW infeed in Region 3. In Figure 8, 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 2s 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 at the required level. The 2s delay in LC1 was intentionally introduced for resources that are not located in the region where the event occurs to minimise the risk of system separation at the beginning of the event occurrence.

The same 1GW loss of generation event was repeated Region 1 in Case 1B, where the comparison of the results with Case 1A is shown in Figure 9. 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 respond faster than the resources located in other regions, thus showing that the EFCC scheme has correctly deployed regional response based on the frequency event location.

### 4.2. EFCC system's performance during faults

In this test case, the EFCC's performance during a Phase-Earth (Ph-E) fault event is evaluated. Since the GB transmission network model in RTDS is a simplified model, 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. In this test, a Ph-E fault was applied in Region 1 and the test results are shown in Figure 10. 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. Regarding the behaviour of the LCs, both LCs have correctly remained non-operative, i.e. do not deploy any response, as required.

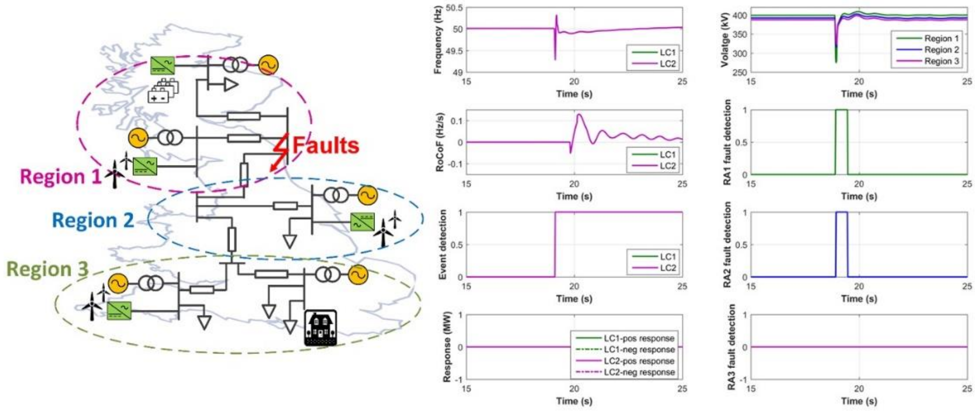


Figure 10. EFCC performance during a Ph-E fault

### 4.3. EFCC system's performance during degraded communication conditions

The real-time communication used by EFCC involves regional communication between PMUs and RAs, and wide-area communication between RAs and LCs. In this test, emulation of a degraded wide-area communication network between the RAs and the LCs will be conducted to evaluate the impact on the LCs' performances. The size of LC's buffering window is configured as 100ms, and it was tested that at this configuration, the maximum latency limit that the LCs can handle is 78ms. In this test, an extreme case where a mean latency of 78 ms with a jitter level of 26 ms was emulate, i.e. this is the maximum latency limit with the maximum jitter level that can be introduced using the communication emulator, so it represents the most severe jitter condition that can be tested at the 78 ms latency limit, equivalent to the loss of 50% of the packets.

A large number of tests were conducted and it was found that in vast majority of the cases, there is no obvious impact on the decision making observed in the LCs, where the test results are reported in [9]. However, it was found that at this high level of jitter, the behaviour of EFCC did vary. In this section, a worst-case scenario is presented to demonstrate that even under the worst case, the EFCC scheme can still provide support to the grid.

The test results are shown in Figure 11. It can be seen that, at this level of latency and jitter, LC1 lost wide-area visibility most of the time during the test (confidence level dropped to 33.33% or 0%) - this is evident in the quality (second plot) and the frequency measurement (third plot) frequently dropped to 0 at LC1. When the frequency event occurred, a slower action from LC1 with a smaller deployed power were observed compared with the case with ideal communication networks. A zoomed-in view of the test results is shown on the right of Figure 11. It can be seen that, the wide-area visibility was lost in a number of instances during the test, which led to the delay in event detection and compromised power deployment actions. However, from these results, it can be seen that, although the EFCC control could become less effective in the extreme case, it could still provide a good level of support to the frequency control during the event.

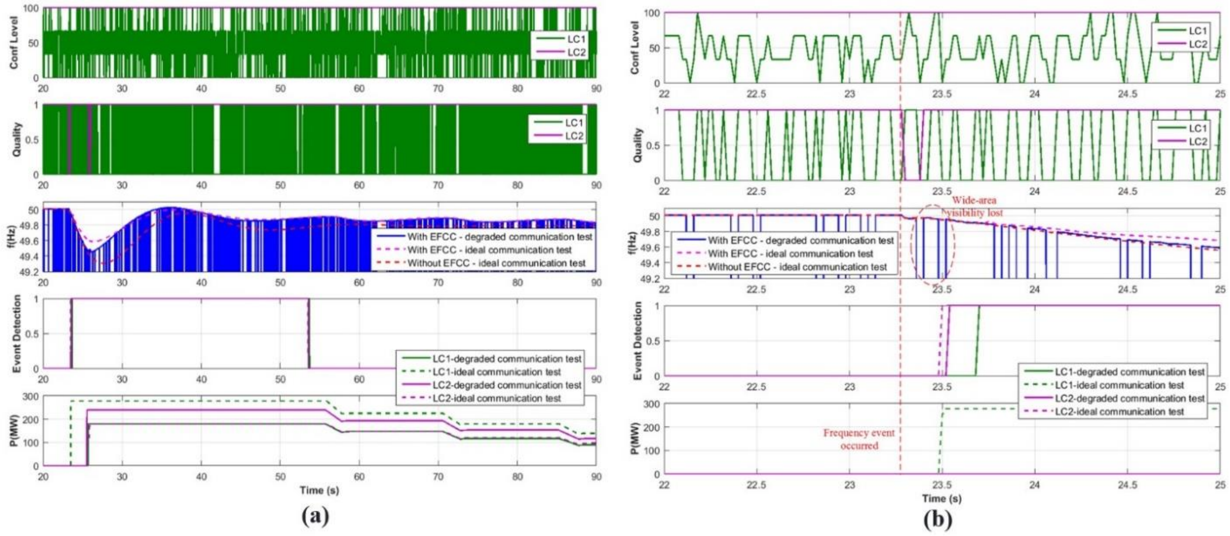


Figure 11. Test results of EFCC with communication network with a mean latency of 78ms and a jitter of 26ms

## 5. CONCLUSIONS

This paper has presented the EFCC system that uses wide-area PMU data for detecting and enabling fast frequency response to address the frequency control challenges in future low-inertia systems. The EFCC system evaluates the regional impact of the frequency disturbances and coordinates the responses from a variety of resources based on their availability and capability to achieve an overall optimal response. In the EFCC system, a distributed control mechanism was used with careful consideration of the impact of potentially degraded communication performance. Case studies have been presented, which demonstrate the EFCC system can effectively dispatch regional frequency responses to enhance frequency control and correctly detect fault events that do not require any response. It was also shown that the EFCC system is capable of effectively handling communication degradation conditions to correctly provide frequency support to the grid when required.

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