GE
Grid Solutions

Smart Frequency Control

Resource Allocation Application

November, 30, 2015

ResourceAllocationPR_v1

imagination at work

Contents

Figures

Tables

1 Introduction

This document follows the first release document describing event detection in NG-EFCC-SPEC-040 and will build upon the development described in that document.

1.1 Background

Resource allocation is the link between event detection and the actual resources as in Figure 1. When an event is detected by the controller, it is the role of the Resource Allocation algorithm to determine the appropriate response from a controllers connected resource based on the detected event. This is a particularly complex task given the diversity of resources which are possible under Smart Frequency Control (SFC). For an appropriate response to be taken there must be a mechanism by which to account for all the available resources in the system. This is called the active portfolio of resources. This portfolio is determined prior to any event occurring, but when an event is detected, resources from that portfolio are called upon to act. Resources which are not in the active portfolio will not act. This portfolio should be managed to ensure there is sufficient response available to respond to a frequency event.

During the early years of a SFC rollout, it is likely that there will be limited resources available for SFC, therefore the portfolio may be quite small and easy to manage. It will become more difficult to manage in the future as more resources become available for SFC. If there are many resources in the system it may become too costly (dependent on the chosen market mechanism) to have all resources in a system active for frequency control all the time. Therefore, the System Operator may choose to maintain a suitable amount of resources for SFC. It then becomes important to find the *optimal mix of resources*. This is to ensure that there is a balance of resource type across the portfolio and that resources are not confined to a single region or comprise a single technology which may share a common characteristic such as short duration and hence reduce the effectiveness of the SFC scheme. The optimisation will be further defined through the future optimisation work package

The portfolio of resources must be handled from a central location as it requires observability of all resources, it is therefore managed by the Central Supervisor (CS). The CS itself does not have an active role in the control decisions during an event as this is performed in a distributed way by each of the Local Controllers (LCs). The CS role is confined to a pre-event state through managing the portfolio of resources. The driver for distributing the control decisions is to minimise delays in delivering a control request to a resource and minimising bandwidth on the communications network. The role of the CS is in a supervision capacity with the LCs each making an autonomous decision on the control values during an event.

During an event, the LCs use Wide-Area (WA) signals (system frequency and voltage angle) to determine a suitable wide-area response to that event, however in the event of loss of wide-area communications, it can also use local frequency signals to continue to provide a useful response. The scheme using a number of LCs will distribute the response across the system in line with regional inertia based on algorithms which rely on angle-difference concepts. The effects of regional inertia are inherent in the angle and frequency behaviour where reduced inertia levels lead to increased swing dynamics (Andreas Ulbig, 2014). These increased swing dynamics mean that the risk of angular instability increases. Therefore, the use of angles in the control algorithms allows both regional inertia to be evaluated while simultaneously minimising the risk of angular instability resulting from poor control actions.

Results show that the proposed control scheme can successfully limit the amount by which frequency drops and can provide a controlled response to which conventional governor control can respond without reaching load shedding limits. In steady state, an angle difference will exist between two interconnected regions dependent upon the power flow, and the difference can be used to determine the stress between the regions. When an event occurs, this angle difference can increase between regions, pushing them closer to angular instability. The control algorithms developed ensures that this angle difference is considered in the controlled response to an event.

1.1.1 Scope

The aspects of the SFC scheme described in this document are highlighted in Figure 1. The resource allocation functions are spread between the CS and the LC, portfolio management in the CS and defining response in the LC.

High-level descriptions of the algorithms have been included in this document and a summary of the test results provided for information purposes.

In this document, resources will be classed into two categories, continuous and discrete. A discrete resource is one which can deploy a fixed response in a single action, e.g. tripping a single load. A continuous resource is one which can deploy a portion of its total available response and can deploy additional response if available, e.g. a gas turbine.

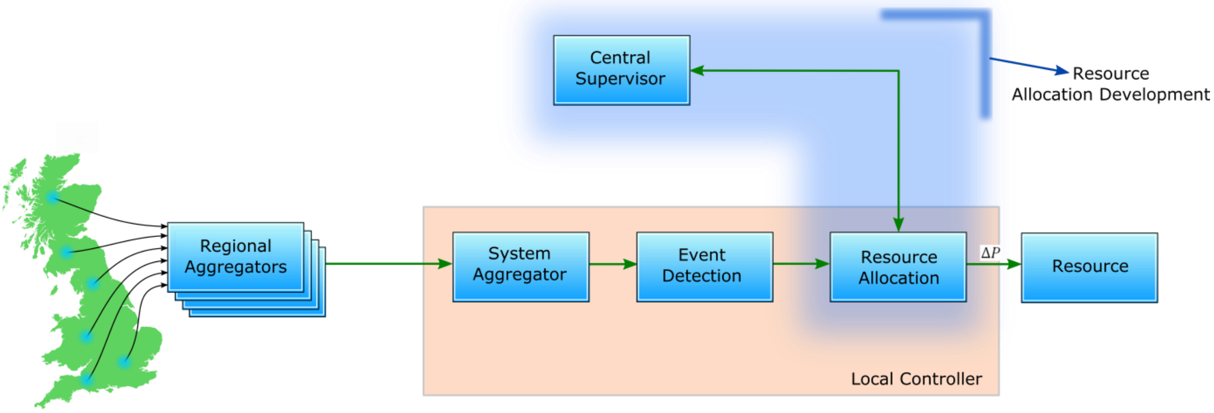

Figure 1 Resource Allocation Development in context of overall scheme

2 High-Level Description of the Resource Allocation Application

In the SFC scheme, Resource allocation must be considered from two distinct perspectives, the first is a pre-event coordination or portfolio management perspective while the second is of a during-event deployment of resources perspective. Before an event is detected, there must be a number of resources in the scheme which are ready to act when an event does occur. These resources are managed by the CS. When an event is detected the local controllers are responsible for deployment of their own resources and will make an autonomous decision on how much to deploy based on the wide-area frequency and angle signals received. The connection between the LC and CS for the portfolio management task is designed not to rely on high-speed connections and delays caused from the communications network will not impact upon the control action itself which is taken locally.

The proposed control scheme is shown in Figure 2. This document focuses mainly on the blue and green links in that figure. The CS will be sited at a single location, ideally at the National Grid control room. It is envisaged that under rollout, the PMUs will communicate directly to the Regional Aggregators via NG's network.

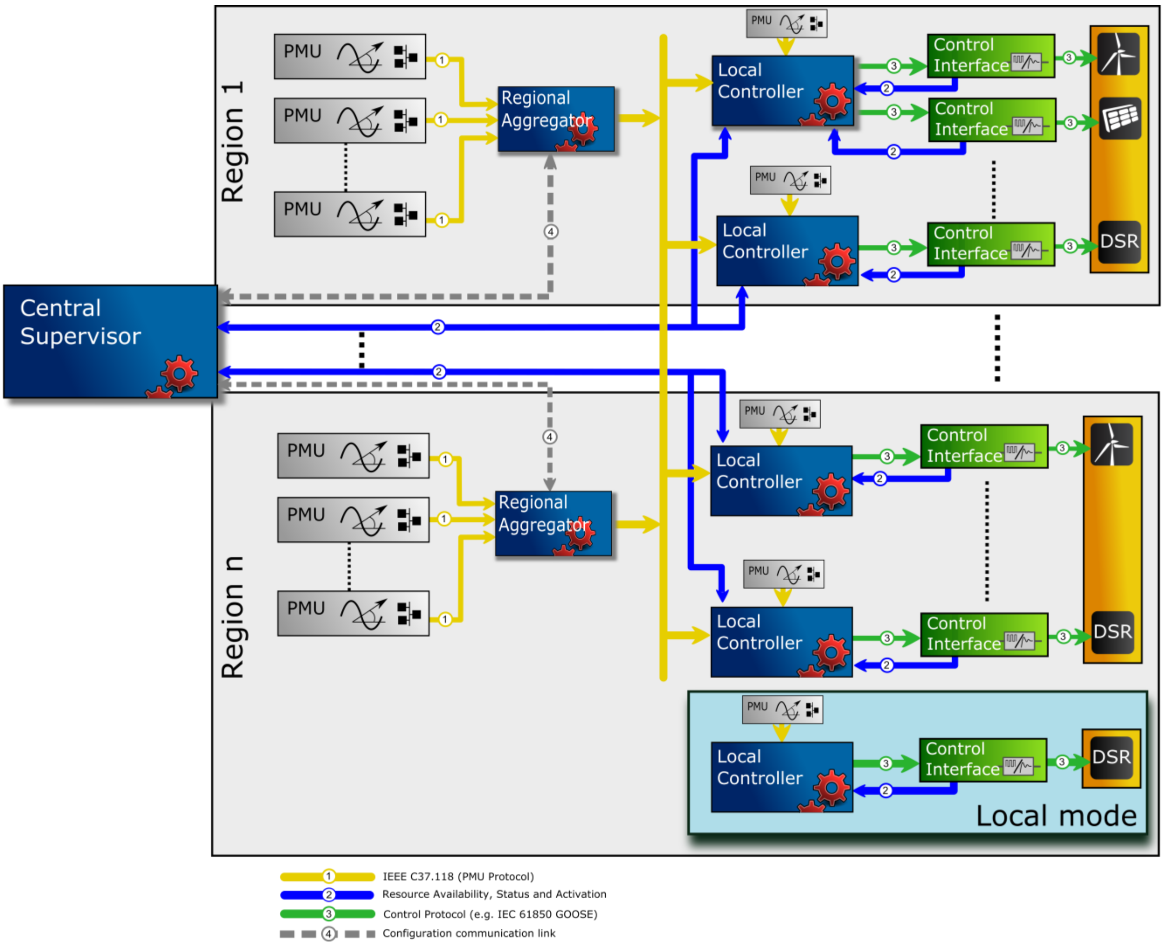

Figure 2 SFC Control Scheme Architecture (IEC 61850 being proposed for Signals (2) and (4))

2.1 Resource Allocation – Portfolio Management

Resource Allocation performs an important role in the management of multiple resources and resource types in the scheme. The resource allocation algorithms should evaluate the available resources in the system and from that, select which resources should be made available for SFC. The high-level roles of the portfolio management are shown in Figure 3 which will be performed at the CS level.

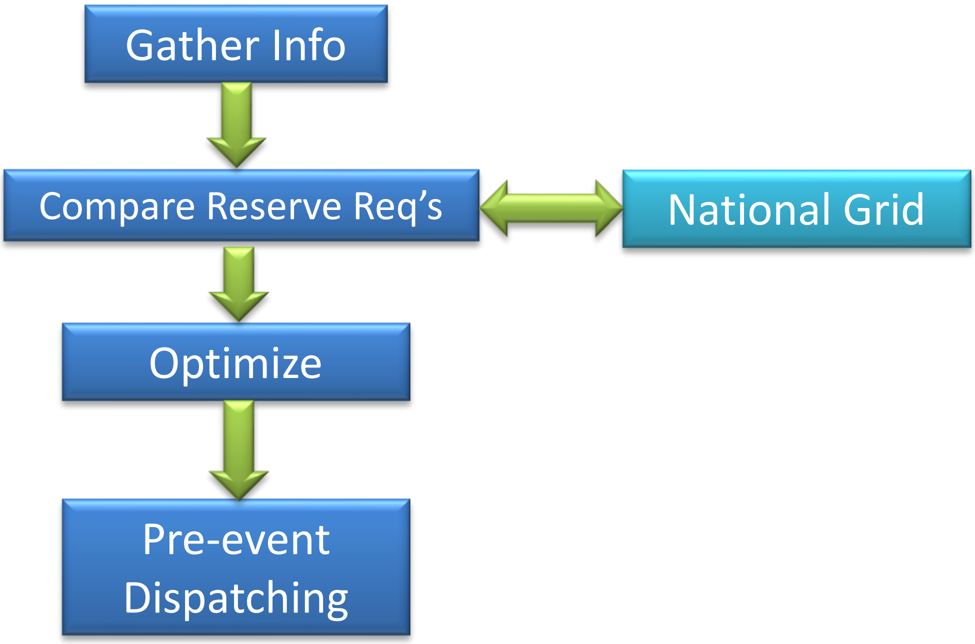

Figure 3 Resource Allocation management Stages

2.1.1 Gathering Resource Information

The first stage of Resource Allocation is to gather information from the service providers to build up the resource profile which should include both the directly controllable resources and indirectly controlled resource (ICR). An ICR is any resource which is not controlled using the wide-area controllers. These can be independent locally controlled resources or existing loads tripped automatically by frequency relays etc. A number of protection mechanisms such as load shedding will exist in the network, which will be independent from SFC, but because they may share similar triggering signals, the SFC scheme should be coordinated with such schemes. To account for these, some ICRs will be visible by the CS such as DSR contracted resources while other ICRs such as conventional load shedding relays will not be observable by the CS and may require an external input method.

In order to create a suitable resource portfolio, the following information is required from the resources:

- Available power
- Resource availability
- Response type
- Response characteristics

2.1.2 Compare Reserve Requirements

The CS should collate system resources and compare to the '*rapid frequency reserve*' requirement, which is a value decided by National Grid (NG) for the system at a particular time. This '*rapid frequency reserve*' is how much resource capacity NG would like '*active*' for a particular operating period, i.e. '*reserved*' for rapid frequency response.

2.1.3 Optimizing Resource Portfolio

Defining the resources which should be armed to form *the 'rapid frequency reserve'* will form the optimisation package which will be developed in collaboration with The University of Manchester (UoM) in a subsequent work stream. The optimisation will be responsible for managing the portfolio of resources to ensure that there is a well balanced mix of resources available at any one time. The definition of a well balanced mix will be described in later work packages.

2.1.4 Pre-event Dispatching

The optimisation stage should define the total portfolio of resources required for SFC including the regional breakdown of resources. From this a set of dispatch decisions will be formed which will arm/disarm the LCs depending on their inclusion in the current portfolio. These are then the devices which should act when an event occurs in the system.

2.2 Resource Allocation – Deploying Resources

When a frequency event occurs in the system, the wide-area measurements are used to determine a value of the required MW response and the best locations to deploy that response. It is based on the system rate of change of frequency (RoCoF) which is measured during the event and an appropriate system inertia estimate which will be computed offline using simulation studies. The frequency data used to determine the system RoCoF is equivalent to that from a single machine equivalent which is a well-documented concept. Once the size of the loss (of generation or load) is approximated, the controllers will determine how to deploy an appropriate response, targeting the areas most affected. This targeting of response is a key innovation of the scheme which aims to reduce the risk of the control actions degrading system stability. This targeting mechanism relies on wide-area observability of the angle behaviour by evaluating the angle relationships across the system during the response.

During a frequency event, angles across the system will be perturbed, with angles closest to the event normally moving furthest from their pre-event state. The magnitude of the angle perturbation will depend on both the inertia in that area of the network as well as the proximity to the originating disturbance. It is important for power system stability that differences between angles across the system do not grow too large. A large angle separation between regions may lead to electrical separation between those regions and lead to potential loss-of-supply to customers to balance the regions. When very fast control actions are taken on the system, this can introduce additional perturbations to the angles. It is important that these control actions aim to restore angles between regions rather than introduce additional separation between regions.

This angular stability is of particular importance in the transient period of the event and control action must be taken carefully to avoid adding further stress. During this period, control actions will be applied which respect the angular behaviour of the system and take the locational element into consideration, whether that is the location of the originating disturbance or the location of lowest inertia near the disturbance.

A simulated example of a generator loss is shown in Figure 4 where all angles are referenced to pre-event state, hence angles at zero at the start. After a generation trip in region 3, angles begin to diverge, with the angle closest to the event (or the region with the lowest inertia) moving furthest from the system equivalent. The increased angular separation between regions indicates increased risk of electrical separation between these regions (e.g. region 3 and region 1). Note that Region 2 appears to move first before moving closer to the system equivalent but it is only leading for a short period. This can be explained by the inter-area oscillatory behaviour where some generators are oscillating against others in the network causing a region to appear initially as the leading region but then lags behind as the oscillations are damped out. A close up of the generator rotor speeds are shown in Figure 5 showing the oscillations between the generators.

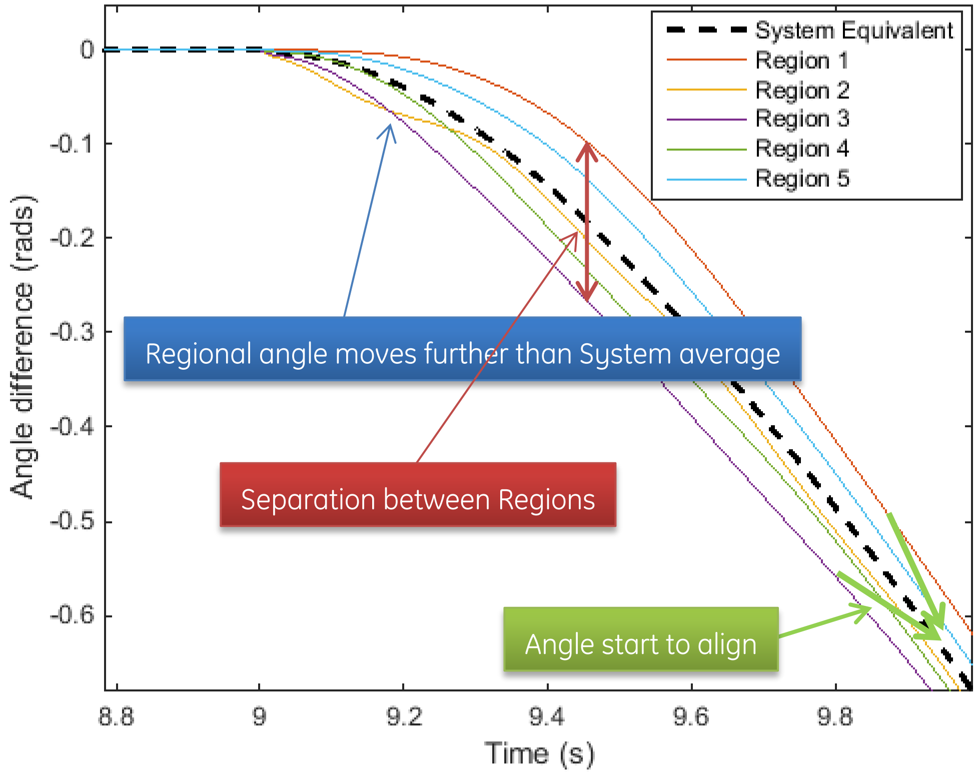

Figure 4 Angle Separation after Generator Loss

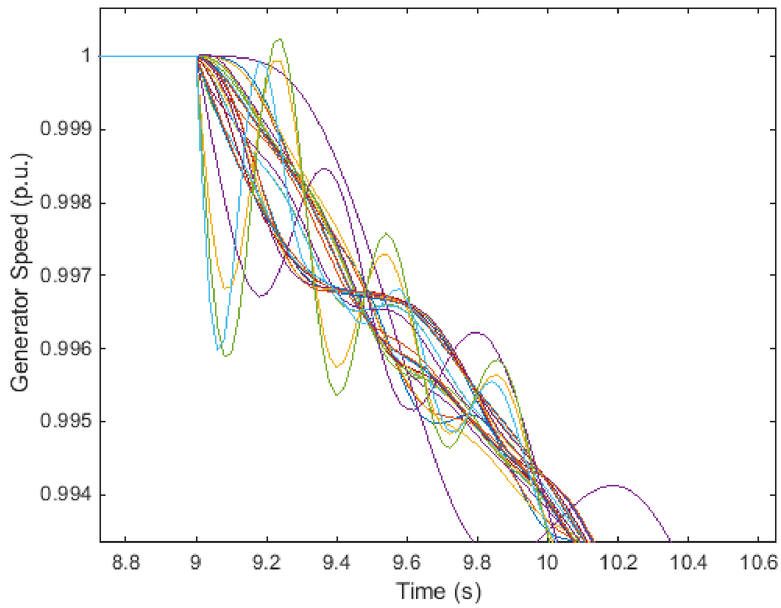

Figure 5 Generator Rotor Speeds

The angles start to align after this initial period (first swing) and the risk of separation between the regions decreases, assuming a damped system. This is covered in a number of textbooks on power system stability. When the risk of first swing angular instability has reduced, the locational element of the control is less important and resources can start to be called upon from elsewhere in the system. This allows controllers that were initially not included in the deployment due to them not being close to the event to start contributing. If the response deployed in the first stage was insufficient, the RoCoF will have decreased but will not yet have reached zero therefore allowing a second opportunity to deploy resource from remaining controllers.

The power that a LC initiates will use a *'ratcheting'* mechanism whereby power can only move in a single direction during response to an event, i.e. in an underfrequency event, the LC can only increase its power and will remain at that output unless it is requested to further increase its power. This is to avoid LCs simply following oscillations in frequency which could negatively impact on system damping but can also reduce the life of resources. An example of this 'ratcheting' can be seen in Figure 6 where the frequency response after an event is shown and a corresponding increase in power requested from the LC.

The LC will monitor the frequency and will determine if additional response is required. When the system begins to recover, it will start to return to its normal output, reducing response.

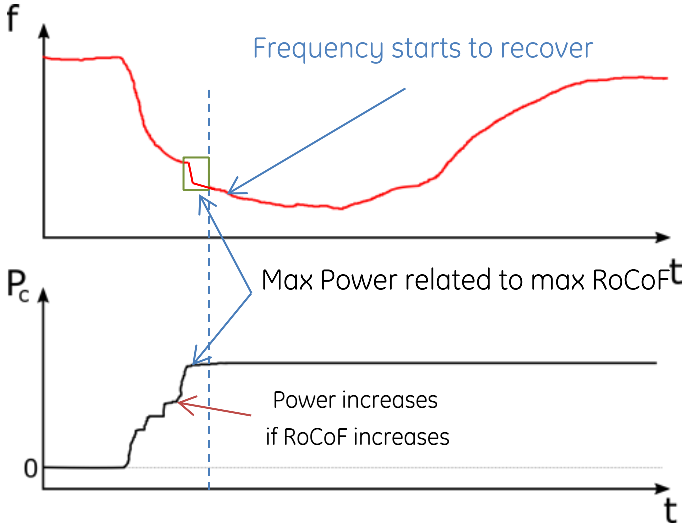

Figure 6 Example of Frequency Response and Control Target Power (For illustrative purposes)

3 Algorithm Description

The first role of Resource Allocation is managing the resource portfolio and considering how much SFC resource the System Operator wants available at any time. The second role is in deploying resource in response to both size and location of an event. The portfolio management is dictated by the resource characteristics and the System Operator requirements. Depending on how often the System Operator changes the requirement or how often the resources themselves change their availability or available power will determine how often the portfolio must be updated. It is envisaged that this may be no more frequent than 15 minute updates. However, the deployment of resource is dictated by the measurements used as the input which utilises a 50Hz sampling frequency, much faster compared to the portfolio management.

3.1 Resource Allocation – Portfolio Management

The allocation of resources which are included in the portfolio and available for response is handled centrally at the CS as it requires observability of all resources in the system. The CS will perform two main tasks,

- Select which resources should be included in the portfolio
- Communicate the portfolio information downstream to the controllers

3.1.1 Scheme Coordination

An SFC scheme can involve a large number of resources dispersed throughout the electrical network with diverse response characteristics. A coordination element is essential to bring all this diversity and dispersion together. An example of the necessity of this element would be a high-wind scenario where all of the SFC available resource was made up of wind power in a remote region. For an event which is electrically distant from the resources, deploying resource may jeopardise angular stability, but also the reliance on a single resource type could mean that if wind speeds in that region began to drop, much of the SFC resource is lost. It is therefore beneficial to have more resource diversity but also geographical spread throughout the network which also allows more accurate targeting of response.

The coordination of the control scheme is handled through the CS which is the only component in the scheme with full observability of all wide-area controllable elements. Each of the LCs in the field that have access to wide-area connections will be linked to the CS. The LC is responsible for collecting resource specific information from its own connected resource and communicating this to the CS. When the CS has received information from the LCs in the system, it can begin allocation, determining a balance of resource types within the region/system and maintaining a reasonable balance of resources across the system. This may result in some of the available resource being disarmed as they may be excess to requirements. These functions will be developed through the 'Optimisation' deliverable and the output of armed resources forms the active portfolio.

Each LC in the scheme requires high-level knowledge of what other resources exist in the system, which is communicated from the CS. Discrete elements such as loads must be controlled differently from continuous elements such as gas turbines, batteries etc. An algorithm has been developed which allows discrete elements to be tripped in a coordinated way with other discrete elements in the system. This is a critical point in order to minimise the risk of over or under response.

During normal operation of the scheme, when a LC detects a change in its connected resource it will send an update to the CS. Additionally, there will be a check to ensure that both the LC and CS have visibility of each other. 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. In each case, the CS may need to update its portfolio to account for these changes.

The CS will include an optimisation function with the aim of achieving the optimal mix of resources within the region, assuming an abundance of resources. This is currently under development. The results from the optimisation should include the set of resources which are included in the active portfolio along with the resource profiles. The resource profiles include information on how much of each resource type has been allocated both regionally and system wide. The CS will then issue arming signals based on the active portfolio. Resources which are not included in the portfolio will be disarmed and will not partake in any frequency response.

The local controllers will be configured based on the information received from the CS. If no information is received from the CS, the local controllers will resort to the local-mode and use a set of locally stored configuration values. When the controllers are configured, resource will be deployed when a trigger is received from the Event Detection function which signals detection of a frequency event on the system.

3.1.2 Building the Resource Profile

A resource profile describes the breakdown of resources within the active portfolio. The portfolio describes all the armed resources in the system where the resource profile then breaks it down to a regional level describing the total resource in a region and what types of resources are included in creating that total, e.g. proportion of wind, battery etc. This function must be performed in the CS as it is the only point where all individual resource information is observable.

In order to create the portfolio, the CS requires information from the resources including:

- Type of resource (Wind, battery etc.)
- Is resource available?
- Value of response available
- Response characteristics

The portfolio is illustrated in Figure 7 showing the total resources armed in the scheme. There is then a breakdown within that portfolio of different resource types, shown by the different colours. The proportions of these will be based on a suitable optimisation algorithm. This is then broken down into a resource profile for each region defining how much is available and the resource types in each region. The information on the system and regional profile is then passed to the LCs which is required by the LC to make a control decision.

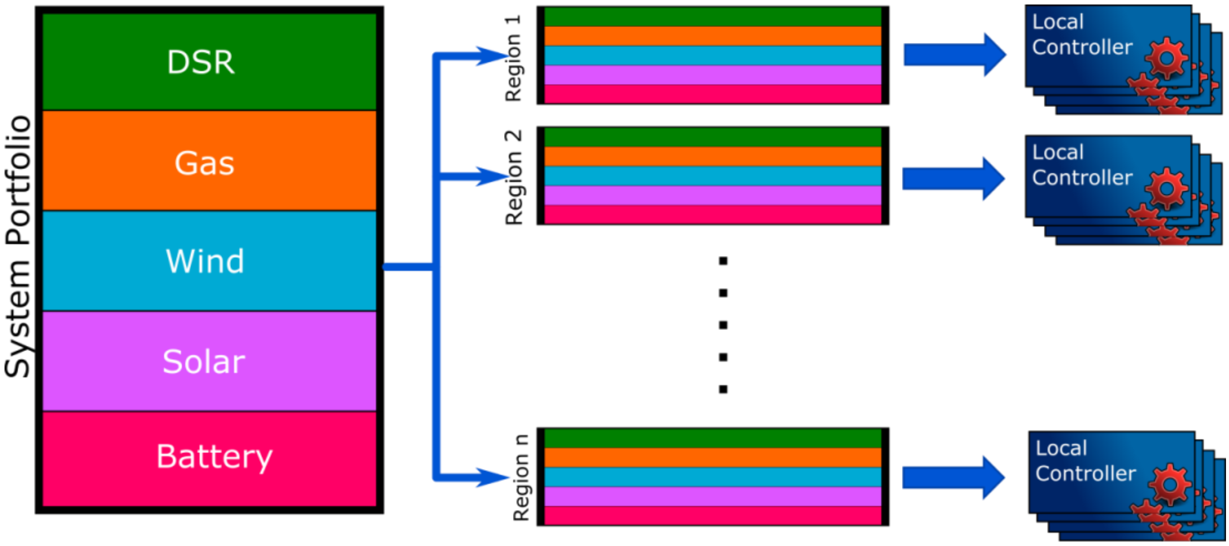

Figure 7 System Resource, Regional Resource breakdown sent to LC

3.1.3 Resource Ranking

For the SFC project the focus is on speed of response, therefore the scheme proposal is to deploy the fastest response first. The response times between the different resources available for SFC can differ. Table 1 summarises the expected resource types and anticipated behaviour from each. These resources can then be ranked in terms of their speed of response where the resource type with the fastest response types will be ranked with the highest priority and should deploy first. When the resources are deployed, the choice of which resource is deployed in any given event will follow this ranking mechanism. The scheme will always aim to deploy the fastest resources first and will continue to select the next fastest resources as required until the target value has been reached.

Table 1 Resource types and behaviour

Resource Type	Controllability	Possible Behavioural Description
Delayed Response e.g. Gas Turbine	Continuous but delayed	GT can be provided a new setpoint however it will take time to ramp to new setpoint
Wind Farm	Continuous but potentially short term	Windfarm may be able to increase or decrease output, however windfarm must return as close to nominal power as possible after a certain duration
PV/Battery	Continuous and fast	PV/Battery combined solution can be provided with a set point and can reach that value very quickly due to the power electronic interface
Discrete Loads	Discrete	These loads are tripped using a breaker (or similar PLC) where all load is dropped in a single discrete step.
Discrete steps load	Discrete steps	May consist of a number of loads at a connection point where there are different combinations of load trips/load reduction

3.1.4 Deploying Discrete Resource Concept

When a target value of power to be deployed is found, continuous resources offer the most flexibility in achieving this target as they can deploy fractions of their maximum power. However, for loads, it is a single discrete tripping decision which limits the ability of achieving the exact target. Two main types of discrete resource under consideration are single discrete elements and discrete steps resources which contain a number of individual load elements coordinated through some customer controller interfaced with a single LC. This may be a customer who has multiple loads which can be tripped in different combinations. Discrete steps loads can be treated in a similar way to continuous resources (in one direction only) using a function such as shown in Figure 8. P_D Is the available demand power from the resource (number of steps relates to number of individual load elements) while P_C is the requested power from the LC. When the requested power P_c from the LC exceeds one of the P_D discrete steps (loads) that individual load will trip. This implementation may be available on sites which have a number of loads they can make available.

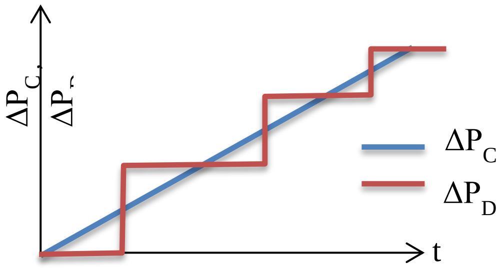

Figure 8 Switchable load bank

In order to deploy single discrete resources such as a single load connected to an individual LC, an optimisation algorithm was developed. The discrete loads in the region are included in the optimisation algorithm which will then select which loads should be deployed and which should not in order to meet the target power value. One of the aims of the optimisation is to avoid tripping the largest loads. The algorithm is computed by each of the LCs in a distributed manner to avoid the effects of communications delays. To distribute the scheme, each LC must know what other discrete elements are in the region but must also be aware of its current ranking among the loads in the region. This information is computed using the CS and then communicated to each of the LCs. Upon receipt of this information, each LC can then determine autonomously whether or not it is required to deploy its load during an event.

3.1.5 Continuous Response

For the continuous responses such as gas or battery, the full resource may not need to be deployed as with the discrete loads. Instead, a portion can be deployed. Additionally, should more response be required, these resources may deploy more if they are not already at maximum output. Within a region, there is less importance on the location in terms of stability as it is assumed to be tightly coupled within a region. Therefore there is no discrimination between resources within the same region. Resources of the same type in the same region will be deployed together with the same percentage power request. I.e. if the region has 300MW of wind and the required response is 150MW, each of the wind resources will provide 50% of capacity, equalling 150MW. A simple set of rules have been designed which the LCs will use to deploy resource according to this methodology. This method makes calculating response by each LC simpler to instruct and minimises the reliance upon a central controller while minimising required bandwidth and delay.

3.2 Resource Allocation – Deploying Resources

When the controllers have been configured by the CS and are aware of what resources are available in the regions, they will be in a 'ready' state waiting for an event. When an event is detected, each of the controllers must determine an appropriate response to that event. The algorithms will determine:

- Which regions need to respond to an event
- Which resources within the regions should act
- How much each resources should deploy
- Coordinate the deployment between all controllers during the event period.

The RoCoF based on system frequency $\frac{df_s}{dt}$ (described by Event Detection Specification, NG-EFCC-SPEC-040) provides an estimate of the required system response based on the system inertia value. The system inertia value does not need to be accurate in real time and the value taken from models should be sufficient. This value is generally well understood within NG for their frequency response studies. Upon detection of an event the scheme will estimate the size of the event. This forms the total system requirement from the scheme. This system requirement is then distributed into a target value for each region. Each LC will then use the regional target value and information received from the CS to determine its own response to contribute towards meeting the regional target.

The controller has two modes of operation, wide-area mode and local mode. If the controller is in local mode, it will deploy its resource in proportion to the observed RoCoF. If it is in wide-area mode, it will use its knowledge of the other resources in the region and system to produce a coordinated response. The intention of the wide-area mode is to deploy resources in a fashion which respects the angular stability of the system. The angular stability is generally more of a concern at the start of the event when the angles are moving. As the event progresses, the movement of the angles will reduce and angles across the system will start to realign. When angles have realigned, the LC will make a transition from wide-area mode to local mode allowing controllers that were prevented from acting in wide-area to now start contributing towards reducing the RoCoF.

The controllers will aim to hold their output when responding to an event as opposed to following a RoCoF signal. They can increase their output should a second event indicated by a larger $\frac{df}{dt}$ be observed. It is important to note that the conventional frequency control (governors) will be responsible for bringing the system back to nominal frequency. The control scheme proposed here aims to halt a fast RoCoF and prevent further decline in frequency, facilitating a controlled handover to the conventional response. The controllers will hold their response and will start to reduce their response gradually allowing for the conventional response to take over.

When the conventional response restores frequency to nominal, each of the controllers will detect this restoration and will reset the control scheme acknowledging the clearing of the event.

3.2.1 Calculating wide-area Response

An estimate of the loss (or excess) of energy in the system is necessary before deploying resources. The control scheme will aim to deploy resources according to the estimated energy gap, refining the value over time. The estimated required system response, $P_{s,}$ is based on the RoCoF of the system and the estimated system inertia. The system RoCoF will use the regionally aggregated signals to create a system aggregated signal. Each of the LCs will use an inertia value combined with the system RoCoF value calculated in the System Aggregator to provide the MW estimate for the total response required from the system.

As the speed of response is a key element to this project, the RoCoF calculation time is limited. Too short a window for RoCoF calculation can provide poor estimates for the real RoCoF behaviour. An adaptive algorithm was developed which makes an initial calculation for RoCoF with the maximum possible sample but will then continue to refine the calculation as more samples are observed. This increases the accuracy of the RoCoF calculation without unnecessary delay. Oscillatory behaviour can also affect the true system RoCoF however the effects of oscillations on the RoCoF have been minimised through careful system architecture design.

The response from the resources may vary over time as the event develops, with some continuous resources asked to increase output, and some fixed value loads to respond later in an event. Not all the resource may be deployed in the first instance, unless required. In severe frequency events, it is not uncommon for subsequent events to occur which further degrade the frequency. (GRID, 2008) This method will handle subsequent events by continually monitoring the RoCoF and upon an increase in the RoCoF, will deploy more resource if available.

3.2.2 Calculating Regional Response – Co-ordination of Response

How the resource is deployed between the regions is governed by the angular behaviour. The impact of an event in a region is observable through the change in the phasor angles. The severity of an event may be down to proximity to the event or amount of regional inertia.

In terms of angular stability, the concern is to avoid any regions accelerating or decelerating too far from other regions. If regions were allowed to move too far, they are at increased risk of losing stability and become electrically separated. Therefore, the aim for the control scheme is to identify those regions which are either accelerating or decelerating the most and determine how to deploy the resources to minimise their movement. The type of behaviour, either accelerating or decelerating will be dependent on the type of event that has been detected.

The output from this step will be a target response value for each region, where the sum of all the response should equal the total system target response.

3.2.3 Local Control

Controllers also have the ability to operate in local mode. This can be due to either loss of communication to the wide-area measurements or control action after wide-area control has acted. In local mode, LCs will be relying on local measurements which are suitably filtered to remove noise and other artefacts.

The deployment from these LCs will be based on a locally measured RoCoF signal and a configured value which defines the worst-case RoCoF. The output will then be determined as a proportion between these two.

3.3 Initiating Target Control at LCs – Calculate LC Response & Trigger

Response will be deployed in two stages, wide-area control and local control using wide-area and local measurements respectively as shown in Figure 9. The wide-area control aims to apply resource quickly in such a way as to minimise the risk of instability from large angle separation. The period of maximum risk can be defined through system analysis. The local control will take over after this period, when angles begin to align and there is reduced risk of angle instability. Figure 10 shows evolution of angle behaviour after a small event with no control with the proposed wide-area and local control timescales superimposed onto it. After the transient period where angles are accelerating and decelerating away from each other, the angles will begin to stabilise and the system will begin to move together as shown in the green box where the local control is proposed.

Figure 9 Timeline of control action

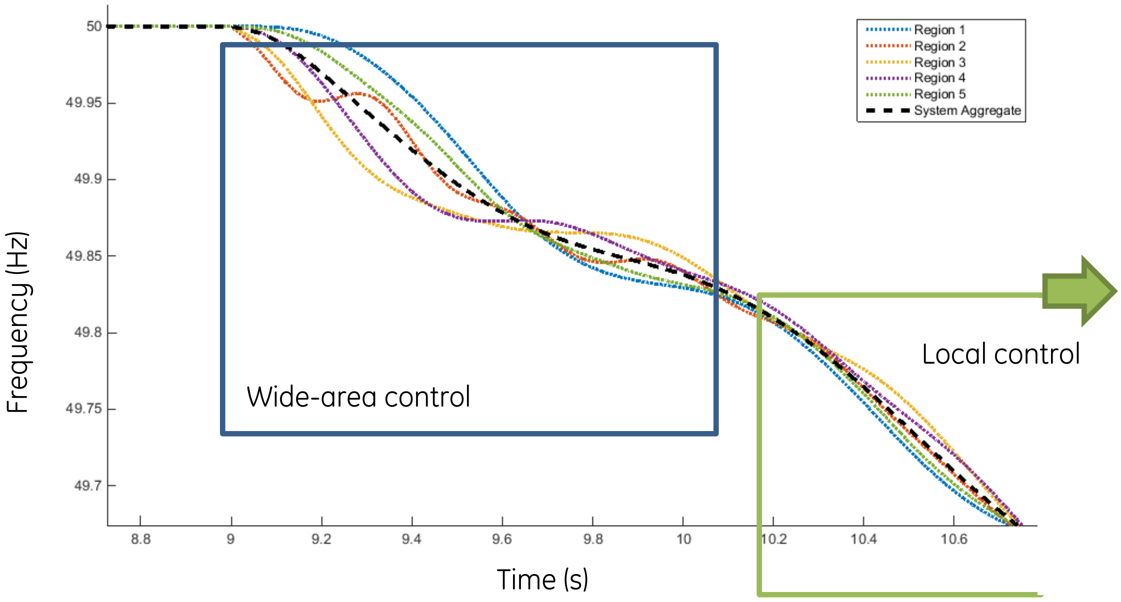

Figure 10 Timeline of intended action based on non-controlled scenario to show angle separation

Figure 11 shows a synthesised example of the intended response compared to conventional governor response. No secondary response is shown. The response (A-D-E) is indicative of the behaviour if no SFC is taken, where the frequency will drop to the load shed limit and governor action will follow, starting at 2s. The green and the blue frequency plots show the potential effect of different quantities of SFC response taken at point B. If the wide-area control stage issues sufficient response, the frequency will begin to recover quite quickly shown in blue. However, if the initial wide-area control stage deploys insufficient response for whatever reason, the local control stage will have a second opportunity to deploy additional resources, point C, and further arrest the frequency decline shown in green.

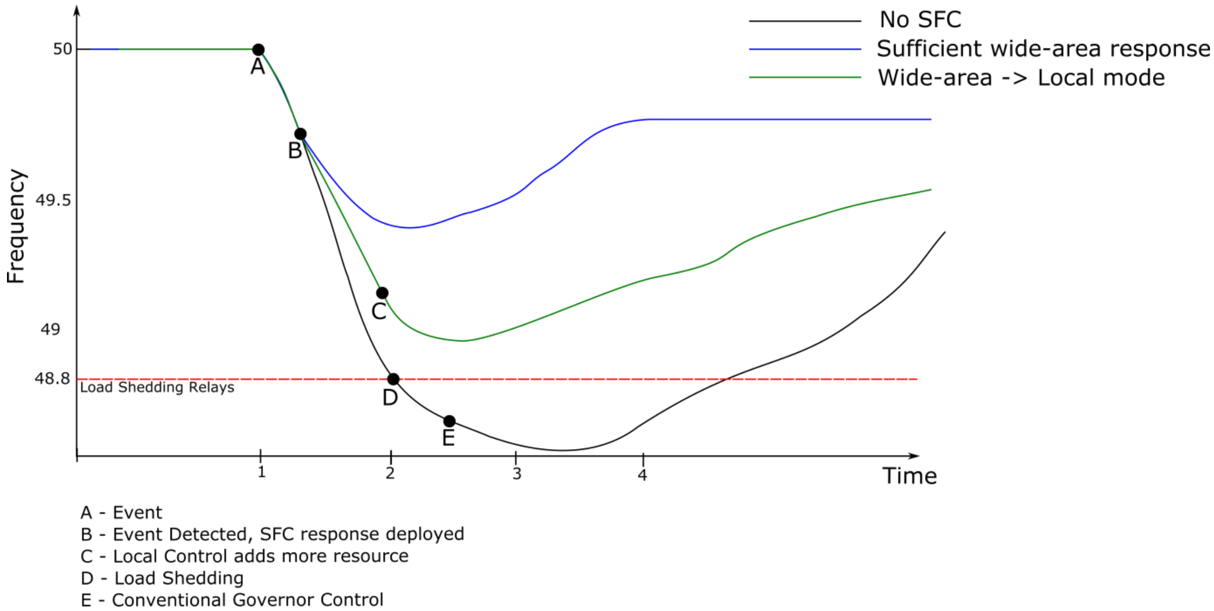

Figure 11 Anticipated Response from SFC scheme

4 Resource Allocation Functional Test Results

A functional specification was circulated to all project partners prior to the algorithm development. Upon completion of the development, each function prescribed by the specification was tested and results circulated to project partners. Due to the intellectual property contained within those results, the details cannot be shared. However, a summary is provided. A test environment was developed based on the use of a power system model and 10 controller models. Tests were designed to test each of the functions and all functional tests related to this deliverable passed.

4.1 High level Control Scheme results

A preliminary model was developed to illustrate some of the interaction between the controller and controllable resources in a power system modelling environment. The results of the controller behaviour and results from the control scheme are described here to provide a high-level overview of the control scheme actions. Further testing and integration will be performed by Grid Solutions in the dedicated testing phase in 2016 which will significantly improve upon these preliminary findings. The aim of the results is to show the proposed operation of the scheme.

Figure 12 shows the result of a generator trip on a system where the frequency quickly falls below the load shed limit (load shedding not modelled). The results of the proposed control scheme are shown on the same figure which deploys resource 180ms after the trip. There is ringdown present (which is the transient response to a shock on the system) due to the immediate deployment of control actions possible only in a model. This would be less severe in a physical system due to delays in response due to ramping etc. With this deployment, frequency decline is halted at a much earlier stage showing the effectiveness of fast frequency control.

Controllers then sustain their output for a period (shown by the purple arrow in Figure 12) before ramping down and returning back to normal (shown by the green arrow). As the resources begin ramping down, the energy imbalance in the system can be much more carefully managed by creating a controlled frequency drop which allows more time for conventional governor actions (shown by the yellow arrow) without risk of hitting load shedding limits.

The sum of the controllers response is shown in Figure 13 where the ramping up, sustain and ramping down behaviour can be clearly seen.

Angle stability

The angle behaviour can be observed in Figure 14 which shows the PMU measured frequency near each bus connected to synchronous generation, where there is some ringdown due to the rapid deployment of resources which would be much less severe in a real system due to the different characteristics from resources. It can be seen that these oscillations are well damped and there is no negative angle separation between any of the generators therefore showing that the control action does not put unnecessary stress on the angular stability of the system. Further more detailed studies and tests will be performed in the later dedicated test stages of the project.

Summary

In summary, it can be seen from this preliminary control scheme and power system model environment that the developed control scheme has positive effects on the frequency and can quickly halt a frequency decline while maintaining angular stability.

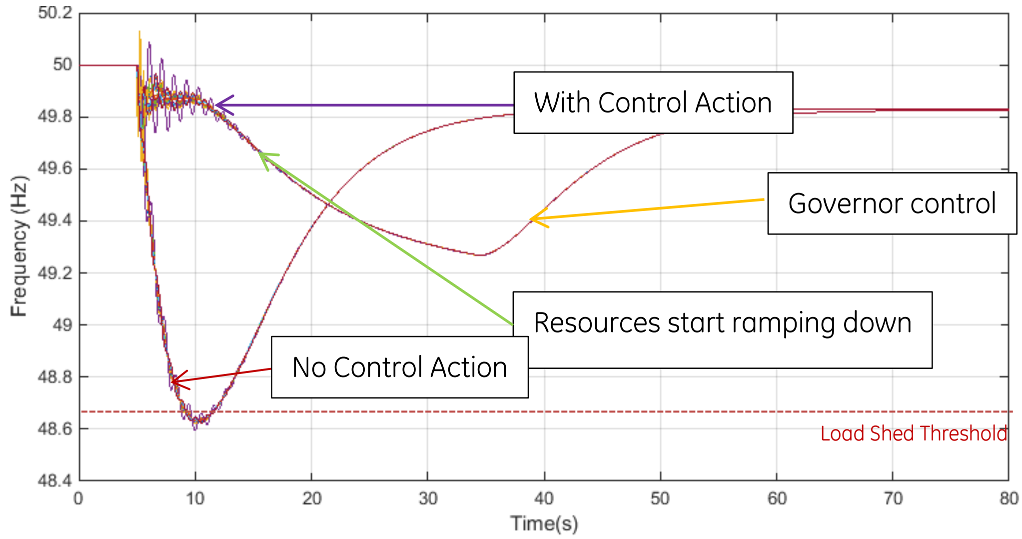

Figure 12 Frequency behaviour with and without control

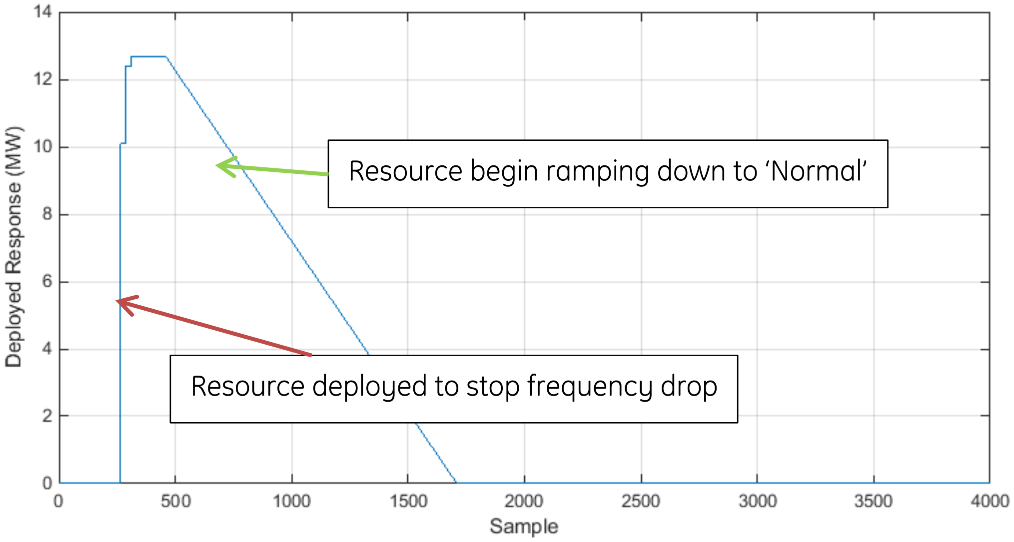

Figure 13 Sum of response from all controllers

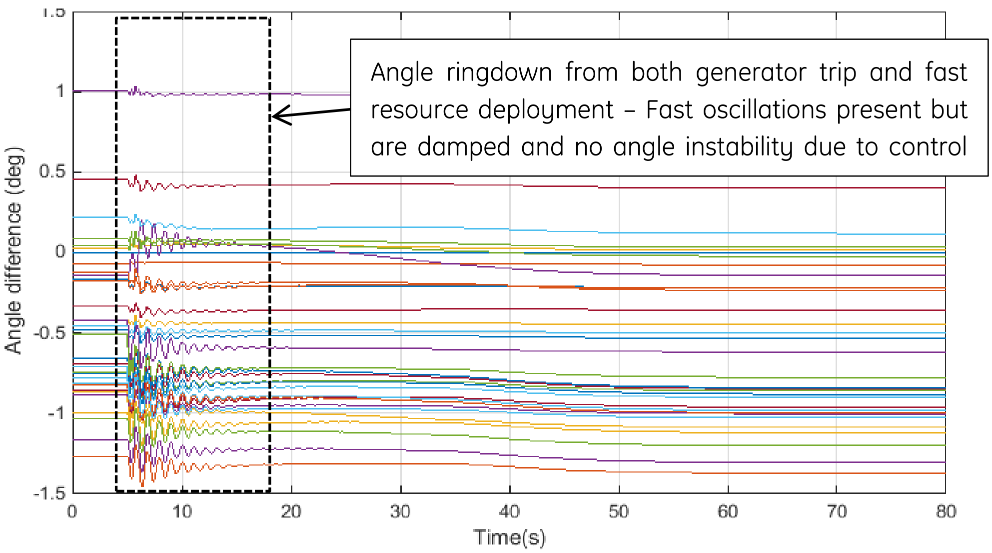

Figure 14 Angle behaviour from generator trip and controlled response (referenced to single generator)

4.2 Comparative Study

The case for angle stability can be made through comparison to a good control scenario seen in 4.1. For the comparison, the same event was simulated but this time the angular behaviour was not considered in the deployment. The same level of response was deployed, but this time in a poorly selected region not relying on the proposed control scheme.

This study was performed to illustrate the importance of angular stability and considering location in the controlled response. In this study, the selected region for control is one that was previously blocked by the proposed wide-area control scheme due to the risk of instability.

The same level of response was deployed in both cases, however the deployment now serves to increase the angle stress whilst minimising the energy imbalance. This is confirmed in Figure 15 where one of the generators loses synchronism leading to a second frequency event as that generator is lost. This is observed in Figure 16 which shows the initial event and the response followed by the second trip and the large oscillations in the system caused from poor control. In Figure 14 where the control scheme brings on the same power but in the correct regions and distributes it according to the regions which require it, the frequency response is much better and angular stability is maintained.

While this is an overly simplified example, it illustrates the effects of poor region selection in the deployment.

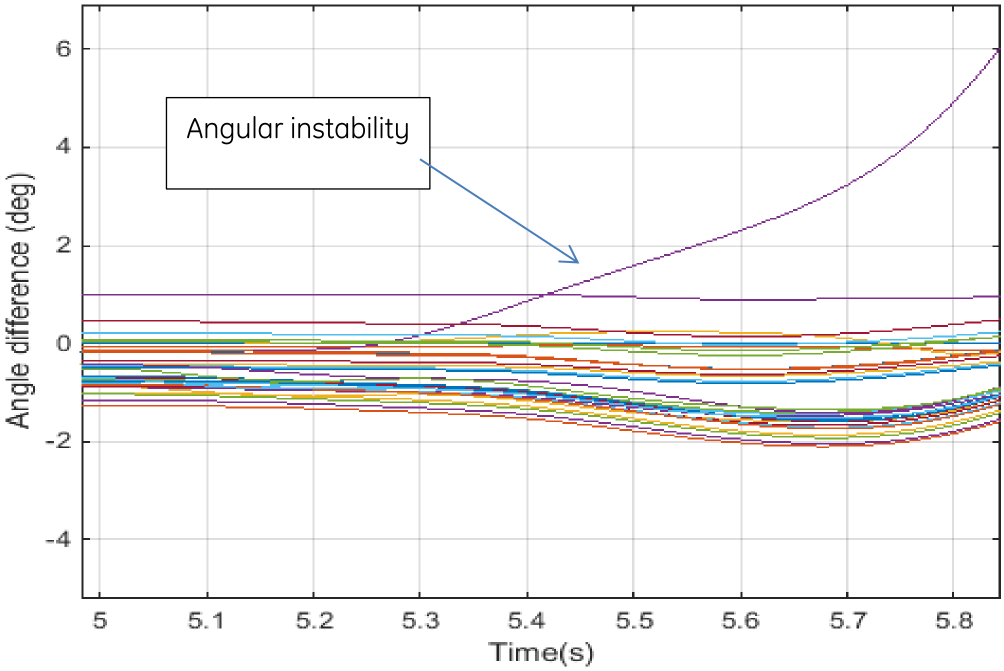

Figure 15 Angular instability due to incorrect locational response

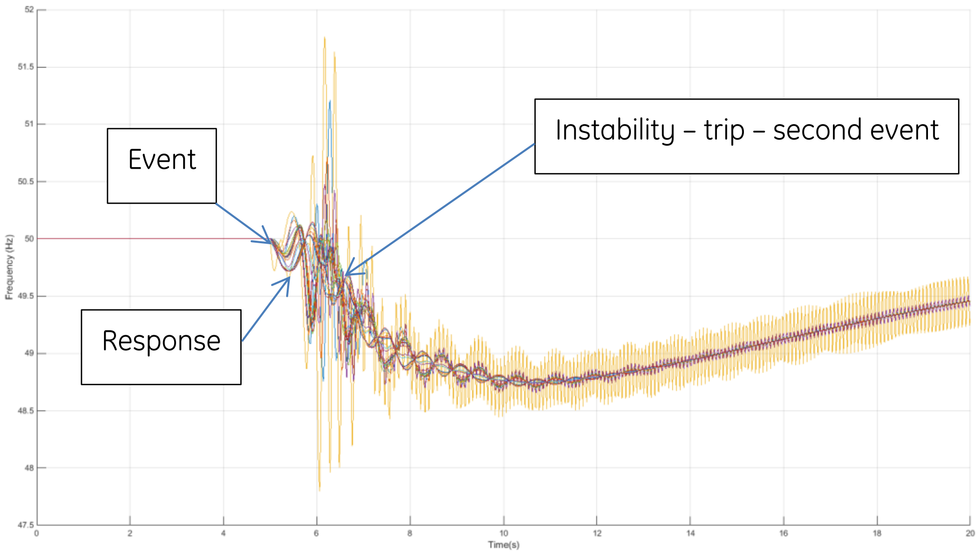

Figure 16 Frequency response from incorrect locational response.

5 Summary

This document is intended to provide a high level summary of the work that was undertaken for the Resource Allocation development in the SFC project. The role of the Resource Allocation is to take the signals from the Event Detection and use wide-area measurements to deploy resources.

The Resource Allocation is divided into two main roles, a management role which is performed on the Central Supervisor and a deployment role which is undertaken by the Local Controllers. The management of resources is a key component in a future SFC scheme given the number of resources that could potentially be available under the right market conditions. It is important to ensure that there are adequate resources available for a scheme at any one time, but also that there is good balance of resources within that mix to provide a suitable response.

Additionally, it is important to coordinate the deployment of the resources across a system when an event occurs. There are a number of objectives which the control scheme should aim to achieve:

- Minimize the energy imbalance
- Target control to most affected areas
- Minimize risk of angular stability

To achieve these, wide-area control is proposed which considers the system angular behaviour in its deployment. Through analysis of the angle behaviour, both the areas most affected and the risk of angular stability can be considered. The control scheme will then use a graduated response where upon overcoming the period where angular stability is most at risk, additional controllers can deploy response in order to further minimise the energy imbalance while minimising the risk of angular instability.

The response from the scheme has been designed such that upon detection of an event, response is deployed based on an estimated size of the event using system Rate of Change of Frequency (RoCoF). Using knowledge of the angular behaviour, this value is further broken down to regional target response values and then target values for each distributed controller. When a controller deploys response, it does not simply follow the measured RoCoF, but will sustain its response. Following RoCoF may lead worsening of the system damping and hence worsening angular stability. The intention for the scheme is not to restore frequency to nominal, as this would require long term response. The intention is instead to use fast response to halt a frequency excursion as quickly as possible, preventing reaching of load shed limits. When the frequency excursion has been halted, it will be up to the conventional governor response to make up the longer term energy imbalance. This is because resources used in SFC have finite response duration. Without SFC, the frequency can drop very quickly, faster than conventional governors can act and load may be shed. With SFC, the frequency drop can be halted, but then the controllers can reduce their outputs gradually creating a much more controlled frequency drop which governors are capable of handling and hence avoiding reaching the load shed limits. It is the purpose for SFC to be used to create that controlled response.

There are a number of functions within Resource Allocation which were defined in a specification to the partners. These functions were validated through a testing process and found to all pass. Some preliminary results showing the effects of a full control scheme were included in this document showing how fast control can halt frequency drops, but also through a comparative study, show the benefits of such a scheme in terms of angular stability.

6 Conclusions

- Resource Allocation has two main responsibilities:
    - Managing portfolio of resources
    - Deploying resource in response to an event
- Functionality is located on both a Central Supervisor and Local Controllers
- Central unit is required for scheme oversight and supervision
- Control decisions are made autonomously by each Local Controller (Distributed)
- Resource Allocation algorithms have been developed and validated
- Two stages of control
    - Wide-Area (tackles angular stability problem while targeting most affected areas)
    - Local mode (allows additional resource to be deployed after wide-area)
- Designed with graceful degradation in mind using a local fallback mechanism

7 Bibliography

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