nationalgrid

The Enhanced Frequency Control Capability (EFCC) Project

Lilian Macleod, Network Operability – National Grid

19th June 2018

GE BELECTRIC centrica Flexitricity MANCHESTER 1824 The University of Manchester University of Strathclyde Glasgow Ørsted SIEMENS Gamesa RENEWABLE ENERGY

Welcome and housekeeping

Please put mobile phones on silent

Fire exits / alarm

Toilets

Wifi
& social media
#EFCCProject

Discussion and debate welcomed

Feedback forms

Agenda

National Grid & GE Welcome and MCS Overview
09:30 – 10:30

Break
10:30 – 10:40

University of Manchester & National Grid (incl demo)
10:40 – 12:00

Lunch
12:00 – 12:45

University of Manchester (incl demo)
12:45 – 14:00

Break
14:00 – 14:15

University of Strathclyde (incl demo)
14:15 – 15:45

Q+A and closing remarks
15:45 – 16:00

What are the future system operability challenges?

Not all about what might happen – what has happened in 2017?

nationalgrid

Transmission System Demand

On Sat 25 Mar 2017 transmission system demand (ITSDO) in Great Britain was for the first time ever lower during the afternoon than it was overnight due to high solar PV generation.

Great Britain goes without Coal Generation for 24 hours

Friday 21st April 2017 was the first 24-hour period since the 1880s where Great Britain went without coal-fired power stations.

National Grid Control R...
@NGControlRoom

Follow

#Solar has just broken another record in Great Britain, providing 8.7 GW (24.3% of demand)

5:08 am - 26 May 2017

National Grid Control Room @NGControlRoom · 25 Dec 2017

On Sunday #wind generated 35.1% of British electricity, more than gas 26.7%, nuclear 23.4%, imports 8.1%, biomass 2.4%, hydro 1.8%, storage 1.0%, coal 0.6%, solar 0.5%

Not all about what might happen – and so far in 2018

nationalgrid

National Grid Control Room @NGControlRoom · Feb 25

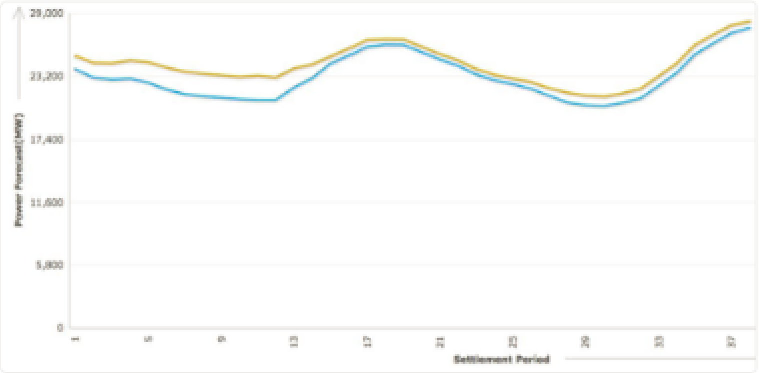
At 11:00am low-carbon sources were providing 59.8% of GB electricity (wind 21.8%, nuclear 18.8%, solar 14.7%, biomass 3.7%, hydro 0.8%), national demand 38.1 GW

National Grid Control Room @NGControlRoom · Mar 18

Yesterday #wind generated 35.7% of British electricity, more than gas 20.3%, nuclear 17.6%, coal 12.9%, imports 6.0%, biomass 4.1%, solar 1.8%, storage 0.8%, hydro 0.6%, other 0.2%, national demand 858 GWh

National Grid Control Room @NGControlRoom · May 5

With over 8 GW of #solar generation today, transmission system demand was 500 MW lower in the afternoon than it was overnight



National Grid Media @Grid_Media · Apr 24

We are currently at 72 hours and counting of no coal generation on the power network - a new record. This period began on 21/04/2018 10:00 BST. The previous record was last week at 55 hours and was from 16/04/2018 22:25 BST to 19/04/2018 05:20 BST.

How are we approaching these challenges?

System Operability Framework Analysis

↓

Product Strategy Roadmaps

Reserve and response	Network Operability Assessment	Reactive power	System Restoration

Published

https://www.nationalgrid.com/uk/electricity/balancing-services/future-balancing-services

How can EFCC resolve the system operability challenges?

nationalgrid

Synchronous generation is declining causing reduction in system inertia and short circuit infeed

Frequency is more volatile when system inertia is low

Faster response services are required to achieve frequency containment within acceptable dynamic performance

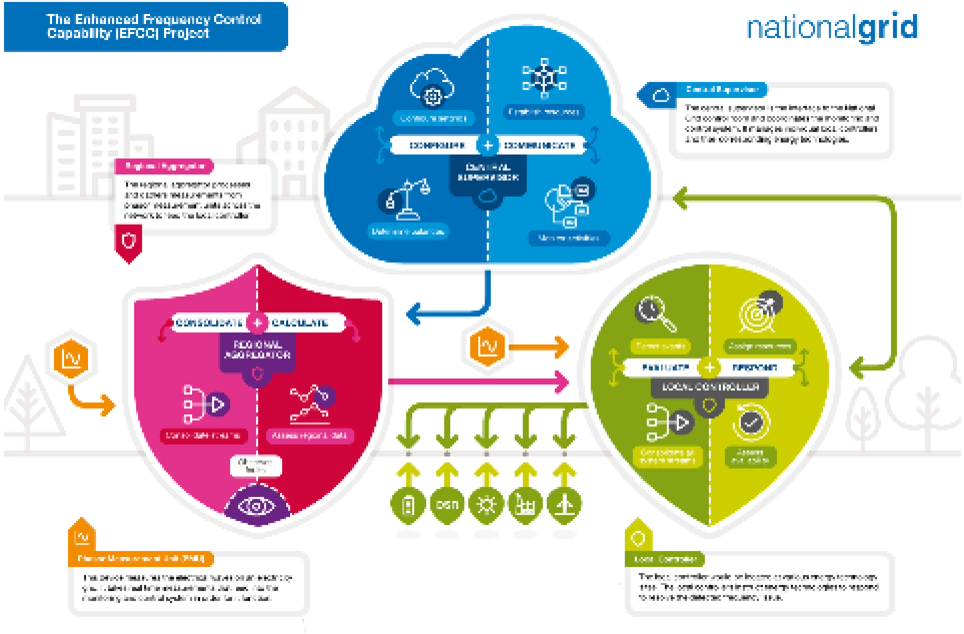
EFCC – a potential solution to future system operability issues

nationalgrid

Solution: Provision of rapid frequency response, from a diverse range of technologies, to assist with frequency management

Innovation: monitoring and control system (MCS) that facilities the coordination of and maximises the contribution from resource providers

Potential: System benefits from accessing and instructing faster response to a disturbance

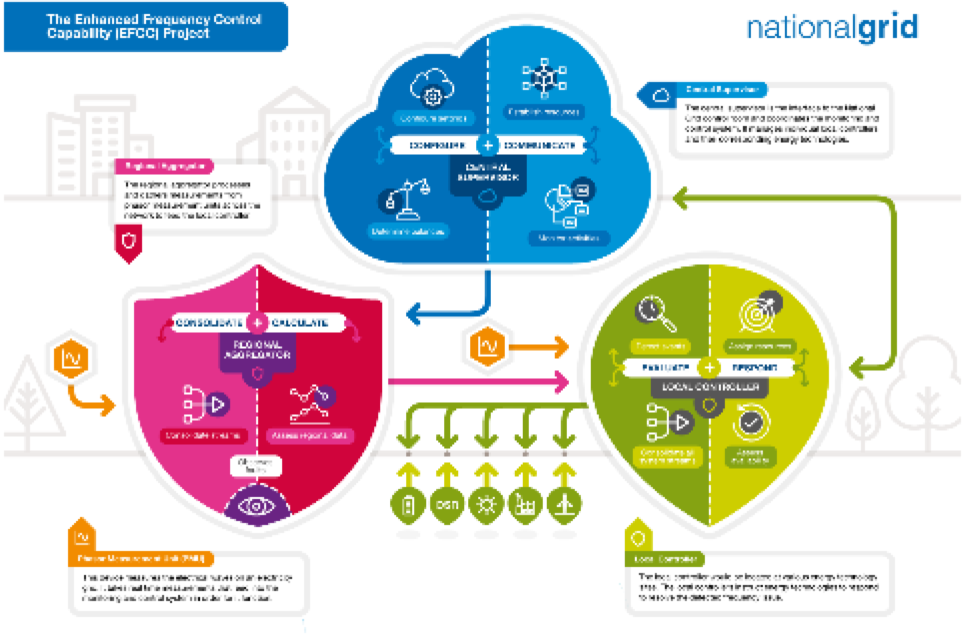


EFCC – journey so far

Proof of concept confirmed - development and testing of a monitoring and control system

Confirmation that resource providers can provide faster response

Potential system benefits of monitoring and control scheme concept identified - commercial benefits currently being assessed

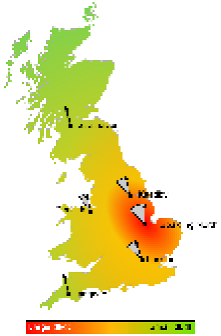


EFCC – monitoring and control system

Sean Norris, Senior Power System Engineer
GE Power

nationalgrid

The Enhanced Frequency Control Capability Project



Development of the control scheme

Seán Norris - GE

BELECTRIC centrica Flexitricity MANCHESTER 1824 The University of Manchester University of Strathclyde Glasgow Ørsted SIEMENS Gamesa RENEWABLE ENERGY

nationalgrid

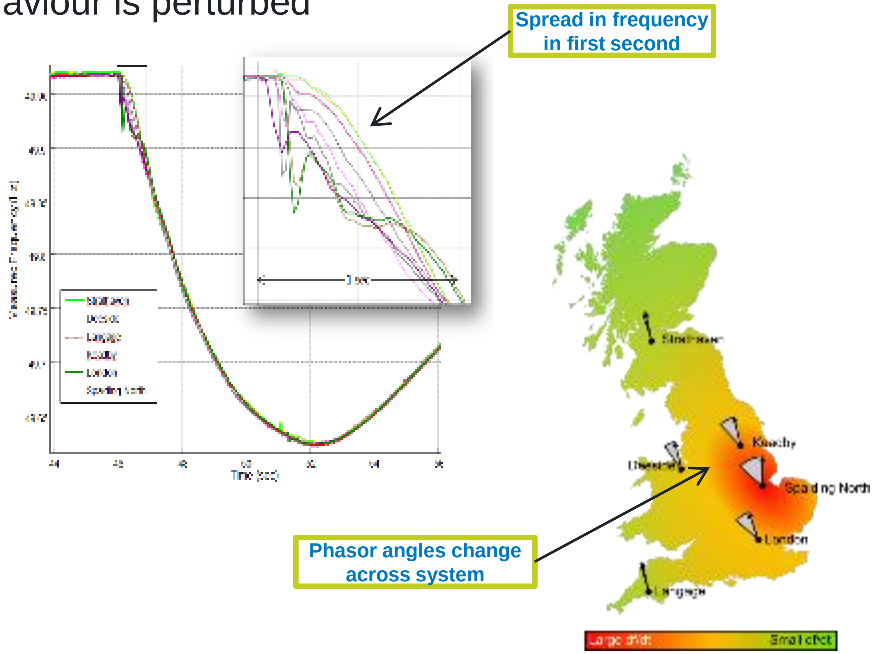
Contents

- The technical challenge
- The control solution
- Development
- Next stage: deployment
- Further work

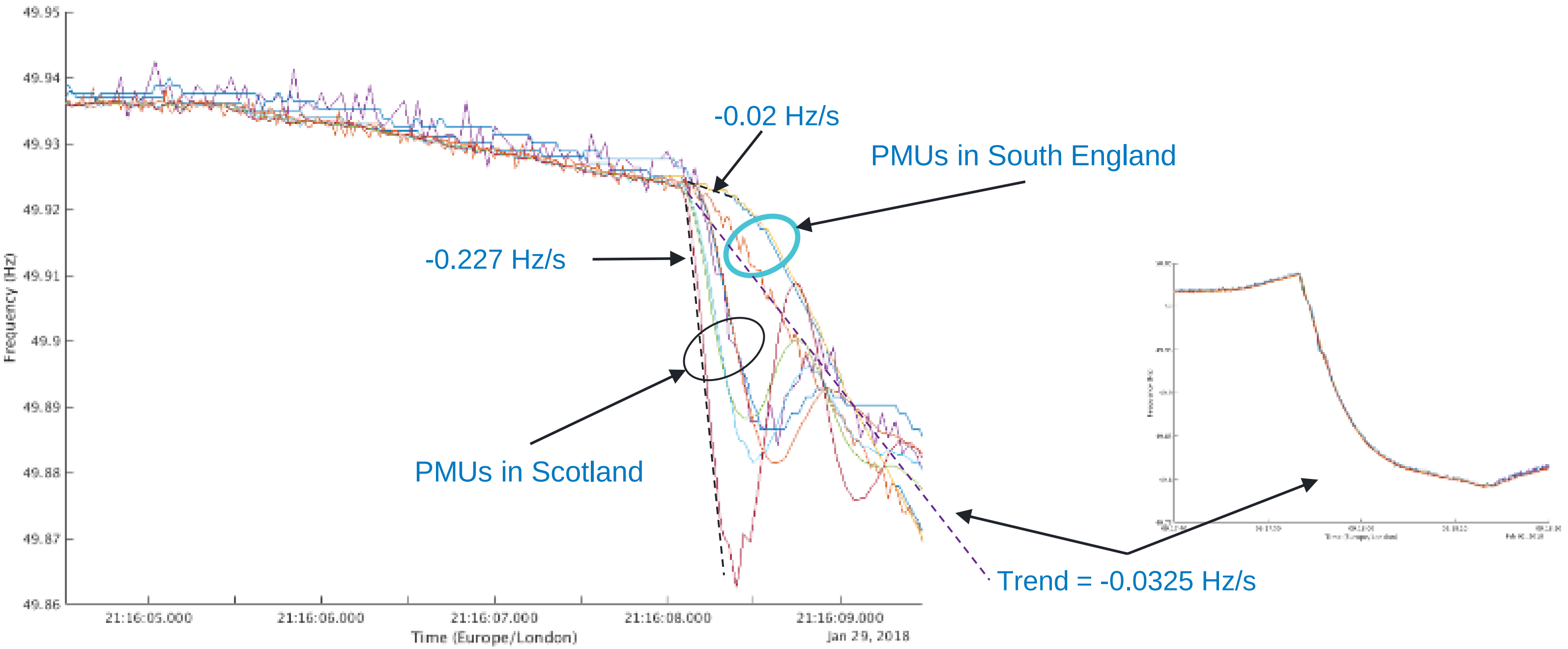
The technical challenge

The fast frequency response (FFR) challenge

- Rate of Change of Frequency (RoCoF) is not equal across system
- Dependent upon event proximity & regional inertia
- Reflects changes in power flows as the angle behaviour is perturbed
- What is the danger of FFR?
  - Similar time frame to first swing angular stability
  - Risk of system splitting
- Consider angle behaviour for a coordinated response
  - Prioritise action closer to event
  - Using wide-area measurements

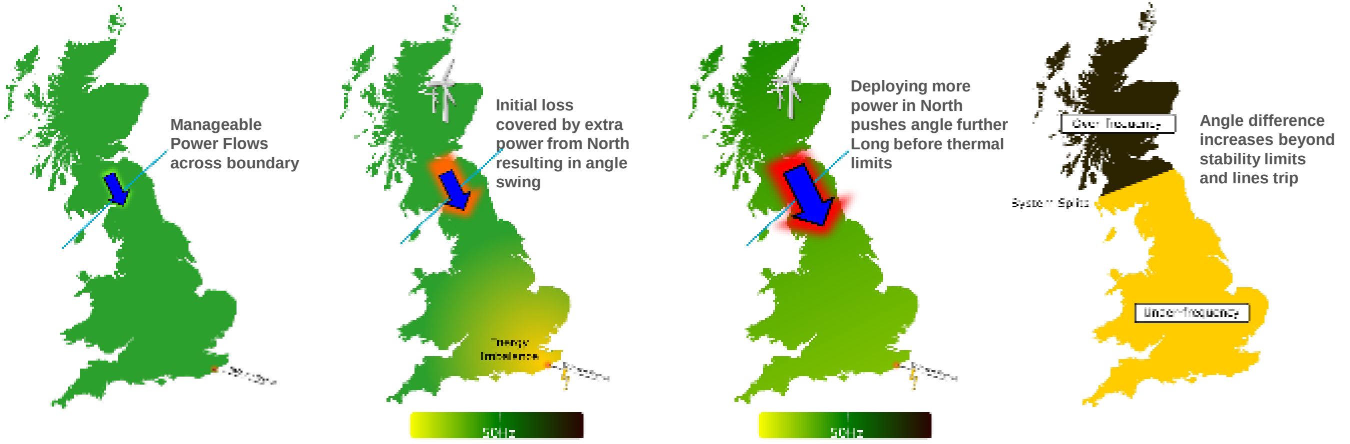


Trip in Scotland



Implications of poor FFR location

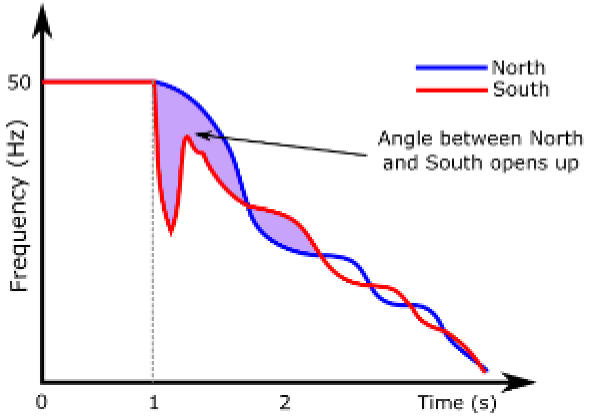
- Example of extreme behaviour during a frequency event

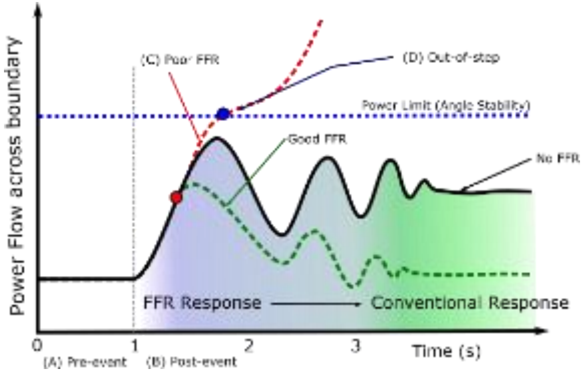


Pre-event | Post-event | Poor fast response | Extreme Result

Target response

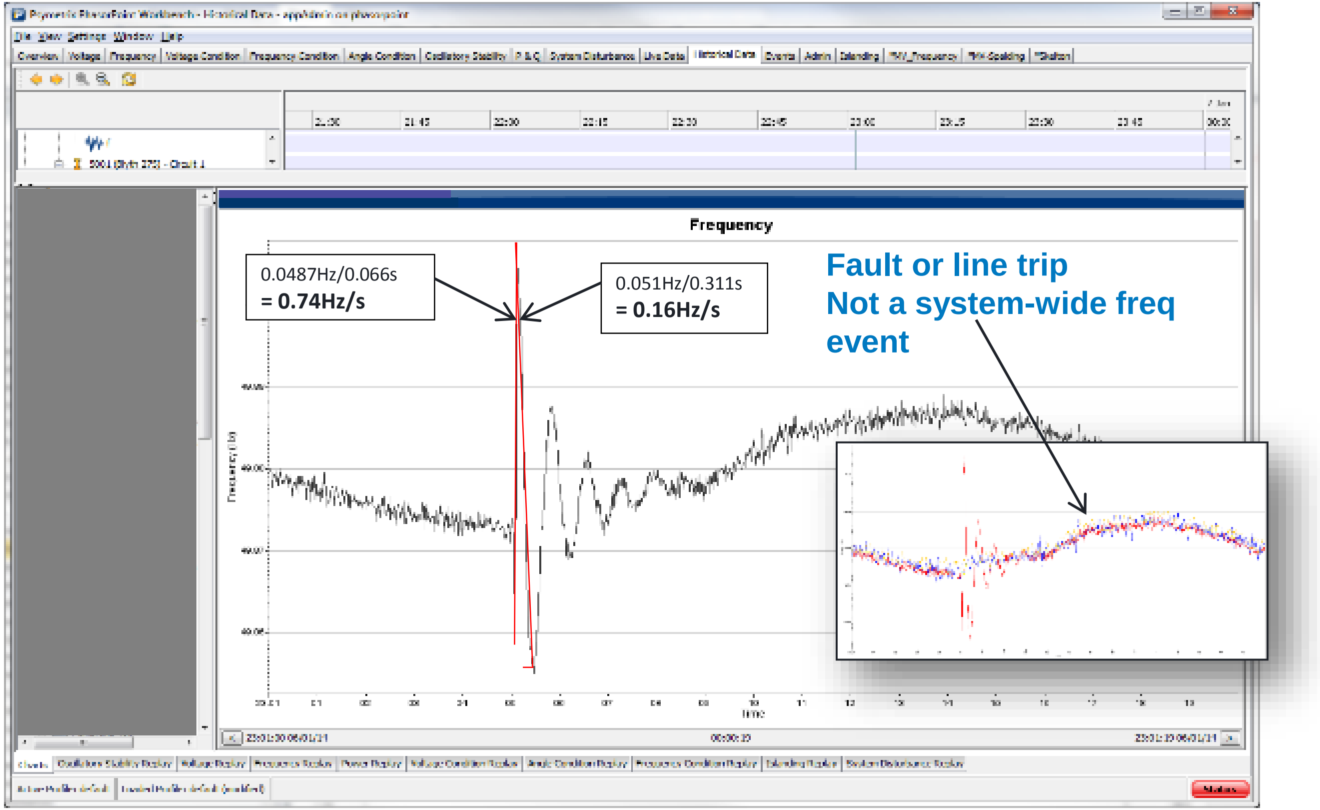
- Aim: Maintain stable angle difference





national**grid**

Local frequency disturbances



nationalgrid

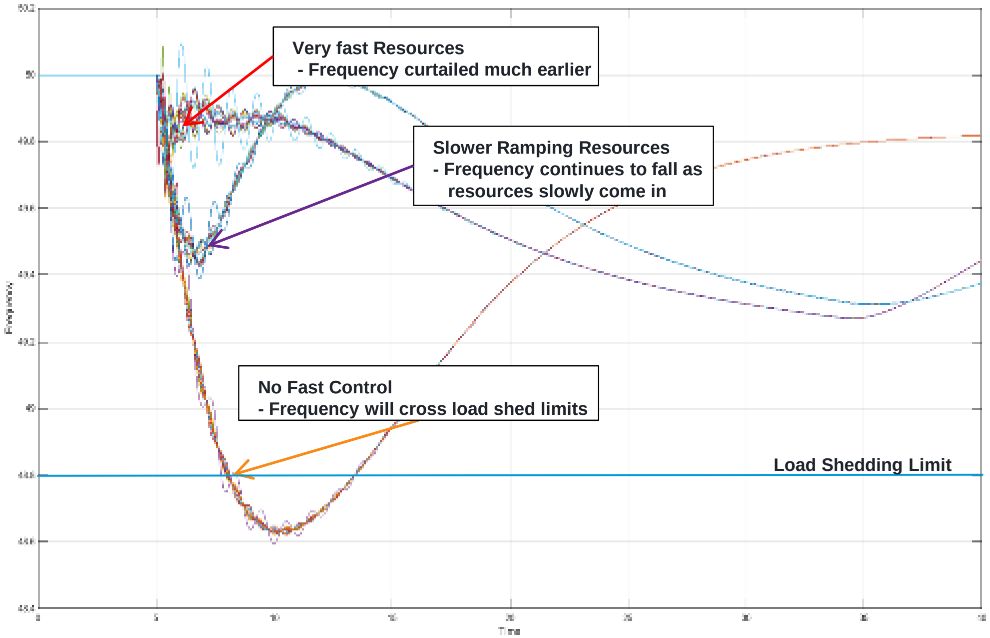
Uncoordinated local control

- Deploying on frequency or RoCoF can lead to **spurious triggering**
  - Line fault or trip event will perturb local frequency
- Responding to non-frequency event negatively impacts stability

- Following frequency or RoCoF can lead to poor **oscillation damping**
  - Delays in measurements/response can excite oscillations

Uncoordinated local control should act slower than wide-area to prevent these negative impacts

Effects of speed of response

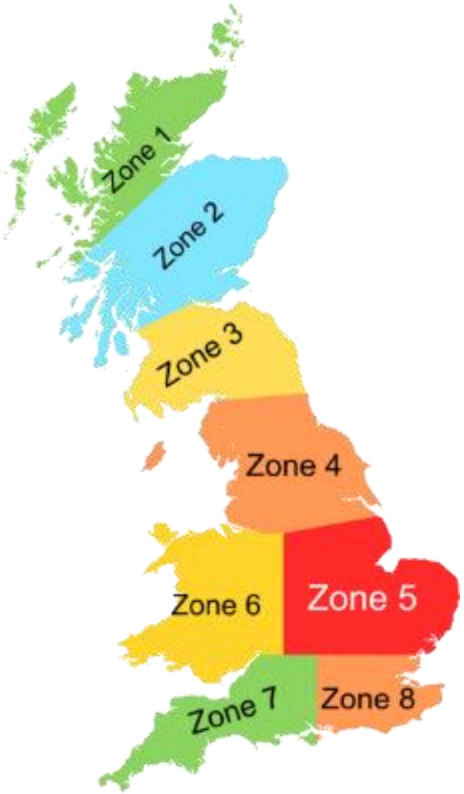


The control solution

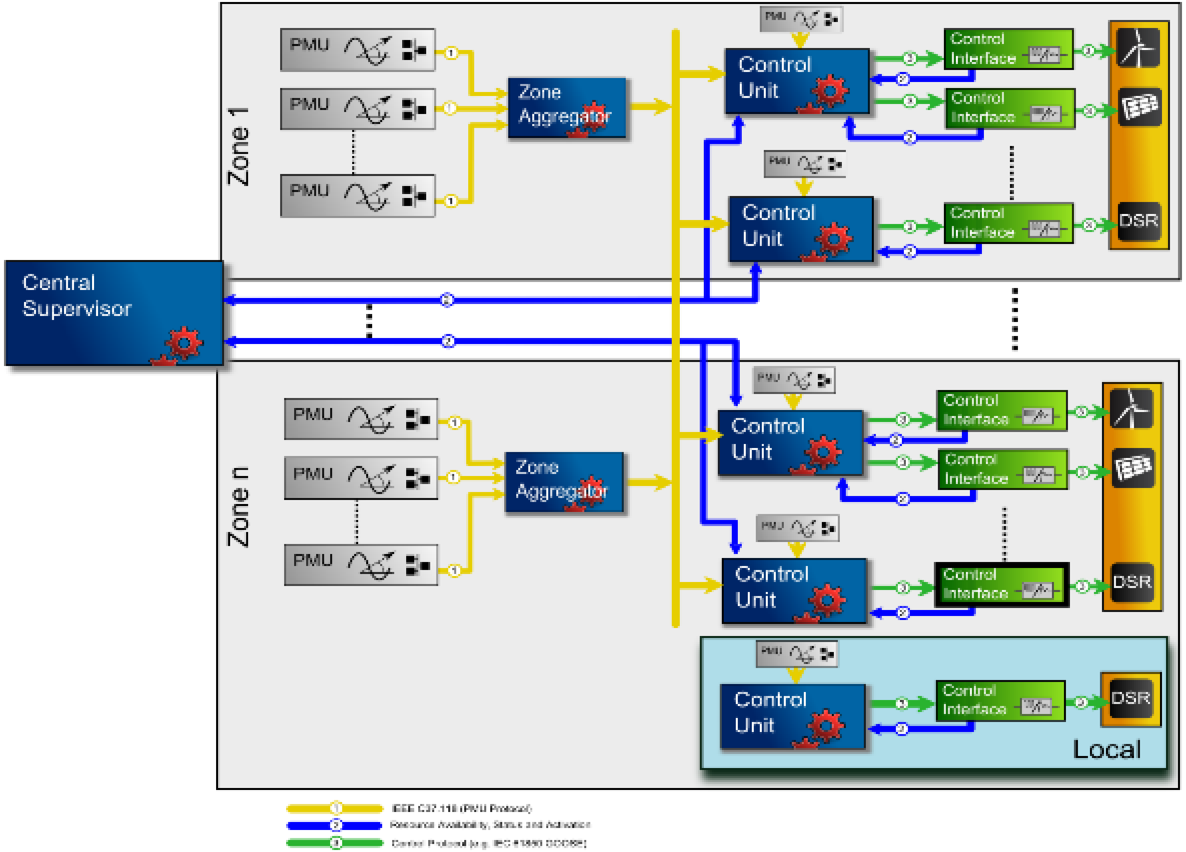
nationalgrid

Distributed control scheme

- Building upon the learning under VISOR – monitoring project
- Now demonstrating Wide-Area Control
- System split into a number of regions
  - Multiple distributed controllers
  - In each region, PMU send data to aggregators
  - Aggregated signals broadcast to controllers
  - Resource information sent to central supervisor



Distributed control scheme

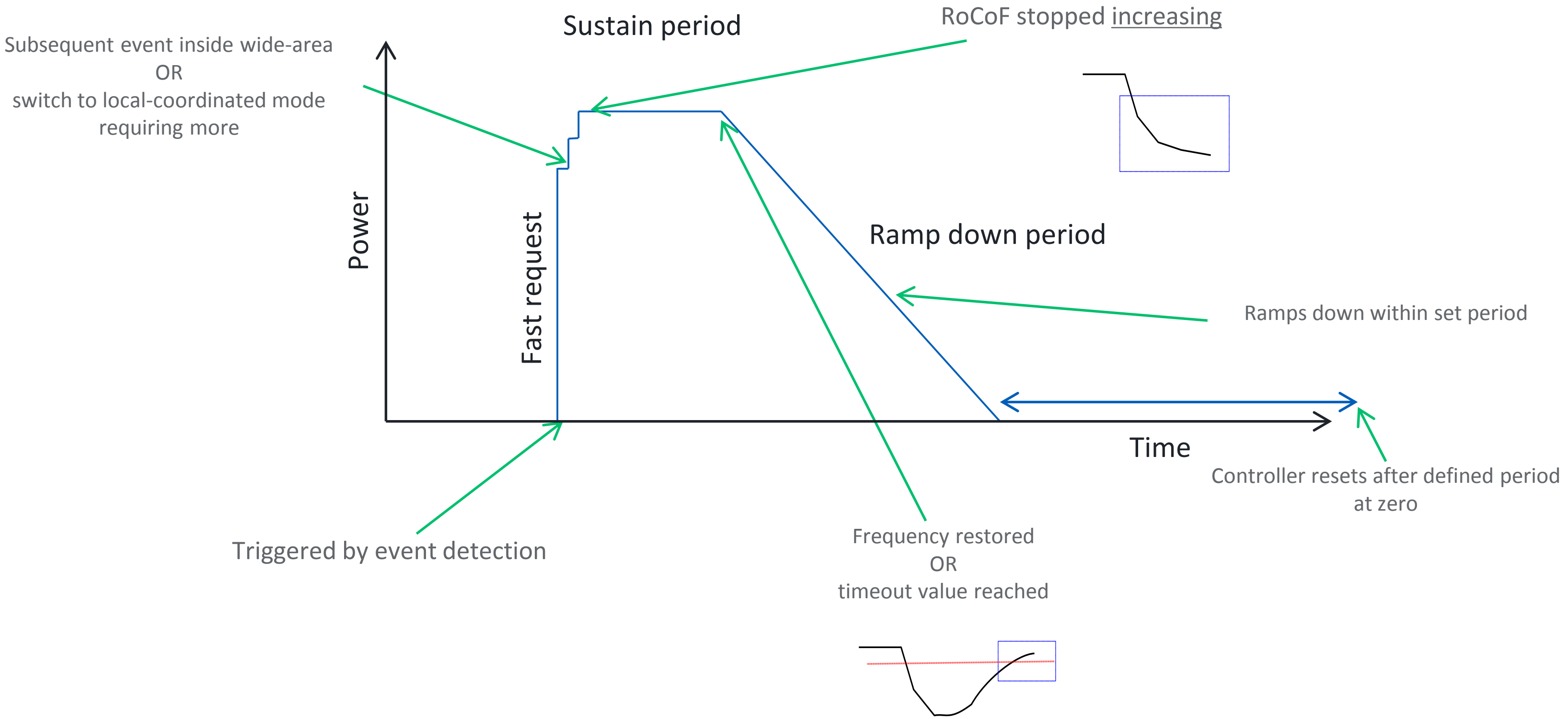


Service provider interaction

1. Service provider realises potential service
2. Service provider installs controller
3. Controller receives wide-area grid measurements
4. Provider can start offering fast frequency response to the grid

Settings, configuration & complexity stays with Electricity System Operator

What type of response to expect?



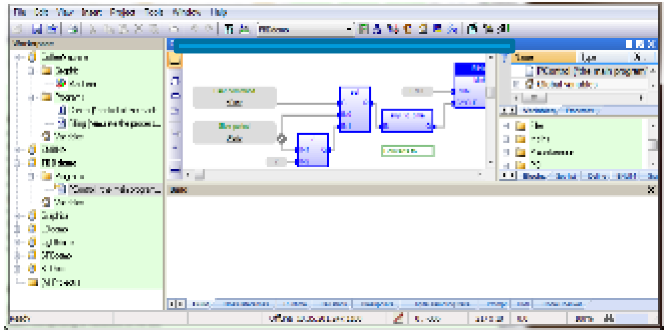
Development

Flexible control platform

- **Flexible** control platform at centre of scheme
  - Library elements and custom elements
  - Greater flexibility for scheme design and algorithms
  - Easily implement future EFCC or **new** schemes

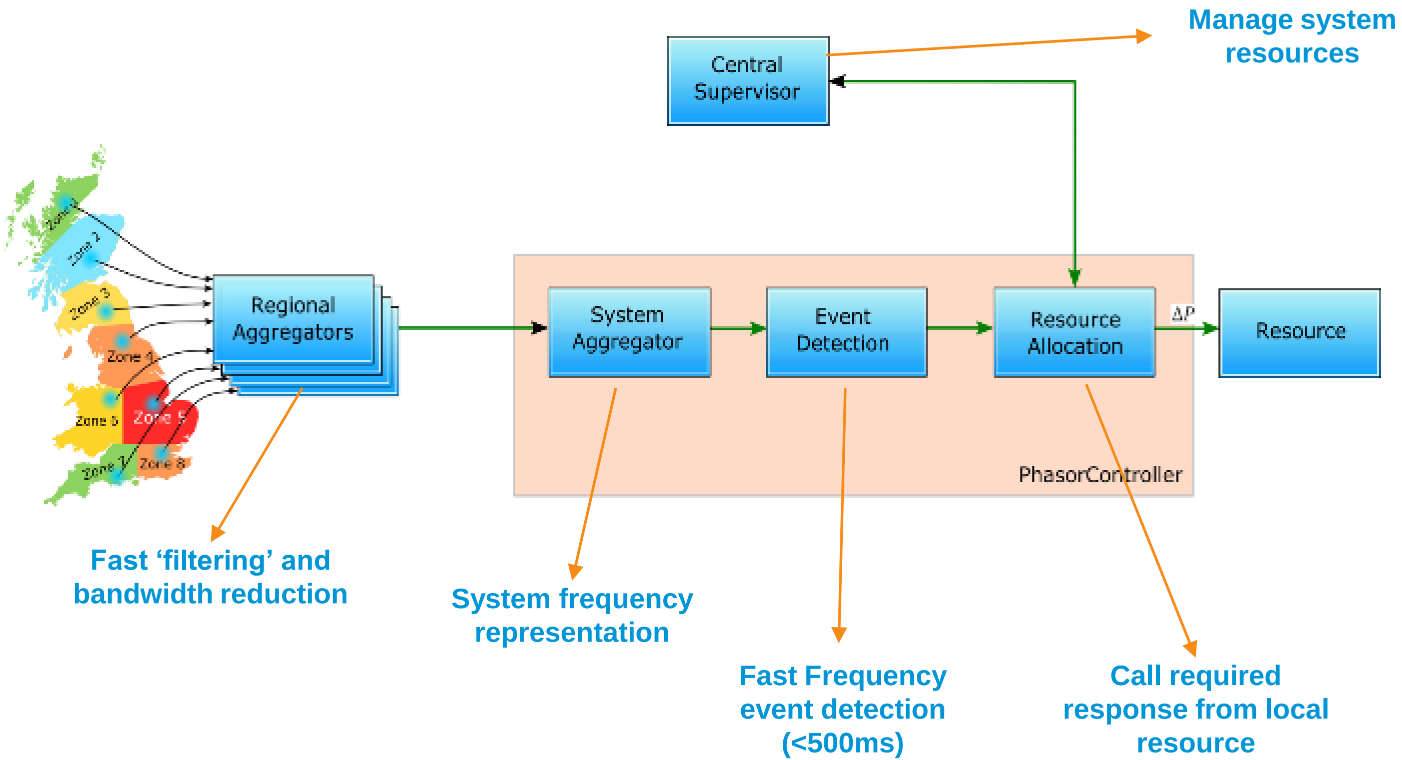
e-terraphasorcontroller

- Variety of implementation protocols:
  - IEC 61850
  - IEEE C37.118
  - Modbus
  - Digital I/O's
  - Other protocols possible



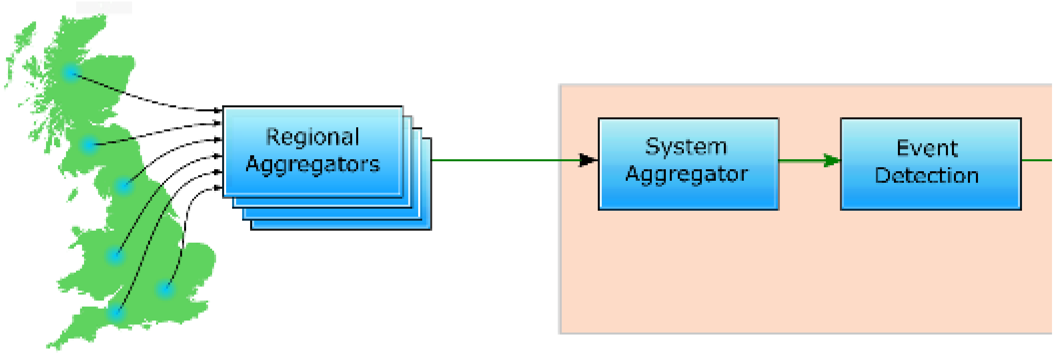
PLC Environment

Control scheme applications



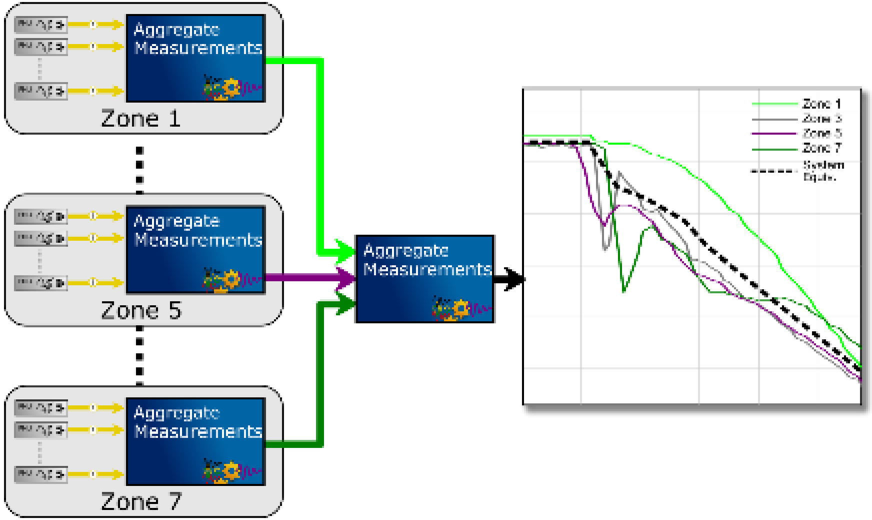
Event detection requirements for SFC

- To detect as quickly as possible, events which warrant system response such as:
  - Significant generator/load loss (including after faults, trips etc.)
  - Interconnector loss
- Target of 500ms from event to trigger for large events
- Not trigger on non-frequency events such as
  - Faults, line trips, oscillations and small generator/load loss



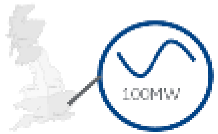
Event detection concept

- Each PMU signal assigned to a region
- Aggregate signals represent the region
- Aggregate regions into system equivalent
- Detect 'system events'

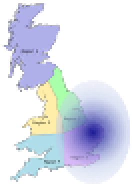


Resource allocation

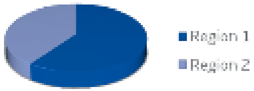
Example of resource allocation



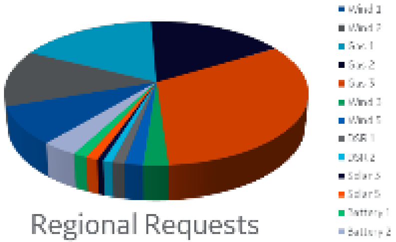
Generator Trips



2 Regions most affected



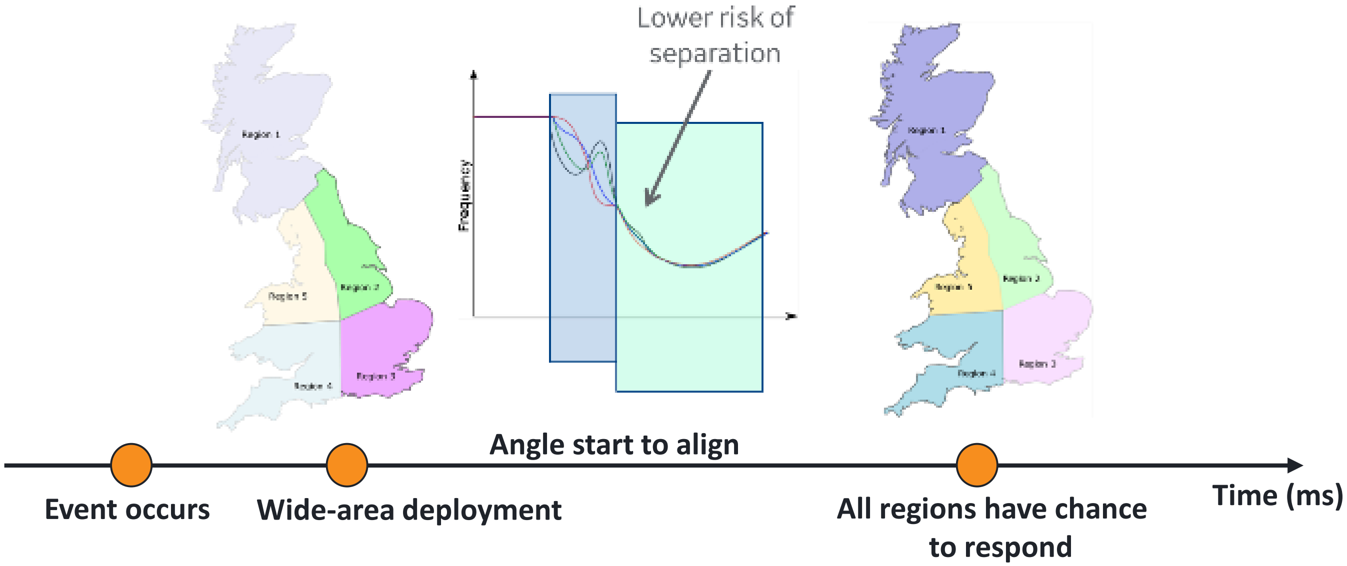
Spread across leading Regions



Regional Requests

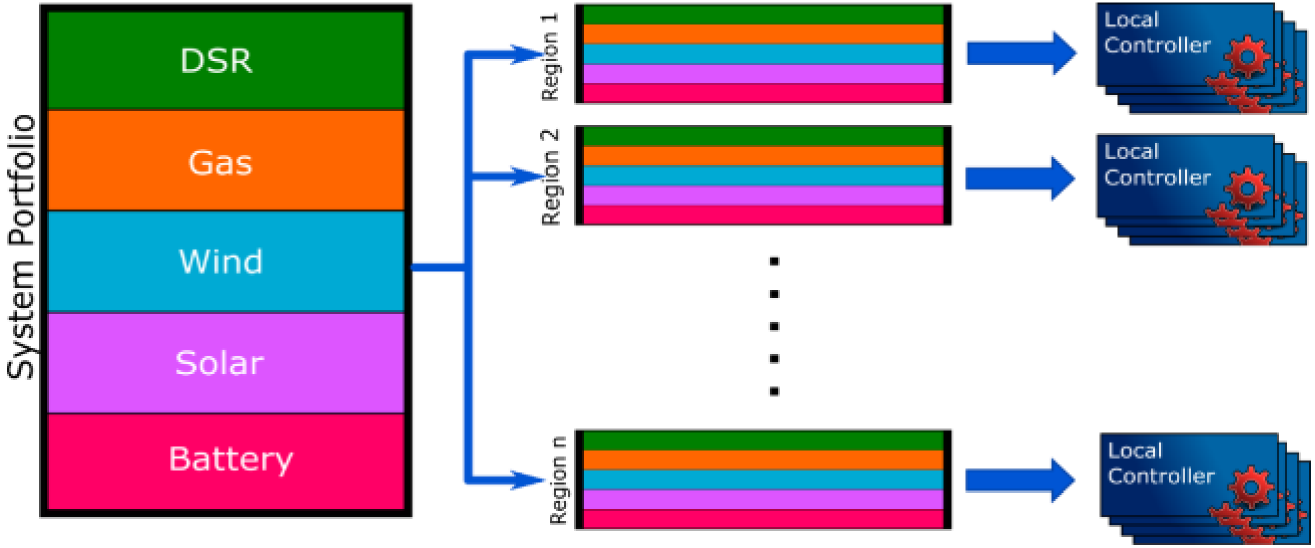
Monitored and Repeated in all regions as necessary

Not enough resource in target regions



Central supervisor

- Can see all the resources available in the system
- Ranks resources according to their characteristics (speed)
- Issues summary information down to each local controller



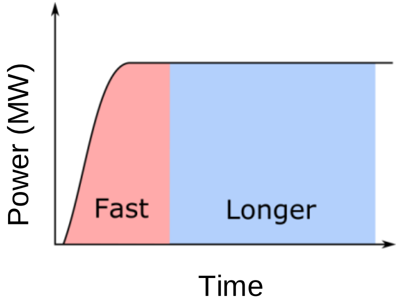
Optimisation

- The ideal response is one that reduces the event's effect before the system degrades

For example:

- Region A loses 500 MW of generation at time 0s
- If 500 MW of load is tripped in Region A at time 0s, the event becomes negligible

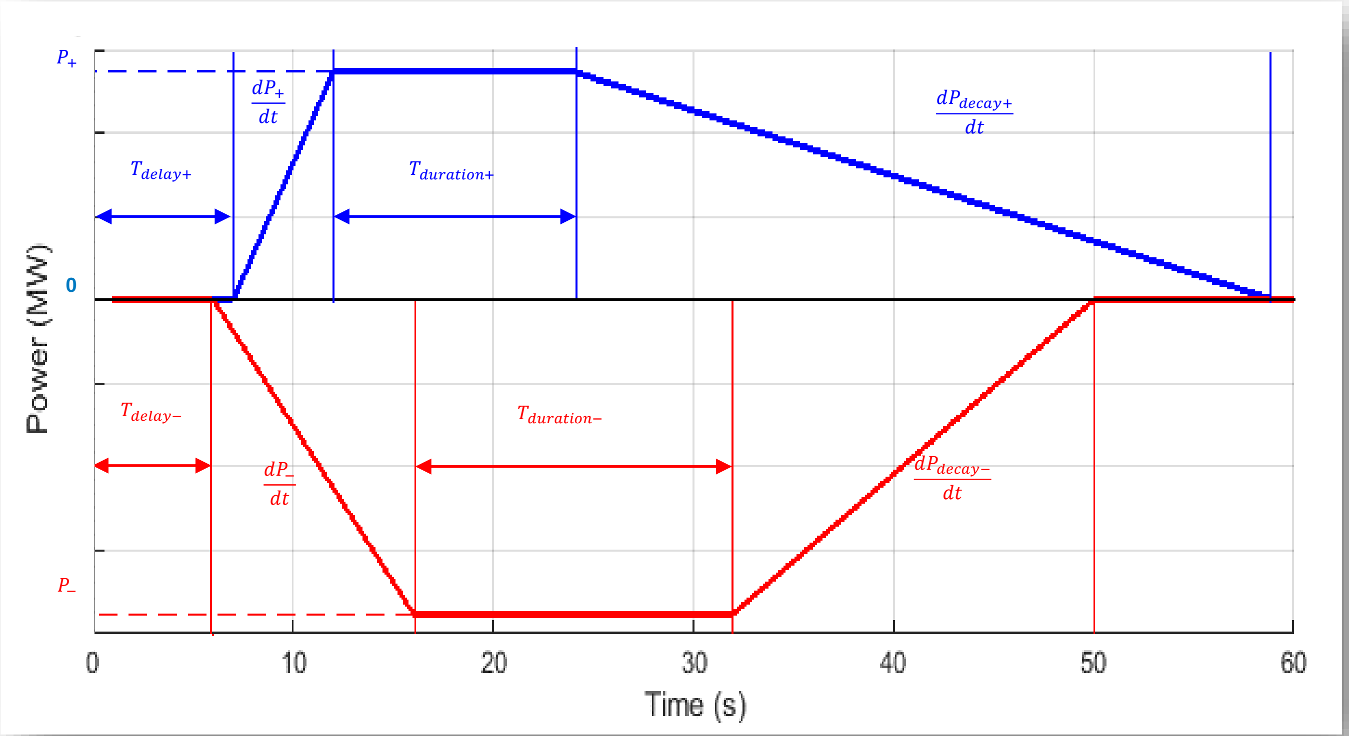
- Not possible in response based system, it provides the target for us



Square wave is best

- 0 s time delay
- Infinite ramp rate
- Sustained response

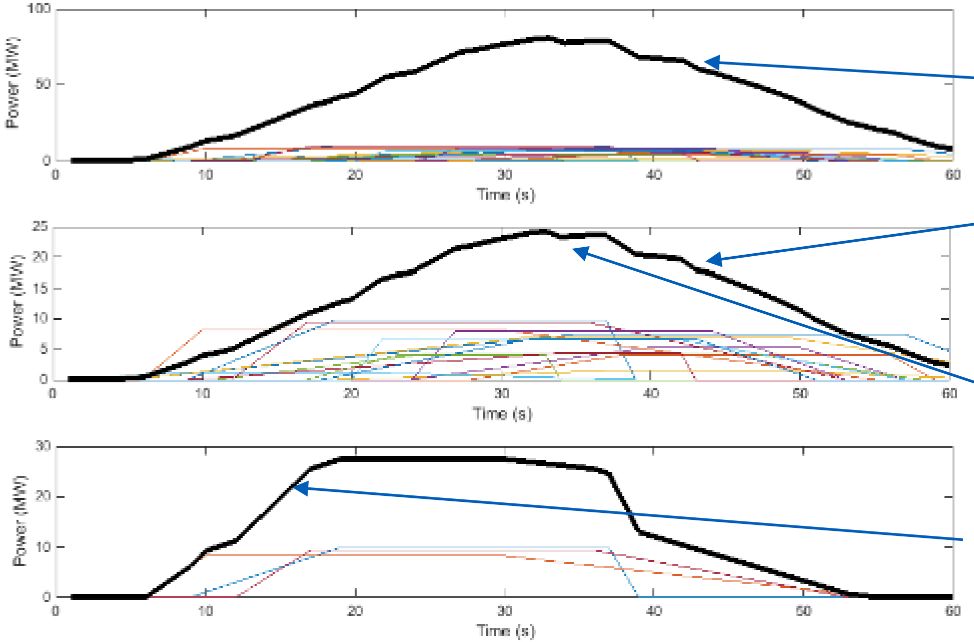
Quantifying response



nationalgrid

Deploying response

- Proportional deployment



If all resources were called upon at same time

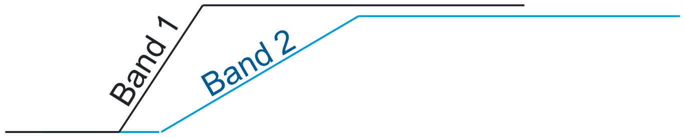
If a proportion (e.g 30%) of all resources were called upon

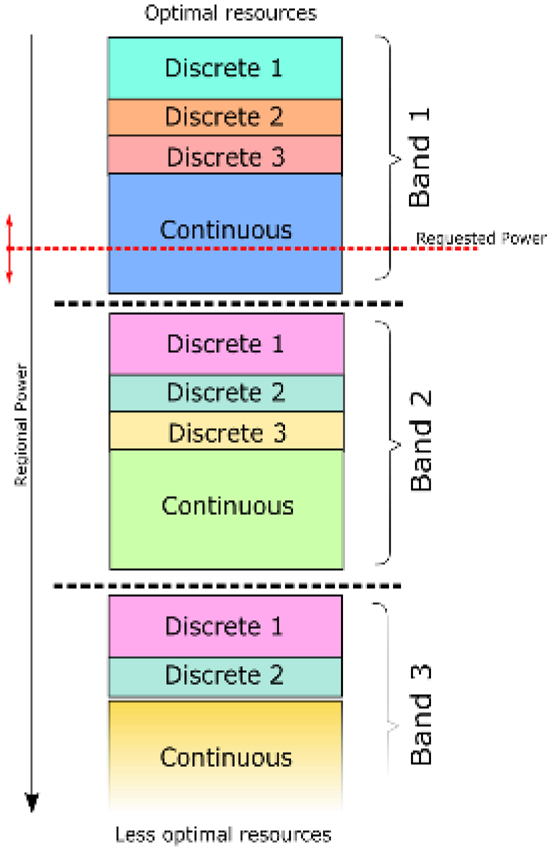
Sustain time may be longer for some resources at part-load

Selecting resources allows shaping of the response characteristic

Current central supervisor output

- List of armed resources
- Ranked according to the results of the optimisation
- Simplified problem focusing on speed and duration
- Local controllers use this ranking for deployment

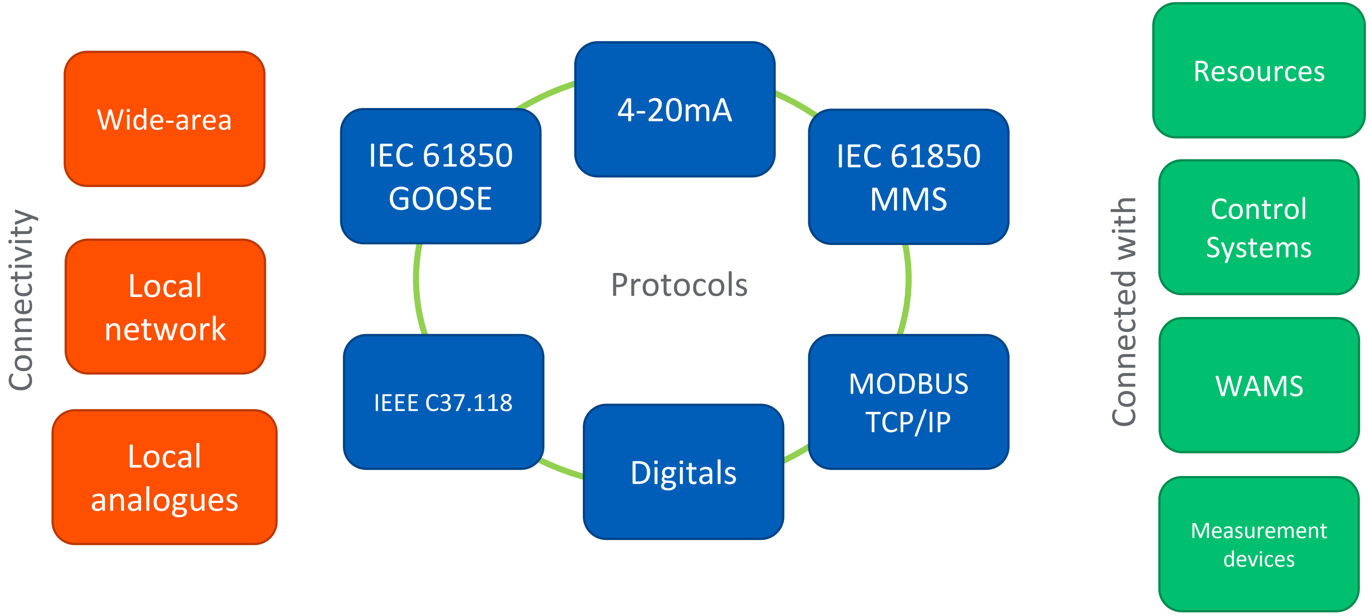




Next stage: deployment

nationalgrid

Interfacing

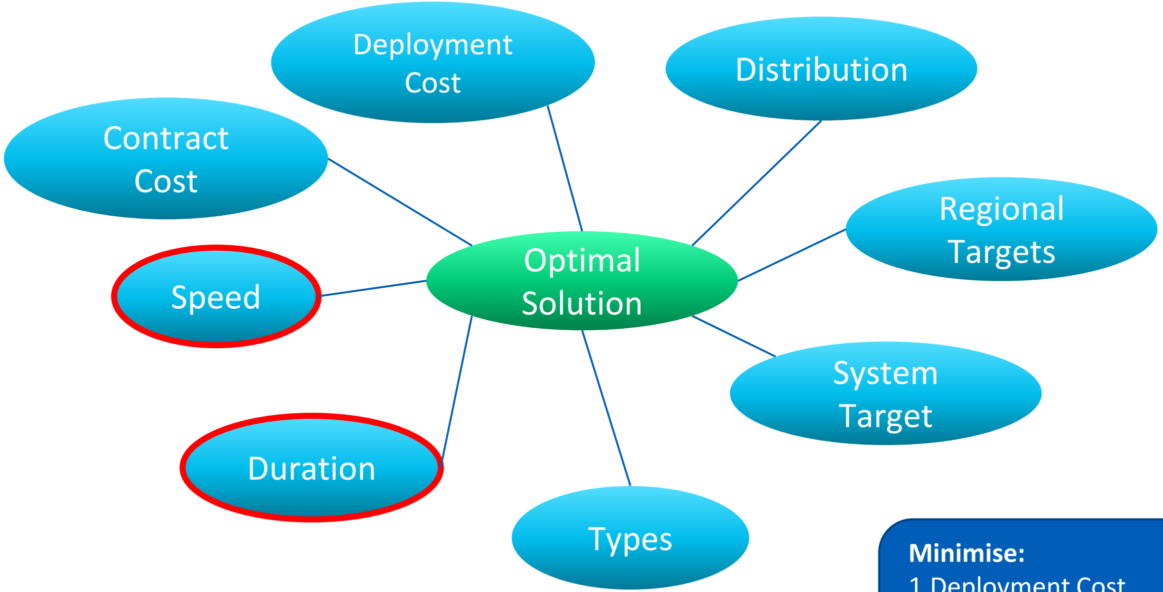


Deployment for field trials

Deployment	Aim
University of Manchester	Test and validate complete scheme in Real Time Digital Simulator (RTDS)
PNDC (University of Strathclyde)	Test and validate scheme with physical (load bank) and virtual resources
Belectric	Test and validate response from controller request connected to PV/battery
Flexitricity	Test and validate response from controller request and 'go-live' scenario in local mode tripping load
Centrica	Test and validate interaction between controller and existing plant control for gas turbine (GT)
National Grid	Test and validate wide-area data capture and demonstrate communications including substation level and control centre

Further work

Ideal solution



Minimise:
1.Deployment Cost
Maximise:
1. Speed of Response
2. Resource Duration (within limits)

Key Lessons Learned

- Fast frequency response has many nuances
  - Transient period, oscillations, faults etc.
- Robustness in algorithms is critical
  - Data is never 100% guaranteed
- Limitations on protocols
- Trade off between speed and reliability is difficult to manage
- Greater understanding of behaviour during a frequency event
  - Also in the equipment used to measure frequency
- WAMs has been instrumental in delivering this project
  - Archive of test data, evaluation, quickly collecting post-event data for analysis

Summary

- Bringing fast frequency services is technically possible
- Wide-area control can work and resources can deliver fast frequency response
- Strong reliance upon the communications network

Questions and Answers

Break – Back at 10:40am

nationalgrid

WP3 - Defining, solving, and optimising the delivery of fast frequency response

Ben Marshall — National Grid
Rasoul Azizpanah-Abarghooee — University of Manchester
Prof. Vladimir Terzija — University of Manchester

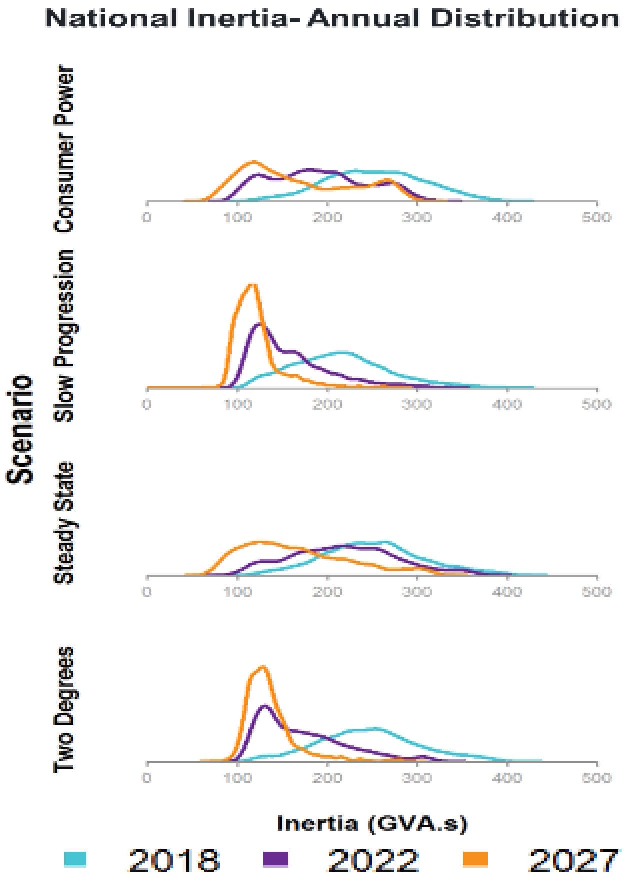
Outline of presentation

- EFCC – what are we trying to solve?
- What are we trying to measure and to control our response to?
- Modelling and assessing the effect of a controlled fast frequency response under EFCC
- Further options for optimisation and what may drive them
- Summary of findings - the pathway of optimisation within EFCC

Unpacking the problem

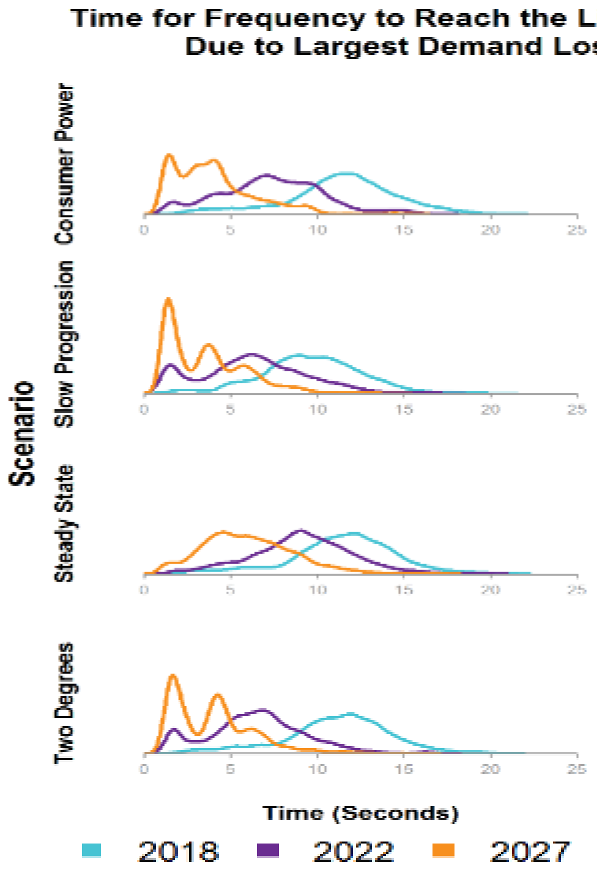
WP3 - Optimisation

What are we trying to solve?



- Lower levels of system inertia over time
- Containment of frequency becoming more challenging over time
- The EFCC challenge - how do we deliver the frequency response needed in an optimal manner as the requirement for it becomes faster?

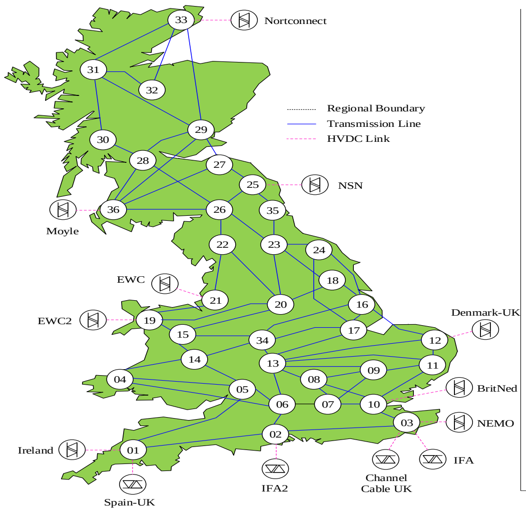
What are we trying to solve?

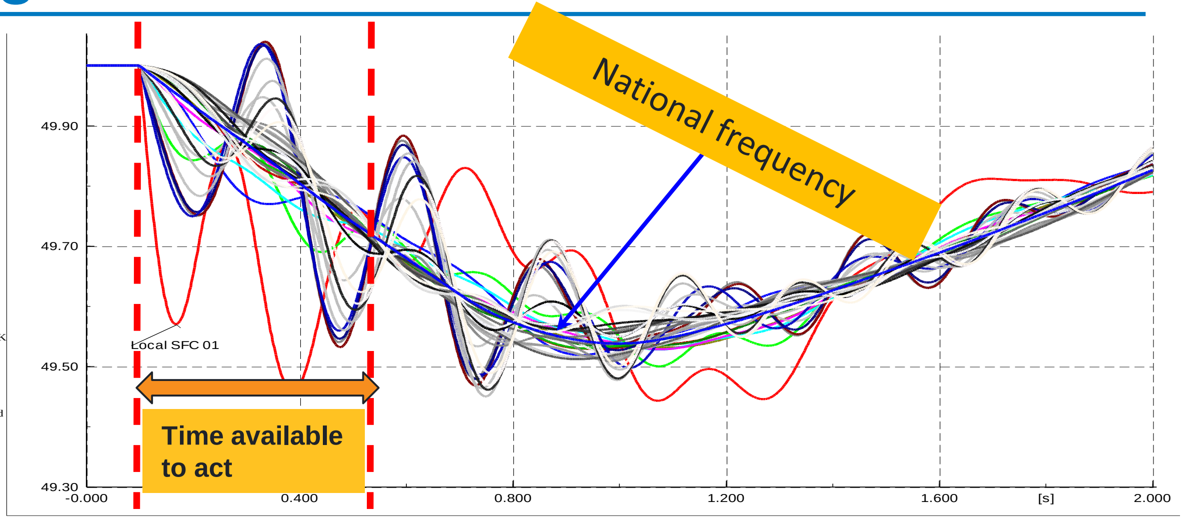


- Lower levels of system inertia over time
- Containment of frequency becoming more challenging over time
- The EFCC challenge - how do we deliver the frequency response needed in an optimal manner as the requirement for it becomes faster?

nationalgrid

What are we trying to measure and control?



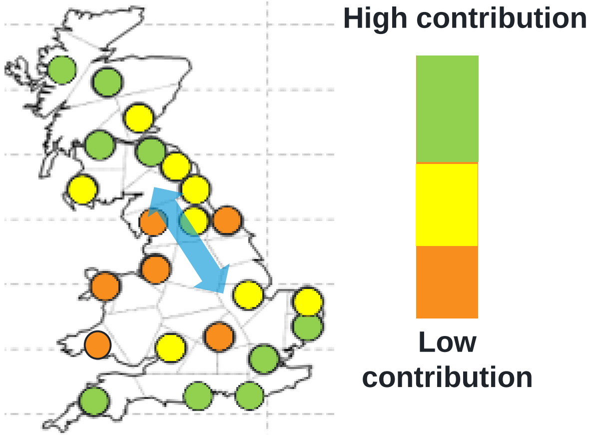


- Dynamically modelling the GB system, the frequency event and its containment
- Identifying and understanding the key factors contributing to differences in frequency change across the system
- How regional frequency differs from national frequency across the period of fast response into the future

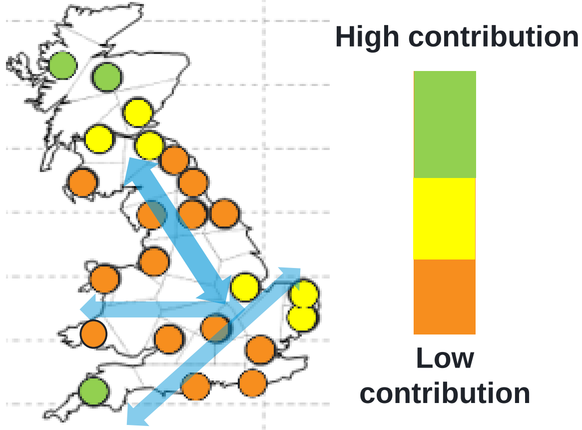
nationalgrid

What drives regional frequency difference?

Today



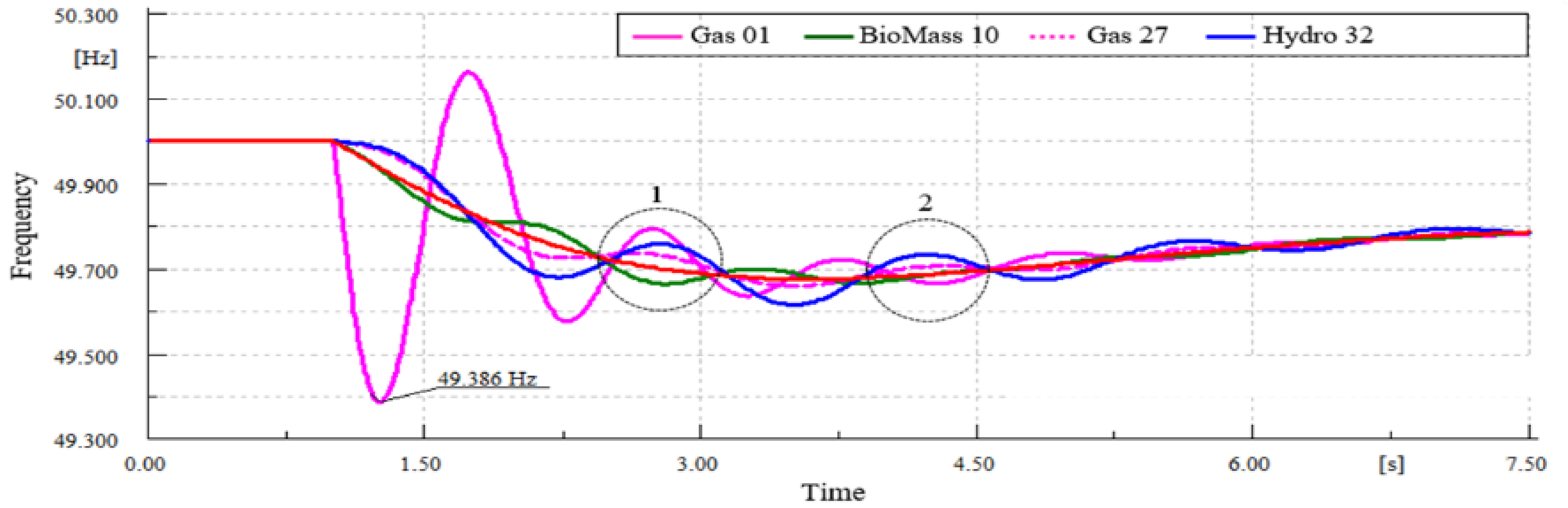
Tomorrow



- Analyse the scale of the oscillation of regional frequency, around national frequency level, and how well it is damped and where.
- **Today** the dominant oscillation is NW-SE with a variety of contributions.
- **Tomorrow** the oscillations are larger, more are visible and less damped from fewer resources.
- Without suitable control non synchronous generation add to these oscillations and reduce damping across future years.

nationalgrid

Why is this change happening?



- As synchronous generation levels reduce, there is a corresponding decline in the damping of the oscillation.
- To avoid fast response driving instability across the GB system, it is important it is deployed in a way that does not drive these oscillations

Unpacking the problem of control

- During a frequency event, frequency is initially different across the GB system
- In the future, the frequency is initially more different for longer periods of time during the same events
- Ability to respond faster requires the capability of being able to measure what to respond to more quickly
  - (local frequency, local df/dt, local angle change), differs from what we want to control
  - (national frequency, national df/dt, suppressing inter-area modes)
- Respond in the right way to the right levels to avoid instabilities being caused by the fast response
- Also requires the capability to model how to do these things

Optimising the solution



WP3 - Optimisation

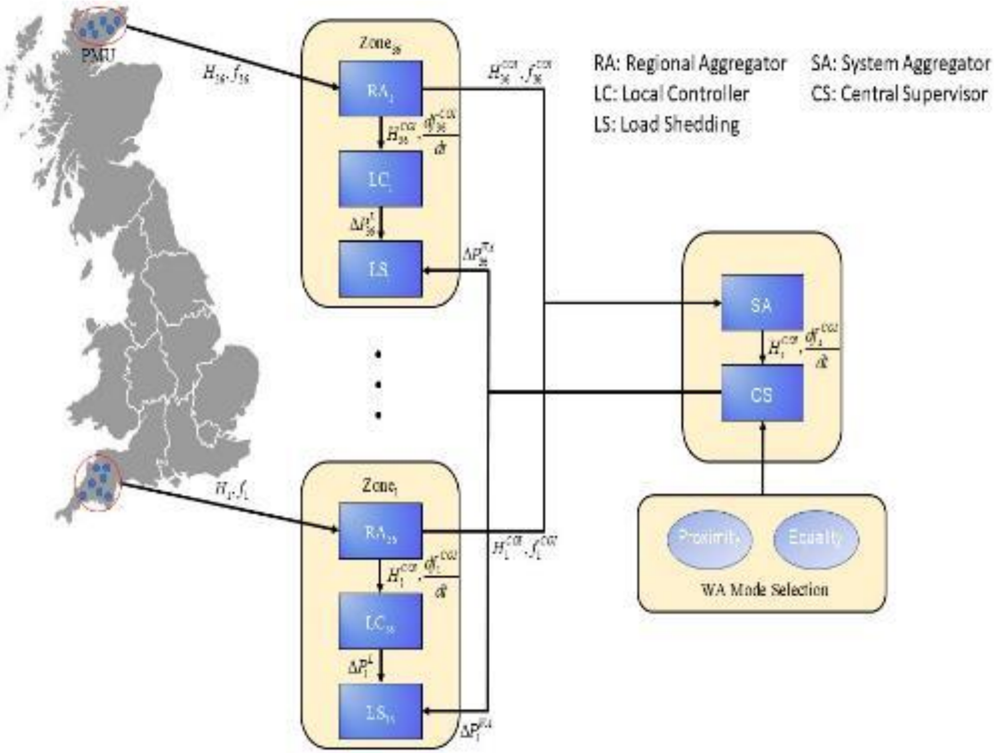
nationalgrid

Fast frequency response in future years

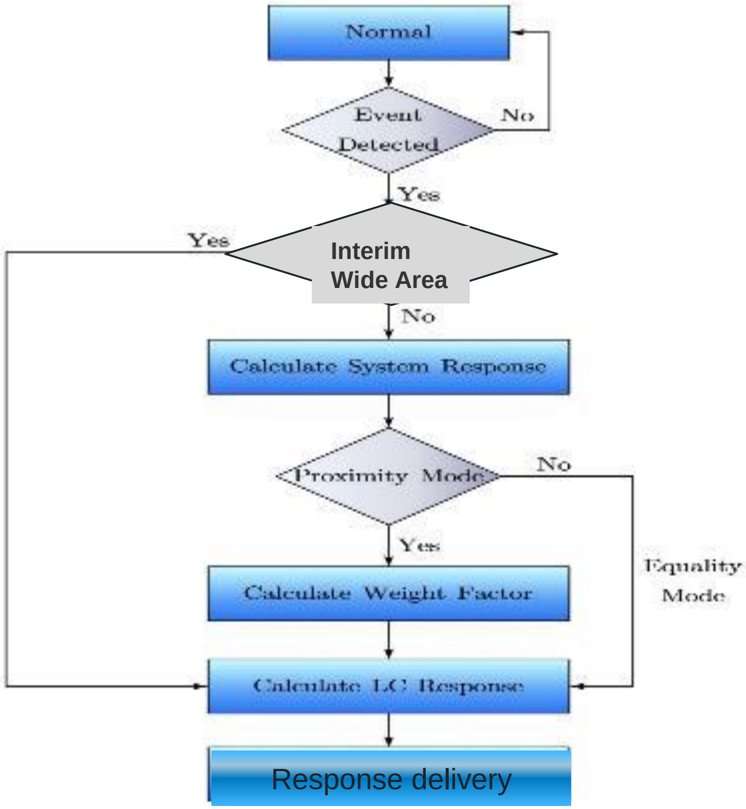
- Modelled the effect of traditional frequency response which is compared to faster, co-ordinated response options

- The modelling drives the right level of response in the right area of the system to support stable system recovery

- Containment of maximum active power loss within 500ms - 700ms of the event is needed to avoid restricting the maximum loss possible at that time



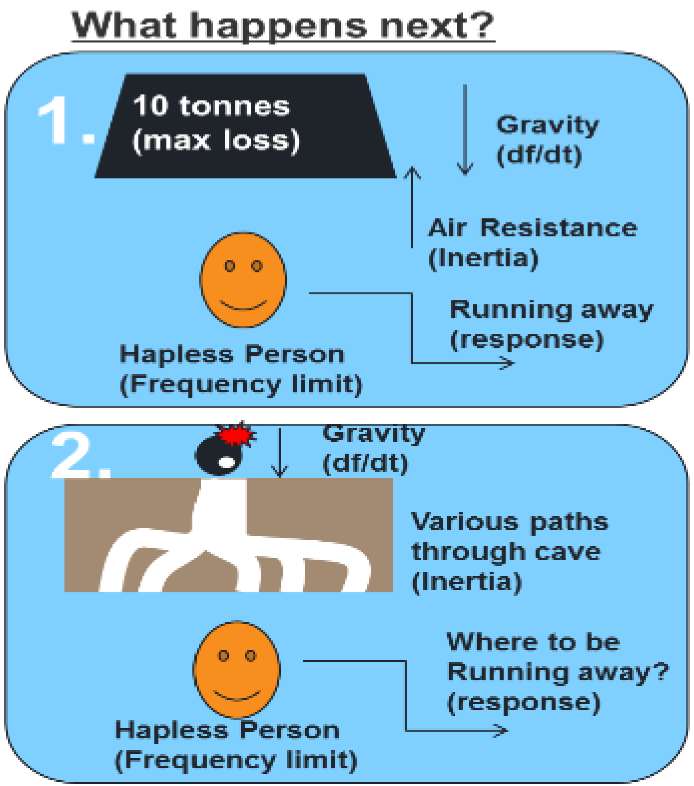
Modelling the effect of EFCC and sensitivities



- The following sensitivities have been considered:
  - **Wide-area control (Proximity)**:
    - Resources closest to event are deployed as priority
    - Mirrors GE's monitoring and control system (MCS) in function
  - **Wide-area control (Equality)**:
    - Resources are evenly distributed across all zones but informed by national need
  - **Interim wide-area control**:
    - Response is regionally provided based on regional information
- Provides a pathway of EFCC optimisation to be mapped and the effect of the MCS to be simulated

nationalgrid

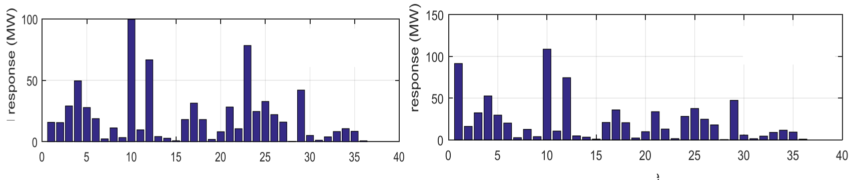
Opportunity for an interim wide-area control



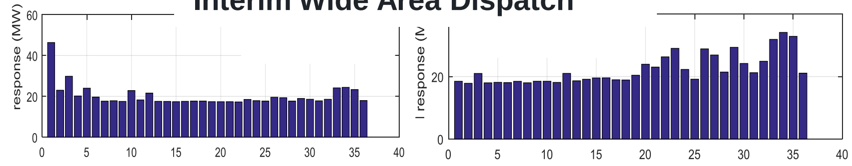
- Interim wide-area control has the potential to be an interim stage of EFCC deployment. It works on the principle of:
  - If you see enough of a “picture” of an event beforehand you can accurately project forward and react with confidence
  - Even if you do not, with enough information you can still act. (i.e. don’t stand under the hole!)
- Provided inertia is high enough and resources diversified this approach works well
- Interim wide-area has a reduced infrastructure requirement

The effect of EFCC control

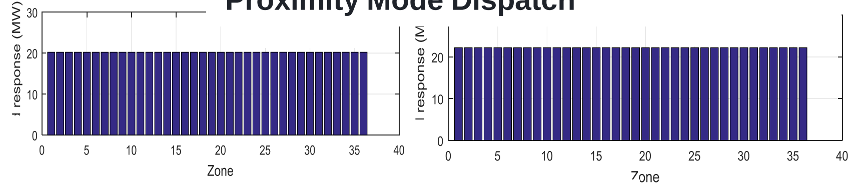
Zone	max loss Without EFCC (2025)	With EFCC implemented
SW	365 MW	**925 MW**
Lancashire	555 MW	1035 MW



Interim Wide Area Dispatch



Proximity Mode Dispatch

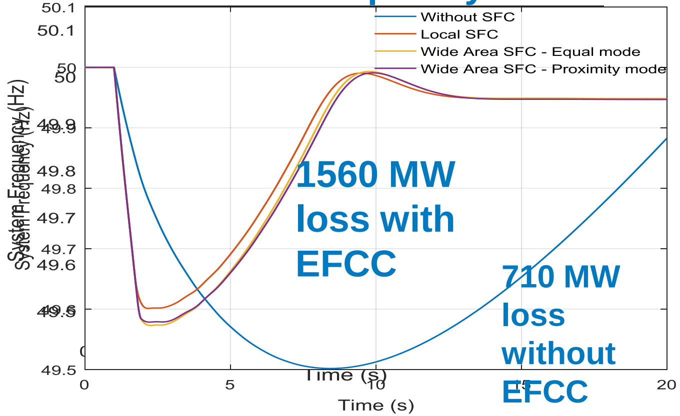


Equality Mode Dispatch

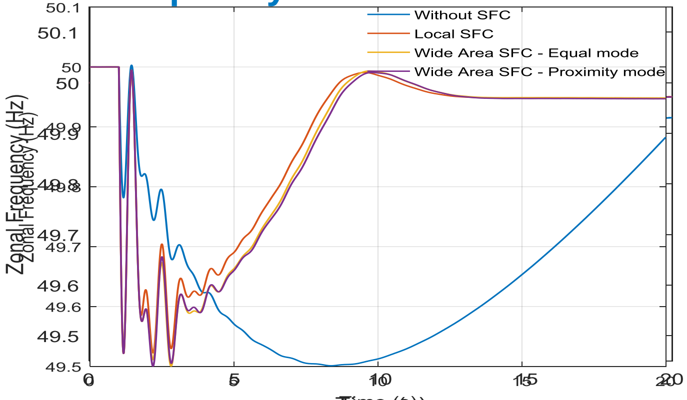
- For the two examples, all EFCC sensitivities recover the frequency effectively for larger losses than are possible without EFCC
  - Up to 2025, interim wide-area control is the most effective
  - Wide-area (Proximity) is most efficient in damping of inter area behaviour
- EFCC concept can accommodate a maximum system loss of between 850MW and 400MW larger than is possible without EFCC

Value of EFCC control

National Frequency 2025



Frequency at disturbed zone



- Key to EFCC optimisation is the deployment of sufficient resources to meet the event. The modelling approach is able to simulate this.
- Whilst deployment of resource close to the event is beneficial, it has identified that up to 2025 this is not essential. The interim wide-area control is sufficient.
- Approach allows us to see regional and national frequency, identify how and to what extent regional resource is important and how best to combine EFCC with other forms of frequency response.

nationalgrid

Summary of EFCC optimisation findings

- Demonstrated how power system modelling can both illustrate the requirement for EFCC and its optimal deployment.

- Highlighted the potential capability of an interim level of wide-area control. This approach is not dependent on real time frequency and df/dt other than locally received but which does need a wide-area picture of the system's state prior to an event.

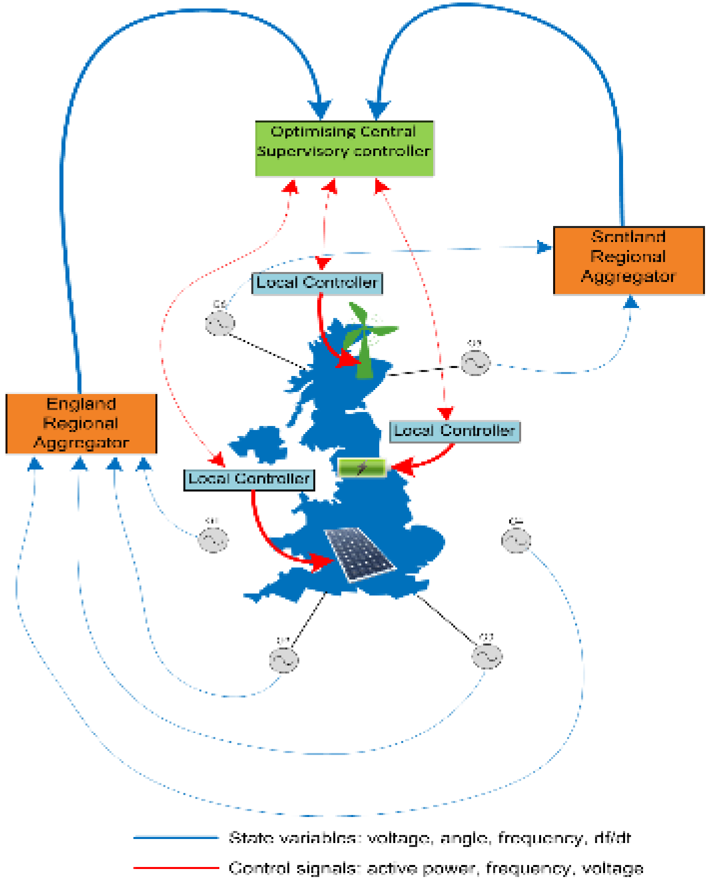
- EFCC requires sufficient time to deliver. Should frequency containment faster than 500ms become necessary, future options beyond EFCC that could potentially address this and when they might be required should be considered.

Further potential benefit

WP3 - Optimisation

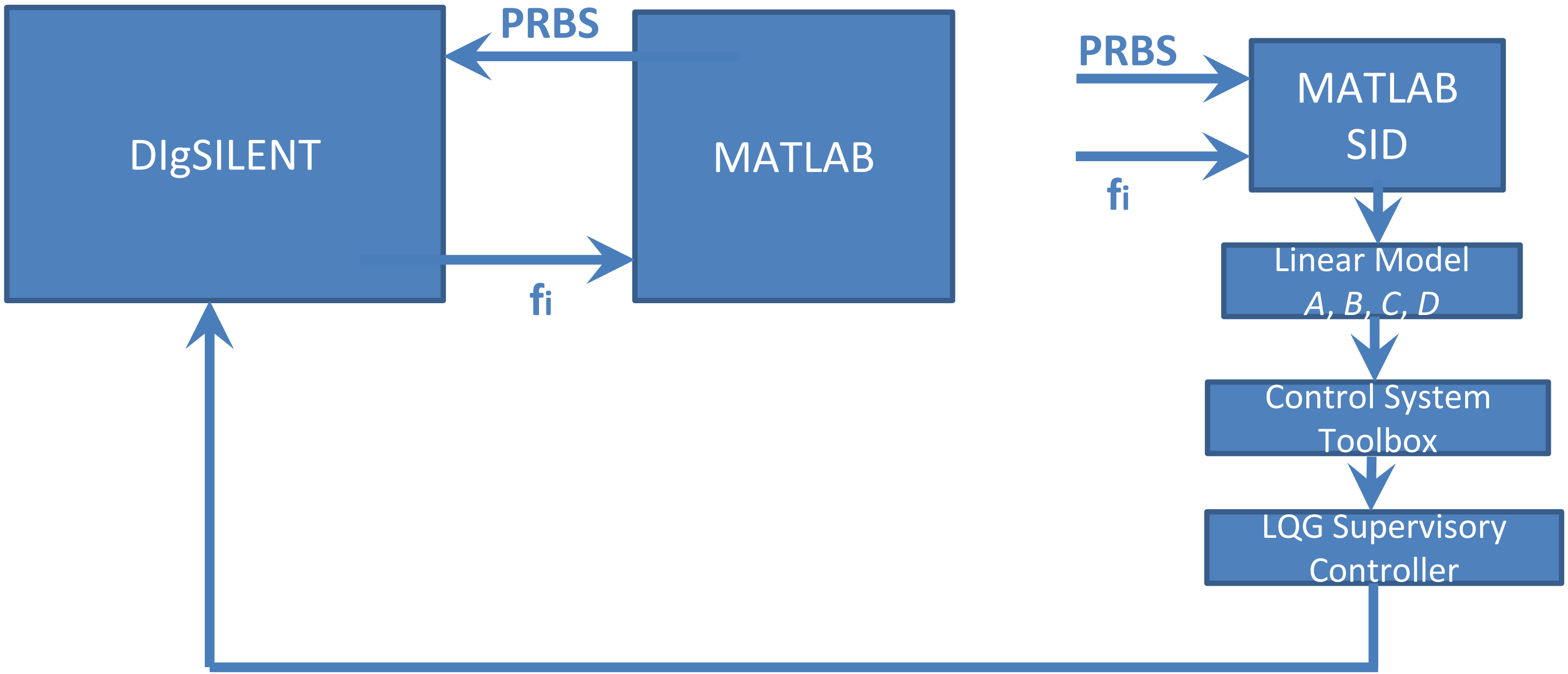
What are the next steps in optimisation the modelling?

nationalgrid

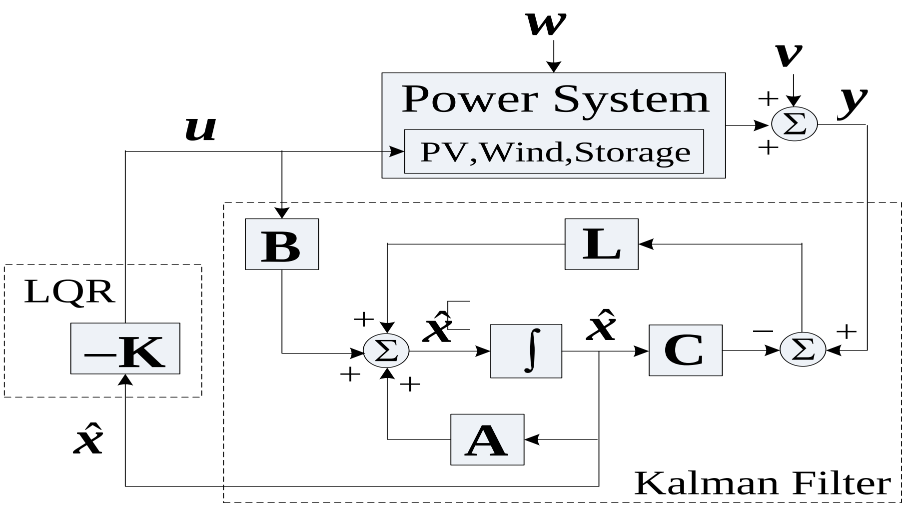


- Further option to fast frequency response is to describe the GB system mathematically in real time and optimise frequency response via that model.
- This further option requires frequency data only and has the potential to be faster than the time required to measure df/dt.
- The concept of creating such a model, capable of informing the optimisation, is illustrated but requires extensive further development.
- This concept would physically require the same monitoring and control architecture necessary for EFCC, together with additional real-time simulation and optimisation.

Methodology overview for design and implementation of supervisory controller



Linear Quadratic Gaussian (LQG) Control



$$J = \mathrm{E}\left\{ \lim_{T\to\infty} \frac{1}{T} \int_0^T \left(\boldsymbol{x}^{\mathrm{T}} \mathbf{Q} \boldsymbol{x} + \boldsymbol{u}^{\mathrm{T}} \mathbf{R} \boldsymbol{u} \right) \mathrm{d}t \right\}$$

Linear state space model of power system

$$\dot{\boldsymbol{x}} = \mathbf{A}\boldsymbol{x} + \mathbf{B}\boldsymbol{u} + \boldsymbol{\Gamma}\boldsymbol{w}$$
$$\boldsymbol{y} = \mathbf{C}\boldsymbol{x} + \mathbf{D}\boldsymbol{u} + \boldsymbol{v}$$

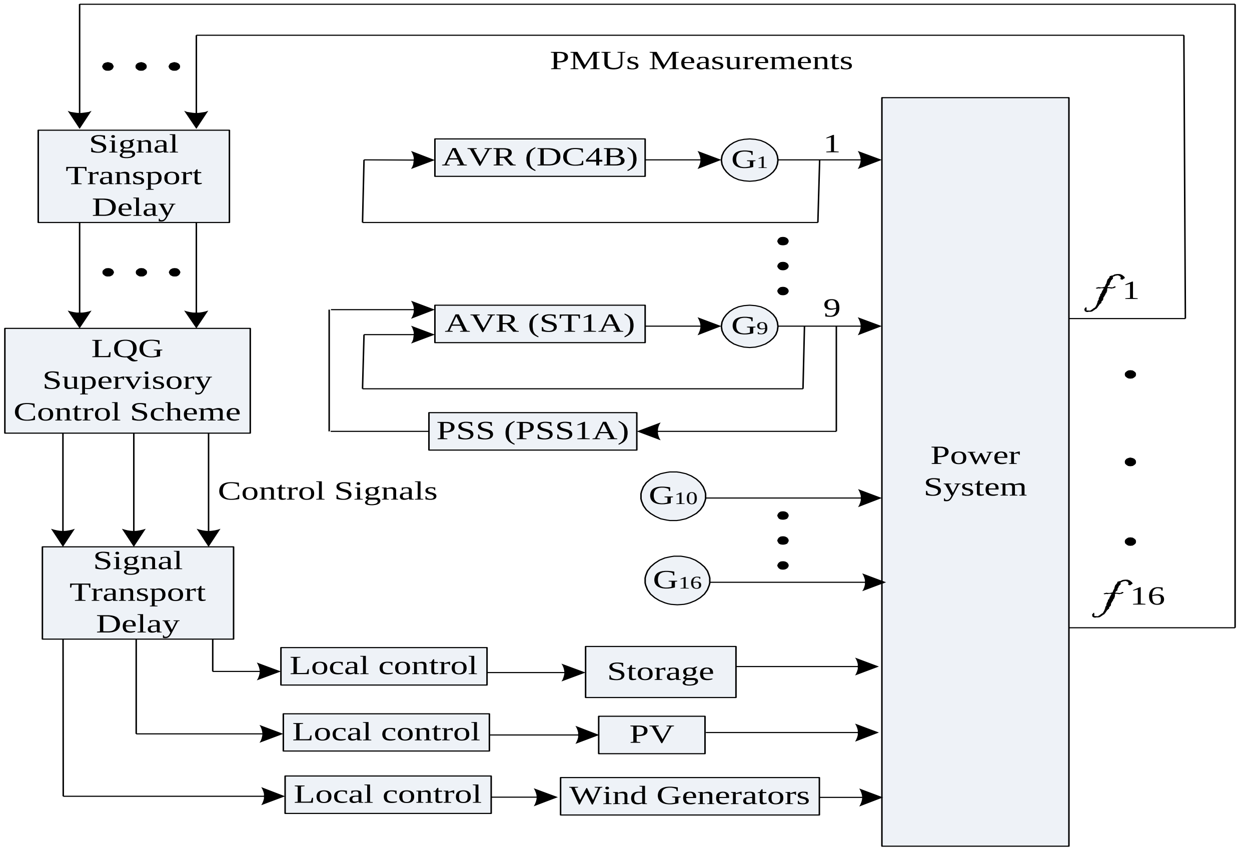
Observer (Kalman Filter)

$$\dot{\hat{\boldsymbol{x}}} = \mathbf{A}\hat{\boldsymbol{x}} + \mathbf{B}\boldsymbol{u} + \mathbf{L}(\boldsymbol{y} - \mathbf{C}\hat{\boldsymbol{x}})$$

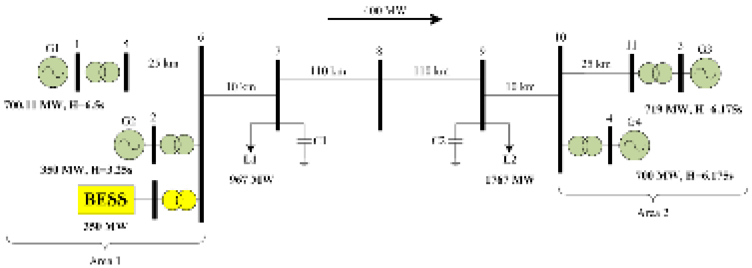
Optimal Full State Feedback Control Law

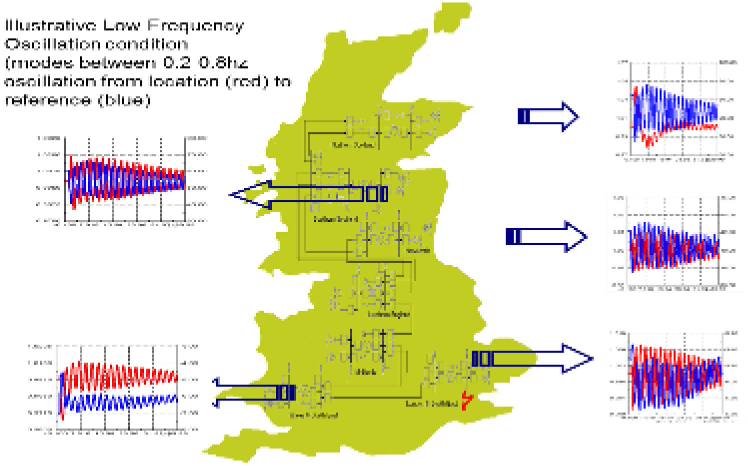
$$\boldsymbol{u} = -\mathbf{K}\hat{\boldsymbol{x}}$$

LQG Supervisory Control Scheme



Further optimisation - case study

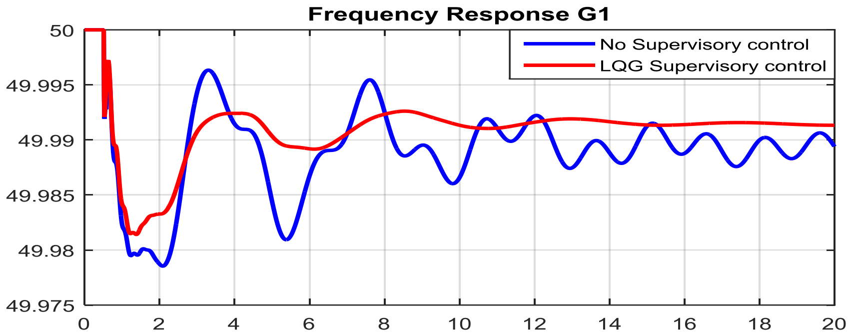


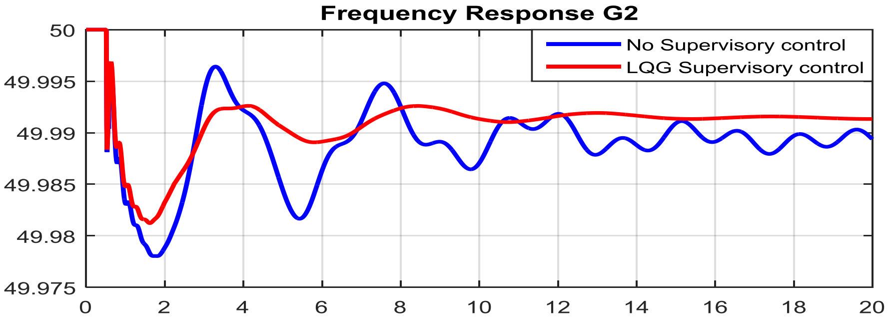


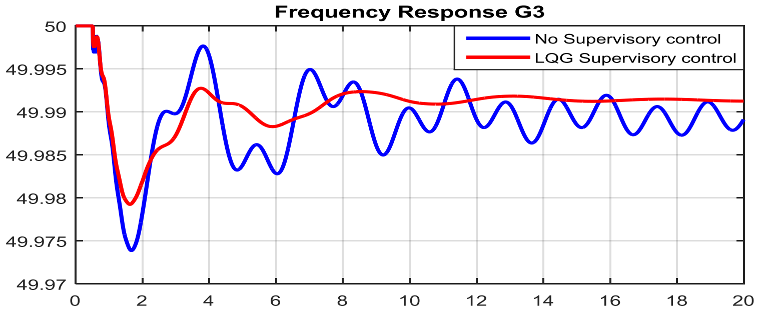
- Test network is a scaled 2-area representation of the GB system. It has been based on the 2020 Consumer Power scenario from the 2016 Future Energy Scenarios.

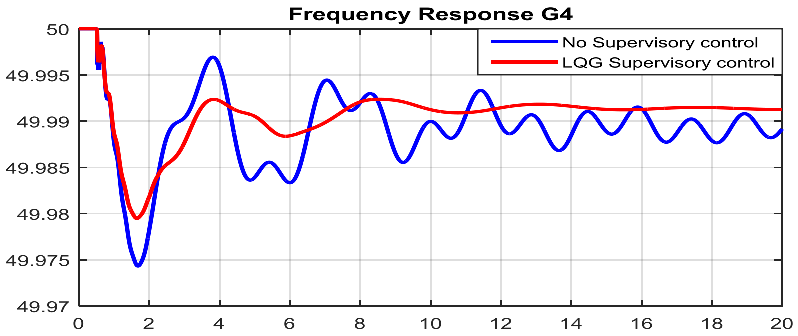
- The model illustrates the Scotland/England and Wales inter-area mode of oscillation and examines the potential for this to be 'excited' during a frequency event in the South West of the GB system.

LQG Supervisory Control Applied on Speed Governors

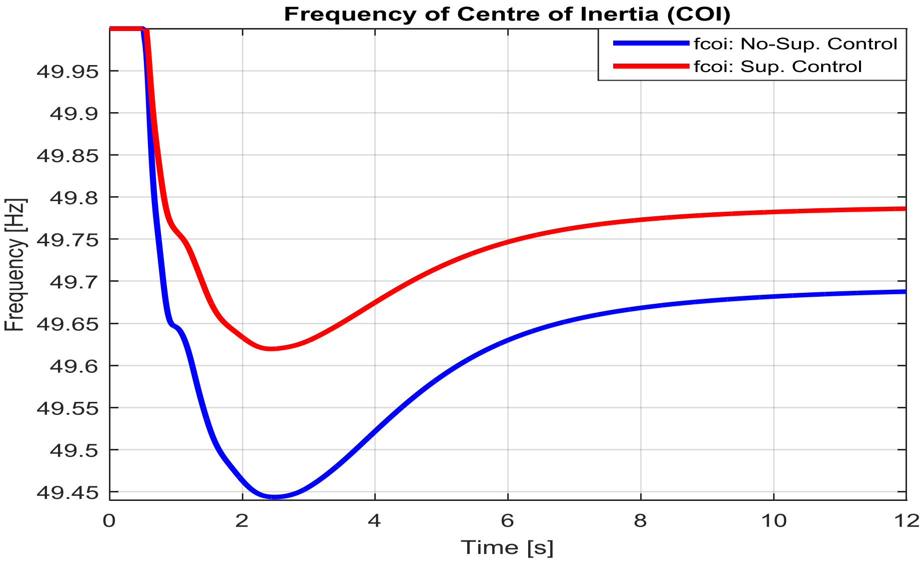






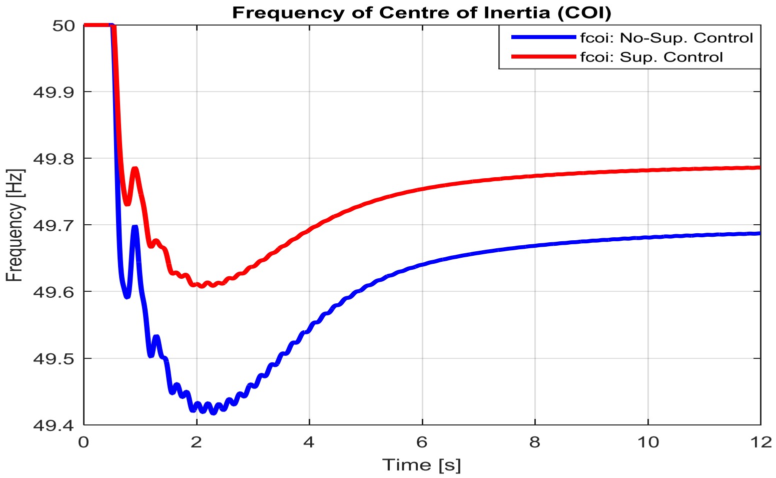


Effect of further optimisation



- Case study illustrates that a linear model of control can enhance optimisation.
- In 2020 the effect is similar to EFCC and drives a faster and stable frequency recovery.
- This case study event can also be satisfied by the EFCC approach, just as effectively.

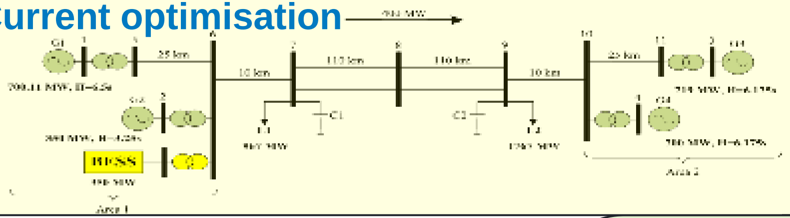
At what stage might this approach be required?



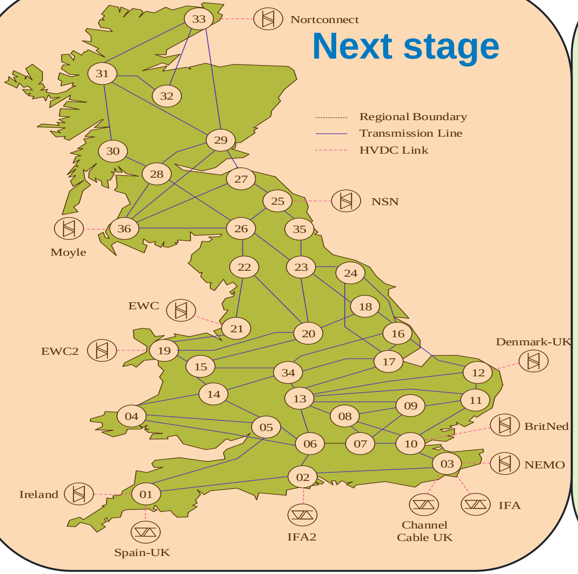
- Case study shows a further **62.5%** reduction in the system inertia from 2020. At this stage, containment within 500ms would become necessary.
- The case study illustrates that the linear optimisation approach would continue to have the potential to contain this frequency event effectively.
- This level of reduction in system inertia would not be expected until **mid-2030s** at the earliest.

Further considerations

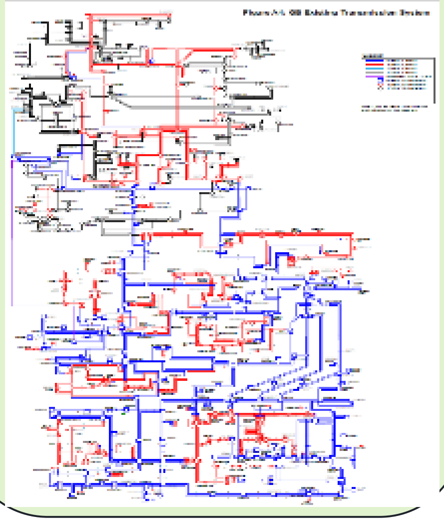
Current optimisation



Next stage



End requirement



- Explore the extent to which this optimisation is sensitive to real-time operational states and network configuration.
- Explore whether approach could be utilised for other system requirements and seek to identify these opportunities further.

Potential EFCC optimisation pathway

Today

RoCoF <0.125 Hz/s

- Optimised frequency response volumes
- Monitor and optimise models
- Diversify providers

Explore and Grow

Interim wide-area control

Early 2020s

1Hz/s>RoCoF>0.125Hz/s
Frequency containment limited

- All of today's benefits
- Enable higher RoCoF operation
- Minimise market redispatch of maximum loss

Apply

Interim wide-area control

Late 2020s

1Hz/s>RoCoF>0.125Hz/s
Frequency containment informed by real-time measurement

- All of early 2020s benefits
- Avoid increasing challenge of market redispatch
- Avoid response resource constraints

Develop and Apply

Real-time informed wide-area control

2030+

RoCoF nearer 1Hz/s
Possibly more rapid real-time measurement action required

- All of late 2020s benefits
- Enable efficient balancing solutions continuing to respect maximum loss
- New modelling capability
- Power oscillation damping?

Explore

Further optimised approach, real-time informed simulation

Lunch - Back at 12:45pm

WP4 - Hardware in the Loop Validation of the EFCC Scheme

Mingyu Sun University of Manchester
Rasoul Azizpanah-Abarghooee University of Manchester
Vladimir Terzija University of Manchester

nationalgrid

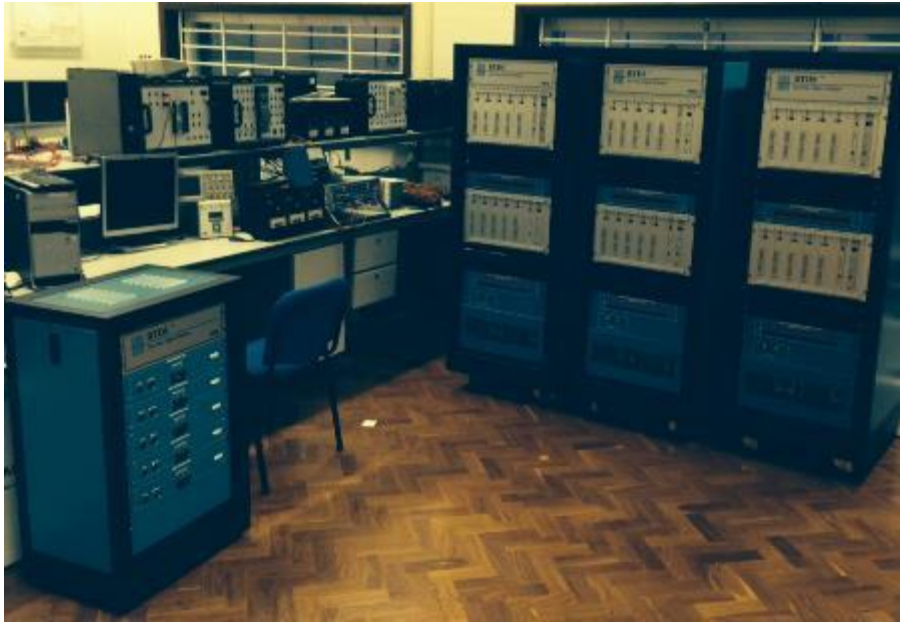
Presentation Outline

- Manchester RTDS Lab and Hardware in the Loop Building Blocks
- Testing Configuration and RTDS GB Network Model
- Role of Manchester in Testing the GE-MCS Equipment
- Testing and Assessing the GE-MCS
- Sensitivity Analysis
- GE-MCS Testing Summary

Manchester RTDS Lab and Hardware in the Loop Building Blocks

Manchester RTDS Lab

- **Manchester Real Time Digital Simulator (RTDS)** is employed to represent the EFCC physical plant and a variety of future scenarios
- **RTDS** consists of 6 racks with 30 PB5 processor card:
  - GTSync card for synchronisation of the RTDS
  - GTNet cards for high level communication (e.g. IEC 61850, C37.118 and IEC 60870 protocols)
  - GTWIF cards to connect to Admin PC

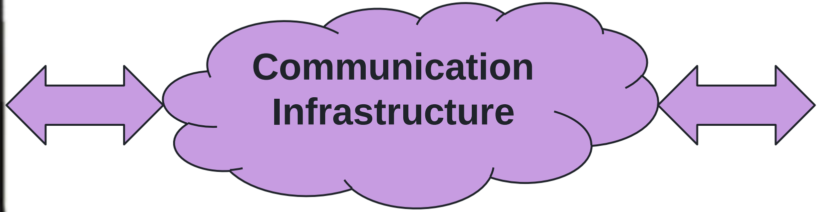


Hardware in the Loop Building Blocks

RTDS

GE-MCS

Admin PC to control simulation runs and visualise the results



RTDS to perform flexible HiL tests

Evaluating **GE-MCS** hardware components:

a) Regional Aggregators (x2)

b) Local Controllers (x4)

c) Central Supervisor (x1)

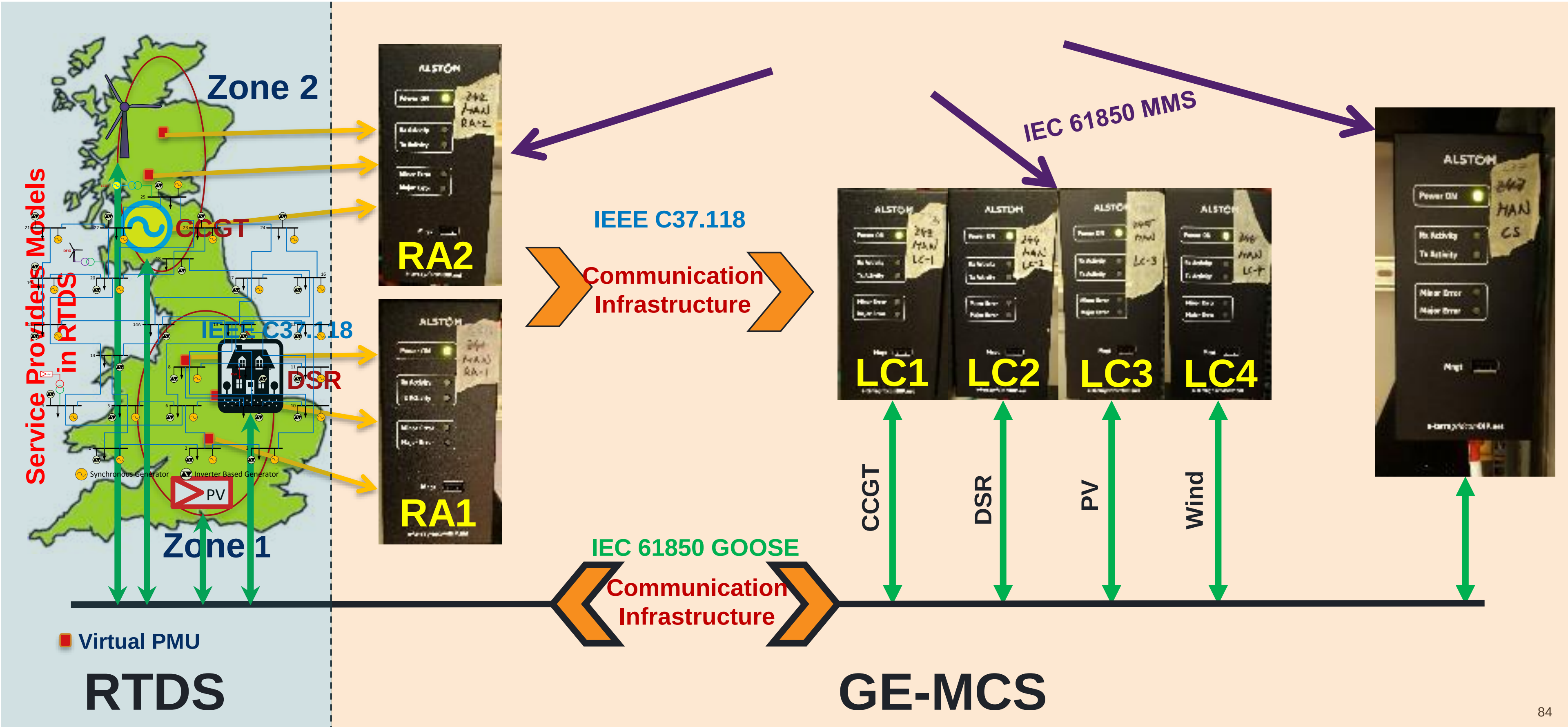
nationalgrid

Hardware in the Loop Building Blocks

- Using **hardware-in-the-loop (HiL)** simulation to assess the GE-MCS for a range of system cases and operational conditions
- Simulating future power networks with high penetration of Non-Synchronous Generation (NSG) and **variable/reduced system inertia** (expressed in GVAs)
- Representation of **load models** through frequency and voltage dependent models
- Representation of **NSG through high fidelity** models
- Modelling virtual phasor measurement units (**PMUs**) and Information and Communications Technology (**ICT**)
- Rigorous testing of resilience and robustness of the **GE-MCS** connected to the primary plant for a broad range of scenarios

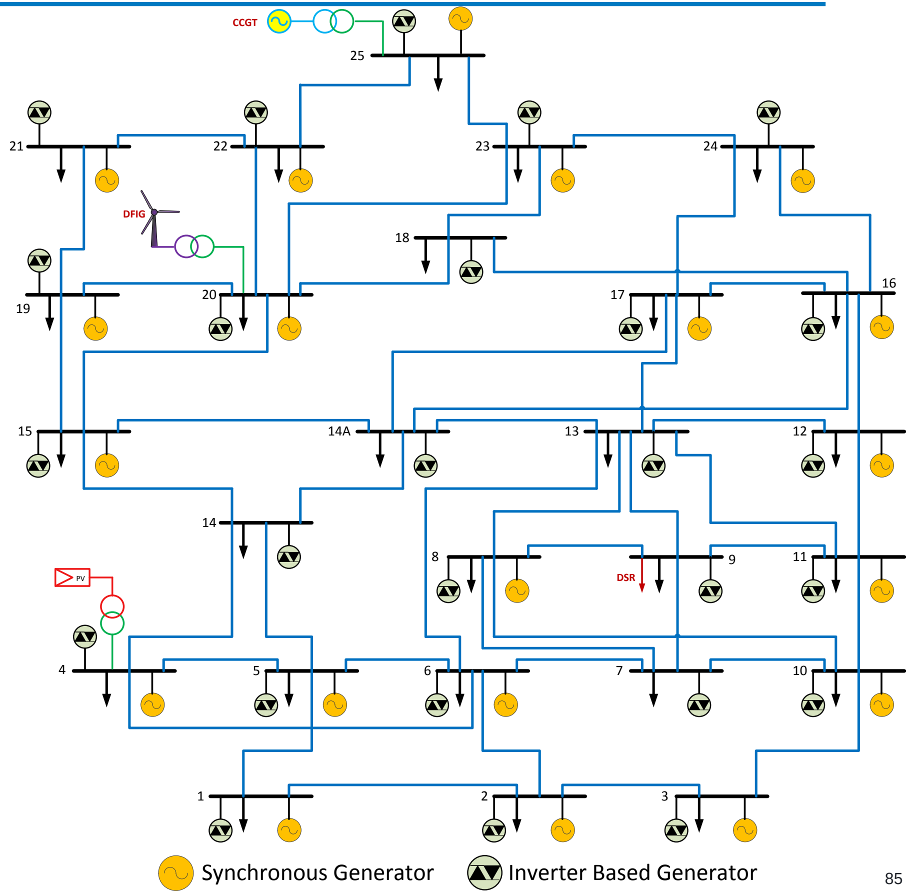
Testing Configuration and RTDS GB Network Model

GE-MCS Hardware Connected to the RTDS GB Model



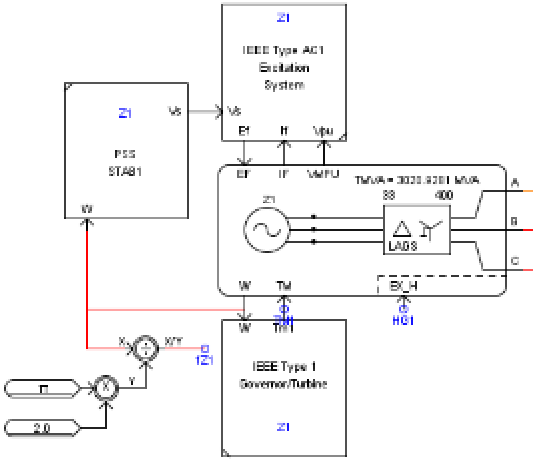
Simplified GB Network Model Modelled in RTDS

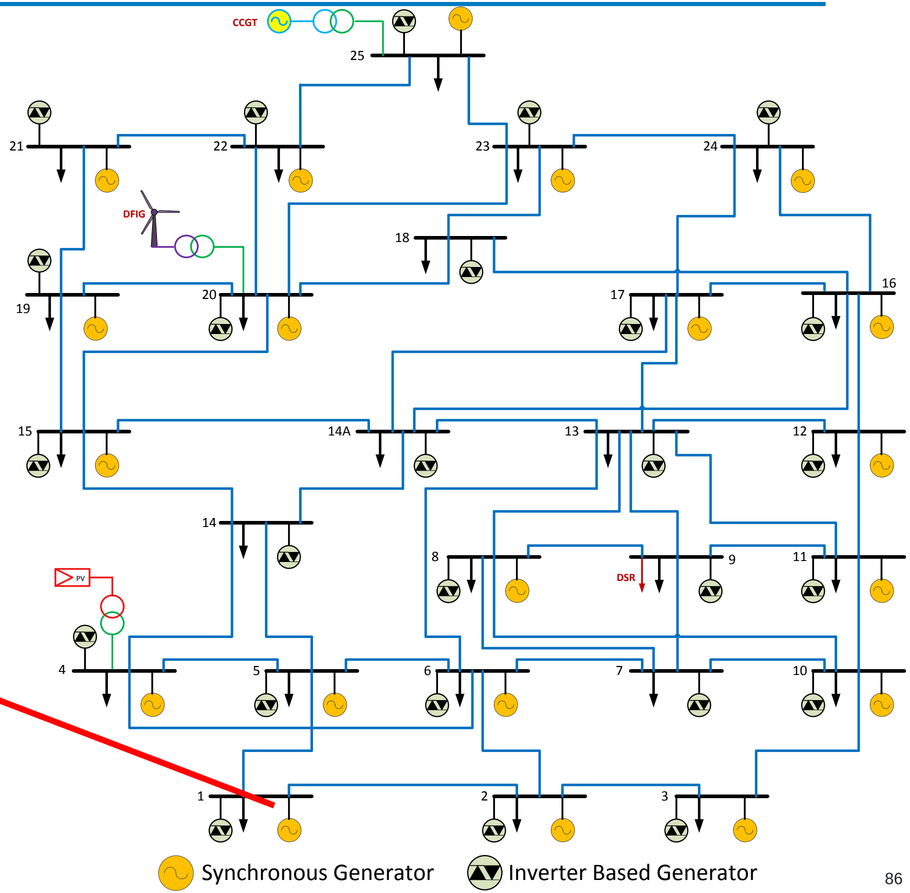
- **Use of the 26 Zone GB Network Model, simplified from the 36-zone GB Network Model created by National Grid in Powerfactory, allowing dynamic simulations using 2 racks of RTDS**
- **The Scotland area is reduced to one representative zone at bus 25**



Simplified GB Network Model Modelled in RTDS

- **The model includes:**
  - 20 synchronous generators

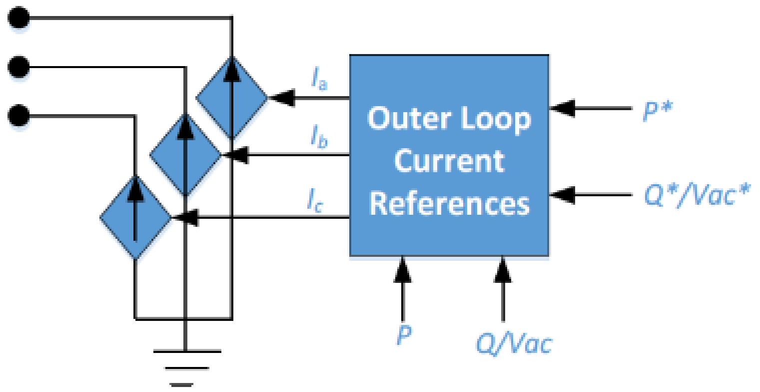


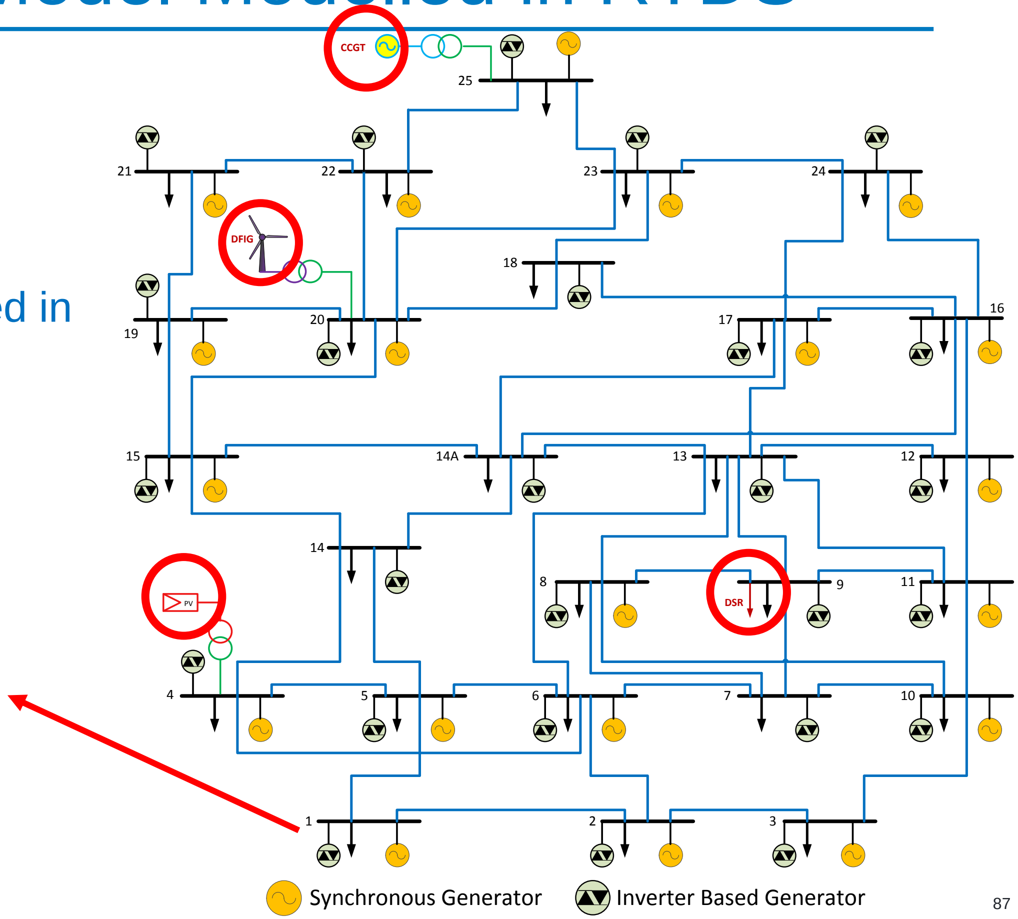


nationalgrid

Simplified GB Network Model Modelled in RTDS

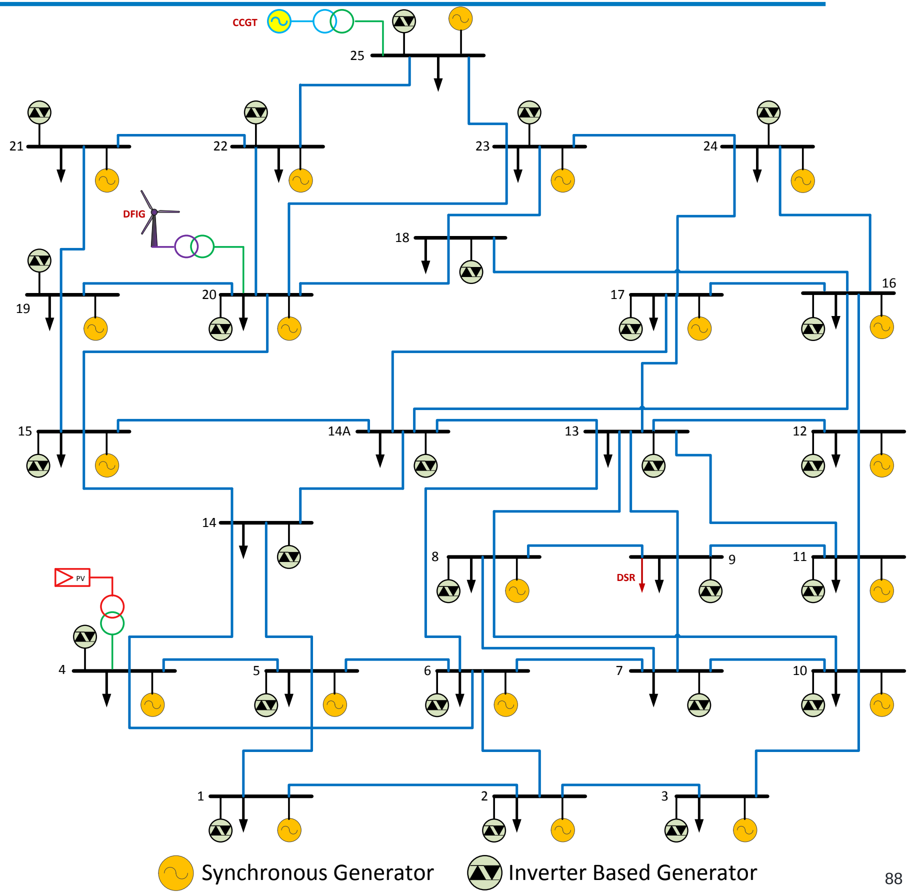
- **The model includes:**
  - 26 Non-Synchronous generators
  - 4 service providers models (circled in red)





Simplified GB Network Model Modelled in RTDS

- **The model includes:**
  - 26 voltage dependent loads with a Combination of constant power load (40%), constant current load (40%), and constant impedance load (20%)



Simplified GB Network Model Modelled in RTDS

- **System inertia**

In EFCC project, system inertia value is used for the estimate of the event size along with the RoCoF value.

User Input

$$\Delta P = \frac{2 \times \sum_{i=1}^{n} (H_i S_i)}{f_0} \times \frac{df}{dt}$$

PMU measurement

H_i is inertia constant of synchronously connected generation at bus i; S_i is rated power of synchronously connected generation at bus i; df/dt is system rate of change of frequency.

Simplified GB Network Model Modelled in RTDS

- **PMU weight calculation**

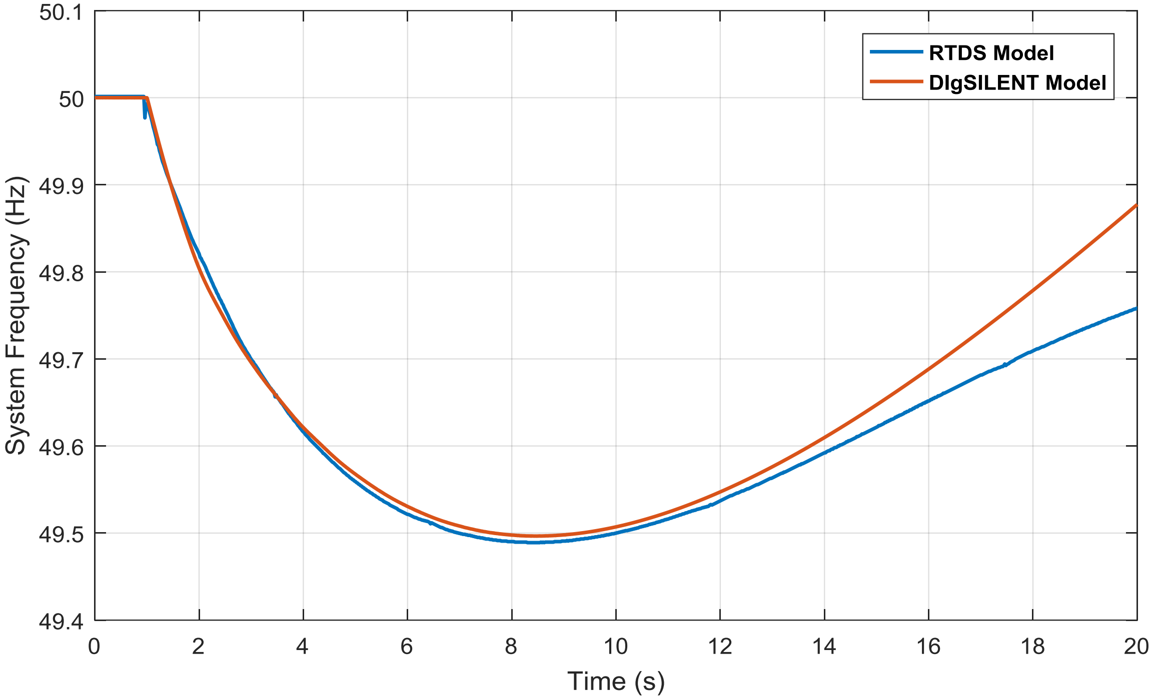
PMUs' weights is calculated and presented in the form of percentage of total inertia of the system.

$$Weight_{PMU}^{i} = \frac{H_{SG}^{i} S_{SG}^{i}}{H_{sys} S_{sys}}$$

H_{SG}^{i} is inertia constant of synchronously connected generation at bus i; S_{SG}^{i} is rated power of synchronously connected generation at bus i; HSys is total inertia constant of synchronously connected generations

Validation of the Simplified 26 Zone GB Network Model

nationalgrid



- Validation of the 26 Zone GB network represented in RTDS against the GB 36 Zone network simulated using PowerFactory (model based on scenario year 2020)
- The total inertia is **83.5 GVAs**
- **Event:** 750 MW at Bus 1
- The initial response (first 10 seconds) practically the same, the difference after Nadir is due to a slower governor droop.
- *Conclusion*: the testing using the Simplified GB model justified

System Frequency = Frequency of the equivalent inertia centre (COI frequency) = National Frequency

Role of Manchester in Testing the GE-MCS Equipment

Testing Regional Aggregator, Local Controller and Central Supervisor

Role of the Manchester Research Team in EFCC Project

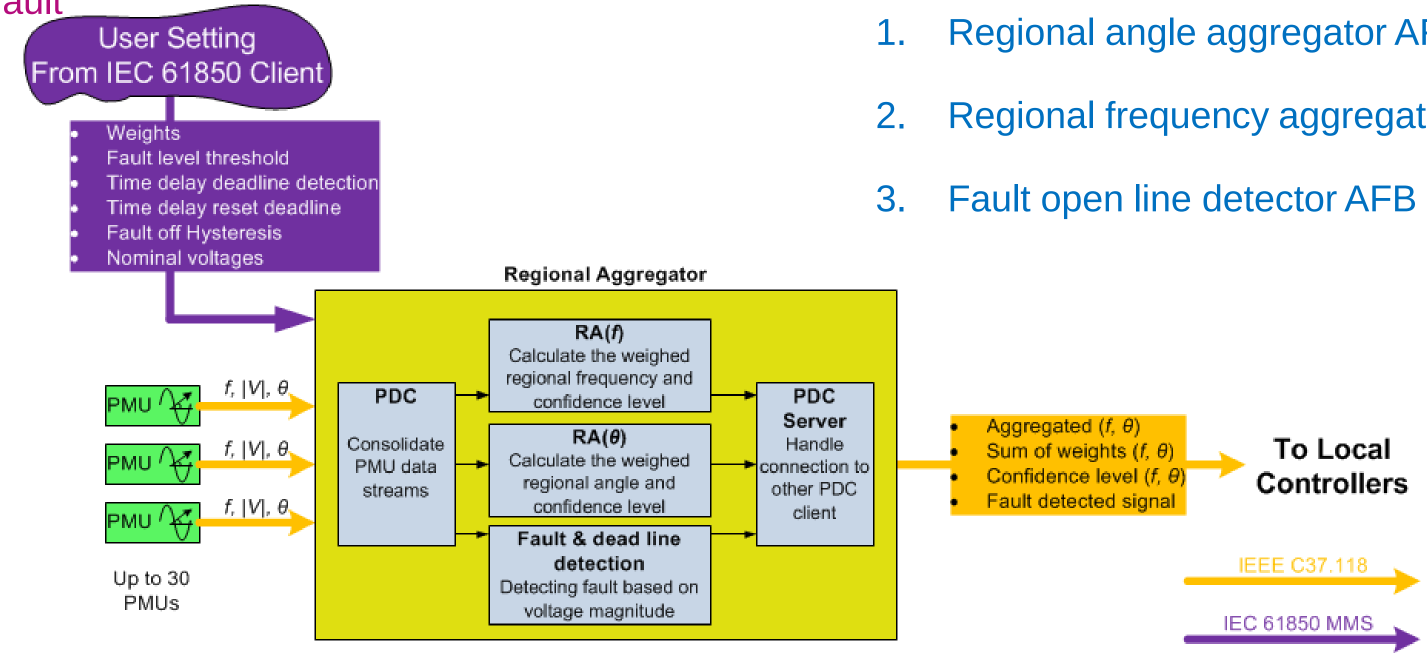
nationalgrid

- Focus on the **Wide Area Mode**
- Test network: 26 zone equivalent GB system
- Testing of:
  A. Individual Application Function Block (AFB)
  B. The entire GE-MCS
- Test scenarios:

  Sudden load connection/disconnection, Short circuit fault, Generator tripping after fault, line opening after fault. Each of above scenarios considers different parameters, i.e. size, duration and locations.

Regional Aggregator Testing

- Its main functionality is to calculate the regional frequency, regional angle and detecting the short circuit fault

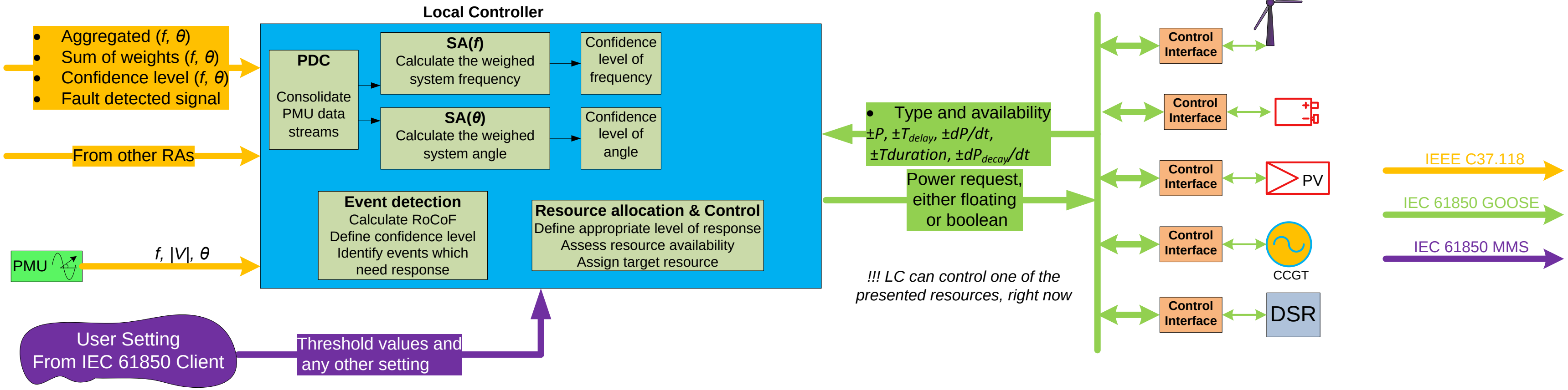


- A Regional Aggregator consists of the following Application Function Blocks (AFBs):
  1. Regional angle aggregator AFB
  2. Regional frequency aggregator AFB
  3. Fault open line detector AFB

Local Controller Testing

- Local controller (LC) determines a suitable wide-area response which will be allocated to service providers
- Local independent response - a backup solution in case of losing wide-area signals

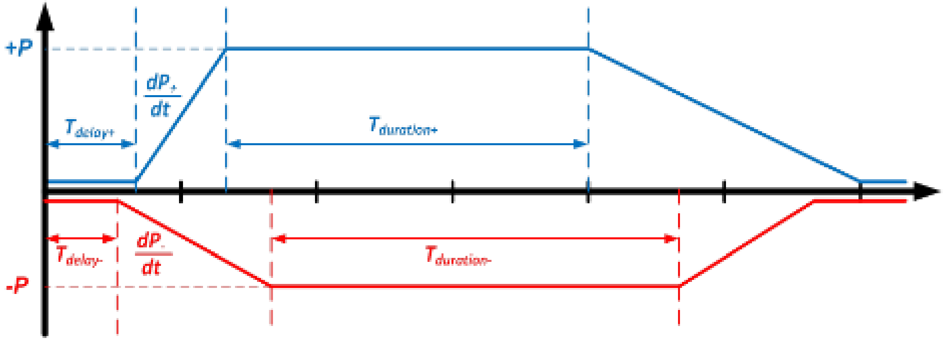
- A LC consists of the following AFBs:
  1. System frequency aggregator AFB
  2. System angle aggregator AFB
  3. Event detection AFB
  4. Resource allocation AFB

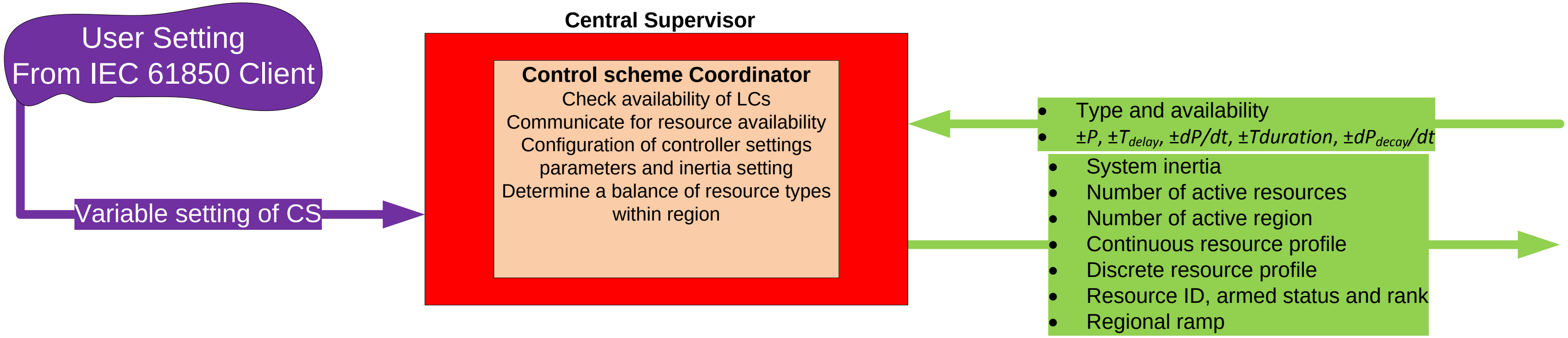


nationalgrid

Central Supervisor Testing

- Its main functionality is to keep all the Local Controllers updated with the latest status of the controlled service provider
- Represented through a single AFB called optimisation AFB in order to prioritize the service providers of the LCs





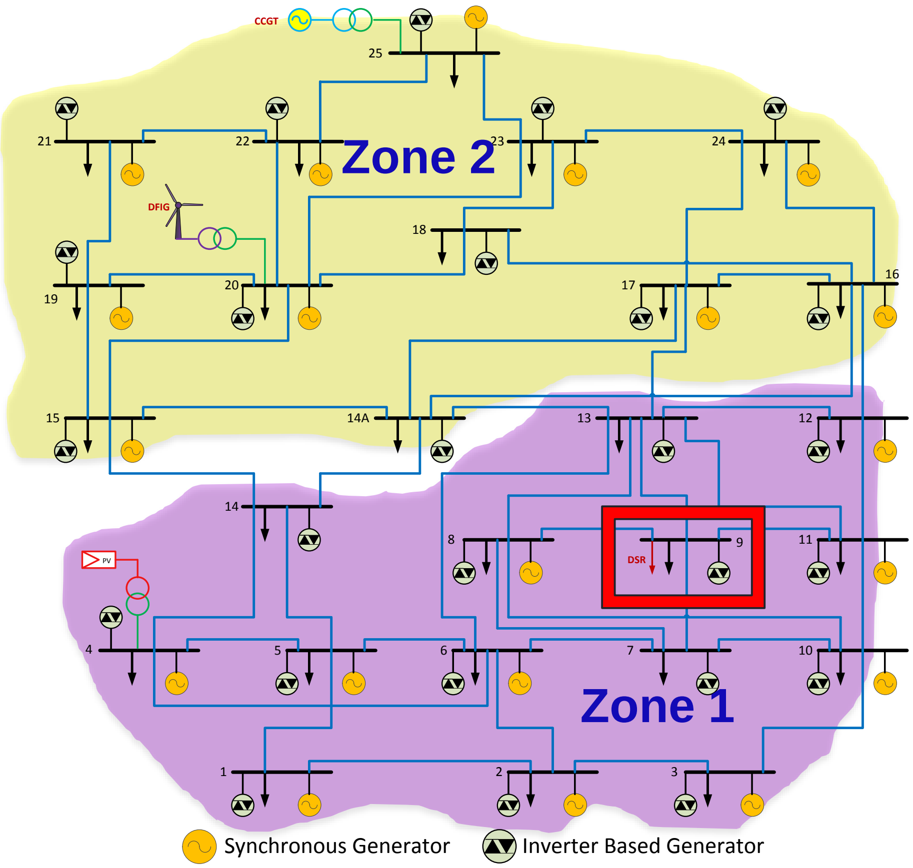
Testing and Assessing the GE-MCS

Review of Test Cases

- The balanced GB power system has the nominal frequency of 50 Hz
- A sudden active power, *P*, mismatch results in an over- or under-frequency deviation
- Disturbances used to cause power mismatch:
  - Sudden load connection (1GW) – equivalent to 1GW HVDC disconnection
  - Sudden load disconnection (1GW)
  - Short circuit fault (generators acceleration leads to frequency increment)
  - Generator disconnection, following a 140 ms short circuit fault

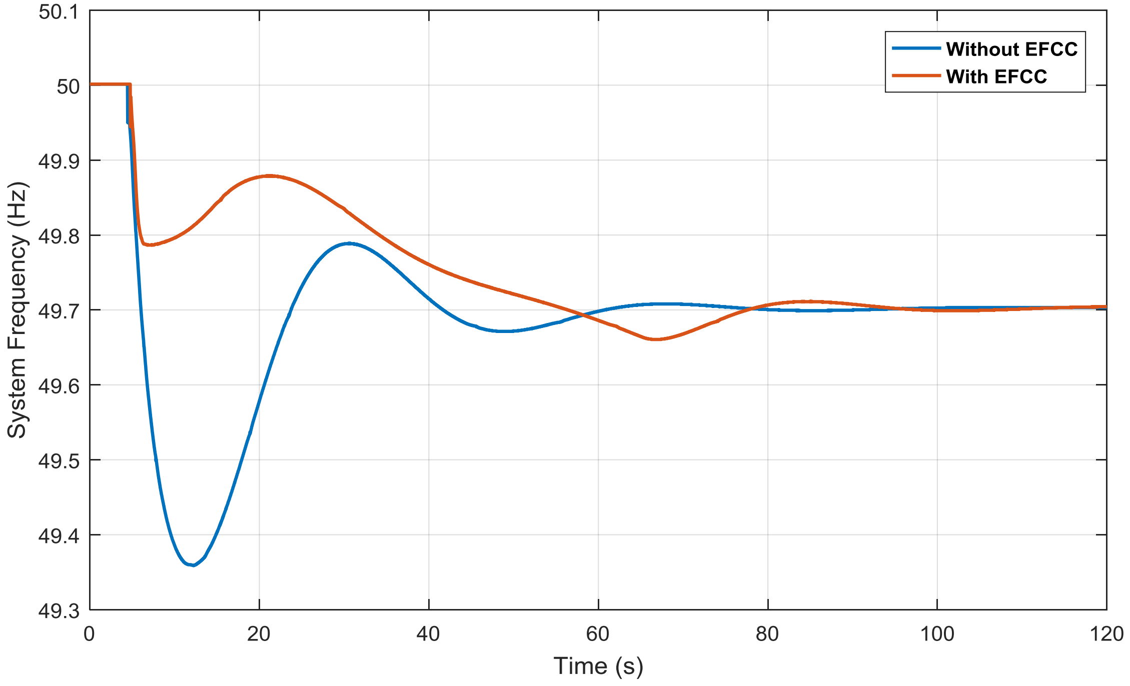
Case 1: Sudden Load Connection (1GW)

- **Demand: 42GW**
- **Inertia: 82 GVA.s**
- **Event: Sudden load connection**
- **Size: 1000 MW**
- **Location: Bus 9**
- **Available Power in zone 1: 1500 MW**



Service Provider	Available Power (MW)
DSR	200
PV	1300
CCGT	200
Wind	300

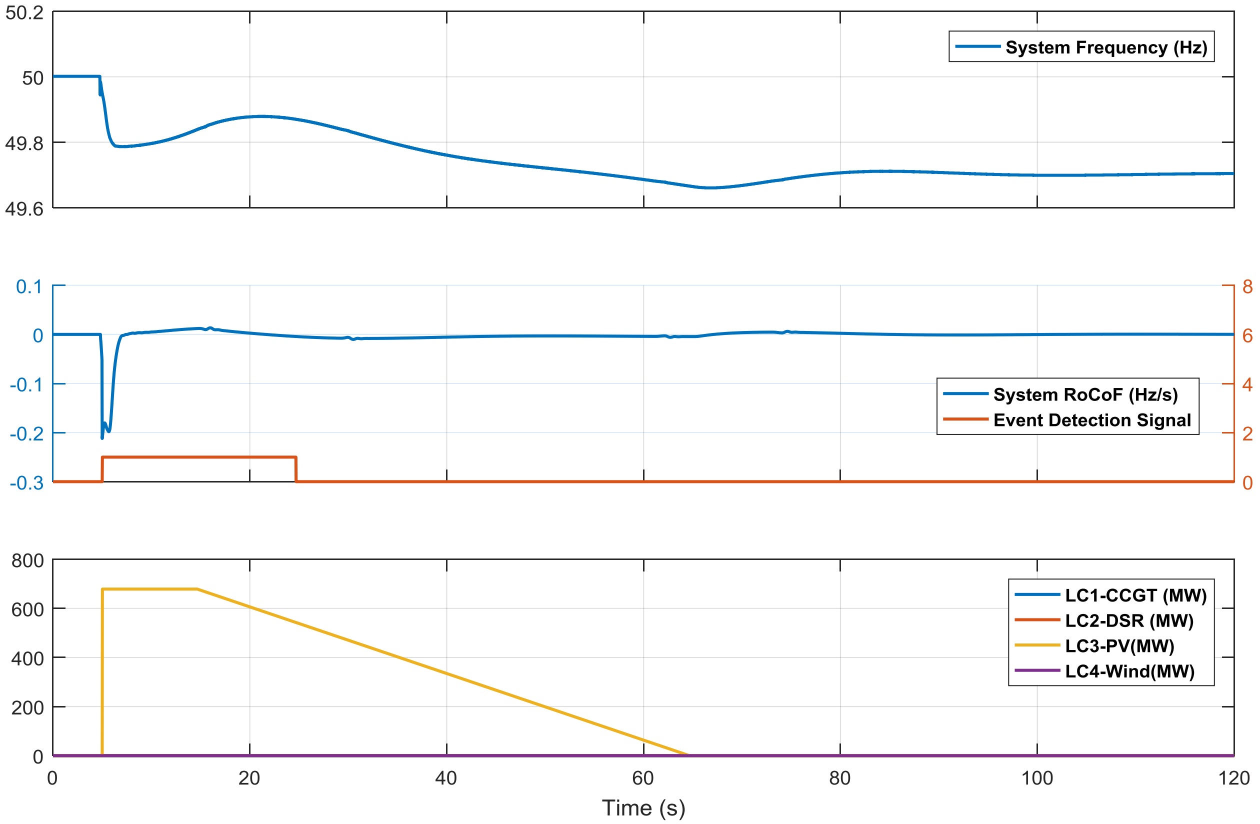
Case 1: Sudden Load Connection (1GW)



- EFCC delivers a faster and more effective frequency response (Lowest frequency is improved from 49.37Hz to 49.66Hz).

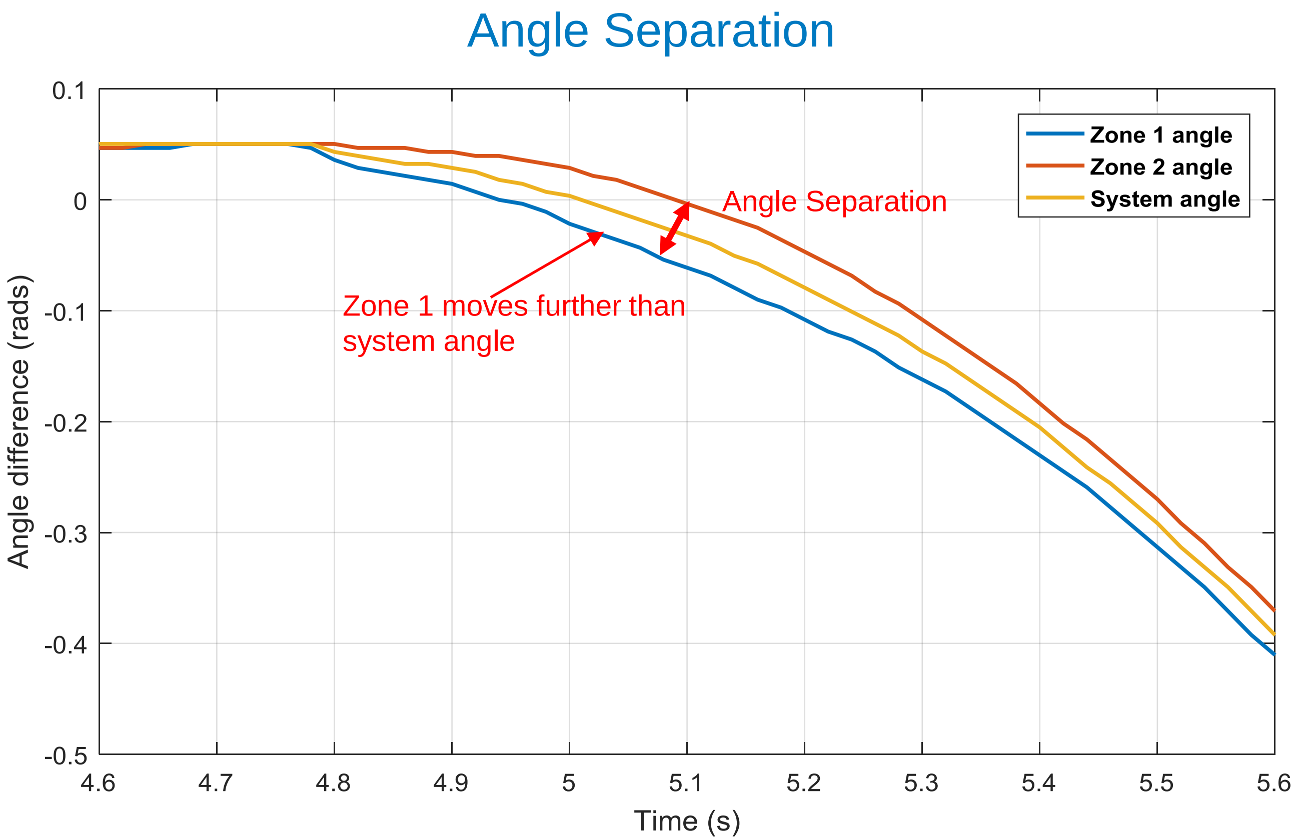
nationalgrid

Case 1: Sudden Load Connection (1GW)



- Measured RoCoF: -0.21 Hz/s
- The event is detected within 500ms in Zone 1.
- Requested response is 600 MW which is calculated based on the measured system RoCoF and system inertia.

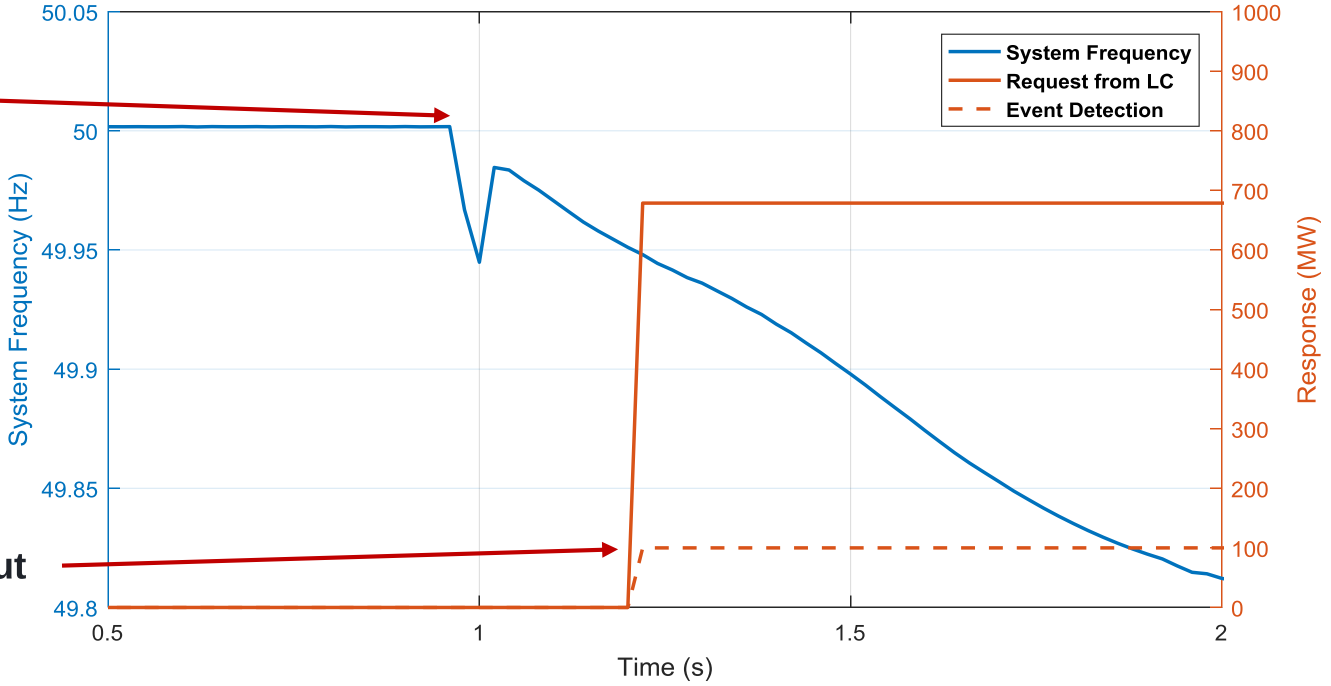
Case 1: Sudden Load Connection (1GW)



Case 1: Sudden Load Connection (1GW)

Event starts at 1s

Event detected and response request sent out by EFCC within 0.23s

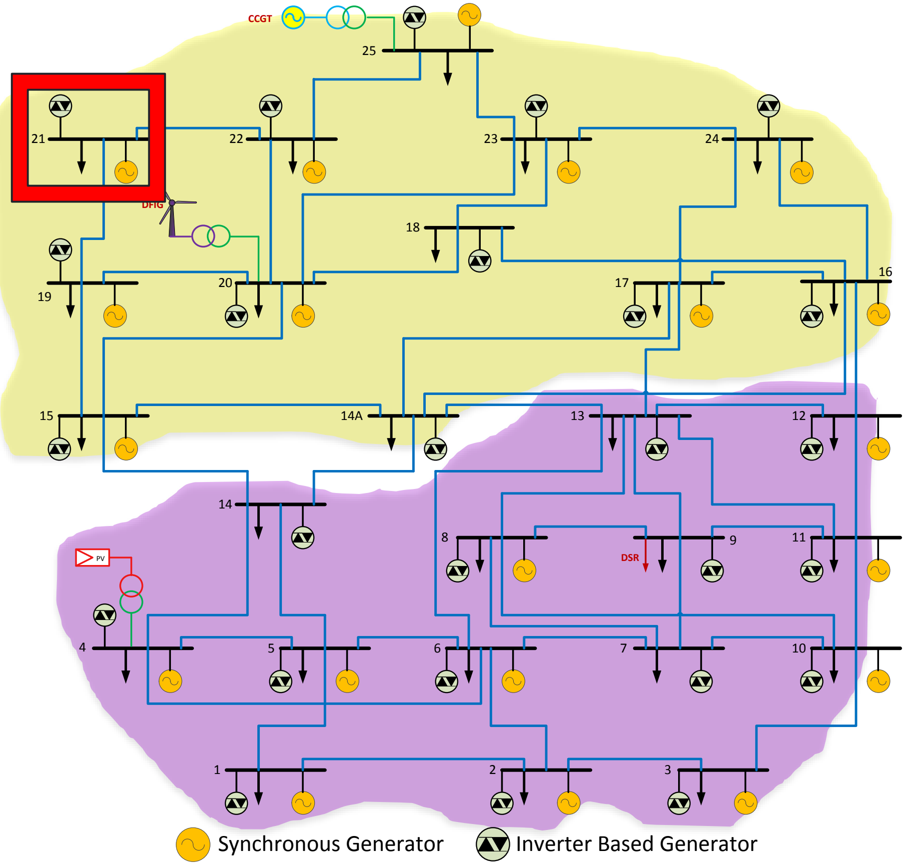


Case 1: Live Demonstration

nationalgrid

Case 2: Sudden load Connection (1GW) (at another location)

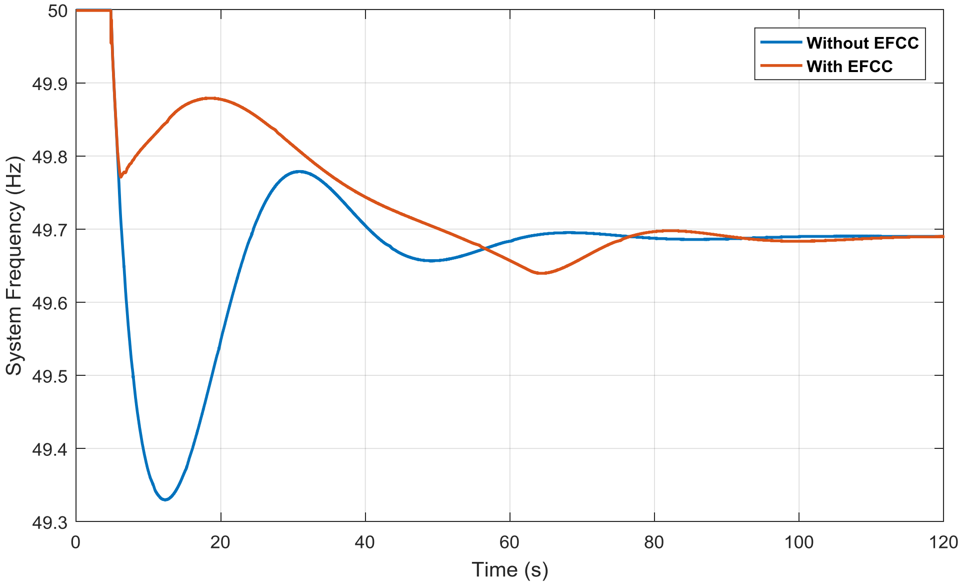
- **Event: Sudden load connection**
- **Size: 1000 MW**
- **Location: Bus 21**
- **Resource availability: 1500MW**



Service Provider	Available Power (MW)
DSR	200
PV	300
CCGT	200
Wind	1300

Case 2: Sudden load Connection (1GW),

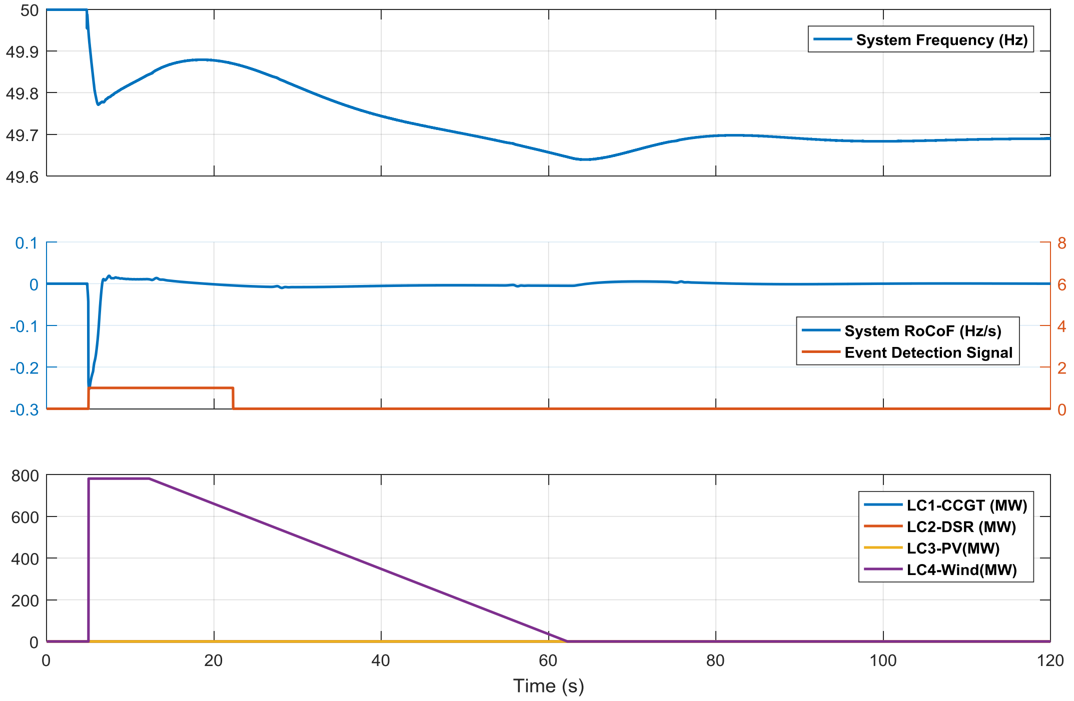
At Different locations



- The lowest frequency is improved from 49.33 Hz to 49.64 Hz

Case 2: Sudden Connection of Load (1GW), nationalgrid

Different location

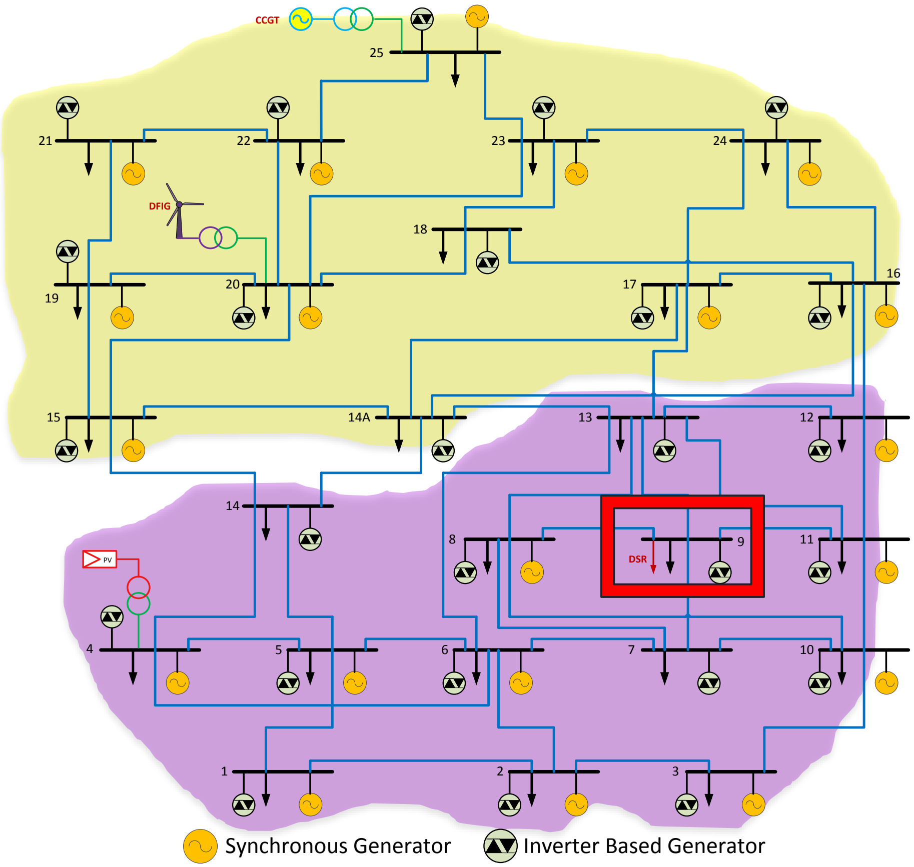


- Measured RoCoF: -0.25 Hz/s
- The event is detected within 500ms in Zone 2.
- Requested response is 790 MW which is calculated based on the system RoCoF and inertia

Case 3: Sudden Load Disconnection (1GW), less resource availability

nationalgrid

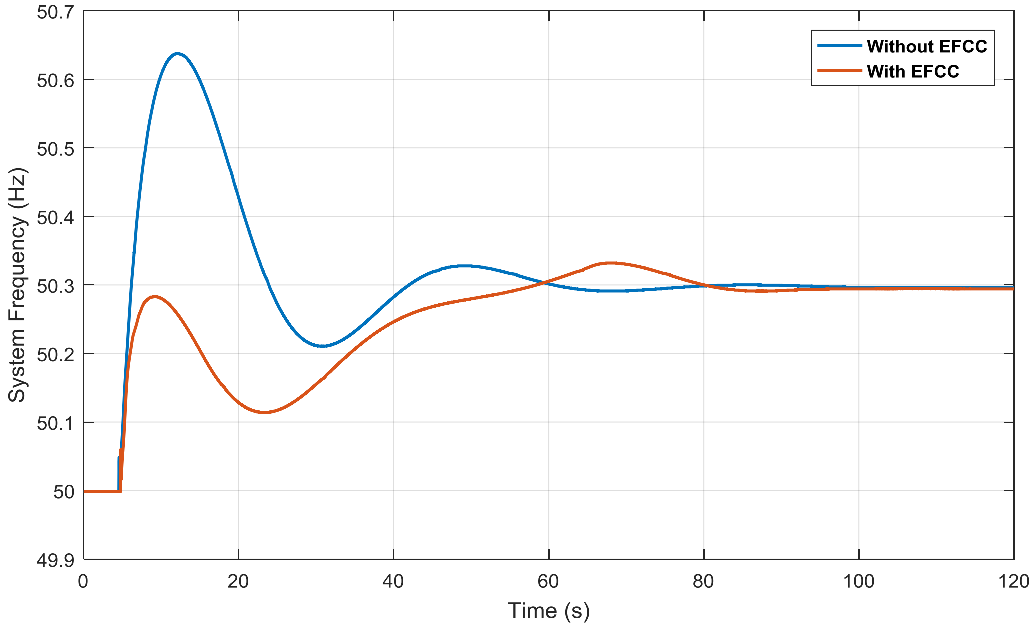
- **Event: Sudden load disconnection**
- **Size: 1000 MW**
- **Location: Bus 9**
- **Resource availability: Just 500MW to challenge the EFCC scheme**



Service Provider	Available Power (MW)
DSR	0
PV	500
CCGT	200
Wind	300

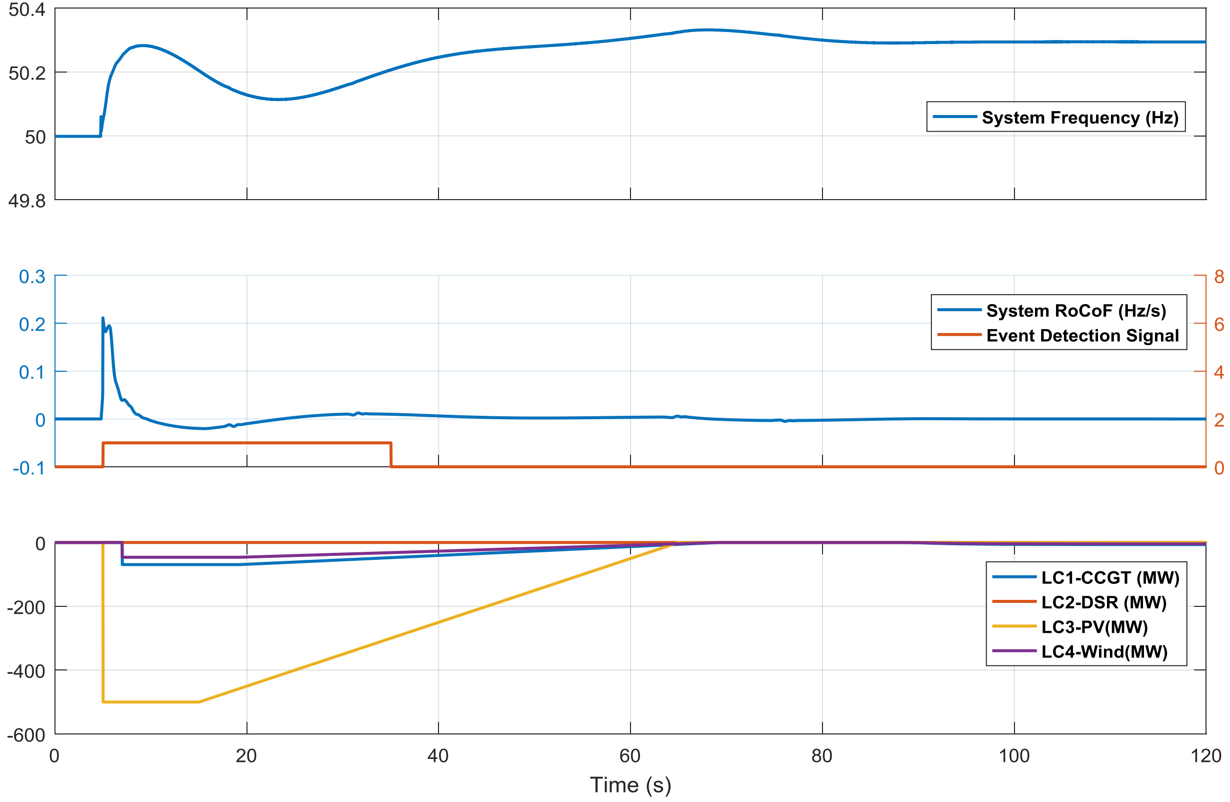
Case 3: Sudden Load Disconnection (1GW), less resource availability

nationalgrid



- The highest frequency is enhanced from 50.63 Hz to 50.33 Hz

Case 3: Sudden Load Disconnection (1GW), limited resources available

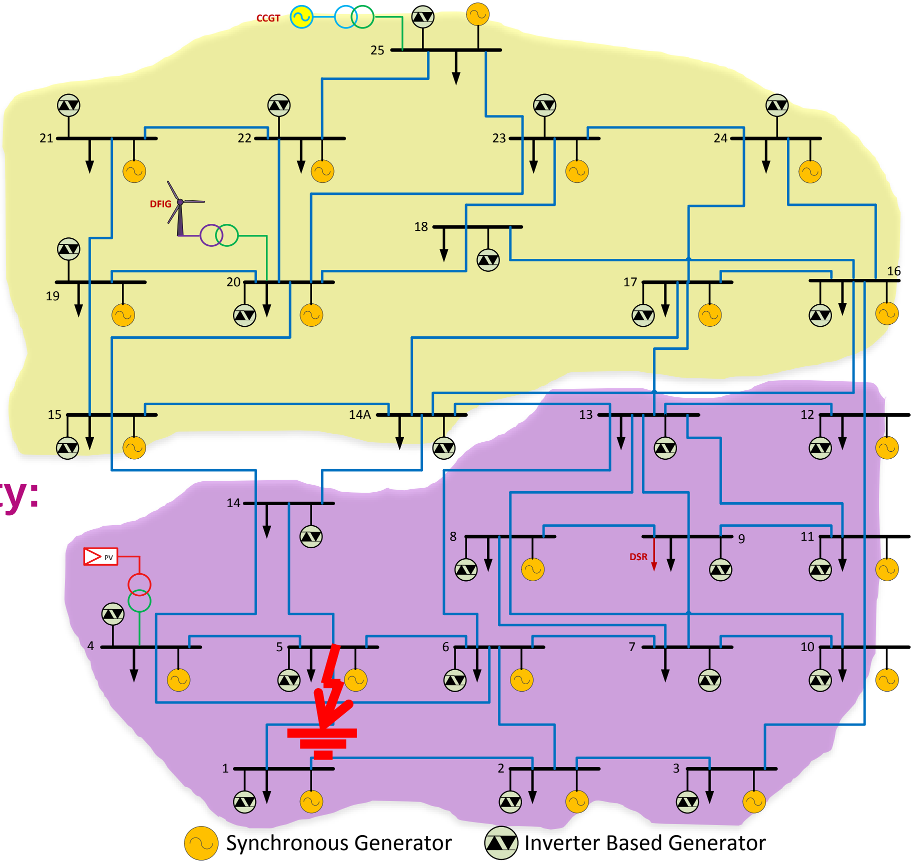


- Measured RoCoF: 0.20 Hz/s
- The event is detected within 500ms in Zone 1
- Requested responses are:
  - 500 MW from Zone 1 (Wide Area Mode)
  - 100 MW from Zone 2 (Local Coordinated Mode)

nationalgrid

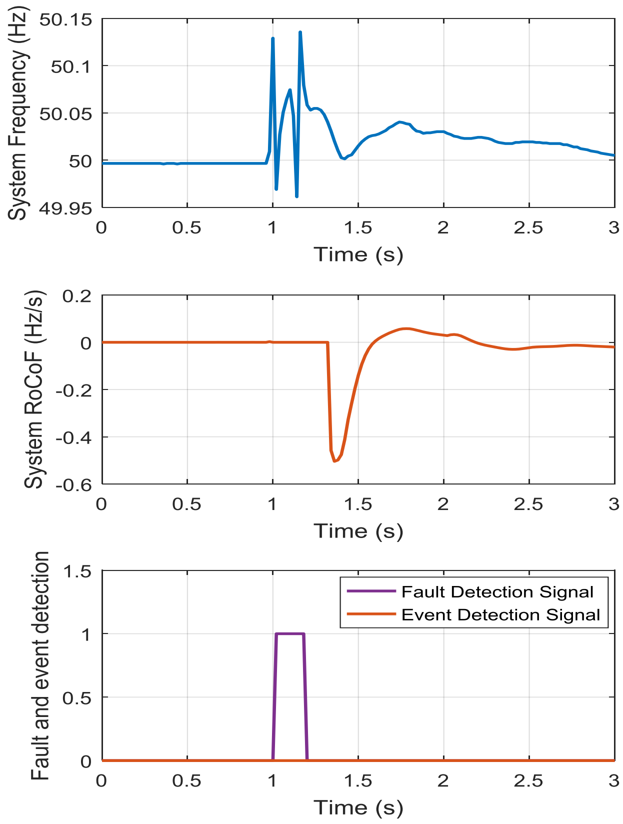
Case 4: Single-Phase to Ground Fault

- **Event: 1-phase to ground fault**
- **Length: 140 ms**
- **Location: Bus 5**
- **Resource availability: 1500MW**



Service Provider	Available Power (MW)
DSR	200
PV	1300
CCGT	200
Wind	300

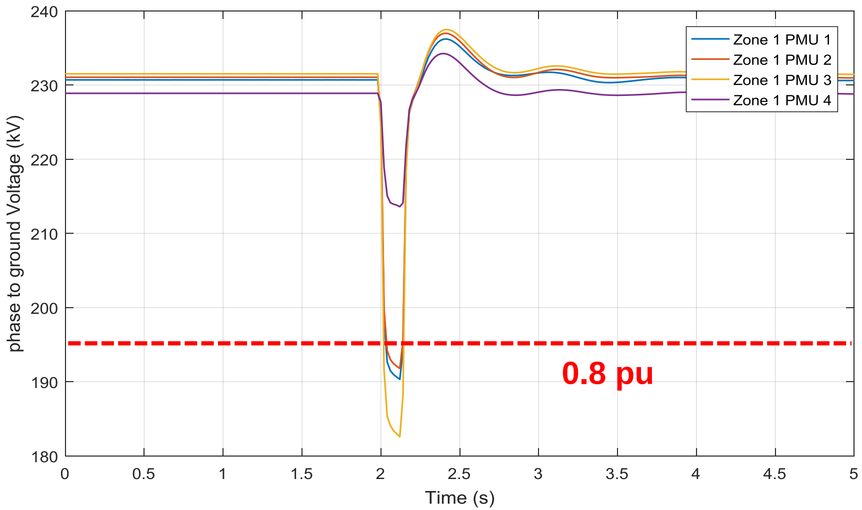
Case 4: Single-Phase to Ground Fault

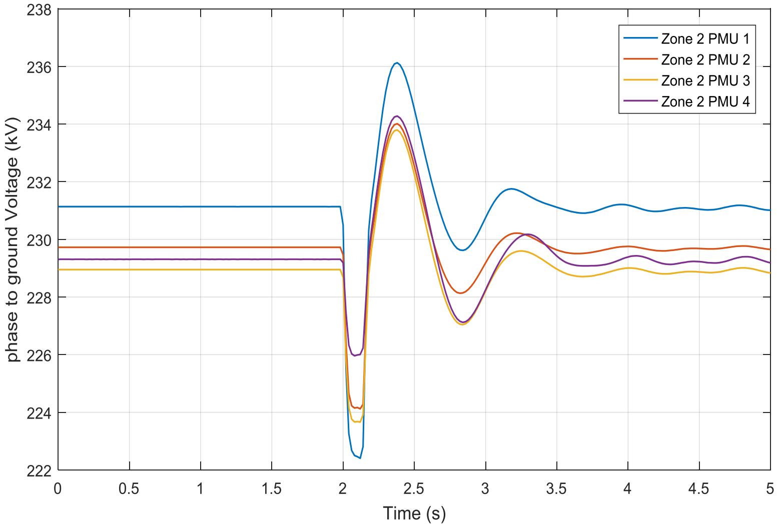


- During the fault, the monitored system frequency is highly distorted, so that the MCS should be blocked in this period.
- The fault event is detected and disturbance detection is blocked. Thus, the event detection is extended for the fault period by extra 120ms to ensure the system is settled down.
- The measured maximum system RoCoF doesn’t trigger the event detection module, because the frequency is in the permissible range ±0.05Hz.

Case 4: Single-Phase to Ground Fault

Bus voltage measured by PMUs





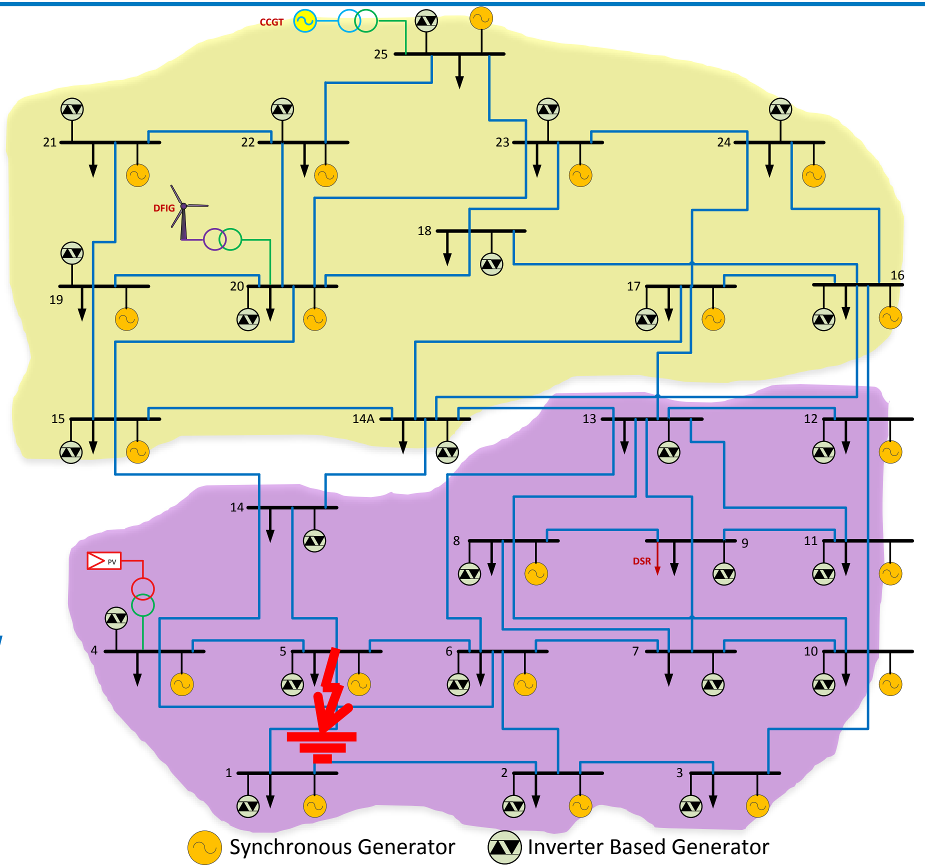
During the fault, voltage at locations closer to the disturbance is lower and voltages in zone 1 is much more depressed compared to zone 2

Case 4: Live Demonstration

Case 5: 1 GW Generator Tripping Following a Short Circuit Fault

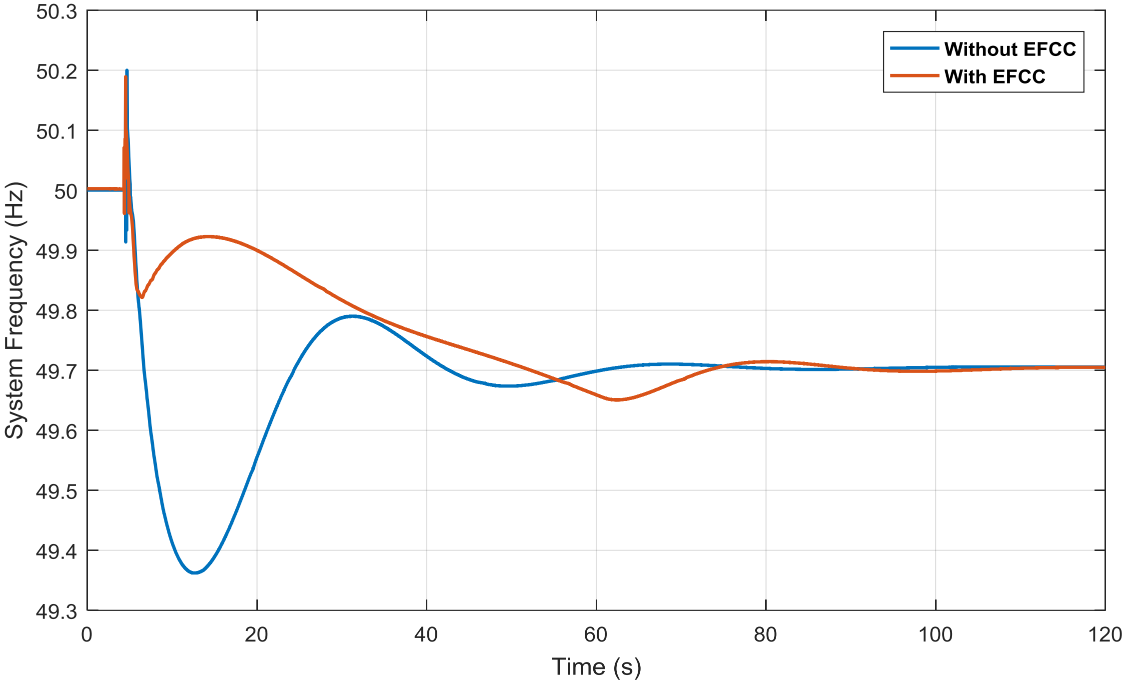
nationalgrid

- **Event: Generator tripping after a fault**
- **Size: 1000 MW with 140ms 1phG fault**
- **Location: Bus 5**
- **Resource availability: 1500MW**



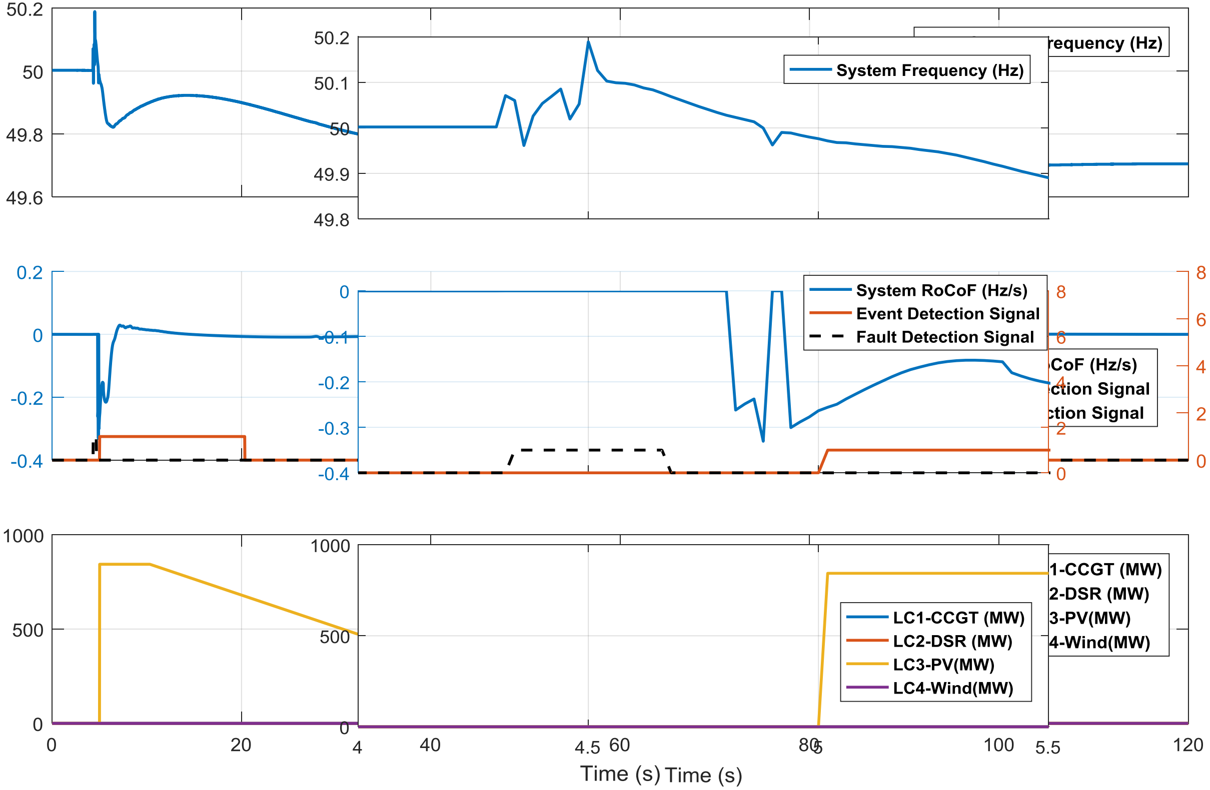
Service Provider	Available Power (MW)
DSR	200
PV	1300
CCGT	200
Wind	300

Case 5: 1 GW Generator Tripping Following a Short Circuit Fault



- The generator tripping is successfully detected after the fault.
- The lowest frequency was moved from 49.36 Hz to 49.65 Hz

Case 5: 1 GW Generator Tripping Following a Short Circuit Fault



- Fault event is detected, blocking by this the event detection is extended with a fault period to ensure the system is settled down.
- The generator tripping is successfully detected after the fault. The response is 800 MW and not affected by the distorted information during the fault.

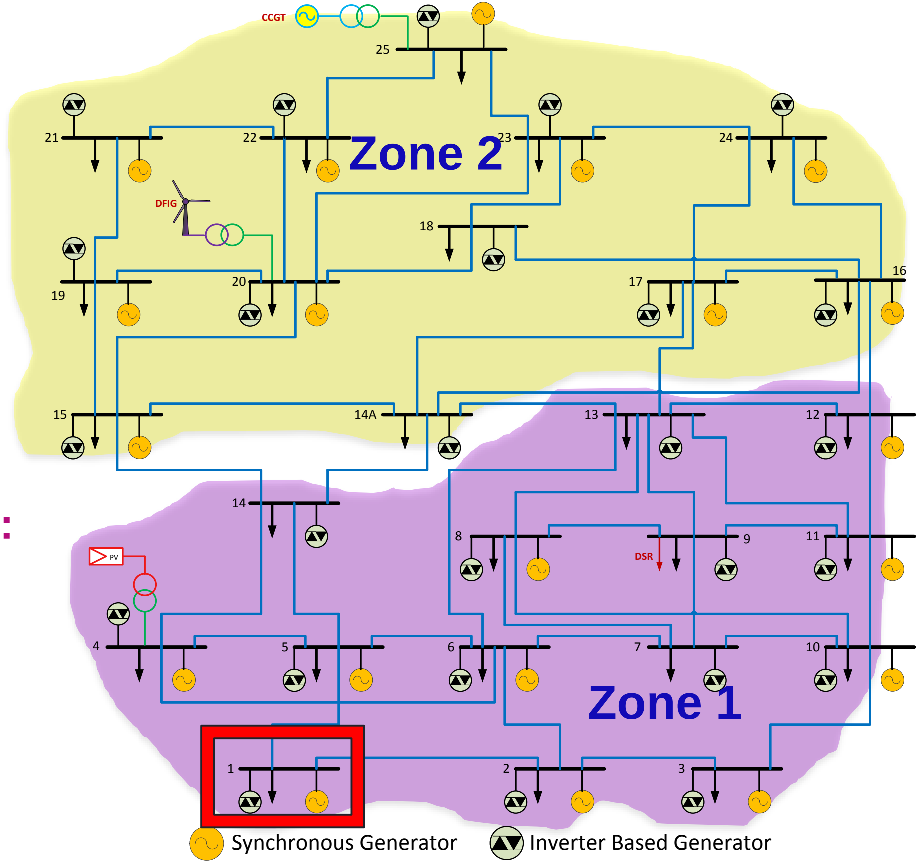
Case 5: Live Demonstration

Sensitivity Analysis

Case 6: Impact of amount of service provider response

nationalgrid

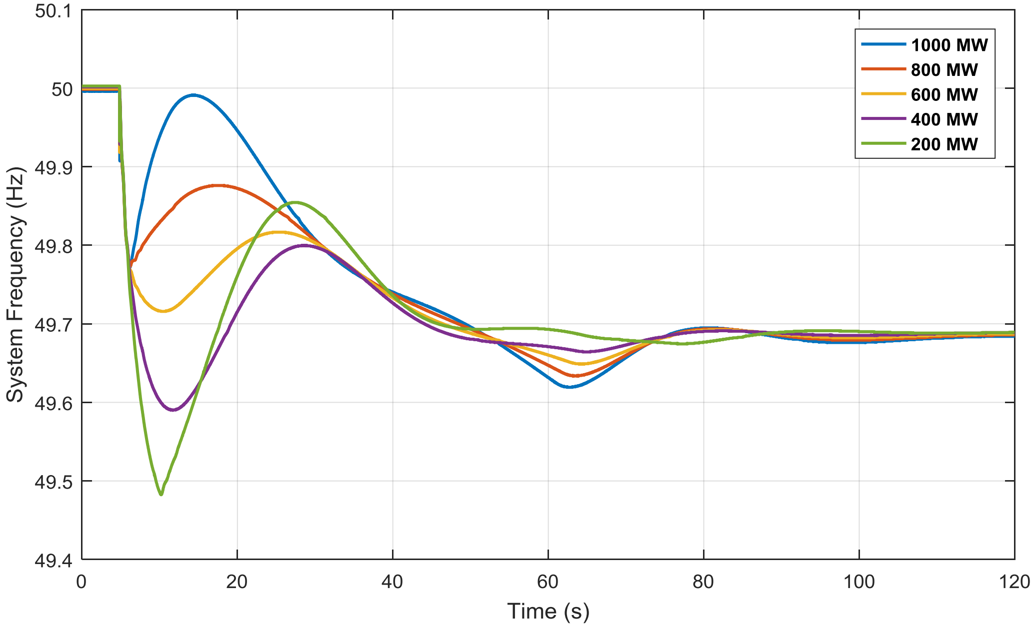
- **Demand: 42GW**
- **Inertia: 82 GVA.s**
- **Event: Sudden load connection**
- **Size: 1000 MW**
- **Resource availability: Only in Zone 1**



Service Provider	Available Power (MW)
Case 1	1000
Case 2	800
Case 3	600
Case 4	400
Case 5	200

Case 6: Impact of amount of service provider response

nationalgrid

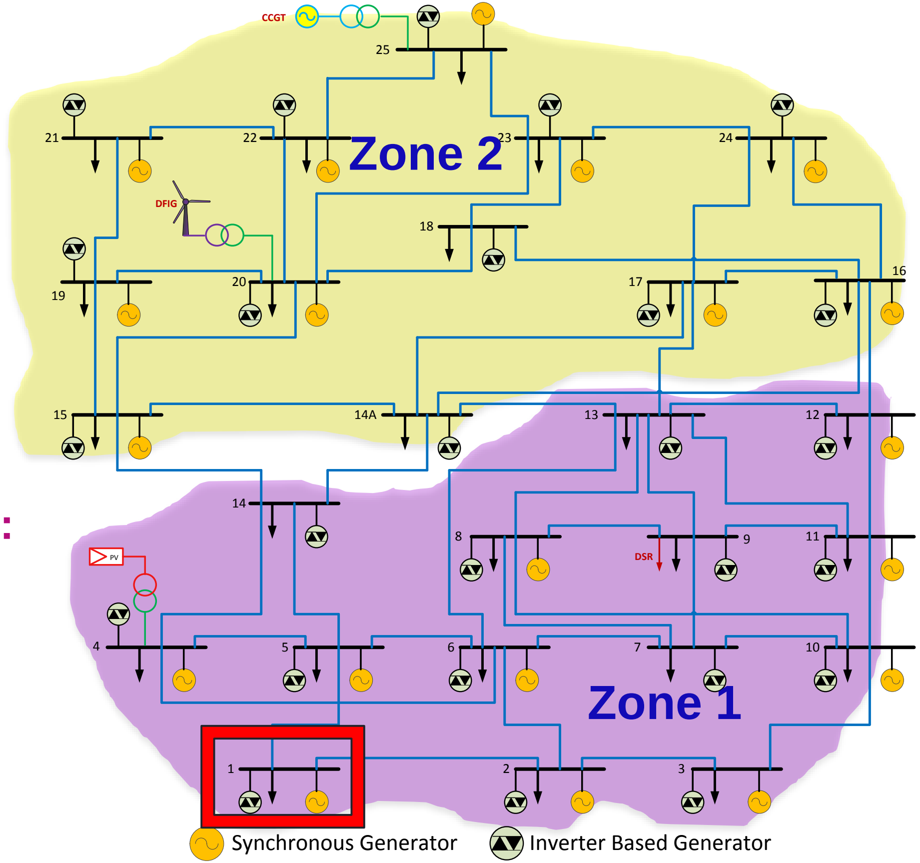


Only when availability is extremely limited to 200 MW, 49.5 Hz limit is violated

Too much response is not always good, causing greater sustained oscillation

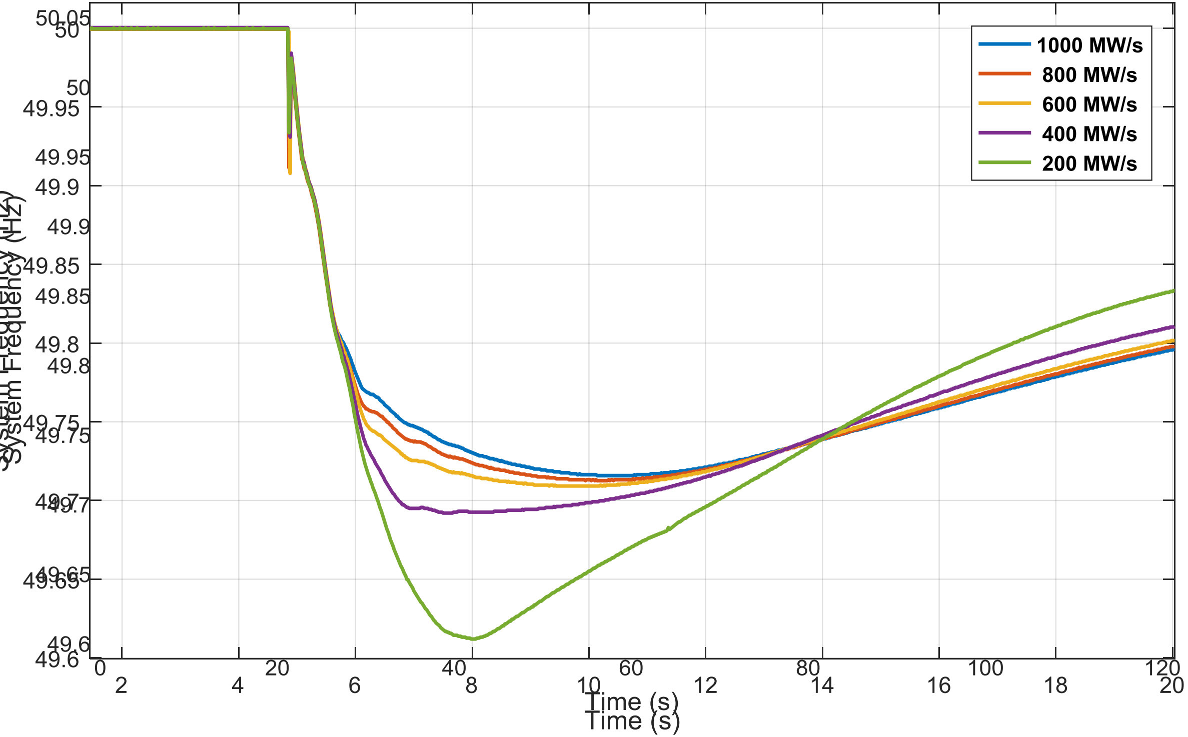
Case 7: Impact of ramping rates of service provider

- **Demand: 42GW**
- **Inertia: 82 GVA.s**
- **Event: Sudden load connection**
- **Size: 1000 MW**
- **Resource availability: 600 MW in Zone 1**



Service Provider	Ramping Rate (MW/s)
Case 1	1000
Case 2	800
Case 3	600
Case 4	400
Case 5	200

Case 7: Impact of ramping rates of service provider



The frequency nadir drops close to 49.6 Hz with minimum 200 MW/s ramping rate.

Higher overshot is observed for 200 MW/s case because of the superposition of delayed response and traditional governor response.

GE-MCS Testing Summary

GE-MCS Testing Summary

- An RTDS representation model of the future GB system minimum demand conditions in 2020 and 2025 is constructed, allowing us to test the performance of the GE-MCS in real time in response to system disturbances tested across the GB network.
- This testing is based on Hardware in the loop principles and includes full dynamic modelling of generation, demand and the resources being deployed under the GE-MCS.
- Frequency event caused by the system load increment/decrement in the low system inertia conditions can be successfully detected.

GE-MCS Testing Summary

- Event detection and resource allocation modules respond within the designed time
- Wide-area based RoCoF calculation and loss of generation estimation are accurate.
- Fault event can be successfully detected and event detection module is intentionally blocked for a defined period of time
- With fast coordinated response of the scheme, a moderate amount of fast service response can effectively counteract the frequency contingencies
- The scheme is efficient in scenarios with the reduced system inertia

Break – Back at 2:15pm

University of Strathclyde

Validation of the EFCC scheme at the Power Networks Demonstration Centre (PNDC)

Dr Qiteng Hong, Dr Ibrahim Abdulhadi and Prof Campbell Booth

EFCC Academic Dissemination Event

Glasgow, 19/06/2018

Overview

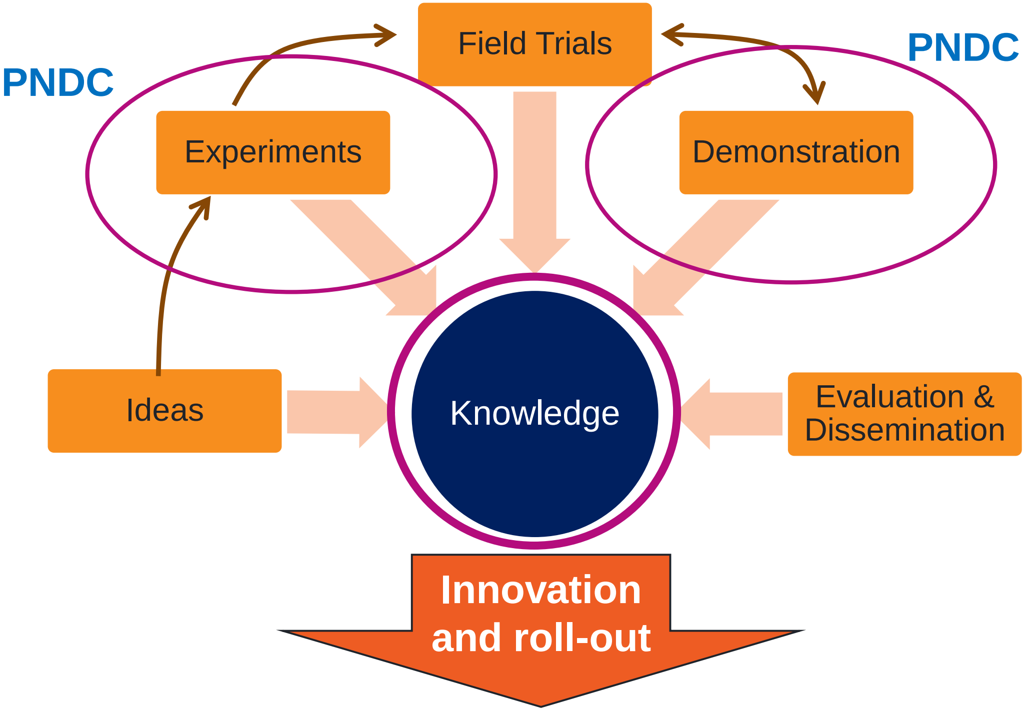
- Brief introduction to PNDC
- Role of PNDC in the testing of the EFCC scheme
- Testing configurations and test results
  - Power-Hardware-in-the-Loop (P-HiL) testbed
  - Wide area mode tests
  - Communication impact tests
  - Local mode tests
- Demo of the EFCC scheme – focusing on communications impacts
- Key learnings and findings
- Conclusions and future work



129

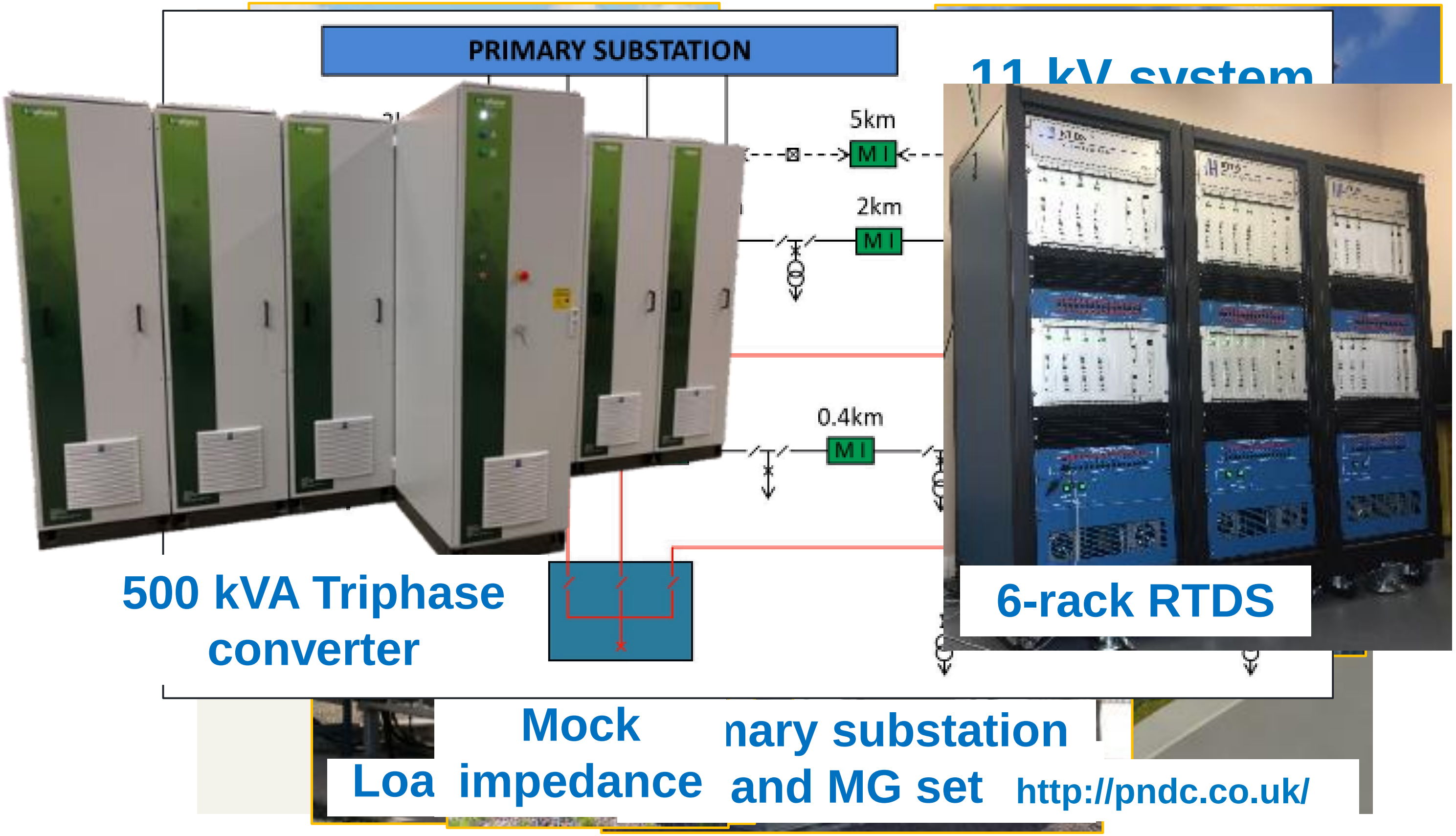
PNDC – what we do?

Provide a realistic and flexible platform for the accelerated testing of smart grid innovations



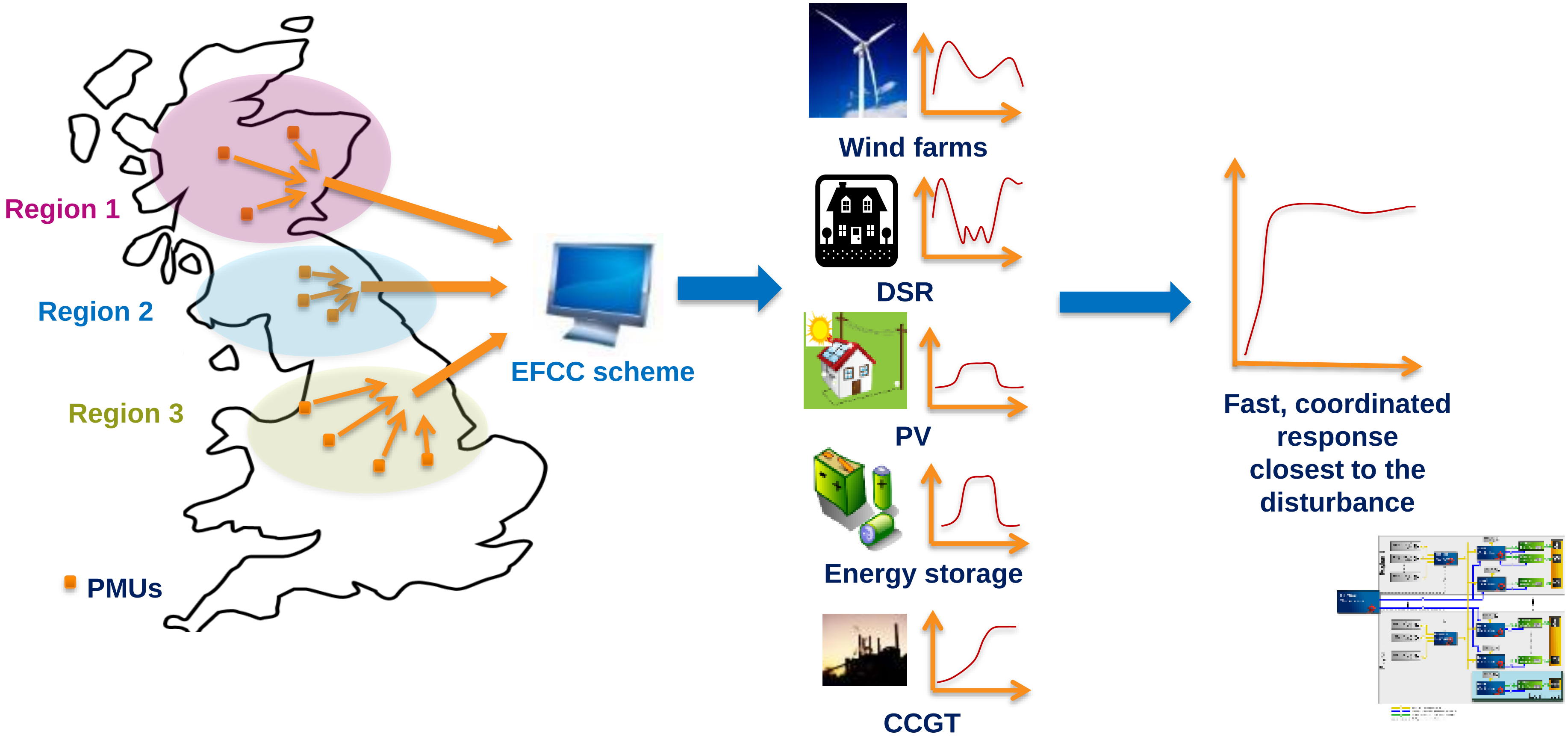
nationalgrid

Main facilities at PNDC



nationalgrid

Overview of the EFCC scheme

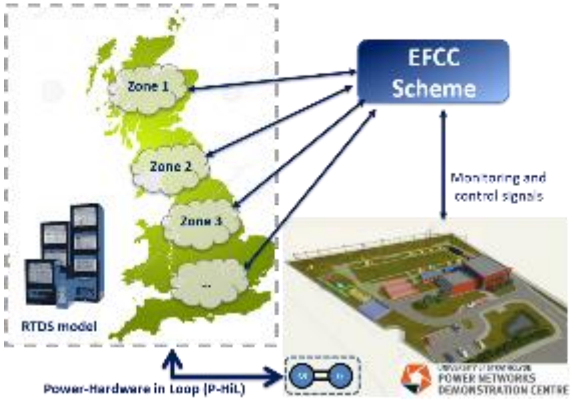


Role of PNDC in the EFCC project

Tests at the University of Manchester:
EFCC controllers connected to pure simulated signal sources

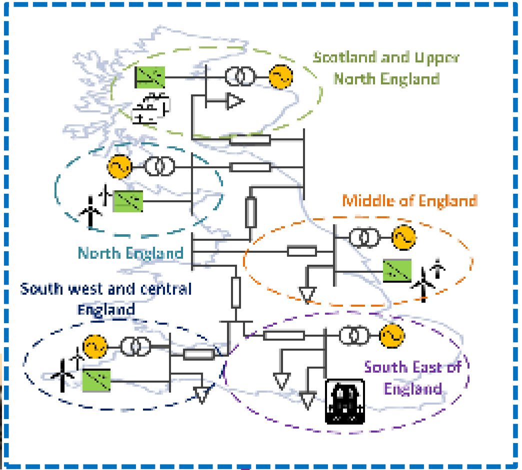
Tests at the University of Strathclyde (PNDC):

- Controllers interfaced with physical network and an actual PMU unit
- Both wide-area and local back-up modes are tested
- Performance of the EFCC scheme evaluated under different communication quality conditions



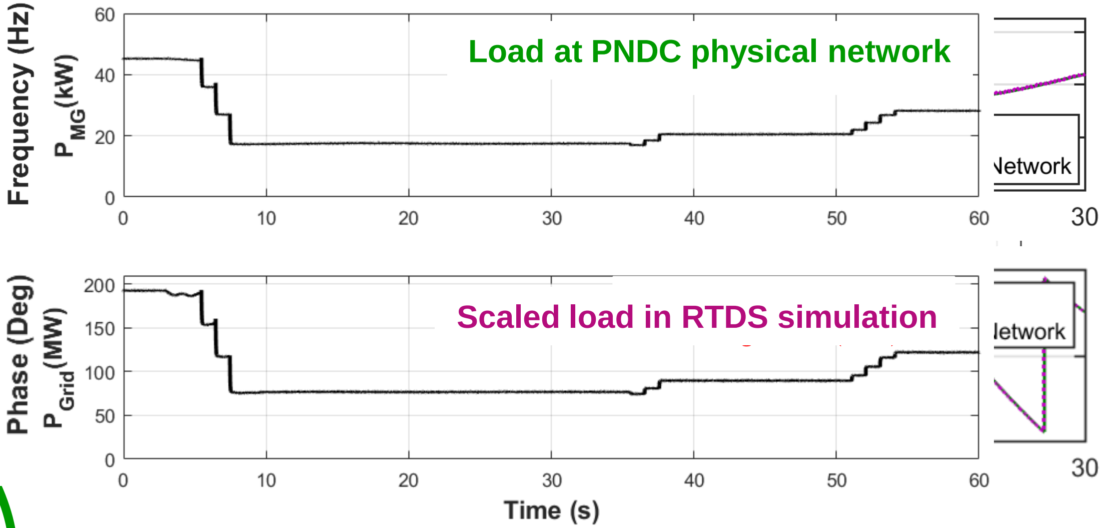
Power-Hardware-in-the-Loop testbed

Reduced GB transmission network in RTDS



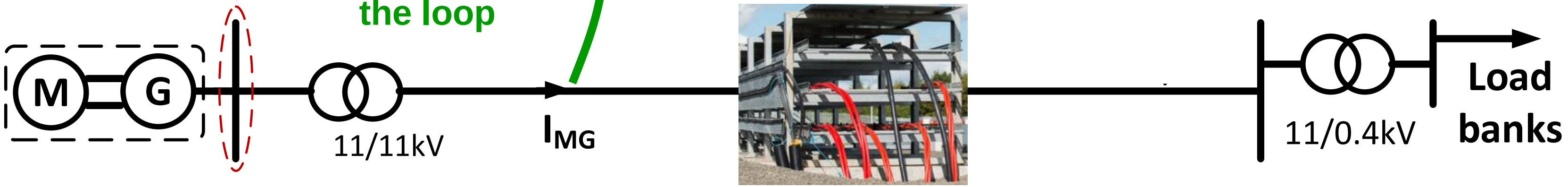
Validation of the RTDS model

PHIL testbed validation

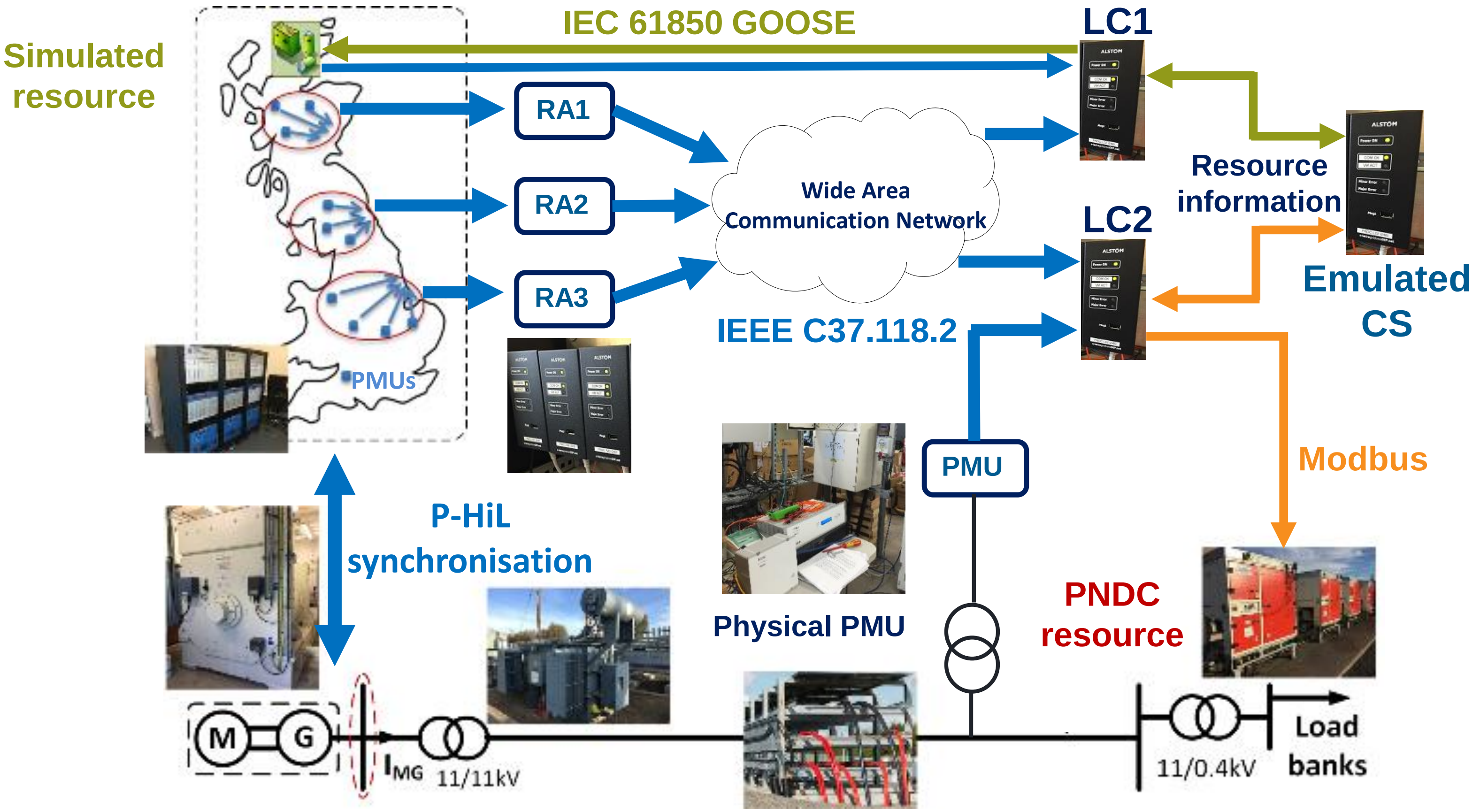


Control MG set to sync with the model

Feedback scaled current to close the loop



Application of the P-HiL testbed for EFCC wide-area mode tests

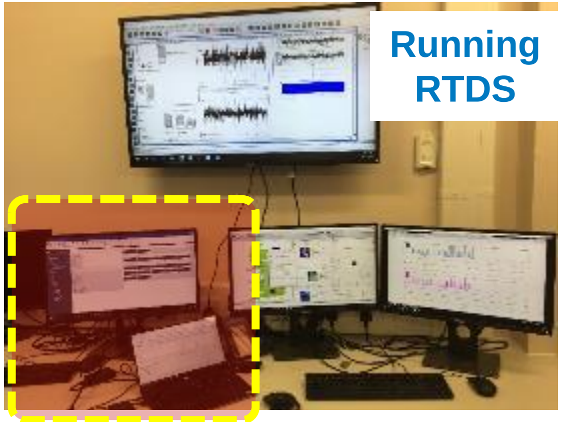


PNDC setup

EFCC controllers

PMU

Injection using amplifier

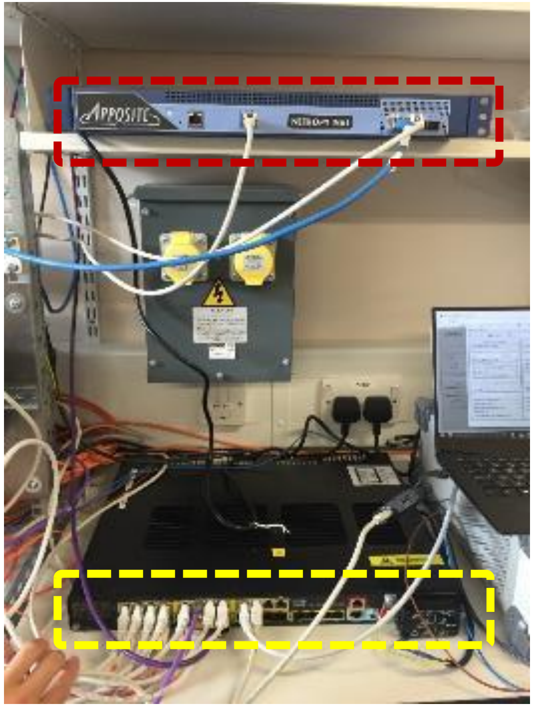


Running RTDS

Configuration using IEC 61850

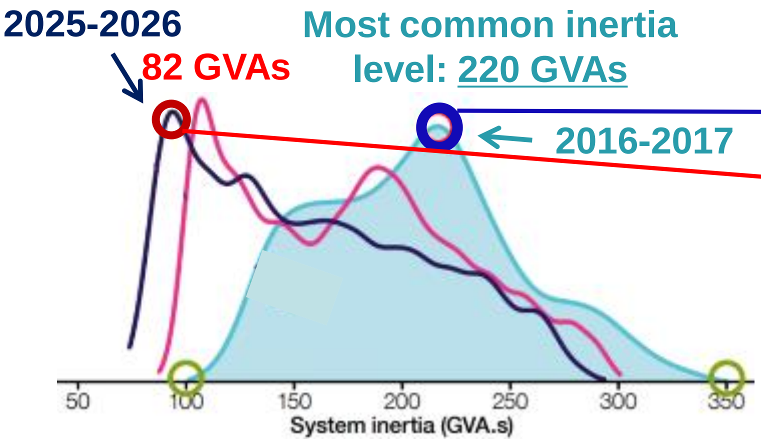
Straton and PhasorPoint

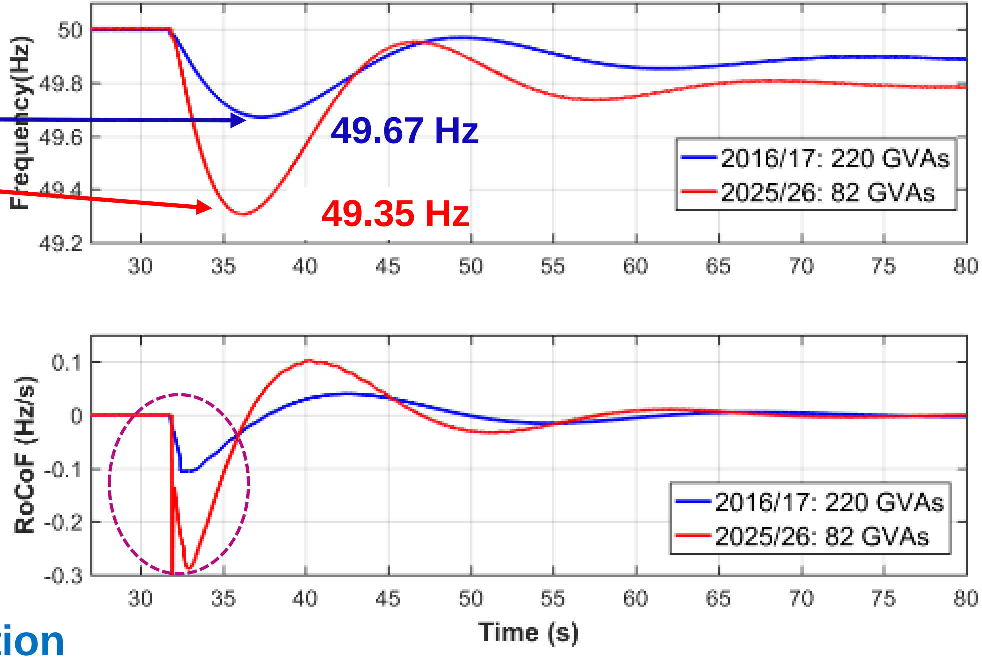
Communication emulator



Communication switch

Wide area mode test cases:



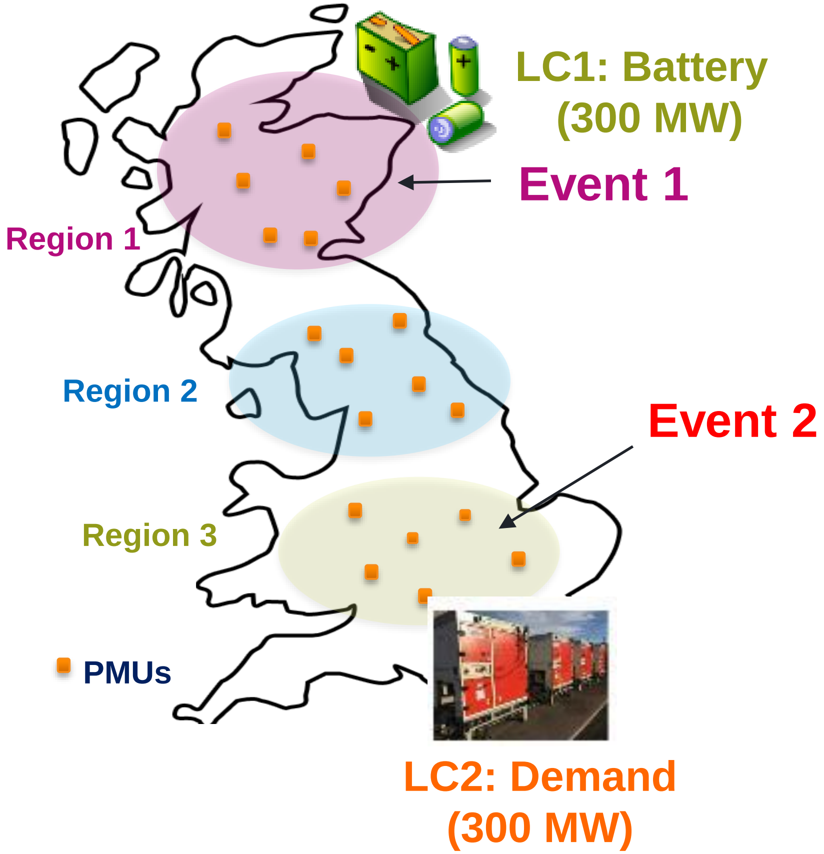


Case studies:

- Case study 1: impact of event location
- Case study 2: impact of resources' locations
- For each case, the impact of resource availability is also investigated

nationalgrid

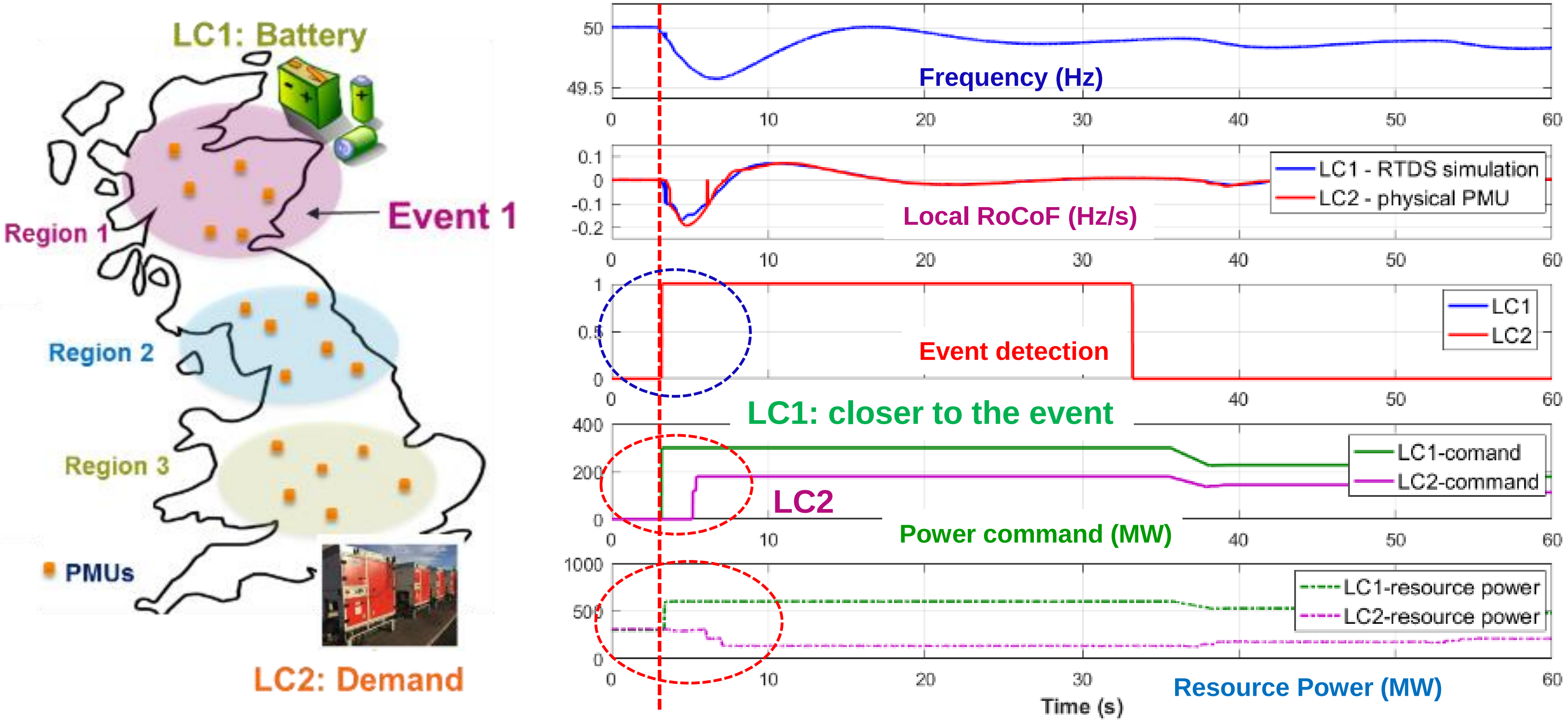
Case study 1: impact of event location



- Inertia level: 82 GVAs
- Event: loss of generation
- Size: 1000 MW
- Testing effectiveness of fast frequency response from EFCC
- Evaluating EFCC's response to events at different locations

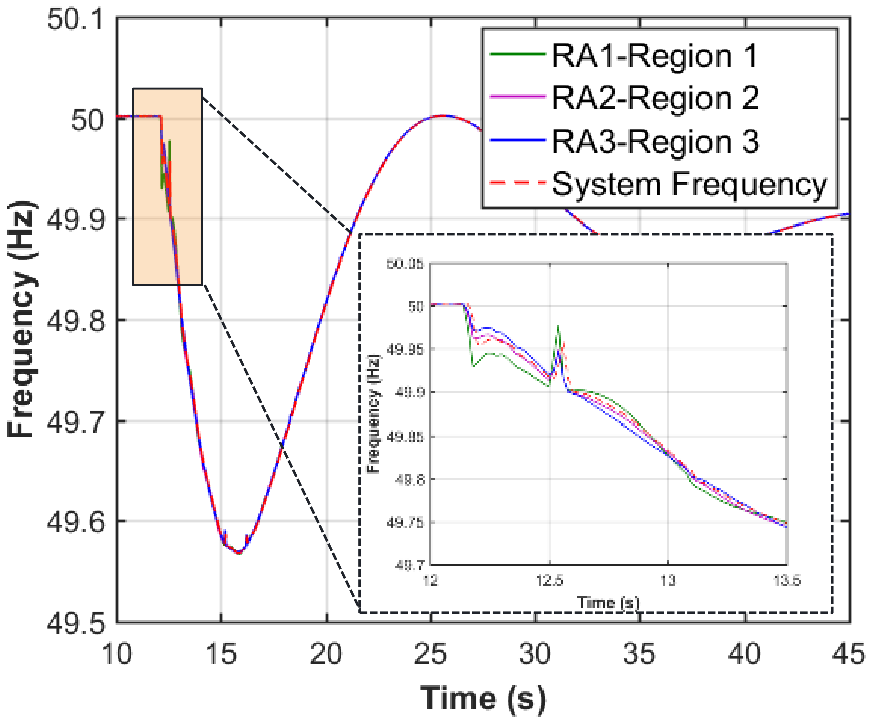
nationalgrid

Event 1: 1 GW loss, Region 1 (LC1 location), 82 GVAs

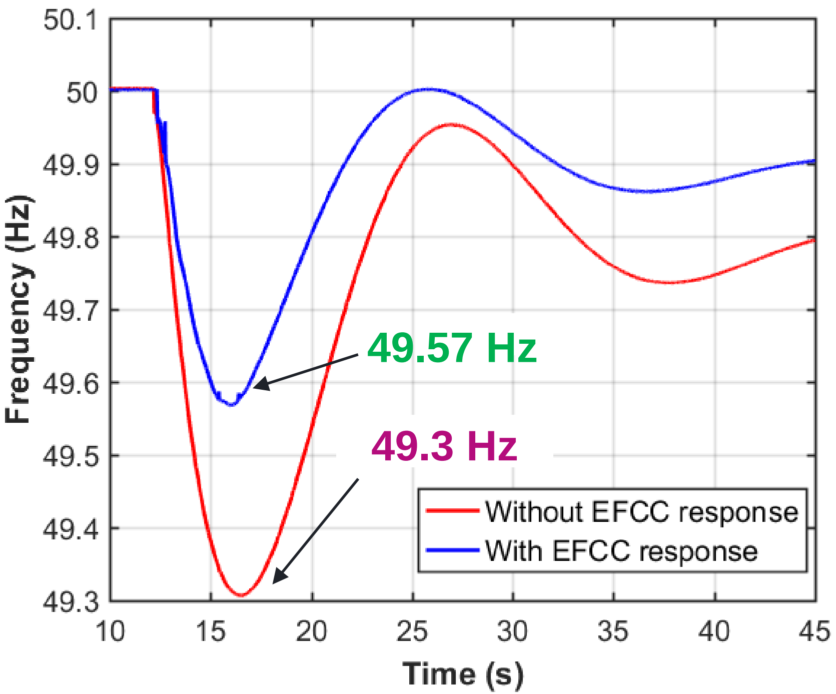


nationalgrid

Event 1: 1 GW loss, Region 1 (LC1 location), 82 GVAs

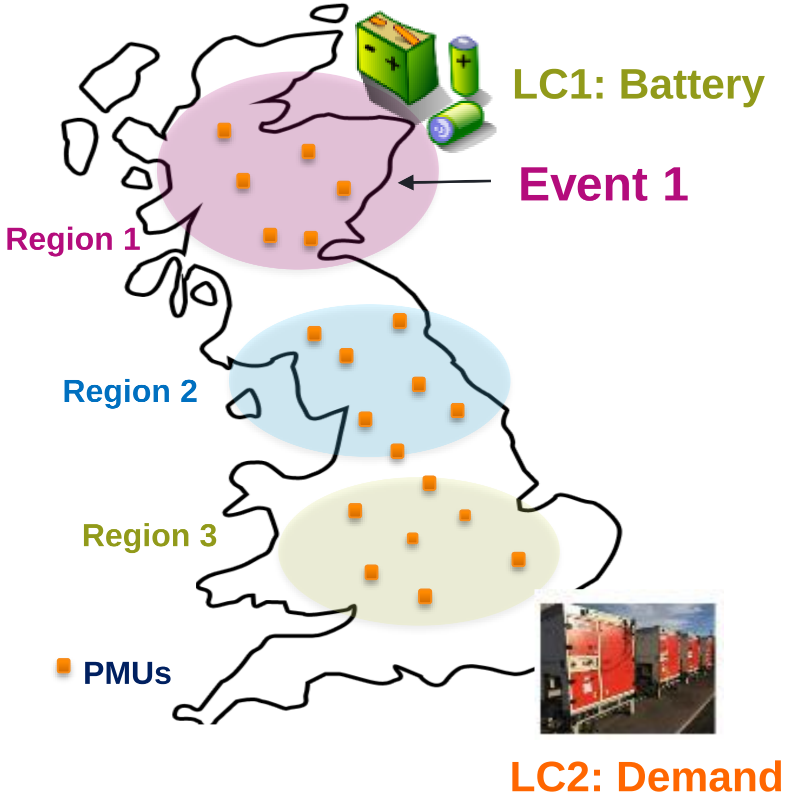


Frequency measured in RAs



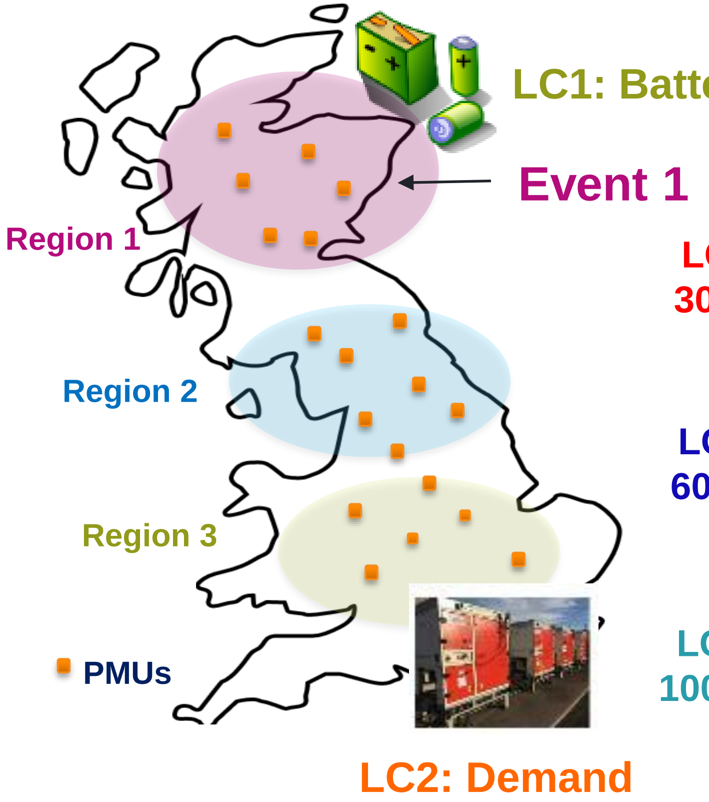
Comparison: with and without EFCC response

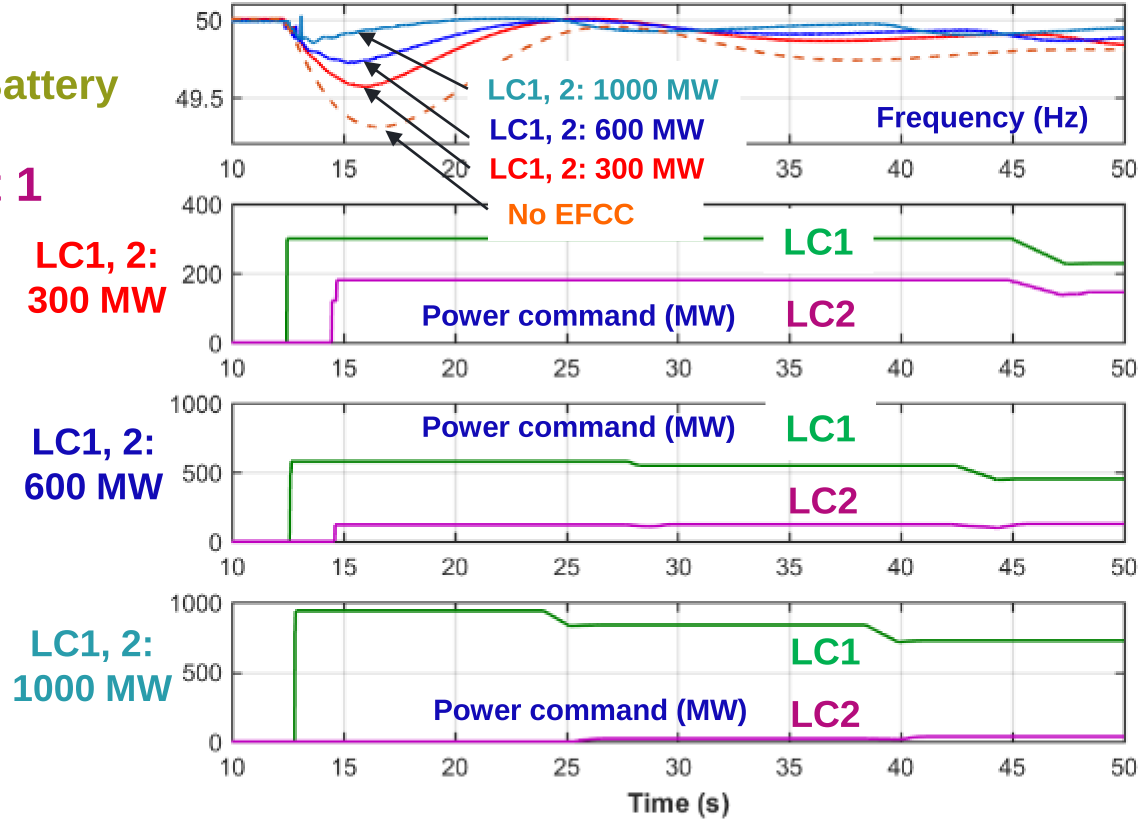
Impact of resource size in event 1



- With the same event
- Increase the reserve power at LC1 and LC2 from **300 MW** to **600 MW**, and then **1000 MW**

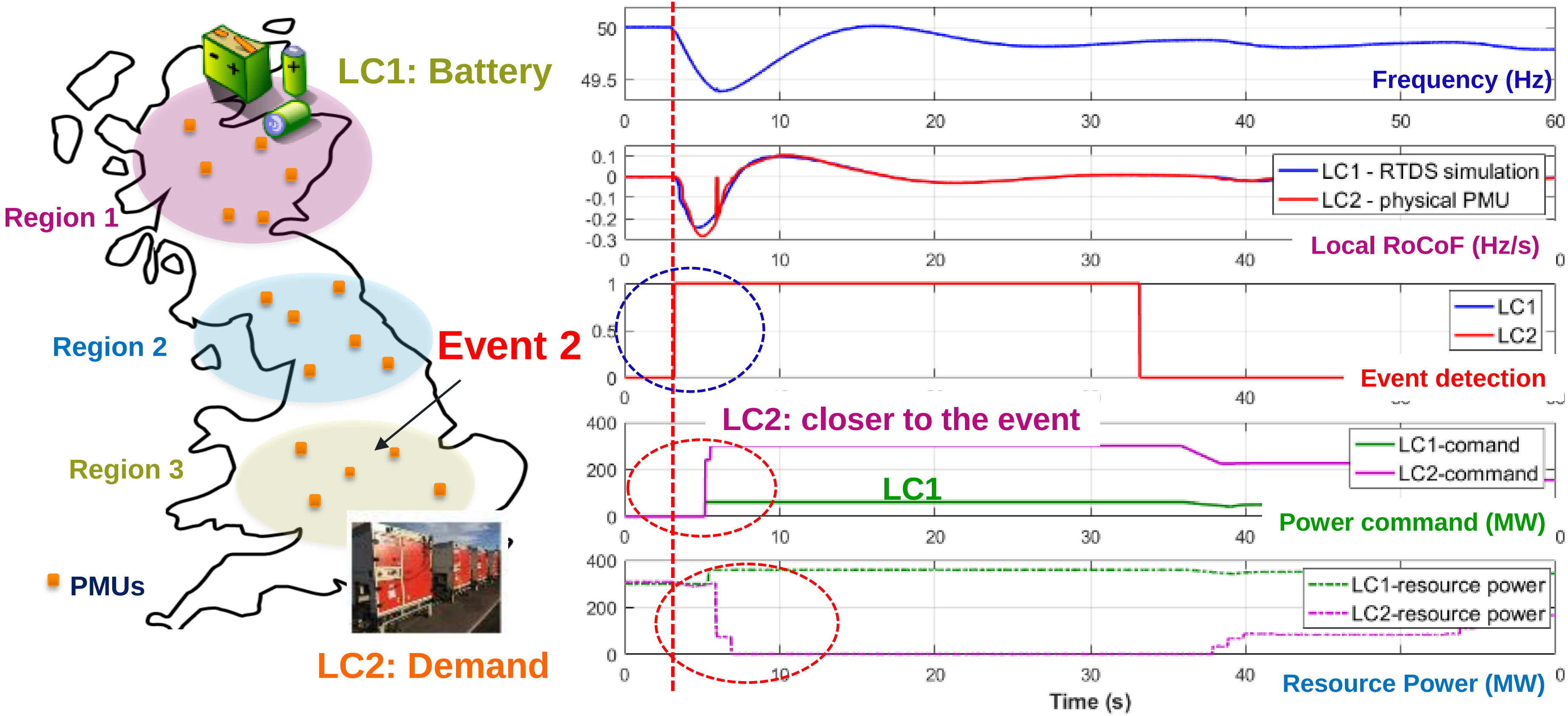
Impact of resource size in event 1



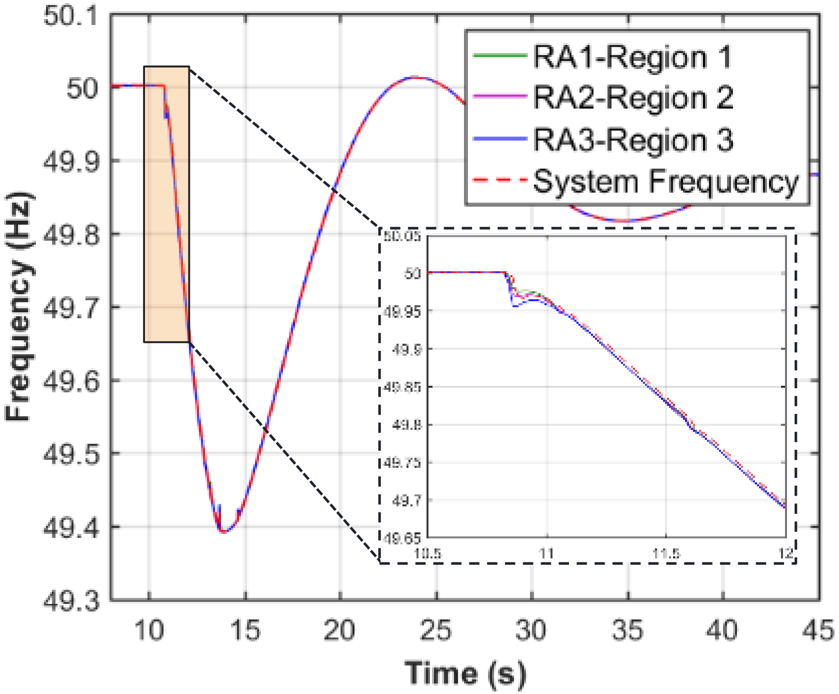


nationalgrid

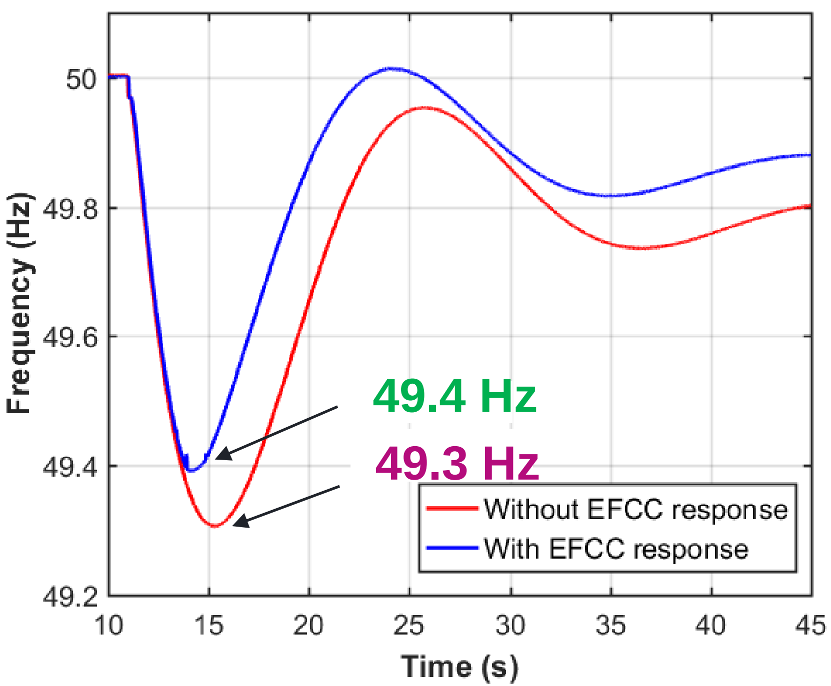
Event 2: 1 GW loss, Region 3 (LC2 location), 82 GVAs



Event 2: 1 GW loss, Region 3 (LC2 location), 82 GVAs



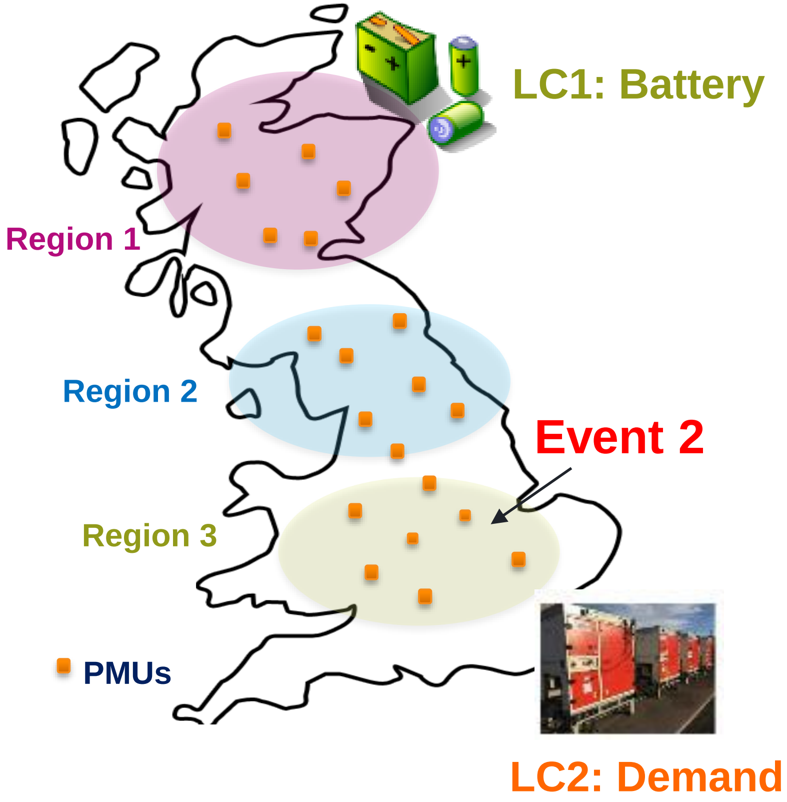
Frequency measured in RAs



Comparison: with and without EFCC response

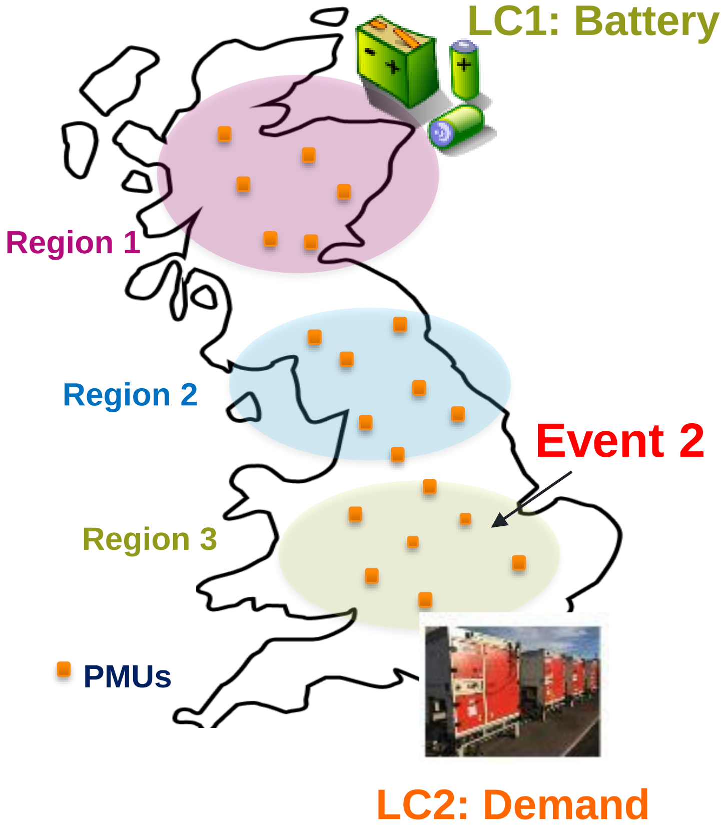
nationalgrid

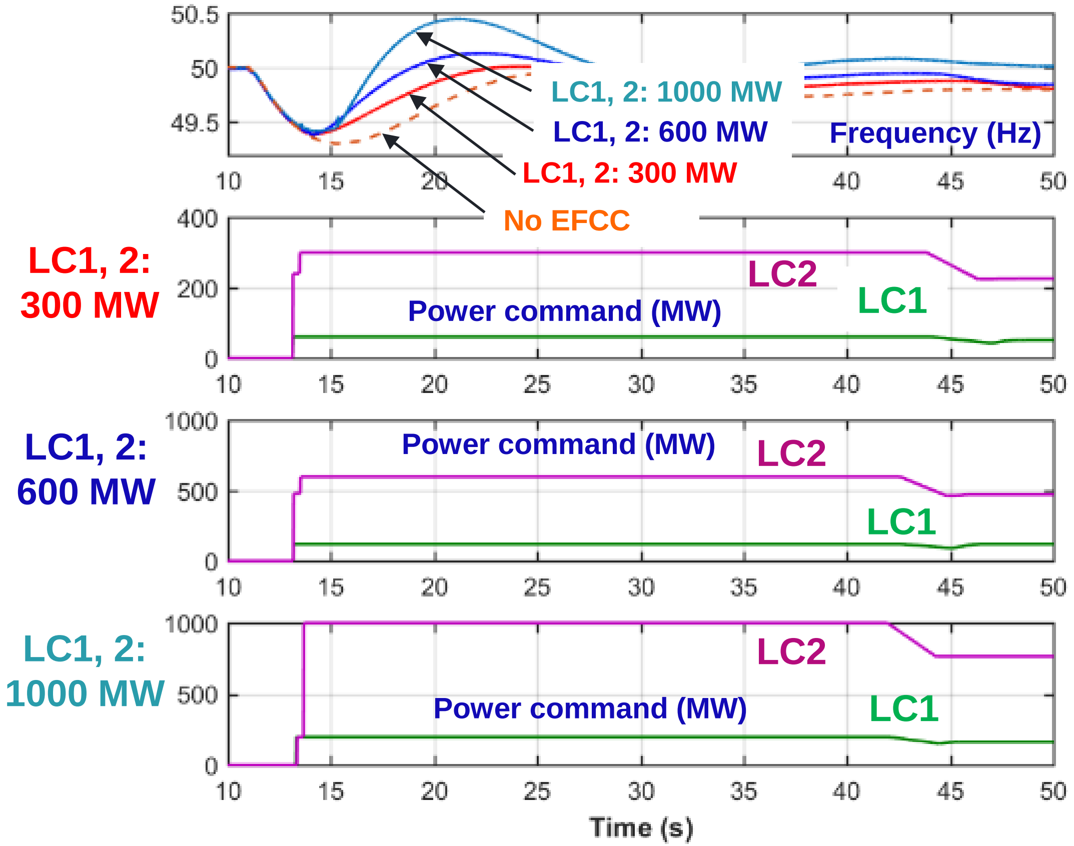
Impact of resource size in event 2



- With the same event
- Increase the reserve power at LC1 and LC2 from **300 MW** to **600 MW**, and then **1000 MW**

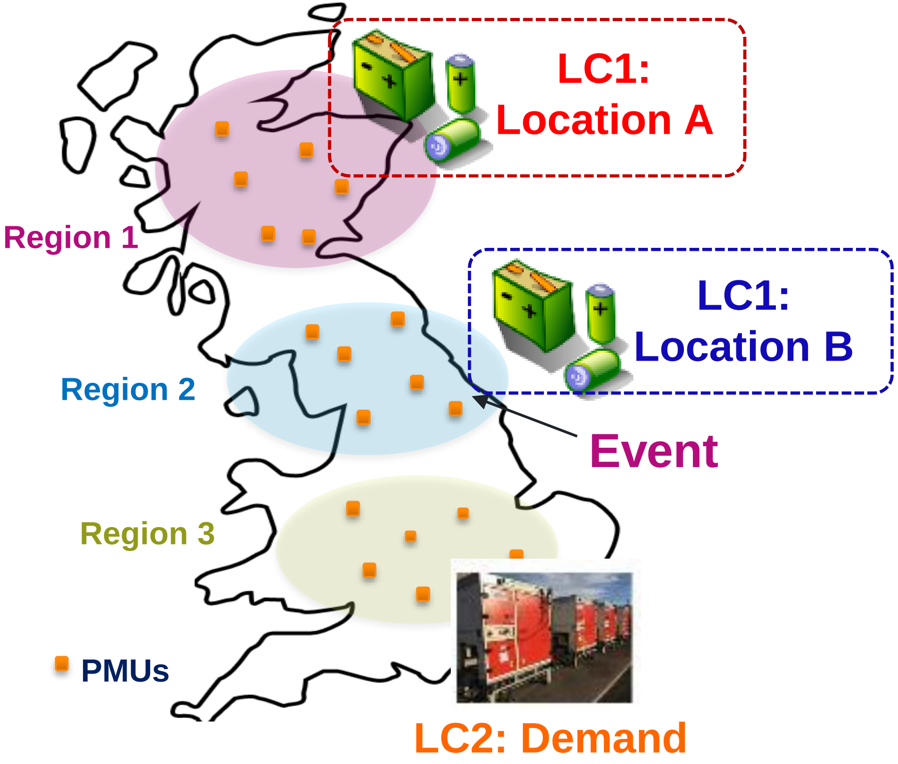
Impact of resource size in event 2





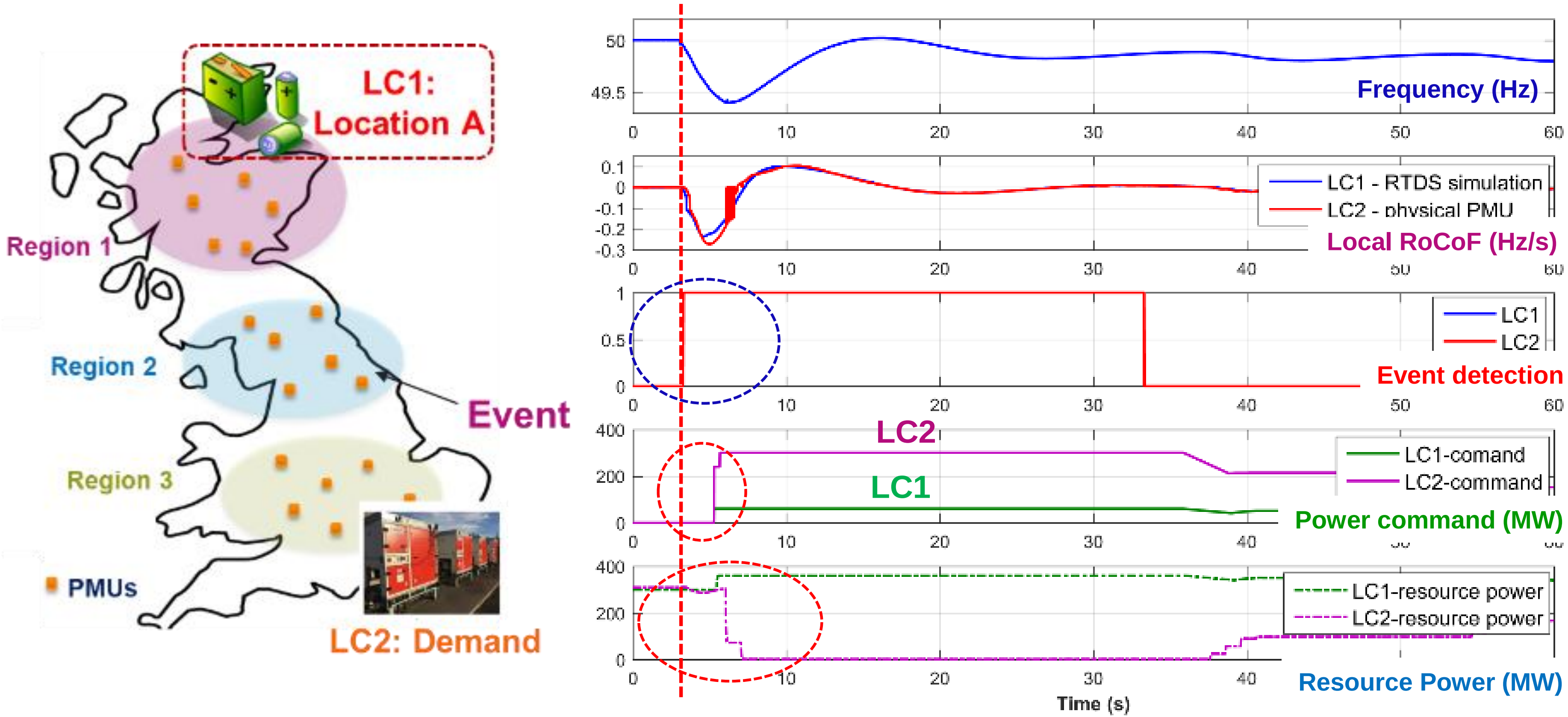
nationalgrid

Case study 2: impact of resource locations

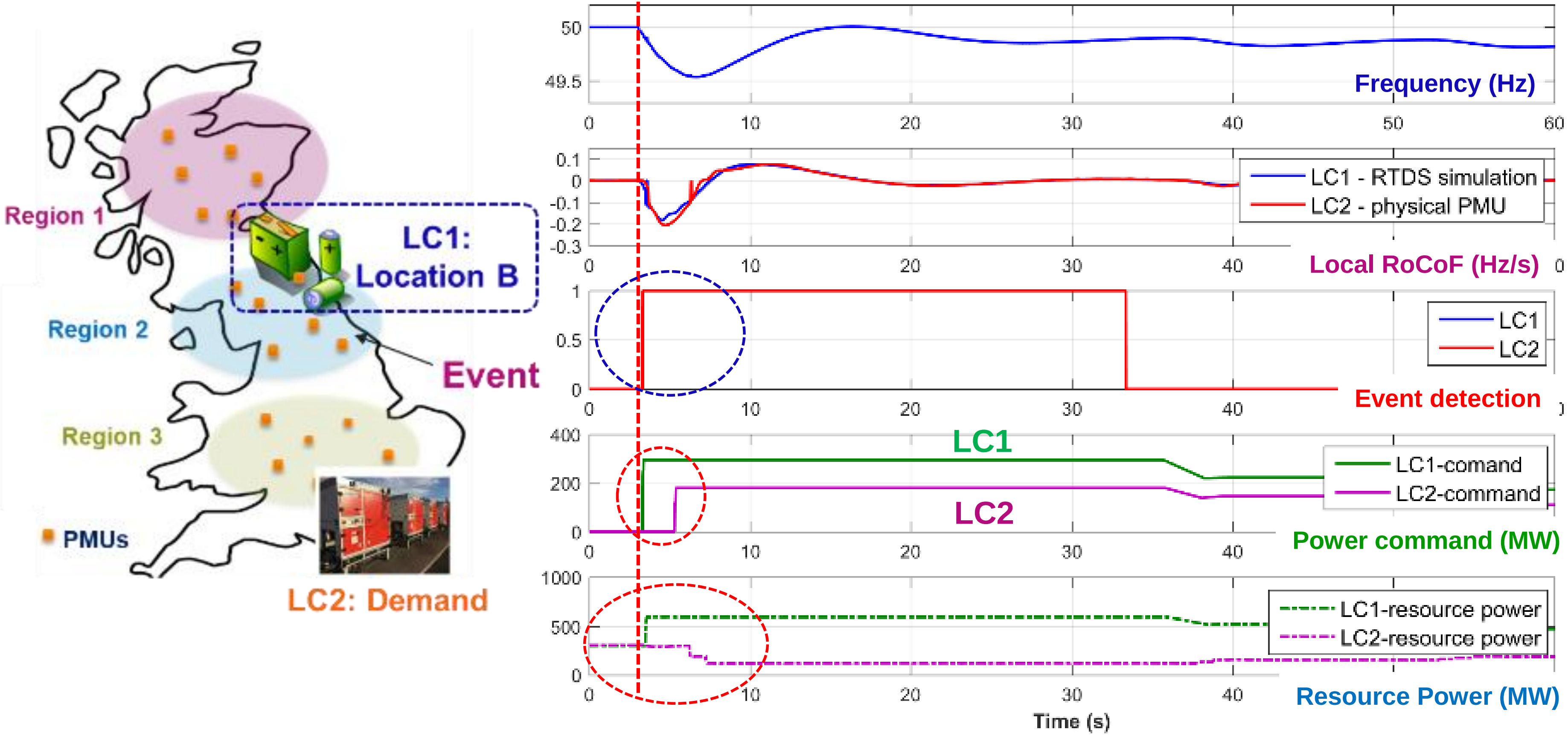


- Inertia level: 82 GVAs
- Event: loss of generation
- Size: 1000 MW
- Testing effectiveness of fast frequency response from EFCC
- Evaluating the impact of EFCC’s resource locations

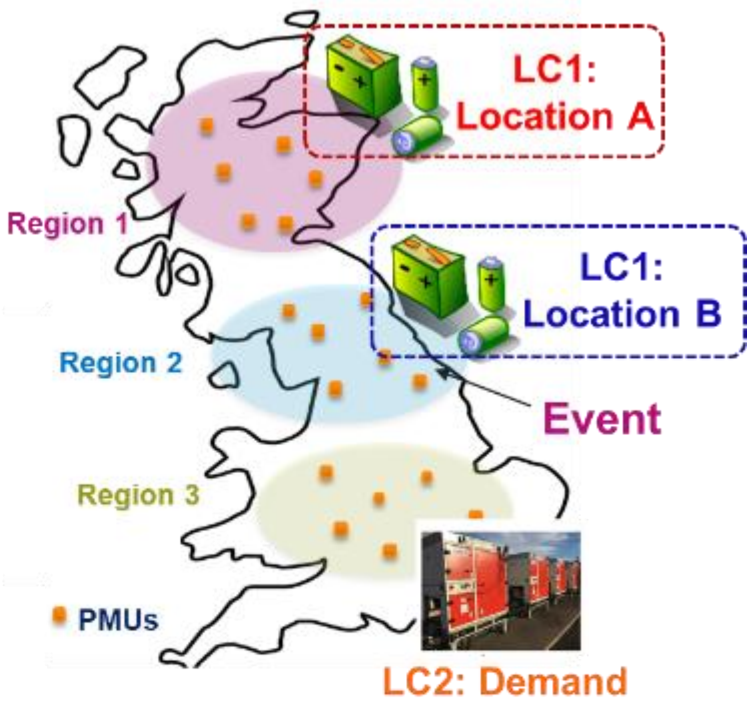
Scenario 1: LC1 at Location A (Region 1), 82 GVAs

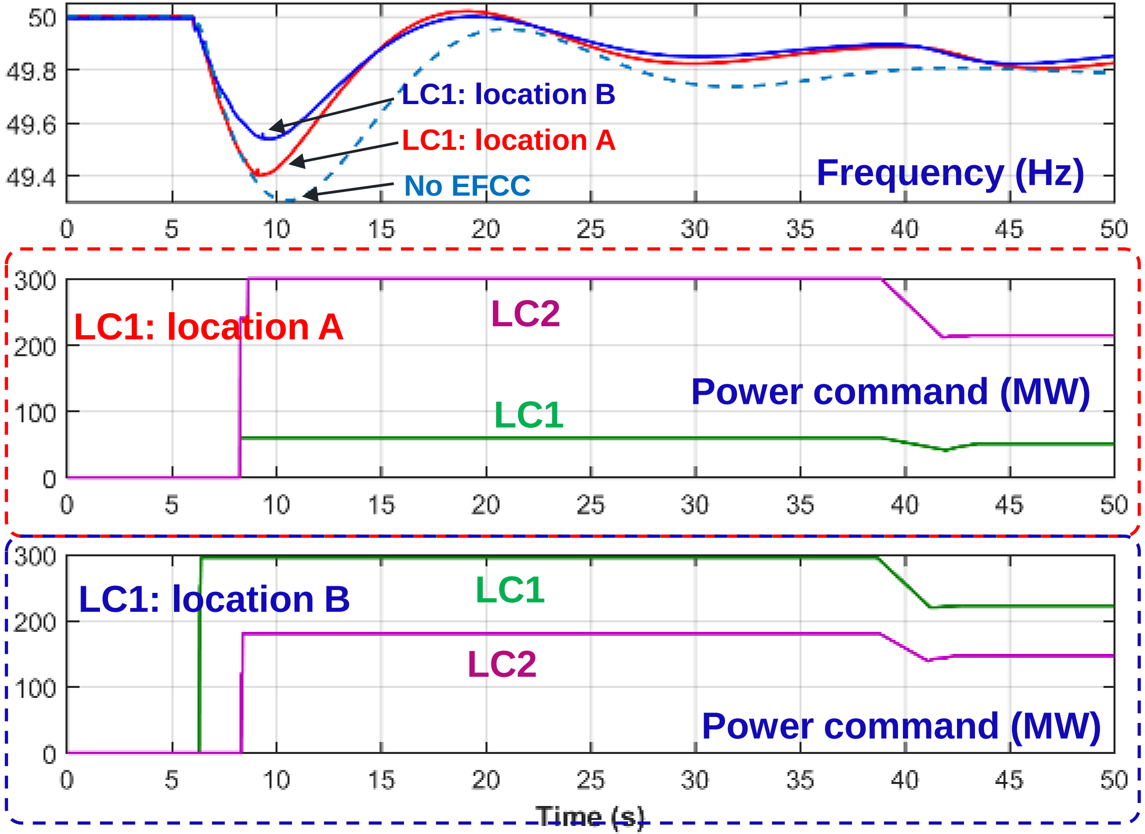


Scenario 2: LC1 at Location B (Region 2), 82 GVAs



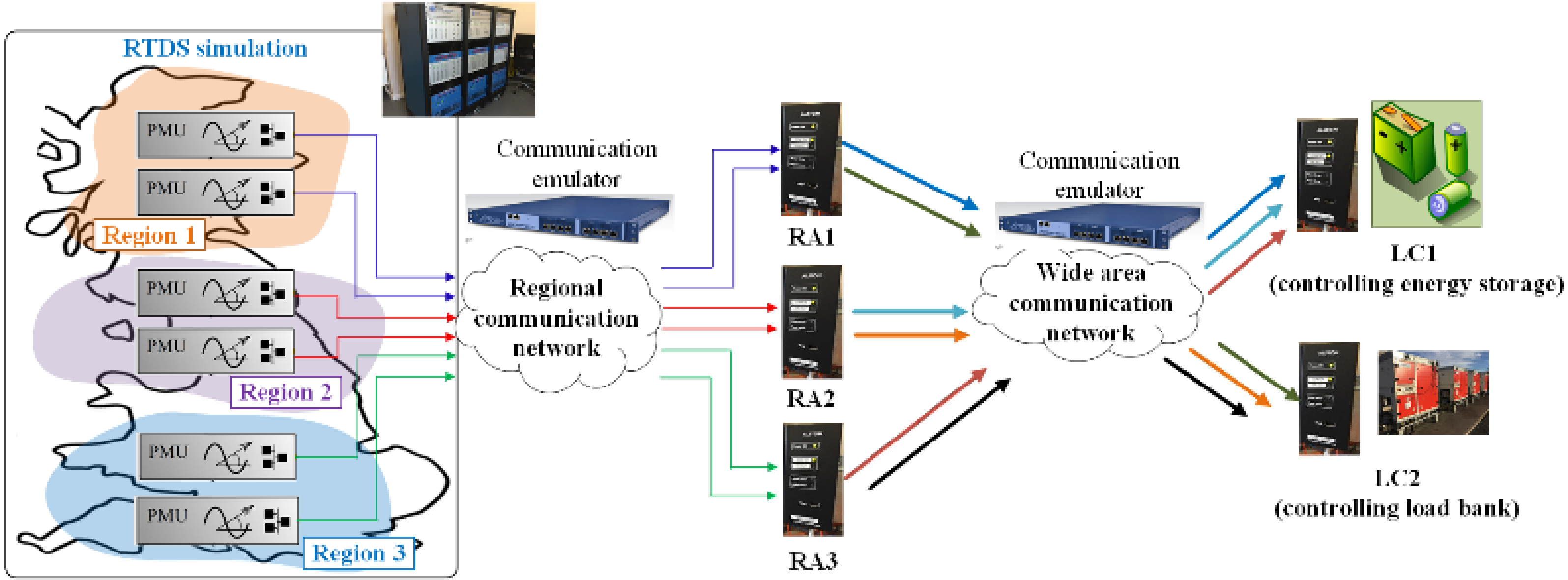
Case Study 2: impact of events at different locations





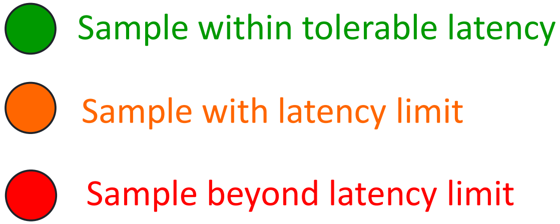
Communication tests

- Aimed at evaluating the impact of communication performance on the operation of the EFCC scheme
- EFCC tested under different levels of latency (delay), jitter (variation in delay), loss of packet, bit error rates, etc.

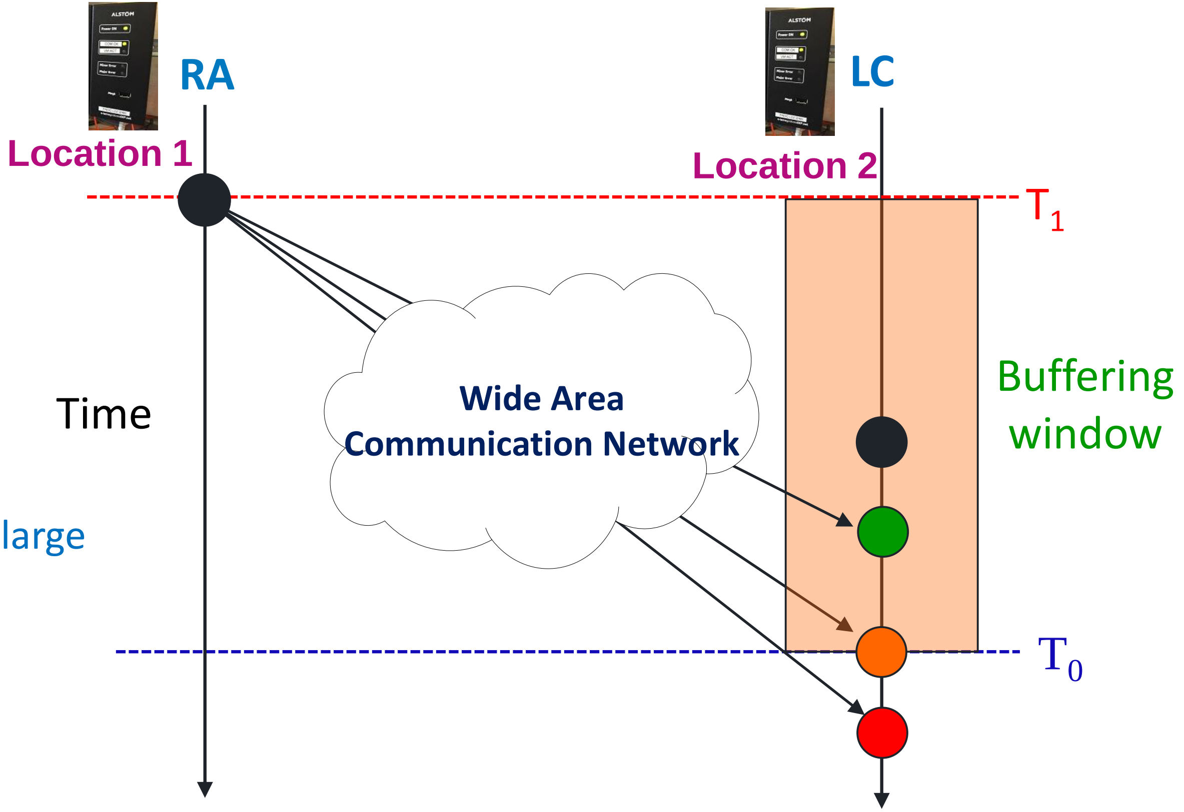


Handling degraded communication condition

- Buffering window is used for handling latency and jitter



- Jitter is the change in latency and large jitters can lead to packets being discarded.

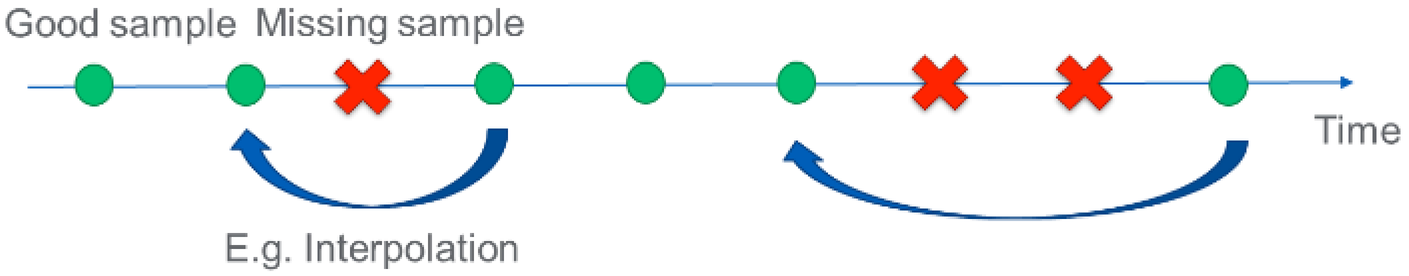


Handling degraded communication condition

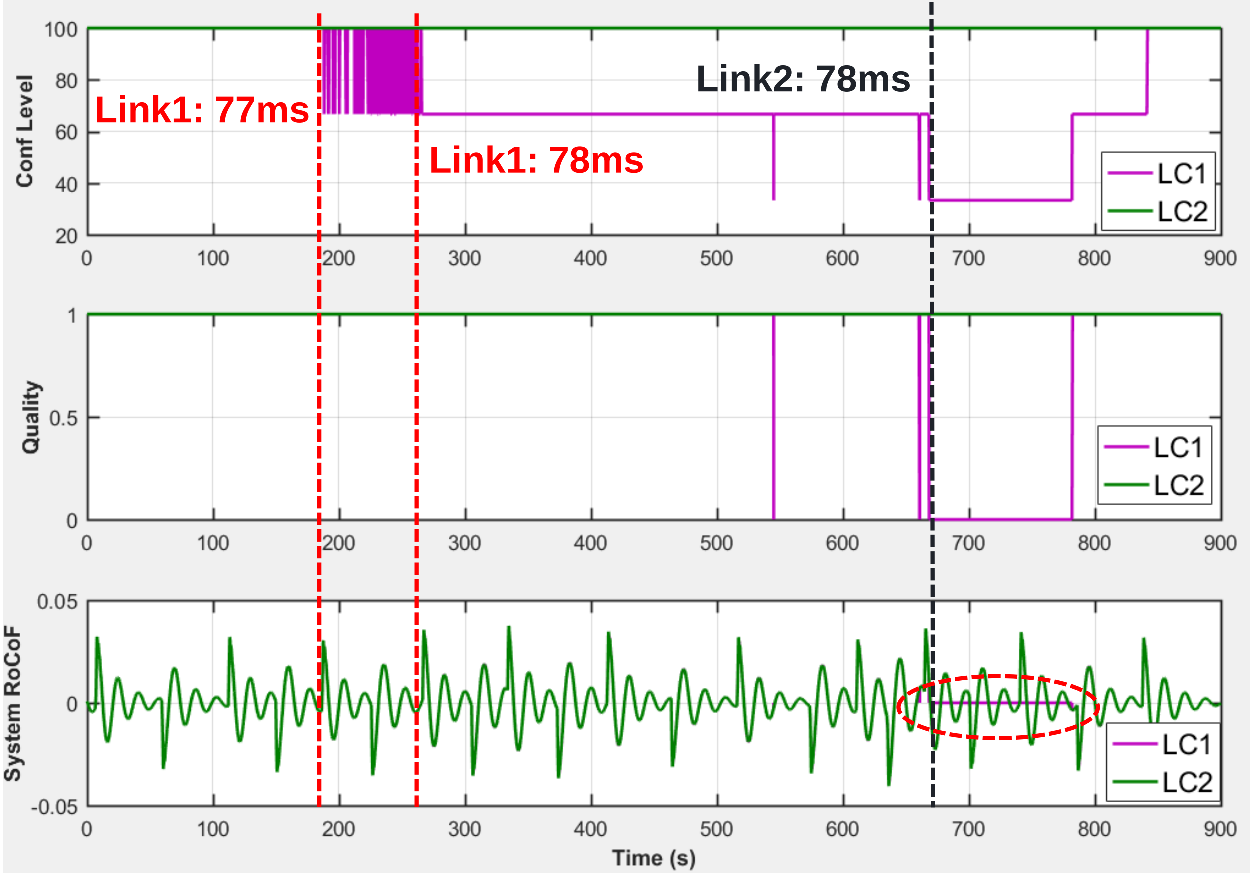
nationalgrid

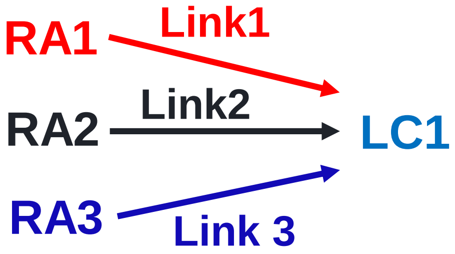
When latency is beyond the tolerable limit or the packets are lost during transmission

- EFCC is communication quality aware
- Techniques such as interpolation have been be applied
- Actual behaviour is application specific
- Graceful Degradation considered in overall design



Impact of communication latency (delay)

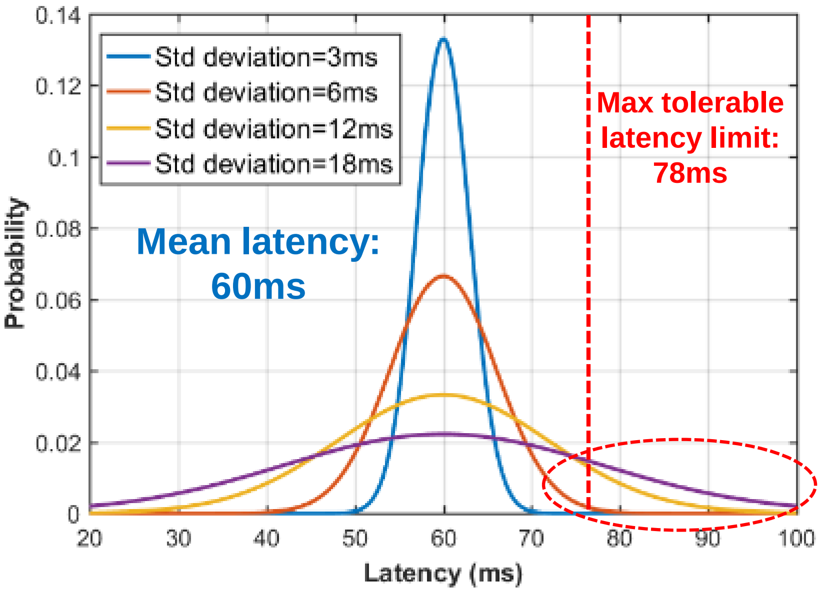




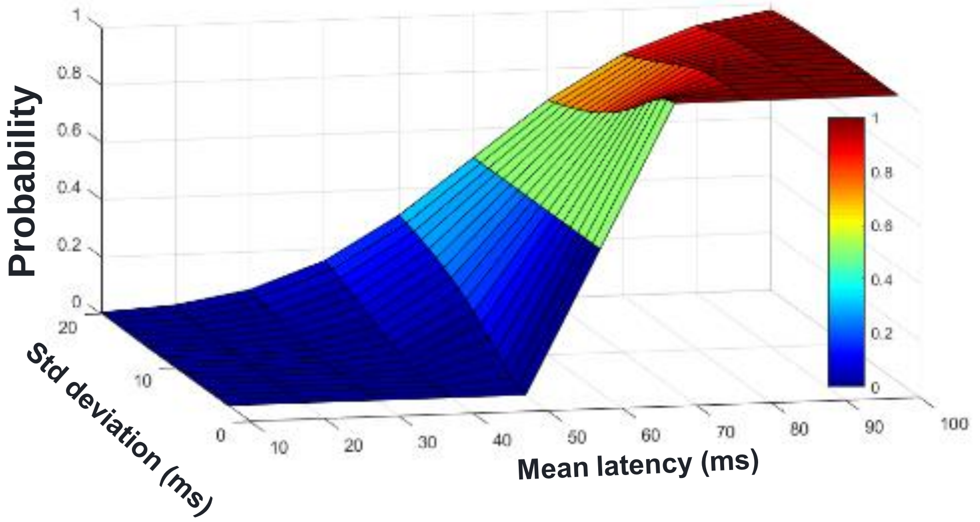
- Maximum tolerable latency 78ms for 100ms buffering window
- Latency larger than the limit will lead to packets being discarded, i.e. risking in loosing wide-area visibility

Impact of communication jitter

- Jitter is the change in communication delay
- Higher jitter levels could lead to higher risks of the violating maximum tolerable latency limit

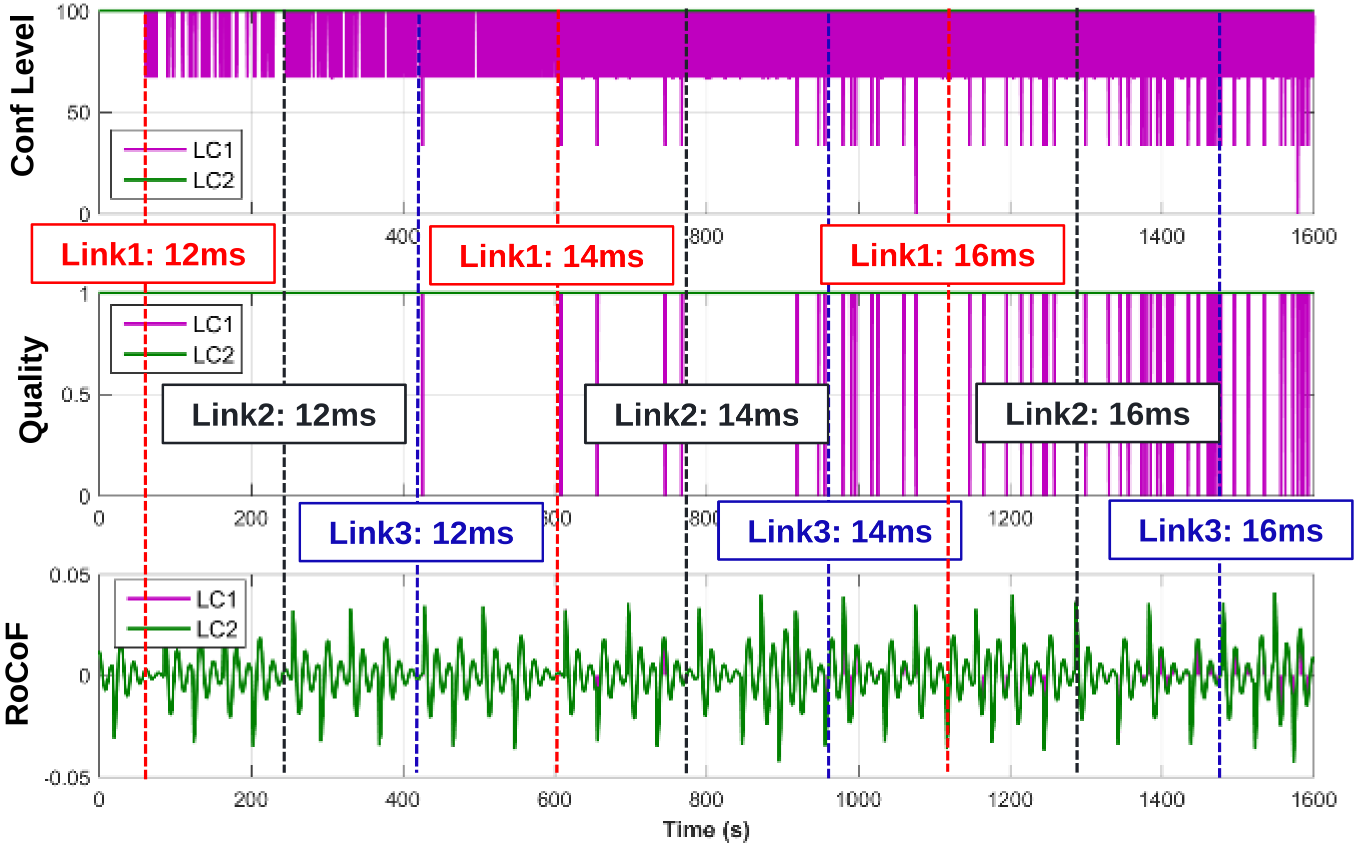


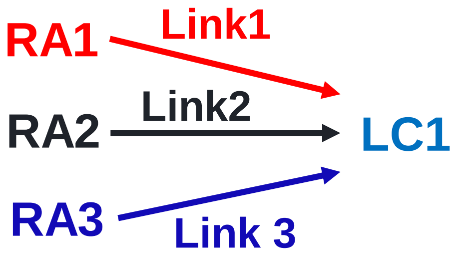
Normal distribution of latency level



Probability of latency larger than the max limit

Latency with jitter tests

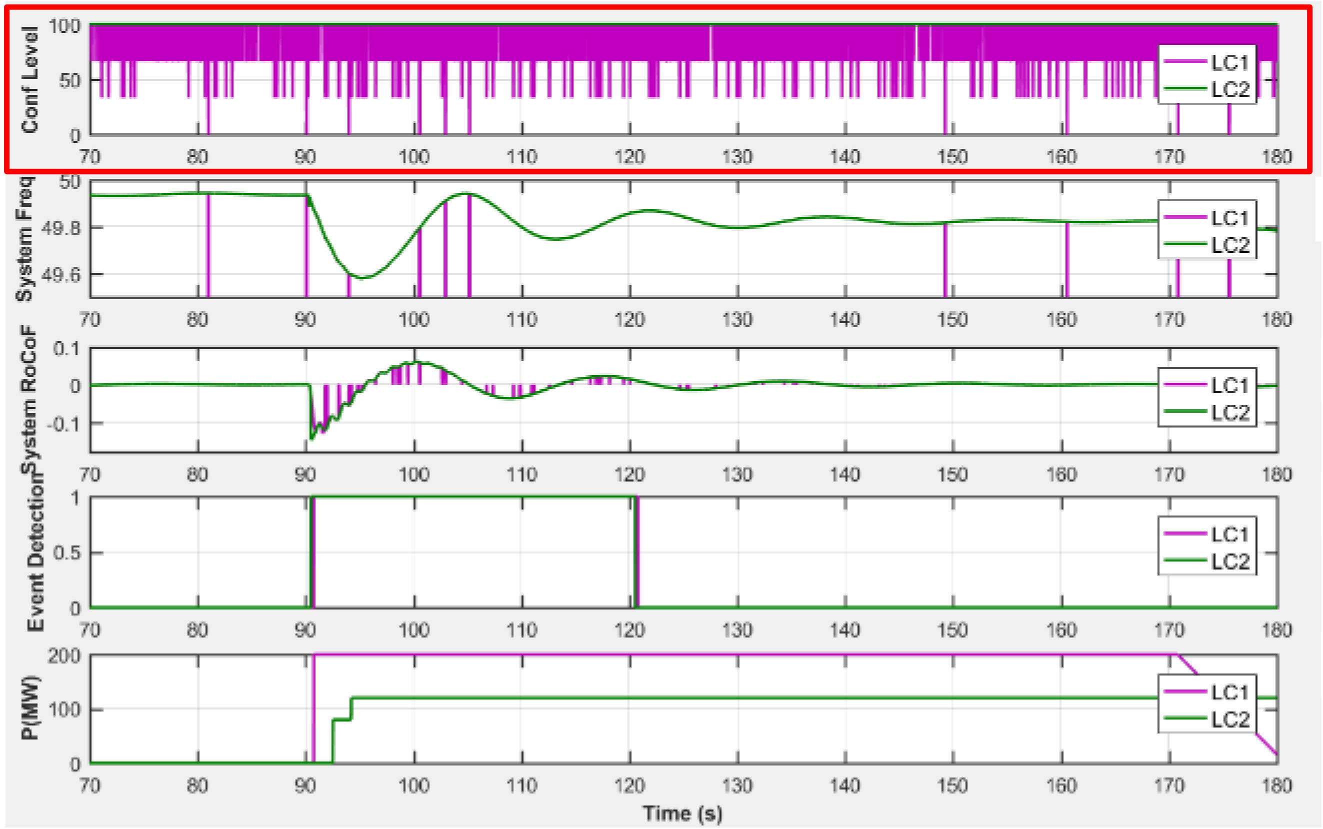




- Mean latency: 50 ms
- Gradually increase latency level in three communication links to LC1
- LC1 capable of handling of the jitter level with expected RoCoF measured

nationalgrid

EFCC operation with mean latency 60 ms and 18 ms jitter



Loss of Packets/delay exceeding threshold

Frequency (Hz)

RoCoF (Hz/s)

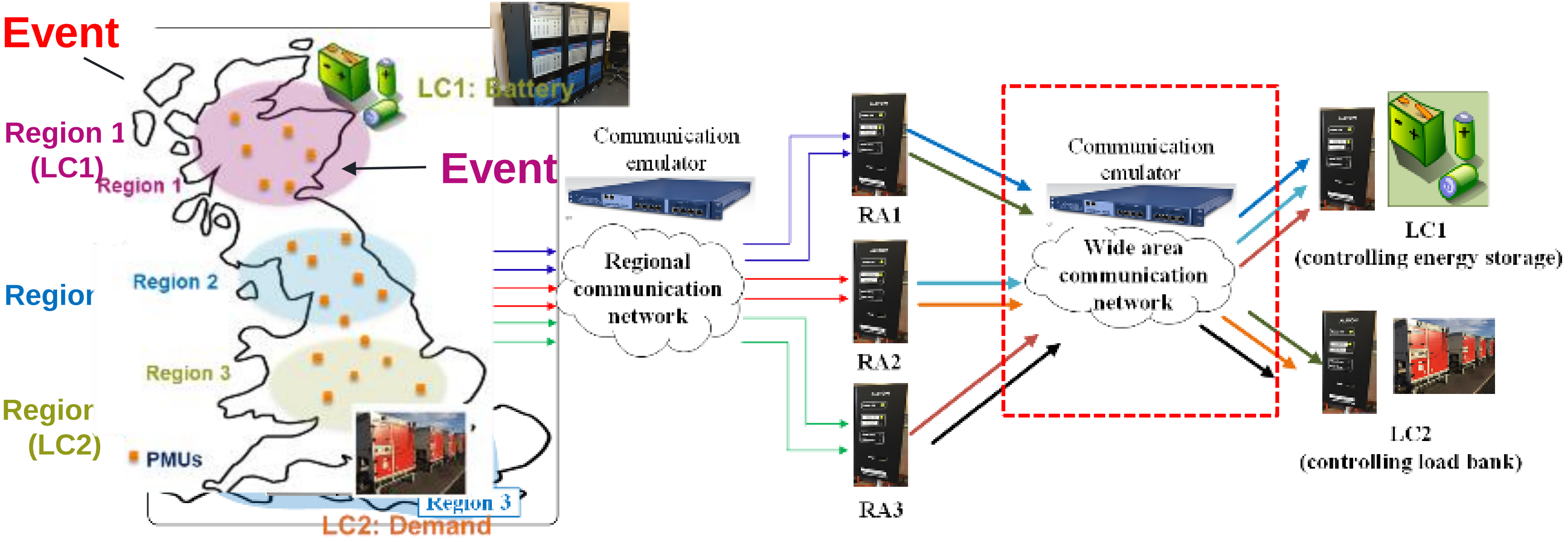
Event detection

Power command (MW)

Demonstration of the EFCC scheme:

Impact of communication performance

- Demo 1: EFCC with idea communication network
- Demo 2: Impact of latency, jitter and loss of packets

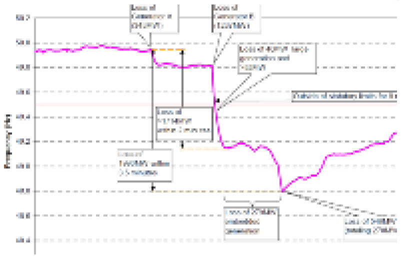


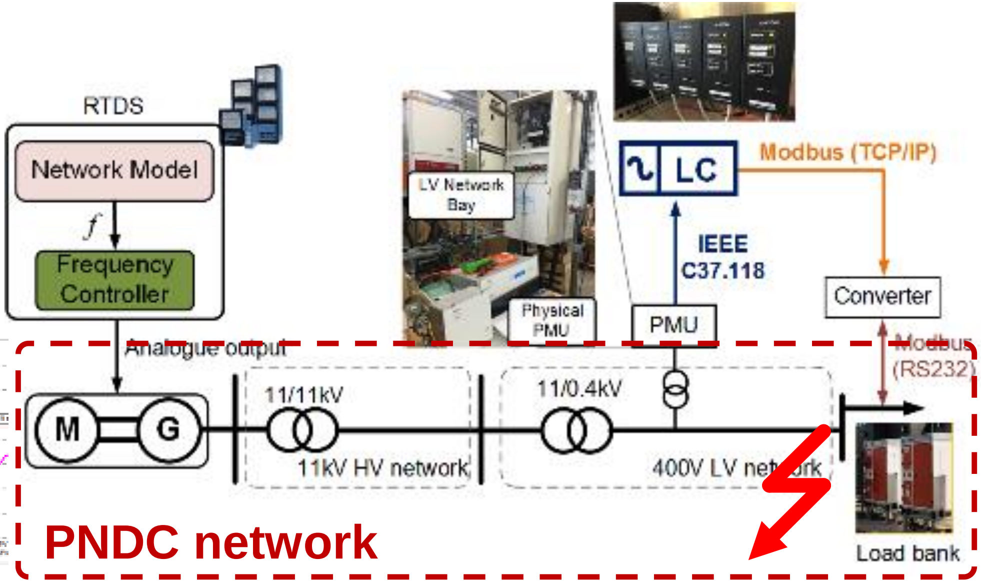
Local mode operation:

- **Local mode: used when wide-area connection is lost or data quality is not sufficiently high for wide-area operation mode**
- **Acting as backup mode – only using local measurement**

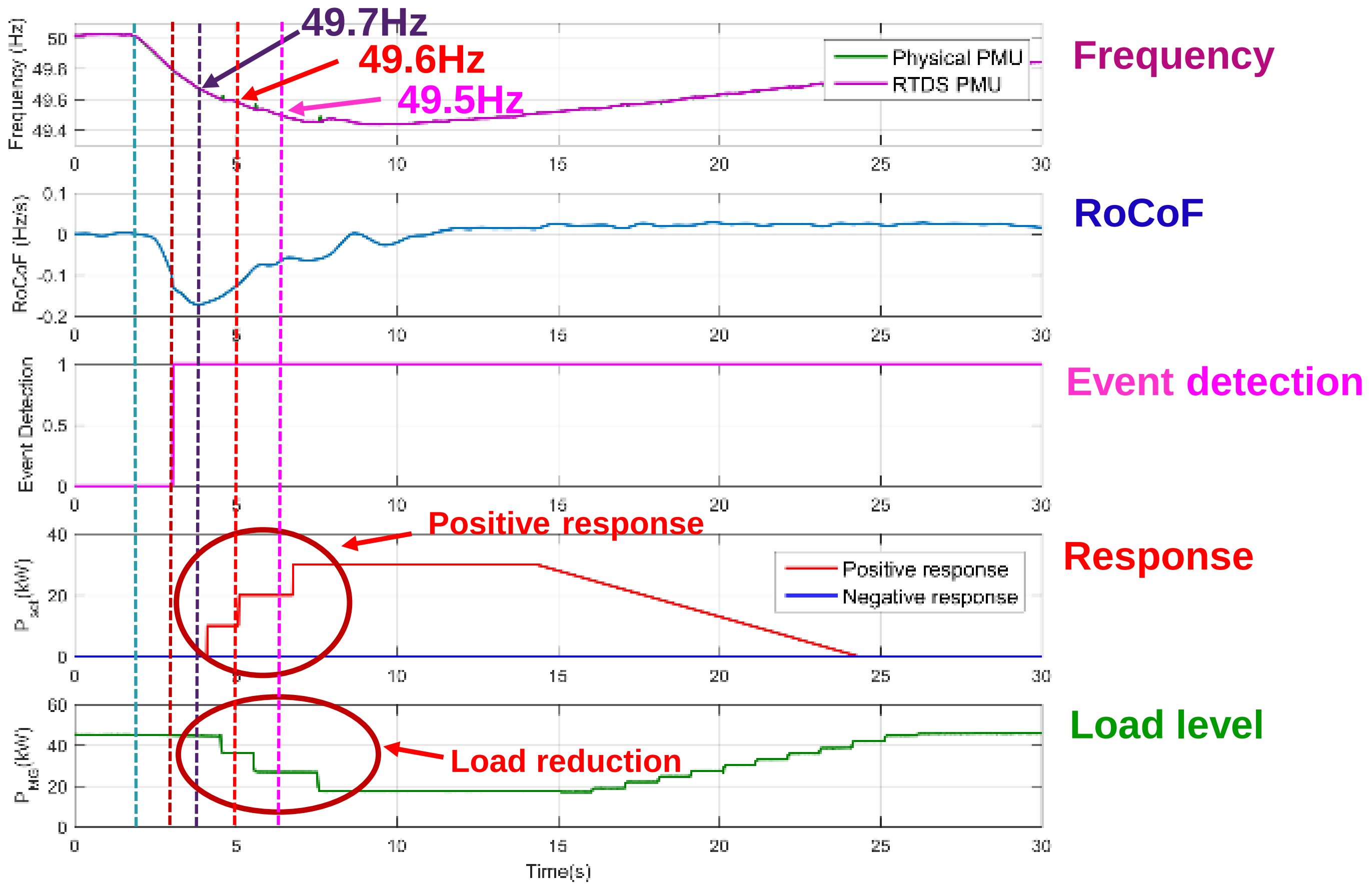
Test setup:

- Motor-Generator (MG) set controlled to emulate frequency disturbances
- Actual faults are also applied in the physical network





Under-frequency event :



Fault tests:

- Actual faults have been applied in the physical network

- Testing the LC's capability to remain stable to the faults

- Fault types tested:
    - Ph-E
    - Ph-Ph
    - Ph-Ph-E
    - 3Ph-E

Fault thrower

Fault resistors

Fault control

nationalgrid

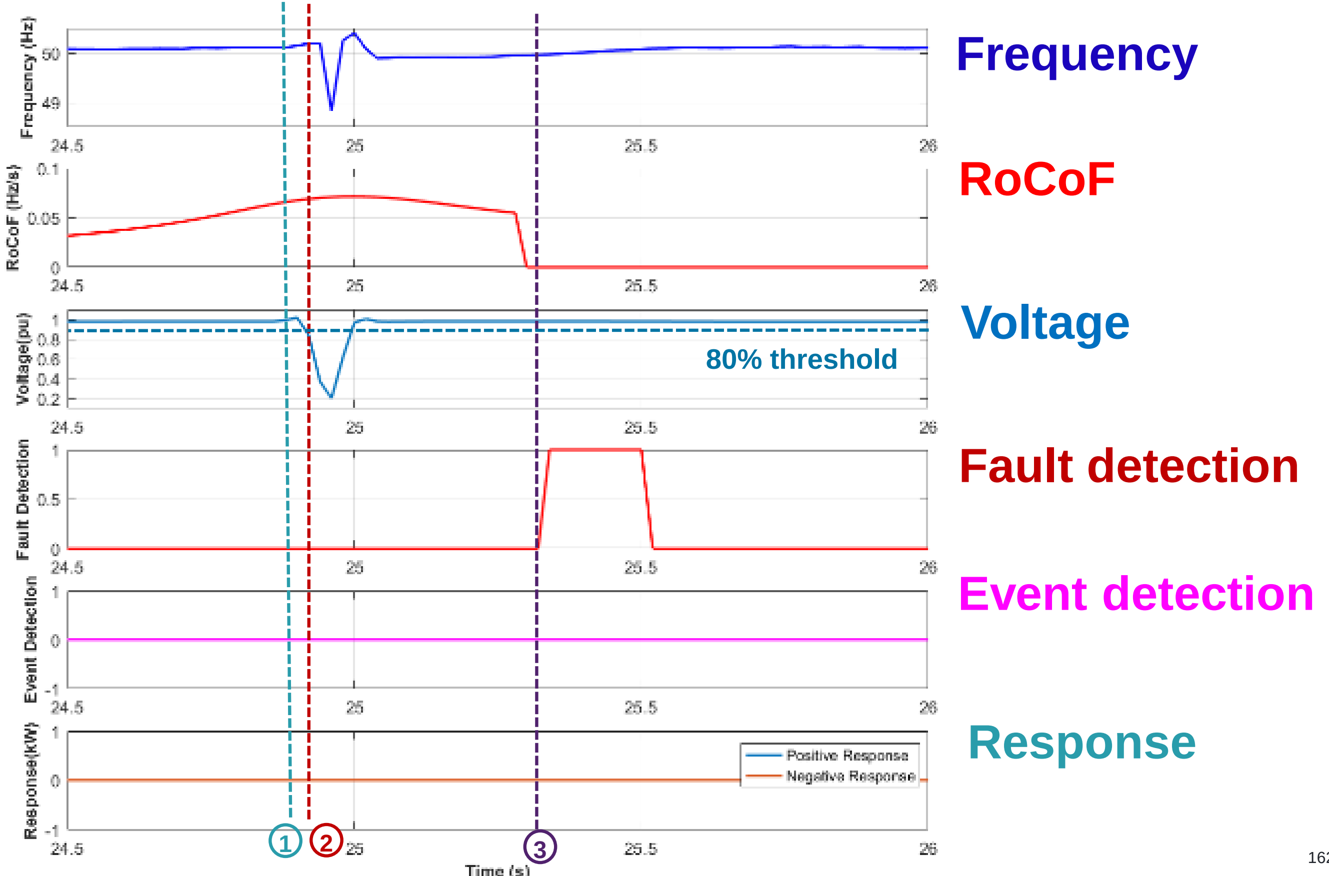
Fault tests in local mode: 3Ph-E fault

Associated settings

- Voltage threshold: 80%
- Event detection RoCoF threshold: 0.1Hz/s
- Event detection frequency threshold: 49.7 Hz

Fault details

- Bolted fault
- Fault duration: 150ms

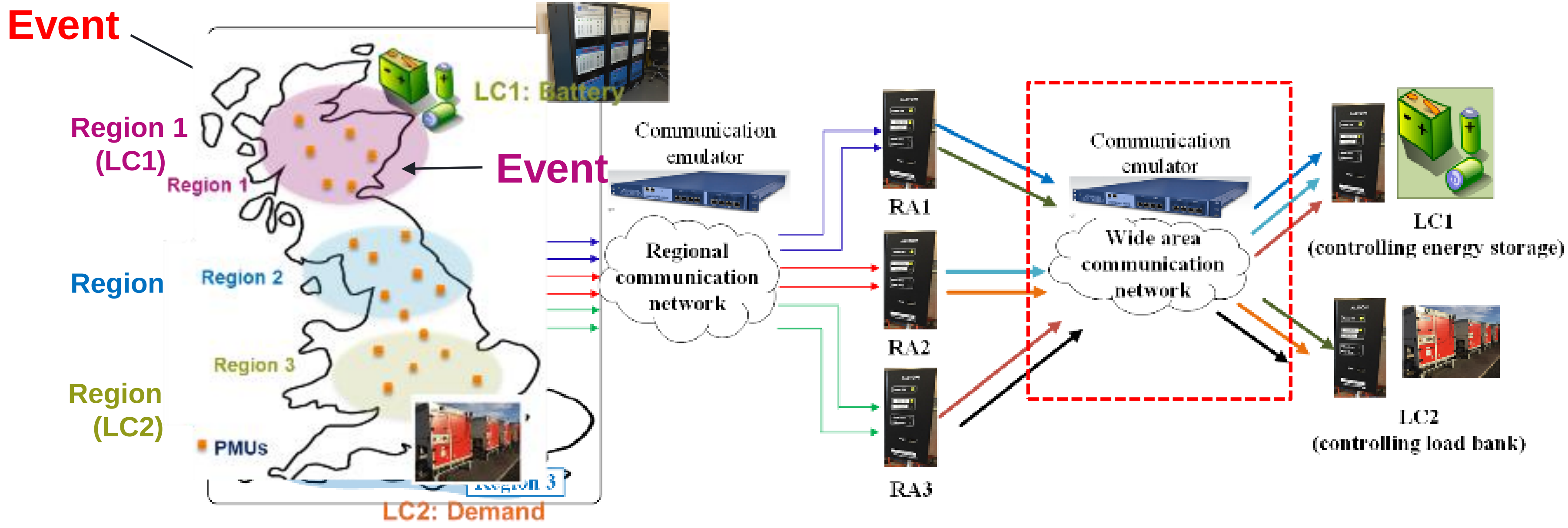


nationalgrid

Demonstration of the EFCC scheme:

Impact of communication performance

- Demo 3: EFCC with complete loss of wide area communication network



nationalgrid

Key learnings and findings

Wide area mode tests:

- Location of disturbances and the response power both have impact on the frequency profiles – electrical distances and regional inertia.
- Frequency and RoCoF are different at different parts of the network, thus important to have wide-area visibility for fast frequency control
- Fast frequency response: more effective compared to the same volume of conventional primary response
- RoCoF measurement can be significantly different with different PMUs, so testing the scheme using actual PMU in physical network before actual implementation is essential
- EFCC scheme capable of instructing fast, coordinated response in the tests – effective in enhancing frequency control in a low-inertia system

Key learnings and findings

Communication tests:

- Size of data buffering window directly determines EFCC's capability to handle degraded communication performance
- Increasing buffering window can mitigate the risk of loosing packets, but can compromise the response speed
- At the PNDC tests, the requirements for communication performance has been quantified
- EFCC scheme appears to be robust in degraded communication conditions

Local mode tests:

- Essential in case of wide area communication failure
- Action should be slower compared to wide area mode due to lack of wide-area visibility

Conclusions and future work

- **PNDC's role: comprehensive validation of the EFCC scheme using the established realistic testbed**
- **The EFCC scheme have been tested under a wide range of operating conditions and disturbances**
  - wide area mode
  - impact of communication performance
  - local mode as backup
- **EFCC scheme capable of instructing fast and coordinated response to enhance frequency control in low-inertia systems**
- **Future work**
  - Further investigation of the role of EFCC in frequency control in future systems, e.g. coordination between EFCC and other frequency control schemes
  - Knowledge dissemination

Questions and Answers Session

nationalgrid

Thank you and have a safe journey