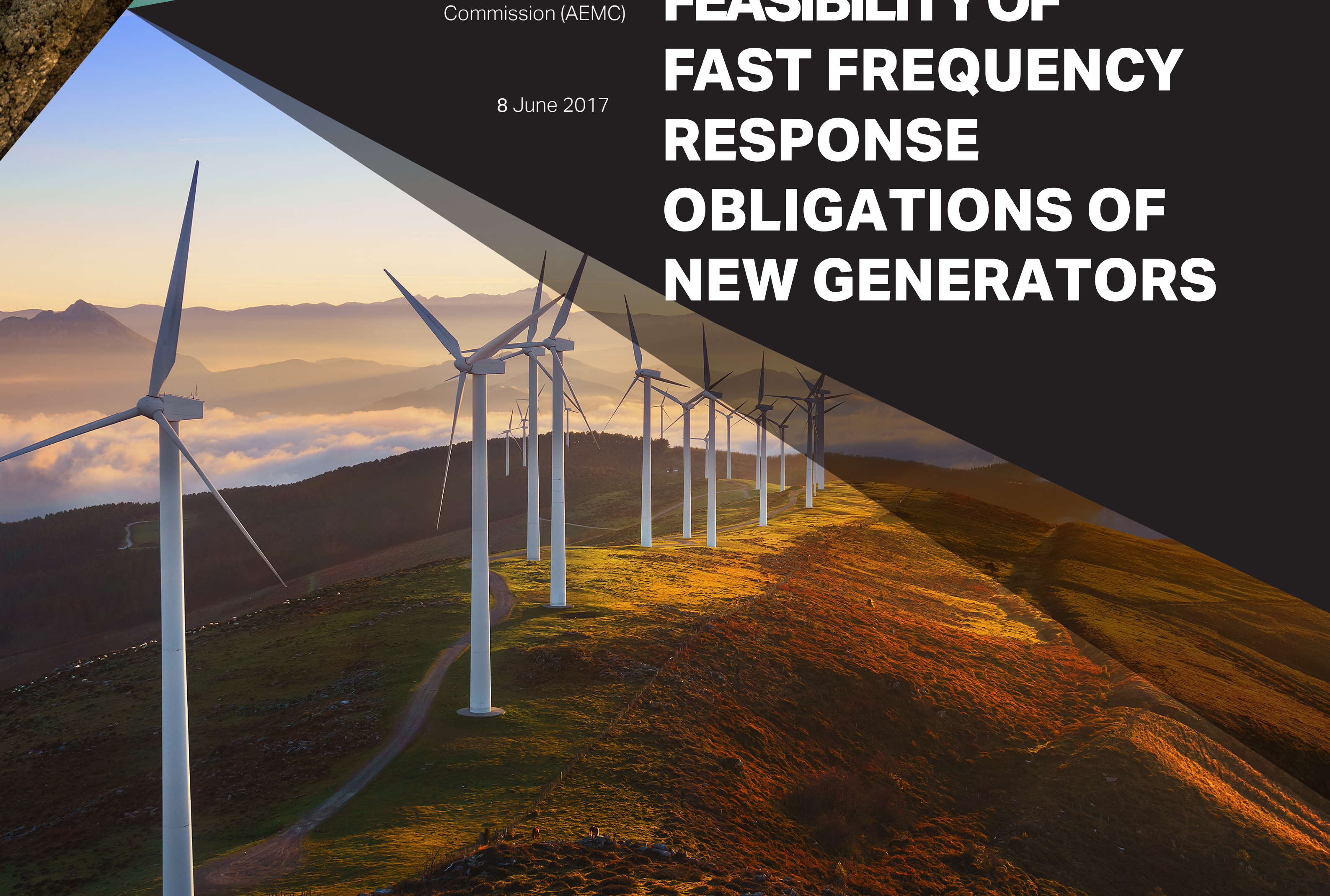
Australian Energy Market Commission (AEMC)

8 June 2017

FEASIBILITY OF FAST FREQUENCY RESPONSE OBLIGATIONS OF NEW GENERATORS



Feasibility of Fast Frequency Response Obligations of New Generators

Client: Australian Energy Market Commission (AEMC)

ABN: 49 236 270 144

Prepared by

AECOM Australia Pty Ltd
Level 21, 420 George Street, Sydney NSW 2000, PO Box Q410, QVB Post Office NSW 1230, Australia
T +61 2 8934 0000 F +61 2 8934 0001 www.aecom.com
ABN 20 093 846 925

08-Jun-2017

AECOM in Australia and New Zealand is certified to ISO9001, ISO14001 AS/NZS4801 and OHSAS18001.

© AECOM Australia Pty Ltd (AECOM). All rights reserved.

AECOM has prepared this document for the sole use of the Client and for a specific purpose, each as expressly stated in the document. No other party should rely on this document without the prior written consent of AECOM. AECOM undertakes no duty, nor accepts any responsibility, to any third party who may rely upon or use this document. This document has been prepared based on the Client's description of its requirements and AECOM's experience, having regard to assumptions that AECOM can reasonably be expected to make in accordance with sound professional principles. AECOM may also have relied upon information provided by the Client and other third parties to prepare this document, some of which may not have been verified. Subject to the above conditions, this document may be transmitted, reproduced or disseminated only in its entirety.

Quality Information

Document	Feasibility of Fast Frequency Response Obligations of New Generators
Date	08-June-2017
Prepared by	Carl Christiansen, Nadia Hillmann
Reviewed by	Winodh Jayewardene

Revision History

Revision	A
Revision Date	08-June-2017
Details	Final
Authorised by	Craig Bearsley Associate Director / Team Leader - Renewables

Table of Contents

Acronyms

Term	Definition
AC	Alternating Current
AEMC	Australian Energy Market Commission
AEMO	Australian Energy Market Operator
DC	Direct Current
EFR	Enhanced Frequency Response
EirGrid	Transmission network company in Ireland
ERCOT	Electric Reliability Council of Texas
ENTSO-E	European Network of Transmission Operators
FCAS	Frequency Control Ancillary Market
FFR	Fast Frequency Response
HVDC	High Voltage Direct Current
NEM	National Electricity Market
NREL	National Renewable Energy Laboratory (USA)
PCR	Primary Control Reserve
PFR	Primary Frequency Response
PJM	Regional transmission network operator in the United States
PMU	Phase Measurement Unit
POR	Primary Operating Reserve
PV	Photovoltaic
RE	Renewable Energy
RFR	Rapid Frequency Response
RoCoF	Rate of Change of Frequency
SFR	Secondary Frequency Response
SIR	Synchronous Inertia Response
SONI	Transmission network company in Northern Ireland
SOR	Secondary Operating Reserve
SPS	Special Protection Schemes
TFR	Tertiary Frequency Response
TSO	Transmission System Operator
WPP	Wind Power Plant
WTG	Wind Turbine Generator

Executive Summary

The AEMC is interested in better understanding the potential to establish meaningful Fast Frequency Response (FFR) technical obligations on new intermittent generators, in particular wind generation. This includes understanding initiatives undertaken internationally, as well as the range of technical capability of existing technologies.

AECOM investigated the approach of various international jurisdictions to FFR. The approaches of each of the jurisdictions could be described as either:

1) A mandated technical requirement to provide FFR (wind specific)
2) A FFR market mechanism with optional participation (technology agnostic)

Some key observations from each of the jurisdictions are provided in Table 1 below.

Table 1 Summary of FFR requirements by jurisdiction

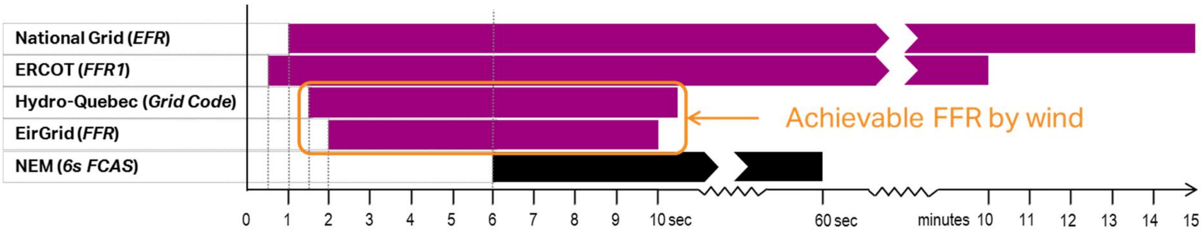
Jurisdiction	Key FFR requirements
Hydro-Quebec Canada	· Compulsory technical obligation placed on new wind generation plants to provide FFR. The obligation is specific to wind and has been in place since 2010. · Technical obligation requires a 6% power boost for 9 seconds. The 6% boost must be provided within 1.5 seconds. This obligation is aligned with the technical capability of wind plants. · Hydro-Quebec has published results of wind turbine FFR performance during contingency events.
ERCOT Texas, USA	· Proposed to introduce two FFR markets as part of a new suite of frequency control markets in 2013; however the proposal was rejected based on concerns that there was no technical requirement for this rearrangement. · The proposed FFR markets were largely designed with demand management services in mind, requiring full response to be sustained for 10 minutes or longer (0.5s response time). This exceeds the FFR capability of wind plants.
EirGrid / SONI Ireland + Northern Ireland	· Introduced new ancillary service markets for inertia, FFR and fast post-fault active power recovery. These new services complement existing ancillary services and are intended to help manage system security, while facilitating up to 75% instantaneous penetration of wind generation. · The FFR service requires full output within 2 seconds and for the output to be maintained until 10 seconds following the contingency event (i.e. minimum 8 second output). · Wind appears capable of offering this FFR service and testing is currently underway to verify eligibility of wind (and other emerging technologies) to provide this service.
National Grid United Kingdom	· National Grid do not have a FFR requirement that can be met by wind generators due to the duration (15 minutes) · The designed Enhanced Frequency Response (EFR) framework, mainly targeting batteries, act as a regulation service rather than contingency service such as FFR. FFR is defined as a fast frequency service procured to arrest frequency deviations, while ERF is used to maintain frequencies as set out in Section 3.5.

The key observation here is that Hydro-Quebec mandated that wind turbines provide a well-defined FFR service, while other jurisdictions developed FFR market mechanisms that could be considered “opt-in”. However, it is clear that the design of the FFR market mechanisms can dictate what technologies are eligible. For example, the ERCOT FFR market requires a minimum of 10 minutes output, which precludes wind from offering this service.

Response Time and Duration

The required FFR response time and duration specified in each jurisdiction varied broadly with times ranging from 0.5 to 2 seconds, and durations from 8 seconds to 15 minutes. This is reflected graphically in Figure 1 below, which also compares the FFR response against Australia’s 6 second FCAS market.

Figure 1 Fast Frequency Response Services specified in various jurisdictions relative NEM’s 6sec FCAS



**EFR is a fast regulation service rather than a contingency response service as provided by FFR*

Discharge durations longer than 10 seconds would exclude participation of wind as a FFR service provider (e.g. ERCOT and National Grid).

Wind Turbine Capability

Wind turbines can provide an around 6-10% power boost without any curtailment for a duration of up to 10seconds.

There is a level of optimisation in the characteristic of this power boost and duration which is effectively determined by control settings which provides a a high degree of flexibility to technology providers by tuning the FFR characteristic (e.g. response time, response duration, output profile, recovery behaviour etc.).

Nonetheless, the FFR characteristics still follow the same basic patterns. This includes a ramp up period, an active power boost period of 5-10 seconds, a power reduction and a recovery period.

Consultation with selected manufacturers concluded that WTG FFR capability is generally designed to meet functional design requirement trends. Currently, this follows the functional requirements setup by Hydro-Quebec. In the future, it is likely that WTG manufacturers will have to work with grid operators to determine how technology providers can best align FFR capability with grid operator requirements.

1.0 Introduction

1.1 Project Scope

AECOM has been commissioned by the AEMC to investigate the feasibility of establishing technical obligations of new intermittent generators to provide FFR.

The focus is on wind turbine technologies; however relevant learnings relating to other technologies (e.g. solar PV) are also reported.

The study includes:

- A review of international markets, to determine how they have specified FFR requirements
- Consultation with suppliers to understand the capability of their equipment. The informal consultation will seek to understand the existing capability within the technology class, the trends and the key characteristics which define FFR behaviour of intermittent generation technologies.

The findings of this report are intended to inform the AEMC's system security work and assist the formation of initial policy positions. The learnings will then be further tested through consultation with industry as part of the AEMC's subsequent work programs.

1.2 Background and Context

Historically, synchronous generators (such as coal and gas fired generators) provided dispatchable generation, inertia, and ancillary services such as frequency regulation and reserve capacity. Market and policy forces are leading to changes in the generation mix however, and much of this technical capability is being lost. With increasing penetration of intermittent generation (e.g. solar and wind) and decreasing sources of system inertia from synchronous generation, there is an emerging need to re-consider how grid security and stability can be maintained.

Various studies [1] [2] [3] [4] have concluded that for reliable operation of electricity systems, a source of inertia is essential to reduce the rate of change of frequency (RoCoF) following a contingency event (e.g. loss of a line, generator or other network element) and to provide fault current.

Fast Frequency Response (FFR) can be provided either by introducing generation (or reducing load). At present this can technically occur within approximately 250-500ms[1] of a contingency event. Various definitions of the terminology used throughout this report related to rapid frequency response, as defined in this study, is presented below.

1.3 Definitions

Table 2 Terminology Definitions

Term	Definition
Synchronous	In the context of this report, refers to AC generation or load technologies (rotating machinery) electrically coupled to the grid with controls in place to regulate and match the nominal frequency on the electrical network (50Hz).
Non-synchronous	Non-synchronous is used to refer to generation or load technologies (solar, batteries, wind) connected to the electrical network by means of power electronics such as inverters, where inverters are used to convert DC to AC in a regulated fashion to match the nominal electric network frequency (50Hz).
Frequency Control Ancillary Services (FCAS)	This includes various services procured from NEM market participants to regulate and stabilise frequency deviations on the network. Generators or large consumers may receive a signal to increase or decrease power output or consumption. · **Regulation FCAS**: correction of supply/demand balance in response to

[1] Some definitions allow for slower response times (e.g. up to 2 seconds for full output)

Term	Definition
	minor deviations in load or generation continuously monitored · **Contingency FCAS**: correction of supply/demand balance in response to a major contingency event such as the loss of a large a generator, load or transmission element from the network.
Rate of Change of Frequency (RoCoF)	The rate at which the frequency increases/decreases following a contingency event that has disturbed the supply-demand balance of the power system.
Synchronous inertia*	Mechanical inertia from the rotating machinery of conventional synchronous generators electrically coupled to the power system. This inertia instantly acts to slow the RoCoF
Primary frequency response* (PFR)	The fast autonomous response procured to arrest frequency deviations, the equivalent of the 6 second FCAS market currently in the NEM. Conventionally sourced from synchronous generators.
Secondary frequency response (SFR)	The relatively fast autonomous response procured to recover and stabilise system frequency, the equivalent of the 60 second FCAS market currently in the NEM.
Tertiary frequency response (TFR)	The response procured to rebalance the frequency to the nominal level (50Hz) and release SFR to recover and be ready for the next disturbance, the equivalent of the 5 min FCAS market currently in the NEM.
Fast frequency response (FFR)*	Rapid injection of active power in response to a sudden change in system frequency. It is sometimes called “synthetic” or “emulated” inertia; however it should not be confused with synchronised inertia (as defined above) as FFR is characterised by a short delay while frequency change is detected, followed by an instruction to inject active power.
Enhanced Frequency Response (EFR)	A service aimed predominantly at storage assets to provide frequency response in 1 second or less, and sustained for 15 minutes. EFR aims to maintain frequency close to 50Hz under normal operation, and is not designed to arrest frequency decline post fault.

**“There is currently much discussion around the interplay between FFR, PFR and inertia. The primary function of FFR is to arrest the frequency decline and “buy time” for PFR to act. The amount of FFR needed and its efficacy is closely tied to the amount and quality of PFR available. For example, faster PFR will reduce the amount of FFR required at any given level of inertia; however at very low levels of inertia, conventional PFR (from synchronous generation) has limited ability to provide arresting energy fast enough. Similarly, withdrawal of FFR should avoid abrupt steps, and should be coordinated with the PFR.”* [1]

2.0 Frequency Stability

Frequency stability is a core requirement of power system stability. Frequency varies depending on the balance of supply and demand: if demand exceeds supply then frequency drops and vice versa. Over frequency is typically easier to address as generation technologies have the capability to quickly reduce output and rebalance supply and demand. Under frequency is more difficult to address for intermittent renewable generators as additional generation needs to be injected into the grid to arrest decline and is subject to availability of the primary resource.

Frequency stability can become an issue when there is sudden change in the supply-demand mix such as loss of an interconnector, a large load, or a large generator. A robust power system must be able to withstand such "contingency events".

2.1 Synchronous Inertia and Rate of Change of Frequency

System frequency begins to change following a disturbance. The initial rate-of-change-of-frequency (RoCoF) immediately after the disturbance is related to synchronous system inertia and the size of the system disturbance.

Conventional synchronous generating plant coupled to the power system have rotating machinery which inherently possesses mechanical inertia. This inertia acts to slow the RoCoF which in turn determines the response time available to arrest the system frequency before reaching the maximum deviation limit.

Technologies such as wind and solar PV are typically connected non-synchronously with power electronic interfaces such as inverters. Increasing uptake of wind and solar inadvertently leads to higher RoCoF as synchronous generation in the networks decreases (with associated inertia loss).

2.2 Frequency Control (Contingency)

While inertia is valuable in slowing RoCoF, with no further action the balance between load and generation will continue to deviate from the stable frequency level. Thus, inertia alone is insufficient to arrest frequency deviations following a system disturbance.

Typically most frequency control services procured fall within three categories:

- Primary Frequency Response (**PFR**): denotes the fast autonomous response procured to arrest frequency deviations,
- Secondary Frequency Response (**SFR**): denotes the relatively fast autonomous response procured to stabilise/recover system frequency,
- Tertiary Frequency Response (**TFR**): is the response procured to rebalance the frequency to the nominal level (50Hz) and release SFR to recover and be ready for the next disturbance.

While frequency deviations can be either higher or lower than the frequency standard, the focus of this report remains on lower (under frequency events) as this is more challenging to address.

2.3 Defining Fast Frequency Response

Historically, 6 second FCAS response procured in the NEM was adequate to manage credible contingencies. However, with increasing uptake of wind and solar (and the associated loss of system inertia), there is an emerging need for faster response. [5]

The period immediately following a contingency event up to the frequency minimum (nadir) is referred to as the arresting period. The amount of inertia in the system at the time of the disturbance determines how much time is available for PFR services to respond.

Higher RoCoF in low inertia systems leads to rapid frequency decline and in turn creates an emerging need for faster performance within the PFR capability. Hence, a new distinct service known as fast frequency response (FFR) has emerged to bridge the gap between inertia and PFR. The primary function of FFR is to arrest the frequency decline and "buy time" for PFR to commence [1].

3.0 International Trends

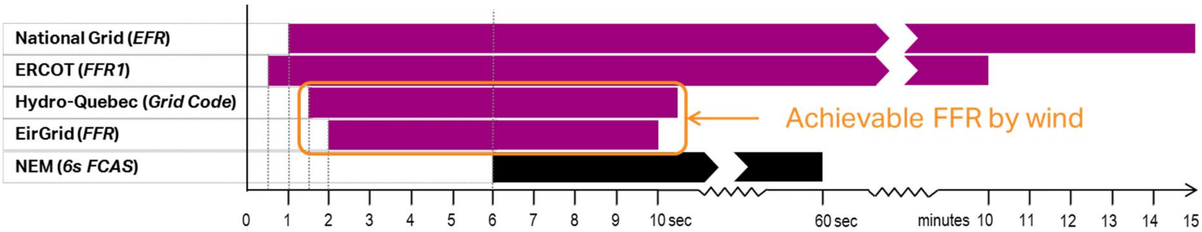
3.1 Overview

A report published in October 2016 on "International Review of Frequency Control Adaption" [3], was prepared in a collaborative process between DGA Consulting and AEMO. This comprehensive review examined international experiences in frequency control across all timeframes and types, with a specific focus on Fast Frequency Response Services. AECOM used this report as the main reference source to assess multiple jurisdictions, in addition to deeper research on areas identified with FFR frameworks.

The study found that a number of jurisdictions considered modifying FCAS frameworks to procure new FFR services, in anticipation that providers of frequency control services will be required to operate with high RoCoF exposure and large quantities of variable generation in the future. Some jurisdictions (such as Great Britain) have mandatory requirements for all generators (including wind farms) to have the capability to provide a range of frequency control services (even if these are never called upon in practice) [3]. No jurisdiction currently has an FFR technical enablement framework in place, however Hydro-Quebec has had FFR grid connection requirements in place for several years. The jurisdictions discussed in the following sections were of particular interest to this review and investigated in further detail.

Figure 2 provides a brief overview of the FFR parameters in the aforementioned jurisdictions, with more detailed discussions in the sections following.

Figure 2 Fast Frequency Response Services specified in various jurisdictions relative NEM's 6sec FCAS



**EFR is a fast regulation service rather than a contingency response service as provided by FFR*

3.2 Hydro-Quebec (Canada)

Hydro-Québec is the electricity utility managing Quebec's electricity system, including generation, transmission and distribution. In 2016, 95% of the grid's power generation was from hydro-electric sources, with wind contributing 4%, and thermal generators producing 1% [6]. Hydro-Quebec also has a 4GW HVDC link to the Easter Interconnection [3].

In 2005, Hydro-Quebec sought tenders for 2,000MW of new wind generation (up to 25% instantaneous penetration during low demand periods), which was being tendered from third parties. Grid studies revealed that this level of penetration may require FFR capability to mitigate the severity of frequency deviations during major disturbances [3]. In 2010, Hydro-Quebec was the first grid operator to connect wind plants with FFR capability.

The requirements only apply to wind farms larger than 10MW, which must be equipped with a frequency control system. The system must be in continuous service, but only act during major frequency deviations (i.e. major disturbances rather than steady-state frequency regulation).

The required level of response is specified to be greater than 6% of the name plate capacity, and sustained for 9 seconds. The full response (6% boost) should be provided in less than 1.5 seconds. [7]

The table below summarises Hydro-Quebec's preferred FFR performance characteristics including response time, duration and ramp down characteristics (following FFR discharge event) as described in the 2013 Grid Code.

Table 3 FFR performance characteristics for wind farms larger than 10MW connecting to the main grid in Quebec [7]

Parameter	Description	Value
Under frequency		
Activation frequency	The frequency deviation which activates FFR	Adjustable between -0.1 Hz and -1.0Hz (from the nominal frequency – 60Hz)
Activation time	The maximum time after the event occurs before the full response is given	≤1.5 second
Active power contribution	The minimum amount of additional power output the plant must produce as FFR	≥6% (of nominal rated power) for each turbine in service
Duration of active power contribution	The minimum time at which the plant must sustain its active power contribution before going into recovery phase	≥9 seconds from the start of the rise of power until the initiation of its descent
Maximum generation reduction during recovery phase	The maximum amount of power reduction when the plant goes into recovery phase.	≤20%
FFR availability	The operating level at which the FFR capability must be available	≥25%
FFR recovery time	Time following an FFR dispatch before FFR capability must again be available	2 minutes
Over frequency		
Activation frequency	The frequency deviation which activates FFR	Adjustable between +0.1Hz and +0.5Hz (from the nominal frequency – 60Hz)
Hydro-quebec require that wind farms be provided with a frequency control system with a droop permanent (sigma) having an adjustable range from 0 to at least 5% and that this parameter will be provided by Hydro-Quebec		

Hydro-Quebec published data of wind farm performance following system disturbances (see Section 4.2) and it is clear that there is reasonably good conformance to the specifications listed in Table 3. However, the output is characterised by variability in the output such that the target of 6% output is not always maintained over the 10 second duration. Similarly, there is noticeable “ramp up” time before the 6% output is delivered (roughly 1-3 seconds).

3.3 ERCOT (Texas, USA)

In 2013, the Electric Reliability Council of Texas (ERCOT) proposed a new suite of frequency control ancillary services [3].These changes were rejected however, because stakeholders believed it was not necessary at this time with sufficient synchronous generation in the network to maintain system security without the new changes.

The ERCOT power system is largely isolated from neighbouring power systems, operating as a stand-alone electricity grid [8] and is powered mainly by gas (40%), coal (30%), nuclear (11%), and wind (18%) [9].

Although the proposed FFR framework was rejected, there is still value in considering the work completed by ERCOT, particularly as it was not rejected for failing to deliver technical outcomes.

Prior to having its proposal rejected, ERCOT designed two discrete FFR services, designed to fit within a new broader suite of ancillary services. This included a new market for inertia as well as reshaped PFR markets.

Table 4 ERCOT's proposed suite of ancillary services [3]

Acronym	Service	Response time
SIR	Synchronous Inertial Response	Instantaneous response from synchronous machines
FFR1	Fast Frequency Response #1	Full response in 0.5 seconds, sustain for 10 minutes. Full capability restored within 15 minutes
FFR2	Fast Frequency Response #2	Full response in 0.5 seconds, sustain as long as needed Full capability restored within 180 minutes.
PFR	Primary Frequency Response	Commence response in 1.5 seconds, full response in 16 seconds, sustain for 1 hour
Reg	Regulation Reserve	Commence response in 4-6 seconds, full response in 5 minutes, sustain for 10 minutes
CRS	Contingency Spinning Reserve	Commence response in 5 minutes, full response in 10 minutes, sustain for 1 hour

The FFR specifications are interesting in that they rule out many technologies from contributing to this service. In particular:

- Most technologies cannot ramp up to “full response” within 0.5 seconds (unless the “full response” is defined to be sufficiently small to eliminate ramping delays)
- Wind cannot sustain its response for the 10 minute period

Rather, it appears that the FFR specifications are suitable for demand response (which is common in Texas with 1400MW of load reserves compliant with FFR requirements [2]). In addition, it appears utility-scale batteries would also be compliant with the FFR1 requirements.

In addition, the large overlap of timeframes between different ancillary services is unusual. In general, it is more efficient to have non-overlapping response, particularly for overlap of the ‘full response” periods. [10]

More detailed FFR specifications are listed in the table below.

Table 5 ERCOT’s FFR requirements (detailed) [2]; [3]

Metric	Requirement
Response	Full response in 0.5 seconds
Output	Must be maintained between 95% and 110% of the awarded obligation
Equipment	Resources need to be equipped with high resolution recorders, for example, PMU
Deployment	Self-deployment through controller or relay
Duration	FFR1: At least 10 minutes FFR2: Indefinite – services provided until recalled by ERCOT (longer than 10 minutes)
Quality control	Deployment records to be provided to ERCOT
Restoration time	FFR1: 15 minutes FFR2: 180 minutes

3.4 EirGrid/SONI (Ireland/Northern Ireland)

3.4.1 New FCAS Framework

EirGrid/SONI is a collaborative body formed between Ireland (EirGrid) and Northern Ireland's (SONI) Transmission System Operators (TSOs). The combined (Ireland + Northern Ireland) system is powered mostly by gas (44%), wind (18%), coal (17%), peat (7%) and imports from Wales (10%) via two underwater HVDC interconnectors (500MW each [11]). It is expected that all new generation built in the future will be renewable. [12]

In 2009/10, EirGrid/SONI carried out various studies to examine technical challenges related to high renewable penetration and subsequent issues associated with high RoCoF following contingency events. In 2011, EirGrid/SONI launched a comprehensive work plan (DS3[2]) to address these challenges.

A key work stream was set up to reshape frequency stability services, to ensure that the electricity system could operate securely with up to 75% instantaneous wind penetration [4]. EirGrid/SONI developed a new ancillary service framework following extensive modelling and research in the DS3 program. The new service was developed to complement existing reserve services for frequency control. Table 6 provides an overview of existing and new proposed FCAS, with a focus on the faster frequency services.

Table 6 EirGrid/SONI's new and existing suite of faster ancillary services [4] (excl. voltage services)

Acr.	Service	Response time	Notes
Existing			
POR	Primary Operating Reserve	5 – 15 seconds	A form of PFR, where additional power output is delivered to arrest the frequency nadir. Full output is required for the 10 second duration.
SOR	Secondary Operating Reserve	15 seconds, sustained for 75 seconds	Additional MW output designed to follow-on from the POR service, commencing at 15 seconds mark and continuing until the 90 second mark. Full output is required for the 75 second duration.
TOR1	Tertiary Operating Reserve 1	90 seconds, sustained for 5 minutes	Additional MW output designed to follow-on from the SOR service, commencing at 90 seconds mark and continuing until the 5 minute mark. Full output is required for the duration of the service.
New			
SIR	Synchronous Inertial Response	Instantaneous for 15-45 seconds	A market service rewarding the provision of inertia from synchronous generators, condensers and demand loads. The active energy output from SIR providers must be between 15 and 45 seconds in duration.
FFR	Fast Frequency Response	2 seconds, sustained for 8 seconds	Additional power output or demand reduction following a contingency event. This service bridges the gap between SIR and POR (with some overlap with POR). FFR providers who maintain or increase their outputs are eligible for POR services.
FPFAPR	Fast Post-Fault Active Power Recovery	250ms following recovery of grid voltage	This service rewards units that can recover their output quickly following a voltage disturbance (e.g. transmission fault). This can mitigate the impact of voltage disturbances on system frequency. Generators are eligible if they can restore their

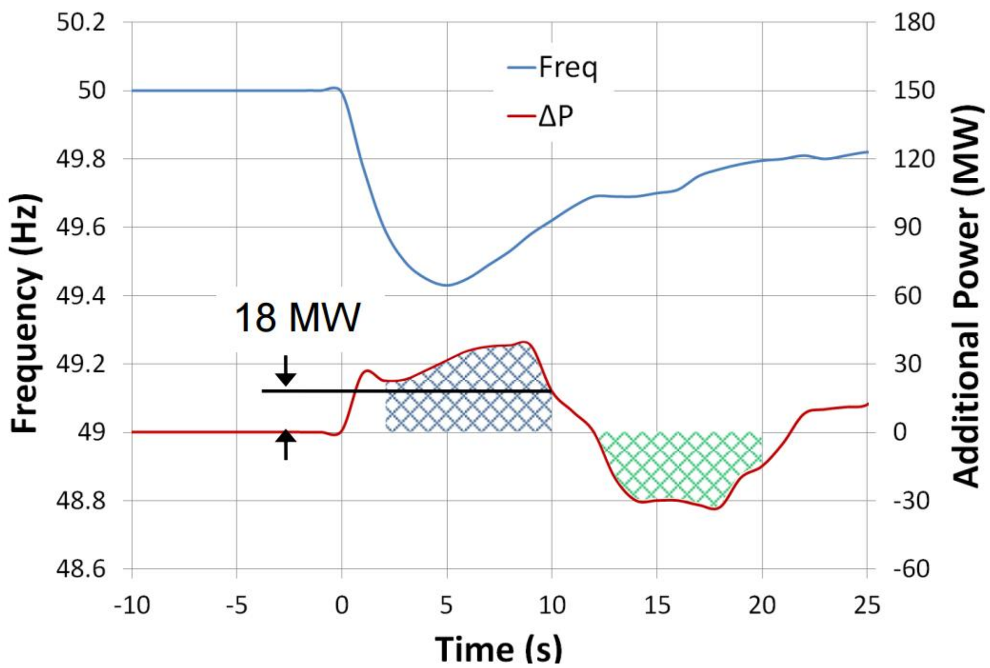
[2] Delivering a Secure, Sustainable Electricity System program = DS3

Acr.	Service	Response time	Notes
			output to 90% of its pre-fault value within 250ms of the voltage recovering to 90% of its pre-fault value. The generator must also remain connected to the system for at least 15 mins following the fault.

At 2 seconds, the FFR service is notably slower than observed in other jurisdictions and significantly slower than the technical ability of many technologies. In addition, no incentive is provided to technologies to provide its output prior to the 2 second response time. The Single Electricity market (SEM) Committee explained in its 2013 decision paper that this was because it deemed no technical requirement for response times faster than 2 seconds. In addition, the slower response times would be more inclusive of more technologies to offer the FFR service. [4]

A key concern in the specification of the FFR requirements was the potential impact of recovery following the provision of FFR. This is particularly relevant to wind technologies which require a recovery period following FFR dispatch. The approach has been to stipulate that the additional energy output in the response period (2-10 seconds) must be greater than any energy losses during the 10-20 second recovery period. This is demonstrated in Figure 3 where the blue hatched area (energy output during response period) should be larger than the green hatched area.

Figure 3 Example of reduced output during the recovery period



The FPFAPR service provides incentives to generators who can provide post-fault active power recovery as it is recognised that if a large number of generators do not recover their MW output sufficiently quickly following a transmission fault, this could lead to a large change in the system frequency. Generators that can recover their MW output quickly following a voltage disturbance (including transmission faults) can mitigate the impact of such disturbances on the system frequency. [4]

In the context of the NEM, active power recovery times are documented in Generator Performance Standards and there is no particular market for this presently.

3.4.2 Progress of works – DS3 program

The DS3 program is well advanced at this stage. In order to facilitate provision of ancillary services from emerging technologies, EirGrid/SONI is running a “Qualification Trial Process”, which seeks to test the ability of emerging technologies to provide ancillary services. Technologies that demonstrate reliable delivery of the services and measurability of that service over 5 contingency events will gain access to the Central Procurement Process (i.e. eligibility for trading ancillary services).

This process will also help inform the development of new codes and standards for the emerging technologies, functional design metrics, and testing and commissioning procedures.

Qualification trials are currently underway, and are considering technologies such as wind, energy storage, demand-side technologies and flywheels. Results are expected later this year. [3]

3.4.3 EirGrid Grid Code Requirements

The latest EirGrid Grid code (2015) sets out technical obligations for wind turbines and includes requirements for active power management in response to changes in system frequency [13].

The technical requirements are very detailed, describing multiple operating modes and required behaviours during contingency events of varying severity. However, the grid code requirements are aligned to the POR market, rather than the new FFR market. This is representative of how the DS3 program has not yet qualified wind for the FFR market, and the grid code may be updated following the results of the Qualification Trial Process for wind under the DS3 program.

3.5 National Grid (United Kingdom)

National Grid, the Transmission System Operator (TSO) in the United Kingdom, established a Frequency Response Technical Subgroup in 2010 to investigate issues such as the ability of wind turbines to contribute to frequency stability in response to increasing high RoCoF events [3]. This subgroup attended meetings with wind turbine manufacturers in order to understand their ability to develop FFR capability [14]. All manufacturers confirmed that FFR could be delivered (within 5 seconds), however delivery depended on the wind resource available at the time of the disturbance.

The Rapid Frequency Response (RFR) service (FFR equivalent service) was to be introduced as a requirement for non-synchronous generators, where mandatory full response would be required within 5 seconds. The Frequency Response Workgroup concluded however, that it could not recommend prioritising development of RFR due to unresolved technical issues associated with wind operation (such as recovery period and inability to provide FFR and Primary Response (PR) simultaneously). [3]

National Grid found that an alternative approach to set faster PR may be preferable, where this capability would require wind turbines to provide full response in 5 sec, and sustain for 25 sec. This is based on active power generated from pitch control rather than inertia, to avoid recovery period issues; however it also requires pre-curtailment which has high opportunity costs. This concept is still under investigation and further development.

Even though the study was specifically related to understanding implications of emulated inertial response from wind turbines, it had a strong focus on development of an adequate measurement and control system as the control strategy applied for FFR was found to be of critical importance.

As a result, National Grid established their “Enhanced Frequency Control Capability (EFCC)/SMART Frequency Control project” which runs till March 2018. The project aims to develop technical solutions in combination with commercial frameworks to ensure that new generation technologies will be able to compete effectively with existing response providers. The Enhanced Frequency Response (EFR) service was established as part of this project, and is to be added to existing services (Table 7). This new service is aimed predominantly at storage assets to provide frequency response in 1 second or less, and sustained for 15 minutes. [3] [15]

Table 7 Frequency control services procured by National Grid

Acronym	Service	Response time
PR	Primary Response	Full response in 10 seconds, sustain for 20 seconds.
SR	Secondary Response	Full response in 30 seconds, sustain for 30 minutes.
EFR	Enhanced Frequency Response	Full response in 1 sec or less, sustained for 15 minutes

Factors to note about this service:

- EFR aims to maintain frequency close to 50Hz under normal operation, and is not designed to arrest frequency decline post fault. [3] This makes it different to FFR services proposed by EirGrid/SONI and ERCOT, which target post fault reactions after a big drop or spike in the frequency.
- EFR systems must be capable of detecting a change in system frequency within 500ms, and able to provide the contracted change in active power within 1 second. [16] [3] [17]
- The assets must be able to deliver at 100% EFR capacity for a minimum of 15 minutes. [3] [17]. This requirement effectively precludes FFR from wind as it could only maintain maximum additional active power output for ~10sec.
- The majority of tenders received by National Grid involved batteries, which can sustain a response for a longer duration. National Grid have indicated that assets with short duration, fast response characteristics “are more suited to post-fault frequency control”, and that the development of such a service (termed “Rapid Frequency Response”, discussed earlier) will be progressed separately to EFR. [3] [17]
- EFR service is symmetrical, which means that assets are to provide EFR in both over and under-frequency scenarios and sustain the increased or decreased power out for 15 minutes. This precludes solar PV, unless it is being operated under curtailed conditions.

3.6 Germany

Germany is a leading jurisdiction in terms of the amount of renewables integrated into their network, where renewable generation peaked at or just exceeded 90% instantaneous penetration on previous occasions [18].

There are multiple reasons why Germany has been able to successfully integrate large penetrations of renewables including factors such as the existing strength of its power grids; flexible operation of coal and nuclear plants; better system control software and day-ahead weather forecasting; modest technical improvements to local-level distribution systems; and exports of power to neighbouring countries. [19] There is no evidence of initiatives currently underway in regards to FFR in Germany.

Germany relies on its control reserves to maintain the system frequency within a narrow range around its target frequency of 50 Hz (regulation), and to eliminate regional deviations in the balance from their reference value (contingencies). [20] The most rapid control reserve service procured by German TSOs is the Primary Control Reserve (PCR) with the following technical aspects:

- Procured by all TSOs connected within the ENTSO-E area
- Automatic and complete activation of primary control reserve within 30 seconds
- Period per incident to be covered: $0 < t < 15$ min [20]

Activation is automatic, decentralised and frequency-controlled, and the energy provided is not measured and settled. In case of a power plant outage, all suppliers activate PCR autonomously. [21]

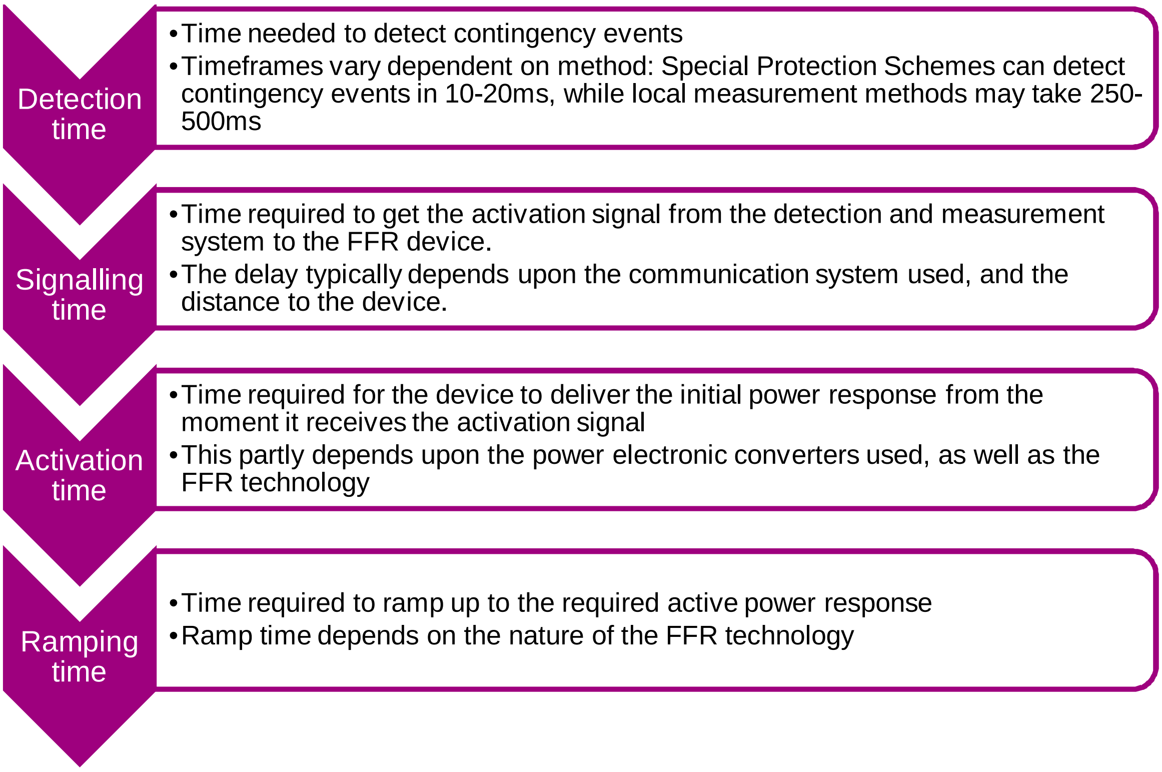
As a member of ENTSO-E (European Network of Transmission Operators), Germany can rely on a highly interconnected network with an established integrated electricity market with 43 TSO’s from 36 countries across Europe [22]. This allows trading across borders and high synchronous generation from neighbouring countries help to regulate and support frequency deviations in Germany. As such, Germany is not likely to encounter high RoCoF challenges until considerably higher renewable penetration is achieved in ENTSO-E networks. [3]

4.0 Technology FFR Capability

4.1 Response times

Response time is a key characteristic of FFR capability. Faster response times provide a better substitute for inertia, and can help arrest the frequency nadir more rapidly following a contingency event. The response time of different technologies is a function of different elements which are described in Figure 4.

Figure 4 Fast frequency response time elements [3] [23]



It is noted that the most challenging component of reliable FFR response is adequate measurement and robust detection of the contingency event.

Even though local detection of contingency events can be done in 2 cycles (40ms); longer periods are desirable to avoid false identification. EirGrid/SONI determined in their extensive studies and analyses, that a timeframe of 500 ms would be an appropriate time for the system to reach coherence [23] [3]. GE agreed that reliable detection generally takes in the order of 500ms; however GE notes that 250ms appears challenging but that rapid progress is being made on this front. [1]

Sometimes, worst case contingency events may require faster detection times. This can be possible through direct event detection, or Special Protection Schemes (SPS). This method places monitoring equipment at the site of the plant considered for worst case contingency (e.g. an interconnector) and connects it to the FFR provider using fibre optic cable. SPS can facilitate a combined detection and signalling time of less than 40ms.

Following the detection and signalling periods, the activation and ramping time is more technology specific. These are discussed further in the following sections.

4.2 Wind

Currently, almost all new WTG technologies can be categorised as either Type 3 (double-fed induction generator – or “DFIG”) or Type 4 (full converter generators). Neither of these WTG technologies are directly coupled to the grid and, therefore, does not provide inertia (in the traditional sense) to the grid.

Instead, power electronics control active power delivery, and are able to command controlled changes in the active power. [1]

By leveraging the kinetic energy contained within the wind turbine's blades, the power output can be boosted briefly. However the boost cannot be sustained. As the kinetic energy is drained from the turbine blades, the resulting slow rotation leads to a drop in energy output. To return the turbine to its pre-fault operating conditions, energy needs to be recovered from the grid. This functionality is sometimes terms "Inertia-based FFR".

An alternative method of providing FFR functionality from wind is to pre-curtail the WTG output, such that "head room" is available. However this method comes at a substantial energy cost.

4.2.1 FFR from wind

The mechanism operates on the basis that the WTG temporarily extracts kinetic energy stored in the turbine rotor and drive train to deliver additional electrical power, however this causes the rotor to slow down. [1] This motion therefore dictates how long power injection can be sustained: higher FFR requires more rapid power injection which can be sustained for shorter periods, while lower FFR requires slower injection which can be sustained for slightly longer periods.

The aeromechanics of wind turbines set the practical upper limit of FFR extracted from wind turbines at ~10% of the power production level at the time of the disturbance. The amount of available inertial response starts to decline rapidly below ~50% rated power, dropping down to zero below ~20% rated power. [1]

Electrical power must temporarily drop below mechanical power in order to recover the inertial energy extracted from the slowing rotation of the turbine. The time required to recover the additional energy injection, and to reaccelerate rotational speed to pre-fault levels, depends on the amount and rate of FFR requested and available wind speed at the time of recovery.

A key observation for operating conditions <u>at or below rated wind speed</u> is that FFR can help to arrest frequency deviations and buy time for primary frequency response to act. Ideally withdrawal of FFR should begin at the nadir, carefully coordinated with the rate of rise of the primary frequency response during the post-nadir recovery period. [1]

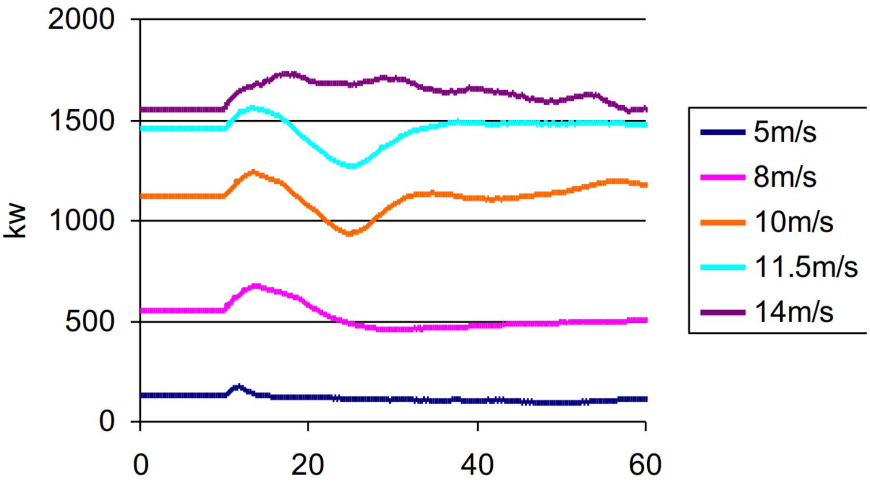
When wind speeds <u>exceed rated speeds</u>, WTGs "spill" excess energy by pitching the blades (in addition to other mechanisms) to keep constant power generation. Under these conditions, available power in the wind is greater than the WTG rated power and it is possible to capture additional energy using pitch control rather than just extracting stored inertial energy by slowing the rotor. At or above rated wind speeds, a recovery period may not be required. [1] While WTGs would be able to exceed the steady-state power output rating under these conditions, additional power is still subject to physical limitations of the equipment, which is currently known to be ~10% of the power level.

4.2.2 FFR from wind demonstration trials

Field tests were carried out in 2008, on a GE WTG for inertial frequency controls under various wind speeds. [1] The results were averaged and plotted as shown in Figure 5. [1]

The results demonstrate the increased power output and recovery period at wind speeds below rated (<14/ms), while no recovery period is observed for the rated wind speed test. Similarly it can be seen that little additional power was available at the low (5m/s) wind speed and corresponding low power level. The frequency response increased power output in the order of 5% to 10% of the turbine rating, for a duration of several seconds. [1] [3]

Figure 5 Field demonstrations of wind FFR capability [1]



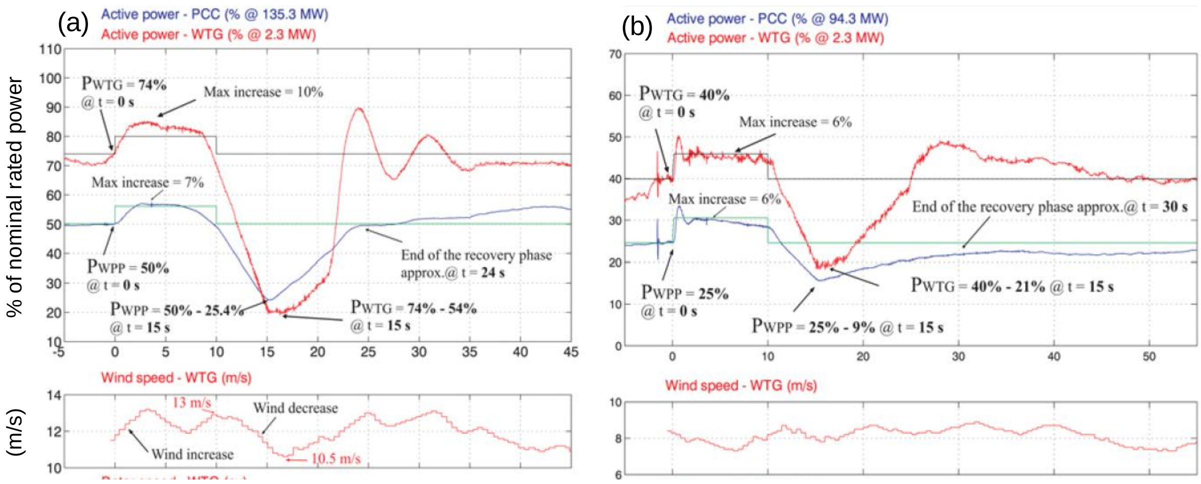
4.2.3 Hydro-Quebec power system experiences with FFR

Hydro-Quebec has set a requirement for wind generators to provide an FFR service. This service is characterised by a 1.5 second response time (including detection), and a 6% (of rate capacity) boost for a 9 second duration (further details are provided in Section 3.2). In 2016, Hydro-Québec published some detailed analyses on practical power system experiences with FFR responses from wind generation under various under-frequency contingency events. [3] [24] For illustration purposes, AECOM has provided two example response events.

Figure 6 shows two examples of recorded behaviour of Type IV wind turbines during two different under frequency events. The top panel illustrates the active power response measured at an individual WTG in red, and the whole Wind Power Plant (WPP) in blue. The bottom panels illustrate the corresponding wind and rotor speeds during the event.

The left panel (a) show the response of a wind farm comprising Enercon E70 2.3MW turbines, operating with settings equivalent to the 'proportional function' defined by Hydro-Québec, while the right panel (b) shows the response of a wind farm comprising Enercon E82 2.3MW turbines operating with settings equivalent to 'step function' defined by Hydro-Québec.

Figure 6 Hydro-Québec measured emulated inertial response in two different events by Type IV wind turbines [3] [24]



In the first instance (a) the individual turbine was operating at ~74% of its rated power, while the whole farm operated at ~50% of rated power. It can be seen that at the time of the disturbance, the individual turbine increased its output by 10% of the rated power, while the whole WPP increased power output by ~7% on average. [3]

The response sustain period of the individual turbine seem to start dropping just before 10 seconds followed by steep power reduction (active power reduces by 54% during this period), while on a holistic wind farm basis the power reduction and recovery is less extreme [3]. Power reduction prior to 10 sec may have been in response to a signal from the operator, or due to the fact that the turbine responded with higher power output (10% instead of 6%) which may have led to more rapid recovery.

At the individual wind turbine, the significant reduction is exacerbated by the corresponding reduction in wind speed from 13 to 10.5m/s. The recovery period lasted for ~14 seconds. [3]

In the second instance (b) the WTG operated at a lower 40% of rated power immediately prior to the event, while the whole WPP operated at 25% of the rated capacity. The WTG and the whole WPP increased active power by ~6% in response to the disturbance, for a duration of ~10 seconds as designed. These wind turbines have longer blades than the previous example, which leads to a higher inertia constant. [3]

In this case, the whole wind farm sees an active power reduction of only 9% for a slightly longer duration of ~20 seconds [3]. It is notable however, that even though the individual WTG recovers power output sufficiently to pre-fault levels within ~25sec, the wind farm power output does not recover completely to the pre-fault levels for the duration of this chart. It is not clear if this may be attributed to lower wind speeds at other locations in the wind farm after the event.

4.2.4 FFR specifications based on wind FFR characteristics

It is notable that the Hydro-Quebec grid standards require that the WTGs increase power output by at least 6% of the nominal power to be sustained for 10sec. The observed response in the results shown above demonstrates that the turbines have the capability to meet these requirements.

In addition to these requirements, GE has made a set of recommendations for use in specifying FFR requirements for WTGs [1]:

- Specification of minimum turbine power below which inertial response is not required
- Specification of preferred interactions/priority with other wind plant controls (e.g. should FFR or curtailment have priority? Should reactive support or frequency support have priority?)
- Specification should not attempt to replicate synchronous machine requirements or capabilities
- Not specified to be identical for all operating conditions
- Not specified to be exactly reproducible with individual turbine tests
- Not specified to be energy neutral (for all events)
- Not specified to be overly prescriptive or requiring of impossible power recovery constraints
- Not specified to require delivery of energy beyond that necessary to improve the frequency nadir

In addition, it is important to note that since WTG FFR characteristics are effectively determined by control settings, there is a high degree of flexibility available to technology providers to provide different FFR characteristics (e.g. response time, response duration, output profile, recovery behaviour etc.)

4.3 Other FFR technologies

4.3.1 Solar PV FFR

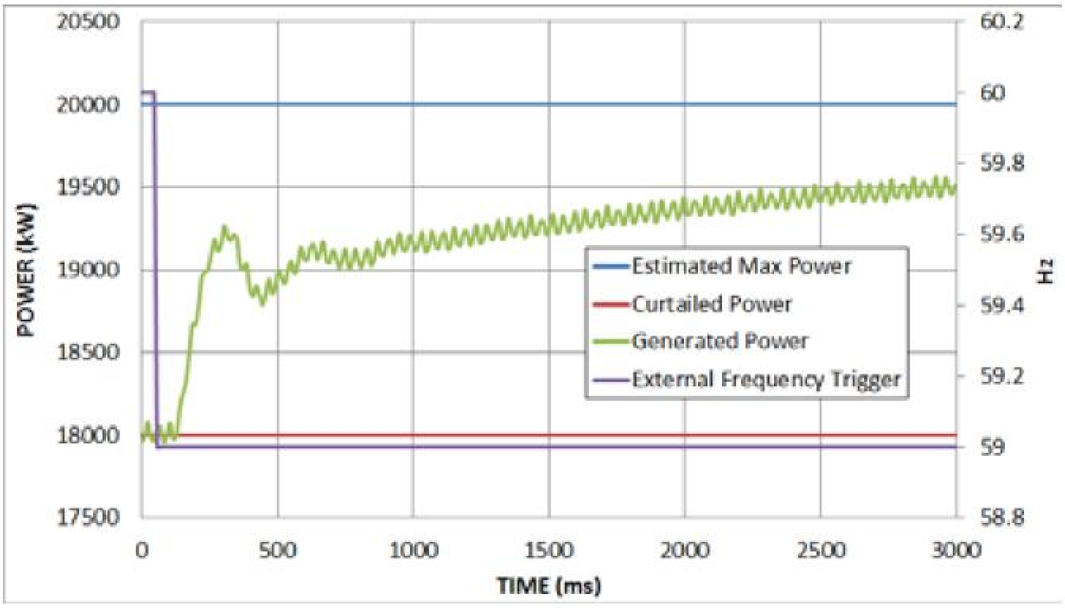
Solar PV has no inherent kinetic energy stored (such as wind). Therefore, if solar PV was to deliver FFR, the inverter would need to be operating at an AC power transfer level lower than the DC power available from the PV panel at the time, and/or power output would need to be curtailed to a level below the available power.

No examples of technical obligations relating to solar PV for FFR were evident based on the literature review.

A trial of solar PV to provide FFR was conducted however for a 20MW solar PV plant and this was documented in a NREL report.

The results indicate that a response time of around 50-100ms is possible and the characteristic of the response depends on the co-ordination between the solar PV MPPT and inverter AC controls. The response based on the trails carried out are replicated in Figure 7.

Figure 7 FFR response for a 20MW PV plant in Puerto Rico



The response of the PV inverter is similar to a battery storage inverter; however there are some differences in the initial response due to differences in the stiffness of the DC bus of a solar PV inverter versus a battery storage inverter [1].

4.3.2 Demand Side Response

Demand side response or load resources can provide high quality FFR. In under-frequency events, rather than asking generators to rapidly increase power, a faster response may be elicited by asking a load to drop power instead.

Modern commercial and industrial loads often have electronically controlled motors and processes which give rise to a class of load resources that can provide sophisticated FFR from demand side response. In ERCOT for example, loads provide half of the interconnected power system's Frequency Responsive Reserves that support the system in a sudden loss of generation event. ERCOT's FFR triggers at 59.7 Hz or 59.8 Hz and provides full response in 500 ms. [1] In New Zealand, the TSO procures a type of Fast Instantaneous Reserve (FIR) specifically from interruptible loads, where load is to be reduced within 1 second and sustained for 60 sec. [3]

It is important that all resources are allowed to participate in potential FFR markets due to the diversity possible market participants. In PJM[3] for example, the minimum size requirement for resource participation was 1MW which acted as barrier to smaller demand response aggregators. [3] [25] Demand side participation increased dramatically after market rules were changed in 2011, where minimum size requirement for resources was lowered from 1MW to 100kW. [25] There is also a practical limit to how much industrial load may be available to participate in fast voluntary load shedding. Rapid communication to a larger number of highly distribute load nodes appears to be gaining practicality. [1]

One of the considerations in using load as an FFR resource is that load may also be providing inertia, which is helping to mitigate RoCoF. Therefore, it may be necessary to assess the characteristics of

[3] PJM Interconnection LLC (PJM) is a regional transmission organization (RTO) in the United States. It is part of the Eastern Interconnection grid operating an electric transmission system serving all or parts of Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia, and the District of Columbia.

potential load-based resources and accept those that can provide the greatest net benefit to the system. [1]

4.3.3 Battery Storage

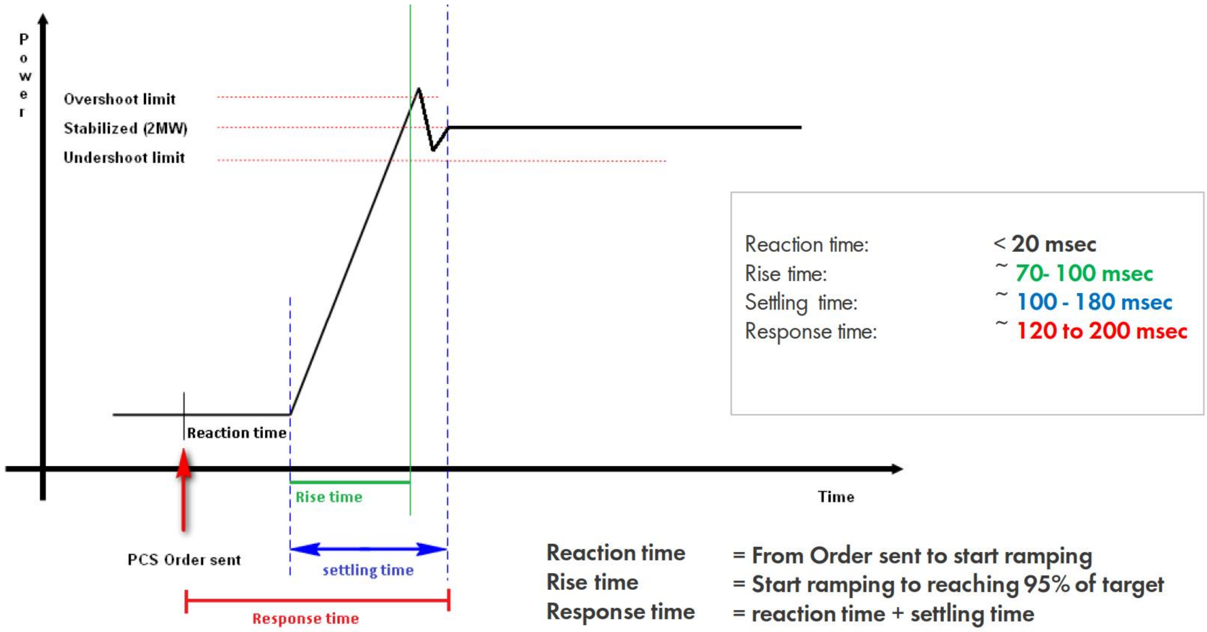
Batteries convert chemical energy into electrical energy, and have the potential to provide useful FFR with extremely fast response times. The technology is generally well established, however significant improvement and further development of the technology is facilitated with increasing uptake globally to supplement intermittent generation.

Battery storage systems comprise a power conversion system (usually inverter and controls) and a battery. Batteries are not limited by chemical response times, but by inverter and control response times. At a plant level, the response time consists of sensing, communication and dispatch to individual inverters [1]. In consultations with battery manufacturers, response time is conservatively estimated to be 120-400 ms. (see an example of a battery response to an FFR signal in Figure 8)

Due to these extremely fast response times, FFR is better implemented directly to the inverters, however the drawback is that the inverter would need to be maintained in a hot standby mode in order to react fast, which induces parasitic losses in the order of 2% of rated power. [1]

The total response time of FFR from batteries is determined by RoCoF detection and communication, which highlights once again the requirement for an adequate monitoring and control system to effectively eliminate significant delays in signalling FFR providers.

Figure 8 Large-scale storage response times (provided in consultation with a battery manufacturer)



5.0 Over Frequency

This report is largely focused on the ability of technologies such as wind and solar generators to deliver adequate response services in the event of under-frequency, where additional power needs to be injected into the network to arrest and stabilise frequency decline. This is of course subject to availability of the energy resource (wind or solar) which cannot be controlled.

Over frequency events would require curtailing output in order to manage the frequency rise. In principal, this can be achieved by either solar PV or wind generation, however the ramp rates would be relatively different.

Ramping down of wind generation has inherent limitations which are defined typically by:

- Converter controls (relatively fast)
- Blade pitching (relatively slow)
- Mechanical loading placed on turbine components.

Based on discussions with turbine supplier, it is understood that ramp rates would be limited to around 20% per second for a modern Type IV wind turbine.

Solar PV inverters do not have any moving parts and the ramp rate would be limited typically by the speed of the maximum power point tracker (MPPT) which would have delays in the order of seconds.

The capability, as mandated in a range of jurisdictions without targeting specific technologies, is shown in Table 8.

Table 8 Over-frequency service requirements in various jurisdictions [3]

Jurisdiction	Notes
EirGrid (Ireland)	EirGrid's Grid Code requires all generators to reduce active power output (automatic or manual) for frequencies above 50.2 Hz in order to contribute to containing and correcting high System Frequency without delay and without receipt of instruction from the TSO. [13] Wind turbines to be shut down completely above 52 Hz. [13]
ERCOT (Texas)	ERCOT has required wind projects to have primary frequency response capabilities, if they are operating at a point where they can do so, since 2010. Wind plants must have adjustable dead bands comparable to conventional resources, and a similar droop to the other resources of 5%. [3]
National Grid (United Kingdom)	National Grid's grid code requires generators to reduce active power output for frequencies above 50.5 Hz at a rate of 2% of the power output per 0.1 Hz of frequency deviation, within 5 min of the deviation occurring. [3]
Eskom (South Africa)	Renewable Power Plants (RPP) in South Africa have a mandatory requirement to provide high frequency response, where they need to reduce active power output for frequencies exceeding 50.5 Hz and completely curtail above 52 Hz. [3] Even though Eskom was not a focus in this review, it is interesting to note that their grid code requires the functionality to effectively spill energy on an ongoing basis in order to provide the ability for an active power increase when required. This frequency set-point is not the default requirement, unless agreed with the TSO. The grid code requires that the frequency set-point can be changed rapidly, commencing within 2 sec and completed within 10 sec. This approach ensures that the TSO can elicit a sophisticated frequency response (to manage both over frequency and under frequency events) from all renewable generators in the system as required, but does not involve substantial ongoing opportunity costs in spilled generation (since this capability is not required to be enabled in unless directed). [3]

6.0 References

[1] GE, “Technology Capabilities for Fast Frequency Response,” 2017.

[2] ERCOT, “ERCOT Concept Paper: Future Ancillary Services in ERCOT,” 2013.

[3] DGA Consulting, “International Review of Frequency Control Adaptation,” 2016.

[4] Commission for Energy Regulation (CER), “Single Electricity Market - DS3 System Services Technical Definitions - Decision Paper - SEM-13-098,” 2013.

[5] I. M. A. B. Ori Agranat, “Fast Frequency Markets and High Penetrations of Renewable Energy in the Australian National Electricity Market,” 2015.

[6] Hydro-Quebec, “Power generation, purchases and exports,” 2017. [Online]. Available: http://www.hydroquebec.com/sustainable-development/energy-environment/power-generation-purchases-exports.html. [Accessed 16 May 2017].

[7] Hydro-Quebec, “Exigences techniques de raccordement de centrales au réseau de transport d'Hydro-Québec,” 2013.

[8] EIA, “Texas: State Profile and Energy Estimates,” 2017. [Online]. Available: https://www.eia.gov/state/analysis.php?sid=TX. [Accessed 18 May 2017].

[9] EIA, “Electric Power Monthly with Data for Feburary 2017,” 2017.

[10] EY, “2014 ancillary service standards and requirements study,” 2014.

[11] Ofgem, “Electricity Interconnectors,” 2017. [Online]. Available: https://www.ofgem.gov.uk/electricity/transmission-networks/electricity-interconnectors. [Accessed 6 June 2017].

[12] EIR Grid Group, “All-Island Generation Capacity Statement 2016-2025,” 2016.

[13] EirGrid, “EirGrid Grid Code Version 6.0,” July 2015.

[14] National Grid, “Frequency Response Technical Sub-Group Report: Grid Code and BSSG,” 2011.

[15] National Grid, “Frequency Response Services,” [Online]. Available: http://www2.nationalgrid.com/uk/services/balancing-services/frequency-response/. [Accessed May 2017].

[16] National Grid, “TESTING GUIDANCE FOR PROVIDERS OF ENHANCED FREQUENCY RESPONSE BALANCING SERVICE,” March 2017.

[17] National Grid, “ENHANCED FREQUENCY RESPONSE - Invitation to tender for pre-qualified parties v2.2,” July 2016.

[18] RenewEconomy, “Did Germany just surpass 100% renewable electricity?,” [Online]. Available: http://reneweconomy.com.au/did-germany-just-surpass-100-renewable-electricity-88700/. [Accessed 31 May 2017].

[19] Renewable Energy Futures to 2050, “How is Germany Integrating and Balancing Renewable Energy Today?,” January 2015. [Online]. Available: http://www.martinot.info/renewables2050/how-is-germany-integrating-and-balancing-renewable-energy-today. [Accessed 31 May 2017].

[20] REGELLEISTUNG.NET - Internetplattform zur Vergabe von Regelleistung, “General information on control reserve - technical aspects,” [Online]. Available: https://www.regelleistung.net/ext/static/technical. [Accessed 7 June 2017].

[21] 50Hertz, “Balancing,” [Online]. Available: http://www.50hertz.com/en/Markets/Balancing. [Accessed 7 June 2017].

[22] European Network of Transmission System Opertors for Electricity, “Who is ENTSO-E,” [Online]. Available: https://www.entsoe.eu/about-entso-e/Pages/default.aspx. [Accessed 31 May 2017].

[23] DNV GL, “RoCoF Alternative Solutions Technology Assessment,” 2015.

[24] C.-E. L. Mohamed Asmine, “Field Measurements for the assessment of inertial response for wind power plants based on Hydro-Quebec TransEnergie requirements,” *IET Journals,* 2015.

[25] Synapse Energy Economics Inc., “Synapse Comments on FAST Proposals in ERCOT,” 2014.

[26] Hyrdo-Quebec, “Transmission Provider Technical Requirements for the Connection of Power Plants to the Hydro-Quebec Tranmission System,” 2009.

[27] EIR Grid Group, “All-Island Generation Capacity Statement 2016-2025,” 2016.

[28] EIRGRID, “North South Interconnector Answering Your Questions,” 2016.

[29] EirGrid Group, “Celtic Interconnector,” EIRGRID PLC 2015, [Online]. Available: http://www.eirgridgroup.com/the-grid/projects/celtic-interconnector/the-project/. [Accessed 05 2017].

[30] National Grid, “Smart Frequency Control Project,” [Online]. Available: http://www.nationalgridconnecting.com/The_balance_of_power/. [Accessed May 2017].

[31] European Commission, “System Operation Guideline,” 2016.