RoCoF Alternative & Complementary Solutions Project

Phase 2 Study Report

31st of March 2016

EIRGRID SONI

Disclaimer

Executive Summary

EirGrid and SONI are the Transmission System Operators (TSOs) in Ireland and Northern Ireland. As Transmission System Operator (TSO) in Ireland and Northern Ireland, it is our job to manage the electricity supply and the flow of power across the island of Ireland. This work is done from the National Control Centre (NCC) in Dublin and the Castlereagh House Control Centre (CHCC) in Belfast.

Electricity is generated from gas, coal and renewable sources (such as wind and solar power) at sites across the island. Our high voltage transmission network then transports electricity to high demand centres, such as cities, towns and industrial sites. We operate the transmission system in a safe, secure and economical way.

One of our key tasks is to maintain balance between electricity supply and electricity demand. Electrical frequency is the measure of balance between supply and demand. When supply and demand are balanced, the electrical frequency is at 50 Hz. We must maintain this balance on the system all day, every day.

Imbalances between supply and demand occur from time to time on the power system. For example, if a large electrical generator suddenly disconnects and its electrical power is lost. In this scenario, the supply from the system is temporarily below the demand and the system frequency begins to fall. EirGrid and SONI are responsible for restoring the balance in the seconds and minutes after the event occurs. Restoring the balance returns the electrical frequency to 50 Hz.

One of our interests in a system imbalance event is the rate at which the frequency falls. This is known as the rate of change of frequency (RoCoF). Events that result in high RoCoF levels can potentially lead to instability in the power system. All power systems, including the Irish power system, have inertia. Inertia is a resistance to change in motion. The inertia on the power system resists the RoCoF and helps maintain system stability. This report investigates the use of different sources of inertia and how they can aid in restricting the RoCoF following large system imbalances. The paper is technical in nature and is aimed at a technical audience.

The report outlines the studies performed as part of the analysis for the second phase of the rate of change of frequency (RoCoF) Alternative and Complementary Solutions project. Our aim was to determine volumes of synchronous and/or synthetic inertia to maintain RoCoF at 0.5 Hz/s.

Our findings from the analysis presented in the report are as follows:

a) Synchronous inertia is a solution to maintaining RoCoF within ± 0.5 Hz/s. Technical studies support current operational policy that relates the system inertia requirement with the largest single infeed. The studies indicate that a system inertia of 20,000 MW.s, or greater, would need to be retained for the majority of dispatches to maintain potential RoCoF within 0.5 Hz/s. This equated to approximately 12,000 MW.s of supplementary synchronous inertia being added to the 1 Hz/s base case scenario in the study. Adding further system constraints to the base case, such as minimum reserve requirements, reduces the amount of supplementary synchronous inertia required.

b) Synthetic inertia could be a solution to maintaining RoCoF within ± 0.5 Hz/s, however, there were challenges associated with these devices. The performance of the synthetic inertia devices, for the purposes of maintaining the RoCoF within ± 0.5 Hz/s, was found to be highly sensitive to the characteristics of the response. In particular, the device response time and ramp rate were of significant importance. In order to meet the RoCoF criteria, it was found that the following criteria would need to be satisfied:

    - to begin responding from 100 milliseconds from the start of the event.
    - to ramp at a sufficient rate to deliver power to the system. For the system to remain within the RoCoF limit, the active power injection must be fully achieved 200 milliseconds after the device begins to respond.
    - a suitable form of control to prevent unintended adverse system issues during the frequency recovery, and

- a minimum of ±360 MW of supplementary synthetic inertia would need to be available for the duration of the RoCoF event.
- Synthetic inertia response is required for both high and low frequency events.

c) A combined synchronous and synthetic inertia response to system events may deliver a suitable result. The results are highly sensitive to the synthetic device characteristics and careful consideration would be required to determine the appropriate combination of synchronous and synthetic devices.

d) A solution involving synthetic devices would likely require a TSO-led project where response characteristics would be developed and clearly defined. The TSOs would need to fully understand the capabilities of these devices through further detailed analysis and/or demonstration testing.

Our analysis presented within this report illustrates that there are credible alternative solutions to the RoCoF issue. Synchronous inertia provides a solution to resolving the RoCoF issue. The provision of synchronous inertia could be from many solutions including:

- significant reduction of existing minimum generation levels of conventional plant,
- synchronous storage devices such as compressed air or pumped-hydro storage,
- rotational stabilisers,
- synchronous compensators,
- flexible generating plant.

We also found that synthetic inertia devices could provide a solution to the RoCoF challenge. A wide range of possible synthetic inertia solutions have been considered as part of the project which include:

- non-synchronous storage devices including battery, flow-battery, flywheel and super-capacitor technologies,
- Wind turbines,

- HVDC interconnectors,
- Demand Side Management.

There is a wide range of possible synthetic inertia technologies and we believe that further detailed analysis or device testing would be required to gain a full appreciation of the capabilities of these devices. Our analysis has indicated that the suitability of synthetic devices for solving the RoCoF issue is highly dependent on the device response characteristic. Widespread application of these devices on the system to resolve RoCoF would require further analysis. We are also of the view that a project to develop an appropriate system-wide synthetic inertia scheme would be required. A project of this nature would require a TSO lead approach with industry engagement.

We believe that the project has demonstrated that alternative solutions are available to resolve the RoCoF issue. At this stage, we believe that further analysis on alternative solutions to the RoCoF issue should only be performed if results from the primary RoCoF projects indicate that alternatives are required. The analysis conducted as part of the RoCoF Alternatives Study should not be perceived as the commencement of a procurement process for synchronous or synthetic devices.

Contents

Glossary of terms

AC electricity – alternative current (AC), a type of power used to deliver electrical power to businesses and residences.

Active Power – is the instantaneous measure of true power, measured in units of watts.

CER - The Commission for Energy Regulation ('the CER') is the independent body responsible for overseeing the regulation of Ireland's electricity and gas sectors. The CER was initially established and granted regulatory powers over the electricity market under the Electricity Regulation Act 1999.

Contingency - The unexpected failure or outage of a system component, such as a generation unit, transmission line, transformer or other electrical element. A contingency also may include multiple components, which are related by situations leading to simultaneous component outages.

Conventional Generation - Types of generation technologies in existence prior to emergence of renewable energy generators.

DC electricity – direct current (DC) is used for sending electricity long distances, frequently underground or beneath the sea and often between countries.

Delivering a Secure Sustainable Electricity (DS3) - The aim of the DS3 Programme is to meet the challenges of operating the electricity system in a secure manner while achieving the 2020 renewable electricity targets.

Demand - The electrical power consumed by the end-user.

Distribution line – is normally considered to be a line that is used to deliver power drawn from the high-voltage transmission systems to end-use customers.

Distribution system – is the system which consists of electric lines, electric plant, transformers and switchgear and which is dedicated to delivering electric energy to an end-user.

Droop - The percentage drop in the frequency that would cause a generating unit under free governor action to change its output from zero to its full capacity.

Distribution System Operator (DSO) - Electricity Supply Board (ESB) Networks is a DSO licenced by the CER to manage and operate the sub-transmission electricity grid across Ireland. NIE Networks (NIE) is a DSO is licenced by the UR to manage and operate the sub-transmission electricity grid across Northern Ireland.

EirGrid – is a state-owned company that manages and operates the high voltage electricity grid across Ireland. EirGrid is responsible for planning for the future of the grid.

EirGrid Group - EirGrid and SONI are part of the EirGrid Group.

Energy import and export – Ireland imports and exports energy on to the transmission system using two interconnectors that link it to the UK; the East West and Moyle Interconnectors.

Event - An unscheduled or unplanned occurrence on the electrical grid, including faults, incidents and breakdowns.

Frequency – the number of complete cycles per second in AC direction. The standard unit of frequency is the hertz, abbreviated Hz. If a current completes one cycle per second, then the frequency is 1 Hz. The standard frequency in Ireland is 50 Hz.

Frequency response - The automatic adjustment of active power output from a generation unit(s) or interconnector in response to frequency changes.

Generator – a machine that converts energy into electricity.

GB (Great Britain) – The lands of England, Scotland and Wales.

Grid – a network or ‘energy motorway’ made up of high-voltage overhead lines and underground cables, as well as transmission stations. The network links energy users with energy creators. It is designed to ensure that power can flow freely to where it is needed.

Grid Code – a technical requirement document prepared by the TSO and approved by the CER to ensure safe, secure operation of the electrical transmission grid system.

Inertia – is the resistance of an object to a change in its motion.

Interconnector – a high voltage transmission line connecting the electricity networks of two separate locations.

NIE Networks - NIE owns and maintains the wires and meters for all electricity customers in Northern Ireland.

Non-synchronous (synthetic) inertia – is the injection of energy from Non-synchronous generation device in response to a system event.

Non-synchronous generation – is a generator which supplies power to the electrical Grid via power electronics. Power electronics are used to adjust the speed and frequency of the generated energy (typically associated with wind energy) to match the speed and frequency of the transmission network.

Renewable energy – is energy from a non-exhaustible resource such as the sun or wind.

Rate of change of frequency (RoCoF) – is the change in system frequency over a certain time. The unit of measurement is Hertz per second abbreviated as Hz/s.

SONI – is the licenced electricity system operator for Northern Ireland and is responsible for planning for the future of the grid.

Synchronous inertia – is the kinetic energy released by a synchronous generator directly after a change in the system frequency. The measurement unit of synchronous inertia is MW.s.

Synchronous generation (conventional generation) – in an AC power system; synchronous generators are directly connected to the grid. The speed and frequency of a generator matches the running network, changes in system transmission frequency are matched by the generator. Types of generation fuel include coal, gas, oil, water and biomass.

Transmission grid infrastructure – is the physical structures which make up the transmission grid. These include the cables and lines used to transmit electricity, the pylons which hold the lines, and the substations used to convert the electrical current and raise or lower the voltage of that current.

Transmission line – a high-voltage power line transmits (sends) electricity across long distances. Voltages in Ireland are: 400 kV, 275 kV 220 kV, or 110 kV.

Transmission network – an electricity network made up of power lines, cables and substations. It links energy creators with the distribution system.

Transmission System Operator (TSO) - The TSO is responsible for managing and operating the high voltage electricity grid. EirGrid and SONI are licenced by the CER and UR as the Transmission System Operator for Ireland and Northern Ireland respectively.

System Non-Synchronous Penetration (SNSP) - is a measure of the non-synchronous generation on the system at an instant in time.

Synchronous compensator – is rotating synchronous device for the specific purpose of either generating or absorption of reactive power.

Utility Regulator (UR) - an independent non-ministerial government department set up to regulate the electricity, gas and water and sewerage industries in Northern Ireland.

Voltage – this is a measure of ‘electric potential’, which is similar to ‘pressure’ in a water system. Just like water needs pressure to force it through a hose, electrical current needs a force to make it flow. This force is called the voltage and is usually supplied by a battery or a generator.

1 Introduction

1.1 Background

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1.2 Rate of Change of Frequency Project

We have a responsibility to enable increased levels of renewable sources, such as wind and solar, to generate on the power system of Ireland and Northern Ireland. We must to deliver this whilst also ensuring secure electricity supply. The Delivering a Secure Sustainable Electricity System (DS3) programme was initiated by EirGrid and SONI to address the challenges of integrating renewable generation on the power system. One of the key projects within DS3 is to resolve increased rate of change of frequency (RoCoF) that may arise on the system following large system disturbances.

Analysis has indicated that high RoCoF events could threaten the security of the power system during times of high system non-synchronous penetration (SNSP). To resolve this issue, EirGrid and SONI proposed increased RoCoF standards for generators connected to the power system. We have also engaged with the Distribution System Operators (DSOs) to change protection settings to allow for the higher standard.

The Commission for Energy Regulation (CER) and Utility Regulator (UR) decided to introduce a Rate of Change of Frequency (RoCoF) standard of 1 Hz/s in Ireland and 2 Hz/s in Northern Ireland. The updated standards will only be introduced when it is appropriate. CER and UR have established a three stage project to achieve this. These three strands are as follows:

1. Generator Studies Project
2. TSO-DSO Implementation Project
3. Alternative Solutions Project

The Generator Studies Project assess if generators can endure the higher 1 Hz/s RoCoF standard. The regulators are targeting a staged introduction of this new RoCoF standard over a period of 18 to 36 months.

The regulators have also instructed EirGrid and SONI to investigate alternatives to the inertia problem. The alternative solutions seek to maintain sufficient system inertia rather than changing the RoCoF standard from 0.5 Hz/s.

1.3 RoCoF Alternatives Project

In November 2014, EirGrid and SONI engaged with industry representatives on the scope of the RoCoF Alternative Solutions Project. We finalised the project plan following feedback from industry. The project outline was divided into two phases:

- **Phase 1:** The initial phase was a review of alternative technology solutions. A range of options were assessed. We used a high-level weighted scoring matrix approach. The scoring criteria we considered included technical suitability, technology maturity and lead-time assessments. This high-level assessment provides the basis for our Phase 2 analysis.
- **Phase 2:** This study involved a more detailed review of options we selected from Phase 1. The analysis focuses on technical and economic aspects of each of the shortlisted options.

1.4 Overview of Phase 1 Analysis

EirGrid and SONI commissioned DNV GL to perform the technology assessment as part of phase 1 of the RoCoF Alternative Solutions project. In June 2015, DNV GL produced the report "RoCoF Alternatives Technology Assessment". The report details the high-level assessment of each technology considered in Phase 1. DNV GL developed a weighted scoring matrix to perform the high-level assessment of each technology.

The paper begins by introducing the concepts of synchronous and non-synchronous (synthetic) inertia. The distinction of these inertia types is important as the technologies in the report fall into one of the two categories. Examples of synchronous inertia devices include conventional generators, synchronous compensators and rotational stabilisers. Synthetic inertia devices include wind turbines, batteries, flywheels and HVDC interconnectors.

The paper introduces the concepts of RoCoF detection methodologies and response time for synthetic inertia devices. DNV GL separated the total response time of a device into four elements:

- Measurement Time – the time required to measure or detect the RoCoF event
- Signal Time – the time to issue a signal to the device to initiate a response
- Activation Time – the time for the device to deliver its initial active power response
- Ramp Time – the time for the device to ramp its active power response

The detection methodology and response time are key parameters for synthetic inertia devices to prevent high RoCoF events. The report recommended that this be analysed in further detail as part of the phase 2 analysis.

DNV GL performed the high-level assessment of the characteristics of 13 technologies. DNV GL developed one-page ‘faceplate’ assessments for each technology. These faceplates were used to contribute to the high-level scoring matrix assessment. Short narratives were included with the assessments of each technology.

The results from the weighted scoring matrix placed synchronous devices higher than non-synchronous devices. This trend reflects that synchronous inertia is currently the most established technology for preventing high RoCoF occurrences. The results also reflect the challenges of RoCoF event detection for non-synchronous devices. EirGrid and SONI note that the scoring matrix did not result in a clear favoured approach to resolving the RoCoF challenge. We also note that rather than having one specific technology solution, a combination of technologies may need to be deployed.

Following our evaluation of the results obtained from the weighted scoring matrix, we determined that it would not be beneficial to discount specific technologies analysed by DNV GL. We decided that the option of construction of an AC interconnection to

Great Britain would be the only option omitted. This was because the timelines for installing an AC connection to GB would be beyond the timeframe of the RoCoF project.

We determined that, rather than assessing individual technology devices in detail in phase 2, we would analyse synchronous and synthetic inertia on a generic basis. We believe that this approach enabled us to conduct more efficient analysis on the full range of devices. We classified each device as synchronous or synthetic. We then assessed devices based on a generic representation in phase two.

1.5 Overview of Phase 2 Analysis

Our objective in the second phase of the RoCoF alternative project was to study the deployment of synchronous and synthetic inertia for prevention of high RoCoF events. The analysis involved a combination of technical and techno-economic studies with the aim of determining the required volumes of synchronous and/or synthetic inertia. Our objective was to maintain RoCoF at 0.5 Hz/s whilst allowing for the System Non-Synchronous Penetration (SNSP) to reach 75%. We also performed sensitivity analysis to investigate the issues around RoCoF detection and response time for synthetic devices. The following studies were performed as part of Phase 2.

- Techno-economic ‘base case’ study: RoCoF set at 1 Hz/s and SNSP set to 75% were the only system constraints included.
- Technical Studies: Frequency Stability studies for each scenario from the hourly economic generation dispatch using EirGrid’s Automated Dynamic Studies tool. Synchronous and/or synthetic inertia is added until the potential RoCoF is reduced from 1 Hz/s to 0.5 Hz/s for each hour in the year.
- Technical Sensitivities: Sensitivity analysis was conducted by varying the characteristic responses of the synthetic inertia devices to determine the impact of modified responses on the volume of inertia requirement for the system.

The sensitivity analysis focused on the device response time to the RoCoF event. Our aim was to inform the requirements for response times for non-synchronous devices to ensure RoCoF is adequately managed. The outcomes specified for the study included:

- A range of quantities of synchronous inertia required to yield a RoCoF of no greater than 0.5 Hz/s will be given for a range of hours over the year.
- A range quantities of synthetic inertia required to yield a RoCoF of no greater than 0.5 Hz/s will be given for a range of hours over the year.
- An outline for proportions of a combination of synchronous to synthetic inertia volumes to yield a RoCoF of no greater than 0.5 Hz/s will be provided.
- An outline of the acceptable response time and active power ramp rate of a synthetic device for the purposes of RoCoF mitigation.

All analyses conducted in Phase 2 of the project were from the perspective of resolving the RoCoF issue only and are not an assessment of each technology's ability to provide DS3 System Services. Assessments of the provision of system services will be conducted as part of the DS3 System Services project. The scope does not include the establishment of the commercial arrangements for the delivery of any potential alternative solutions. The project is essentially a technology assessment and does not constitute a first step in a procurement process.

1.6 Report Outline

This report describes the analysis performed as part of phase 2 of the RoCoF Alternative Solutions Project. A discussion on the study results is provided in section 0 of the report. Section 3 provides a description of the Phase 2 study outline including the approach, assumptions and device modelling methodology. Section 4 outlines the results obtained from the techno-economic and technical studies. Study findings are presented in section 5.

2 Discussion of results

This study aimed to analyse the deployment of synchronous and synthetic inertia with a view to preventing high rate of change of frequency (RoCoF) events. Frequency stability studies were performed to provide an indication of the volumes of synchronous and/or synthetic inertia devices required to maintain system RoCoF within 0.5 Hz/s calculated over 500 milliseconds (ms) for 99% of cases analysed. A wide range of sensitivities were considered however it is recognised that further analysis would be required in certain aspects of the study. The study initially generates techno-economic dispatches with the system constrained only by SNSP and RoCoF. The SNSP limit was set to 75% and RoCoF was set to 1 Hz/s. The study is concerned with resolving the initial RoCoF on the system and therefore the period for analysis is limited to 2.5 second after the system event. Transient stability, voltage stability or other frequency stability requirements outside of this time period were not considered as part of the study.

2.1 Selection of the techno-economic base case

The techno-economic analysis indicates the differences in inertial requirements for a system constrained by RoCoF at 1 Hz/s and a system with a 0.5 Hz/s constraint. The results obtained for the 0.5 Hz/s constraint resulted in inertia levels that are similar to those currently employed on the power system.

To evaluate the impact of additional constraints on the techno-economic model, the following sensitivities were investigated:

- Reduced minimum generation level of large conventional generators.
- Inclusion of primary/secondary operation reserve (POR/SOR) constraint.

These sensitivities are not considered in the technical analysis. The purpose of these sensitivity studies was to determine how additional constraints would affect the base case inertia level.

The results from the techno-economic analysis indicated that reduction of minimum generation, in itself, would not result in material change in the inertia levels deployed.

It should be noted that the reduction of minimum generation levels could act as a solution for introducing supplementary synchronous inertia to the system.

Analysis of an additional primary/secondary operating reserve constraint indicated that on average approximately 2,500 MW.s of additional inertia would be constrained on the system. This indicates that an extra mid to large unit would be deployed on the system to meet the additional constraint.

2.2 Base case results

Results suggest that the device response time following a system frequency event is crucial when attempting to maintain RoCoF within ± 0.5 Hz/s calculated over 500 ms in a system with low inertia. In 59% of the analysed cases, the RoCoF exceeded 0.5 Hz/s between 200 and 500 milliseconds after the system event.

2.3 Synchronous inertia studies

The synchronous inertia studies determined the volume of supplementary inertia requirement, following the sudden loss of generation or load, required to maintain RoCoF within ±0.5 Hz/s (calculated over 500 ms) in 99% of solved simulations.

Supplementary synchronous inertia is represented as a standard synchronous machine with no additional frequency response capability.

A tabulated summary displaying which scenarios meet the acceptance criterion, as defined in Section 3.2.10, is presented in

Table 2.3.1. This summary table presents the cases where RoCoF is maintained within ±0.5 Hz/s and where the frequency nadir or zenith breaches the 49 Hz or 51 Hz frequency limits, respectively. A ‘tick’ in a green cell signifies that the criteria are met for the corresponding scenario. An ‘x-cross’ in a red cell signifies that the criteria was not met for the corresponding scenario. A grey shaded cell indicates where a study was not performed for a particular sensitivity.

Table 2.3.1: Summary table of supplementary synchronous inertia scenarios

Volume (MW.s)	Event type	Criteria					
		>-0.5Hz/s	<+0.5Hz/s	>-0.8Hz/s	<+0.8Hz/s	>49Hz	<51Hz
2400	Under frequency	X	✔	✔	✔	X	N/A
4000		X	✔	✔	✔	X	N/A
5600		X	✔	✔	✔	X	N/A
8000		X	✔	✔	✔	X	N/A
12000		✔	✔	✔	✔	X	N/A
16000		✔	✔	✔	✔	✔	N/A
20000		✔	✔	✔	✔	✔	N/A
5600	Over frequency	✔	X	✔	✔	N/A	X
8000		✔	X	✔	✔	N/A	X
12000		✔	✔	✔	✔	N/A	X
16000		✔	✔	✔	✔	N/A	✔

Figure 2.3-1 displays the synchronous inertia duration curves from the techno-economic and technical studies. The results from the technical studies correlate well with the results from the techno-economic studies where the RoCoF constraint was at 0.5 Hz/s. The similarity of both duration curves offers further validity to the technical study approach. Both sets of results also provide support for the existing operational policy of maintaining system inertia relative to the largest system infeed. The minimum system inertia requirement is found to be greater than 20,000 MWs in 94% of cases.

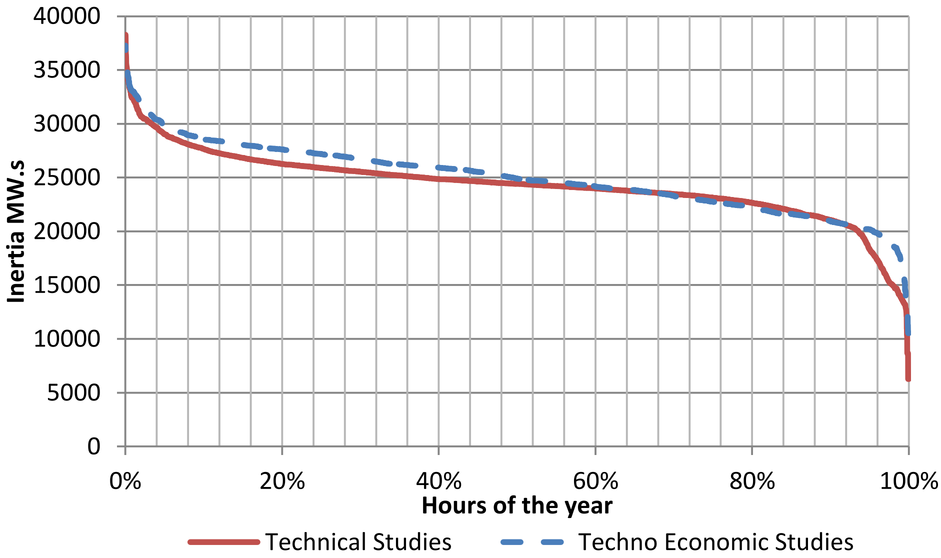

Figure 2.3-1: Duration curves of the required synchronous inertia calculated by the technical studies and the techno-economic inertia requirement calculated as per case A of Table 4.1.1

The synchronous inertia studies indicated that the initial RoCoF could be maintained within the ±0.5 Hz/s in 99% of the cases analysed. The results also indicated that, unlike the synthetic inertia case, no adverse issues during the frequency recovery phase. This is due to the inherent nature of synchronous inertia devices and how they react to system frequency events. The results confirm that synchronous inertia provides the most a robust solution to preventing high RoCoF events.

2.4 Synthetic inertia studies

The synthetic inertia studies determined the volume of synthetic inertia, following the sudden loss of generation or load, required to maintain RoCoF within ±0.5 Hz/s (calculated over 500 ms) in 99% of solved simulations. Synthetic inertia is required to consume and provided power.

Supplementary synthetic inertia is represented by a customised model configured to provide an active power response with particular characteristics. The primary characteristic of the active power response is such that the active power output is ramped up or down and held for a defined duration. Sensitivities of the synthetic inertia response were performed in the study. The following device performance sensitivities were examined:

- Frequency-triggered synthetic inertia examining various trigger set-points.
- RoCoF-triggered synthetic inertia examining various trigger set-points.
- Frequency-triggered synthetic inertia with a RoCoF-triggered blocked recovery.
- Time-triggered synthetic inertia examining various trigger set-points.
- Controlled droop synthetic inertia response examining various droop settings.
- Frequency-triggered synthetic inertia with a droop controlled recovery.
- Varied response ramp-rate for the synthetic device.
- Frequency triggered synthetic inertia with load model variations.

Table 2.4.1 summarises the study scenarios and whether these scenarios met the acceptance criterion. This summary table also presents whether RoCoF is maintained within ±0.5 Hz/s and whether the frequency nadir/zenith exceeds 49/51Hz, respectively. A 'tick' in a green box signifies that the criterion is met for the corresponding scenario. An 'x-cross' in a red box signifies that the criterion was not met for the corresponding scenario. A grey shaded cell indicates where a study was not performed for a particular sensitivity. Further sensitivity analysis is discussed in the appendices section.

A description of the findings for each of the synthetic inertia sensitivity scenarios is shown below:

Fast ramping frequency triggered synthetic inertia response

Fast ramping supplementary synthetic inertia of 360 MW would resolve RoCoF if the frequency trigger was set to 49.9 Hz and 50.1 Hz. A frequency trigger within 0.1 Hz of nominal frequency would, for some events, result in over-provision of active power following small frequency excursions. This could possibly result in unintended operational issues which in turn could lead to a violation of RoCoF during frequency recovery. Therefore, an uncontrolled, static provision of synthetic inertia response appears to be an unsuitable solution to resolving the RoCoF issue.

At a trigger setting of 49.8 Hz and 50.2 Hz, that event the 'no-limit' synthetic inertia response would not maintain RoCoF within ±0.5 Hz/s in 99% of cases. A frequency trigger within 0.2 Hz of nominal frequency would require an active power response in excess of the power systems LSI or LSO to resolve RoCoF. This fast injection/consumption of active power would lead to violations of RoCoF during recovery and an overshoot of the nominal frequency. However, it should be noted that frequency sensitivity of the load may improve the performance of the synthetic devices and result in the 400 MW synthetic inertia case reaching the criteria.

Following the initial frequency triggered analysis, subsequent frequency triggered synthetic inertia sensitivity studies were set to trigger at 49.8 Hz with no other additional time delay.

Table 2.4.1: Summary table of synchronous inertia scenarios

	Volume	Event Type	Response Setting	Criteria					
				>-0.5Hz/s	<+0.5Hz/s	>-0.8Hz/s	<+0.8Hz/s	>49Hz	<51Hz
Frequency trigger	80 MW	Under frequency	49.8Hz	X	✔	X	✔	X	N/A
	160 MW			X	✔	✔	✔	X	N/A
	200 MW			X	✔	✔	✔	X	N/A
	240 MW			X	✔	✔	✔	✔	N/A
	300 MW			X	✔	✔	✔	✔	N/A
	360 MW			X	✔	✔	✔	✔	N/A
	400 MW			X	✔	✔	✔	✔	N/A
	440 MW			X	✔	✔	✔	✔	N/A
	No Limit			✔	X	✔	✔	✔	N/A
	360 MW		49.9Hz	✔	✔	✔	✔	✔	N/A
	400 MW			✔	✔	✔	✔	✔	N/A
	440 MW			✔	✔	✔	✔	✔	N/A
	No Limit			✔	X	✔	✔	✔	N/A
	240 MW	Over frequency	50.2Hz	✔	X	✔	✔	N/A	✔
	300 MW			✔	X	✔	✔	N/A	✔
	360 MW			✔	X	✔	✔	N/A	✔
	400 MW			✔	X	✔	✔	N/A	✔
	No Limit			✔	✔	✔	✔	N/A	✔
	300 MW		50.1Hz	✔	X	✔	✔	N/A	✔
	360 MW			✔	✔	✔	✔	N/A	✔
	400 MW			✔	✔	✔	✔	N/A	✔
	No Limit			✔	✔	✔	✔	N/A	✔
RoCoF trigger	No Limit	UF	0.2Hz/s	X	✔	X	✔	X	N/A
			0.3Hz/s	X	✔	X	✔	X	N/A
			0.4Hz/s	X	✔	X	✔	X	N/A
Time trigger	360 MW	Under frequency	0ms	✔	✔	✔	✔	✔	N/A
			100ms	✔	✔	✔	✔	✔	N/A
			200ms	X	✔	✔	✔	✔	N/A
			300ms	X	✔	✔	✔	✔	N/A
	400 MW		0ms	✔	✔	✔	✔	✔	N/A
			100ms	✔	✔	✔	✔	✔	N/A
			200ms	X	✔	✔	✔	✔	N/A
			300ms	X	✔	✔	✔	✔	N/A
Controlled droop response db= 0.05Hz	No limit	Under frequency	4%	X	✔	X	✔	X	N/A
			2%	X	✔	✔	✔	✔	N/A
			1%	X	✔	✔	✔	✔	N/A
			0.75%	X	✔	✔	✔	✔	N/A
			0.5%	X	✔	✔	✔	✔	N/A
			0.25%	✔	✔	✔	✔	✔	N/A
Step and droop response	No limit	Under frequency	4%	✔	✔	✔	✔	✔	N/A
Variation of ramp-rate	No limit	Under frequency (49.8Hz)	2300MW/s	X	✔	✔	✔	✔	N/A
			1450MW/s	X	✔	✔	✔	✔	N/A
			1150MW/s	X	✔	✔	✔	✔	N/A
			750 MW/s	X	✔	✔	✔	✔	N/A
			575 MW/s	X	✔	✔	✔	✔	N/A
			450 MW/s	X	✔	X	✔	✔	N/A
			350 MW/s	X	X	X	✔	✔	N/A
			300 MW/s	X	X	X	✔	✔	N/A
Influence of load model variation	360 MW	Under frequency (49.8Hz)	1%	X	✔	✔	✔	✔	N/A
	400 MW			X	✔	✔	✔	✔	N/A
	No limit			✔	X	✔	✔	✔	N/A
	360 MW		2%	X	✔	✔	✔	✔	N/A
	400 MW			X	✔	✔	✔	✔	N/A
	No limit			✔	X	✔	✔	✔	N/A

RoCoF-triggered synthetic inertia examining various trigger set-points

A RoCoF controlled response to a system event calculated over 500 ms was not seen to be a suitable technique to provide an alternative to increasing the RoCoF limit. A significant number of cases analysed were seen to breach the RoCoF criteria.

This was true even for more aggressive RoCoF trigger levels. As mentioned above, a significant portion of RoCoF events exceeded 0.5 Hz/s between 200 and 500 milliseconds after the event. Therefore, the synthetic inertia devices would need to respond in advance of these times. The TSOs recognise that devices may be capable of detecting RoCoF over a shorter time period, however, there would be challenges in accurately detecting a RoCoF event in shorter time frames which could result in similar operational issues observed in the static frequency triggered cases. Further analysis of alternative RoCoF detection methodologies would be required to understand these potential issues.

Time-triggered synthetic inertia examining various trigger set-points

The time triggered sensitivity aimed to quantify the impact of device detection and response time on the ability of synthetic devices to prevent high RoCoF events. The case does not consider any specific frequency or RoCoF triggering. The simulation only considers a specified time delay as the trigger and aims to give an indication of the time in which a device must react to an event irrespective of the underlying event detection method utilised.

The studies showed that a slower response time for the synthetic inertia response would result in a greater the number of cases that exceed a RoCoF of 0.5 Hz/s. These simulations suggest that the active power response should begin to respond approximately 100 ms after the event to resolve RoCoF in 99% of the cases analysed. This conforms with the finding that a large number of events exceeded the RoCoF limit between 200 and 500 milliseconds and therefore a rapid response time is required.

Controlled droop synthetic inertia response examining various droop settings

This study investigated the use of a droop controlled synthetic inertia response. The study indicated that the standard setting of a 4% droop would be insufficient in preventing high RoCoF events. It was found that a more aggressive droop of approximately 0.25% would be required to resolve the RoCoF issue for 99% of the cases analysed. The application of such a droop on the system would need to be analysed further by the TSO to ensure that the wider frequency stability of the grid is not compromised by this setting.

Frequency-triggered synthetic inertia with a droop controlled recovery

This sensitivity aimed to provide a solution to the unintended frequency recovery issues observed in the frequency-triggered static synthetic inertia responses. In this case, the synthetic device was configured to employ a frequency-triggered active power injection response to the RoCoF event. Following this initial response, the device monitored system frequency RoCoF to determine when the system frequency started to recover. Once the recovery was detected, the device transitioned to a droop controlled response to adjust its active power injection. This configuration was shown to be successful in the simulations by reducing the number of adverse recovery events observed in the results. It should be noted that the device would still be required to react to the initial RoCoF event in a suitable timely manner to prevent higher RoCoF events.

Variation of ramp-rate of supplementary inertia

This analysis highlights that the ability of a synthetic inertia device to prevent high RoCoF events is highly sensitive to the ramp rate of the device. The results indicated that a slower ramp-rate for the active power response resulted in a greater number of cases exceeding the RoCoF limit of 0.5 Hz/s.

Frequency triggered synthetic inertia with load model variations

The composition of the load was found to significantly influence the results for synthetic inertia devices. The impact of load frequency response is seen to have a larger impact in cases of low system inertia. Further analysis of the frequency response of the load will be required to understand the impact of load response. The base-case load model used in these studies is a conservative load model.

In summary, synthetic inertia performance is highly sensitive to a number of parameters in the response characteristic. In particular, device response time and active power ramp rate are key parameters for the synthetic inertia device. The results indicate that a response time of approximately 100 ms would be required to prevent RoCoF events in excess of 0.5 Hz/s in 99% of cases analysed. Similarly, a rapid ramp rate in the region of 1500 MW/s would be required to prevent high RoCoF events.

It should be noted that synthetic devices that inject large amounts of active power to prevent a RoCoF event could cause adverse issues during the frequency recovery phase. To avoid these unintended consequences, a controlled recovery was proposed would be required. The analysis demonstrated that a droop controlled response in the frequency recovery period would offer a suitable resolution to these issues.

2.5 Synchronous and synthetic inertia combination studies

The purpose of this study was to analyse various combinations of synchronous and synthetic inertia volumes to determine an indication of a solution that could deploy both types of devices. This aimed to provide an indication of the possible relationship between adding synchronous and synthetic inertia to the system. Only under-frequency events are analysed in this set of studies.

Table 2.5.1 summarises the results for the scenarios investigated in the study. This summary table presents whether each scenario met the RoCoF criteria of ±0.5 Hz/s and the frequency nadir criteria of 49 Hz. A ‘tick’ in a green box signifies that the criterion is met for the corresponding scenario. An ‘x-cross’ in a red box signifies that the criterion was not met for the corresponding scenario. A grey shaded cell indicates a scenario where the study was not performed.

The results indicate that there are several combinations of synchronous and synthetic that would meet the criteria. It should be noted that the results are highly sensitive to the response characteristic of the synthetic devices. The results were found to be highly dependent on the performance of the synthetic devices. It is likely that there would be careful consideration into the breakdown of synchronous inertia and synthetic inertia. In practice, the TSOs would need to appropriately design the frequency response of the devices to the required system needs. Further analysis would be required to fully understand the possibilities for combining synchronous and synthetic devices.

Table 2.5.1: Summary table of supplementary synthetic and synchronous inertia scenarios

Synthetic inertia (MW)	Synchronous inertia (MW.s)	Criteria				
		>-0.5Hz/s	<+0.5Hz/s	>-0.8Hz/s	<+0.8Hz/s	>49Hz
80	4000	X	✔	✔	✔	✔
80	8000	✔	✔	✔	✔	✔
80	12000	✔	✔	✔	✔	✔
120	8000	✔	✔	✔	✔	✔
160	5600	X	✔	✔	✔	✔
160	8000	✔	✔	✔	✔	✔
160	12000	✔	✔	✔	✔	✔
200	4000	X	✔	✔	✔	✔
200	7200	✔	✔	✔	✔	✔
240	2400	X	✔	✔	✔	✔
240	4000	X	✔	✔	✔	✔
240	5600	X	✔	✔	✔	✔
240	6400	✔	✔	✔	✔	✔
240	8000	✔	✔	✔	✔	✔
240	12000	✔	✔	✔	✔	✔
300	5600	✔	✔	✔	✔	✔
360	4000	X	✔	✔	✔	✔
No limit	5600	✔	X	✔	✔	✔
No limit	8000	✔	✔	✔	✔	✔

3 Phase 2 Study Methodology

This section outlines the approach to the phase 2 studies. The section includes a discussion on the techno-economic studies, the technical studies and an outline of the device modelling used for the studies. A process flow chart is displayed in Figure 3.1-3.

3.1 Approach

The Phase 2 analysis involves performing technical and techno-economic analysis. These studies have several interdependencies and therefore they are carried out in a sequential fashion with a number of iterations required in order to obtain a suitable result. As mentioned in the previous section, the objective of the studies is to determine the volume of synchronous and/or synthetic inertia required in order to maintain the RoCoF at 0.5 Hz/s whilst also achieving levels of 75% SNSP. The studies are therefore to be carried out in the following sequence:

- Techno-economic ‘base case’ study: RoCoF set at 1 Hz/s and SNSP set to 75%. Other constraints are considered as part of sensitivity analysis.
- Technical Studies: Frequency Stability studies are performed on each dispatch from the techno-economic hourly dispatch. Synchronous and/or synthetic inertia is added to the case until the RoCoF is reduced from 1 Hz/s to 0.5 Hz/s for the year to determine the volume requirement for the system.
- Technical Sensitivities: Sensitivity analysis is conducted by varying the characteristic responses of the synchronous and/or synthetic inertia devices. These sensitivities are discussed in more detail in the next section.

A diagram of the proposed study process is shown below:

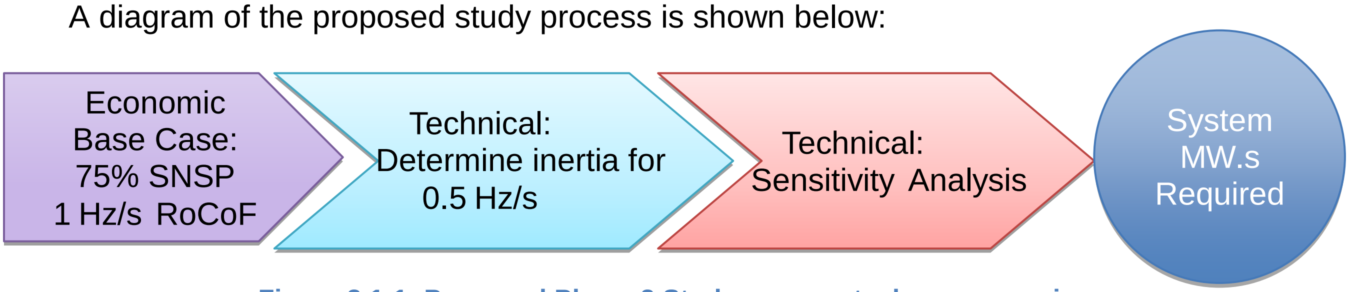

Figure 3.1-1: Proposed Phase 2 Study process techno-economic.

3.1.1 Techno-economic

The techno-economic analysis uses a production cost modelling approach. The techno-economic model is a market only model, with no ‘new supplementary inertia technologies’. The base case studies consider a model that is free from operation constraints such as must run units or reserve. The base case studies consider a model that is unconstrained with the exception of an SNSP limit set to 75% and RoCoF set to 1 Hz/s. The output from the model will therefore be reserve unconstrained dispatch that obeys the SNSP limit of 75%, while ensuring that RoCoF is maintained at 1 Hz/s for the loss of the largest infeed /outfeed.

For the purposes of the study, other operational constraints such as minimum number of conventional units are omitted. This assumption has been made, as the focus of the study is to determine required system inertia to maintain RoCoF at 0.5 Hz/s and to prevent overlapping non-energy market products masking the requirement. Requirements for other system constraints are beyond the scope of the study.

This techno-economic model provides an hourly dispatch that can be used in the technical studies to determine the inertia volumes required to reduce the RoCoF on the system to 0.5 Hz/s.

Further details of the generation of the base case scenario from the techno-economic studies are described in Section 3.2.1.

3.1.2 Technical studies

Technical studies will be performed based on the generation dispatches produced from the techno-economic analysis. The technical analysis is proposed to be performed using the Automated Dynamic Studies Tool. This approach allows for a full year’s hourly dispatch from techno-economic studies to be analysed in the technical studies. The process of converting the techno-economic dispatches into scenarios for the technical analysis is described in section 2.2.4.

The technical studies will be broken into three parts to consider the addition of synchronous and non-synchronous devices. Generic representations of the synchronous and synthetic devices are utilised for the study and a description of these models are described in section 2.3. The cases considered for the addition of supplementary inertia are as follows:

- Synchronous inertia study – determines the volume of synchronous inertia devices required on the system to maintain 0.5 Hz/s RoCoF.
- Synthetic, inertia study – This study looks at the additional 'inertia' required to maintain the potential RoCoF to below 0.5 Hz/s being achieved by deploying synthetic inertia devices. The synthetic responses are varied to determine the sensitivity of high RoCoF prevention to device response time. The total volume of synthetic inertia required from RoCoF containment is then determined.
- Synchronous and synthetic inertia combination study – in this study the combination of synchronous and synthetic inertia is used to maintain the RoCoF at 0.5 Hz/s. An indication of the proportions of synchronous to synthetic inertia can be estimated through this analysis.

A diagram of the study cases are shown in Figure 3.1-2.

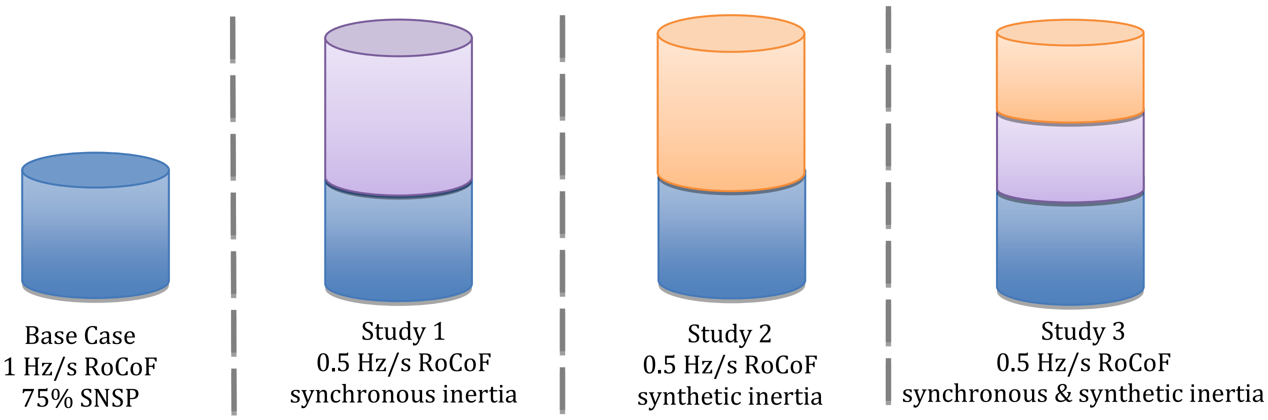

Figure 3.1-2: Technical analysis cases to determine volume of synchronous and synthetic inertia.

A flow diagram of the study approach is shown in Figure 3.1-3.

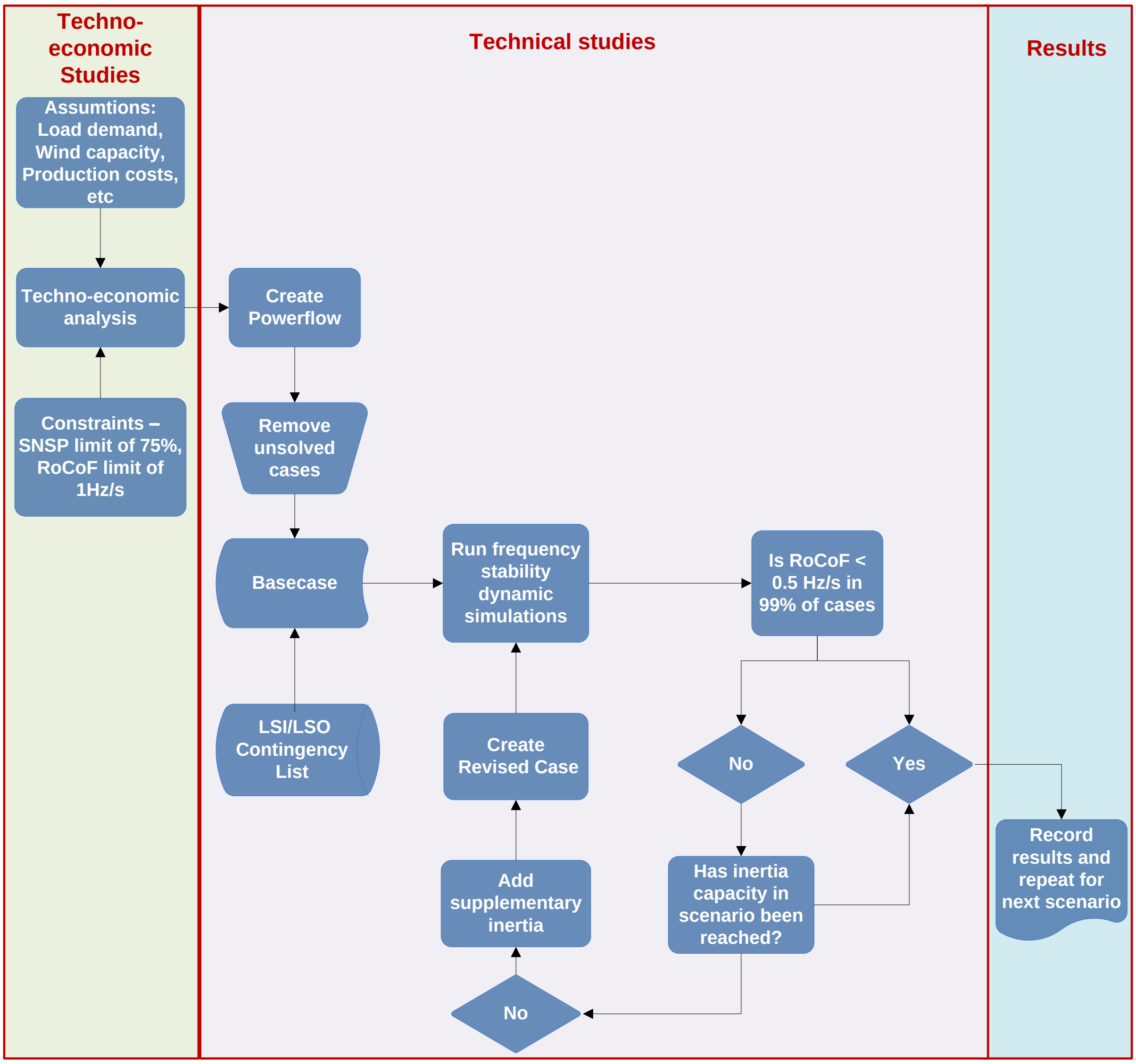

Figure 3.1-3: Approach flow chart

3.2 Generation of base case

The aim of the technical studies is to assess the rate of change of frequency (RoCoF) levels observed on the system for the loss of a large infeed or out-feed. The study therefore focuses on the response of the system in the initial 2.5 seconds after the frequency event. The study will focus on the first 500 ms when the RoCoF tends to be at its highest. The response of the system after this time period is considered out of scope for the study. Similarly, transient and voltage stability criteria are not assessed as part of the study.

As previously discussed, the philosophy of this study is to investigate a base case where for a significant proportion of the year, RoCoF is greater than 0.5 Hz/s. In the technical studies additional supplementary inertia is then added to the power system to reduce RoCoF within the existing limit. In order to develop cases where the power system could observe RoCoF events greater than 0.5 Hz/s, a number of assumptions are made in the system model.

The following sub-sections describe the assumptions made to generate the base case necessary to meet the study philosophy.

3.2.1 Generation dispatch

The hourly generation dispatch is based on production cost modelling methodology. This modelling approach ensures that the dispatch achieved minimizes production cost for a given set of inputs and constraints.

The power market modelling tool called Plexos [4] [5] is used to generate the dispatches for a given period.

The sources of the key modelling inputs for the study year are:

1. Individual generating unit's technical data, which is publically available from the all island project, validated SEM Generator Data Parameters [6].
2. Renewable generation build out for study year published in the EirGrid /SONI Generation Capacity Statement 14-23 [7].
3. The climatic year, wind and solar profiles based on historical profile data.
4. The hour-by-hour electricity demand based on the median demand forecast published in the EirGrid /SONI Generation Capacity Statement 14-23 [7].
5. Fuel and carbon prices based on the World Energy Outlook 2012 fuel forecast for 2020 [8].

The Plexos model selected for this study is based on a market model the transmission network is not included. A simplified single node market dispatch model is a suitable approach for development of the techno-economic dispatches. The technical studies will use a detailed transmission power system network model. In today's electrical power system environment RoCoF events do not exceed 0.5Hz/s due to the constraints placed on the power system. In addition to relaxing the RoCoF constraint for the study, other operational constraints are also relaxed or removed. The following assumptions displayed in Table 3.2.1 are selected to assist in developing a base case environment suitable for the purpose of this study:

Table 3.2.1 Study assumptions for generation dispatch

Property	Value	Description
SNSP	75%	Constraint enabled. All non-synchronous generation, all island demand and interconnection import/export are monitored to ensure SNSP metric is obeyed.
RoCoF	1.0 Hz/s	Dynamic Constraint enabled. The Loss of Large Single Infeed/Outfeed contingency is monitored for all study periods. The constraint ensures enough inertia is carried to prevent a RoCoF greater than 1Hz/s
Interconnection **Moyle** **EWIC**	 Import 450 MW Export 80 MW Import 500 MW Export 500 MW	 Assumes Moyle second pole has been reconnected [9].
All Island Demand	TER 38,480 GWh TER Peak 6993MW	TER (Total Energy Requirement)
Installed Large Scale Wind Capacity	4732 MW	The existing wind capacity is increased to the expected 2020 levels [7]. This allows SNSP to be able to increase to the 75% limit.
Must Run Units	0 units	No must runs included in study
Second North South	In service	The study assumed that the second proposed North-South Tie-line is built.
Frequency Reserve Products	-	Outside Scope of this study

- Conventional generators remain at their existing capabilities in the simulations, including minimum generation levels and reserve provision. Generators may have the ability to extend their existing capabilities in the future. Section 4.1, describes techno-economic sensitivity analysis where modified to determine the impact on generation dispatch due to reduced minimum generation levels.
- No supplementary inertia devices are included in the techno-economic model portfolio. Supplementary inertia will be included in the technical studies.
- This study does not include future conventional generation portfolio capability as this is beyond the scope of the analysis. This type of analysis is considered as part of the DS3 System Services workstream.

3.2.2 Technical study - load demand and model

3.2.2.1 Load demand

As mentioned above, load demand is based on expected 2020 levels [7]. In the technical studies, the geographical spread of load and the PQ profile for each hour of the year is based on the 2014 actual loading profile. The 2014 profile is scaled pro-rata to the 2020 generation dispatch levels provided by the techno-economic model.

3.2.2.2 Load model

The load model used in this study is a ZIP model and consists of the following elements:

- 30% of the load represented as Constant Impedance;
- 30% of the load represented as Constant Current; and
- 40% of the load represented as Constant Power.

This model has been validated against system frequency events and is considered a prudent representation of the load. This model does not contain a frequency sensitive component which would help counteract frequency excursions. Sensitivity analysis described in Section 3.3.2, investigates the influence of frequency dependant loads.

3.2.3 Technical simulations network model

The technical study simulations are completed using the present all-island electrical transmission network is augmented to include other assumptions discussed within this report. Details of these assumptions are in Section 3.2.1. All technical simulations assume an intact network as the analyses focuses on system frequency stability.

3.2.4 Techno- economic output transfer to technical simulations

Technical simulations are completed with the Automated Dynamic Studies tool. The Automated Dynamic Studies tool is an EirGrid developed tool, which automates the interaction of the techno-economic model with the technical model for each hour of the year. The Automated Dynamic Studies tool receives inputs from the techno-economic model output, a previous years load profile and an electrical power systems network model. The Automated Dynamic Studies tool uses Powertech's DSA Tools PSAT to create power-flows for each hour of the year. The power-flows feed into the frequency stability simulations, which are performed in the DSA tools TSAT package. Figure 3.2-1 displays the Automated Dynamic Studies tool process.

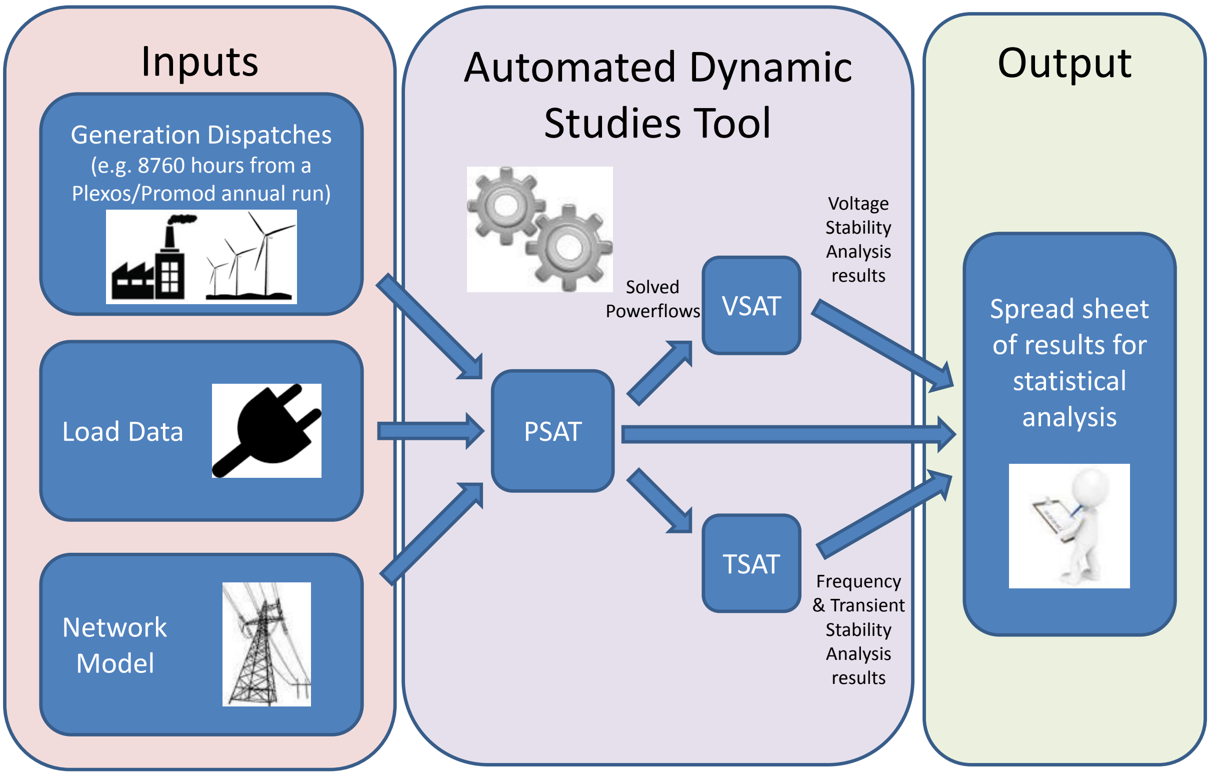

Figure 3.2-1: Automated Dynamic Studies Tool Process

3.2.5 Resolved cases

The techno-economic study provides the generator dispatch for every hour of the year. The dispatches are produced with limited network constraints. Therefore, the generation dispatch may be solved in the techno-economic tool without consideration of some technical constraints. This approach is chosen as the focus of the study to determine required system inertia to maintain RoCoF at or below 0.5 Hz/s and the requirements for other system constraints are beyond the scope of the study. This approach results in some techno-economic cases not successfully solving as power-flows in the Automated Dynamic Studies tool. The main factors for non-convergence include:

- Voltage issues due to the geographic low number of generators dispatched and the geographic dispersion of generators.
- Several of the failed cases were due to wind approaching the limit of installed capacity. It should be noted that this study does not include all planned transmission reinforcements which would have resulted in convergence issues in some cases.
- Un-resolved simulations are excluded from the analysis. Of the 8760 cases created 8000 cases were acceptable for analysis in the study.

3.2.6 System protection models

The aim of this analysis is to provide an understanding of the quantity of supplementary inertia required to resolve the generation base case discussed above if RoCoF remains at the 0.5 Hz/s limit in the future. Protection relays with RoCoF and frequency settings would trigger in the case that a system event, such as a trip of the LSI/LSO, causes frequency excursions above existing standards. These schemes aim to resolve the imbalance and bring the system back within normal operating conditions.

Sympathetic disconnection of generation or load following an event could distort the determination of the supplementary inertia volume requirement and therefore the protection trip settings are modified to avoid this. The following wind farm protection settings will be altered:

- Removed RoCoF protection relays functionality,
- Removed vector shift protection relays functionality,
- Increased over-frequency protection settings to 52 Hz, and
- Decreased under-frequency protection settings to 48 Hz.

3.2.7 Power system static response

3.2.7.1 Interconnector response

In 2012, an undersea fault damaged one of the two Moyle Interconnector cables resulting in the availability of one pole only. EirGrid and SONI expects the damaged cable will be repaired and re-commissioned in 2017 [9]. The Moyle Interconnector could be, during certain periods, the Largest Single Infeed/Outfeed (LSI/LSO) in 2020. The study considers the second pole of the Moyle Interconnector is available.

The static reserve responses provided by interconnectors are disabled in the power system technical simulations. This assumption is based on the fact that the static responses could be within the synthetic inertia period and, therefore, could distort the system volume requirement. The interconnector import/export limits are as follows:

- Moyle Interconnector 450/80 MW, and
- East-West Interconnector 500/500 MW.

Moyle Interconnector is limited to an export of 80 MW primarily due to issues with transmission access rights in Scotland, which may limit its export capacity to 80 MW from 2017 [7].

3.2.7.2 Turlough Hill response - Pump mode

Static reserve response is available from Turlough Hill units where Plexos dispatches units in pump mode. Turlough Hill is not expected to provide synthetic inertia within the required period.

3.2.7.3 Short Term Active Response (STAR) interruptible load

STAR is a scheme operated by EirGrid where electricity consumers contract with EirGrid to make their load available for short-term interruptions. These loads are automatically disconnected following a frequency dip the reaches the pre-defined threshold.

The availability of STAR load in the study is dynamically calculated for each hour of the year based on the load at the bulk supply point (BSP). Due to the variance in the system load over a year, the modelled STAR load varies between 9 MW and 25 MW at the BSP. STAR load disconnects from the system if the frequency drops below 49.3 Hz with a time delay of 0.35s. STAR load is not expected to provide synthetic inertia within the required period.

3.2.8 Simulation time

RoCoF is the rate of change of frequency over time. Typically, if the RoCoF limit is violated it is expected to be either during the initial N-1 generation/load imbalance or during system frequency recovery. To resolve this imbalance synchronous and/or synthetic inertia is available to the system and has the ability to react to the imbalance within a short time frame. Based on this requirement, the simulation length is limited to 2.5 seconds post event.

3.2.9 Contingencies

This analysis only considers high RoCoF events caused by a sudden imbalance between generation and load. Only events caused by a sudden loss of the Largest Single Infeed (LSI) or Largest Single Outfeed (LSO) are considered. A list of possible contingencies that could result in LSI or LSO events is generated for the analysis. The following contingencies are analysed:

<u>Largest Single Infeed (LSI)</u>

- East-West Interconnector (Import),
- Moyle Interconnector (Import),
- Aghada 2 generator - AD2,
- Moneypoint 1 generator - MP1,

- Moneypoint 2 generator - MP2,
- Moneypoint 3 generator - MP3,
- Whitegate generator - WG1,
- Coolkeeragh generator - C30,
- Dublin Bay generator - DB1, and
- Great Island 4 generator - GI4.

Largest Single Outfeed (LSO)

- East-West Interconnector (Export), and
- Moyle Interconnector (Export).

In each hourly case, the contingency resulting in the worst RoCoF event is selected for the inertia volume requirement. A frequency event resulting from a voltage-dip-induced frequency dip (VDIFD) contingency or a system separation contingency are not considered as part of this study.

3.2.10 Acceptance criteria

Frequency stability criterion is defined to determine the additional inertia requirement. For the purposes of the study, the focus will be on maintaining rate of change of frequency (RoCoF) with ±0.5 Hz/s (calculated over 500 ms) for an N-1 event. Simulations are considered as secure if the criterion above is met for the worst-case contingency.

The base case scenario is executed and the supplementary inertia is added to the system if the RoCoF requirement is not satisfied. This process continues until the number of secure cases in the full year dispatch is in the 99^{th} percentile, i.e. less than 1% of cases do not meet the RoCoF criterion. The level of inertia that achieves this number of secure cases is deemed as the inertia requirement for the system.

The system RoCoF is calculated based on the average of measurements from five geographically spread locations. The five measured locations are:

- Finglas 220 kV,

- Knockraha 220 kV,
- Moneypoint 380 kV,
- Letterkenny 110 kV, and
- Castlereagh 275 kV.

3.2.11 RoCoF calculation methods

RoCoF is calculated using different methods in the techno-economic and technical studies.

The techno-economic studies deliver static power system economic solutions based on a mixture of constraints and production costs. RoCoF is calculated using the equation displayed in Eq. 2.1 [10].

$$RoCoF = \frac{\text{System frequency} \times \text{Active power}_{\text{lost}}}{2(Inertia_{\text{system}} - Inertia_{\text{lost}})} \qquad \text{Eq. 2.1}$$

The technical simulations calculate frequency for a series of time steps allowing RoCoF to be calculated per the proposed Grid Code method. Grid Code rolling average method calculates RoCoF as the frequency at a particular time less the frequency 500 ms prior multiplied by two for Hz/s [2].

3.2.12 Locations for inertia devices

Supplementary inertia is added to the system using lumped models dispersed geographically in four locations across the island. The following buses are selected to deploy the inertia at four-transmission locations in the North, South, East and West of Ireland:

- Magherafelt 275 kV,
- Knockraha 220 kV,
- Maynooth 220 kV, and
- Flagford 220 kV.

These locations are selected solely to ensure that the additional inertia is geographically spread across the island. The selection of these buses should not be interpreted as being the specific locations where the inertia devices will be required. Detailed locational analysis would be required to ensure that devices are deployed in the optimum locations and this level of analysis is beyond the scope of this study.

3.3 Modelling of Synchronous and Synthetic Inertia Devices

3.3.1 Supplementary inertia dynamic models

There are a total of eight devices modelled in TSAT, four synchronous inertia and four synthetic inertia devices. Configuration of each device model is independent. Each device is discretely modelled as a 100 MVA machine and responds independently to the frequency seen at its local bus following the event.

3.3.1.1 Synchronous inertia dynamic model

Synchronous inertia is represented as a standard synchronous machine using the standard PSS/E model. This model is available as a standard model[1] within TSAT and the parameters of each model are tabulated in Table 3.3.1.

Table 3.3.1: Tabulated summary of synchronous inertia device parameters

Nominal Output	Machine Base	Inertia constant	Reactance
1 MW	100 MVA	Scenario dependant	0.2 pu

The synchronous machines will have no other frequency governing capability other than the inertia response of the unit. The inertia constant parameters for each of the four synchronous machines are set equally and are increased uniformly to represent increasing supplementary inertia available on the system.

Figure 3.3-1 displays an example of the typical response from a synchronous inertia device. The synchronous inertia device responds following the sudden disconnection of the LSI. The response dampens overtime as the frequency recovers.

[1] A TSAT standard dynamic model, is a model which is contained within TSATs internal model library and does not require customisation/modification of the internal control blocks.

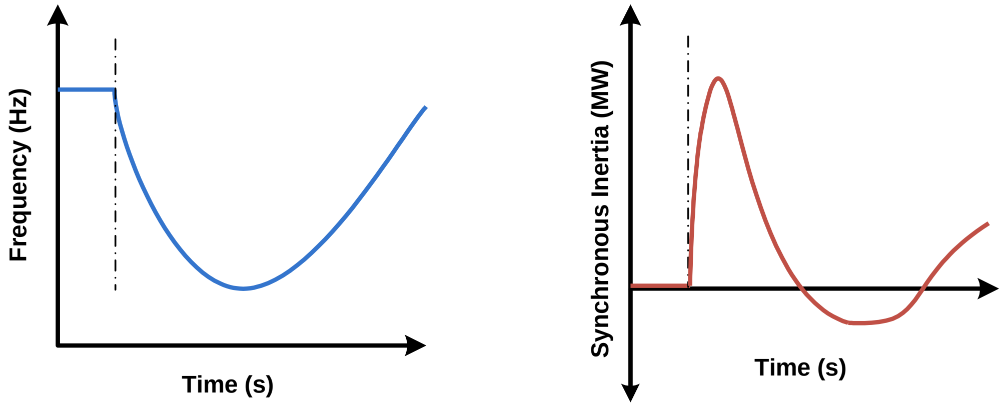

Figure 3.3-1: Example of synchronous inertia response (MW).

3.3.1.2 Synthetic inertia dynamic model

The representation of synthetic inertia is with a specialised 'user-defined' model configured to provide an active power response with a particular characteristic. The synthetic inertia model exports a nominal 1 MW of active power in steady state. The characteristic of the active power response is dependent on the individual analysis objectives. The slope and limit of active power injection are variables that can be adjusted in the simulation. The device model has the ability to trigger on various signals including a frequency or RoCoF threshold. Varying time delays can be included in the models to account for varying detection times. Variations in these parameters determine the impact of different synthetic device responses on the ability to prevent high RoCoF events. The study assumes that synthetic devices are capable of continuously providing active power response in the study period. None of the devices consider internal calculation times associated with physical devices.

The key parameters considered for the synthetic response are as follows:

- Response time: this is the time required for the synthetic device to detect and react to a frequency event. In advance of it detecting the event, the device will have zero response. (This is in contrast to a synchronous device which will inherently respond in a proportional manner to changes in system frequency.)
- Active power ramp: This is the rate at which the active power will ramp in response to the frequency changes. Devices connected to the grid via power electronics typically have a rapid active power ramp; however, this may be limited by the source behind the power electronics.

- Active power amplitude: This is the amount of active power response injected by a device in response to a frequency event. This parameter will be important for determining the volume of devices required to resolve the RoCoF issue.
- Active power duration: This is the length of time that the device will provide active power before its store of energy has been depleted. This is also a key parameter in determining volume of response required. As the study focuses on time frame of 2.5 seconds post event, it is assumed that synthetic devices are capable of continuously providing active power response for the duration of the study.
- Recovery time: This is the time required for the device to return to its pre-event set point after the provision of the inertia provision. This parameter is not considered in this study.

Figure 3.3-2 displays an overview of the simplified synthetic inertia functionality. These power system models offer an indication of the feasibility of different response types in supporting the system frequency stability. The input of each synthetic inertia device is the frequency measured at the device’s transmission connection point. The measured frequency feeds into the selected frequency response function. This function determines the active power response of the device. The active power response is delivered at the bus where the frequency is measured.

Only synthetic inertia functionally required for the particular scenario studied is included within each simulation. Detailed discussion on the particular responses for each scenario is in the synthetic inertia results section of this report.

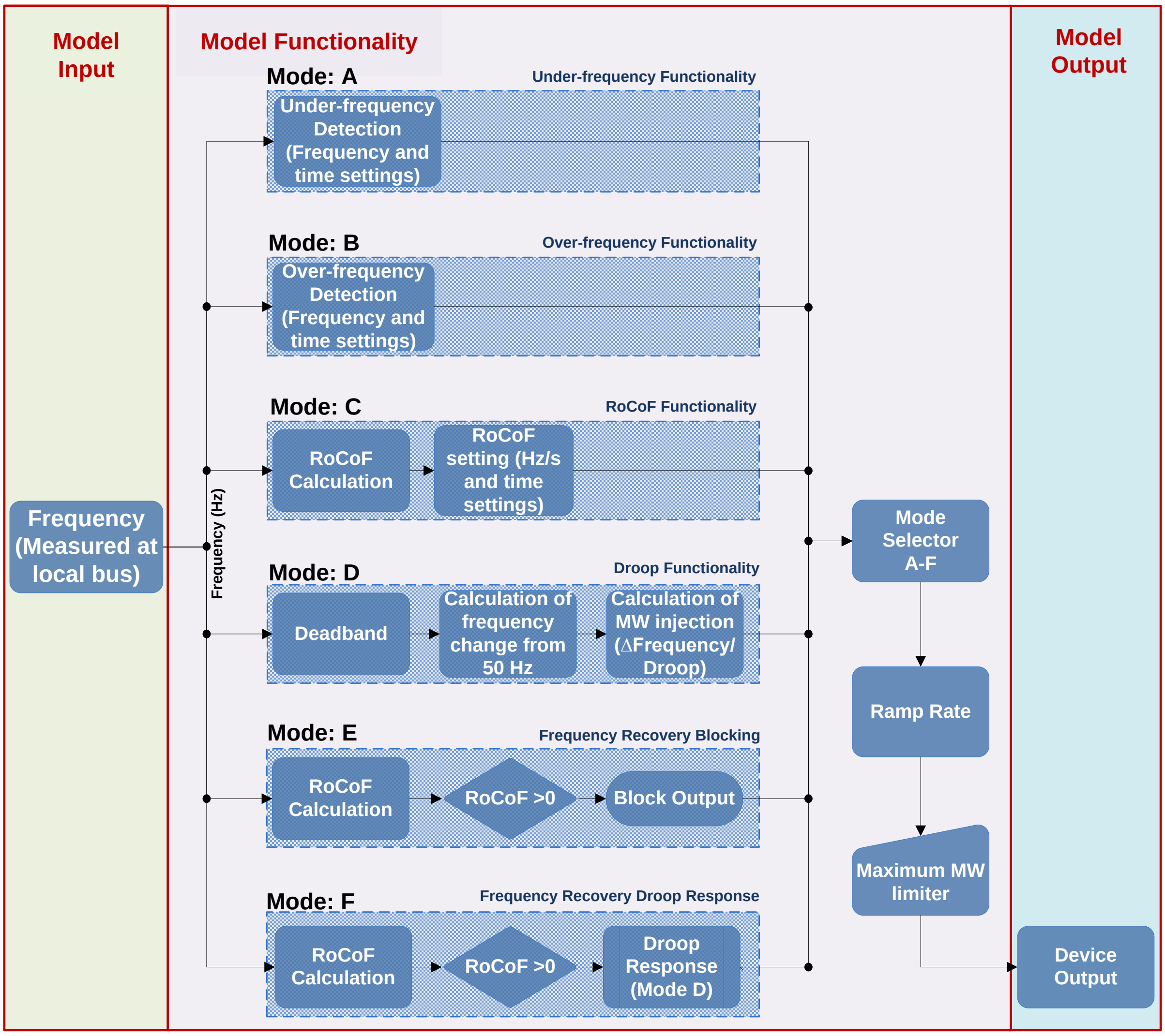

Figure 3.3-2: Simplified functionality overview of the synthetic inertia device model.

Figure 3.3-3 to Figure 3.3-7 displays an illustrative synthetic inertia device modelled responses, following a sudden disconnection of the LSI. Responses following a sudden disconnection of the LSO are not displayed. LSO sudden disconnections would result in the system frequency rising and the device would therefore consume rather than inject active power.

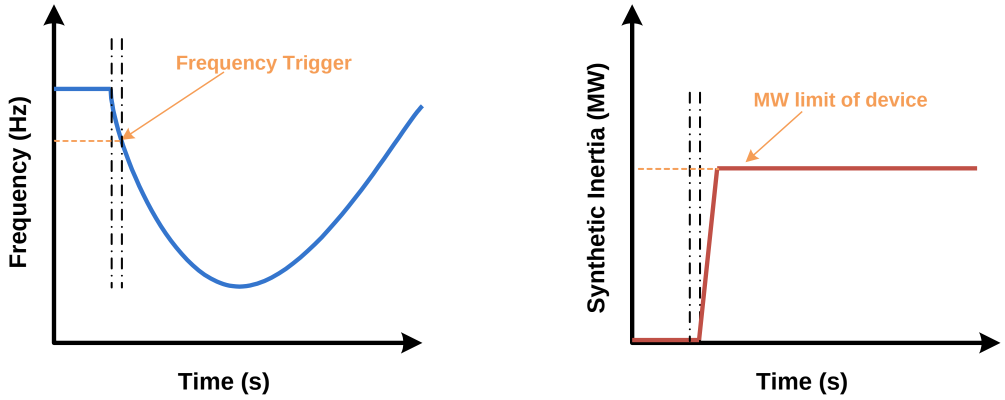

Figure 3.3-3: Control Mode A, Stepped response of the supplementary inertia following an under frequency trigger. At the moment, frequency exceeds the defined trigger the device responds at a defined ramp rate until the active power limit is encountered. This is similar to the RoCoF triggered response (Control Mode C) with the exception that synthetic inertia is triggered following a violation of the RoCoF threshold. A sudden disconnection of the LSO would result in the device consuming rather than injecting active power, Control Mode B.

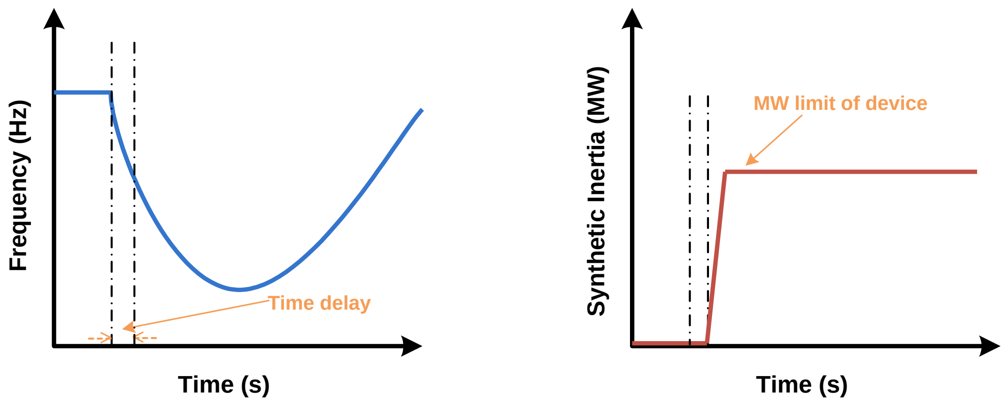

Figure 3.3-4: Control Mode A, Stepped response of the supplementary inertia following a time delay. The device responds at a fixed ramp rate once the time delay is exceed.

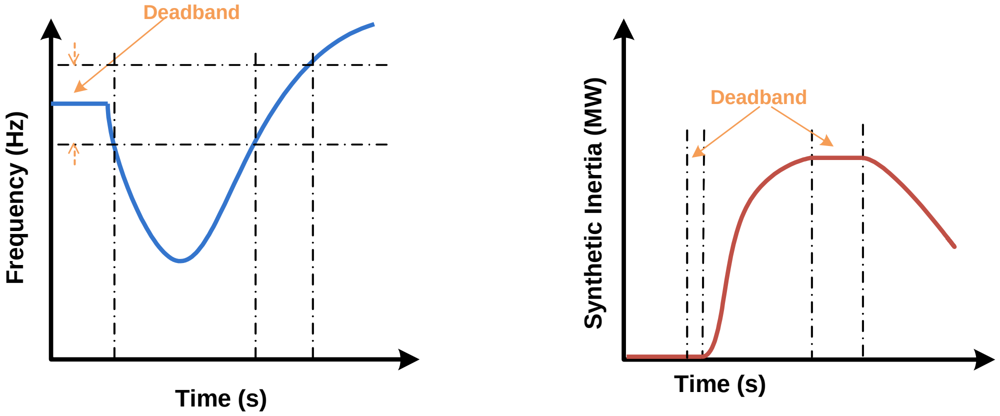

Figure 3.3-5: Control Mode D, Droop response of the supplementary inertia. The device delivers a defined droop response where frequency is outside a defined deadband.

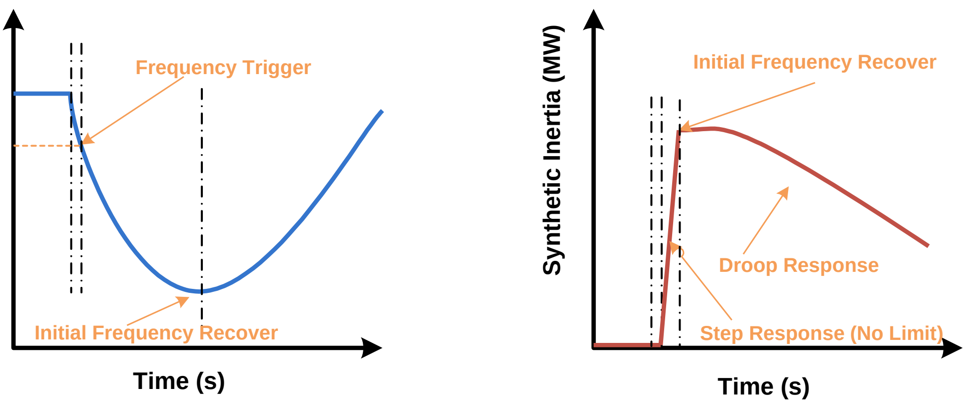

Figure 3.3-6: Control Mode A combined with F, Step and droop response of the supplementary inertia. The device delivers a stepped injection of active power where the defined frequency trigger is exceeded followed by a defined droop response during frequency recovery where frequency is outside a defined deadband.

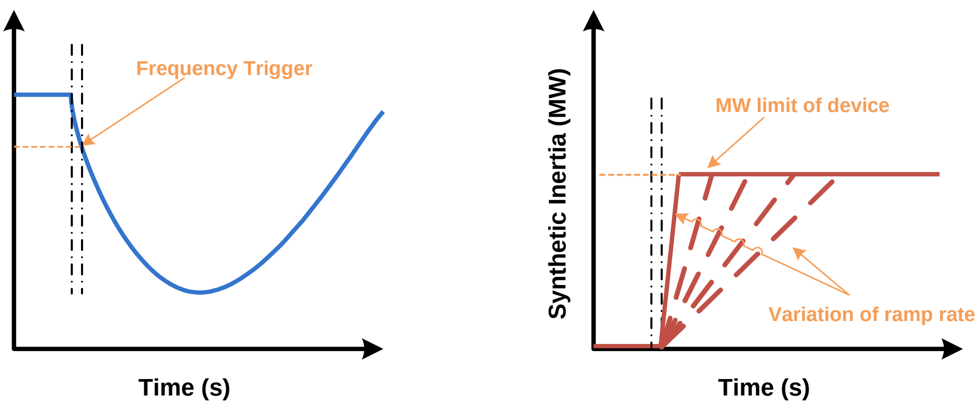

Figure 3.3-7: Control Mode A, Stepped response at different ramp rates of the supplementary inertia.

3.3.2 Scenarios analysis

3.3.2.1 Scenario

The scenarios considered for this study include the following:

- Synchronous inertia devices with increasing inertia constants to determine inertia volume.
- Synthetic inertia devices with increasing active power injection to determine the inertia volume requirement to prevent high RoCoF events. Synthetic inertia devices are increased in 40 MW intervals. Synthetic device performance is varied based on the sensitivity of device function and trigger points. The following performance characteristics and trigger set-points are analysed for the synthetic device:
    - Frequency-triggered synthetic inertia examining various trigger set-points.
    - RoCoF-triggered synthetic inertia examining various trigger set-points.
    - Time-triggered synthetic inertia examining various trigger set-points.
    - Varied response ramp-rate for the synthetic device.
    - Droop controlled synthetic inertia.
    - Frequency triggered synthetic inertia with a droop controlled recovery. This will allow the device to provide governing action post injection of MW.
    - Influence of load model variation.
- Combination of synchronous inertia and synthetic inertia with varying proportions.

Detailed descriptions of each scenario are discussed in the relevant Results sections.

3.3.2.2 List of scenarios

The scenarios for the addition of supplementary inertia are listed below. The lists are categorised as synchronous inertia, synthetic inertia and combined inertia scenarios. These scenarios are displayed in Table 3.3.2, Table 3.3.3 and Table 3.3.4 respectively. Table 3.3.2, Table 3.3.3 and Table 3.3.4 provide the synthetic inertia frequency trigger threshold, time delay and active power response rate.

Table 3.3.2: Summary list of synchronous inertia volumes study scenarios

Supplementary synchronous inertia volume (MW.s)	Event type
2400	Under frequency
4000	
5600	
8000	
12000	
16000	
20000	
5600	Over frequency
8000	
12000	
16000	

Table 3.3.3: Summary list of synthetic inertia response study scenarios

	Supplementary synthetic inertia volume	Event Type	Response Setting
Frequency trigger	80 MW	Under frequency	49.8 Hz
	160 MW		
	200 MW		
	240 MW		
	300 MW		
	360 MW		
	400 MW		
	440 MW		
	No Limit		
	360 MW		49.9 Hz
	400 MW		
	440 MW		
	No Limit		
	240 MW	Over frequency	50.1 Hz
	360 MW		
	400 MW		
	440 MW		
	No Limit		
	300 MW		50.2 Hz
	360 MW		
	400 MW		
	No Limit		
RoCoF trigger	No Limit	Under frequency	0.2 Hz/s
			0.3 Hz/s
			0.4 Hz/s
Time trigger	360 MW	Under frequency	0ms
			100ms
			200ms
			300ms
	400 MW		0ms
			100ms
			200ms
			300ms
Controlled droop response (Deadband = 0.05Hz)	No Limit	Under frequency	4%
			2%
			1%
			0.75%
			0.5%
			0.25%
Step and droop response	No limit	Under frequency	Droop 4%
Variation of ramp-rate	No limit	Under frequency	2300 MW/s
			1450 MW/s
			1150 MW/s
			750 MW/s
			575 MW/s
			450 MW/s
			350 MW/s
			300 MW/s
Influence of load model variation	360 MW	Under frequency	UF Trigger 49.8 Hz, 1%
	400 MW		
	440 MW		
	360 MW		UF Trigger 49.8 Hz, 2%
	400 MW		
	440 MW		

Table 3.3.4: Summary list of synchronous and synthetic inertia combination study scenarios

Synthetic inertia (MW)	Synchronous inertia (MW.s)
80	4000
80	800
80	12000
120	8000
160	5600
160	8000
160	12000
200	4000
200	7200
240	12000
240	2400
240	4000
240	5600
240	6400
240	8000
300	5600
360	4000
No limit	5600
No limit	8000

4 Results

4.1 Techno-economic dispatch

4.1.1 Plexos discussion

The objective of the techno-economic study is to produce an hourly generation dispatch over one year where the system is allowed to operate up to 75% SNSP and have a potential RoCoF of up to 1 Hz/s. The objective function of the techno-economic study is to minimise production cost for a given generation portfolio and demand profile at an hourly resolution. A binding constraint will cause the cost minimisation function to re-dispatch and / or commit / de-commit units.

To evaluate the impact of additional constraints on the techno-economic model, sensitivities on minimum generation levels and the inclusion of primary/secondary operation reserve (POR/SOR) were carried out.

Minimum generation refers to the minimum active power output which a conventional generator can generate continuously [2]. In this sensitivity, the minimum generation level is reduced for all conventional generators.

Primary/secondary operational reserve (POR/SOR) is the additional increase in active power within a defined time compared to the pre-incident output [2]. In this sensitivity, a POR and SOR constraint is included.

The constraints considered in the eight techno-economic scenarios considered are displayed in Table 4.1.1.

Table 4.1.1: Techno-economic scenario constraints

Techno-economic scenario	Constraints			
	SNSP (%)	RoCoF (Hz/s)	Minimum generation (%)	POR/SOR (% of LSI)
A	75	0.5		
B			35	
C				75
D			35	75
E		1		
F			35	
G				75
H			35	75

4.1.2 Plexos output

An inertia duration curve for each of the techno-economic scenarios is illustrated in Figure 4.1-1. The following is observed in this figure:

- A reduction in a generators minimum dispatch to 35% of full load may permit an increase in SNSP and a reduction in curtailment, if conditions are appropriate. In this low constrained electrical power system the techno-economic studies suggest that reducing convention generators minimum dispatch to 35% of full load does not affect the results displayed in the base case inertia duration curve. This is primarily due to wind generation replacing conventional generation and the techno-economic solution dispatching the generation on regardless of minimum generation levels rather than de-committing a unit. This result does not discount the benefits associated with further reductions in minimum generation levels.
- Inclusion of primary and secondary operating reserve constraints equates to approximately one additional large inertia machine (2500 MW.s) on average over the year. This constraint has the overall impact of reducing the number of hours in the year where RoCoF could be above 0.5 Hz/s.
- The majority of the 0.5 Hz/s RoCoF constrained hours are above the existing operational all-island inertia floor of 20,000 MW.s [11].

As the focus of the study is to determine the required system inertia to maintain RoCoF at 0.5 Hz/s, the techno-economic scenario selected as the base case for the technical studies is the 1 Hz/s constrained scenario (Case E). The 0.5 Hz/s RoCoF constrained scenario results in a similar inertia floor as is observed on the present system.

Reducing convention generator’s minimum stable output to 35% does not materially affect the case and therefore this constraint is excluded. Including the reserve constraint would be equivalent to adding another large conventional generator to the dispatch, which would reduce the number of hours of the year where 0.5 Hz/s is exceeded. The requirements for other system constraints are beyond the study scope.

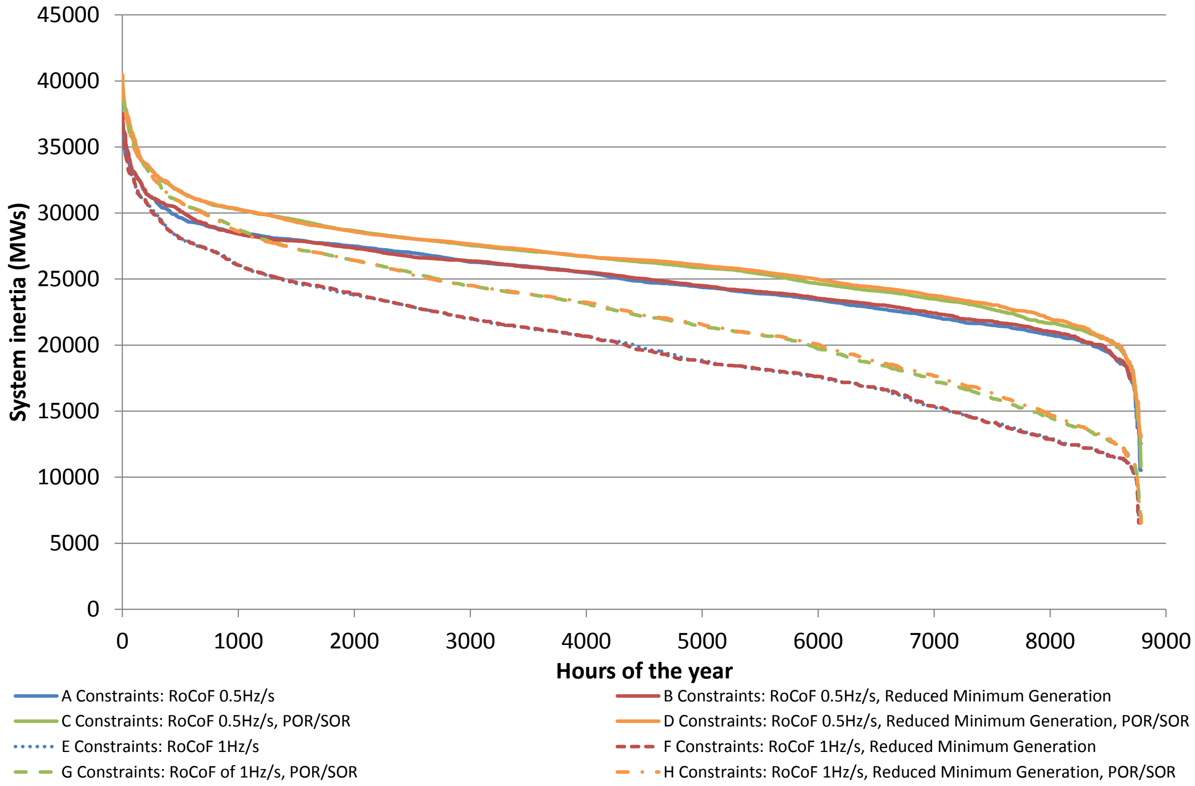

Figure 4.1-1: Duration curves for each of the eight techno-economic studies.

4.2 Base Cases

The techno-economic study provides the generator dispatch for every hour of the year with constraints of 75% SNSP and RoCoF of 1 Hz/s. As discussed in section 3.2.5, convergence issues in the simulated power-flows resulted in a number of the hours being discounted.

The number of successfully compiled hourly cases is 8,013. This equates to approximately 9% of the year's hourly cases that failed to converge. Many of the un-resolved cases could have been resolved by re-dispatching generators to reinforce voltage levels in weaker areas of the grid. It is expected, that re-dispatching generation to solve the power-flows would not materially alter the findings of the study and therefore this was not explored further. The objective of the study is to analyse cases where RoCoF exceeds 0.5 Hz/s and the requirements for other system constraints are beyond the scope of this study. Furthermore, it was decided that analysis of over 8,000 cases would provide a sufficient sample to draw conclusions from the study.

It is expected interconnectors have the ability to trigger a response within the timeframe required to prevent high RoCoF events and therefore could, if required, be considered as synthetic inertia. In order to accurately understand the volume requirement of synthetic inertia, interconnector response has been disabled. The rationale behind this assumption is discussed in section 3.2.7.1 and is analysed in the following sub-sections. This approach will therefore deliver a clearer estimation of the additional synthetic inertia requirement.

The objective of the analyses below is to identify the volume of hours of the year where an additional inertia response is required to meet the criteria.

4.2.1 Base Case analysis of under-frequency events

The following subsections relate to under-frequency events only. Over-frequency events will be discussed in Section 4.2.2. The initial studies consider the base case scenarios without any supplementary inertia included in the system. The initial analysis will consider the impact of omitting interconnector responses.

4.2.1.1 Simulation scenarios

The simulation scenarios are:

- Base case excluding interconnector frequency response, and
- Base case including interconnector frequency response.

4.2.1.2 Discussion of results

Figure 4.2-1 displays the percentage of cases where RoCoF exceeds specific thresholds. This includes ±0.5 Hz/s and ±0.8 Hz/s. The percentage of cases where the frequency nadir is below 49 Hz is also presented.

From the bar chart, 53% of cases in the dispatch will require an additional inertial response to arrest changing frequency prior to exceeding a negative RoCoF of 0.5 Hz/s. It is observed that the existing interconnector response alleviates RoCoF in approximately 3% of simulations. The principal reason for the minor differences in violations is due to the existing interconnector frequency response settings. The present interconnector response is frequency triggered and delivers static primary operating reserve. Therefore, the existing configuration does not typically provide a response within the timeframe necessary to resolve RoCoF.

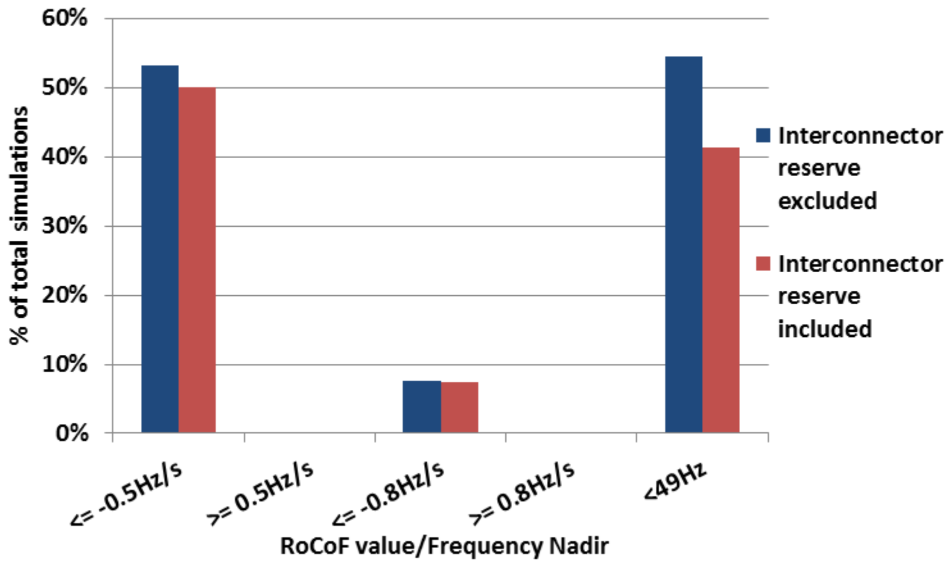

Figure 4.2-1: Basecase - Percentage of cases where RoCoF exceeds each setpoint and frequency nadir is below 49 Hz.

4.2.2 Base Case analysis of over-frequency events

The following subsections relate to over-frequency events only. Interconnectors are exporting active power in 1,874 hours of the year in the techno-economic solution. The initial studies consider the base case scenarios without any additional inertia included in the system. The initial analysis will consider the impact of omitting interconnector responses.

4.2.2.1 Simulation scenarios

The simulation scenarios are:

- Base case excluding interconnector frequency response, and
- Base case including interconnector frequency response.

4.2.2.2 Discussion of results

Figure 4.2-3 displays the percentage of cases where RoCoF exceeds specific thresholds. The percentage of cases where the frequency zenith is above 51 Hz is also presented.

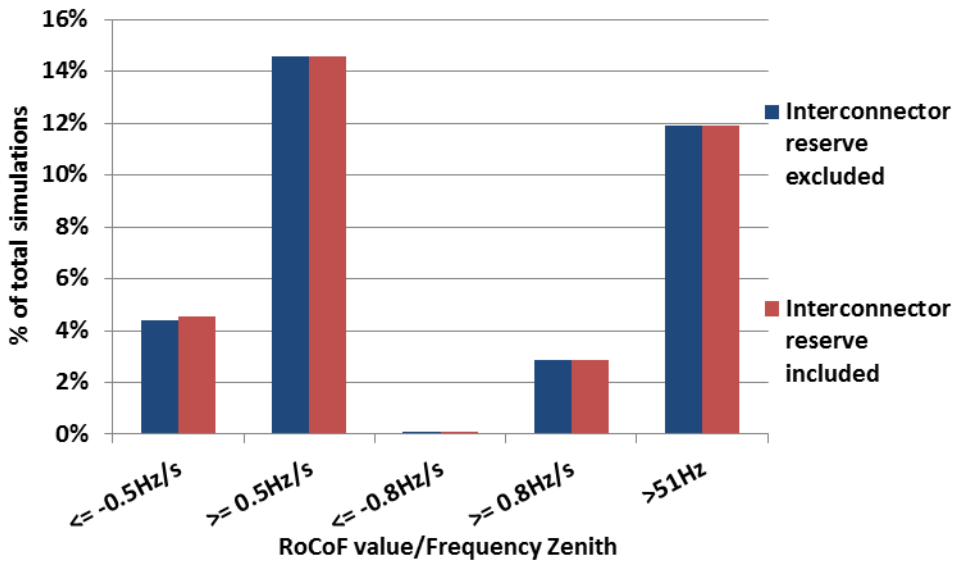

Figure 4.2-2: Over-frequency basecase - Percentage of cases where RoCoF exceeds each setpoint and frequency zenith is above 51 Hz.

The bar chart illustrates that:

- 15% of hours of the year will require an additional active power injection to arrest changing frequency prior to exceeding a positive RoCoF of 0.5 Hz/s.
- The existing interconnector responses do not materially affect RoCoF in these simulations. This can be explained by the fact that one of the interconnectors has been disconnected and therefore the response that can be provided is limited to the remaining interconnector.

4.2.3 Minimum response time

The objective of this section is to provide:

1. An understanding of the time that supplementary inertia devices must operate within and offer active power support to abate the frequency change before RoCoF limits are exceeded.
2. An indication of approximately how many cases in the dispatch require a supplementary inertia response.

Figure 4.2-3 displays:

- A duration curve, coloured blue, of the time to exceed a negative RoCoF of 0.5 H5 Hz/s following a sudden disconnection of the LSI.
- A duration curve, coloured red, of the time to exceed a positive RoCoF of 0.5 Hz/s following a sudden disconnection of the LSO.
- A duration curve, coloured green, of the time to exceed the absolute worst RoCoF of ±0.5 Hz/s within each case following a sudden disconnection of either the LSI/LSO.

These technical simulations are completed with the Automated Dynamic Studies tool. The time axis in Figure 4.2-3 is the time to exceed RoCoF after the event occurs. In these simulations all events occur at 0.5 seconds. The RoCoF calculation in the technical simulations uses the proposed Grid Code calculation method calculated over 500 ms.

RoCoF exceeds ±0.5 Hz/s in over 60% of cases as displayed by the green curve in Figure 4.2-3. The majority of the RoCoF breaches occur within 0.5 seconds. Cases where RoCoF does not exceed 0.5 Hz/s in the simulation are deemed acceptable and are not marked on the plot. A case may violate both positive and negative RoCoF limits for under-frequency and over--frequency contingencies as displayed by the blue and red curves in Figure 4.2-3, respectively.

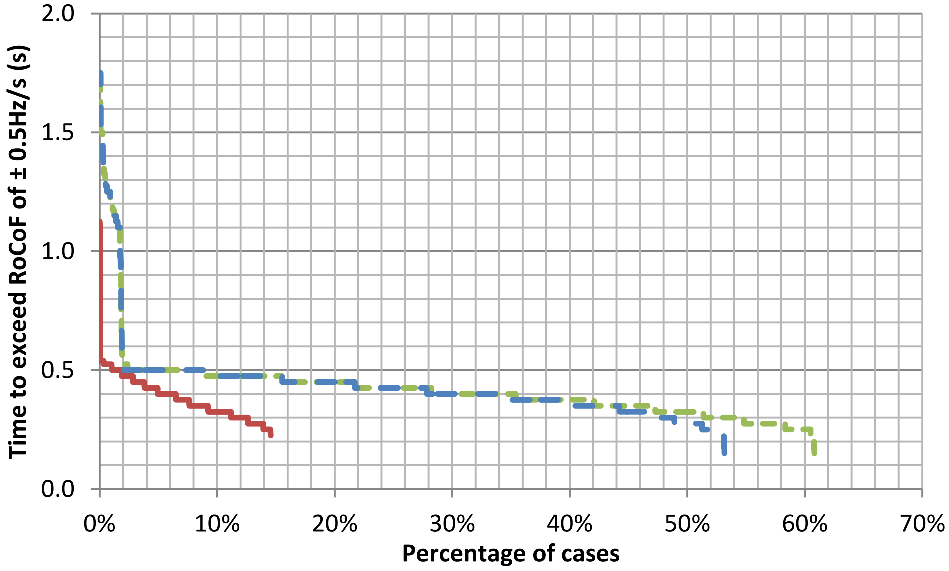

Figure 4.2-3: Duration curve - Time after the event for RoCoF to exceed ±0.5 Hz/s. Negative RoCoF violations following the LSI trip (blue). Positive RoCoF violations following the LSO trip (red). Worst-case violation negative or the positive contingencies (green curve).

4.2.4 Worst-case contingency

Analysis of the techno-economic dispatch revealed ten contingencies that were either the Largest Single Infeed (LSI) or Largest Single Out-feed (LSO) for every hour of the year. These ten contingencies were chosen for analysis in this study and are listed in Section 3.2.9.

The worst-case contingency is the contingency which produces the lowest frequency nadir in the simulation time frame (or highest zenith in the case of over-frequency events). Selecting the contingency with the worst-case nadir/zenith provides a proxy for the contingency with the worst-case RoCoF. The worst-case contingency from case to case may differ due to different system conditions resulting in different system frequency response. Figure 4.2-4, displays a breakdown of the worst-case contingency for the full range of dispatches. The contingencies are split into conventional generation and interconnector import/export.

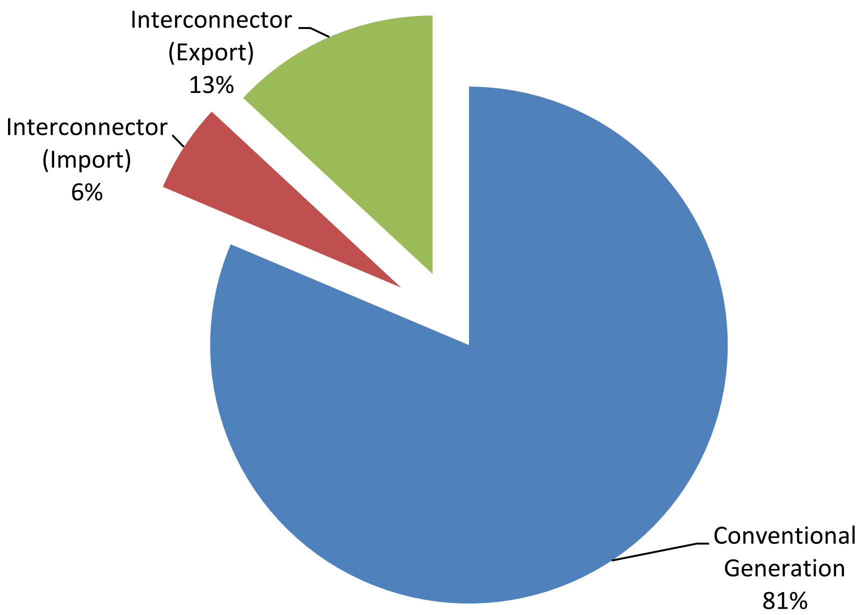

Figure 4.2-4: Breakdown of Worst-case contingencies.

In many cases the loss of a large generator is worse than the loss of an interconnector. This is because the loss of a generator results in the loss synchronous inertia mass as well as the loss of the active power infeed of the unit. This results in the lowering of the remaining overall system inertia following the event. Interconnectors do not possess synchronous inertia and therefore the post-event system inertia remains unchanged following an interconnector contingency.

4.3 Synchronous inertia studies

The objective of the synchronous inertia study is to determine the volume of synchronous inertia devices required on the system to maintain RoCoF within ±0.5 Hz/s in 99% of simulations.

4.3.1 Under-frequency events

4.3.1.1 Provision of supplementary inertia

Synchronous inertia devices provide an inertial response to the system that is instantaneous and proportional to the change in system frequency.

4.3.1.2 Simulation scenarios

Quantities of supplementary synchronous inertia between 2,400 MW.s and 20,000 MW.s are added to the cases.

4.3.1.3 Discussion of results

As described in section 2.3.2.1, the synchronous devices are modelled as generic synchronous machines with low active power output. These machines do not include additional controls such as governor droop or automatic voltage regulation. A damping constant is included in the model to assist with the damping of these synchronous inertia devices. Each device's synchronous inertia is defined as per the quantity detailed in 4.2.2.1 for each scenario. The supplementary synchronous inertia quantity is split equally between the four devices. The response will begin dampening after release of the initial kinetic energy.

Figure 4.3-1 displays the percentage of cases where RoCoF exceeds positive or negative RoCoF values of 0.5 Hz/s and 0.8 Hz/s. It also shows the percentage of cases which violate 49 Hz within 2.5 seconds of the event. A subset of the scenario results are displayed in this plot.

In Figure 4.3-1, the following is observed:

- Additional synchronous inertia of 12,000 MW.s resolves RoCoF for 99% of the cases studied, however it does not ensure that the nadir does not breach 49 Hz in 2.4% of cases.
- It is noted that additional fast-frequency response (FFR) and reserve provision would be required to support the system after the initial synchronous inertia is exhausted. The calculation of FFR and reserve volumes is beyond the scope of this study.
- No unintended adverse frequency recovery behaviour is observed for the synchronous inertia case.

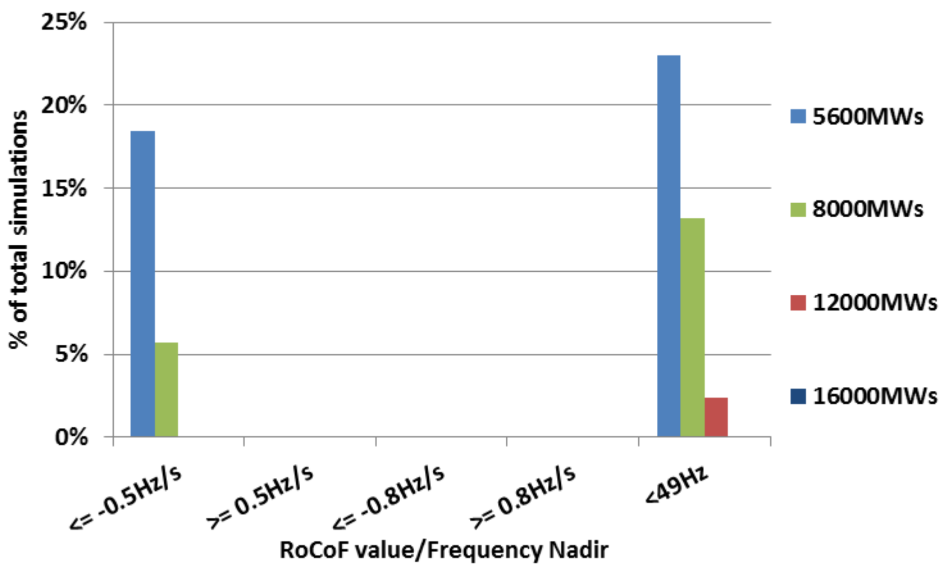

Figure 4.3-1: Synchronous inertia - Percentage of cases where RoCoF exceeds a value and frequency nadir is below 49Hz.

Figure 4.3-2 provides a duration curve illustrating the additional inertia requirements and total system inertia necessary to resolve the RoCoF issue. In this duration curve, only cases where RoCoF exceed -0.5 Hz/s are included. The inertia duration curve resulting from the studies produces system inertia volumes that are comparable to those observed on the system currently and support current operational policies. Furthermore, the results compare well with those demonstrated in the techno-economic studies.

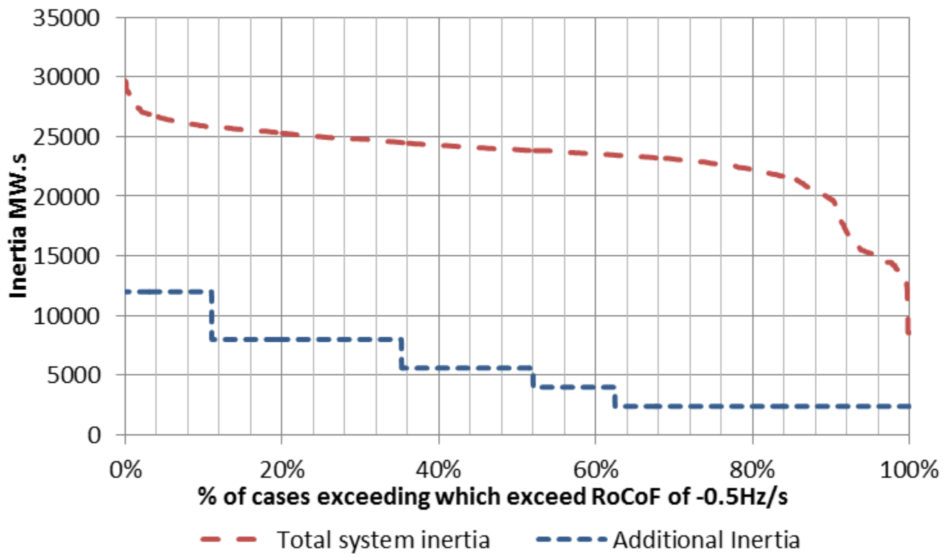

Figure 4.3-2: A duration curve only analysing cases which require additional inertia to ensure RoCoF does not exceed a negative RoCoF of 0.5 Hz/s. The Red Curve represents the total system inertia (additional inertia plus base case inertia). The Blue Curve represents the additional inertia. Note: Both duration curves are produced independently and plotted above.

4.3.1.4 High level conclusion

The minimum additional synchronous inertia requirement is 12,000 MW.s to resolve RoCoF in 99% of cases. The overall inertia volume (base system inertia plus additional inertia) is comparable to existing system inertia levels and remains above the current inertia limit of 20,000 MW.s in 90% of cases [11].

4.3.2 Over-frequency events

4.3.2.1 Provision of the supplementary inertia

As discussed above for the under-frequency cases, synchronous inertia devices provide an inertial response to the system that is instantaneous and proportional to the change in system frequency.

4.3.2.2 Simulation scenarios

Quantities of supplementary synchronous inertia between 5,600 MW.s and 16,000 MW.s are added to the cases.

4.3.2.3 Discussion of results

The synchronous inertia model and inertia quantities for these over-frequency simulations mirror the initial discussions in Section 4.3.1.3.

Of the power-flow cases considered, 1,874 cases contain an LSO large enough to cause RoCoF to exceed the existing positive RoCoF limit when suddenly disconnected. Currently, the only LSOs large enough to initiate significant over-frequency events are the Moyle and East-West interconnectors. Interconnectors do not possess synchronous inertia and therefore the sudden disconnection of these LSOs does not result in a change in the system inertia magnitude following the event.

Figure 4.3-3 displays the percentage of cases where RoCoF exceeds positive or negative RoCoF values of 0.5 Hz/s and 0.8 Hz/s. It also shows the percentage of cases, which violate 51 Hz within 2.5 seconds of the event. A subset of the scenario results are displayed in this plot.

The following points are observed from Figure 4.3-3:

- 12,000 MW.s of additional synchronous inertia is sufficient to maintain RoCoF within 0.5 Hz/s and contain the zenith within 51 Hz 99% of cases studied.

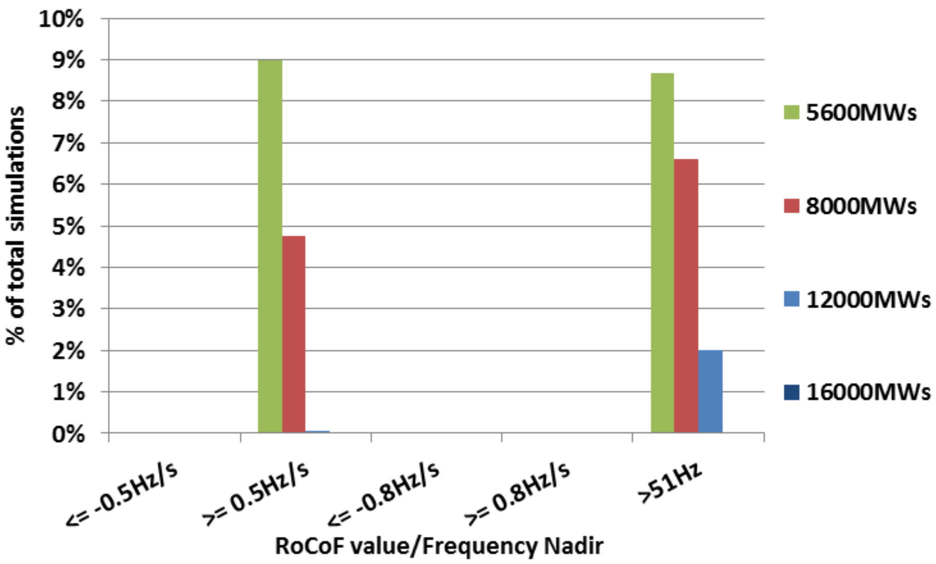

Figure 4.3-3: Synchronous inertia - Percentage of cases where RoCoF exceeds a value and frequency nadir is above 51Hz

4.3.2.4 High level conclusion

The minimum additional synchronous inertia requirement to resolve RoCoF in 99% of cases is 12,000 MW.s. The levels of synchronous inertia volumes predicted from the technical studies correlate with those predicted from the techno-economic dispatch case with a 0.5 Hz/s RoCoF constraint. The results are also comparable to present synchronous inertia levels on the system.

4.3.3 Comparing techno-economic and technical results

A plot overlaying duration curves of the required synchronous inertia calculated by the technical studies and by the techno-economic studies calculated as per case A of Table 4.1.1 is displayed in Figure 4.3-2.

The required synchronous inertia calculated by the technical studies is a combination of the worst case under-frequency or over-frequency result for each hour of the year where the cases solve. Techno-economic cases which did not converge in the technical studies were removed from the comparison. Case A of the techno-economic studies allows the system to operate up to 75% SNSP and have a potential RoCoF of up to 0.5 Hz/s.

The similarity of both duration curves in Figure 4.3-2 offers further validity to the technical study approach.

It should be noted that current operational policy is to maintain system inertia relative to the largest single infeed. EirGrid and SONI have also specified an inertia floor of 20,000 MW.s. These study results provide support for this inertia policy.

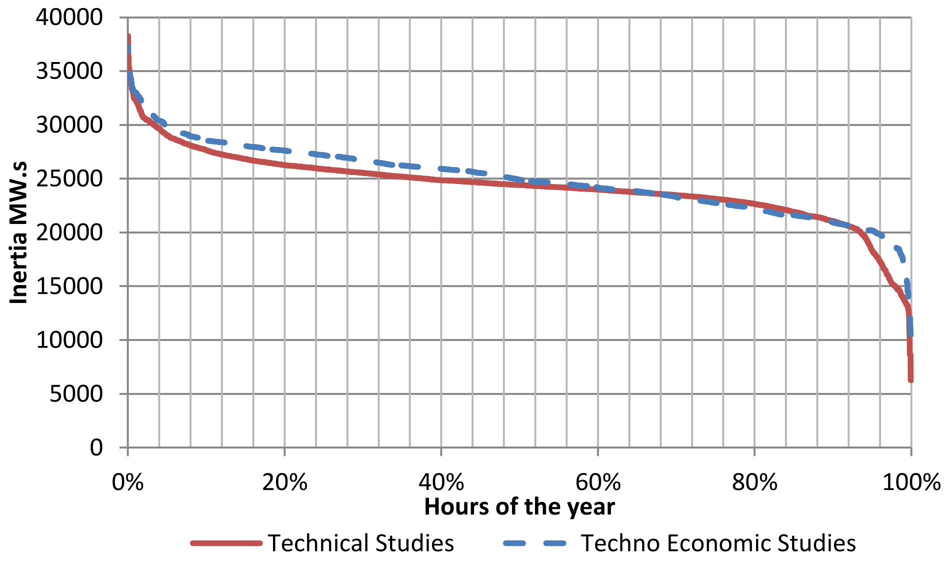

Figure 4.3-4: Duration curves of the required synchronous inertia calculated by the technical studies and the techno-economic inertia requirement calculated as per case A of Table 4.1.1

4.4 Synthetic inertia studies

The objective of theses synthetic inertia studies is to determine the volume of synthetic inertia required on the system to maintain RoCoF within ±0.5 Hz/s in 99% of simulations. A number of different options are explored for synthetic inertia provision including frequency triggered, RoCoF triggered and time triggered responses. These options are discussed in the following subsections.

4.4.1 Frequency triggering of the supplementary inertia

The frequency trigger sensitivity study provides an indication of the volume required if the synthetic inertia response is provided by a static active power injection triggered at a specified frequency threshold.

4.4.1.1 Under-frequency events (49.8 Hz) – No time delay

4.4.1.1.1 Triggering of the supplementary inertia

Following an under-frequency event the synthetic inertia devices, (set to control Mode A), inject active power into the system when frequency decreases below 49.8 Hz.

4.4.1.1.2 Simulation scenarios

The supplementary synthetic inertia is incrementally increased from 80 to 440 MW. A case where the synthetic inertia limit was not limited was also considered.

4.4.1.1.3 Discussion of results

As discussed in section 2.3.3.2, the supplementary synthetic inertia response is injected at four locations across the system. The devices are triggered when frequency measured at the local bus decreases below 49.8 Hz following a system event. No additional time delay is included in this case and active power is injected at a rate of 2300 MW/s. The synthetic inertia device will continue to inject active power to the defined limit or until the local frequency recovers to 49.8 Hz. The response is maintained at this value for the remainder of the simulation.

Each device's synthetic inertia is limited in each of the scenarios, with the exception of the no limit case. The defined limit is the aggregated limit of the four devices. The limits for each synthetic inertia device are identical.

Figure 4.4-1 displays the percentage of cases where RoCoF exceeds a positive or negative value of 0.5 Hz/s and 0.8 Hz/s. It also shows the percentage of cases, which violate 49 Hz within 2.5 seconds of the event. A subset of the scenario results are displayed in this plot.

In Figure 4.4-1, the following is observed:

- The scenario with a maximum synthetic inertia limit of 440 MW does not resolve RoCoF requirements within the necessary number of cases.
- At this frequency trigger setting, synthetic inertia with no active power injection limit resolves the negative RoCoF threshold. A duration curve of the active power injected for this scenario is displayed in Figure 4.4-2. A drawback of this method is that the positive RoCoF observed as the frequency recovers is in breach of 0.5 Hz/s in 7% of cases. This is a result of an unintended consequence of over injecting an active power response that results in a high frequency event.

These results suggest that, synthetic inertia triggering at 49.8 Hz does not provide enough active power within the required period to ensure RoCoF is within ±0.5 Hz/s. RoCoF in a low inertia system could potentially be 0.4 Hz/s prior to any synthetic inertia response being injected. Consequently, this only allows a short period to inject a large quantity of active power to prevent the high rate of change of frequency.

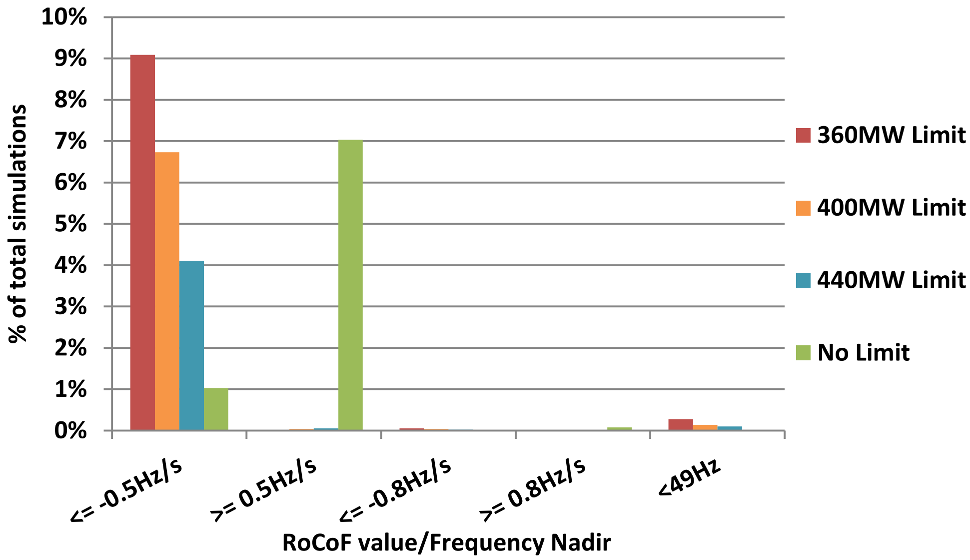

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Figure 4.4-1: Frequency triggering of synthetic inertia at 49.8 Hz - Percentage of cases where RoCoF exceeds a value and frequency nadir is below 49Hz

Figure 4.4-2 displays a synthetic inertia duration curve of the quantities of synthetic inertia required to ensure RoCoF does not exceed -0.5 Hz/s. A trend line is added to the stepped results.

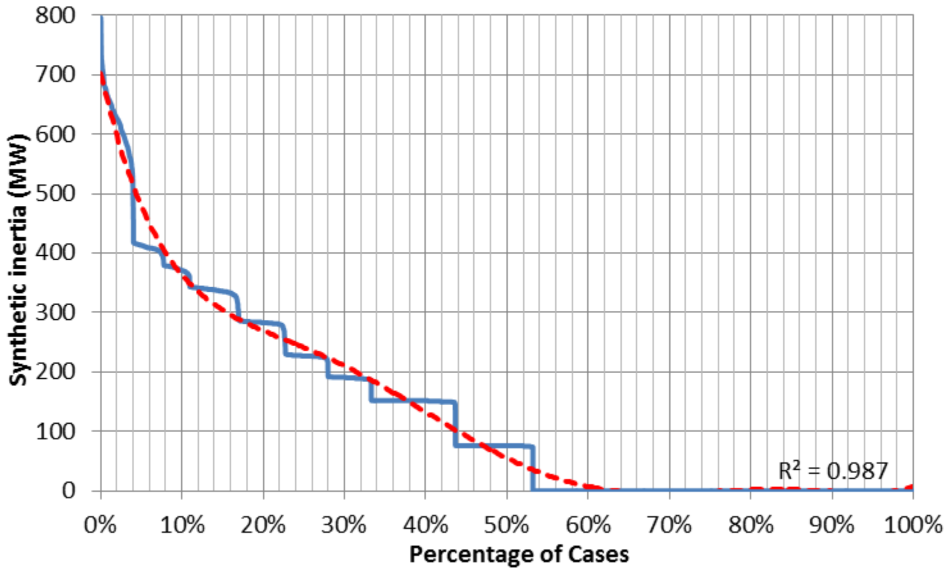

Figure 4.4-2: Synthetic inertia duration curve – Quantities of synthetic inertia

4.4.1.1.4 High level conclusion

At this trigger setting, even with an unlimited injection of active power from synthetic inertia devices, the system RoCoF does not remain within ±0.5 Hz/s in 99% of cases.

4.4.1.2 Under-frequency events (49.9 Hz) – No time delay

4.4.1.2.1 Triggering of the supplementary inertia at 49.9 Hz

This scenario follows a similar process to that described in Section 4.4.1.1, however the trigger point for the device is set at 49.9 Hz rather than 49.8 Hz.

4.4.1.2.2 Simulation scenarios

The supplementary synthetic inertia is increased from 80 to 440 MW. A case where the synthetic inertia limit was not limited was also considered.

4.4.1.2.3 Discussion of results

Figure 4.4-3 displays the percentage of cases where RoCoF exceeds a positive or negative value of 0.5 and 0.8 Hz/s. It also shows the percentage of cases, which violate 49 Hz within 2.5 seconds of the event.

In Figure 4.4-3, the following is observed:

- Synthetic inertia of 360 MW resolves RoCoF requirement in 99% of the cases, and
- The no-limit injection case is again seen to result in the unintended consequence of causing a positive RoCoF event in the frequency recovery. Simulations suggest positive RoCoF will exceed the 0.5 Hz/s limit in 9% of cases.

Although a frequency trigger of 49.9 Hz theoretically provides a solution to the RoCoF issue, it could lead to operational issues. It is expected that at this frequency threshold there could be nuisance injection/consumption of large quantities of active power (>360 MW) for relatively small frequency excursions. This fast injection of active power may cause the frequency to recover at greater than +0.5 Hz/s and cause a subsequent over-frequency event. This would be a particular issue if the unit disconnected was not the LSI.

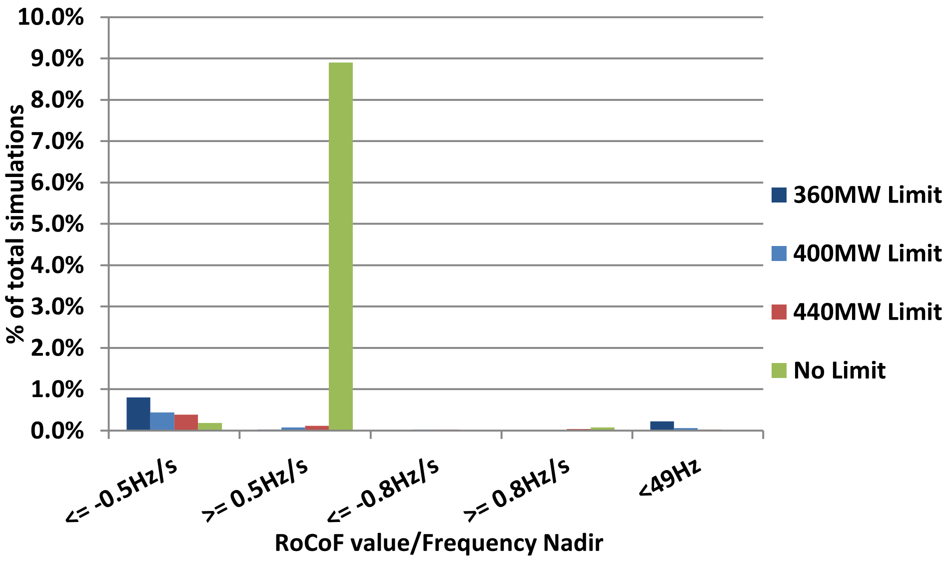

Figure 4.4-3: Frequency triggering of synthetic inertia at 49.9 Hz - Percentage of cases where RoCoF exceeds a value and frequency nadir is below 49Hz

4.4.1.2.4 High level conclusion

Simulations have shown synthetic inertia of 360 MW meets the RoCoF requirement for a trip of the LSI. For a trip of generation with a frequency nadir just below 49.9 Hz, there is a possibility of injecting large quantities of synthetic inertia that would be in excess of the active power of the tripped generation. Over-providing active power following small frequency excursions could lead to over-frequency events and there is also a possibility of violating RoCoF during the frequency recovery.

4.4.1.3 Over-frequency events (50.2 Hz) – No time delay

4.4.1.3.1 Triggering of the supplementary inertia at 50.2 Hz

The synthetic inertia model and inertia limits for these simulations mirror the discussion in Section 4.4.1.1 with the exception that the frequency trigger, (set to control Mode B), is 50.2 Hz and it triggers on over-frequency events.

4.4.1.3.2 Simulation scenarios

The supplementary synthetic inertia is incrementally increased from 240 to 400 MW. A case where the synthetic inertia limit was not limited was also considered.

4.4.1.3.3 Discussion of results

Figure 4.4-4 displays the percentage of cases where RoCoF exceeds a positive or negative RoCoF value of 0.5 and 0.8 Hz/s. It also shows the percentage of cases, which violate 51 Hz within 2.5 seconds of the event.

Synthetic inertia of up to 400 MW does not maintain RoCoF below 0.5 Hz/s within the necessary number of cases.

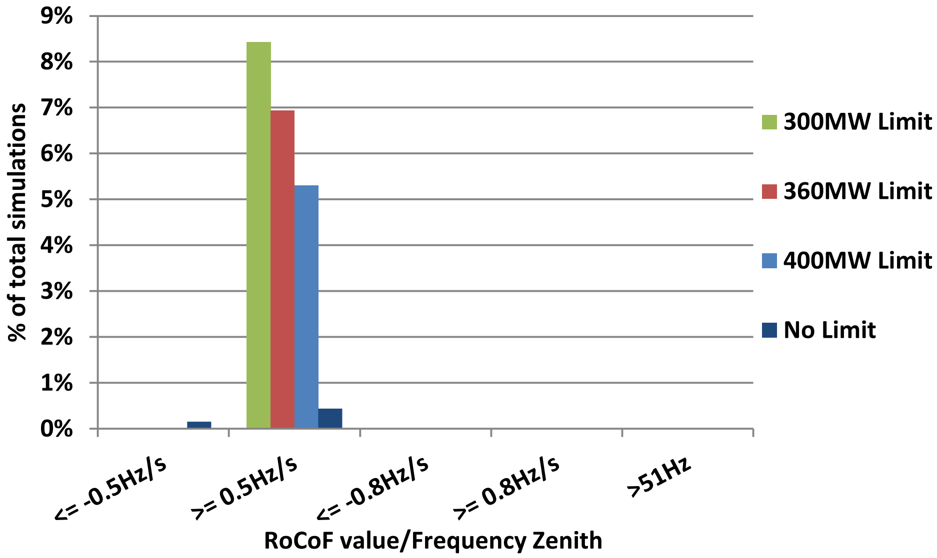

Figure 4.4-4: Frequency triggering of synthetic inertia at 50.2 Hz - Percentage of cases where RoCoF exceeds a value and frequency nadir is above 51Hz

4.4.1.3.4 High level conclusion

Synthetic inertia triggered at 50.2 Hz does not maintain RoCoF below 0.5 Hz/s within the necessary number of cases following an over-frequency event.

4.4.1.4 Over-frequency events (50.1 Hz) – No time delay

4.4.1.4.1 Triggering of the supplementary inertia at 50.1 Hz

The synthetic inertia model and inertia limits for these simulations mirror the discussion in Section 4.4.1.1 with the exception that the frequency trigger, (set to control Mode B), is 50.1 Hz and it triggers on over-frequency events.

4.4.1.4.2 Simulation scenarios

The supplementary synthetic inertia is incrementally increased from 300 to 400 MW. A case where the synthetic inertia limit was not limited was also considered.

4.4.1.4.3 Discussion of results

Figure 4.4-5 displays the percentage of cases where RoCoF exceeds a positive or negative RoCoF value of 0.5 and 0.8 Hz/s. It also shows the percentage of cases, which violate 51 Hz within 2.5 seconds of the event.

The bar column shows that synthetic inertia of 360 MW is sufficient to maintain RoCoF below 0.5 Hz/s within the necessary number of cases. As was the case with the under-frequency events with a frequency trigger of 49.9 Hz, a trigger of 50.1 Hz could lead to nuisances triggering during normal operating conditions.

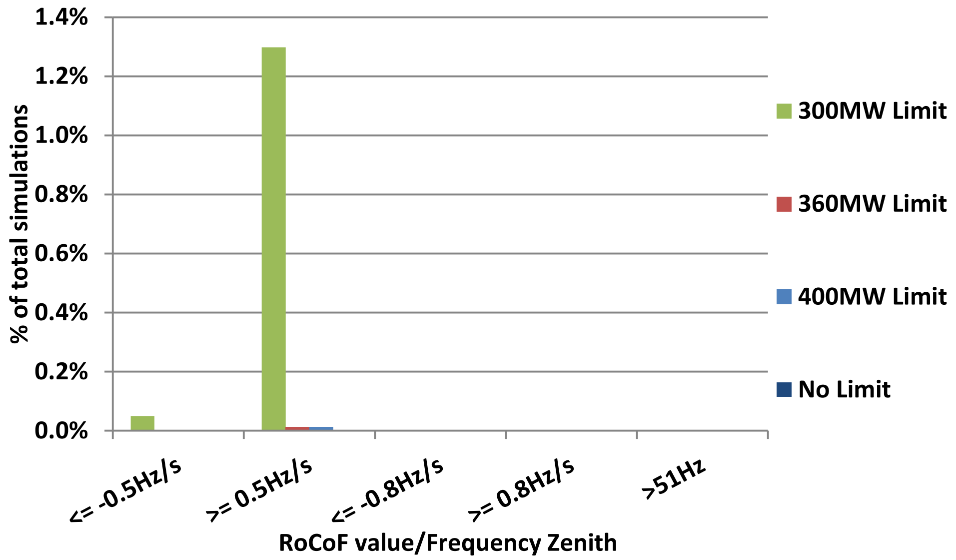

Figure 4.4-5: Frequency triggering of synthetic inertia at 50.1 Hz - Percentage of cases where RoCoF exceeds a value and frequency nadir is above 51Hz

4.4.1.4.4 High level conclusion

Simulations have shown synthetic inertia of 360 MW meets the RoCoF requirement for a trip of the LSO. For a trip of generation with a frequency zenith just above 50.1 Hz, there is a credible possibility of injecting quantities of synthetic inertia that could exceed the active power of the tripped generation. This would result in the unintended consequence of an under-frequency and negative RoCoF events.

4.4.2 Intermediate conclusion

The previous subsections analysed the suitability of frequency triggered synthetic inertia response at a near-instantaneous ramp rate in terms of maintaining RoCoF at 0.5 Hz/s. In summary, the previous subsections highlight:

- A frequency trigger within 0.1 Hz of nominal frequency would resolve the RoCoF issue, however, operational challenges would exist with this solution. For some events (or even during normal operation) undesirable injecting/consuming of active power following small frequency excursions, could result in unintended over- and under-frequency events that possibly lead to a violation of RoCoF during frequency recovery. Therefore, this approach appears to be an unsuitable alternative.
- A frequency trigger within 0.2 Hz of nominal frequency would require an active power response in excess of the power system LSI or LSO to resolve RoCoF. This fast injection of excess active power lead to unintended over- and under-frequency events which violated RoCoF limits during the frequency recovery.

For the purpose of subsequent frequency triggered synthetic inertia studies a frequency trigger of 49.8 Hz with zero time delay is selected.

4.4.3 RoCoF triggering of the supplementary inertia

The objective of this sensitivity study is to provide an indication of the volume requirement if a device calculating RoCoF over 500 ms triggers the synthetic inertia response.

4.4.3.1 Triggering of the supplementary inertia

Following an under-frequency event triggered by the sudden disconnection of the LSI, the synthetic inertia devices, (set to control Mode C), inject active power into the system while RoCoF exceeds the defined threshold.

4.4.3.2 Simulation scenarios

The supplementary RoCoF triggered synthetic inertia available for all cases in each of the simulation scenarios is listed below:

- Synthetic inertia - RoCoF 0.2 Hz/s (calculated over 500ms),
- Synthetic inertia - RoCoF 0.3 Hz/s (calculated over 500ms), and
- Synthetic inertia - RoCoF 0.4 Hz/s (calculated over 500ms).

4.4.3.3 Discussion of results

As discussed in section 2.3.3.2, the supplementary synthetic inertia response is injected at four locations across the system. The devices are triggered when the RoCoF measured at the device’s local bus is greater than the defined RoCoF threshold. RoCoF is calculated over 500 ms as per the Grid Code definition. Active power is injected with no additional time delay at a rate of 2300 MW/s. The synthetic inertia device will continue to inject active power until the RoCoF value falls below the defined threshold. The device maintains this response for the remainder of the simulation.

Figure 4.4-6 displays the percentage of cases where RoCoF exceeds a positive or negative value of 0.5 and 0.8 Hz/s. It also shows the percentage of cases, which violate 49 Hz within 2.5 seconds of the event. It is observed from the plot that, even at a relatively low RoCoF trigger setting of 0.2 Hz/s, 29% of cases exceed the negative RoCoF limit. Figure 4.2-3 suggests that devices on the power system need to begin to respond within 200 - 500 ms of the event for 51% of the years cases.

It should be noted that the worst case contingency in the base case, results in the most extreme rate of change of frequency and this will trigger synthetic inertia earlier than lower RoCoF cases. The earlier injection of active power into the system therefore alleviates the RoCoF and results in a higher frequency nadir. Contingencies that result in lower RoCoF would result in synthetic inertia being injected into the system later, therefore resulting in lower frequency nadirs. Consequently, the worst-case contingency in the base-case may no longer be the worst-case contingency in the scenario when inertia has been added.

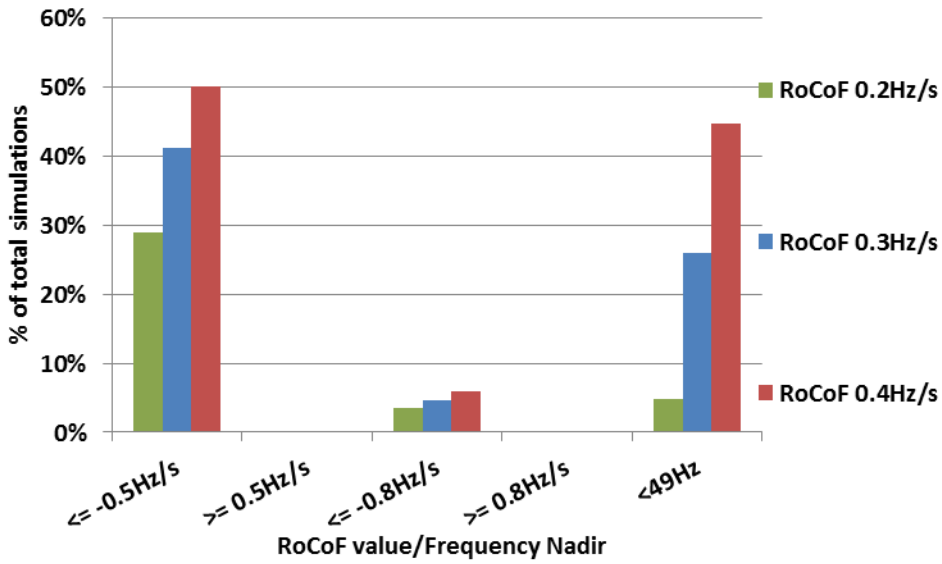

Figure 4.4-6: Synthetic inertia response while the defined RoCoF threshold is exceeded, no active power limit - Percentage of cases where RoCoF exceeds a value and frequency nadir is below 49Hz.

4.4.3.4 High level conclusion

RoCoF triggered response to a system event calculated over 500 ms does not resolve the RoCoF issue in a sufficient number of cases studied. This method therefore appears an unsuitable technique to resolve the RoCoF issue.

4.4.4 Time triggering of the supplementary inertia

The objective of this sensitivity study is to provide an indication of minimum response times for synthetic inertia devices, (set to control Mode A), and the impact of delayed response on the synthetic inertia requirement. The purpose of the analysis is to indicate the minimum acceptable response time and recognises that a wide range of measurement techniques could be used to achieve the required response times.

4.4.4.1 Triggering of the supplementary inertia

The synthetic inertia devices inject active power into the system following a defined time delay following the disconnection of the LSI. No frequency or RoCoF triggers were used in these scenarios. The simulation only considers a specified time delay after the event as the trigger and aims to give an indication of the time in which a device must react to an event irrespective of the underlying event detection method utilised.

4.4.4.2 Simulation scenarios

The analysis shown in section 3.4.1 indicates that synthetic inertia in the range of 360-400MW is required to maintain RoCoF within 0.5 Hz/s for 99% of cases. For this study only the 360MW and 400MW synthetic inertia volumes are considered. The time delays in device response are varied for each of these scenarios. The delays were increased from 0 ms to 300 ms in 100 ms intervals.

4.4.4.3 Discussion of results

The static stepped response characteristic of the synthetic inertia devices is identical to those discussed in Section 4.4.1.1.3. This sensitivity does not employ a frequency trigger and instead employs a defined time delay before injecting an active power response. The time delay starts from the moment of the event. All synthetic inertia devices are set with the same time delay in each scenario. The sensitivities consider two separate synthetic inertia limits, 400 MW and 360 MW. Active power injection ceases if the frequency at each device's local bus returns to nominal or the active power limit is met. The device maintains its active power response for the remainder of the simulation.

Figure 4.4-7 provides an indication of how a slower response influences the number of cases to violate the RoCoF limit of 0.5 Hz/s. The figure illustrates that a time delay of greater than 200 ms results in a significant number of cases exceeding the RoCoF limit. The number of cases that exceed the negative RoCoF limit of 0.5 Hz/s, is within the 1% criteria for the 0 ms and 100 ms time delay cases. This indicates that a synthetic inertia device should respond within 100 ms to prevent a high RoCoF event.

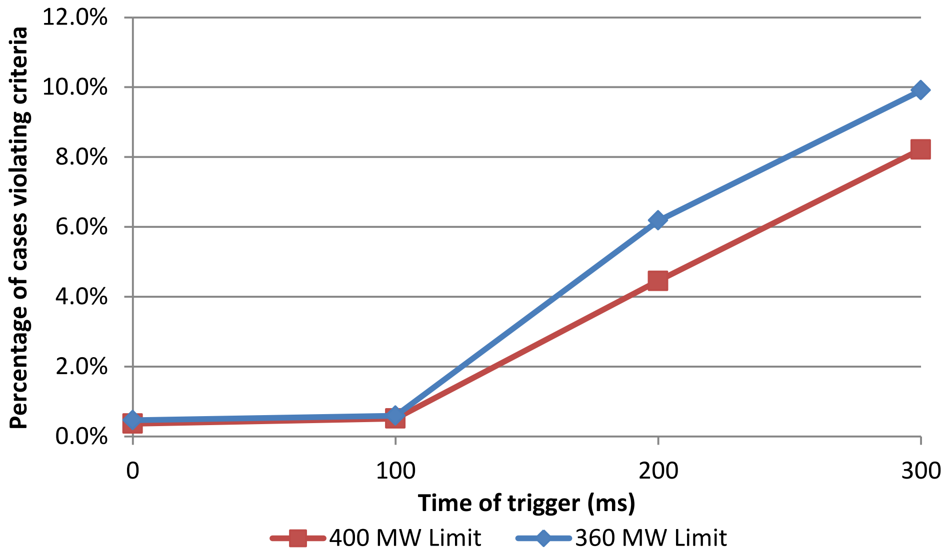

Figure 4.4-7: Variation in time delay of synthetic inertia injection - Percentage of cases where a negative RoCoF of 0.5 Hz/s is violated as the time of active power injection increases.

Figure 4.4-8 and Figure 4.4-9 displays the percentage of cases where RoCoF exceeds a positive or negative RoCoF value of 0.5 Hz/s and 0.8 Hz/s for a 400 MW and 360 MW limit, respectively. It also shows the percentage of cases, which violate 49 Hz within 2.5 seconds of the event.

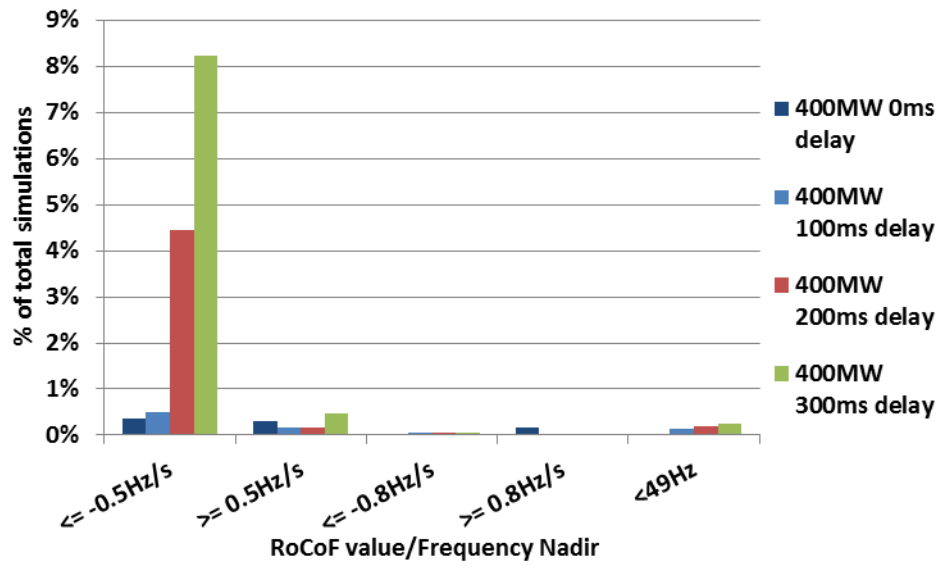

Figure 4.4-8: Variation in the time of the synthetic inertia injection, limited to 400 MW - Percentage of cases where RoCoF exceeds a value and frequency nadir is below 49Hz.

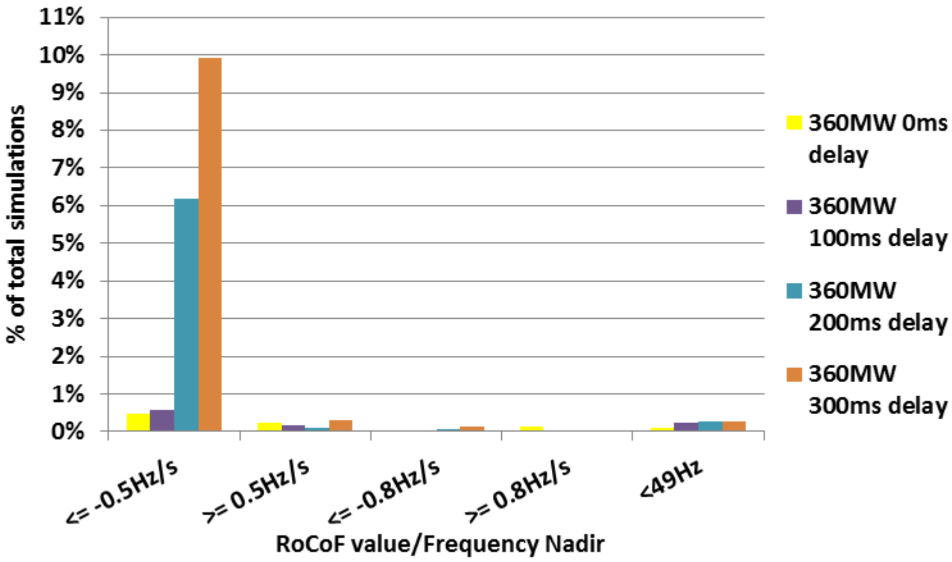

Figure 4.4-9: Variation in the time of the synthetic inertia injection, limited to 360 MW - Percentage of cases where RoCoF exceeds a value and frequency nadir is below 49Hz.

4.4.4.4 High level Conclusion

The response time associated with a synthetic inertia device is essential in determining whether it can resolve the RoCoF event. The simulations indicate that synthetic devices should respond within 100 ms to ensure that 99% of the cases studied maintain RoCoF within 0.5 Hz/s.

4.4.5 Controlled droop response of the supplementary inertia

The objective of this sensitivity is to provide an indication of the volume requirement if the synthetic inertia response is droop controlled.

4.4.5.1 Triggering of the supplementary inertia

In this sensitivity, the synthetic inertia devices, (set to control Mode D), inject active power based on a droop controller. The devices begin to inject active power into the system when frequency falls outside a dead-band of ±0.05 Hz.

4.4.5.2 Simulation scenarios

Various droop levels are analysed for the supplementary droop-controlled synthetic inertia devices. The droop levels investigated are 4%, 2%, 1%, 0.75%, 0.5% and 0.25%.

4.4.5.3 Discussion of results

The synthetic inertia device operates on droop control when the local bus frequency is outside the set dead-band of ±0.05 Hz. The simulated droop-control delivers the quantity of active power as per Equation 3.4-2. $\Delta\mathrm{F}$ is calculated from the simulated frequency change. $\Delta\mathrm{P}$ injects active power based on the scenarios droop setting. There is no limit to the quantity of active power available for injection into the system and no additional time delays are modelled in these scenarios.

$$droop = \frac{\Delta\mathrm{F}(\%)}{\Delta\mathrm{P}(\%)} \qquad \text{Equation 3.4-2}$$

Figure 4.4-10 displays the percentage of cases where RoCoF exceeds a positive or negative RoCoF value of 0.5 Hz/s and 0.8 Hz/s. It also shows the percentage of cases, which violate 49 Hz within 2.5 seconds of the event.

Figure 4.4-10 illustrates that the industry standard droop setting of 4% is not sufficient to maintain RoCoF within 0.5 Hz/s. The simulation results indicate that an aggressive 0.25% droop would be required to maintain the RoCoF within the defined limit for 99% of study cases.

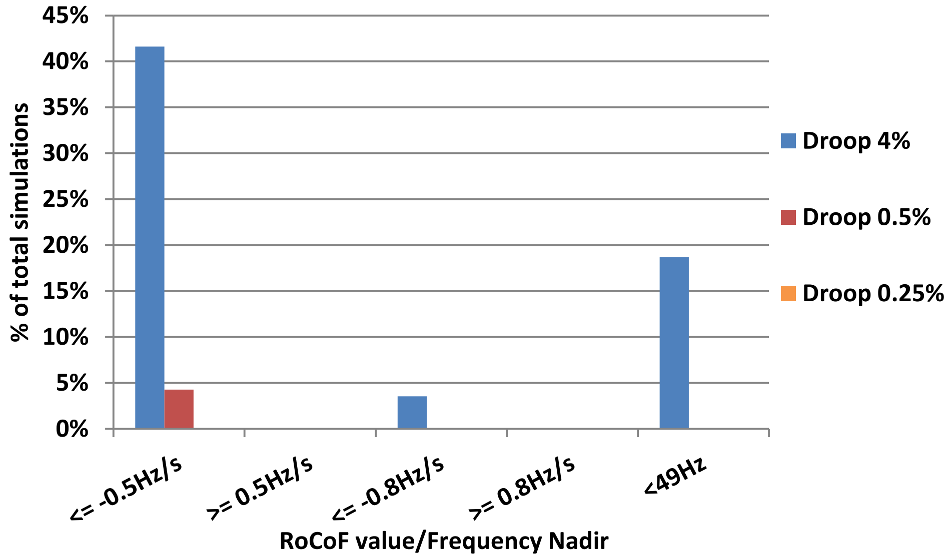

Figure 4.4-10: Droop-control sensitivity - Percentage of cases where RoCoF exceeds a value and frequency nadir is below 49Hz

4.4.5.4 High level conclusion

A droop response of approximately 0.25% would be required if droop control alone was to provide a RoCoF alternative. A more aggressive droop results in less synthetic inertia volume required to support the system. It is noted that employing a large penetration of devices with different droop characteristics may have system stability implications. This would need to be investigated in more detail along with the effect of any associated response time delays.

4.4.6 Step and droop response of the supplementary inertia

The objective of this sensitivity study is to analyse the use of droop-control to mitigate the unintended frequency recovery issues observed in the static synthetic inertia cases presented in Section 3.4.1. The solution involves using a frequency triggered synthetic inertia response followed by a 4% controlled droop during the frequency recovery.

4.4.6.1 Triggering of the supplementary inertia

In this sensitivity, the synthetic inertia devices, (set as a combination control of Mode A and F), inject active power into the system when frequency decreases below 49.8 Hz. At the moment frequency begins to recover, the synthetic inertia response shifts from a static response to a droop-controlled response (see Figure 3.3-6). The synthetic device is set with no maximum active power limit. The droop control function is triggered once the system frequency has reached its nadir and RoCoF is 0 Hz/s. Droop is set to 4% and droops from the devices pre-droop controlled output. No additional time delay is associated with the droop response.

4.4.6.2 Discussion of results

The initial static response of synthetic inertia is identical to the frequency triggered response presented in Section 4.4.1.1.3 with no active power limit. Following the initial static response, the model contains a RoCoF measurement relay and droop-control functionality. The RoCoF relay determines when frequency is no longer decreasing. Once the device detects that the frequency has reached its nadir the control of the active power injection shifts from static to droop-controlled response.

Figure 4.4-11 displays the percentage of cases where RoCoF exceeds a positive or negative RoCoF value of 0.5 Hz/s and 0.8 Hz/s. It also shows the percentage of cases which violate 49 Hz within 2.5 seconds of the event.

In Figure 4.4-11, the results of this scenario are compared to the following synthetic inertia scenarios:

a. triggered on frequency with no active power limit as displayed in Section 4.4.1.1.3, and

b. controlled 4% droop as displayed in Section 4.4.5.3.

This scenario is a hybrid of both control schemes; fast active power injection as per scenario ‘a’ and a controlled recovery as per scenario ‘b’.

The results demonstrate that the fast active power injection resolves the initial RoCoF violations while the controlled droop response improves the unintended RoCoF violations on recovery.

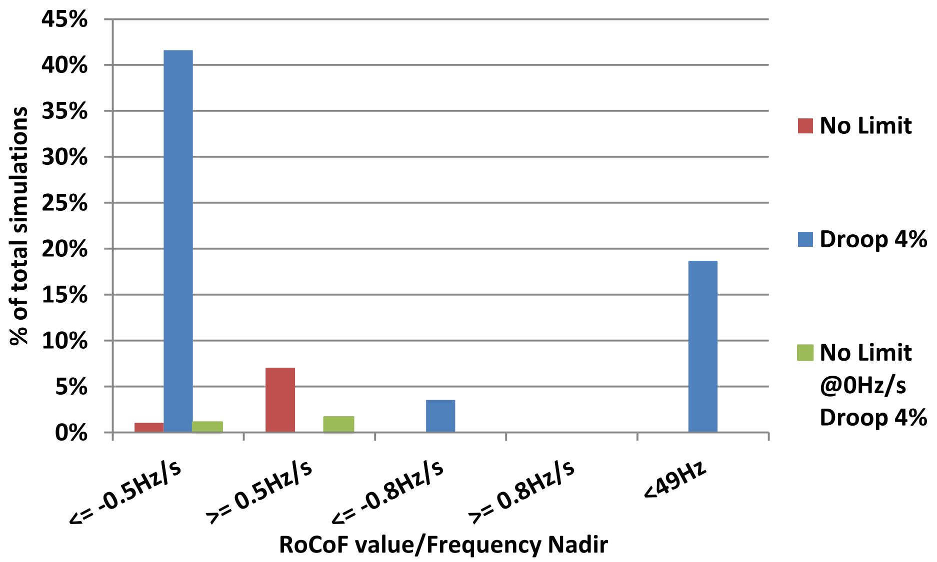

Figure 4.4-11: Combined static and droop-controlled response sensitivity - Percentage of cases where RoCoF exceeds a value and frequency nadir is below 49 Hz

4.4.6.3 High level conclusion

The injection of large amounts of active power to prevent a RoCoF event could cause adverse issues during the frequency recovery phase as discussed in Section 4.4.1.1.3. The inclusion of a controlled droop response during the recovery phase is seen to alleviate the issues associated with unintended under-frequency events which violated RoCoF limits during the frequency recovery. A combination of static and droop control offers a more stable solution to resolving the RoCoF issue.

4.4.7 Variation of ramp-rate of supplementary inertia

The objective of this sensitivity is to provide an indication of the effect of a reduced ramp rate of synthetic inertia on the ability to maintain RoCoF within 0.5 Hz/s for 99% of studied cases.

4.4.7.1 Triggering of the supplementary inertia

The synthetic inertia devices, (set to control Mode A), inject active power into the system when frequency decreases below 49.8 Hz. The ramp rate of injection of active power per second is varied for each scenario.

4.4.7.2 Simulation scenarios

The ramp rates of the supplementary synthetic inertia are varied for each of the simulation scenarios. Ramp rate are

- 2300 MW/s,
- 1450 MW/s
- 1150 MW/s
- 750 MW/s,
- 550 MW/s,
- 450 MW/s,
- 350 MW/s, and
- 300 MW/s.

4.4.7.3 Discussion of results

The initial static response of the synthetic inertia devices is the same as those presented in Section 4.4.1.1.3. The sensitivity related to varying the ramp rate for the active power injection. In this sensitivity, synthetic inertia is limited to 400 MW. The active power injection is blocked once the frequency recovers to 49.8 Hz. The device maintains the active power response at this level for the remainder of the simulation.

Figure 4.4-12 displays the percentage of cases, which violate a negative RoCoF of 0.5 Hz/s at different ramp rates of synthetic inertia with red circles. A close fitting exponential trend line (R^2=0.9934) is added to the plot and represented by a dashed green line.

This analysis highlights that ramp rate of active power injection has a significant impact on the ability of a synthetic inertia device to prevent high RoCoF events in excess of 0.5 Hz/s.

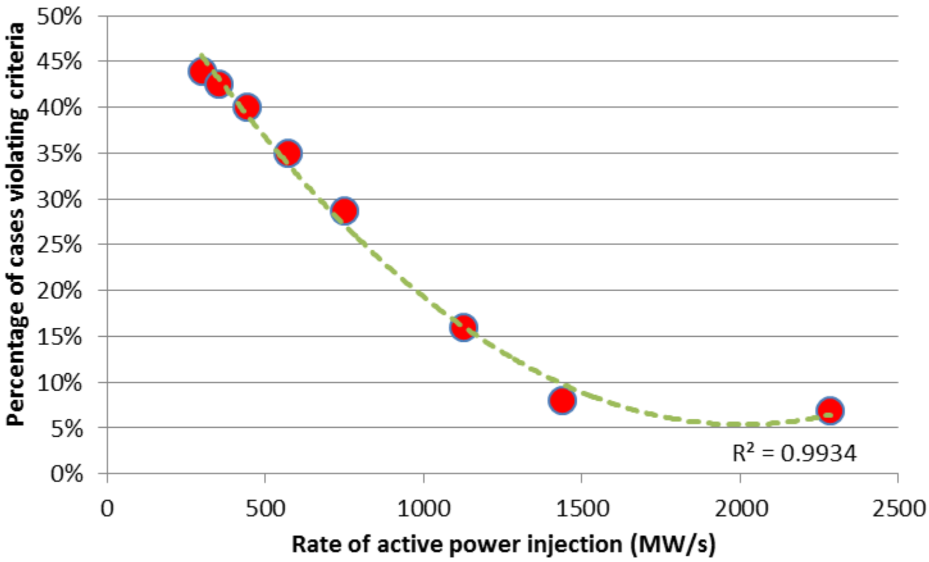

Figure 4.4-12: Variation in ramp rate with a 49.8 Hz frequency trigger and 400 MW synthetic inertia limit - Percentage of cases where a negative RoCoF of 0.5 Hz/s is violated as the rate of active power injection changes.

4.4.7.4 High level Conclusion

This analysis highlights that the ramp rate of active power injection has a significant impact on the ability of a synthetic inertia device to prevent RoCoF events in excess of 0.5 Hz/s. The necessary rate of injection for the system to remain within the RoCoF limit is in the region of 1500 MW/s.

4.4.8 Influence of load model variation

This sensitivity investigates the impact of the frequency response of demand on the required synthetic inertia volume. The original load model is altered using a series of standard complex load models that vary the composition of the system load to provide various frequency responses from the load.

4.4.8.1 Triggering of the supplementary inertia

The synthetic inertia devices, (set to control Mode A), are modelled with the frequency response characteristic described in Section 3.4.1.3. The devices are triggered when frequency decreases below 49.8 Hz.

4.4.8.2 Simulation scenarios

The supplementary synthetic inertia is increased from 360 MW to 440 MW in 40M W steps. The load models with frequency dependences of 1% and 2% are used in the simulation.

4.4.8.3 Discussion of results

The aggregated composition of the system load, and the frequency response of the load, influences the frequency recovery of the system. This model consists of a mixture of constant impedance (Z), constant current (I), and constant power (P) components. The model is denoted as the ZIP model and does not contain a frequency sensitive component. The composition of the ZIP is discussed in more detail in Section 3.2.2.2.

The frequency-dependence of load would aid system frequency recovery by counteracting the generation-demand imbalance caused by the loss of the largest in-feed or out-feed. Frequency dependent load models of 1% and 2% are selected to provide an indication of how the load composition would effect synthetic inertia requirements for the trip of the LSI.

Figure 4.4-13 displays the percentage of cases where RoCoF exceeds a positive or negative RoCoF value of 0.5 Hz/s and 0.8 Hz/s with the worst-case ZIP load model and the frequency-dependent load model. It also shows the percentage of cases, which violate 49 Hz within 2.5 seconds of the event.

These sensitives suggest a frequency-dependent load reduces the number of violations by 1% to 3%.

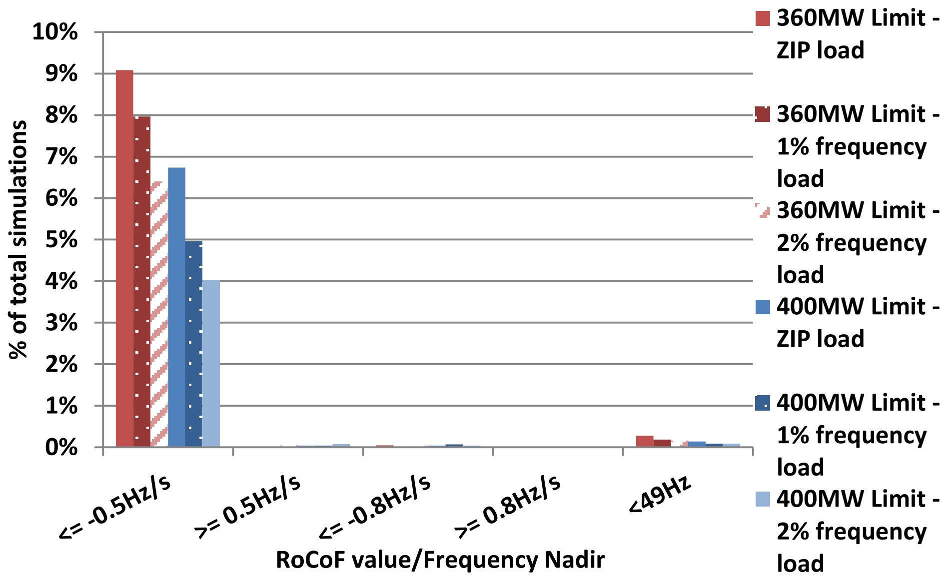

Figure 4.4-13: Variation in load composition - Percentage of cases where RoCoF exceeds a value and frequency nadir is below 49Hz

4.4.8.4 High level Conclusion

The composition of the load has a major influence on the volume of supplementary inertia required to provide an alternative to increasing RoCoF.

4.5 Synchronous and synthetic inertia combination studies

The objective of the following studies is to determine different proportions of synchronous to synthetic inertia which can maintain RoCoF below -0.5 Hz/s in 99% of simulations.

4.5.1 Under-frequency events

4.5.1.1 Triggering of the supplementary inertia

Following an under-frequency event, triggered by the sudden disconnection of the LSI, supplementary synchronous and synthetic inertia is injected into the system. Synthetic inertia frequency trigger is 49.8 Hz in the following simulations.

4.5.1.2 Simulation scenarios

The supplementary synthetic and synchronous inertia available in each of the simulation scenarios is tabulated below:

Table 4.5.1 Cases for synchronous and synthetic inertia combination studies

Synthetic inertia (MW)	Synchronous inertia (MW.s)
80	4000
80	800
80	12000
120	8000
160	5600
160	8000
160	12000
200	4000
200	7200
240	12000
240	2400
240	4000
240	5600
240	6400
240	8000
300	5600
360	4000
No limit	5600
No limit	8000

4.5.1.3 Discussion

Synchronous and synthetic modelled devices are discussed in Section 4.3.1.3 and 4.4.1.1.3. The difference in this analysis is that both sets of inertia devices are available to respond. There is no direct communication between the devices.

The cases simulated do not show any violation of the 49 Hz criteria. A best-fit trend line for the combinations of synchronous versus synthetic inertia is displayed in Figure 4.5-1. Combinations that meet the criteria are coloured in green with failed combinations in red. The trend line is based on combinations of synchronous versus synthetic inertia, which comply with the acceptance criteria. Therefore, the plot provides only an indication of the ratio of synchronous versus synthetic inertia. This trend is specific for the synthetic inertia response selected for these simulations.

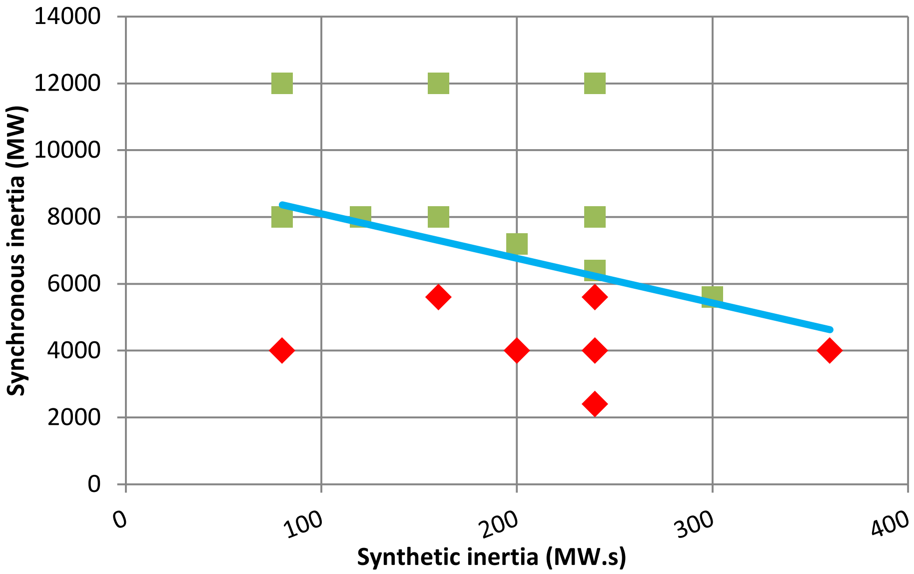

Figure 4.5-1: Synchronous and synthetic inertia – Best-fit linear line of synchronous versus synthetic inertia.

4.5.1.4 High level Conclusion

The combination of synchronous and synthetic inertia is found to deliver a solution where the devices responses can complement each other. These results are highly sensitive to the performance of the synthetic devices. It is likely that there would be careful consideration of the technical specification of synthetic inertia. In practice, the TSOs would need to appropriately design the frequency response of the devices to the required system needs. Further analysis would be required to fully understand the possibilities in combining synchronous and synthetic devices.

5 Summary and next steps

5.1 Phase 2 study findings

Our findings from the analysis presented in the report are as follows:

a) Synchronous inertia is a solution to maintaining RoCoF within ± 0.5 Hz/s. Technical studies support current operational policy that relates the system inertia requirement with the largest single infeed. The studies indicate that a system inertia of 20,000 MW.s, or greater, would need to be retained for the majority of dispatches to maintain potential RoCoF within 0.5 Hz/s. This equated to approximately 12,000 MW.s of supplementary synchronous inertia being added to the 1 Hz/s base case scenario in the study. Adding further system constraints to the base case, such as minimum reserve requirements, reduces the amount of supplementary synchronous inertia required.

b) Synthetic inertia could be a solution to maintaining RoCoF within ± 0.5 Hz/s, however, there were challenges associated with these devices. The performance of the synthetic inertia devices, for the purposes of maintaining the RoCoF within ± 0.5 Hz/s, was found to be highly sensitive to the characteristics of the response. In particular, the device response time and ramp rate were of significant importance. In order to meet the RoCoF criteria, it was found that the following criteria would need to be satisfied:

    - to begin responding from 100 milliseconds from the start of the event.
    - to ramp at a sufficient rate to deliver power to the system. For the system to remain within the RoCoF limit, the active power injection must be fully achieved 200 milliseconds after the device begins to respond.
    - a suitable form of control to prevent unintended adverse system issues during the frequency recovery, and
    - a minimum of ±360 MW of supplementary synthetic inertia would need to be available for the duration of the RoCoF event.

- Synthetic inertia response is required for both high and low frequency events.

c) A combined synchronous and synthetic inertia response to system events may deliver a suitable result. The results are highly sensitive to the synthetic device characteristics and careful consideration would be required to determine the appropriate combination of synchronous and synthetic devices.

d) A solution involving synthetic devices would likely require a TSO-led project where response characteristics would be developed and clearly defined. The TSOs would need to fully understand the capabilities of these devices through further detailed analysis and/or demonstration testing.

5.2 RoCoF Alternatives Project Summary

The RoCoF Alternatives project was initiated by the regulatory authorities to investigate the potential options available to prevent high RoCoF events from occurring. EirGrid and SONI were tasked with investigating alternative solutions for the RoCoF issue. We commenced on a phased approach to the project that encompassed high-level technology assessments and detailed technical and techno-economic studies.

EirGrid and SONI appointed DNV GL to perform the technology assessment. DNV GL's report offered insight into the capabilities of a wide range of technologies for the purposes of high RoCoF prevention. The report highlighted that both synchronous and synthetic inertia devices could be deployed to resolve the RoCoF issue. We used these findings and feedback from industry to develop a project scope for the second phase which involved detailed technical analysis of a wide range of possible solutions.

EirGrid and SONI published the 'RoCoF Alternative & Complementary Solutions Project Phase 2 Study Report' in December 2015. Our report illustrates that there are credible alternative solutions to the RoCoF challenge. Synchronous inertia provides a solution to resolving the RoCoF challenge. The provision of synchronous inertia could be from solutions including:

- maintaining system inertia through reducing the current minimum generation levels of conventional plant,
- synchronous storage devices such as compressed air or pumped-hydro storage,
- rotational stabilisers,
- synchronous compensators,
- flexible generating plant.

We also found that synthetic inertia devices could provide a solution to the RoCoF issue. A wide range of possible synthetic inertia solutions have been considered as part of the project which include:

- non-synchronous storage devices including battery, flow-battery, flywheel and super-capacitor technologies,
- Wind turbines,
- HVDC interconnectors,
- Demand Side Management.

There is a wide range of possible synthetic inertia technologies and we believe that further detailed analysis or device testing would be required to gain a full appreciation of the capabilities of these devices. Our analysis has indicated that the suitability of synthetic devices for solving the RoCoF issue is highly dependent on the device response characteristic. Widespread application of these devices on the system to resolve RoCoF would require further analysis. We are also of the view that a project to develop an appropriate system-wide synthetic inertia scheme would be required. A project of this nature would require a TSO lead approach with industry engagement.

5.3 Next Steps

EirGrid and SONI have completed the second phase of the RoCoF alternatives project with the publication of this report. We believe that the project has demonstrated that alternatives solutions are available to resolve the RoCoF issue.

The regulatory authorities designated the RoCoF alternatives project as a prudent analysis that could be used in the event that the generator studies or TSO-DSO projects prove unsuccessful. To date the progress in both the generator studies and the TSO-DSO projects has been positive. Both projects are currently proceeding in line with the overall project timelines. At this stage, we believe that further analysis on alternative solutions to the RoCoF issue should only be performed if results from the primary RoCoF projects indicate that alternatives are required. The analysis conducted as part of the RoCoF Alternatives Study should not be perceived as the commencement of a procurement process for synchronous or synthetic devices.

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7 Appendix

7.1 Additional sensitivity

7.1.1 Under-frequency events (49.8 Hz) – Time delay included

The objective of this sensitivity is to provide an indication of the volume requirement if the synthetic inertia response included time delays.

7.1.1.1 Triggering of the supplementary inertia

Following an under-frequency event triggered by the sudden disconnection of the LSI, the synthetic inertia devices, (set to control Mode A), inject active power into the system after a time delay when frequency decreases below 49.8 Hz.

7.1.1.2 Simulation scenarios

The supplementary synthetic inertia response with varied time delays for all cases in each of the simulation scenarios are listed below:

- Synthetic inertia with no active power limit:
  - no time delay included,
  - different time delay for each of the four devices - 0, 100, 200, 300 ms, and,
  - different time delay for each of the four devices - 0, 200, 400, 600 ms.
- Synthetic inertia limited to 400 MW:
  - no time delay included,
  - different time delay for each of the four devices - 0, 100, 200, 300 ms, and,
  - different time delay for each of the four devices - 0, 200, 400, 600 ms.

7.1.1.3 Discussion of results

The static response of the synthetic inertia devices are discussed in Section 4.4.1.1.3. The exception to this discussion is that a device time delay is included within some of the scenarios. The first time delay considers a 100 ms delay between each device and the second time delay considers a 200 ms delay between each device. The selection of which device contains which time delay is arbitrary. This set of sensitivities considers both an unlimited and 400 MW limit synthetic inertia response. The devices inject synthetic inertia into the system when the frequency exceeds the threshold and any applicable limit is not exceeded.

At a frequency trigger of 49.8 Hz and no synthetic inertia limit a 100 ms time delay difference between devices does not resolve RoCoF in 33% of cases or 36% of cases with a 200 ms time delay as displayed in Figure 7.1-1. Similar violations can be observed in the 400 MW synthetic inertia limit displayed in Figure 7.1-2. The quantity of synthetic inertia no limit scenario cases that violate the RoCoF limit during frequency recovery increases as the time delay increases. This is due to the inherently lower frequency nadirs observed due to the delayed active power recovery rate. Additional time delays therefore result in a higher number of cases failing the specified RoCoF criteria.

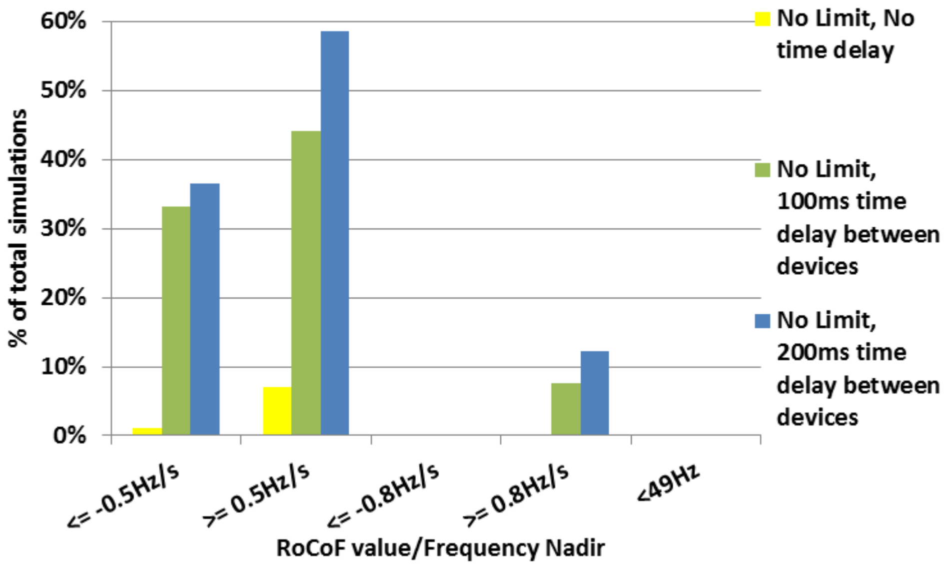

Figure 7.1-1: Variation in the time of the synthetic inertia injection, no active power limit - Percentage of cases where RoCoF exceeds a value and frequency nadir is below 49 Hz.

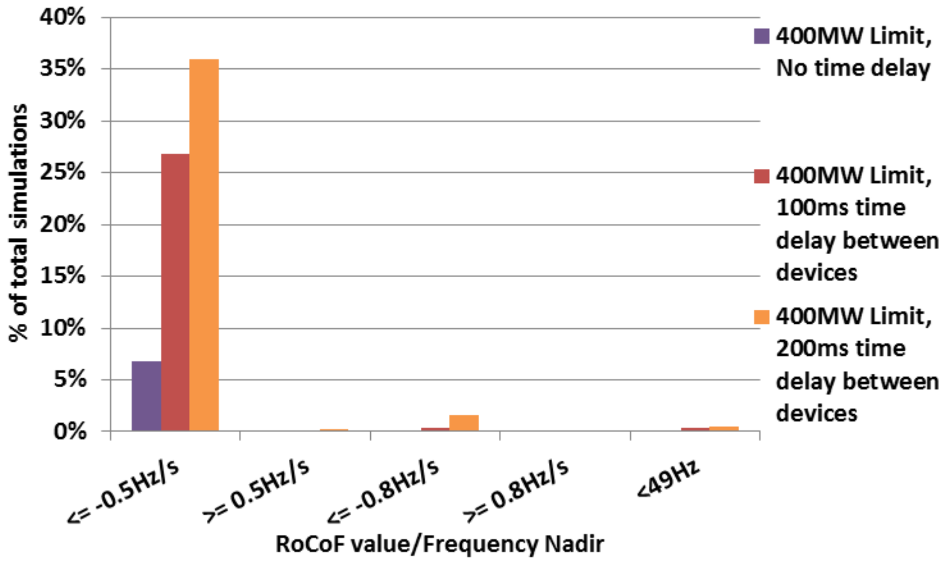

Figure 7.1-2: Variation in the time of the synthetic inertia injection, limited to 400 MW - Percentage of cases where RoCoF exceeds a value and frequency nadir is below 49 Hz.

7.1.1.4 High level conclusion

Synthetic inertia must respond rapidly in order to maintain RoCoF with ±0.5 Hz/s. Further time delays have been shown to compound the number of violations. At the frequency trigger considered and with these varied time delay setting, the injection of active power is not fast enough to adequately resolve RoCoF.

7.1.2 Step response of supplementary inertia with blocking on recovery

The objective of this sensitivity study is to analyse potential solutions to the unintended frequency recovery issues observed in the frequency triggered synthetic inertia cases presented in sections 3.4.1. The solution involves blocking the synthetic inertia response is during frequency recovery.

7.1.2.1 Triggering of the supplementary inertia

The synthetic inertia devices, (set to control Mode A and D), are triggered when frequency measured at the local bus decreases below 49.8 Hz following a system event. The device then measures the system RoCoF and when RoCoF reduces to a defined threshold the synthetic inertia response is blocked.

7.1.2.2 Simulation scenarios

The supplementary synthetic inertia step response with RoCoF controlled response available for all cases in each of the simulation scenarios is listed below:

- Synthetic inertia with no active power limit, RoCoF block setting is -0.1 Hz/s,
- Synthetic inertia with no active power limit, RoCoF block setting is 0 Hz/s,
- Synthetic inertia with no active power limit, RoCoF block setting is 0.1 Hz/s, and
- Synthetic inertia with no active power limit, RoCoF block setting is 0.2 Hz/s.

7.1.2.3 Discussion of results

The initial static response of the synthetic inertia devices is the same as the no-limit case discussed in discussed in Section 4.4.1.1.3. The updated model for this sensitivity measures RoCoF and blocks the injection of synthetic inertia based on a defined threshold. If the system RoCoF again drops below the defined blocking threshold, the synthetic inertia response will resume.

Figure 7.1-3 displays the percentage of cases where RoCoF exceeds a positive or negative value of 0.5 ad 0.8 Hz/s. It also shows the percentage of cases, which violate 49 Hz within 2.5 seconds of the event.

The initial injection of synthetic inertia is identical in all scenarios; however the method of synthetic inertia blocking is different. Therefore, the number of negative 0.5 Hz/s violations are similar in all cases. The difference between these scenarios is in the frequency recovery characteristic. This is defined by the RoCoF threshold setting that is used to block the synthetic inertia injection. Simulations suggest synthetic inertia with no-limit and with a recovery blocking control, materially complies with the acceptance criteria.

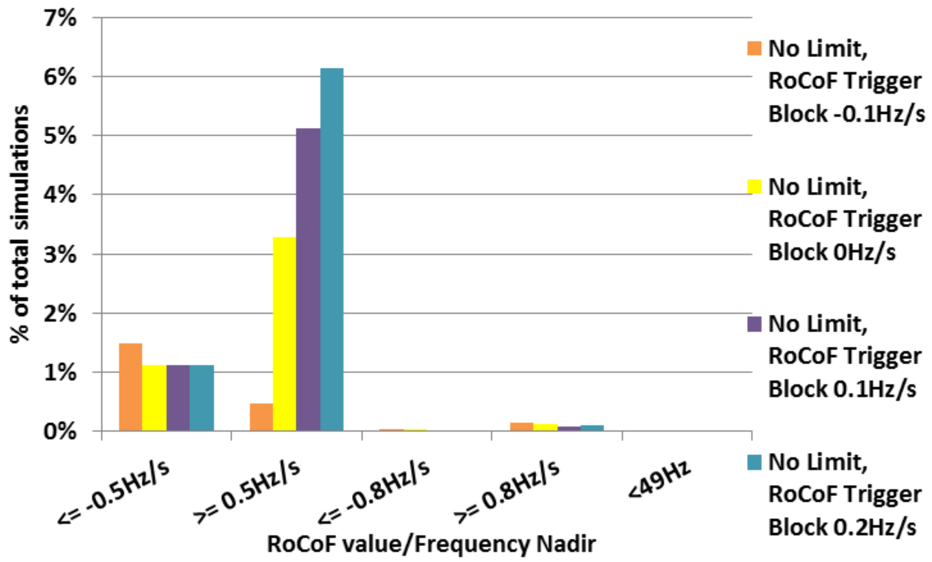

Figure 7.1-3: Synthetic inertia with a 49.8 Hz frequency trigger and RoCoF blocking trigger - Percentage of cases where RoCoF exceeds a value and frequency nadir is below 49Hz.

7.1.2.4 High level Conclusion

Static injection of synthetic inertia active power should be followed by some form of control to avoid unintended frequency recovery issues. The controlled blocking method must be tuned carefully to ensure that the frequency recovery is appropriately managed.