Fast Frequency Markets under High Penetrations of Renewable Energy in the Australian National Electricity Market

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Abstract

Frequency stability is a vital indicator of the health of a power system, reflecting the moment-to-moment balance between generation and load, and therefore overall power system security. Frequency deviations, and particularly fast frequency variations, threaten ongoing system operation and can be difficult to control. Growing penetrations of renewable energy generation in electricity industries globally, including the Australian National Electricity Market ('NEM'), are raising new challenges for very short-term frequency management, and these form the focus of this paper.

Following a contingency event in a power system, system frequency begins to change. The mechanical inertia inherent in the rotating machinery of a conventional synchronous generating plant is electrically coupled to the power system, and hence acts to slow the rate of change of frequency. Synchronous generators thus immediately and inherently respond to such contingencies, and their inertia is therefore extremely valuable for maintaining frequency stability and hence system security. Furthermore, inertia is useful as a regulation service, slowing the rate of change of frequency due to imbalances during normal operation.

In the NEM and elsewhere, significant inertia is currently available from the coal, gas-fired and hydro plants. However, renewable generators such as solar PV and wind are typically connected asynchronously to the power system with power electronics interfaces. This means they are not physically coupled to system frequency. Hence, they typically do not currently offer inertia to fast frequency changes. A future with increased renewable energy penetration (and decreased synchronous generation) therefore raises concerns about the adequacy of inertia in the system.

It is currently unclear as to the optimal amount of inertia that will be required over various timeframes, and its value as an ancillary services 'commodity' as renewable energy penetrations increase. Given that some level of fast frequency response ('FFR') is required, questions are raised about the best approach (regulatory or market) to ensure the required amount of inertia is available. This research explores these questions. By using a backward dynamic programming algorithm, various FFR market designs are modelled for the NEM. Generation dispatch is solved for characteristic weeks of the year, to understand the overall impact on the electricity industry.

The results suggest that a FFR market could have an impact on consumers' costs, and the dispatch and profitability of generators. The capability of renewable energy generators to produce inherent inertia could become highly valuable, while thermal generators could become more attractive to operate. Exit of thermal generators may also be encouraged, due to the possibility of converting to synchronous condensers.

The results of the modelling indicate that a market-based approach to valuing inertia could be a cost-effective solution to ensuring its sufficiency in the power system.

1. Introduction

The Australian Energy Market Operator ('AEMO'), which is both a market and system operator in the National Electricity Market ('NEM'), has a primary focus on ensuring power system security: meaning that the power system is capable of operating, in spite of potential issues that may occur. Events that threaten security are known as *contingency events*, and can include the disconnection of a major generator or large load, or the sudden failure of a major transmission line (AEMO, 2010b).

Frequency instability is both an outcome and an indicator of a contingency event. An excess of generation (or lack of consumption) results in the system frequency increasing, while a lack of generation (or excess of consumption) results in the system frequency decreasing (AEMO, 2010a). Thus, a stable frequency represents an ongoing balance between supply and demand. Some equipment in electricity systems require a stable frequency to operate, including many generators, loads and network equipment. Cascading impacts of frequency deviations mean that rapid changes in system frequency can be difficult to control. In order to achieve AEMO's primary goal of power system security, it is therefore imperative that a stable frequency is maintained within tight deviation and rate-of-change constraints.

Within the NEM, the system frequency is set to 50 Hz. AEMO employs several frequency control ancillary services ('FCAS') markets to maintain a stable frequency around this value. These markets price both regulation and contingency services. The regulation markets aim to correct frequency deviations due to minor imbalances between generation and consumption, while the contingency markets aim to address frequency deviations due to contingency events. There are six contingency markets, ranging from 6-second to 60 second and 5-minute responses, for both raise and lower requirements (AEMO, 2010a).

Synchronous generators have a store of kinetic energy due to the rotational momentum in their rotors. As these generators are directly coupled with the electricity grid, a change in the grid frequency results in a change in their rotor speeds, which is opposed by rotational inertia. This *inertia response* acts to dampen the rate of change of frequency ('RoCoF'). In this manner, inertia acts as a fast frequency response ('FFR'),[1] due to its immediate and inherent nature (EirGrid and SONI, 2011). Non-synchronous generators, such as solar PV and most wind turbines typically do not exhibit an inertia response, as they are not physically coupled to the power system frequency, and are rather connected with power electronics.

Currently, there is a significant provision of inertia in the NEM, due to the large amounts of coal, gas-fired and hydro generation. With these levels of high inertia synchronous generation, a 6-second FCAS response is adequate for the most severe credible contingencies. However, the NEM seems likely to become significantly more reliant on renewable energy, particularly wind and solar PV, and hence less reliant on fossil fuel generation (Brindmead et al., 2014). This decrease in synchronous generation will, ceteris paribus, lead to a decrease in inertia within the power system and the provision of frequency response over shorter timeframes (i.e. FFR).

AEMO and Electranet recently performed a study regarding the impact of high levels of renewable energy penetration in South Australia, a State with instantaneous solar PV and wind penetrations occasionally exceeding 100% of local demand. In this study, it was noted that if South Australia were in an islanded state without any synchronous generation, a "state-wide power outage could eventuate" (AEMO and Electranet, 2014). Thus, the need for adequate FFR in a power system to ensure power system security is clear.

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[1] FFR is the resistance to or dampening of frequency changes over short time timeframes, in the order of seconds (measured in MW s).

At present, most power markets do not value inertia as a commodity. This research starts with the premise that if FFR is valuable to a power system and may be in short supply in the future, a market-based approach is a suitable way to value it and incentivise its provision. However, such arrangements will require careful consideration, to ensure cooperation with other market arrangements in electricity industries. With this in mind, Section 2 will review the current context of FFR within power systems, while Section 3 will outline the methodology used to simulate the operation of three proposed FFR markets in the NEM. Section 4 will highlight the key results from the simulations, at different levels of renewable energy penetration. Finally, Section 5 will discuss the prominent outcomes of the research, notable limitations of the analysis, and recommendations for future work.

2. Context of Fast Frequency Response within Power Systems

This section will provide an overview, with particular reference to the NEM context, of FFR requirements in power systems, possible sources of FFR, and ways of ensuring adequate supply of FFR to ensure system stability.

2.1. *The need for tight frequency controls*

When considering market design to satisfy FFR requirements, it is necessary to understand the scale and determinants of FFR requirements. In particular, it is useful to understand which market participants require tight frequency control to be present, on the basis that markets should align any participant requirements as well as offerings with market value. The following sections outline the impacts of transient (as opposed to long-lived) frequency excursions, which can be addressed by FFR, on different electricity system participants.

Thermal generators require tight frequency controls to operate effectively (Electricity Supply Industry Expert Panel, 2011), as low frequency events can lead to overheating (Klimstra, 2014), caused by a high volts-per-hertz ratio (Kirby et al., 2002). This is particularly the case for high efficiency generators, such as CCGT (AEMC Reliability Panel, 2008). Thus, transient frequency variations are a concern for thermal generators.

Hydro generation is capable of tolerating large frequency excursions, without risking mechanical integrity (Electricity Supply Industry Expert Panel, 2011). Large **wind turbines** (typically using a doubly fed induction generator ('DFIG') mechanism) use power electronics to control their output frequency, and match the grid frequency (Tarnowski et al., 2009). These turbines are predicted to become highly prominent in the future, and for these turbines, frequency variations are also of negligible concern (AEMO, 2013).

Solar PV produces DC electricity, and inverters are used to convert the output to AC electricity. The standard for the grid connection of energy systems that use inverters (AS4777) states that if the grid frequency is too high or too low, the energy system must be disconnected from the grid (Australian Standards, 2005), primarily to avoid contributing to frequency instability. While a much wider frequency limit would not fundamentally be problematic for PV systems (Hancock, 2011), under the current allowed inverter frequency range, large transient frequency excursions could be an issue for solar PV generators.

Transformers in the network have been noted to be "sensitive to frequency variations and may be overloaded if the frequency drifts substantially from the nominal [frequency]" (Freris and Infield, 2008). This is primarily a concern with respect to long-lived frequency variations. Furthermore, a higher than normal volts-per-hertz ratio, caused by a lower than normal frequency, will cause the transformer to overheat, and eventually fail (Kirby et al., 2002).

Appliances that have motors sometimes require a steady frequency to operate at a constant speed, while appliances that use the grid frequency for timing devices will require a steady

frequency to operate reliably (Freris and Infield, 2008). However, the relevant standard for AC appliances (AS/NZS60335.1) does not indicate a large concern over frequency variations, rather outlining a range of frequencies that can be tested for operation (Australian Standards, 2011). Thus, transient frequency variations are unlikely to be a concern for these loads.

2.2. Sources of fast frequency response

For the purposes of modelling and proposing market design options, current and potential future sources of FFR in the NEM are discussed in the following section.

Synchronous generators (coal, gas-fired, hydro or nuclear) are directly coupled with the grid. When the generator is operating, a fixed amount of inertia is available for the power system, based on the output and capacity of the generator, and the generator's inertia constant (DNV Kema Energy & Sustainability, 2012).

An **induction motor** exhibits a degree of inertia response (in a similar manner to synchronous generators), commonly referred to as *load relief* (NERC, 2011).

A **synchronous condenser** is an electrical machine that is directly coupled with the grid, however does not generate power. As with a synchronous generator, when the synchronous condenser is operating, a fixed amount of inertia is available to the power system, based on its total capacity and inertia constant (DNV Kema Energy & Sustainability, 2012). Synchronous condensers are currently widespread in electricity industries, offering a range of services.

Wind turbines (particularly DFIG turbines) have a store of kinetic energy in their rotors, and it is believed that this kinetic energy can be harnessed as synthetic inertia with the aid of power electronics, and transferred to the grid (Ullah et al., 2008). Furthermore, at certain wind speeds, the blade pitch can be manipulated to generate more than the rated power output of the wind turbine, also providing a source of synthetic inertia (AEMO, 2013). Older fixed speed wind turbines do contribute inertia (in a similar manner to synchronous generators) however have become less common in electricity industries (AEMO, 2013).

If a generator is **curtailed** (operating below maximum output) during normal operation, then its power output could be increased to help address low frequency events. During high frequency events, the generator output could also be reduced. Although this could provide a FFR, it would result in decreased revenue for the generator (AEMO, 2013). Alternatively, **battery storage** could be used to achieve the same as curtailing a generator's output (Tielens and Hertem, 2012). **Central management of loads** has also been suggested as a way of providing FFR (Tielens and Hertem, 2012).

2.3. Methods to ensure adequate fast frequency response

In the majority of power systems, a large percentage of the load is met by synchronous generation, and there has not yet been a need to introduce measures to ensure adequate FFR is available. Measures to date have been introduced in Ireland, where a limit on the instantaneous amount of non-synchronous generation has been set at 50% (EirGrid et al., 2015). Additionally, in Quebec, large generators are required to provide a FFR (Hydro Quebec TransEnergie, 2009). However, these regulatory requirements, which are both static and proscriptive, are unlikely to represent an optimal approach. Another option would be to establish a FFR market. This idea has received little attention in the literature to date, and is currently not used in any power systems (Riesz and MacGill, 2013). This paper seeks to consider the impacts of such a market in the context of the NEM. Modelling of options for, and possible outcomes of, such a market will be described in the following sections.

3. Methodology

When simulating electricity dispatch within the NEM, both supply and demand must be adequately considered. Thus, the make-up of the generation portfolio, operating characteristics of these generators, and their operating constraints needs to be known, as well as the demand profile for a given time period. Due to the operating constraints of the generators, there are numerous possible states that the electricity system can be operating in for every time period. Furthermore, the electricity system is limited in terms of moving from one state to another. This complexity means that generators need to use a unit commitment approach to manage their operating capabilities. Within the NEM, unit commitment is managed by each of the generators individually. The generators simply provide bids (price and quantity) to AEMO, who then chooses which generators to dispatch in order to meet the required demand (based on a least-cost methodology).

In order to take into account unit commitment constraints in a cost-optimisation for electricity dispatch, an exhaustive approach could be employed to determine every possible path of states over the time period of interest. However, this would be both inefficient and computationally intensive. Alternatively, a dynamic programming ('DP') approach could be used, which seeks to take into account each time period in a sequential manner, considering only the allowable transitions of states from one period to another (Bradley et al., 1977).

A backwards DP algorithm was designed for this study in Matlab ('BDPAlg'), which finds the least-cost solution for operating a simplified version of the NEM wholesale market over a week. BDPAlg was designed to consider both electricity and FFR dispatch, taking into account a specified carbon price, FFR price and FFR demand (Agranat, 2015). In reality, the market would determine the FFR price. However, as the capacities of all external FFR sources in the future are uncertain, several FFR price and FFR demand scenarios were used in the analysis. BDPAlg was used to analyse three proposed FFR markets, differing in terms of how FFR provisions and requirements are earned and paid for, under various renewable energy penetrations. Details of these markets, and details of the model are provided in the following sections, including generators, and the FFR price and demand levels considered.

3.1. States of operation

BDPAlg considers several large-lumpy generators; coal, open-cycle gas turbine ('OCGT'), combined-cycle gas turbine ('CCGT'), solar PV, wind and hydro. BDPAlg takes into account the maximum possible ramp rates and minimum operating levels of the thermal generators, as outlined in Table 1 (Vithayasrichareon et al., 2015).

Table 1. Operating Constraints of Thermal Generators

	Coal	OCGT	CCGT
Unit Size (MW)	600	160	500
Ramp Rate (MW/ hr)	8	12	10
Minimum Operating Levels	50%	0%	40%

To adequately consider the minimum operating levels, secondary coal and secondary CCGT generators were added to BDPAlg. These secondary generators can operate at 0% or 100%. If the secondary generator is operating at 0%, then the primary generator does not operate. With this in mind, there are a total of 56,056 states possible to consider for every time period.

3.2. Generator inputs

The operating characteristics of the generators modelled are outlined in Table 2, with further details on generator modelling provided below.

- The maximum outputs of thermal generators are based on the total capacities of each generator type in the NEM (AEMO, 2015). Outputs of solar PV and wind generators are based on hourly traces of generation (Australian Government, 2012), while historical hourly generation data is used for the hydro generation. This is because hydro dispatch cannot be appropriately optimised over the one-week period modelled, given its seasonal- and weather-dependent operation.
- The short-run marginal cost ('SRMC') of the thermal generators is based on their variable operation and maintenance cost, thermal efficiencies, heat rate, and projected fuel price for 2030. The SRMC of the renewable energy generators is based entirely on their variable operation and maintenance cost (AEMO, 2014a, Vithayasrichareon et al., 2014).
- Emissions factors for each generator are based on values for existing generators in the NEM (Vithayasrichareon et al., 2014).
- Inertia constants for each generator are based on values from Bjornstedt (2012). It is assumed that all DFIG wind turbines will provide inertia (currently, they are only *capable* of providing inertia, yet do not actually do so). Furthermore, 35% of wind turbines in the NEM are DFIG (AEMO, 2013).
- A FFR requirement constant ('FFRRC') is used to reflect the comparative need each generator has for tight transient frequency controls. A dimensionless number between 1 and 5 is assigned (5 being the highest need), based on the factors discussed in Section 2.1 of this paper.

Table 2. Operating Characteristics of all Generators Considered

	Coal	OCGT	CCGT	Solar PV	Wind	Hydro
Maximum Output (MW)	25,062	6,326	2,284	N/A	N/A	N/A
SRMC ($/ MWh)	14.66	90.11	67.16	0.00	2.71	7.07
Emissions Factor (t CO_2/ MWh)	0.96	0.70	0.40	0.00	0.00	0.00
Inertia Constant (s)	6	6	6	0	1.4	3
FFRRC	4	4	5	2	1	1

3.3. FFR markets

Prior to the modelling of the FFR markets, an External FFR Base Case ('EFBC') was modelled to enable analysis of the impacts of the proposed FFR markets. The EFBC solves the spot market dispatch with no consideration for FFR requirements, thereby reflecting current dispatch in the NEM. Following this, the EFBC directly attributes the entire cost of FFR provision to consumers, assuming only external FFR resources are used (there is currently no requirement for FFR in the NEM).

The designs of the proposed FFR markets are outlined in Table 3. Furthermore, it is assumed that generators always bid into the market at their SRMC, and never exercise market power.

Table 4. Designs of Proposed FFR Markets

	GEIIGPII	GEIICPD	GEIIGPFR
Who earns?	Generators, if their inherent inertia is above the required inertia per MW[2]	Generators, based on their inherent inertia	Generators, based on their inherent inertia
	External FFR resources, if there is insufficient inherent inertia in the power system		
How much do they earn?	FFR price received is capped at the FFR price, and reduced when there is excess inherent inertia in the power system		
Who pays?	Generators, if their inherent inertia is below the required inertia per MW[1]	Consumers	Generators, based on their FFRRC
How much do they pay?	FFR price paid is always set to the FFR price		

[2] In every time interval, a required level of inertia per MW output is set; this is defined as the FFR demand divided by the electricity demand.

3.4.   FFR price

Preliminary analysis was undertaken to understand the impact of the FFR price on the FFR markets. Two scenarios were considered; a FFR price based on the LRMC of a synchronous condenser ($0.3095/ MWh s) (DNV Kema Energy & Sustainability, 2012), and a FFR price based on the LRMC of a battery storage system ($3.3830/ MWh s) (Poullikkas, 2013). The analysis suggested that the FFR price has a significant impact on the functioning of the FFR markets. Due to future uncertainty about the availability of external FFR, no intermediate FFR price was obvious. Thus, a probabilistic approach was used, which was aligned with the limited computational resources available for analysis of different FFR price scenarios within this study. A 50% probability of each FFR price previously mentioned was used for the renewable energy penetration analysis.

3.5.   FFR demand

To understand the impact of FFR demand on the FFR markets, two scenarios were considered; a FFR demand of 21,518 MW s and a FFR demand of 127,215 MW s. The first (low) scenario is based on the required RoCoF for generators in the NEM, under the minimum access standard of 1.0 Hz/ s (NER, 2015), and a contingency event reflecting the outage of a large generator in the NEM of 660 MW (AEMO, 2015). The second (high) scenario is based on the advised RoCoF for Ireland's power system of 0.5 Hz/ s (EirGrid and SONI, 2011), and a contingency event reflecting the maximum outage of all interconnectors in the NEM of 4,488 MW (AEMO, 2014b). This preliminary analysis suggested that the level of FFR demand has a significant impact on the functioning of the FFR markets. For the renewable energy penetration analysis, a moderate FFR demand of 127,215 MW s was used, based on a RoCoF of 1.0 Hz/s and a contingency event of 21,518 MW. The calculations of FFR demand were based on the model developed by Ulbig et al (2014).

3.6.   Carbon price

Preliminary analysis was also carried out to understand the impact of the carbon price on the FFR markets. Two scenarios were considered; a no carbon price scenario ($0/ t CO_2) and a high carbon price scenario ($150/ t CO_2) (BREE, 2012). This preliminary analysis suggested that a high carbon price exaggerates the impacts of the FFR markets. Thus, a moderate carbon price of $55/ t CO_2 was considered, as this aligns reasonably with some expectations for the NEM in 2030 (BREE, 2012) for the renewable energy penetration analysis.

3.7.   Scenarios considered

A typical summer and a typical winter week demand profile for 2029-2030 were considered using previous AEMO estimates (Australian Government, 2012). In each case, six levels of renewable energy penetrations were considered; 15%, 30%, 45%, 60%, 75% and 85%. These penetrations define the capacities of solar PV and wind generation in the NEM (Vithayasrichareon et al., 2014).

4.   Results

This section will provide an overview of the key results from the simulations run, focussing on the amount of solar PV and wind generation spilt, the amount of inherent inertia and external FFR required, and the impacts on consumers' costs and generators' profitabilities.

4.1.   Spilt solar PV and wind

All of the FFR markets place a value on the production of inherent inertia, with BDPAlg assuming that the wind generator contributes inherent inertia (due to the presence of DFIG wind turbines), and the solar PV generator does not. A sufficiently high FFR price and FFR

demand results in the wind generator having a lower SRMC than the solar PV generator, causing a change in the merit order. Ultimately, this results in wind generation displacing solar PV generation. This trend increases as the renewable energy penetration increases, as there is more wind generation that can be dispatched, and more solar PV generation that can be spilt. This effect is evident for all FFR markets, independent of the demand profile used.
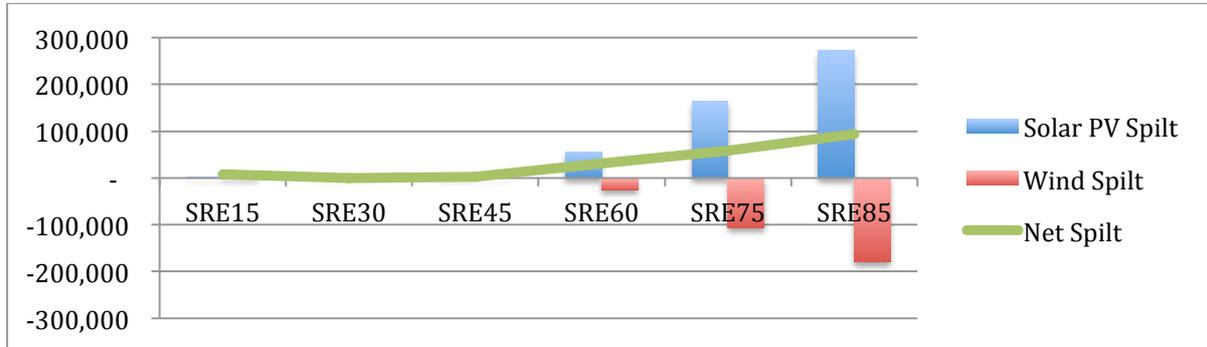
Figure 1. Amount of solar PV and wind generation spilt, compared to the EFBC, at different renewable energy (SRE) penetrations (GEIIGPII Summer Demand Profile)

4.2. Inherent inertia and external FFR

As all of the FFR markets value inherent inertia, less FFR will need to be sourced externally, compared to the EFBC. However, as the renewable energy penetration increases, renewable energy generators will displace thermal generators, leading to a reduction in inherent inertia (for both the EFBC and the FFR markets). This effect is evident for all FFR markets, independent of the demand profile used.
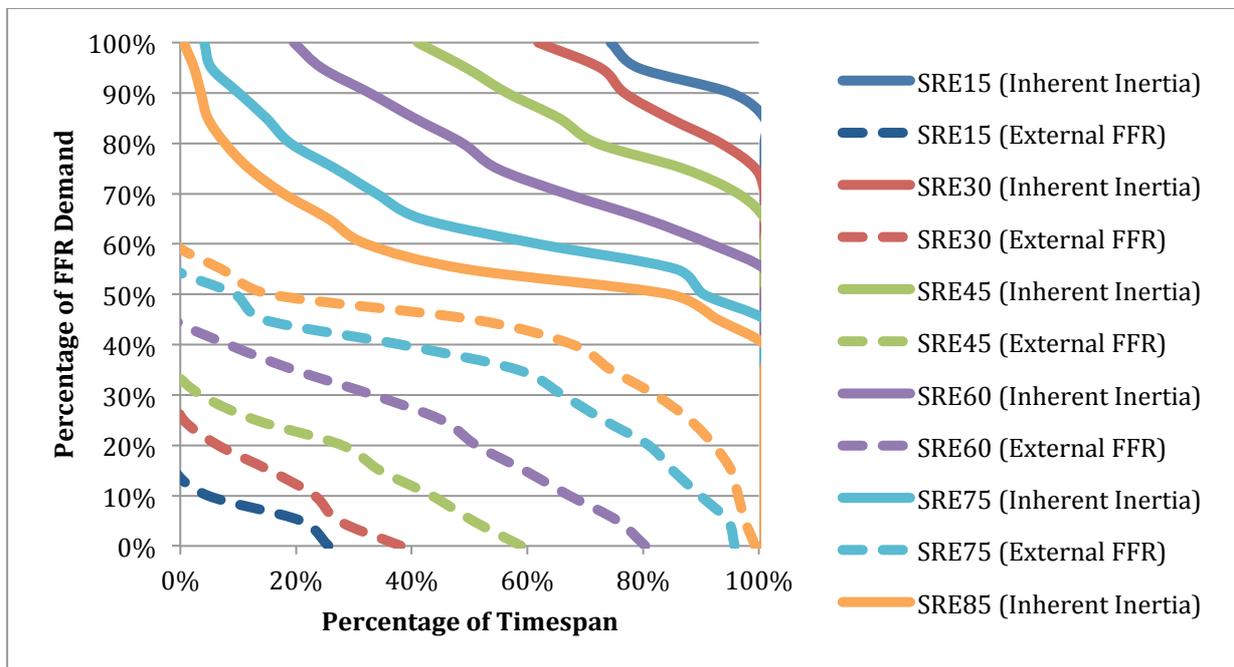

Figure 2. Amount of inherent FFR and external FFR at different renewable energy (SRE) penetrations (GEIIGPII Summer Demand Profile)

4.3. Consumers' costs

As outlined previously, all of the FFR markets will result in less FFR sourced externally compared to the EFBC. This will result in a reduction of consumers' overall costs for energy

and FFR services whenever there is a FFR market, compared to the EFBC. Costs for consumers are further decreased with higher RE penetrations under the GEIIGPII and GEIICPD FFR markets due to decreasing bids of the thermal generators (because of an increasing value of inherent inertia). However, the cost reduction is less significant as the renewable energy penetration increases under the GEIIGPR FFR market due to increasing bids of the thermal generators (because of a higher cost allocation of the total FFR cost).

It is important to note that consumers' costs under the EFBC exceed their current costs in reality, as FFR is not currently priced in the NEM.
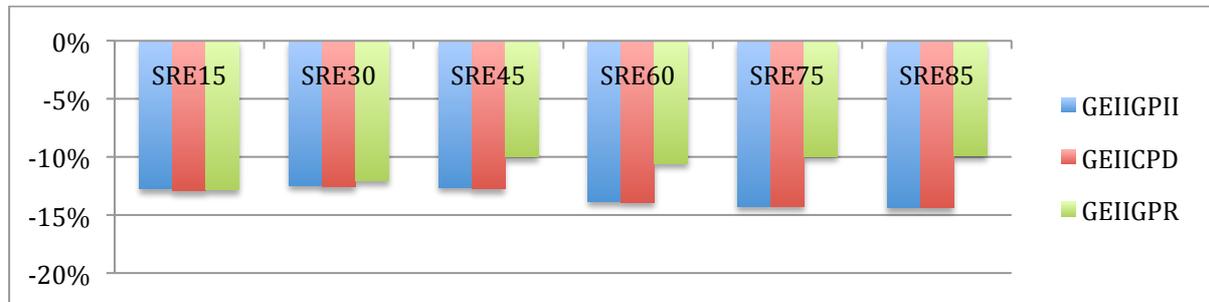
Figure 3. Changes in consumers' costs compared to the EFBC for all FFR markets at different renewable energy (SRE) penetrations (Summer Demand Profile)

4.4.   *Profitabilities of the generators*

The GEIIGPII and GEIICPD FFR markets aim to reward and penalise generators for their inherent inertia. As expected, this results in increased profitabilities for the thermal generators, and decreased profitabilities for the renewable energy generators. As the renewable energy penetration increases, these trends become more prominent. This is because inherent inertia becomes more valuable when there is less of it in the power system.

The GEIIGPR FFR market aims to reward generators for their inherent inertia, yet penalise generators based on their comparative need for tight transient frequency controls. In contrast to the results for the other two market designs, this market results in negligible changes in profitabilities for the coal and OCGT generators and a decrease in profitability for the CCGT generator, compared to the EFBC. Furthermore, the solar PV generator (which provides no FFR) experiences a decrease in profitability, while the wind and hydro generators (which provides some FFR) experience increases in profitabilities, compared to the EFBC. As the renewable energy penetration increases, more external FFR is required. This results in the magnitude of the decrease in profitability of the CCGT generator decreases, while the magnitude of the decrease in profitability of the solar PV generator increases, and the increases in profitabilities of the wind and hydro generators increase.

5.   Discussion and Conclusion

With the notion that inertia is important, several key questions that consider the security of electricity markets with high penetrations of renewable energy, become more pertinent. These questions ask; who earns, who pays, what is the price, and what is the demand. This research suggests that market arrangements can assist in addressing some of these questions.

The results of this study indicate that the capability of a renewable energy generator to provide synthetic inertia could become highly valuable (as was evident with the wind-solar PV trade off). As noted previously, the literature suggests that wind turbines could provide this resource. However, this may also be possible for solar PV generators (through storage

integrated within the module, possibly using supercapacitors or solid state batteries). This could lead to greater investment incentives for particular renewable energy technologies.

The preliminary analysis undertaken in our study suggests that FFR markets will only have a significant impact on the electricity industry if there is a high FFR price and a high FFR demand (regardless of renewable energy penetration). Furthermore, the presence of a FFR market that values the inherent inertia provided by generators will result in less external FFR required. Ultimately, as the costs in the electricity industry are inevitably passed on to consumers, a reduction in the amount of external FFR required (which is generally more expensive than inherent inertia) will result in reduced consumers' costs.

The presence of a FFR market could result in thermal generators being more valuable in future electricity industries with high renewable energy penetrations than typically thought. Beyond payment for the inertia they provide, the presence of a FFR market could actually encourage the exit of some thermal generators, as there could be a financial incentive in converting to synchronous condensers. These findings seem likely to have important implications for the decarbonisation of the electricity system.

This model had a few key limitations that could be considered in future research:

- The DP algorithm could take into account more discrete time periods, a longer timespan, and more generators (both types and units). Furthermore, the algorithm could consider each region individually, accounting for interconnector constraints.
- A spot market for FFR could be developed, taking into account a dynamic FFR demand (based on region-specific requirements) and all available FFR resources (including demand-side options) to set a dynamic FFR price.
- Greater consideration for the allowable RoCoF could be incorporated, bearing in mind the low sensitivities of renewable energy generators to transient frequency excursions.

Despite the limitations of the model, the results indicate that within the context of increasing renewable energy penetrations, valuing inertia as a commodity is essential in ensuring sufficient inertia is available, and to contain costs for consumers. Overall, this research paper advocates for a market-based approach, outlining how various FFR markets could impact the electricity industry under different scenarios of future renewable energy penetrations.

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