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Review of very short term frequency management strategies for integration of high penetrations of non-synchronous utility-scale PV in electricity markets

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Abstract

The increasing penetration of large-scale variable renewable energy (VRE) power plants creates new frequency stability challenges for grid operation. Balancing in electricity systems has traditionally involved matching dispatchable, highly reliable, generation to variable and uncertain loads. The increasing penetration of variable and somewhat unpredictable renewable energy increases the balancing challenge. In particular, for Photovoltaic (PV) plants, changes in very short term weather conditions such as cloud movement can result in an abrupt change in power output. In traditional electricity systems, balancing over very short timeframes has been assisted by the inertia in synchronous generators which are directly coupled to the grid, store considerable energy through their mass and high speed of rotation, and therefore inherently and instantaneously resist frequency deviations. However, some key VRE generation technologies have non-synchronous grid connections through power electronics. As such, they do not provide inherent inertia to resist immediate frequency deviations as supply demand balance changes over time. However, there are opportunities for these renewables to provide very rapid frequency response actions under some circumstances.

At present, limits on the total percentage of non-synchronous generation capacity have been introduced or are being considered in a number of electricity industries with high variable renewable generation to ensure sufficient system inertia. In restructured, market oriented, industries, there are opportunities to establish suitable ancillary service arrangements that provide commercial incentives for market participants to provide inertia. Adding to the complexities yet opportunities for market based frequency management, very fast response power injection or removal from renewables and other suitable technologies, sometimes termed synthetic inertia or fast frequency response (FFR), can reduce, or perhaps even replace, the need for inertia. Suitable market arrangements might see highly innovative solutions towards short-term frequency management.

This paper presents a review of the challenges that utility PV may raise for short-term frequency management, and opportunities that it may offer towards solving these challenges. It considers research to date investigating the temporal and locational characteristics of utility PV generation over very short time frames, their implications for fast frequency management, and areas requiring further investigation. It then considers work exploring opportunities for utility PV plants to provide very fast frequency response, as well as other possible technology options. Finally, it considers existing and possible future regulatory and market approaches to managing short term frequency management with high penetrations of variable renewable generation.

1.   Introduction

Increasing penetrations of large-scale variable renewable energy (VRE) generation in electricity industries around the world are creating new frequency stability challenges for grid operation. Reliable and secure operation of the grid requires that supply must precisely meet demand at all times and locations across the grid. Failure to correct supply-demand imbalances drives frequency disturbances that can impact on the operation of generators and loads that have stringent frequency control requirements, such as high efficiency gas turbines, and even threaten the entire system. Such balancing has traditionally involved matching dispatchable, highly reliable, thermal and hydro generation to variable, uncertain loads. System frequency is disturbed by inevitable ongoing changes in demand (load following) but is particularly put at risk by contingency events such generation and network trips. High VRE penetrations present additional challenges due to the variable and somewhat unpredictable characteristics of the wind and solar resources that these generation technologies draw upon. Electricity industries typically set frequency bands within which system frequency is allowed to fluctuate under normal, and contingency conditions (Gannon, 2014). Secure operation requires that the system can be bought back within the normal frequency range within a reasonable time period after a contingency event. Many electricity industries distinguish between credible (N-1) and non-credible contingencies, where the later reflect extremely unfortunate, often multiple incidents, circumstances that cannot be cost-effectively managed within standard contingency arrangements. Non-credible contingencies typically see greater frequency deviations, and more extreme emergency responses that may disconnect particular generators or loads in order to ensure overall system security.

In addition to maintaining frequency within acceptable limits, the system must also avoid exceeding a set rate of change of frequency (RoCoF), which is the frequency deviation per second in Hz/s. Some types of generators are particularly susceptible to high RoCoF which can force then off-line, regardless of whether or not system frequency lies within an acceptable band. The maximum RoCoF specified by different electricity industries ranges from ±0.5 Hz/s (UK, non-synchronous) (Ruddock, 2016) to ±2.5 Hz/s (Denmark) (PPA Energy, 2013). Frequency deviations or RoCoF that cannot be managed by contingency frequency response services could eventually lead to load shedding or a cascading effect if frequency cannot be brought within limits and generators need to disconnect to avoid damage from operation outside of frequency limits.

Inertial frequency response which is a passive, physical response provided by large conventional power plants with synchronous generators, plays an important role in restricting RoCoF after a contingency event (Riesz et al., 2015), before more significant situations arise and even greater interventions are required. In this context, inertia refers to the resistance to change in rotational velocity of a rotating mass that is synchronously connected to the power system. Synchronous connection refers to the direct coupling of mechanical rotational speed and electrical frequency and is inherent in conventional generators with synchronous (or induction machine) rotating machinery (Tielens and Van Hertem, 2016). These generators provide inertial frequency response, countering frequency deviation events (Sharma et al., 2011) immediately, automatically and proportionally to the RoCoF experienced, therefore allowing more time for primary reserve response to be activated. Higher RoCoF and a lower frequency nadir following a large generation loss are more likely where system inertia is reduced (Silva et al., 2016).

Rebours et al. (2007) and Díaz-González et al. (2014) reviewed frequency response services in different electricity industries. Due to its inherent and ubiquitous nature in conventional electricity systems, the value of inertia has not typically been explicitly recognized in electricity industry operation. However, higher penetrations of non-synchronous renewable generation in electricity industries are reducing the presence of inertia, and the link between inertia and primary frequency response has become more apparent. For instance, a study in Ireland has shown that lower levels of inertia will require faster frequency response (EirGrid, 2011). Strategies to maintain system inertia are therefore now under development.

The key reason for falling levels of synchronous generation and hence inertia is the growing deployment of VRE. In particular, wind and photovoltaics (PV) generation is rapidly displacing conventional generation in electricity systems around the world, due to falling costs, and targeted policy support directed towards reducing electricity industry greenhouse gas emissions. Once built, these plants have low short run marginal cost, so displace fuel-reliant thermal generators whenever they operate and thus reduce system inertia (Sharma et al., 2011). This is already becoming evident in the Australian State of South Australia, given its high reliance on wind and distributed PV generation (AEMO, 2016), and in a number of other electricity systems around the world, such as Texas (Matevosyan, 2014) and Ireland. In addition to displacing generators that provide inertia, the potential loss of significant capacity of VRE can also increase risks to system operation when it coincides with contingency events.

While increasing concerns have led to a growing number of case studies on the impact of high VRE penetration on system inertia, these studies have been primarily focused on wind generation, which has typically been present in higher penetrations to date. However, utility-scale PV penetration is increasing in a number of electricity systems, so an improved understanding of the impact of utility-scale PV on frequency stability and system inertia is essential.

This paper presents a review of the literature that explores the frequency stability challenges raised by utility-scale PV, and the capability of PV plants to provide useful frequency response. The paper is organized as follows. Section 2 reviews the challenges raised by the variability and lack of inertia of utility-scale PV. Section 3 explores the capability of PV technology to offer fast frequency response. Finally, key strategies for managing high RoCoF and implementations in current electricity industries are presented in Section 4.

2.   Frequency management challenges raised by utility-scale PV

Frequency response challenges arise from the operational characteristics of PV systems, in particular, a highly variable and somewhat unreliable primary solar energy resource, the absence of any significant energy storage in the plant, very low operating costs that means the plants are typically operated at the highest possible output, and a power electronics interface that offers no inherent inertia. Increasing the percentage contribution of PV to electricity supply will, therefore, raise a wide range of additional challenges for secure electricity industry operation. Managing such challenges, in turn, increases the cost of operating the system (NREL, 2012; Remund et al., 2015).

2.1. PV variability

2.1.1. Temporal issues

The impact of PV variability on electricity industry operation varies with the timescale, and the extent to which PV output might change over different timescales will have different implications for network operation. For example, over one minute, the potential impact is typically in terms of required levels of regulation reserves. Variability from minutes to hours would affect load following services and from hours to days can involve unit commitment. However, as this study focuses on frequency response, the variability at the timescale of seconds is of most interest (Sayeef et al., 2012).

At the timescale of seconds, the term "ramp rate" is used to quantify a change in PV output. The magnitude of ramp rate depends on the abruptness of changes in solar radiation, and the area over which the PV is being aggregated (e.g. the size of a solar farm). The main source of changes in PV output over a very short time interval is cloud transients (ARENA, 2015; Sayeef et al., 2012). The speed that clouds can travel at determines the rapidity of potential insolation change at a particular location. The weather/climatic conditions of a particular location, especially the nature of its cloud cover, determine the longer-term probability distribution of output change over different time periods. A study of solar variability in Alice Springs, Australia found that with 5 second averaged irradiance recorded over a highly variable day, the change in irradiance exceeded $500 W/m^2$ but this only occurs 10% of the time. The study notes that it will be a concern for other generation sources to compensate for these short-term changes especially, when the event is applied to utility-scale PV of (ARENA, 2015). Many studies, e.g. (Marcos et al., 2011), have also found that significant step changes are rare but not to be neglected.

Although a study in Spain with one second data resolution (Marcos et al., 2011) showed that significant changes (>20%) in solar radiation at a single site over one second are infrequent (occurring less than 0.1% of the time), over one minute (60 s), changes of 50% can occur 0.7% of the time. It is important to consider the timescale over which changes in PV plant power output would have a significant impact on frequency management.

2.1.2. Geographical dispersion

Many studies (ARENA, 2015; Marcos et al., 2012, 2011; van Haaren, 2014) note that the geographical dispersion of many utility-scale PV projects can greatly reduce the impacts of solar irradiance variation due to cloud transients and provide a smoothing effect to the aggregate output of all PV power plants. Moreover, the smoothing effect is also evident over the area of a PV plant. A utility-scale PV power plant that covers a large area will result in ramp rates due to clouds passing significantly less than those measured over a single point, as clouds do not cover, nor pass from, an entire power plant instantaneously. A study of a 13.2MW PV plant (Sayeef et al., 2012) shows that the plant output did not exceed changes of 20% in any 10-second period whereas a single point solar irradiance measurement experienced changes of 80%. The impacts on network stability are therefore significantly reduced with geographical diversity, even over the area of a single utility-scale PV plant.

2.1.3. Impact of PV variability on frequency stability – Temporal and Geographical

The impacts of such variability will depend, of course, on the characteristics of the power system that PV is integrated within. Cloud transient impacts on system frequency excursions have been assessed by Yue and Wang (2015a). The study modelled cloud transients over 3

PV plants of two different capacities, to represent different levels of PV penetration (18% and 35%) within a given power system, assuming (1) uniform irradiance level on all panels within the same array, (2) the same irradiance variation profiles for all arrays with time lags representing the cloud movement. In the model, two synchronous generators were displaced to accommodate PV in the system, which reduced the available system inertia. Frequency response is constrained by the ramp rates of the conventional generators. The results showed that the 35% PV penetration level resulted in larger frequency deviations than 18% PV penetration, however, RoCoF did not exceed the critical RoCoF set by the relevant electricity industries mentioned in Section 1 because the example network in this study possessed sufficient reserve (Yue and Wang, 2015a). The study points out that RoCoF would be aggravated under high PV penetration if significant cloud transients coincided with other contingency events.

It should be noted that this study simplifies the cloud transient by assuming uniform irradiance within the same array regardless of its spatial array size and geographical dispersion of the panels in the same array. The impact of cloud transients over larger arrays with spatial dispersion may not be as significant as this study suggests because increasing geographical diversity would result in smoother aggregate PV generation.

Further studies are required to better understand the implications of more plant locations on PV variability and frequency excursions.

2.2.   *Zero inertia in PV systems*

Unlike conventional thermal generators, PV systems do not store kinetic energy in a rotational mass, and are indirectly coupled to the power system through electronic solid-state devices. They do not, therefore, provide inherent inertia to the power system. A range of studies (Sharma et al., 2011; Silva et al., 2016; Tielens and van Hertem, 2012; Yan et al., 2015) show that the fraction of non-synchronous VRE generation is highest during low load when many synchronous generators are offline. This currently occurs most often during the night time when wind generation is high. Conversely, PV can only generate electricity during the day time, which tends to coincide with periods of higher demand when there are more synchronous generators running. The studies therefore conclude that PV generation is likely to have a smaller effect on system inertia compared to wind. However it should be noted that sufficiently high PV penetrations will also inevitably lead to low system inertia during the middle of the day when PV generation is at its maximum.

Eto et al. (2010) and Undrill (2010) conclude that reduced system inertia due to increased variable renewable generation plays a minor role in establishing requirements for adequate primary frequency control (up to 15 seconds), because an increase in normalised system inertia of 250% only results in 23% increase in frequency nadir.

The effect of PV penetration on frequency, when compared to a system with no PV integration, has been investigated by NREL (Achilles et al., 2008). The study was conducted by modelling a system with high proportions of PV generation for different cases including a generation trip and load trip. Where PV was modelled as meeting 30% of load during high load, with de-committed conventional power plants, the power imbalance of the system was increased compared to the zero PV case, and a significant frequency reduction from 60 Hz to 43.6 Hz occurred because of the cascading effect of disconnecting of inverters in PV systems, in reality, the system would activate load shedding. The modelling indicates that high PV contribution is of less concern when the conventional power plant is not de-committed, while

the consequences of a contingency event depends on the magnitude of the power imbalance and the amount of inertia provided by online generators.

Known seasonal and daily profiles can be used to partially predict the need for frequency control reserves and/or additional system inertia resulting from high PV penetration. Silva et al. (2016) analysed the dynamic frequency control risk for high penetration of wind, which shows seasonal and diurnal patterns, peaking in summer when low load coincides with high wind generation. Although no such study has been conducted for PV generation, seasonal and diurnal patterns can also be expected in line with relationship between daily and seasonal cycles of solar resource availability and load. To minimize the unnecessary provision of frequency control reserves, a further study to investigate dynamic reserve requirement according to seasonal and diurnal characteristic of PV generation would be useful.

While a number of relevant studies on frequency impacts of wind generation have been published, research investigating the frequency impacts of high PV penetration on electricity systems has been limited to date. High PV ramp rates and strong diurnal correlation leading to periods of low inertia might particularly contribute to frequency management challenges are areas where further research would be of benefit.

3.   Capability of PV in Fast Frequency Response

While wind turbines have rotating parts that can potentially be more closely coupled to the grid which is called emulated inertia, PV systems cannot mimic the inertial behaviour. Nevertheless, PV can offer the ability to significantly change its output within a few seconds. Gevorgian et al. (2016) proposes that PV could offer fast frequency response (FFR) which would require a full response within around 0.5 seconds after the start of a contingency event (Figure 1), significantly faster than currently required for typical frequency control regulation services such as the Australian National Electricity Market (NEM)'s fast (6 seconds) regulation FCAS market. Such FFR, which could also be offered by other renewable energy technologies and batteries, is expected to reduce RoCoF and increase the time to frequency nadir which allow more time for primary frequency to deploy, and therefore reduce the need for inertia from synchronous generators and emulated inertia from wind generation.
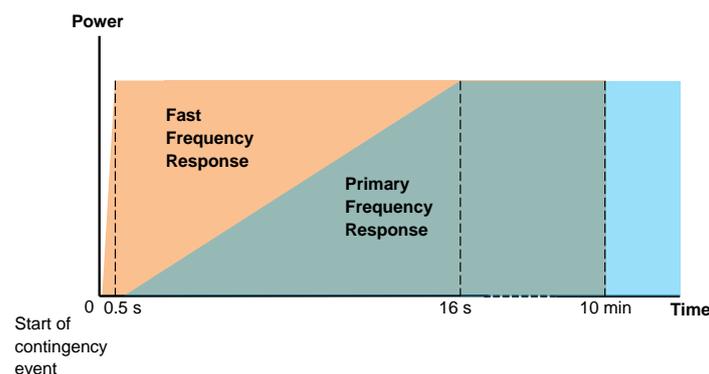
Figure 1. ERCOT Fast Frequency Response time frame

3.1.   *Frequency response of PV with an energy storage system (ESS)*

A significant body of recent research demonstrates the technical feasibility of "standalone" ESS to provide fast response to frequency deviation (Aghamohammadi and Abdolahinia, 2014; Delille et al., 2012; Luo et al., 2015; Ulbig et al., 2014). In some countries, including the UK, ESS has already been employed as a FFR service (Luo et al., 2015). Recent studies

(Delille et al., 2012; Knap et al., 2016; Yue and Wang, 2015b) are focused on determining methods to appropriately size ESS capacity to reduce RoCoF and ensure sufficient frequency response during contingency events.

With an ESS, and using a similar electronics interface, PV systems are undoubtedly capable of providing frequency response due to the fast-acting (Ulbig et al., 2014) (at millisecond-scale) and dispatchable characteristics of ESS. Yue and Wang (2015a) demonstrate that a system with energy storage delivers better frequency management than a system with one additional synchronous generator, due to the faster response time of the battery.

ESS can also be used to mitigate the impact of variable PV output on grid stability by applying frequency regulation to the PV system output. A method using ESS to reduce frequency deviation caused by PV power plants in an PV-diesel hybrid isolated grid is introduced in (Datta et al., 2011), which involves controlling charge/discharge of the integrated ESS. This results in less ramping of power output from the diesel generators and almost zero frequency deviation (reduced from ±0.3 Hz/s). The great flexibility of PV integrated ESS reduces the requirement for frequency regulation from less flexible conventional generators. A similar control method could potentially also provide frequency response capability.

Nonetheless, neither PV with ESS, or standalone EES can fully mimic the instantaneous inertial response of synchronous generators. ESS acts with a delay of 177.4 ms (Knap et al., 2016) after high RoCoF is detected, when initial RoCoF can be extremely high in a high renewable penetration system. Knap et al., (2016) noted that in such scenarios, RoCoF relays could be adjusted to withstand high RoCoF for a short period of time.

3.2.   Frequency response of PV without energy storage system

A PV system is isolated from the grid by an inverter and hence, it does not automatically change its power output in response to frequency deviation experienced in the grid. Moreover, PV systems are not generally able to increase their output given that they are typically already operating at their MPP. Currently, there is no obligation for PV to participate in frequency control in most electricity industries around the world despite the growing challenges raised by PV regarding system frequency stability.

A common concept proposed so that PV systems have more flexible power control is to curtail the energy output by controlling PV systems to operate away from their MPP. This would allow the PV systems to have power reserves available (Figure 2), and hence make PV generation capacity partially dispatchable upwards as well as downwards.

Realisations of this concept are presented in Pappu et al. (2010) and Zarina et al. (2014) by adding a DC-DC converter. Zarina et al. (2012) simulated the case of system under-frequency when there was 650 kW increased in load. The addition of the controller was able to release 130 kW reserve within 3 seconds and improve a frequency drop by 0.13 Hz. Whereas, Pappu et al. (2010) simulated the case of over-frequency and was able to cut down the energy output by 1.1 kW within 10 ms. A controller design proposed in Nanou et al. (2015) can provide maximum power point tracking, droop control and fast frequency response. The controller is able to receive a curtailment command from the grid. Simulated results show the effectiveness of the design in both under- and over-frequency response. Under the circumstances of load increased by 380 kW with 20% PV power reserve (120 kW) available, the minimum

frequency nadir can be improved by 40%. However, it is important to note that all these results are from simulation and have not been implemented in real application.
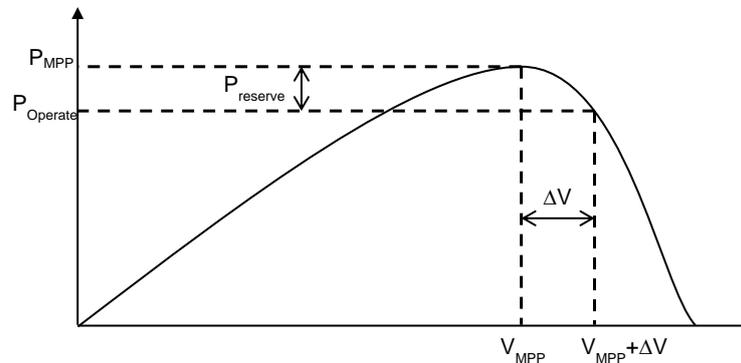
Figure 2. Concept of reserve power in PV array

In real applications, First Solar's utility-scale PV plant in Texas has tested frequency droop control to examine the possibility of participating in ERCOT's FFR. The plant operated at 50% curtailment (12MW) and when commanded to deploy full capacity took 2.5 seconds to reach its full capacity and another 2.5 seconds to ramp back down. However, this is slower than ERCOT's 0.5 second requirement, but was considered to be the limit of internal ramp rate in the plant's SMA inverters (Gevorgian et al., 2016).

A comparison study between frequency response of PV systems with and without ESS, Zarina et al., (2014) found that a 10 MW nominal PV system with PV reserve (without energy storage) can provide more frequency response capability for the same capital cost. The PV system without ESS can offer 1MW reserve of PV whereas the system with ESS can only offer 0.44MW of energy from battery. With regard to the timeframe of frequency response (to last for minutes after a contingency event), the study concludes that the reserve of PV capacity is more useful as it can deliver higher reserve capacity at the same capital cost.

There are an increasing number of studies exploring the capability of utility-scale PV to provide FFR and proposing control circuits for the purpose. Although some PV generation has to be spilled, it looks to be worth considering oversizing PV capacity as an alternative to the installation of ESS, particularly as the cost of PV modules is declining.

4.   Very short-term frequency response strategies

In some countries such as Ireland and Greece, the level of the contribution to load from non-synchronous generation is limited by the system operator, in order to maintain adequate amounts of system inertia and frequency stability (Tielens and Van Hertem, 2016). Although this approach is considered inefficient, and limits have been set conservatively, electricity industries are gradually increasing the limit with the improvement of grid codes to handle increasing penetration of renewable generation. Meanwhile, many electricity industries are also exploring potentially more effective regulations to address this concern, which will be discussed in this section.

4.1.   *Mandates and grid codes*

One of the options to reduce the risk of high RoCoF is to require participants to meet specific technical requirements. For instance, frequency deviation can be exacerbated by disconnection of non-synchronous generators on under-frequency, which are usually triggered when large frequency deviation is detected. Adjusting the under-frequency trip of the

generators' power system protection equipment to ride through these events can be mandated to mitigate this issue. Another option is to mandate the provision of services such as emulated inertia or FFR (Tielens and Van Hertem, 2016). This has been done in Quebec where a wind farm of 10 MW or more is obligated to provide emulated system inertia (Hydro Quebec, 2009). In the UK, the term "Rapid Frequency Response" (RFR) is used for FFR as a contingency response service. It was proposed that mandatory RFR response from non-synchronous generator is required to be fully delivered within 5 seconds and last for at least 25 seconds. However, this mandate has not successfully implemented due to the technical constraints of the wind turbine power electronics interface. It is recommended that faster detection and activation of primary frequency control would be more reasonable. This could include mandating the requirement for wind generation participation in primary frequency control (Palermo, 2016).

Grid codes and requirements must be aligned with the technical capability of the participating technologies. Care must be taken to ensure that new grid codes do not create barriers for new entrants, and that over specified requirements do not lead to an oversupply of services beyond what is actually required (Riesz et al., 2015).

4.2. Unit commitment strategy

Maintaining a certain minimum level of online synchronous generation at all times is one strategy to manage frequency risk under high penetration of variable renewables. However, where implemented, this has resulted in significant non-synchronous generation curtailment (e.g. 55% wind curtailment in Ireland (EirGrid, 2015)). The inertia requirement should be set dynamically according to the level of non-synchronous generation and the number of online synchronous units e.g. for a simulated case in Ireland, the wind curtailment level of dynamic setting is reduced by 30% from the curtailment level of static inertia requirement. It has been suggested that metrics for setting the non-synchronous generation limit should also include the risk of generation or load loss, and the post-contingency system inertia following the loss (Daly et al., 2015), noting that the case of loss of the largest trip would not always lead to the most significant impact on frequency stability. For example, the loss of a 500MW HVDC link might not be as severe as a trip of a 400 MW synchronous generator because this generator trip would cause both system power imbalance and reduced system inertia.

Unit commitment strategies and dynamic inertial requirement have been mentioned in many studies as a potential measure to ensure adequate levels of system inertia and avoid an overestimation of contingency reserve requirement (Eftekharnejad, 2012; Riesz et al., 2015; Silva et al., 2016; Tielens and Van Hertem, 2016). In the Australian NEM, the dynamic regulation reserve requirement is readjusted every dispatch interval with consideration of the factors influencing frequency stability (Riesz et al., 2015). This reduces the reserve requirements and hence cost. However, contingency reserve is not currently set dynamically in the NEM.

To date, relevant studies have been focused on market modelling with high wind penetration. Therefore, an evaluation of unit commitment strategies to assist frequency management with high penetration of PV systems is still needed.

4.3. Remuneration for system inertia and fast frequency response providers

Because inertia has become valuable to system operation, some electricity industries are planning to remunerate the providers of system inertia through new ancillary market services. In Texas, ERCOT is designing a Synchronous Inertial Response (SIR) service and exploring

to create one-sided market for SIR to manage RoCoF excursions by incentivising the presence of inertia. Wind generation can also participate in providing this service by producing Emulated Inertial Response (EIR) as an alternative to SIR (Singarao and Rao, 2016).

To complement SIR, ERCOT is also proposing a Fast Frequency Response (FFR) service, which is intended to provide a very fast injection of active power to arrest RoCoF before reaching the frequency nadir. Participants will be required to provide the response within 0.5 second, to last for a few minutes (Singarao and Rao, 2016) . Fast-acting technologies such as ESS and utility-scale PV, described in the previous section, will potentially be able to provide this service.

EirGrid is also designing markets for similar services, but the fast frequency response requirement in EirGrid is 2.5 seconds, a full 2 seconds slower than the requirement of ERCOT. The UK has already implemented an Enhanced frequency Response (EFR) service which requires a response within 1 second (Palermo, 2016), and it has already become apparent that ESS is well placed to provide this service (Lin, 2016), with most of the first reverse auction being won by ESS providers. However, this service is targeted at regulation services, not contingency services.

Despite some improvement in system operation and the development of new regulations, unit commitment strategies and ancillary market services to manage frequency under high penetrations of variable renewable energy, in many electricity industries, these efforts are currently targeting the participation of wind generation rather than PV generation. Given the unique operational characteristics PV, frequency management strategies will need to be carefully designed to also suit this technology.

5.   Conclusion

An increasing penetration of variable renewable generation such as PV increases risks of frequency excursions and higher RoCoF within power systems which can pose serious challenges for frequency stability. This paper has reviewed the challenges of and strategies for managing frequency under high penetrations of utility-scale PV, where less system inertia is available. There have been a number of studies on the frequency impacts of VRE and possible mitigation strategies, however, these are primarily focused on wind generators. Further impact assessment of high utility-scale PV penetration is required to better understand the implications of plant location and size on PV variability and frequency excursions, and the seasonal and diurnal patterns that would assist prediction of dynamic frequency management requirements. Initial approaches to managing frequency under high penetration VRE have assumed that inertia is required, but there is growing recognition of the role that fast frequency response (both for regulation and contingency services) might play in replacing or at least reducing the need for inertia. Further investigation of PV's potential to offer FFR response either via curtailment or in combination with ESS would therefore be useful. In addition, grid codes and technical requirements, and modeling in the academic literature have focused on managing high wind penetration. A review of grid codes and requirements, unit commitment/contingency reserve strategies, and frequency market design to assist frequency management with high penetration of PV systems is still needed, given the different technical capabilities and operational characteristics of PV (for instance PV cannot emulate inertial response like at least some types of wind generators). Case studies on small isolated grid where PV penetrations are high and inertia low, or even non-existent, may also provide useful insights.

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