Emulated Inertial Response from Wind Power: Ancillary Service Design and System Scheduling Considerations

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SUMMARY

Worldwide, variable-speed wind turbine and solar photovoltaic generation are displacing conventional power plant in market schedules. Committing out-of-merit conventional units to redress system synchronous inertia or primary frequency response shortfalls incurs start-up and production costs, and may also engender additional greenhouse gas emissions and wind/solar curtailment. In order to ensure that future system frequency response requirements are met in a low carbon manner, new sources of frequency stability ancillary services will need to be incentivised or mandated via grid codes. Non-synchronous devices (batteries, flywheels, variable-speed wind turbines), with appropriate control architectures, can provide a fast frequency response following a system disturbance, i.e. a temporary injection of active power, supplied faster than existing primary frequency response deployment times.

Operational considerations relevant to transmission system operators when designing a fast frequency response ancillary service are presented, particularly if sourced from wind power emulated inertial response. It is shown that careful consideration regarding the design of fast frequency response characteristics is required in high wind power systems: the system frequency response behaviour may be degraded if a holistic approach to fast frequency response design is not taken.

A method to characterise the system-wide (aggregate) emulated inertial response from wind power is presented, which can be integrated as a form of fast frequency response within unit commitment and economic dispatch. Endogenous incorporation in unit commitment and economic dispatch ensures that non-synchronous fast frequency response sources do not only supplement existing fossil fuel-based spinning reserve provision, but also reduce the need to commit synchronous generators for frequency control reasons. However, given the inherent energy recovery/payback experienced by variable-speed wind turbines providing emulated inertial response when operating below rated output, it is imperative to consider the impact of such negative power trajectories on system primary frequency response requirements.

KEYWORDS

Emulated inertial response - Reserve allocation - Unit commitment - Wind power generation.

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1 INTRODUCTION

Conventional synchronous power plant have constituted one of the fundamental components of electric power systems, providing the energy and ancillary services required for secure system operation. However, the growth of marginally zero cost, non-synchronously-connected, variable renewable generation (wind, solar photovoltaics) is resulting in a decommission of conventional plant [1], [2]. A reduction in the number of synchronous generators online can lower the levels of synchronous inertia and available governor response. System synchronous inertia has a direct effect on the post-disturbance initial rate of change of frequency (ROCOF) and the time to maximum frequency deviation. If online system inertia falls sufficiently, current deployment speeds of primary frequency response (PFR) may no longer be adequate to arrest a frequency fall – potentially increasing the regularity of under/over frequency load/generation shedding. To bridge the emerging gap between the synchronous inertial response (SIR) timeframe and the PFR timeframe, faster (speed of response) system reserve categories may be needed.

Variable-speed wind turbines (VSWT), with the appropriate control schemes, can provide a fast temporary injection of active power following a large system disturbance, via a controlled extraction of stored rotational energy [3], [4]. Such a response is termed as an emulated inertial response (EIR), and although VSWT EIR incorporates many variants, it essentially provides a fast frequency response (FFR), defined here as a response that is supplied faster than existing system PFR deployment times.

The impact of wind power variability and uncertainty on system operating reserve requirements is shown in [5]. As the wind penetration increases further, wind power’s non-synchronous nature becomes an operational challenge [6]. While a method to dynamically schedule system synchronous inertia is presented in [2], in order to further decarbonise power systems, there may be a need for operational practises that allow for a reduction in the minimum number of synchronous units required online for system frequency control. Scheduling faster forms of reserve from non-synchronous technologies such as battery storage, demand response, flywheels, and VSWT EIR (of focus here) may be a critical component of low inertia power system operation. The paper proceeds as follows: Section 2 outlines the unit commitment and economic dispatch (UC) and frequency stability models used, Section 3 details the operational considerations required to design FFR from wind power, and Section 4 describes a method to characterise a system’s wind power EIR resource, for integration within UC.

2 HIGH WIND POWER SYSTEM MODEL

2.1 Unit Commitment and Economic Dispatch

In order to assess the impact of rising non-synchronous penetrations on system active power schedules, and hence system frequency response, hourly UC schedules of the Ireland and Northern Ireland system are produced. Two study years, 2012 and 2020, are analysed, illustrating contrasting levels of installed non-synchronous capacity: the annual energy supplied by wind generation increases from 17% to 37% due to the installed wind power capacity increasing from 2100 to 4500 MW, and high voltage direct current (HVDC) interconnection between Ireland and Great Britain increases from 500 to 1000 MW. The unit technical and cost data are based on [7]. An instantaneous system non-synchronous penetration (SNSP) [6] is included, (1).

\[
\text{SNSP} = \frac{(P_{\text{wind}} + P_{\text{HVDC import}})}{(P_{\text{load}} + P_{\text{HVDC export}})}
\]  

(1)

where \(P_{\text{wind}}\) is the total active power output from wind generation, \(P_{\text{load}}\) is the system demand level (including pumped storage in pumping mode), and \(P_{\text{HVDC import/export}}\) is the import/export via HVDC interconnection. The SNSP limit is set at 50% and 75% for 2012 and 2020 respectively, as per operational forecast. An aggregated (by fuel type) model of the Great Britain system is used.

\[1\] Depending on system size and portfolio, the response timeframe of PFR may change. The Ireland and Northern Ireland system definition is taken here, i.e. full deployment within 5 s, and maintained for a further 10 s.
PLEXOS [8] and the Xpress-MP mixed integer programming solver [9] are used to produce the UC schedules. The model co-optimises the expected costs of system operation and reserve. The expected costs include fuel and carbon [10], variable operation & maintenance, and start-up costs. Multiple, non-overlapping categories of operating reserve are modelled: full deployment within 5 s, 15 s, 90 s and 5 min, and sustained until 15 s, 90 s, 5 min and 20 min, respectively. The reserve requirements are a function of the largest system infeed (online generator or HVDC import), and vary with category [11]. ‘Static’ reserve, i.e. reserve from HVDC links, industrial load and pumped storage in pumping mode, can contribute to operating reserve, albeit minimum ‘dynamic’ (online conventional unit governor response) requirements are enforced.

2.2 Short-Term Frequency Stability Analysis
Each time-step (hour) of a year-long UC schedule initialises a frequency stability time-domain simulation, for the loss of largest infeed. A single busbar dynamic model has been developed in MATLAB and Simulink [12], with models for each type of generator: steam, combined cycle gas turbine, open cycle gas turbine, hydro, fixed-speed wind turbine, and variable-speed wind turbine. The system frequency, assumed uniform across the system, is used as an input to generator, load and HVDC models, and is calculated by integration of the active power imbalance. The inertia of individual generators is combined to form a single inertia term, which determines the post-event ROCOF. The model has been verified against traces of the overall system frequency response taken following major generation/demand imbalance events, with further details of the model found in [3], [6]. A 500 ms rolling window is used for ROCOF calculations, which corresponds to the measurement window used by ROCOF relays in Ireland.

It is not only online generator inertia that is in decline: with the rise of rectifier load, e.g. data centres, and the use of variable frequency drives in newer motors, the inertia of the load is reducing. Hence, as a prudent assumption, no load inertia contribution is included. The importance of load inertia estimation [13] may increase in the (near) future.

In order to illustrate the impact of an increased non-synchronous penetration on system short-frequency stability, the normalised frequency of occurrence of (a) the initial ROCOF and (b) the time-to-nadir following loss of the largest infeed at each hour in 2012 and 2020 is shown in Figure 1. The results presented are for ‘base’ scenarios, i.e. no wind power EIR is enabled. Figure 1 demonstrates that there may be an increase in the initial ROCOF magnitude and a decrease in the time-to-nadir as the non-synchronous penetration increases: in 2012 (50% SNSP), no simulation case exhibits initial ROCOFs that are in excess of 0.5 Hz/s; in 2020 (75% SNSP), 9.5% of cases exceed 0.5 Hz/s.

![Image](image_url)

Figure 1: Relative frequency of (a) maximum ROCOF and (b) time-to-nadir, for loss of largest infeed at each hour in 2012 and 2020, Ireland and Northern Ireland system
2.3 Wind Power Emulated Inertial Response

Commercial VSWT EIR controls, in general, can supply a temporary active power injection of 5-10% of rated capacity for 5-10 s, once a reduction\(^2\) in system frequency, beyond a deadband, is detected [14]. A VSWT’s rotor speed, and hence EIR provision, is a function of wind speed. Below rated operation, VSWT EIR is followed by an ‘energy recovery’/‘payback period’, i.e. the power output of the turbine is temporarily reduced below the pre-event operating point, due to the turbine tracking back to optimal aerodynamic efficiency. The energy recovery of wind turbines operating at rated output can be reduced or eliminated via pitch control. Wind turbines operating below \(\sim 0.2\) pu rated output (e.g. \(\sim 0.7\) MW for a 3.6 MW turbine) are unavailable for EIR provision due to stall concerns. Given the variation of local wind speeds across a system, the EIR of a single wind turbine may not be an accurate representation of the system-wide VSWT EIR (consisting of VSWTs operating at different wind speeds). Five doubly-fed induction generator (DFIG) models, operating at distinct wind speeds, are used to approximate the different wind conditions across geographic areas in Ireland and Northern Ireland [15]. The DFIG model and proportional EIR control scheme model are based on [16]. While results are presented using a proportional EIR model, the FFR design principles proposed in Section 3 are relevant for all EIR control designs, e.g. proportional, fixed trajectory, or ROCOF (‘\(df/dt\)’) response (albeit it must be noted that the latter is difficult to implement due to measurement issues).

Figure 2 shows the emulated inertial response of the representative DFIGs to a loss of largest infeed event. Figure 2(a) shows the per unit response of each turbine model. It can be seen that the turbine energy recovery is dependent on the pre-event VSWT local wind speed/power output level, whereas once the turbine is available for EIR provision (\(\geq \sim 6\) m/s wind speed/\(\sim 0.2\) pu output), the injection does not noticeably vary with pre-event turbine active power output. Figure 2(b) shows distributions representing the proportion of wind power coming from turbines at different operating levels, based on historical wind power data for the Ireland and Northern Ireland system. The EIR of the five DFIG models is weighted dependent on the system wind level, as per Figure 2(b). With knowledge of the system wind power output, the distribution of the number of turbines operating at different levels, and how VSWT EIR varies with the pre-event wind speed, the system wind power EIR (injection and energy recovery) can be determined. Figure 2(c) shows the EIR contributions coming from turbines at different operating levels. Summing the values shown in Figure 2(c) yields the aggregate wind power EIR, Figure 2(d).

![Figure 2: Wind power EIR model: (a) turbine response as a function of wind speed, (b) proportion of system wind power output coming from turbines at differing wind speeds, (c) EIR sourced from wind turbines at differing wind speeds, (d) aggregate EIR. Per unit values are on a turbine active power rating base in (a), and on a total number of turbines online base in (b). Wind power output is 2500 MW (55% installed capacity)](image)

\(^2\) Currently, commercial VSWT EIR is asymmetric, i.e. the controls respond to an under-frequency event only. However, if incentivised, EIR controls could be designed to respond to over-frequency events.
3 DESIGN OF WIND POWER FAST FREQUENCY RESPONSE

VSWT EIR is a controlled response that can be tuned [17] to meet a system’s grid code requirement (such as Hydro-Québec [18]) or ancillary service definition (such as Ireland and Northern Ireland [19]). In [20] a market design for primary frequency response is proposed, in which several characteristics are specified for PFR providers – leading towards a satisfactory system frequency response. Such considerations, in general, can be applied to fast frequency response design. However, other considerations encapsulating the non-synchronous, energy-limited nature of resources such as batteries, flywheels, and wind power EIR are also required for prudent FFR design. Incentivisation characteristics for FFR, particularly if sourced from wind power, are outlined below, as the nature of the FFR definition will impact on the wind power EIR resource characterisation implemented within UC. The guidelines below add to those already outlined in [20]: the response should (i) act fast enough to aid in minimising the frequency nadir so as to avoid the triggering of load shedding, (ii) aid in reducing – and in the case of wind power EIR not degrade – the time to reach acceptable steady-state frequency error, and (iii) not cause instability or oscillatory system frequency behaviour.

1. **Response Magnitude:** An overly aggressive (high magnitude) initial EIR is advised against, as it may result in a ‘double dip’ frequency response, i.e. a response which exhibits a second frequency dip that is lower than the initial nadir, as shown by the “aggressive initial EIR” scenario in Figure 3. A double dip frequency response occurs due to the significant energy recovery that results from VSWTs considerably deviating from their pre-event rotor speed in order to provide a high magnitude initial injection. Double dip system frequency behaviour is in conflict with the recommendations of [21]: a system frequency response should exhibit a monotonically decreasing function of frequency deviation magnitude. TSOs must ensure that EIR providers do not maximise the initial injection, so as to increase revenue, at the potential expense of the system response.

![Figure 3: Impact of (a) wind power EIR design on (b) system frequency response. The case does not include static reserve from HVDC or pumped storage so as to reveal the effect of wind power EIR](image)

2. **Response Duration:** An overly sustained (duration of injection) EIR is advised against, as the time away from maximum power point tracking – as well as the magnitude of the initial injection – has a significant impact on the extent of the EIR energy recovery, as shown by the “over-sustained EIR” scenario in Figure 3. The energy payback characteristic marks a key difference between EIR and PFR from conventional sources.

The FFR timeframe should be chosen such that it is of greatest value to the system. Sustaining the response substantially beyond the full deployment time of PFR may increase the extent of the energy recovery, while overlapping with an already procured PFR. Furthermore, conventional unit
governor response typically ramps to, and hence provides energy well before, full provision. In contrast, non-synchronous devices can ramp to full provision within ~100-200 ms. Utilising FFR to bridge the gap between the SIR and PFR timeframes may provide maximum value to the system. In Figure 3, a “moderate EIR” tuning scenario is also shown, in which the emulated inertial response is smaller in initial injection than the “aggressive initial EIR” scenario, and shorter in duration than the “over-sustained EIR” scenario. The “moderate EIR” scenario improves the system frequency nadir, without degrading the steady-state frequency error.

The results presented are for the Ireland and Northern Ireland system with high wind penetration. Thus, the definition of ‘aggressive’ and ‘over-sustained’ may differ for other systems: larger systems may define a response that is of greater initial magnitude (5-10% of rated capacity), and sustained for a longer duration (5-10 s), without detriment to the system frequency response. Furthermore, a TSO may mandate a delay of FFR energy recovery so that the system frequency recovers to an acceptable steady-state error in the shortest time possible.

3. **Disturbance Detection Accuracy:** The FFR definition should be agnostic regarding the control technique employed. However, clear policies regarding measurement accuracy and controller sensitivity should be outlined. The control method employed must result in a reliable response provision, e.g. ROCOF measurement-based FFR may not be advisable, due to the difficulties in attaining a noise-free ROCOF measurement. In the case of frequency deviation-based control, a deadband should be implemented so that a response is limited to large events only.

4. **Coordination with Operating Reserve and Synchronous Inertial Response Requirements:** FFR requirements that recognise SIR and PFR levels are recommended. Figure 4 shows the impact of PFR on the extent to which wind power EIR improves the system frequency nadir. Two cases, with equal system demand, wind generation and online synchronous stored rotational energy levels, but contrasting PFR, are compared. In each case, the system frequency response to the loss of the largest infeed is analysed, with and without EIR enabled. Figure 4 illustrates that there is a significant difference in nadir improvement between the base (no EIR) and EIR scenarios, for high and low PFR availability. With a high PFR level, implementing EIR controls results in a nadir improvement of 0.08 Hz over the base scenario. With a low PFR level, implementing EIR controls results in a negligible nadir improvement (< 0.01 Hz).

Procuring new forms of PFR, such as demand response, battery storage, and wind power PFR, may be may be a key enabler in realising the benefits of wind power EIR.

![Figure 4: Impact of online PFR level on wind power EIR’s effect on system frequency response. The case does not include static reserve from HVDC or pumped storage so as to reveal the impact of PFR. The same EIR controls are applied to both cases. Wind power output is 2500 MW (55% installed capacity) ](image)
5. Design Case Selection: Given the variability of system operating conditions possible, a range of design cases should be considered for holistic FFR design. For a given system size, generation portfolio, and sources of reserve provision, the optimal EIR shape is a function of the system demand, wind penetration, and initial active power imbalance [17]. Thus, although sub-optimal for any individual case, a response that is robust across a multitude of operational cases is recommended.

Figure 5(a) presents the maximum system infeed as a function of SNSP, for hours of high SNSP (> 50%) on the Ireland and Northern Ireland system in 2020. Figure 5(a) illustrates that there is a trend for the maximum system infeed to decrease as wind penetration increases. Hence studying the loss of the largest infeed at the time of the maximum SNSP may not yield the global worst-case frequency response. Figure 5(b) shows the magnitude of the maximum system frequency deviation as a function of the maximum ROCOF, for loss of the largest infeed at each hour in 2020 (with no EIR enabled). It can be seen that there is a positive correlation between ROCOF and frequency deviations, albeit the utilisation of static reserves (which tends to form the frequency nadir once triggered) create a notable spreading of the distribution, if frequency deviations exceed -0.4 Hz (the first static reserve threshold). Figure 5(c) shows the proportion of wind turbines with an active power output of 0.2 pu or above, as a function of system wind power output, and is based on historical data from the Ireland and Northern Ireland system. The number of turbines online, and above the active power output required for EIR provision, is a key determinant of the aggregated wind power EIR. Given the variability exhibited in Figure 5(c), tuning EIR based on one wind penetration level may result in times when wind power EIR degrades system frequency response due to an overly aggressive response.

Figure 5(d) shows the relationship between the pre-event system synchronous stored rotational energy (inertia) and wind power output. Figure 5(d) illustrates that periods of high wind power output can result in a reduction of online synchronous inertia. Such high wind/low inertia periods may be when wind power EIR plays a valuable role in system frequency containment.

![Figure 5: Relationship between (a) SNSP and max infeed online for hours of high SNSP (> 50%), (b) max ROCOF and frequency deviation magnitudes for loss of the largest infeed at each hour, (c) system wind power and proportion of wind turbines that can provide EIR, (d) system wind power and online SIR at each hour, 2020](image)

Table 1 shows four cases, taken from the 2020 UC, chosen for FFR design. Each selected case is characterised by system variables (such as system wind generation, demand, synchronous stored rotational energy (inertia), primary frequency response, maximum system infeed, and SNSP) of varying levels. Three qualitative levels (low, medium, and high) give a high-level description of each system variable in each design case. For example, the “maximum single infeed” case takes a UC timestep in which the largest HVDC link is at full import, the system demand is high, and a relatively low
wind penetration results in a medium inertia level online. In contrast, the “high” ROCOF” case takes a UC time-step in which the system demand and maximum infeed are low, and a high wind penetration results in a low online system inertia level. Note that the design cases are taken from credible UC cases, as opposed to a fabricated worst-case; if wind power EIR is tuned solely based on a constructed worst-case, minimal nadir improvements would be seen for all other operational conditions.

Table 1: Design cases

<table>
<thead>
<tr>
<th>Case I.D.</th>
<th>SNSP (%)</th>
<th>Largest Infeed (MW)</th>
<th>PFR Availability (MW)</th>
<th>Inertia (GWs)</th>
<th>Wind Power (GW)</th>
<th>Load (GW)</th>
<th>ROCOF (Hz/s)</th>
<th>Freq. Dev. (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Single Infeed</td>
<td>32</td>
<td>500</td>
<td>419.5</td>
<td>28.8</td>
<td>0.9</td>
<td>5.7</td>
<td>-0.41</td>
<td>-0.54</td>
</tr>
<tr>
<td>High Wind Penetration</td>
<td>53</td>
<td>406</td>
<td>357</td>
<td>26.5</td>
<td>3.7</td>
<td>6.6</td>
<td>-0.42</td>
<td>-0.50</td>
</tr>
<tr>
<td>Low Frequency Nadir</td>
<td>30</td>
<td>418</td>
<td>339</td>
<td>24.4</td>
<td>1.3</td>
<td>4.0</td>
<td>-0.48</td>
<td>-0.70</td>
</tr>
<tr>
<td>High ROCOF</td>
<td>59</td>
<td>276</td>
<td>263</td>
<td>12.6</td>
<td>1.6</td>
<td>2.5</td>
<td>-0.70</td>
<td>-0.50</td>
</tr>
</tbody>
</table>

Variable Colour Code | Low | Medium | High

Typically, grid codes specify that PFR must be fully activated within, and sustained until, stated time limits [22]. FFR may also need to fit within a “full availability by” and “deployment end” template. By tuning [17] the EIR response, the magnitude and duration of EIR can be shaped to meet a system FFR definition. By following the five FFR design principles outlined earlier in Section 3, the EIR controls [16] are tuned so that the response is robust for each of the design cases outlined in Table 1. Figure 6 illustrates (a) the EIR control signal fed into each DFIG model, and (b) the aggregate EIR injection and recovery, for each design case. The control signal shape differs between design cases due to the differing frequency response in each case; the same EIR controls are applied to each of the five DFIG models, and are used in each case. The peak EIR injection in the “maximum single infeed” case is much lower than that in the other design cases due to a lower system wind power output, Table 1. The distinct difference in the ‘withdrawal’ component of the EIR control signal (Figure 6(a)), and hence the aggregate EIR (Figure 6(b)), in the “high ROCOF” case is caused by the triggering of HVDC interconnector static response. 50 MW of static reserve is deployed at 49.6 Hz, after which the system frequency nadir is formed. The VSWT EIR energy recovery immediately follows the nadir formation, causing the system frequency response to move away from a traditional ‘fishhook’ shape the “high ROCOF” case. Figure 7 shows the system frequency response.

Figure 6: Wind power EIR (a) control signal, and (b) aggregate response, for each design case. Per unit values are on a turbine active power rating base in (a)

3 ‘High’ refers to the magnitude of the ROCOF. All disturbances analysed are under-frequency (negative ROCOF) events. See also footnote 2.
Figure 7 shows that with the implementation of a robust EIR, the frequency nadir is improved in each design case, and no double dip frequency event occurs (i.e. no second dip that is lower than the first). However, due to improved system frequency nadirs, the static reserve provision at 49.6 Hz is not triggered in the EIR scenarios of the “low frequency nadir” and the “high ROCOF” cases, resulting in increased steady-state frequency errors in comparison to the base scenarios. Deploying static resources in tandem with EIR requires carefully management.

With the FFR magnitude and duration determining the duration and depth of the energy recovery period, each TSO must quantify a prudent FFR shape. Defining a minimum standard regarding the ratio between FFR initial injection and subsequent recovery may be a technology-agnostic solution. Similar nadir improvements to those shown in Figure 7 could be achieved by employing a higher magnitude EIR control signal to that shown in Figure 6(a), on a smaller proportion of the installed wind power capacity, for example if there is 50%, as opposed to 100%, EIR technology penetration. If coupled with other forms of non-synchronous FFR, e.g. batteries, flywheels, and/or prudently coordinated with system PFR, the potential for nadir improvement could increase while reducing/eliminating the impact of the energy recovery period on the system frequency response.

4 WIND POWER EMULATED INERTIAL RESPONSE WITHIN UNIT COMMITMENT

In order to ensure that new resources are harnessed in a cost effective manner, endogenous incorporation of their availability and capability within system scheduling procedures is necessary. A method to characterise wind power EIR, so that it can be integrated within UC, is presented.

4.1 Comparison with Conventional Unit Spinning Reserve Requirements

A system’s PFR requirement, $PFR^{req}$, can be incorporated within UC as (2).

$$PFR_{i,t}^{req} = \sum_{i=1}^{NG^{on}} PFR_{i,t} \geq P_{i,t} \forall i \in NG^{on}, \forall t \in NT$$

where $P$ is the active power output/flow of an online generator/interconnector, $i$, the largest of which sets $PFR_{i,t}^{req}$, for each time-step, $t$, in the time-step set, $NT$, is met by the sum of each unit’s PFR capability, $PFR$, in the online generator set, $NG^{on}$. $PFR$ is typically modelled within UC as (3).

$$PFR_{i,t} = \min \{PFR_{i,t}^{max}, \alpha (P_{i,t} - P_{i,t}^{max})\} \forall i \in NG^{on}, \forall t \in NT$$
where $PFR^{max}$ is the maximum PFR a unit can provide, $\alpha$ is the reserve decrement rate, and $P^{max}$ is a unit’s maximum active power capacity. Eq. (3) is a UC representation of the governor response characteristic, $R$, that enables a response in the PFR timeframe, (4):

$$R_i = -((\Delta f/f^0)/\Delta P_i/P_i^{max}).$$

The magnitude of a unit’s governor response, $\Delta P$, is based on the system frequency deviation, $\Delta f$, from nominal, $f^0$. In UC, PFR dependence on $\Delta f$ is neglected, as a system event (and resultant $\Delta f$) cannot be predicted before the fact. A similar assumption will be required regarding proportional EIR. In contrast, a fixed trajectory EIR is not $\Delta f$-dependent, once the deadband has been exceeded.

Given that the availability of the aggregate wind power EIR is not deterministic, it may be difficult to define minimum requirements for wind power EIR. However, setting the system SIR and PFR requirements as a function of wind power EIR availability may enable wind power EIR controls to yield system operational cost savings, for example: during periods of high wind power EIR, it may be possible to relax the system SIR requirement, potentially decommitting fossil fuel-fired generation (if all other operational security aspects, such as ROCOF, are maintained). Relationships between system SIR, FFR and PFR requirements may be bespoke to each power system.

### 4.2 Characterisation of the Aggregate (System-Wide) Wind Power Emulated Inertial Response

Once the FFR design has been defined (such as that shown in Figure 6), the EIR injection and recovery characteristics of VSWTs can be determined. Table 2 shows the EIR characteristics for the five distinct DFIG active power output levels/wind speeds modelled.

<table>
<thead>
<tr>
<th></th>
<th>DFIG 0 &lt; 6 m/s (0.2 pu)</th>
<th>DFIG 1 6 m/s (0.2-0.5 pu)</th>
<th>DFIG 2 8 m/s (0.5-0.7 pu)</th>
<th>DFIG 3 11 m/s (0.7-1 pu)</th>
<th>DFIG 4 12 m/s (1 pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection (pu)</td>
<td>0</td>
<td>0.015</td>
<td>0.015</td>
<td>0.015</td>
<td>0.015</td>
</tr>
<tr>
<td>Recovery (pu)</td>
<td>0</td>
<td>0.0034</td>
<td>0.0036</td>
<td>0.0045</td>
<td>0</td>
</tr>
</tbody>
</table>

Using 15-min historical data from all metered wind farms (~120) on the Ireland and Northern Ireland system in 2009, and the EIR capabilities at different wind levels shown in Table 2, the aggregate wind power EIR availability can be characterised, assuming variable-speed wind turbines are enabled with EIR technology. Figure 8 shows the system wind power EIR availability as a function of system wind power output. The 5th percentile and mean values, for each wind level (5% bins), are also shown. The aggregate EIR injection availability follows a similar trajectory to the distribution of turbines online and above ~0.2 pu, Figure 5(c). The aggregate recovery is smaller in magnitude due to the shallower, but longer nature of the recovery in comparison to that of the injection.

Figure 8 highlights that, if VSWT EIR is to be considered in unit commitment and economic dispatch, the energy recovery period may need to be considered. The system PFR requirement may need to increase during periods of high EIR availability, as a depletion of online PFR, due to a large post-event EIR energy recovery may degrade system frequency response quality. Such considerations may decrease the cost benefit of wind power EIR.

The variability of the EIR availability may be of interest to TSOs. Figure 9 shows the standard deviation of wind power EIR availability injection and recovery. Such variability may imply that the flexibility of PFR sources may need to increase.
Figure 8: Characteristic of the aggregate (system-wide) wind power EIR availability, as a function of system wind power output. Per unit values are on an installed wind power capacity base.

Figure 9: Standard deviation of aggregate wind power EIR availability as a function of system wind power output. Per unit values are on an installed wind power capacity base.

CONCLUSIONS

- In high wind power systems, a holistic set of fast frequency response design principles is required to ensure the system frequency response is robust for all operational scenarios.
- The nature of the fast frequency response definition impacts on the wind power emulated inertial response resource characterisation implemented within unit commitment and economic dispatch.
- A method to incorporate wind power emulated inertial response as a form of fast frequency response within unit commitment can be developed using historical wind power data.

LIMITATIONS & FUTURE WORK

- The methodology presented is intended for the creation of day-ahead operational policies. In order to fully assess the risks of high ROCOFs to system short-term frequency stability, dynamic simulations of a full network model should be conducted.
- As the number of online conventional units reduces further, care will be needed to maintain a secure distribution of synchronising torque across a system, so as to ensure transient stability.
• Wind power EIR may introduce an uncertainty into the operating reserve timeframe. Studying the impact of the stochastic nature of wind power, and hence its reserve provision, may be prudent.

ACKNOWLEDGEMENT

This work was conducted in the Electricity Research Centre, University College Dublin, Ireland, which is supported by its Industry Affiliates Programme (http://erc.ucd.ie/industry/). Pádraig Daly is supported by the Irish Research Council’s Embark Initiative.

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