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Quantifying the Aggregate Frequency Response from Wind Generation with Synthetic Inertial Response Capability

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Abstract—Modern variable-speed wind turbines, although decoupled from the system frequency, can respond to significant power imbalances through power electronic controls as synthetic inertial or governor-like droop responses. However, frequency response capabilities from wind power plant cannot be considered a direct replacement for traditional frequency responsive services. Before such capabilities should be incorporated into systems, their most effective implementation should be considered and a methodology for system operation under high synthetic inertia technology penetration should be identified. This paper considers a possible system frequency response requirement from wind generation and investigates issues surrounding quantification and scheduling of the future system resource, taking the combined Ireland and Northern Ireland system as an example. The distribution of local wind speeds, the variation in the response provided by different control structures, as well as the uncertainty associated with the aggregated capability at any one time, and the implications for the development of ancillary service market incentives or grid code requirements are considered. The impact of uncertainty over the aggregate wind response available is assessed and a strategy for the forecasting, management and coordination of such a resource on future power systems is proposed.

I. INTRODUCTION

As wind penetration levels increase on power systems worldwide, many system operators are investigating the potential for wind generators to be responsive in the event of a frequency transient following a contingency [1], [2]. Modern variable-speed wind turbines, although decoupled from the system frequency, can respond to significant power imbalances using power electronic controls through synthetic inertial or governor-like droop responses [3]. Such technology presents an opportunity for system operators to mitigate against many of the frequency response issues resulting from the changing dynamic response capability of modern power systems with increased displacement of conventional plant. In the case of synthetic inertial control, which is the focus of this research, wind power plant can temporarily increase their power output by harnessing the stored rotational energy of their rotors, through power electronic controls [4]. However, a synthetic inertial response is inherently different to synchronous inertia, as demonstrated in [5], and the implementation of such a capability at scale requires careful management.

In [6] it was shown that large-scale employment of wind generation with synthetic inertial controls, which have not been tuned for the specific system in question, could potentially lead to undesirable frequency response characteristics. In general, the inclusion of such controls at scale can be seen to alter the general shape of the system frequency response from that traditionally observed, however, some variation from the conventional response must be accepted in light of dramatically changing dynamic characteristics. In [7] it was shown that optimisation of the control parameters could potentially mitigate some of the undesirable effects of synthetic inertia, such as a significant aggregate energy recovery phase. It was demonstrated that particular settings may work well for designed system conditions, but may be noticeably sub-optimal for other conditions, or as the installed population of responsive turbines increases.

In addition to the avoidance of any potential issues associated with the large-scale implementation of synthetic inertial technology, the technical and economic value of the response to a system and its predictability must also be fully understood to ensure that it is employed effectively. This paper proposes an approach to how such controls might be employed most effectively on a large scale. While [7] has assessed the need for off-line optimisation of wind turbine synthetic inertial controls at a planning phase of the system, and its importance in informing the development of ancillary service market incentives and grid code requirements, the scheduling and predictability of a frequency response resource from wind generation, which is necessary for day-to-day system operation, has yet to be investigated. In the event that synthetic inertial controls from wind power plant are implemented on future power systems at scale, system operators require a methodology for best predicting and managing the contribution from wind generation. This paper highlights issues facing system operators charged with coordinating and dispatching the frequency response capability when considering high wind penetration levels, incorporating synthetic inertia technology. Section II provides an overview of synthetic inertia technology, Section III proposes the likely requirements for such controls on future systems, Section IV highlights issues associated with the operation of a system with such technology. Section V proposes an
implementation strategy of such a response and Section VI summarises the conclusions of this work.

II. SYNTHETIC INERTIAL RESPONSE

Although modern variable-speed wind turbines are mechanically decoupled from the system frequency of the conventional plant on the system, they can be supplied with supplementary controls which allow them to harness the inertial energy associated with their rotating blades following a frequency transient, allowing them to temporarily increase their power injection by the order of 5-10% of rated capacity. While the response can be very fast, it is inherently different to the inertial response provided by conventional synchronous plant, as it relies on active controls as well as the aerodynamic characteristics of wind turbines. Wind turbines will tend to operate at a certain tip/speed ratio in order to remain at optimal efficiency. For turbines operating below their rated speed, harnessing of their stored rotational energy through synthetic inertial controls results in a slowing down of the rotor and hence a reduction in the aerodynamic energy harnessed by the turbine. As a result, the initial power injection from the turbine is followed by an energy recovery phase as the turbine tracks back to its optimal efficiency. For turbines operating above rated wind speed prior to the event (i.e. blades pitched out of the wind), their blades can be pitched back into the wind to reduce or avoid the energy recovery phase. Turbines operating close to their minimum operational speed should not provide a synthetic inertial response in order to avoid stall conditions. In addition, the reliance on active power controls and monitoring of system events introduces inherent delays into the provision of the response from wind generation. In comparison, the inertial response from conventional plant is inherent and independent of plant operating conditions prior to an event.

Due to the role of power electronics in controlling the inertial response, the trigger signal for the response from wind generation is not limited to the rate of change of frequency, upon which a synchronous inertial response is dependent. There have been a number of control approaches proposed by both industry and academia, which can broadly be separated into three main categories. The first approach is based on the rate of change of system frequency, in line with the relationship between the response from conventional plant and the transient. However, measurement of the rate of change of frequency on a system can be difficult. The second control option provides a fixed power injection following a deviation in frequency beyond a certain threshold. While this response implies a greater level of certainty over the response from a single wind turbine, the presence of such a static response at high penetration levels may prove problematic [7]. The third control approach is based on a response proportional to the deviation in frequency from nominal, considering a certain deadband. Responses can also be based at either the wind turbine or wind power plant level. Regardless of the control approach employed by a turbine or wind power plant, the response from wind generation is fundamentally different to that from conventional plant and thus the issues raised and methodologies proposed are relevant to all control approaches.

It should be noted that the resultant response from a wind turbine is a function of the wind speed, but this is unlikely to be a deterministic response during the transient period following a significant frequency deviation. Furthermore, priority is given to the load management functions of the wind turbine control and thus the synthetic inertial response is also dependent on the wind turbulence and mechanical states of the drive train and tower. For example, an individual turbine might transiently be running at a speed greater than the steady-state condition associated with a particular power level, because of a gust, coinciding with the grid event. Under this condition, the power delivered in the immediate post event time-frame would be greater than that for a steadier wind condition. While the inertial performance of an individual wind turbine is stochastic in practice, the aggregation of the response across a system negates much of this uncertainty.

III. FUTURE SYSTEM REQUIREMENTS

In light of the development of numerous innovative synthetic inertial control designs [8], [9], as well as an evolving frequency response capability of modern power systems with high wind penetration levels, a number of systems have begun developing requirements for wind generation in order to future proof the frequency response capability of their respective systems [10]. A small number of systems worldwide are beginning to face the consequences of extremely high wind penetration levels, with their operation evolving and adapting to the new dynamic characteristics. Hydro-Quebec has already defined an inertial response capability requirement for large wind power plant, stating that they must have an equivalent inertial capability to that of a conventional plant with an inertial H constant of 3.5 s [11]. In New Zealand, the definition of future grid code requirements for frequency response services from wind generation are being investigated [12]. In Ireland and Northern Ireland, a public consultation is under-way regarding the design and development of a new suite of ancillary services, including frequency responsive services which could be provided by wind generation [13]. Further grid code requirements and market incentives are being considered, developed and refined in different jurisdictions worldwide [14], [15]. In order to effectively harness the true value offered by this technology it is vital that the strengths and weaknesses of such technology are fully understood.

As the penetration of non-synchronous generation increases, the provision of short-term frequency responsive services, up to and including primary operating reserve, is depleting. Reduced synchronous inertia results in a higher rate of change of frequency following a contingency event. The impact of such a trend on the frequency responsiveness of the future combined system will vary significantly with system and conditions, however, evolution of the frequency response capability of the system is inevitable and must be well understood in order to develop operational strategies to ensure secure and stable system operation. The effectiveness of the mechanisms put in place for the inclusion of synthetic inertial control will play a key role in the ability of wind generation to improve the frequency response of the system.
Assuming that the inclusion of a synthetic inertial response from wind generation is of technical and economic value to the system, it is implied that the response from wind generation may displace services otherwise provided by conventional plant. While wind generation can indeed provide a frequency response, the actual ‘value’ of this service must be identified in order for it to be accommodated in normal system operation and future ancillary service markets. At the outset, it is important to recognise the limitations of the technology. All synthetic inertial controls rely on active power controls and detection of the system frequency event and so cannot impact on the initial rate of change of frequency (ROCOF). Depending on the size of the system, the ROCOF may or may not be an area of concern for operators. For example, on small systems, the initial rate of change of the system frequency, which may be used to trigger ROCOF relays on other equipment cannot be improved by the employment of synthetic inertial controls. Furthermore, the power/energy provided by synthetic inertial controls can only act in a temporary time frame and must ultimately be paid back. Sustained responses cannot be provided by turbines operating below rated wind speed in normal (not curtailed) operation. As such, the value of synthetic inertial controls from wind generation lies in arresting the rate of change of frequency in the time frame subsequent to the initial ROCOF, as well as improving the nadir. In light of these response characteristics, it is important that any incentive or requirement for synthetic inertial controls from wind generation is designed for the rapid delivery of the service, in recognition of its true value to the system.

The island system of Ireland and Northern Ireland is taken as an example in this paper due to its ambitious wind generation targets (40% electricity from renewables by 2020) for a single synchronous system, and already reaching instantaneous penetrations of 50% on numerous occasions [16].

IV. SYSTEM OPERATION

Traditionally the level of reserve and inertia available on power systems across all time frames has been relatively deterministic in nature. System operators have been capable of dispatching the required level of reserve and ensuring sufficient inertia to meet defined standards. With the inclusion of synthetic inertial controls from variable resources such as wind generation, however, the nature of this previously dispatchable resource is likely to become more uncertain in nature. Using historic data from Ireland and Northern Ireland some noteworthy trends in the variability of the potential resource can be observed. In Figure 1 the number of turbines online in the combined Ireland and Northern Ireland system, based on historic wind power output data from all major wind power plant on the combined system, is illustrated. It can be observed that while the number of turbines operating is relatively deterministic at low and high levels of system wind generation, the number of turbines contributing at mid wind generation levels is likely to vary more as the geographical distribution of wind varies across a system. For example, for a system-wide wind generation level of 0.3 pu the proportion of turbines (fixed-speed and variable-speed) operating on the system may vary between 0.5 and 1 pu. i.e. the distribution of the aggregate wind profile may comprise of a number of turbines operating at medium/high wind speeds or a lower number of turbines operating at lower wind speeds.

However, due to the impact of synthetic inertial response provision on the operation of a turbine, it is likely that turbines operating at low levels will not be required to provide a response to a frequency transient. In Figure 2 it is assumed that only variable-speed turbines operating above 0.2 pu can be expected to provide an emulated inertial response. As a result, the shape of the number of turbines available to provide a response and the curve region of greatest variability is shifted to the right compared to the number of turbines online in Figure 1. Fixed-speed wind turbines

In Figure 3, the power output probability distribution of the turbine fleet capable of contributing a response is illustrated in more detail, for varying system-wide wind generation levels. While the proportion of those turbines enabled with synthetic inertia which are capable of providing a can be seen to vary, the degree of variability can also be seen to diminish as the system wind generation level increases beyond 0.6 pu. The variance of the distribution is significantly higher at lower system-wide wind generation levels, implying increased uncertainty when predicting the frequency response capability of the combined wind generation fleet at such levels. It should be noted that the average capacity factor for wind generation on the island of Ireland and Northern Ireland is 35%. [17] and so the system wind generation level will often be in the region
of greatest uncertainty in terms of the number of turbines capable of contributing a response, if fitted with synthetic inertial controls.

Fig. 3. Probability distribution of proportion of turbines online for varying system wind generation levels

A. Online resource assessment

As outlined in Section II, the response characteristic of a wind turbine is dependent on its operating condition at the time of the frequency event. Of the turbine fleet enabled with a synthetic inertial capability, turbines operating at a low level will not contribute a response, turbines operating sufficiently above minimum speed, but below rated wind speed will give a response but will experience an energy recovery phase subsequent to the initial power injection, and turbines above rated wind speed or operating in a curtailed mode will avoid the energy recovery phase. In this analysis, turbines across the system are divided into three operating bands, below 0.2 pu (non-responsive), above 0.2 pu but below rated and turbines operating above rated wind speed. Figure 4 illustrates the average trend in the proportion of turbines operating in each of these states for varying system-wide wind generation levels. For the purpose of this analysis, it is assumed that turbines operating within each of the upper two bands will provide similar responses, on average, regardless of how wind speeds might vary within each band. It should be noted that this figure does not capture the variability of the output of turbines for various distributions. The proportion of turbines operating at a low output, and thus not capable of providing a synthetic inertial response, reduces from a maximum at low system-wide wind generation levels. The proportion of turbines operating above minimum speed but below rated increases with increasing system wind, as does the proportion of turbines operating above rated. It should be noted here that Figure 4 represents historic data of wind profiles. It is likely that future data may include a higher proportion of curtailed turbines as instantaneous system wind penetration level limits, network loading restrictions etc. are reached more regularly.

Although the wind frequency response resource available is not likely to vary as much as the wind power output, it will display some uncertainty and variability in real time. In Figure 5, the proportion of turbines operating above 0.2 pu, and thus capable of contributing an inertial response, is plotted alongside the system wind generation level. It can be observed that for medium wind generation levels, that the number of turbines capable of contributing a response may vary over a short time frame because of the inherent variability of the wind resource, and so a system operator cannot assume an exact number of turbines for a given wind forecast.

Fig. 4. Turbine average operating levels

Identifying the number of turbines online and capable of contributing a synthetic inertial response and its translation into a frequency responsive resource is an important consideration for a system operator tasked with scheduling sufficient reserve over all time-frames. Given that the potential value added to the system by synthetic inertia lies in the energy delivered during the initial frequency descent, for the Ireland and Northern Ireland example, it is suggested that this translates as the energy delivered in the first 3 seconds subsequent to the event. As an illustration, Figures 6 and 7 illustrate the present day frequency response of the combined Ireland and Northern Ireland system for different system conditions given a set of control parameters optimised for this particular system [7]. Cases 1-5 represent system conditions with non-synchronous penetration levels ranging from 3% to 50%. It can be observed that the initial power increase of the proportional response and hence energy delivered is similar despite a range of distinct system frequency responses. While the response provided by turbines operating above rated wind speed, or in a curtailed state prior to the event, will not exhibit an energy recovery phase, unlike those turbines operating below rated, the energy delivered in the first 3 s is assumed relatively constant. As a result, the 3 s energy resource available on the system, in the case of a significant event, can be assumed to be proportional to the number of turbines capable of providing such a response, ignoring the inherent inertial
response contribution from fixed-speed wind turbines in this analysis. While control approaches based on fixed controls naturally deliver a fixed injection for any event on the system if triggered, for controls based on df/dt or proportional control structures it can be assumed that the energy delivered in the initial 3 s period following the event does not vary significantly on a per turbine basis, assuming that the control parameters are optimised for the system in question [7]. This time frame will vary with differing system dynamics in larger systems.

If it is assumed that the (3 s) energy delivered by turbines for a significant event does not vary significantly, the potential resource available from wind generation can be quantified based on the number of turbines online and capable of contributing a response. The cumulative probability function of this resource is illustrated in Figure 8. For example, for the curve representing system wind generation levels between 20 and 25% the resource available is above 0.36 pu 90% of the time. Such probability curves allow the system operator to determine the aggregate synthetic inertial resource for a given confidence level. It should be noted that while the 3 s response may be considered independent of the longer term response will vary with the operating condition of the turbine.

B. Practical Implementation and Service Procurement

The question of whether wind-based frequency flexibility should be acquired through grid codes or whether it is more suited to ancillary service markets is relevant in the context of the scheduling of frequency response capabilities from wind generation and other technologies. While synthetic inertia offers measurable value to system operation [5], there are challenges and risks associated with a dependency on market signals for such a time critical service, which is potentially provided through a range of individual control solutions from different manufacturers. While it may be considered unfair to require a response without reimbursement, it is vital that any incentive schemes for responses based on active controls take account of the differing response characteristics from active controls compared to those from conventional plant. In the case that turbines are incentivised to provide, for example, a particular sustained power increase following an event, wind power plant operators could attempt to maximise profits by formulating a response which maximises their individual output. In the absence of information on the behaviour of other generators, this scenario could leave the system vulnerable to an aggregate wind response which maximises generator revenue but is potentially harmful to the system recovery, as illustrated through the double dip in the frequency response caused by significant concurrent energy recovery periods from a large fleet of turbines in [7]. Thus it may be advisable for system operators to clearly define the degree of freedom offered to wind generators regarding the control structures employed.

Once the system operator has gained a good knowledge of the nature of the response provided by wind generation, the uncertain characteristics of the response are related to the number of turbines contributing across the system and the impact of their mechanical state at the time of the event. The variability and uncertainty of the actual response provided by individual turbines operating at similar wind speeds is somewhat addressed by the aggregation of the response across a large area and this paper illustrates that the response can be predicted using historical data with some
confidence. Furthermore, with the addition of real-time wind turbine output and availability data, the system operator can update the forecast of wind generation frequency response capability in future systems.

The communication network requirements for the aggregate resource quantification and wind power plant reporting requirements necessary for the frequency response resource assessment proposed here do not exceed those already in place in many grid codes incorporating significant wind generation levels. For example, in Ireland and Northern Ireland, system operators have real-time information available on the power output of each plant as well as the availability of turbines within plant [18]. Therefore, the suggested approach, of using data on the number of turbines online for managing the response of wind generation would therefore require minimal additional investment for system operators.

The approach proposed here assumes prior offline optimisation of the response from wind generators for a given technology penetration and installed wind capacity, as described in [7]. Such off-line optimisation analysis would require updating in line with any significant changes in the dynamic profile of the system (e.g. yearly, with increasing installed wind capacity). Assuming such analysis has been performed on the dynamic performance of the system under extreme events, the system operator can be confident in the impact of the synthetic inertial response from wind generation across the system.

V. CONCLUSION

The incorporation of synthetic inertial controls from wind generation in future systems requires a new set of tools to those traditionally employed in dispatching and/or predicting short-term reserve sources. The uncertainty and variability which must be considered when managing the aggregate synthetic inertial response capability of a system, as well as considerations by operators employing such capability is presented here. Furthermore, before ancillary service market incentives or grid code requirements are defined, the value of the response offered by wind generation must be fully appreciated. The probabilistic approach in this paper is presented against the background of the suggestion that a fast transient response from wind which is delivered prior to the frequency nadir is optimal.

Effective coordination of a wind-based frequency response on future systems will require a shift in many of the conventional operating methods employed today, perhaps including a more probabilistic approach to the scheduling of inertia and short-term reserves. The optimal response from wind generation will also depend heavily on the system setup and the operating conditions of other plant. The communication technology employed at wind power plant level will play a crucial role in ensuring the reliability of supply and monitoring a distributed and variable flexibility resource. Care must be taken to ensure that the uncertainty associated with response provision is minimised, while maintaining relatively simple but robust operational rules for system operators.

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