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<td>Authors(s)</td>
<td>Ruttledge, Lisa; Flynn, Damian</td>
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<tr>
<td>Publication date</td>
<td>2012-11-15</td>
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<tr>
<td>Publication information</td>
<td>Betancourt, U. and Ackermann, T. (eds.). Proceedings of 11th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants</td>
</tr>
<tr>
<td>Conference details</td>
<td>11th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, Lisbon, Portugal, 13-15 November 2012</td>
</tr>
<tr>
<td>Publisher</td>
<td>Energynautics GmbH</td>
</tr>
<tr>
<td>Link to online version</td>
<td><a href="http://www.windintegrationworkshop.org/lisbon2012/">http://www.windintegrationworkshop.org/lisbon2012/</a></td>
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<tr>
<td>Item record/more information</td>
<td><a href="http://hdl.handle.net/10197/8260">http://hdl.handle.net/10197/8260</a></td>
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Emulated Inertial Response from Wind Turbines: The Case for Bespoke Power System Optimisation

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Abstract—The dynamic characteristics of power systems with increasing wind penetration levels are changing rapidly as the nature of the frequency response capability of these systems develop with the evolving plant mix. Consequently, the protocols for how these systems are operated are changing. While modern variable speed wind turbines do not inherently contribute to the inertial response of the system, they can offer a controlled response to system frequency imbalances, which harnesses the stored rotational energy of the blades. Unlike conventional machines, however, the tunable emulated inertial response of a variable speed wind turbine is dependent on the operating condition of the wind turbine and provides a distinct response to conventional generators. In some cases it is possible that inappropriate tuning of such a response could hinder the recovery of the system frequency following an imbalance. In this paper the emulated inertial response from wind generation on power systems of varying size is optimised, and the impact of system conditions on the response required is examined.

Keywords—Emulated inertial response, wind turbines

1. INTRODUCTION

As wind penetration levels increase on power systems worldwide the dynamic characteristics of these systems are changing, due to more synchronous generators being displaced by wind turbines. Consequently, as fewer conventional thermal plants are dispatched on systems with high wind penetration levels, the level of synchronous inertia and other ancillary services provided by thermal plant reduces, resulting in faster and more significant changes in frequency following an imbalance [1]. In light of concerns for the operation of systems with high wind penetration levels many grid codes are being adopted to ensure sufficient ancillary services are available [2], [3]. Some systems are looking in particular at the potential for wind plants to offer a partial solution to the uncertainty and variability they introduce. The specific grid code requirements of different systems for frequency support from wind power plant are likely to vary, depending on their respective system dynamics due to varying wind penetrations, synchronous generation levels, and the underlying plant portfolios. For example, in the Hydro Québec system, it is required that, in the case of a significant frequency deviation, wind turbines provide an active power response equivalent to that of a synchronous machine with an inertial constant of 3.5 s for a period of 10 s. The European Network of Transmission System Operators for Electricity (ENTSO-E) are also considering that individual transmission system operators (TSOs) shall have the right to require a wind power generating facility to deliver an equivalent performance to conventional generation by an increase of active power related to the rate of change of frequency [3], [4].

In response to changes in power system dynamics worldwide and a shift in the expectations placed on wind generation to help stabilise frequency behaviour, much work has been carried out in designing and developing control mechanisms which allow variable speed wind turbines to contribute responses similar to those already available from thermal plant [5]-[8]. Emulated inertial control, or fast acting frequency response, is one such product, the implications of which have yet to be seen at scale. While design strategies differ between manufacturers, in general, the emulated inertial response control causes the power output of a wind turbine, or farm, to temporarily increase in the range of 5 to 10% of the rated turbine power, following a significant under-frequency excursion. Due to the differing electromechanical characteristics of modern variable speed wind turbines to those of conventional generators the response provided by wind generation should be considered distinct to that from thermal plants. It is important to note that the provision of ancillary services from wind generation is likely to change the nature of the frequency response of power systems to contingency events, and so system operation may need to change accordingly. While the majority of research to date has focused on exploring the limits and capabilities of wind turbines in providing an emulated inertial response, or providing a response that mimics that of a synchronous generator most closely, the potential impact of the aggregate response of wind generation on the system merits more attention.

One fundamental difference between the inertial response of conventional plant and that obtained from variable speed wind plant is that the latter is tunable. If wind generation is required to contribute a fast acting frequency response, such as an emulated inertial capability, the tuning of the response could have a significant impact on the system frequency behaviour. Furthermore, due to the geographical diversity and variability of wind farm outputs and the variation in the number of turbines online, the
combined stored rotational energy from variable speed wind turbines could vary greatly with different regional weather patterns [9]. Subsequently, the resulting impact on factors such as conventional plant commitment, and assessment of the optimal system frequency response becomes probabilistic in nature.

The analysis carried out in this study examines the optimal frequency response from wind turbines on future power systems with varying wind, load and conventional plant conditions. Guidelines on how the shape of the emulated inertial response should vary with different system characteristics will be highlighted and the implications of these variations on system operation will be discussed. Section II introduces the emulated inertial control concept, its characteristics and a number of variations of the technology. Section III describes the dynamic power system models employed and assumptions made in optimising the frequency response capability of the test systems. Section IV presents the results and illustrates how optimal tuning of emulated inertial control parameters could vary with different system conditions. Section V considers the implications of the results of this study on future power system operation, and Section VI summarises the conclusions of this work.

II. EMULATED INERTIAL CONTROL

A number of different wind plant controls have been proposed and developed by both academia and industry to allow wind generation to contribute a synthetic inertial response in recent years. Generally, in variable speed wind turbines with such capability a reduction in system frequency is detected and active controls increase the power set point of the turbine, which then injects stored rotational energy from the rotating blades to the grid. The attainable response from wind turbines is dependent on their operating condition prior to the imbalance. Following the initial injection of energy, assuming the turbine was not curtailed prior to the event, energy is extracted from the grid to restore optimal operation and aerodynamic efficiency. As a result, an energy recovery period, when the power output of the wind turbine falls below that prior to the event follows the initial increase in power output. In contrast, while thermal plant also recover to nominal frequency following an event, they only do so in conjunction with the system frequency recovery. Wind turbines operating above rated wind speed can reduce or potentially avoid this extraction of energy from the grid by pitching their blades to harness previously untapped energy. However, wind turbines operating at or close to their minimum operational speed cannot be expected to provide such a response without stalling.

Broadly speaking, synthetic inertial controls can be split into two main categories: those triggered by a deviation in frequency beyond a deadband and those based on the initial rate of change of system frequency. Due to difficulties in measuring the initial rate of change of frequency in practice, as well as the apparent move by the wind industry towards controls based on a deviation in system frequency, only variations on the former control strategy are considered here. Generic wind turbine controls were developed based on existing designs described by both manufacturers and academics [10]-[12]. Two distinct control approaches based on a deviation in system frequency are considered. In the first, the additional power requested from the turbine is proportional to the deviation in frequency from nominal and can be summarised by

$$\Delta P(s) = \frac{K T_w s}{(1 + T_s)(1 + T_w s)} \text{max} \left( (f_d - f_{\text{min}}), 0 \right)$$

where $K$ is the gain applied to the frequency deviation, $T_s$ and $T_w$ are time constants associated with the rise and decay of the response, $f_d$ is the frequency deviation from nominal and $f_{\text{min}}$ is the frequency deadband. The second control scheme introduces a fixed response to the power set point for a deviation in frequency from nominal beyond the deadband, irrespective of the severity of the frequency transient. The tunable variables of this response are subject to the ramp rates of the trapezoid (represented below by $t_1, t_2, t_3, t_4$) and the gain, $k$, which determines the magnitude of the response, as represented in Equation 2. The reaction times of both responses are also dependent on the deadband employed in the controls, which ensures that the controls respond to significant frequency events only.

$$\Delta P(t) = f(k, t_1, t_2, t_3, t_4, f_{\text{min}})$$

Fig. 1 illustrates representative control signals added to the power set point of the turbine. The actual response delivered to the grid includes an energy recovery, once the set-point offset returns to zero, as a result of the turbine tracking back to optimal aerodynamic efficiency.

While it has been shown elsewhere that incorporating wind generation emulated inertial controls can indeed improve the frequency nadir of a power system following a contingency event [5], the full impact on the system response has not yet been fully explored. Many current design proposals focus on maximising the magnitude of the emulated inertial response from wind generation to a system imbalance. However, the system demand requirement and the overall generation portfolio vary greatly from system to system. Hence, the requirements for a frequency response from wind generation may well vary with different systems. In [13] and [14] it is shown that a ‘one size fits all’ approach may not be appropriate when designing wind turbine control structures and while the technology exists for wind generation to contribute to the frequency responsiveness of the system, an overly aggressive response could potentially hinder the response to a contingency event, such as the loss of the largest generating unit or of the largest load/outfeed. Understanding the individual requirements of different systems and how these may vary with demand and wind penetration levels is vital for future system operation, and is of particular interest in the development of market mechanisms and incentive schemes for ancillary services from variable generation sources in the coming years.
III. SYSTEM MODELLING

Three distinct test systems are examined under varying wind and load conditions. Dynamic models, developed using Matlab and Simulink, have been used to represent the dynamics of the three systems. The models incorporate conventional generation, comprising steam and CCGT generators, as well as fixed speed and variable speed wind generation, with and without emulated inertial controls, for both control approaches outlined in the previous section, as illustrated in Fig. 2. Static sources of reserve are not included here in order to facilitate transparency in the investigation of the optimal response required from wind turbines and the impact of employing sub-optimal controls.

In each simulation, the system is dispatched according to the system size, load, wind generation, and reserve levels. The parameters which are responsible for the shaping of the inertial response control loop are optimised. While in reality all turbines across the system will see different wind conditions and thus operate at various different operating levels, for clarity, this analysis assumes minimum variation between the output of turbines and only two operating conditions are considered: operation at wind speeds of 8 m/s and 11 m/s. The cost function being minimised, C, is the difference between nominal frequency and the nadir as described in Equation 3.

\[ C = F_{\text{nominal}} - \min (f) \]  

where \( F_{\text{nominal}} \) is the nominal frequency of the system, and in these simulations the pre-disturbance frequency, and \( f \) is the vector of the system frequency samples following a contingency event.

IV. RESPONSE OPTIMISATION

The emulated inertial response from wind generation on each of the three systems, under varying wind penetration and reserve levels was optimised, for the loss of the largest single infeed. This section illustrates the importance of choosing appropriate tuning parameters in both the proportional and fixed response approaches.

A. Wind penetration level

Fig. 3 illustrates the frequency trace following the loss of the largest infeed on System C, the large system, under high wind penetration levels (75%), incorporating a proportional response. In addition to the wind response from optimised controls for this scenario and the resulting frequency trace, the traces resulting from the implementation of optimal parameters for low and medium wind penetration levels were also employed. The optimisation function, in its attempt to improve the frequency nadir, tends to increase the response from wind generation up to the point that increasing the initial injection any further would cause a recovery which would result in the subsequent frequency nadir being lower than the initial frequency dip. For the lower wind penetration
cases, it is assumed that fewer wind turbines are contributing to the response. Consequently, each individual turbine can provide a larger response without imposing a damaging energy recovery on the system. If, however, as shown here the parameters tuned for a lower wind penetration level are applied to the high wind scenario, the larger response from wind results in a second dip in the system frequency, lower than the original nadir.

![Graph showing frequency vs. time for different wind penetration levels.](image)

Fig. 3 System C, 75% wind penetration, tested with 50% and 25% wind penetration parameter sets

In Fig. 4 the response of System A, the small system, under high wind conditions, employing the proportional control parameters for high medium and low wind penetration levels, is illustrated. On smaller systems, with lower levels of synchronous inertia the frequency experiences greater variability due to the wind response. As the optimisation function attempts to improve the overall nadir, without concern for the response settling time, the optimal response is found when the energy recovery of the emulated wind response results in a second frequency dip reaching the same level as the original nadir, determined by the initial power injection from wind, as illustrated in the base case in Fig. 4. This ‘see-saw’ effect in the balancing of the optimal wind response follows since if wind gives less energy than the optimal, the frequency recovers more quickly but at the cost of a lower initial nadir. If the response is tuned to give more energy than the optimal, the initial nadir is improved but at the expense of a more severe second dip in frequency. It should be noted that while the frequency nadir objective function is considered here, optimisation of the time to return to steady state would result in different results. If instead, the optimisation objective was modified to consider the settling time of the response it could be expected that a smaller inertial response would be requested, such that the system frequency falls further but recovers more quickly. As illustrated in Fig. 4, due to the lower inertia levels, inappropriate tuning of the wind controls at such high wind penetration levels may result in a significant second dip in frequency.

In addition to the system-wide wind penetration level, however, the distribution of power across all wind turbines can also impact the optimal controls. Fig. 4 also includes the response of the system at high wind levels if wind controls were tuned assuming all turbines saw a wind speed of 8 m/s, instead of the 11 m/s they actually experience. In order for wind turbines at a lower operating condition to contribute the same overall wind power, more turbines must be online and therefore capable of contributing to the response. When more wind turbines are contributing to the emulated inertial response the resulting energy recovery period is more significant and so the optimal response in this case is smaller than when fewer turbines operate at a higher level. When the detuned controls are applied to the system with turbines operating at 11 m/s wind speeds, the frequency nadir drops marginally lower (49.48 Hz compared to 49.52 Hz) and recovers faster, as would be expected. This response highlights the importance of carefully choosing the objective function for the optimisation of the system frequency response. While the nadir is improved in the base (11 m/s) case, the response resulting from the sub-optimal 8 m/s gains recovers faster and so may be preferred on some systems. While in reality the distribution of wind turbine operating conditions is far more complex than two distinct operating points, this methodology demonstrates that the operating conditions of turbines is an important parameter when optimising the response from wind.

![Graph showing frequency vs. time for different wind penetration levels.](image)

Fig. 4 System A, 75% wind penetration, tested with 50% and 25% wind penetration parameter sets

B. Reserve level

While the previous analysis assumes that each system is dispatched with sufficient reserve to just cover the loss of the largest infeed, with increased variability and uncertainty the exact level of headroom available from dispatched units may be more or less than originally scheduled. Fig. 5 illustrates the frequency response if the reserve level on System B, with 50% wind penetration, is depleted to 90% of the largest infeed, with wind response parameters optimised assuming a minimum reserve requirement of 100% of the largest infeed.

![Graph showing frequency vs. time for different wind penetration levels.](image)

Fig. 5 Optimised for System B, 50% wind penetration level, reserve to cover 100% of largest infeed, tested with controls for 100% & 90% of largest infeed in reserve
It can be seen that if less reserve is available following a contingency event, the energy recovery from wind generation causes a more significant second dip in the frequency. Depending on the system conditions, such a slow recovery of frequency could leave a system more vulnerable to subsequent imbalances before it recovers to steady state.

C. System size

In addition to variations in the proportion of wind and conventional plant on a system, the system size and the relative size of the largest infeed also have implications for the optimal shape of the frequency response from wind generation. In Fig. 6, the response of System C to the loss of the largest infeed with 50% wind penetration level and with WTGs operating at a wind speed of 11 m/s is shown. In addition to the base case, in which the control parameters are optimised for this particular system and scenario, the response of the system employing controls optimised for Systems A and B, under the same relative system conditions, are also included. Lower inertia levels on the two smaller systems means that the frequency response on these systems experiences faster and larger variations than on the large system, similar to the ‘see-saw’ effect illustrated in Fig. 4. As a result, the difference between the nadir and the steady-state frequency is higher, allowing for an enhanced wind response and subsequent larger energy recovery from wind, without causing a second frequency dip larger than the original. So, when the optimal controls from Systems A and B are applied to the larger system while the initial frequency nadir is improved the frequency experiences a deeper second dip.

D. Fixed ΔP response

A number of design proposals for wind turbine control schemes have involved the injection of a fixed increase of power, independent of the magnitude of the frequency deviation. Fig. 7 illustrates the response of System A, under medium wind penetration conditions, with wind turbines operating at 11 m/s, with proportional controls optimised for the system, as well as with a fixed ΔP control, optimised for the loss of the largest infeed. In the case of the loss of the largest infeed, both responses, though distinct, are comparable in performance, since both represent optimised controls for that particular event. In this case, a fixed response holds the advantage of predictability of the stresses on the machine, compared to the proportional response which can only be identified after the event. If however, the System A experiences the loss of 100 MW instead of 400 MW, the proportional response results in a faster recovery of the system frequency, while the fixed response, which is independent of the system frequency results in a temporary over-frequency followed by a deeper nadir. While both control approaches can be optimised for the system condition, the actual size of the contingency cannot be forecast. If controls are optimised for a large contingency but a smaller infeed is lost, a fixed response from wind could lead to a deeper frequency excursion than a proportional control.

V. DISCUSSION

Tuning frequency responsive controls from wind plants, such as emulated inertial control, is likely to play a key role in the frequency responsiveness of future power systems with high wind penetration levels. While it may seem intuitive that a large emulated inertial response from wind generation is most desirable, the results presented demonstrate that this may not always be the case. At low wind penetration levels, which many systems currently experience, the overall impact of the wind response on the power balance of the system is low. However, at high wind penetration levels the shape of such responses will impact the frequency transient, directly.

In this analysis it is assumed that the optimal frequency response of the system is that which obtains the highest nadir. In small systems, with low inertia levels, this objective function results in a clearly defined double dip in frequency, as the system begins to recover before the system experiences a further imbalance due to the energy recovery of the wind turbines. Individual system operators may choose to place higher importance on different elements of a frequency characteristic, such as the initial rate of change of system frequency or the time to return to steady state, which further compounds the need for bespoke optimisation of the wind generation response. This cost function may be adapted as grid operators become more familiar with the impact of such wind controls on the power system and lay down requirements for operation.

These findings have implications for the development of ancillary services markets or grid code requirements.
Differences between the emulated inertial response from wind plant and the frequency response of conventional plant must be recognised if market mechanisms and incentive schemes are to be designed appropriately and secure system operation is to be maintained. It is vital that the true nature of the response from wind generation, including the energy recovery period is considered, so as to avoid incentivising a large initial injection of energy from wind plant to maximise revenue at the expense of the recovery of the system. It is clear that a recognition of the interaction between the response from wind generation and that from conventional generation is crucial in ensuring an acceptable frequency transient following an imbalance. Consequently, an holistic system-wide approach is vital in the determination of the optimal response from various contributors to the system frequency response. System operators must ensure that the manner in which energy is delivered from wind turbines is appropriately optimised as a function of system demand, wind penetration level, geographical wind distribution and reserve level.

This paper suggests that the control parameters of the response from wind should be tuned depending on the operating conditions of the system. However, it is impractical for these control parameters to change with each short-term variation in system conditions. Further work will investigate the potential for the development of a robust portfolio of system modes with corresponding control parameter scheduling strategies for wind generation response, in order to inform operators and planners in how best to incentivise wind flexibility.

VI. CONCLUSION

If wind turbines are either incentivised or required through grid codes to provide an emulated inertial response on systems with high wind penetration levels, appropriate tuning of such a response is vital for the secure operation of the system. While past power system operation may be viewed as a well established art, prudent system operators must recognise that incorporating frequency responsiveness from variable sources such as wind generation will change the nature of the response of the system and so must be treated differently. This analysis highlights the need for bespoke optimisation of frequency responsive controls on systems incorporating emulated inertia from wind turbines depending on the system wind, load and reserve levels, and illustrates some of the specific considerations which should be made in evaluating such requirements. It is important that due diligence is exercised by TSOs as systems evolve to incorporate frequency response capabilities which have not yet been experienced at scale. The manner in which these capabilities can best contribute to the system should be considered in detail before structures to incentivise such capabilities are implemented.

ACKNOWLEDGMENTS

This work was conducted in the Electricity Research Centre, University College Dublin, which is supported by Atricity, Bord Gáis, Bord na Móna, Commission for Energy Regulation, Cylon, EirGrid, EPRI, Electricity Supply Board (ESB) Networks, ESB Energy Solutions, ESB Energy International, Siemens, Gaelectric, SSE Renewables, SWS and Viridian. This publication has emanated from research conducted with the financial support of Science Foundation Ireland under grant number 09/IN.1/I2608.

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BIOGRAPHIES

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