Frequency Controlling Wind Power Modeling of Control Strategies

Mats Wang-Hansen, Robert Josefsson, and Haris Mehmedovic

***Abstract*—Conventionally operated full power converter wind plants show high short-term power output variability caused by variable winds, and does not contribute to the power system inertia due to the decoupled generator speed and grid frequency. There is, however, abundant inertial resources in wind plant rotors for both smoothing of output power and for synthetic inertia contribution. Together with added frequency controlling functionality, this could facilitate inclusion of wind power in islanding systems, enabling greater system loads and enhancing power system stability. This paper describes modeling of power smoothing and frequency controlling wind plants and assesses different control strategies as well as the grid frequency performance gains achievable over hydro powered islanding systems and over islanding systems incorporating both hydro power and conventional wind plants. The results show that wind plant power output could be smoothed in the short time frame, and support frequency in both primary and secondary frequency control timescales including droop functionality.**

***Index Terms*—Frequency control, FPCWT, inertia, PMSG, power smoothing, primary frequency control, wind power.**

I. INTRODUCTION

YEAR-END 2012 Sweden had 4-GW wind power, 1.5-GW gas fired power, 6-GW thermal, 9-GW nuclear, and 17 GW of hydropower installed capacity. Sweden's all-time high load is 27 GW and the typically light summer loads are in the range of 9–14 GW [1]. A power system area ending up in island operation will, therefore, most likely incorporate a large share of wind power. When in island operation, a power system is sensitive to disturbance and prone to frequency variation. Present grid operator practice for islanding grids in Sweden is, due to the frequency stability concern, to shut down wind plants until the islanded part of the grid is reconnected with the Nordic grid. As wind plant controllers have become more sophisticated, the role of wind plants in island operation could be reevaluated. Wind plants with added control functionality may both be included in islanding operation and also aid system stability through participation in primary and secondary frequency control and through inertia contribution.

Conventional wind plant operation is based on optimization towards maximum energy recovery, an operation mode known as *maximum power point tracking*, or MPPT mode. Operation with other objectives, foremost with the aim of obtaining frequency supportive performance, has been investigated for some years [2]–[4]. Most studies focusing on frequency support use fictitious wind time series for simulation input, which create artificially stable initial conditions. Measured high resolution time series as wind input would be preferred to obtain realistic initial conditions predisturbance and realistic recovery phases postdisturbance. Studied power systems are also usually fictitious and rarely include a realistically sized islanding system including other generators with authentic parameterization.

Two different ways of maintaining a primary power reserve to enable upward power regulation have been established in the literature, namely the delta control and balance control [3], but they are not clearly defined and thoroughly explained. Power ramp rate control is another advanced control mode mentioned, but only positive ramp rates during increasing winds are considered and no related ramp rate regulation is imposed during decreasing winds. The reasoning is that it is impossible to extract more energy than available in the wind at any given time. At the same time it is reported that inertia contribution is possible [2], [5], which is essentially nothing less than an over-outtake of power for a limited amount of time, and thereby somewhat contradictory to the available energy extraction limit argument. Continuous use of wind plant rotors as flywheels to smoothen output power is little examined although the pilot wind/hydrogen islanding grid in [8] has shown good use of external flywheel for power smoothing. Frequency support is mostly investigated under circumstances of external disturbances and the focus lies primarily on inertial response. The wind plants' own destabilizing effect on the islanding frequency through fluctuating power output is little examined and alternative speed and pitch control algorithms to smooth output power is also little examined, and few discuss the cofunctionality between frequency controlling wind power and other generation sources participating in primary frequency control.

The contribution of this paper lies primarily in the modeling of the combined power smoothing and frequency control for wind plants simulated with authentic wind series in an authentic islanding grid incorporating hydro plants. Further, the considerations behind various types of wind plant control are assessed and the different parts of the controllers and their contributions to the overall control performance are quantified and discussed. Finally, the tradeoff between smooth regulation on wind-induced frequency variations and transient frequency response is thoroughly examined.

The objective of the study is to compare conventionally operated wind plants with frequency controlling wind plants and to

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quantify and review the frequency stability improvements that could be achieved by deploying such modified wind plants in islanded power systems.

II. MODELING

A. Approach

To allow for good representation of a real case study, authentic wind series selected from more than one year of 1-s sampled wind measurements were used as simulation input data. A statistical analysis of the wind data singled out wind series representative for normal and for extreme wind conditions with regards to rapid and sustained change in wind strength, resembling step change in wind strength.

The controller design was developed to meet multiple objectives as there are two separate challenges that have to be addressed in order to successfully integrate wind plants into islanded power systems, and they are 1) smoothing of output power, and 2) response to external frequency disturbances. The former require a slow and steady control of output power, while the latter require a very fast and sizeable control of output power. They are contradicting objectives that have to be coordinated in an efficient way.

B. Case Study

The case study power system is an authentic regional islanding system in Sweden consisting of 240-MW installed hydropower capacity in a 130-kV grid with 204-MW static load. The modeled wind plant size of 60 MW is comparable to the current installed capacity in the system and 120 MW is a reasonable future prognosis.

C. Hydro Plants

The hydropower generator models are classic one-mass synchronous generators incorporating governor and voltage control with parameter settings (see Table I) from measured values in actual hydropower plants from the case study system. All hydropower plants included in the model participate in primary frequency control with droop settings of 4.5%.

D. Wind Plants

The wind plants are classic one-mass synchronous generator models combined with turbine models for the rotor and aerodynamic energy, converter models for the back-to-back converters and dc-link, and speed and pitch controller models controlling the power order and the blade pitch system. The wind plant model cluster together forms a representation of a full power converter turbine with variable speed and pitch control. The majority of the simulations were run with the 60-MW model, and complementary simulations were run with the 120-MW model. Both models are aggregated lumped parameter models (see Table II) with one turbine representing the whole wind plant.

TABLE I
HYDRO PLANT PARAMETERS

Unit	**Parameters**		
	Rated capacity (MVA)	***Inertia (MWs/MVA)***	***Droop R (%)***
Hydro Bravo 1	25	2.04	4.5
Hydro Bravo 2	26	2.50	4.5
Hydro Charlie 1	27	2.25	4.5
Hydro Charlie 2	27	2.25	4.5
Hydro Echo 1	90	3.05	4.5
Hydro Echo 2	90	3.05	4.5

TABLE II
WIND PLANT PARAMETERS

Unit	**Parameters**	
	Rated capacity (MVA)	***Inertia (MWs/MVA)***
Wind plant 1	60	7.1
Wind plant 2	120	7.1

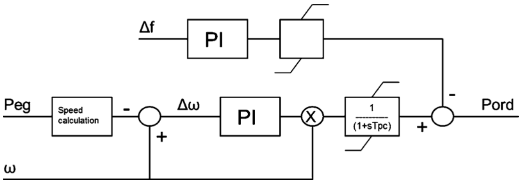


Fig. 1. Modified speed-controller with input signals Δf-frequency deviation, Peg-generated power, and ω-wind turbine rotor speed and output signal Pord which is the power order to the converter.

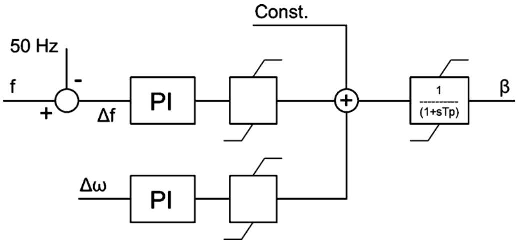


Fig. 2. Modified pitch controller with input signals f-frequency and $\Delta\omega$-wind turbine rotor speed, a constant for pitch offset and output signal β which is the pitch angle of the blades.

E. Wind Time Series

The wind time series used in the 60- and 120-MW plant models corresponds to the size of the wind plant. “Normal wind” constitutes the median wind variations during a year and “Extreme wind” constitutes the worst case variations during a year.

F. Wind Plant Controllers

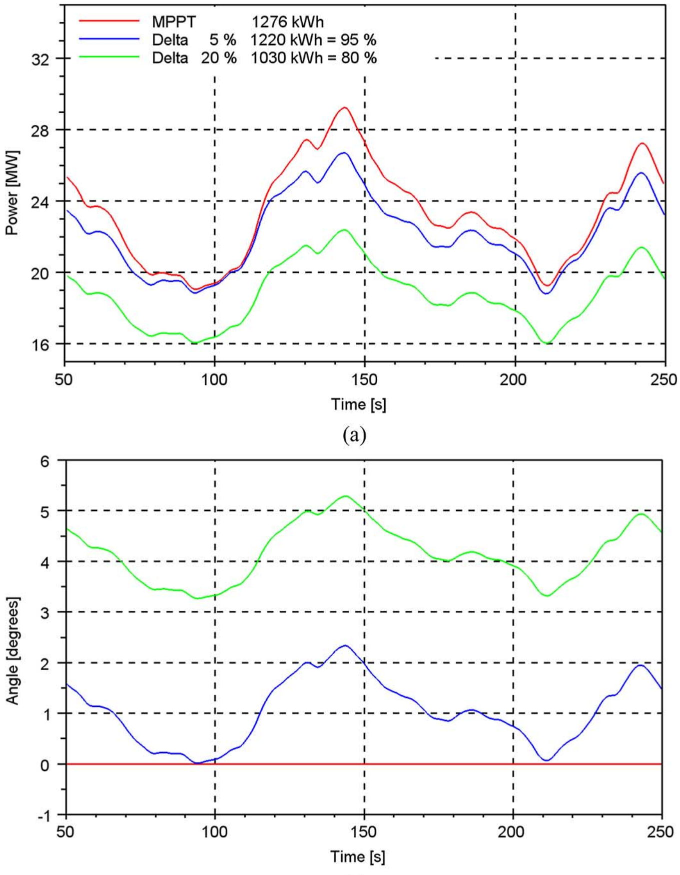
There are two separate controllers, the speed controller shown in Fig. 1 and the pitch controller shown in Fig. 2.

1) Speed Controller: A decisive feature of the speed controller is the addition of the frequency signal after the original power order has been computed. In this way, the low pass power order filter ensures a steady power output during normal circumstances but does not obstruct fast response from the controller when grid disturbances occur. The controller design with low pass power order filtration removes rapid power changes and instead injects or subtracts kinetic energy to or from the rotor. One challenge of this strategy is the potential of braking the turbine rotor to a full stop when it is already under-speeded at the onset of a frequency disturbance. Rapidly decaying winds could cause such an initial condition. Implementation of a linear weighting of the frequency signal from 1 at full speed to 0 at 40% speed solves this problem, but at the same time also removes frequency responsive behavior below 6% power output which is the power output at 40% speed. The speed curve is a second-degree polynomial of speed as a function of power, injective from 0 to 1 p.u. produced power. This curve could have been shifted towards higher speed for delta pitch angles, but is kept identical to that of 0° pitch for simplicity. There is also an inherent power smoothing effect of operating with a lower than optimal λ in delta mode. Decreasing winds temporarily increase λ towards the optimal value and thereby increase Cp, and increasing winds temporarily decrease λ and thereby Cp, which means that the power output will be smoother than with initial operation at optimal lambda. The downside is that the recovery time after load steps will be longer due to the lower prefault speed and thus a resulting lower postfault speed and lower λ which together cater for less aerodynamic lift to speed up the plant.

a) PD versus P Controller: A proportional derivative (PD) controller is the only way to ensure that the inertial contribution of the wind plant is similar to that of a conventional generator, through the implementation of a regulation on df/dt as in [2] and [10]. The inclusion of a derivative part in the controller has the drawback of instable behavior and it does not contribute to the droop-like load sharing characteristics. Further, it introduces transient torques harmful for the relatively soft drivetrains [6] of wind plants. The model choice of this paper is, therefore, the pure proportional (P) controller.

2) Pitch Controller: The pitch controller utilizes an identical frequency controller as that of the speed controller, but the parameterization is different, aiming at fast pitching response for small frequency errors. The desired functionality is an aggressive pitch controller that reaches early the maximum allowable pitch rate, 5° per second, facilitating quick changes in captured power. The pitch controller also holds the key function of the delta control as it is in the pitch that the blade degree offset is introduced in the form of a constant addition to the normal pitch signal.

a) Delta Control: The idea of delta control is to introduce a steady power offset compared to the available wind energy at any given time. This idea sounds simple but is impossible to implement accurately since a wind plant never knows the momentary wind speed and thus cannot know how much energy is available. The available energy calculation is qualified guessing based on rotational speed, torque, and assumed power coefficient (Cp); e.g., if the wind plant produces 0.5 p.u. power and the blades are pitched 5° and the Cp assumption is 0.40, the plant guesses that it could produce at optimal $\mathrm{Cp} = 0.50$ and that the power delta, therefore, is 20%. This guess is right as long as the rotational speed is in fact optimal, but slightly erroneous when wind conditions are rapidly varying. If the rotational speed deviates significantly from the optimization speed, the guess becomes poor since the Cp value assumed is not the one actually in effect. A reasonable approximation to the idea of a steady power delta is, however, as explained above to increase the blade pitch angle by a firm degree offset and reduce the Cp value with a certain percentage at optimal tip speed ratio (λ).



(a)

(b)

Fig. 3. Delta mode in normal wind, (a) power and (b) pitch angle.

Other speeds than optimal will occur once the wind plant participate in primary frequency control and the comparison of actual power to any available power during frequency controlling action then becomes ambiguous. The chosen delta strategy of this paper is called variable delta as its base angle is a firm offset in the pitch controller, but at the same time it performs pitching action on speed changes of the turbine. The result is a delta which is smaller when the wind decreases and larger when the wind increases, making for a smoother and more steady power output.

III. Results and Discussion

It can be seen in Fig. 3(b) that the pitch delta of the model is variable, changing between 3° and 5.5° for 20% energy delta and changing between 0° and 2.5° for 5% energy delta. It is worth noticing that the pitch controller behaves in the exact same way only with a level offset for the two delta levels, meaning that the speed-part of the pitch controller gives the same output with both delta levels. The conventionally operated *maximum power point tracking* (MPPT)—mode is steady at 0° pitch.

A. Frequency Control Strategies

Interestingly, the power patterns for the frequency controlled wind plant in Fig. 4, shows that the low pass filtered power output even works well without a delta. However, it is also clear that the production is situated at a much more stable level with both 5% and 20% delta. As long as the wind variations

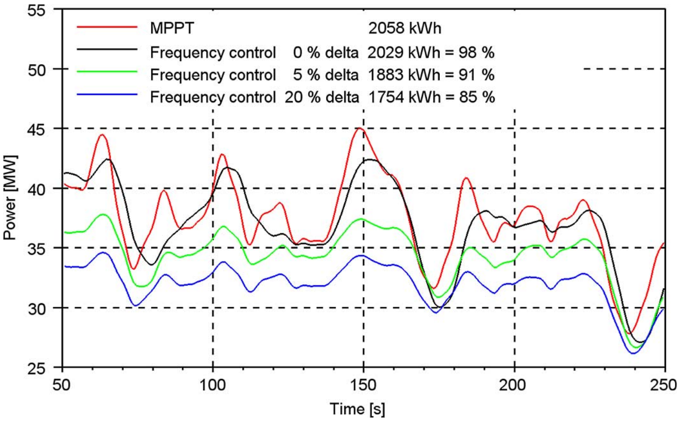
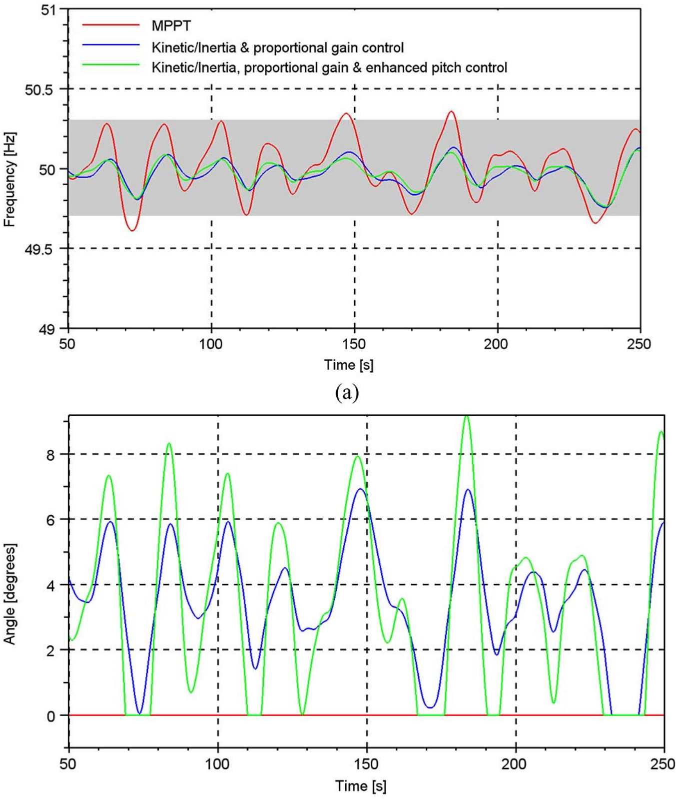


Fig. 4. Power and energy yield for different delta levels with a 60-MW frequency controlling wind plant and extreme wind.



(a)

(b)

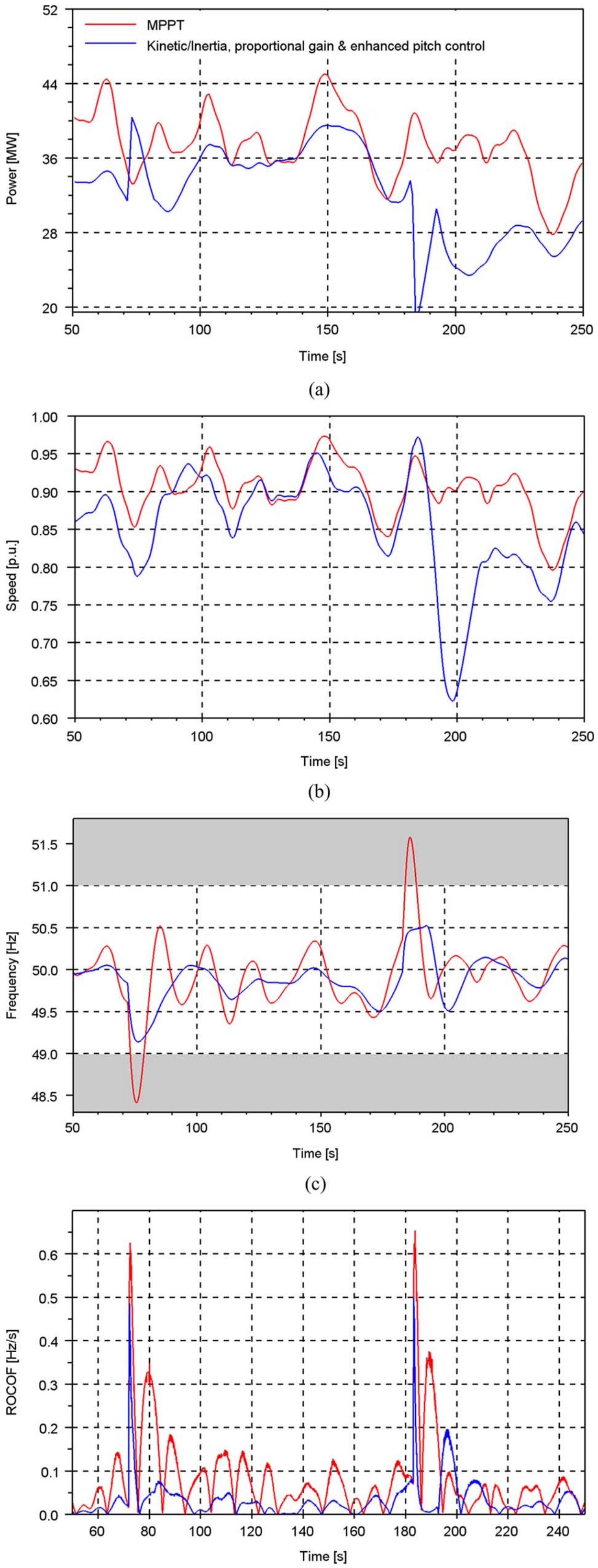
Fig. 5. (a) Frequency and (b) pitch angle. Controller mode comparison with a 60-MW frequency controlling wind plant, extreme wind conditions, and 20% delta.

are not more challenging, it seems that 5% delta is sufficient to smooth production, which corresponds well with the findings in [2]. Fig. 5(a) shows the difference in frequency performance between the two controlling strategies Kinetic/Inertia & Proportional gain (KIP)-control and the Kinetic/Inertia, Proportional gain & Enhanced Pitch (KIPEP)-control. The difference is small, but the KIPEP is slightly faster, arresting frequency excursions earlier. The maximum frequency deviations are reduced with more than 50% compared to the MPPT-mode with both strategies and Fig. 5(b) shows that the KIPEP-controller increases the pitching activity significantly compared to the KIP-controller. The average pitch angle is around 4° in both frequency controlling cases, whereas it is 0° in MPPT-mode.

B. Load Step Response

All simulations with load steps were carried out with 20% delta. The load steps were induced at the worst instants possible in the 60-MW extreme wind scenario. Load connection was done at a point of rapidly decreasing wind and load shedding was done at a point of rapidly increasing wind. This approach should ensure that the frequency results presented are achievable no matter the wind conditions. When load steps are induced, the frequency controlling wind plant shows a distinct response with sharp linear power ramps both during load connection and load shedding, as seen in Fig. 6(a). The power output differs from the normal pattern under periods of 10–15 s, and after load increase a recovery period of equal duration is seen when the wind plant produces less power than normal to get up to speed and restore the kinetic energy reserve. The amplitude of the power injection is 8 MW or 0.13 p.u., and the rise time is 1, 6 s which gives a power ramp of approximately 5 MW/s, or 0.08 p.u./s., which agrees well with the findings of [5] and [9]. The maximum rate of change of frequency (ROCOF) shown in Fig. 6(d), is reduced by 22% from 0.62 to 0.48 Hz/s with frequency controlling wind power. And the duration of a ROCOF above 0.3 Hz/s is reduced from 1.9 to 0.8 s for load connection and 2.1 to 0.6 s for load disconnection. The speed as shown in Fig. 6(b) is lower during the course of the simulation and decreases as expected when additional power is delivered as kinetic/inertia response after load connection at $t = 72$ s. The speed dive is, however, not particularly deep and only lasts for about 15 s. Fig. 7 shows that maximum frequency deviations are reduced from ±1 Hz to less than ±0.5 Hz with the 120-MW wind plant, and that the wind induced frequency variations almost disappear. The maximum ROCOF is reduced from 0.65 to 0.40 Hz/s and the duration of an ROCOF above 0.30 Hz/s is reduced from 3.9 to 0.25 s for load connection and from 1.5 to 0.20 s for load disconnection. Fig. 8 shows that there is a difference in the load step response between the two controlling strategies. The KIP controller contributes with equal power as the KIPEP initially, but the contribution of the KIP declines during the first 50 s of the increased load period, whereas the KIPEP stays at its initial contribution level for the duration of the increased load period. The droop-like response is, therefore, stronger with the KIPEP controller. The power output rise time is similar for both strategies at 11 MW/s which is close to 10% of rated power per second.

The comparison in Fig. 9 show that frequency stability improves with more added wind power in the system. The frequency excursion is arrested earlier in both wind/hydro-scenarios and postfault frequency oscillations are substantially reduced. The frequency droop is also smaller, most clearly seen in the 120-MW case where the steady state average frequency deviation is approximately half that in the pure hydro case. The halved droop is natural considering the halved additional load served by the hydro plants, reduced from 24 to 12 MW. This also shows that the 120-MW wind plant increases its output with 10% (12 MW) and that the hydro plant increases its output by 5% (12 MW) for the same steady state frequency deviation,



(a)

(b)

(c)

(d)

Fig. 6. (a) Power, (b) speed, (c) frequency, and (d) ROCOF in a 60-MW extreme wind scenario, with 24-MW load connection at $t = 72$ s and 24-MW load disconnection at $t = 183$ s.

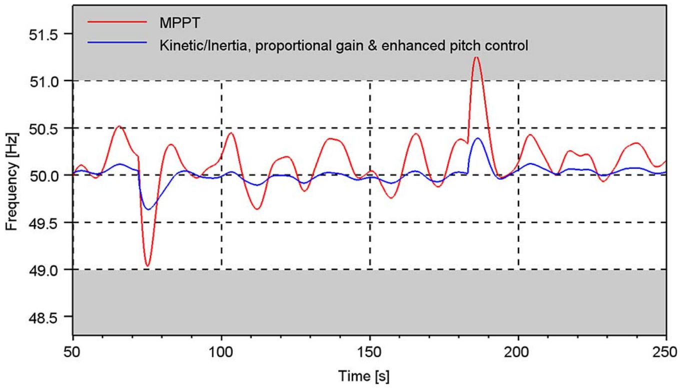


Fig. 7. Frequency response, comparison between 120-MW MPPT and 120-MW KIPEP frequency controlled wind plant, extreme wind.

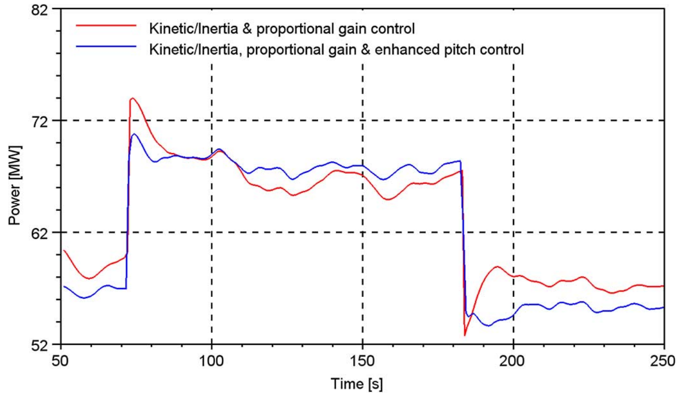


Fig. 8. Power at 24-MW load step, comparison between 120-MW KIP and KIPEP-controlled plant in extreme wind conditions.

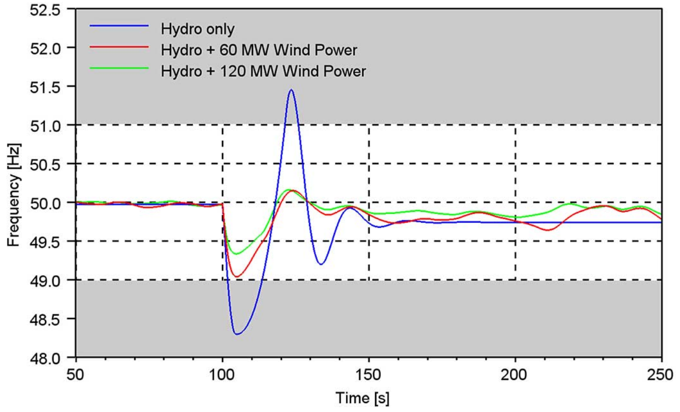


Fig. 9. Frequency response after 24-MW load step at $t = 100$ s. Comparison of hydro power only, hydro +60-MW KIPEP frequency controlling plant, and hydro +120-MW KIPEP frequency controlling plant in normal wind conditions.

which translated into a droop setting for the wind plant would be 2.25% or double the sensitivity of the hydro plant's 4.5%. There is, however, no explicit droop setting in the parameters of the wind plant controller; it is more a combined result of several different settings and the feedback function of the grid frequency. A pure straightforward droop setting is difficult to obtain in reality, mainly due to the effect that an increased power output has on the rotor speed of the wind plant. The increased steady state speed resulting from increased power output affects the MPPT calculation and thereby changes the base line power level that the droop-power term is added to. The theoretical additional power term is known, but it is complex to calculate how much offset on the MPPT calculation it creates in the process, and thereby to calculate the net outcome of the MPPT change and additional power term.

IV. CONCLUSION

The results show that islanding grid performance could be substantially improved through the inclusion of power smoothing and frequency controlling wind power. Further they show that the frequency stability gets better with more installed wind power, both regarding wind induced frequency variations and external disturbances such as load steps or loss of other generating units causing sudden change of load. The findings of this paper suggest that the control architecture in the wind plants be kept as simple as possible, involving only modifications of the algorithms in the speed controller and only introducing an offset in the pitch controller. No additional pitch controller modifications are necessary to achieve well-functioning control performance.

The hardware of the wind plant could be left as it is, but it is worth mentioning that while all results in this report is achieved deploying converter models with absolute current limits of 1.0 p.u., real life wind plants could achieve greater performance due to higher converter ratings. Five-percent power delta seems to be sufficient for control in most cases, but 20% delta ensures very good control performance and is, therefore, preferable from a system-stability perspective. It is also found that wind plants could be expected to participate in load sharing in a droop-like manner, resulting in less frequency droop after disturbance, and less risk of other generators hitting their maximum power outputs.

Continued frequency controlling capability after load connection in a droop-scenario demands a delta size large enough to accommodate a steady state power output increase without reducing the steady state pitch angle to zero. Five-degree pitch offset is in this model sufficient to achieve a delta size of 20%, sufficient for accommodation of normal and extreme wind changes as well as 10% load steps, which is Swedish National Grid's maximum allowable load step in island operation. It can also be concluded that the wind plants contribute to frequency stability both during normal and extreme wind conditions. When winds are close to the plant low cutout wind speed, the frequency support in the investigated model will no longer be active due to the speed weighting of the frequency signal which approaches zero. When winds are above rated wind speed, the maximum theoretical power injection is the difference between the current power level and full power rating of the converters, which means that a larger delta leaves room for a greater available power support.

Further, the results indicate that the manufacturer maximum blade pitch rate affects the frequency controlling performance and that excessive turbine over-speeding is not likely to be caused by frequency controlling activity as long as the blade pitch rate is larger or equal to the modeled 5° per second.

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