Fixed-Speed and Variable-Slip Wind Turbines Providing Spinning Reserves to the Grid

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Fixed-Speed and Variable-Slip Wind Turbines Providing Spinning Reserves to the Grid

Abstract—**As the level of wind penetration increases, wind turbine technology must move from merely generating power from wind to taking a role in supporting the bulk power system. Wind turbines should have the capability to provide inertial response and primary frequency (governor) response. Wind turbine generators with this capability can support the frequency stability of the grid. To provide governor response, wind turbines should be able to generate less power than the available wind power and hold the rest in reserve, ready to be accessed as needed. In this paper, we explore several ways to control wind turbine output to enable reserve-holding capability. The focus of this paper is on fixed-speed (also known as Type 1) and variable-slip (also known as Type 2) wind turbines.**

Index Terms—**wind turbine generator, variable speed, induction generator, governor response, inertial response, renewable energy.**

I. INTRODUCTION

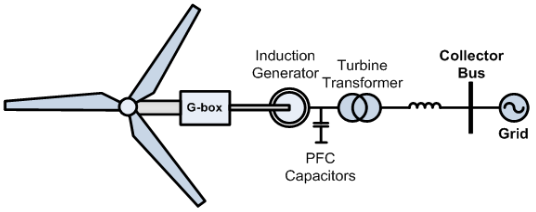
Wind power generation may reach 300 GW by 2030, achieving a level of penetration of 20% total energy production [1]. Recent advances in wind turbine technology allow efficient and rapid deployment of wind power plants (WPPs). As more WPPs are integrated into the bulk utility power system, the adverse effects of wind power uncertainty and variability on the power system are expected to become more noticeable. The issue of frequent and significant frequency excursions from nominal value is of particular concern, especially in a synchronous power system with high wind power penetration [2]. WPPs with fixed-speed (Type 1) wind turbines contribute to system frequency support because each wind turbine generator (WTG) is directly connected to the power grid. The material reported in [3–9] laid the groundwork for understanding inertia and frequency issues related to wind. The work reported here seeks to develop techniques to improve individual wind turbine response to frequency events. Individual wind turbine reserve-holding capability scales up to provide significant reserve-holding capability at the WPP level. Control modifications needed to operate WTGs with reserves are presented in this paper. Detailed simulations in the time domain have been conducted to demonstrate the efficacy of the proposed control modifications.

This paper is arranged as follows. Section II presents basic aerodynamic characteristics of wind turbines. The behavior of squirrel-cage induction generators (used in Type 1 wind turbines) and wound-rotor induction generators with external rotor resistance (used in Type 2 wind turbines) is explored based on steady-state characteristics. Section III describes dynamic simulations to investigate different scenarios applied to the WPP with the implementation of reserve power.

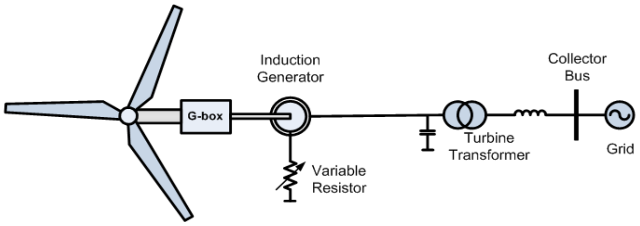
II. BASIC WIND TURBINE OPERATION

A. Type 1 and Type 2 Wind Turbine Generators (Induction Generators)

Different wind turbine types use different energy conversion systems (generator, power converter, and control algorithms). The strategies used to control the prime mover are generally similar. Common elements include mechanical brakes and blade pitch control to avoid a runaway condition and reduce stresses on the mechanical components of the wind turbine. For any wind turbine, a set of curves known as the C_P versus tip speed ratio (TSR) describes the aerodynamic characteristics of the wind turbine rotor. C_P is the performance coefficient—i.e., the proportion of power in the wind that is extractable. The TSR is the ratio of the speed of the tips of the blades to the incoming wind speed. An example of C_p versus TSR curves can be seen in Figure 2, which shows that an optimum TSR exists for each value of pitch. Consider the simplest type of wind turbine. This wind turbine has a stall-controlled induction generator without a pitch controller. The power limit is set by the aerodynamic stall instead of by the pitch control. The pitch angle can be considered zero.



(a) Type 1 WTG



(b) Type 2 WTG

Figure 1. Physical diagram of a (a) Type 1 and (b) Type 2 WTG

1) Stall-Operated Wind Turbine

The wind turbine is started as an induction motor as the wind speed reaches cut-in. The rotor speed is driven by the available wind and is driven above synchronous speed at a very small slip (1% at most). As the wind speed increases at constant rotational speed, the TSR decreases and the operating C_P travels along ABCD when the rated power is reached at the wind speed designed for the wind turbine. As the wind speed increases further, the operating C_P decreases further and the TSR gets even smaller.

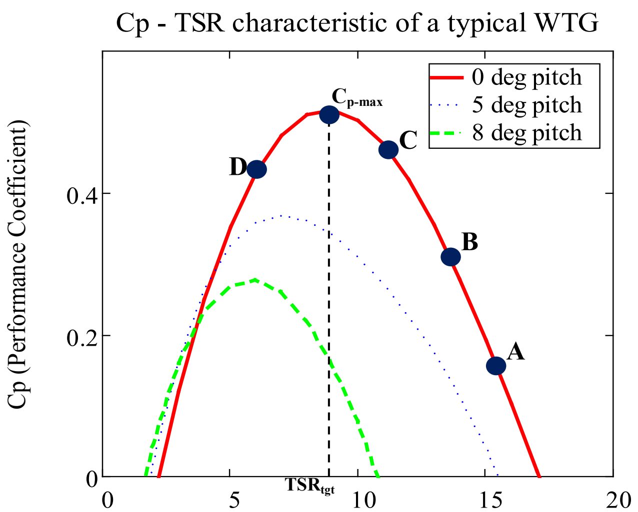


Figure 2. *C_P* versus tip speed ratio

2) *Pitch Control*

Modern wind turbines are equipped with pitch controllers to limit the aerodynamic power driving the generator. The blade pitch control is activated in the high wind speed region to limit the stresses imposed on the mechanical components, to limit the output power generated, and to avoid a runaway condition if the wind turbine loses connection to the grid. Limiting the aerodynamic torque driving the generator is important to ensure that the mechanical components of the turbine (gearbox, generator shaft, low-speed shaft, etc.) will not be stressed due to overloads caused by wind fluctuations and turbulence.

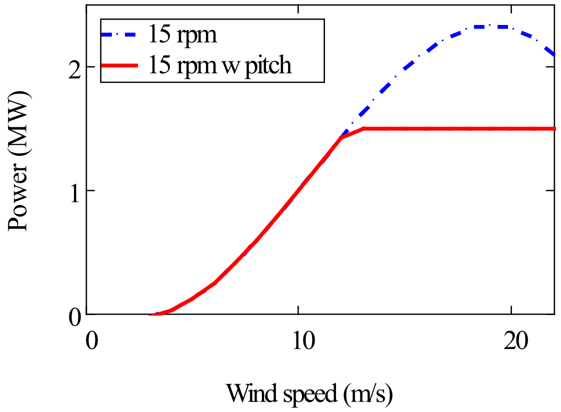


Figure 3. Output power limiting with pitch control

Figure 3 shows the power curve of a pitch-controlled fixed-speed wind turbine at 15 rpm. The mechanical components can be designed to withstand the power as limited by the pitch controller. In this case, the output of the wind turbine is limited to 1.5 MW. Figure 2 shows the effect of changing the pitch angle on the C_P-TSR curve. Increasing the pitch angle shrinks the C_P-TSR curve.

In Type 1 wind turbines, the power output is dictated by the characteristic of the induction generator. There is no power converter connected to the stator winding or the rotor winding. In Type 2 wind turbines, there is an external rotor resistance that can potentially be used to control the output power of the induction generator; however, using the rotor resistance control may result in additional losses. In the approach proposed in this paper, the pitch controller is used to allocate part of the available aerodynamic power as reserve power and the turbine delivers the remainder to the power system grid.

3) *Pitch Control to Allow Reserve Power Capability*

With the pitch controller, it is possible to operate wind turbines at different pitch angles (or scheduled pitch angles). This allows the WTG to set aside the reserve power to be called when needed—for example, when a large generator drops from the grid because of fault occurring in the transmission lines, the reserved power may be called to substitute the loss of generated power; thus, the power system frequency will not drop significantly.

Figure 4 shows an example of a WTG operating at a reduced output power. The operation follows the path **ABCDE**. The shaded area represents the reserve power available that can be retrieved. The disadvantage of this algorithm is that during productive winds, the output power has to be shed; thus, there is some productivity loss.

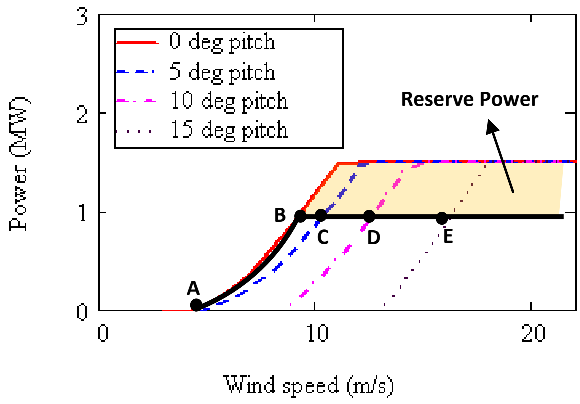


Figure 4. Scheduled reserve power with pitch controller

4) *Type 1 Wind Turbine Generator—Power Speed Characteristic*

Type 1 WTGs use squirrel-cage induction generators and operate in a very narrow slip range (about 1% rated slip). The real power versus the rotational speed is shown in Figure 4. Both the power and the rotor speed are given in per-unit quantities. The output current versus the rotational speed is given in Figure 5. Note that the induction generator is always absorbing reactive power from the line; thus, reactive compensation is usually implemented by switched capacitor banks, and the size of the capacitance is controlled so that the wind turbine generates power at unity power factor.

As shown in Figure 4, the normal operating point at rated wind speed is at point A, where the output power is at 1.0 per unit. The aerodynamic power driving the generator fluctuates with wind speed; thus, the pitch is continuously controlled to limit the aerodynamic power developed by the blades, which also limits the aerodynamic torque driving the induction generator. Instantaneously, individual WTGs may generate more or less at 1.0 per unit with small variation (indicated by the two-sided arrow); however, the average power will always be limited to 1.0 per unit. At the point of interconnection, the average output from hundreds of wind turbines will smooth out to an almost flat output when the wind speed is at or higher than rated wind speed.

To allow power to be held in reserve, the wind turbine is operated with an output power set-point lower than what is actually available, e.g., at high wind speeds, the pitch can be controlled to generate 80% of rated power although it is capable of generating 100% of rated power. The operating point moves from A to B, as shown in Figure 4.

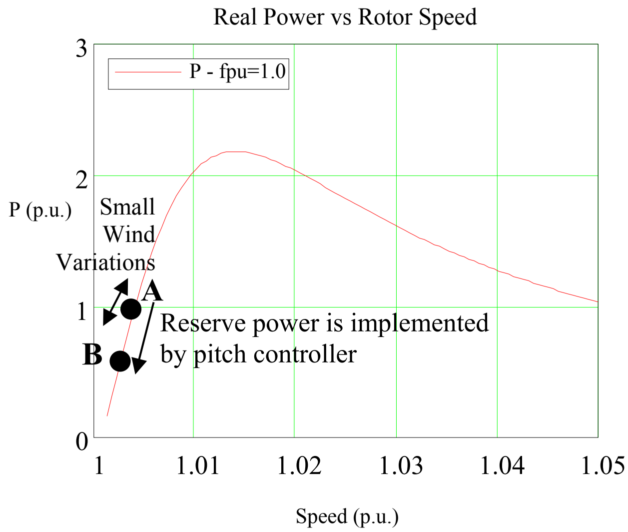


Figure 4. Output power versus rotor speed (Type 1 WTG)

5) Type 2 Wind Turbine Generator—Power Speed Characteristic

The Type 2 WTG uses a wound-rotor induction generator instead of the squirrel-cage generator as in the Type 1 WTG. The wound rotor is connected to an adjustable external rotor resistance.

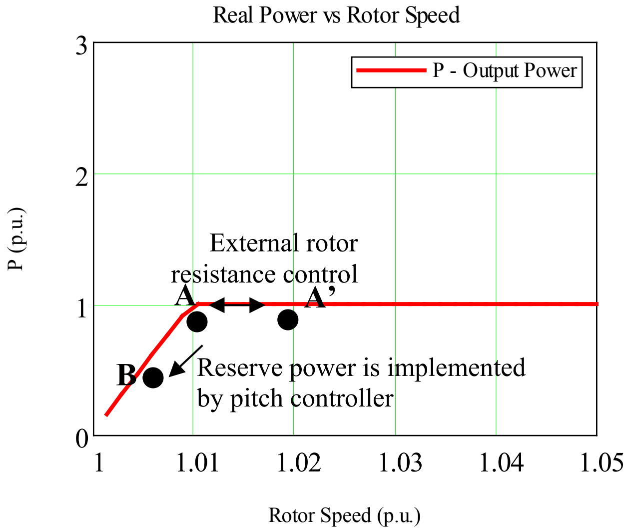


Figure 5. Output power versus rotor speed (Type 2 WTG)

Below rated wind speed, the external rotor resistance is shorted; thus, the behavior of a Type 2 WTG is the same as a Type 1 WTG when the wind speed is below its rated value. Above rated wind speed, the external rotor resistance is controlled to allow the effective rotor resistance to be varied to maintain the output power constant even as the wind speed varies; thus, although the wind speed changes, the external rotor resistance can be adjusted so that the output power stays constant. This is indicated by A and A' in Figure 5. The adjustable rotor resistance is implemented by using simple power electronics and resistors. Note that although the rotor resistance can be varied, in practice the pitch controller is still used to control the speed to minimize the external rotor resistance because deployment rotor resistance generates heat that must be dissipated. To minimize the heat generated, the pitch control is used. To allow power to be held in reserve, the wind turbine is operated with an output power set-point lower than available power as in the Type 1 WTG. The operating point moves from A to B, as illustrated in Figure 5.

6) Two Types of Reserve Power

Figure 6 shows a block diagram of the proposed controller for providing reserve-power capability. There are several groups of control blocks performing different functions. Block 1 computes the input to the pitch controller to limit the rotational speed at rated value when the wind speed is high to avoid a runaway condition.

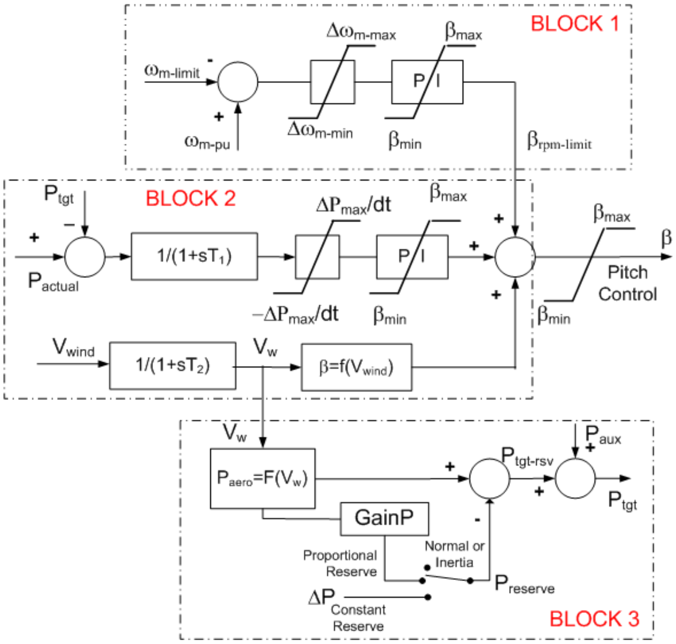


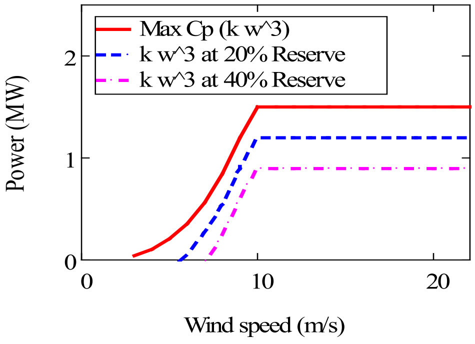
Figure 6. Pitch controller used to set reserve power for Type 1 and Type 2 wind turbines

Block 2 computes the input to the pitch controller to limit the average output power of the wind turbine based on the target power P_{tgt}. The target power P_{tgt} varies with wind speed and the level of reserved power defined. In Block 2 there are two paths used: one path uses wind speed as an input to provide a feed-forward value by pre-computing the steady-state values of the pitch angle under normal situations (without reserve power) with the help of a lookup table to map higher wind speeds versus blade pitch angle; the other path takes the commanded target power P_{tgt} as an input to control the desired output power, which may include controlling the reserve power below rated wind speed and limiting the rated power above rated wind speed. The P-I controller helps to fine-tune the power controller to follow the target power.

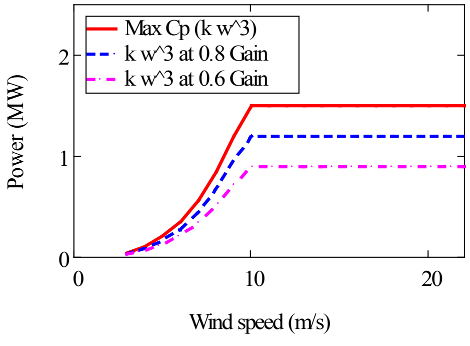
In Block 3, the target power is computed to guide the pitch controller in adjusting the output power from the WTG. The input to Block 3 is the filtered wind speed that is be translated to aerodynamic power using the power curve of the turbine (similar to the one shown by the solid line curve in Figure 3) via a lookup table. The output of the lookup table is the actual output of the turbine without accommodation for reserve power. Block 3 also has a provision for users to select the method for holding reserve. These methods are explained in the next subsection. If governor droop control to help the grid by decreasing or increasing the reserve power is implemented, the additional inputs from the droop control can be accounted for in the proposed controller via the auxiliary output power P_{aux}.

7) *Two Types of Reserve Power*

To set aside some reserve power, a constant value of reserve power (constant reserve - ΔP) or a constant proportion of the available aerodynamic power (proportional reserve—refer to the switch available in Block 3) may be selected. Figure 7 (a) shows wind turbine power curves if the reserve power to be held is a constant value (20% and 40% of *rated* power); Figure 7 (b) shows the power curves if the reserve power to be held is a constant percentage (20% and 40% of *target* power—i.e., maximum C_P operation).



(a) Constant ΔP



(b) Proportional reserve

Figure 7. The reserve power held using two different methods

III. DYNAMIC SIMULATION

The performance of the proposed controller was investigated through dynamic simulations. The induction generator is represented by typical fifth-order dynamic representation. Dynamic models were developed in PSCAD/EMTDC and tested using 150s of real wind speed data. In each case, the rated power of the wind turbine is 3 MW.

1) *Reserve Power Implementation*

Figure 8 shows the traces of output power and pitch angle for a Type 1 wind turbine. It also shows the traces for constant reserve operation. Comparison between normal operation and the operation with reserve is presented. In Figure 8, a constant reserve power is commanded (20% of rated power—i.e., 0.6 MW). The output power shows both the available wind power (blue line) and the output power with reserve power held (green line). The pitch angle is shown to vary at a slower rate than the wind speed variation. The pitch controller is slower than the power electronics controller when used to limit the output power; thus, only the average power is limited to the rated output power. As shown in Figure 8, there are times when the peak of the output power briefly exceeds the rated power (3 MW) of the wind turbine.

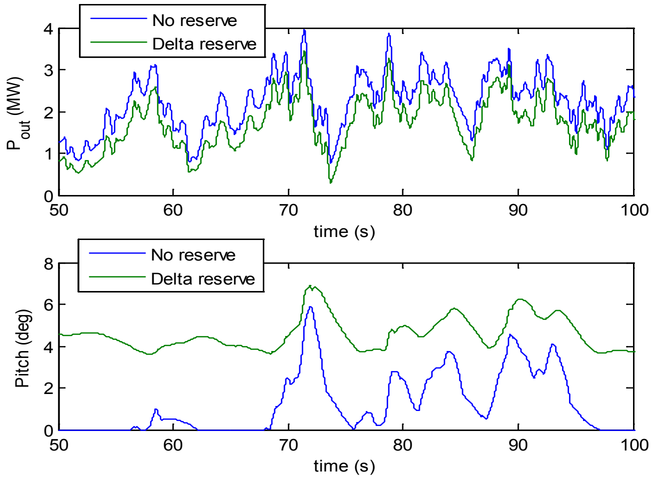


Figure 8. Output power and pitch angle for constant reserve power ($\Delta P_{reserve}$) implementation on a Type 1 wind turbine

As described previously, there is an external rotor resistance control that can be used in Type 2 wind turbines. In this implementation, the rotor resistance is used to limit the generator output current to a constant value, according to the percentage of the reserve power to be held. For example, if the reserve power to be held is 20% of *rated* power, the output current will be limited to 80% of rated current by controlling the external rotor resistance. Note that the rotor resistance control is much faster than the pitch controller; thus, the current regulation can be accomplished very effectively.

The effect of fast control of external resistance control can be shown by comparing the output power fluctuations between Type 1 wind turbines and Type 2 wind turbines, as shown in Figure 9. In Type 2 wind turbines, the power output is practically clamped at the maximum output power of the wind turbine, which is equal to the rated power (3 MW); whereas in Type 1 wind turbines, the output power sometimes exceeds the rated value of 3 MW.

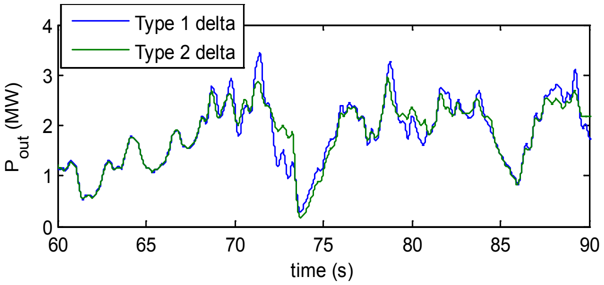


Figure 9. Output power comparison between the output power of a Type 1 wind turbine and a Type 2 wind turbine with $\Delta P_{reserve}$ = 20% of the rated power in time domain

The Type 2 WTG was simulated and the output was plotted against wind speed. Figure 10 and Figure 11 show the output power comparison between base case and the operation with reserved power. As expected, the actual output power was scattered. However, when we used the polynomial fitting of 7th order, the output power characteristic was similar to the one predicted in Figure 7. The scattered points can be accounted to the changes of the kinetic energy stored in the rotating mass (blades, generator, gearbox, etc.) because the rotational speed of the wind turbine changes with time.

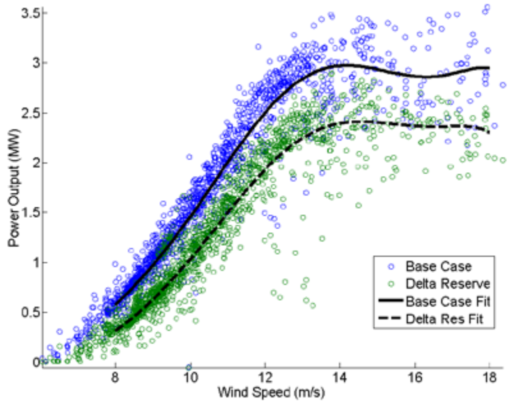


Figure 10. Output power comparison between the base case and delta reserve power of a Type 2 wind turbine based on the dynamic simulation with $\Delta P_{reserve}$ = 20% of the rated power

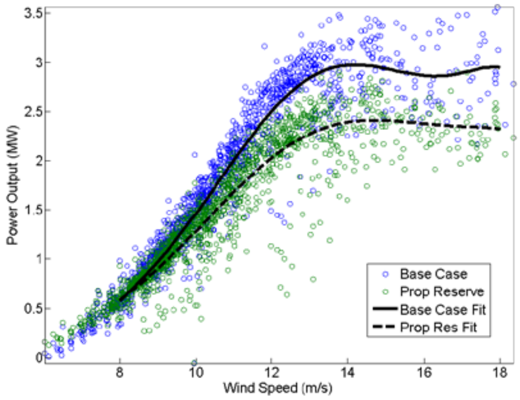


Figure 11. Output power comparison between the base case and proportional reserve power of a Type 2 wind turbine based on the dynamic simulation with $\Delta P_{reserve}$ = 20% of the rated power

IV. CONCLUSIONS

This paper describes the reserve power implementation in a WPP for Type 1 and Type 2 wind turbines. We chose Type 1 and Type 2 wind turbines because they are still available on the market and because the reserve power is more difficult to control with pitch control. The power converters in Type 3 and Type 4 wind turbines make it easier to implement spinning reserves; however, as shown in this paper, spinning reserve power can be implemented successfully even with only the pitch controller. When scaled up to the plant level, these capabilities can offer significant frequency support to the bulk power system grid and should be considered in a high wind penetration scenario.

V. ACKNOWLEDGMENT

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