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Improvement in Active Power Control Methods for a Wind Farm Based on Modified Wind Turbine Control in Danish Grid Codes

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Abstract – The importance of power system stability has been emphasized with an increase of wind energy penetration in the power system. Accordingly, the guarantee on various control capabilities, including active and reactive power control of wind farms, was regarded as the most important aspect for the connection to the grid. To control the wind farm active power, the wind farm controller was introduced. The wind farm controller decides the power set points for each wind turbine generating unit and each wind turbine generating unit controls its power according to the set points from the wind farm controller. Therefore, co-relationship between wind farm controller and wind turbine controllers are significantly important. This paper proposes some control methods of wind farm active power control based on modified wind turbine control for power system stability and structures to connect wind turbine controllers to wind farm controller. Besides, this paper contributes to development of control algorithm considering not only electrical components but also mechanical components. The proposed contributions were verified by full simulation including power electronics and turbulent wind speed. The scenario refers to the active power control regulations of the Eltra and Elkraft system in Denmark.

Keywords: Wind farm control, Ancillary service, Modified active power control

1. Introduction

Existing large-scale power plants not only provide power, they also play a role in maintaining the stability of the power system. Recent grid codes emphasize that wind power plants should play the same role as existing power plants participating in control for power system stability. This is because of an increase in wind power penetration and an increase in their contribution to grid stability. Therefore, the assurance of various control capabilities, including active-reactive power control, has become an important part of grid standards. If a wind turbine or wind farm is intended to make a new connection to the grid, it must present the implementation and properties of its control features to the transmission system operator (TSO) in detail according to the above active power regulations. Only then, a new wind farm can connect to the power grid with permission [1, 2].

In the regulations for grid connections to the Energinet.dk in Denmark, there is a mixture of power grid connections for large-scale wind power plants, which are gradually increasing due to a recent trend of large-scale wind turbines and technology development, along with power grid connections for small generators which were initially introduced. As the detailed regulations are continually modified and enlarged, they are a good reflection of the technical and operational requirements needed for connecting modern wind power. They can therefore serve as a good reference for verifying wind farm control systems. Accordingly, this study employs the active power regulations of the Energinet.dk in Denmark to explore the active power control capabilities that must be in place in a wind turbine or wind farm, as well as verify the control technology by simulation. To date, a variety of articles have appeared on wind farm control; however, none has appeared on wind farm control as being connected to wind turbine control [3-7]. Furthermore, many articles review all regulations of a specific country on wind farm active power control, but there have been no articles that describe the method for wind farm control in order to satisfy the active power regulations [8-11]. A report by Sorensen from Riso in Denmark addresses wind farm control and wind turbine control; however, it does not contain a description of wind farm control that connects to the detailed wind turbine control block, which, in turn, combines aerodynamic, mechanical, and electrical algorithms [12]. This paper only presents an electrical control algorithm without a combination of mechanical-electrical control. However, actual wind farm control performance is greatly affected by the performance of the wind turbine controllers, which are sub-controllers. Beside, interaction of mechanical-electrical control algorithm is significantly important because they should not interfere in each other when active power regulations are performed. Therefore, the focus of this paper is on wind turbine control for active power control on a wind farm.

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Accordingly, a wind farm can be properly controlled with high performances by modifying wind turbine control. Section 2 of this paper describes Energinet.dk's active power regulations, and Section 3 describes the wind turbine control method for controlling a wind farm. Section 4 describes the wind farm controllers for transmitting demands to each wind turbine, and Section 5 verifies the active power control performance based on simulation results. Finally, Section 6 presents an overview of the article and its conclusions.

2. Active Power Regulations

According to the active power control regulations of Energinet.dk, a wind farm connected to a power grid must be able to control the active power output through set-point demands within the range of 20~100% of the regular power. Within 5 min, the average power error must be controlled so that it is within 5% of the set point. Furthermore, the by-minute adjustment range must be able to adjust to 10~100% of the regular power. These regulations conditionally assume the generator's available active power for all wind speeds, and they are meant to operate within these conditions. The main active power control capabilities are as follows.

2.1 Active power regulations

The Danish grid code shows that a wind farm must be able to cut back fixed power to ensure a generation reserve. It must be able to adjust the amount of power to help the power system maintain the balance of supply and demand. Additionally, the wind farm must be able to limit the absolute power amount with the goal of preventing line overload, and it must be able to stop power at a desired point in time. It also must be able to detect abnormalities on the grid and automatically reduce power. Moreover, it must be able to restrict the power increase gradient so that power can increase within the dynamic characteristics of other generators for balancing supply and demand. These active power control regulations have been made clear in Energinet.dk in Denmark.

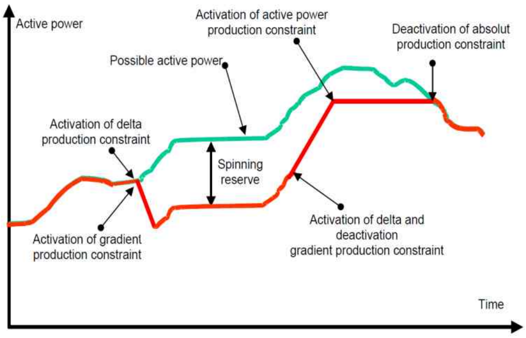

Fig. 1. Active power regulations in Danish grid codes

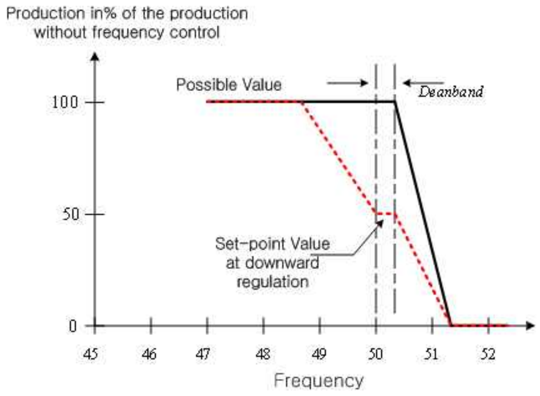

Fig. 2. Frequency regulation

2.2 Frequency regulation

If the penetration of the wind farm in the grid greatly increases, stable frequency control of the grid will be difficult if there are sudden load changes or high wind power fluctuation. Therefore, wind farms must be able to automatically adjust power as needed in order to help control frequency during changes in grid frequency. They must be able to maintain connections within specified ranges for a fixed amount of time even though there are sudden changes in frequency. Generally, when the total generated power in the grid is large compared to the total amount of load, the frequency increases; when the amount of generation is small compared to the load, the frequency decreases. Therefore, the wind turbines in a wind farm must be able to change power according to frequency changes as depicted in Fig. 2. The figure shows the frequency control regulation.

In Fig. 2, the solid line shows active power requirements according to the frequency. The dotted line shows that power increases/cutbacks must be possible in order to regulate frequency when the delta production constraint is being used.

3. Control of Wind Turbine Generating Unit

The aerodynamic power of wind turbines is shown in Eq. (1) [13, 19].

$$P_a = \frac{1}{2}\rho\pi r^2 \upsilon^3 C_p(\lambda,\beta) \tag{1}$$

Here, P_a is the aerodynamic power, ρ is the air density, r is the blade radius, υ is the wind speed, C_p is the power coefficients, λ is the tip speed ratio, and β is the pitch angle. The blade's tip speed ratio is shown in Eq. (2).

$$\lambda = \frac{r\cdot\omega}{\upsilon} \tag{2}$$

Here, ω is the blade's rotational speed. The power of a wind turbine unit is possible to be controlled by controlling C_p, which is a function of λ and β, as shown in Eq. (1).

Fig. 3 shows the changes in energy efficiency according to the changes in the tip speed ratio and pitch angle of the blades used in this article. It must be possible to control the TSR and pitch speed angle in order to control the energy efficiency so that the power of the wind turbine unit can be controlled. Therefore, the wind turbine controller can be divided into a pitch controller and a torque controller. Here, the pitch controller is used to control the blade's angle of attack, and the torque controller is used to control the blade's rotational speed so that the TSR can be controlled to control the power efficiency of the wind turbine.

Generally, a pitch controller is composed of a speed feedback loop, power feedback loop, pitch schedule, and tower fore-aft damper. However, the concrete schemes differ according to the wind turbine's type, manufacturer, and control algorithm. A torque controller is composed of a speed feedback loop and a drive train damper [14-19].

Fig. 4 shows the overall control block of a wind turbine reflecting on the control algorithms in [14-19].

The pitch controller's speed feedback loop controls the blade's rotational speed so it does not rotate more than it should. The power feedback loop determines whether the pitch controller is on or off near the rated wind speed and prevents power fluctuations. The peak scheduling block works to reduce the load during normal wind speed and to raise power efficiency during startup. Furthermore, the tower fore-aft damper suppresses vibration in the tower's fore and aft. The torque controller's speed feedback loop controls the blade's rotational speed during lower than normal wind speed, and the drive train damper operates to reduce the gearbox's load. In case of more large-scale wind turbine, tower sideward damping filter is necessary to suppress vibration in the tower's sides is added to the final demand of the generator torque. Existing wind turbines using algorithm depicted as in Fig. 4 are typically divided into a maximum power point tracking section, fixed speed control using torque controller section, and power limit to the rated power using pitch controller section. Therefore, a new control algorithm must be added for the active power control required by a wind farm controller.

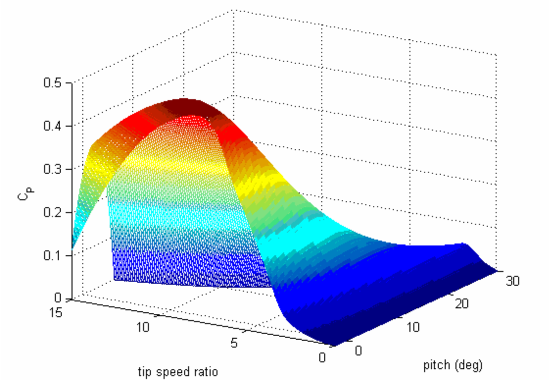

Fig. 3. Power coefficients by TSR and pitch angle

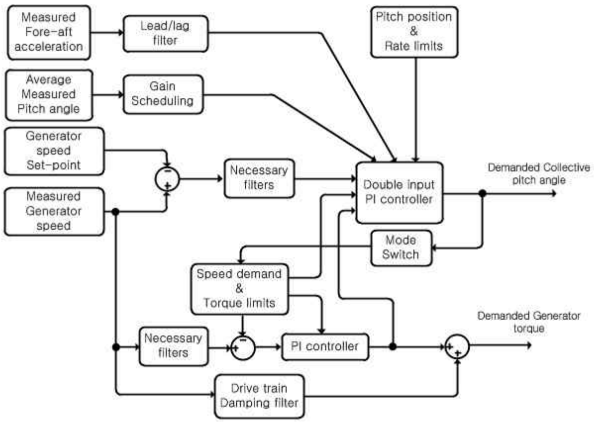

Fig. 4. Control block of wind turbine generating units

Wind turbine control methods to satisfy active power control regulations can be divided into two important schemes.

- Power control through a variable torque limiter, and
- Power control by speed demand change.

The six kinds of active power control regulations other than the power gradient constraint generally use a set-point control style, which limits or allows via TSO's requests. Wind turbines must use these two control styles.

3.1 Power control by Variable torque limit

Electrical control related to the active power limit can be performed through a variable torque limit. Torque control that uses a variable torque limit can control the power limit according to the power demands distributed by the wind farm controller. Fig. 5 shows wind turbine control through variable torque control.

As the compensated power demands change, the torque limit restricts the power of the digital PI controller, which has 5~10 ms sampling time and a near 1 s time constant.

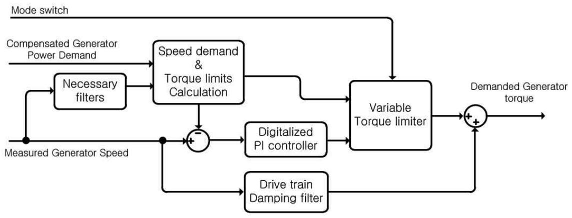

Fig. 5. Control method by variable torque limits

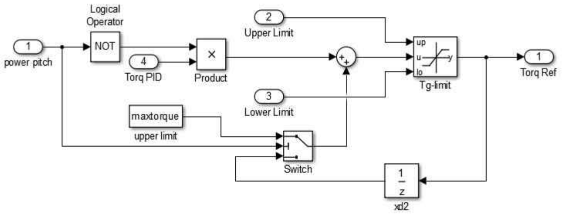

Fig. 6. Control method by variable torque limits

The torque limits calculation is performed in two regions according to the specific speed value. In the low speed region, the reference of the speed is the minimum speed of the wind turbine and the torque is limited by the max torque function according to the speed on C_p curve. In the high speed region, it is opposite to that in the low speed region. The detailed torque limiter block dealing with the torque limiting value calculated by the torque limits calculation is shown in Fig. 6.

When this method is used, the wind turbine control is more robust than the other torque control system using only PID controller. Because the maximum and minimum torque values calculated by PID controller are finally limited and the wind turbine system goes more stable.

Adding the final torque reference to the compensation torque for the drive train damping becomes the final power torque demand. A mode switch is used to determine whether the torque controller is operating, depending on the changes in the wind speed. Each torque controller and pitch controller should operate independently without interference from each other.

Here, it is necessary to modify the variable torque limiter part in Fig. 5 in order to limit the active power according to the Danish grid code. Fig. 7 shows the modified variable torque limiter block.

In many industries, wind turbine controllers use rated constant torque values as the input for the min/max calculator block in Fig. 7 in order to ensure stability during above-normal wind speeds. However, to control active power according to the Danish grid code, a power control loop block, which is composed of a PI controller, can be added to control the high and low values of the limiter. Then, the Min/Max calculator decides the final reference value. The detailed calculator block is as shown in Fig. 8.

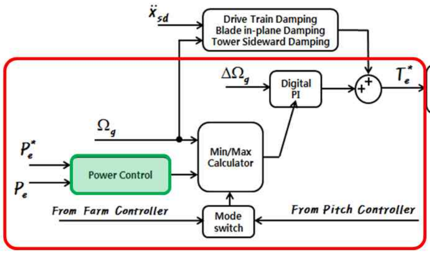

Fig. 7. Modified variable torque limiter

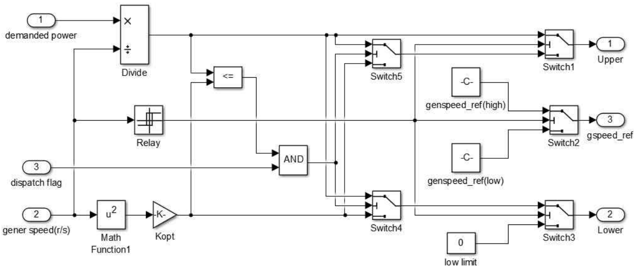

Fig. 8. The detailed Min/Max calculator block

Finally, the torque demand which is an output of the speed control loop can be proceeds to the q-axis current input of the power conditioning system (PCS) through a further calculation process. These control algorithms hierarchically designed for the power control of a wind turbine make the power control of wind turbines easier using simple limit implementation.

Here, the bandwidth of power control loop should slower than that of speed control loop. And the speed control loop must implement anti wind-up.

The torque control blocks of the wind turbine can be shown in Fig. 9.

3.2 Power control by speed demand change

Power control uses a variable torque limiter and is electrical control. Thus, if the aerodynamically incoming energy is reduced through pitch control, a balance of electrical-mechanical energy will be achieved. This means not only torque limiter is necessary but pitch control is also necessary in order to control the active power. Power control of the wind turbine unit according to power demands is made possible by determining the speed pitch control loop's speed demands while considering loss. At this time, the strategy for determining the speed demand has a very large effect on changes in the wind turbine's load. It is therefore necessary to make this determination while considering changes in the wind turbine's load on account of changes in rotational speed. If the speed demand determined in the pitch control loop for power control

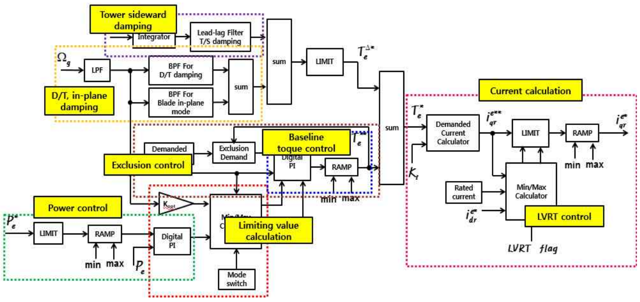

Fig. 9. Total torque control blocks

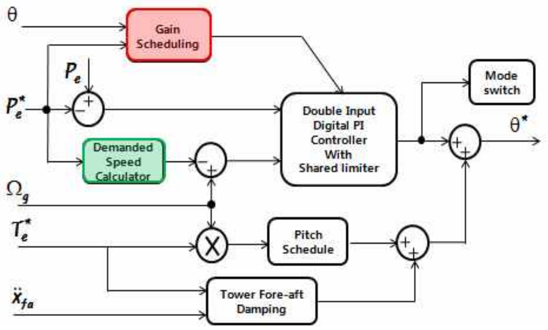

Fig. 10. Modified pitch control loop

becomes the torque control loop's speed demand input, a balance of mechanical-electrical energy can be achieved during changes in the rotational speed. Fig. 10 shows the pitch control block which was modified for power control.

The significant point in the modified pitch control loop is the gain scheduling block. Generally, gain scheduling is performed to achieve a uniform time constant of control systems. For a wind turbine, in above-normal wind speeds, changes in power or torque sensitivity due to changes in pitch angle are larger than that due to changes in wind speed or blade's rotational speed, so a gain scheduling which takes the pitch angle as an input is used most commonly. However, when power control is performed, it is accompanied by changes in the generator's rotational speed and power in the section that performs pitch control, so a multi power gain scheduling technique which reflects the power level and pitch angle simultaneously must be used [12]. Here, the gain to be used in multi power gain scheduling can be found through steady-state analysis in Matlab software or other mathematical calculation programs and can be implemented using 2-D look-up table.

The final value decided by the double input PID controller is added to the tower fore-after damper, then the final reference value of the pitch controller is decided. The tower fore-after damper is to reduce the tower fore-after displacement then to reduce the load by the frequent movement of the tower. Therefore, pitch angle can move to reduce the acceleration of the tower and reduce the load of the tower. In order to design the tower fore-after damper, the stability problem happened by the compensation using tower acceleration signal should be considered. To assure the stability of tower fore-after damper, lead-lag filter can be adapted. Then, filter margin should be considered properly. Fig. 11 shows the bode diagram of nacelle velocity to the velocity command in frequency domain. In Fig. 11, at the zero crossing point of magnitude, the phasor margin is not enough. When lead-lag filter is adapted, the magnitude is reduced and the stability can be insured as shown in Fig. 12.

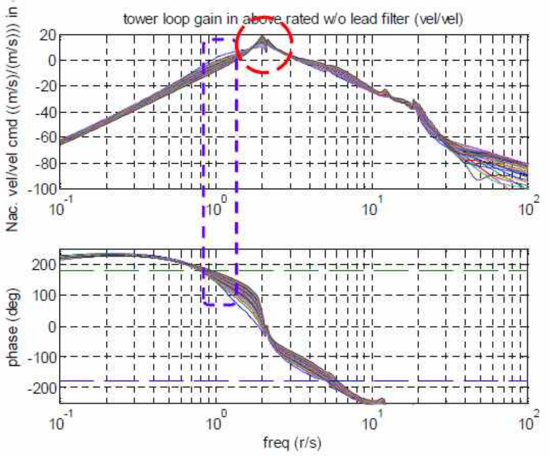

Fig. 11. Bode diagram of Tower damper w/o filter

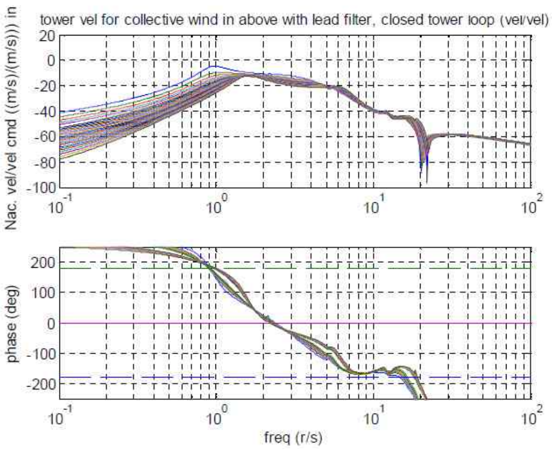

Fig. 12. Bode diagram of Tower damper with filter

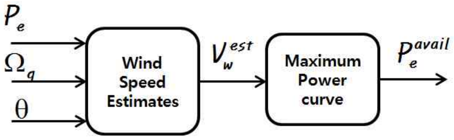

Fig. 13. Available active power estimates

The active power controls which can possibly apply the above two control styles are only balance regulation, absolute production constraint, stop regulation, system two-stage protection, and frequency regulation. However, Danish active power control regulations are based on a closed loop, so available active power at the current wind speed is needed for delta control. Therefore, it is necessary to estimate the available active power extracted from the wind blowing at that moment and transmit it to the wind farm controller. Fig. 13 shows the control block for estimating the available active power, and the power gradient constraint is discussed in the next section.

The available active power can be found from the maximum power curve using the estimated instantaneous wind speed. Here, the instantaneous wind speed can be calculated by estimating the aerodynamic torque using a Kalman filter based on the active power, generator rotational speed, and pitch angle. A 3-D look-up table is then used to deduce the available active power [20].

4. Power Distribution by Wind Farm Controller

As the capacity of wind farms connected to a grid increases, it becomes practically impossible for a grid operator to directly control each wind turbine. Therefore, a wind farm controller must be used to control the wind farm.

A wind farm controller can receive active power and reactive power demands from TSO and give the active-reactive power demands to each wind turbine. Power requested by the operator can be sent to the point where the wind farm controller connects to the grid. Fig. 14 shows the wind farm control structure.

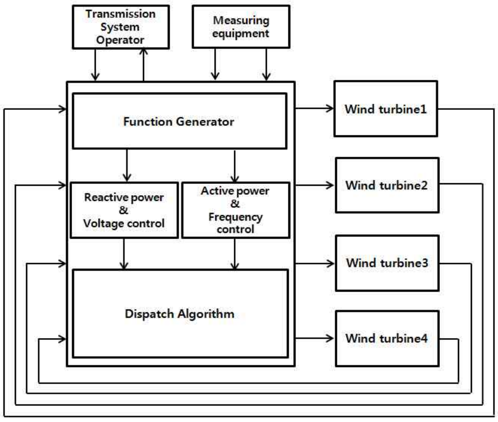

Fig. 14. Wind farm control structure

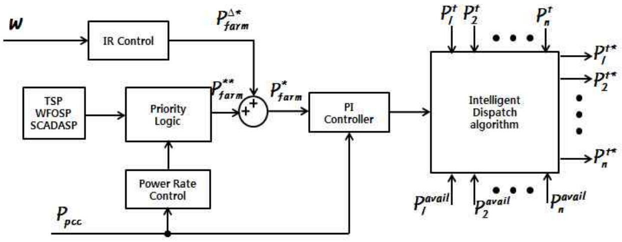

Fig. 15. Wind farm active power control blocks

A wind farm controller does not only communicate appropriately between the grid operator and wind turbines to determine the power demands that the turbines must handle and ensure reserve power. The controller must also be able to determine the priority order between the control functions and decide whether or not a grid accident has occurred while operating the wind farm. Therefore, advanced communications and monitoring technology is required.

When actually controlling a wind farm, the active power control is performed through a set-point control style as needed by the grid operator for stable grid operation. Therefore, in the case of a wind farm controller, it has the role of distributing the power requested by the grid operator to each wind turbine. Consequently, the wind farm control performance is greatly affected by the wind turbine control performance. The wind farm controller, which receives the active power, available active power, wind turbine status, etc. as input from the wind turbines, determines the priority order of the active power control functions. Based on the determined functions, it determines the wind farm's ultimate power demands through the PI controller. The determined wind farm power demand considers the status of the wind turbines, determines the power which each wind turbine must handle, and distributes it. Fig. 15 shows the wind farm active power control block.

The wind farm controller's ramp rate feature can be implemented by simply using a rate limit. However, there are a variety of other implementation methods, such as applying an offset at the wind farm level or directly controlling the power changes at the wind turbine level [21]. Fig. 16 shows an example of a general ramp rate controller applied at the wind turbine level.

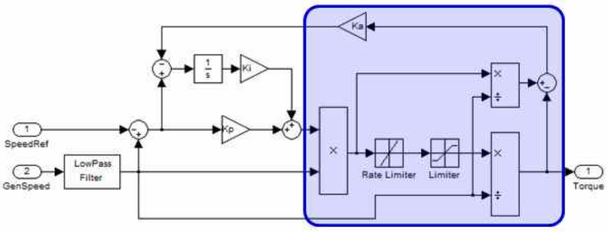

Fig. 16. General ramp rate control block

A variety of methods exist for dispatching power demands to the wind turbines, such as the load equalization of wind turbines in a wind farm, the power equalization, and the same power ratio [22]. In this article, the same power ratio method shown in (3) was used to simplify the simulation because it is the simplest to implement.

$$P_{ref}^{\%} = \frac{P_{ref}^{farm}}{P_1 + P_2 + P_3 + \cdots P_n} \tag{3}$$

Here, $P_{ref}^{\%}$ is the ratio of power demands to the instantaneous power of each wind turbine, P_{ref}^{farm} is the wind farm power demand from the grid operator, and P_n is the instantaneous power of each wind turbine.

Cases exist in which two or more of the wind farm's active power control functions are simultaneously used. In such cases, the functions are performed according to the power function priority order determined in the priority logic of Fig. 15. That order is as follows according to [1].

a. System Protection
b. Frequency Regulation
c. Stop Regulation
d. Balance Regulation
e. Power Gradient Constraint
f. Absolute Power Constraint

5. Simulation Results & Analysis

In order to satisfy the active power control regulations, this section uses a simulation to verify the wind farm control performance and analyzes the results. For the simulation, a wind farm model composed of four wind turbines was built.

The electrical parameters to design of the wind farm are as below.

Wind farm control introduces the concept of a wind farm controller, which calculates and distributes power demands for each wind turbine to satisfy the active power control requirements from the grid operator while granting priority to active power regulations. Here, 2MW class wind turbines were built, as shown in Fig. 17 including

Table 1. Parameters of Transformers for wind turbines

Parameters	Values	Units
Rated capacity	2.5	MW
High voltage side Volt.	10	kV
Low voltage side Volt.	0.69	kV
% Impedance	5	%

Parameters of a Transformer for the wind farm

Parameters	Values	Units
Rated capacity	8.8	MW
High voltage side Volt.	154	kV
Low voltage side Volt.	22.9	kV
% Impedance	7.2	%

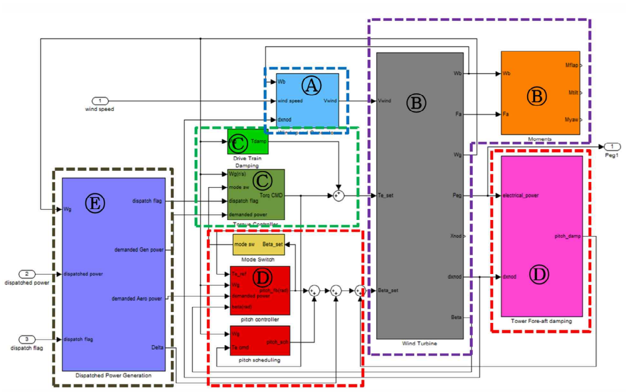

Fig. 17. Control method by demanded output ratio

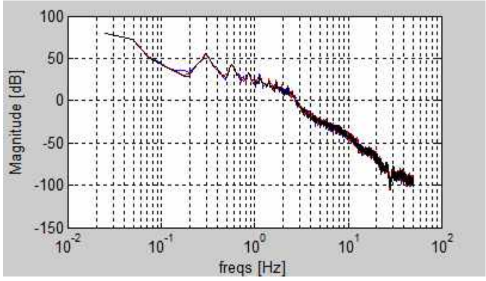

Fig. 18. Wind energy spectrum

components of Ⓐ~Ⓔ.

Ⓐ Wind speed generator based on an azimuth angle
Ⓑ Non-linearized wind turbine
Ⓒ Pitch control system
Ⓓ Torque control system
Ⓔ System control for active power regulation

The unit wind generation system was created with a non-linear model that includes the dynamic properties of the wind turbines. Based on the azimuth angle, it uses a wind speed model in which each blade includes a 1p, 2p, and 3p energy spectrum. Then, 3p, 6p, and 9p energy spectrums are included at the hub [23]. Fig. 18 shows the wind energy spectrum based on the azimuth angle.

Non-linearized wind turbine modeling was performed to reflect the thrust force coefficients, power coefficients, and torque coefficients produced by the GH-bladed. And it also includes electrical components such as permanent magnet synchronous generator, back-to-back converter and the controller designed in [24, 25] but modeled as a RMS model using differential equations in MATLAB/ SIMULINK.

The specifications of the wind turbine used for simulation is as below.

Table 2. Specifications of a wind turbine

Specifications	Values	Units
Rated power	2	MW
Rated generator speed	146	rad/s
Radius of blades	40	m
Height of a tower	83	m
Rated wind speed	11.8	m/s
Optimal TSR	6.908	
Bandwidth of wind turbine controller	1	rad/s

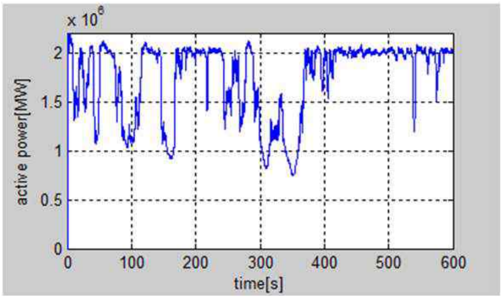

Fig. 19. Active power of a WT at 10m/s wind

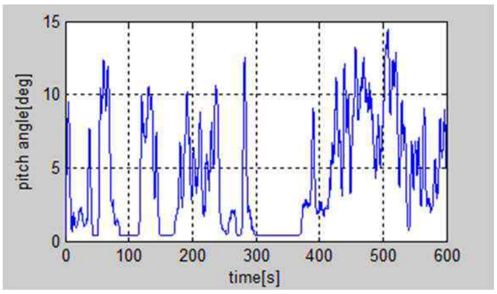

Fig. 20. Pitch angle of the wind turbine at 10m/s wind

Before simulation of the wind farms control, the validation of wind turbine control was performed. When the mean wind speed is 10m/s, the active power of the wind turbine is as shown in Fig. 19.

Then, the pitch angle is varied to limit the wind turbine's power to the rated power as shown in Fig. 20.

If the active power limit is implemented to 0.9MW to verity the basic algorithm for the wind farm control, the active power is limited to 0.9MW then, the speed of blades also reduced according to the optimal Torque-speed curve pre-defined as shown in Fig. 21 and Fig. 22.

The wind turbine control system has lower level controllers, such as the pitch control system and torque

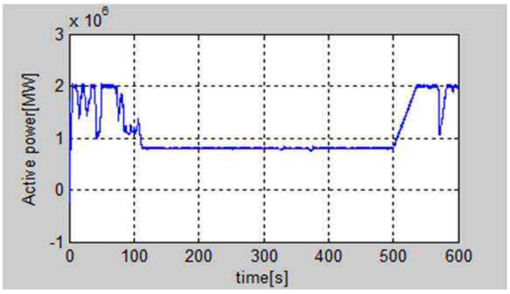

Fig. 21. Active power limit to 0.9MW

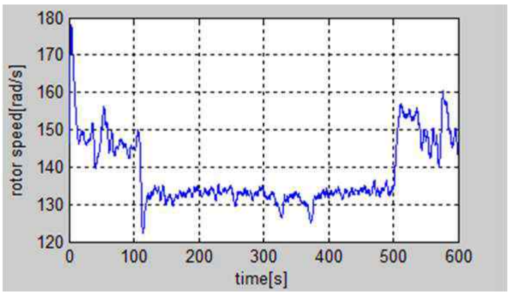

Fig. 22. Blades' rotational speed when active power limit

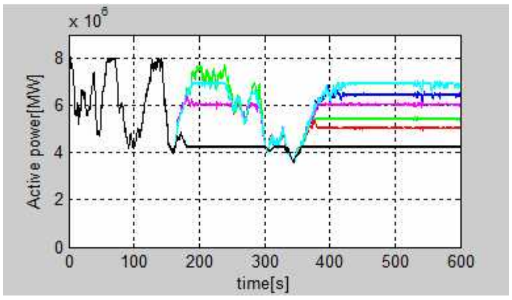

Fig. 23. Results of stop regulation

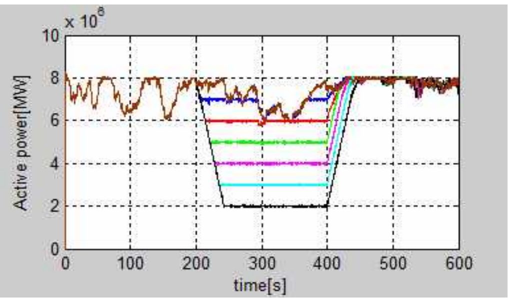

Fig. 24. Results of balance regulation

control system and it controls its power using power control loop. In order to control active power of a wind farm, it receives flag signals from the wind farm controller and controls the wind turbines according to the requested control style. Below are the simulation results.

5.1 Stop regulation

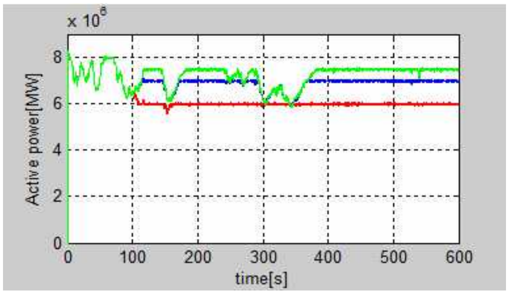

Fig. 25. Results of absolute power constraint

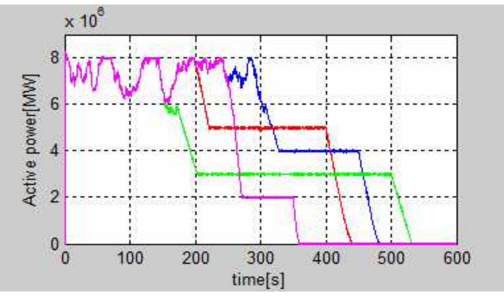

Fig. 26. Results of system two-stage protection

Fig. 23 shows the results of the stop regulation simulation. The simulation was run assuming that 'set-point' demands were coming from the grid operator at 145 s, 155 s, 176 s, 297 s, 380 s, and 400 s. In the results, it can be seen that all power was stopped at the requested time, except when there was reduced power due to reduced wind speed.

5.2 Balance regulation

Fig. 24 shows the simulation results when balance regulation is given the highest priority in balancing supply and demand. A simulation was performed where the constructed wind generation farm which normally carries 8 MW was set for 100% power control from 2 MW to 7 MW in 1 min. Here, the gradient of power increase or decrease can be adjusted by consulting the grid operator. It can be seen that all power was controlled to the requested 'set-point,' except at 7 MW when there was a power decrease due to a wind speed decrease.

5.3 Absolute power constraint

Fig. 25 shows the absolute power constraint simulation results. Absolute power constraint and stop regulation are performed according to the judgment of the grid operator. Therefore, while the essential request conditions can vary, the observed situations are similar from a control perspective. The simulation was run assuming that absolute power constraint demands for 7.5 MW, 7 MW, and 6 MW are being produced at 100 s. In the results, it can be seen that the wind farm power was controlled so that it did not exceed the constraint values.

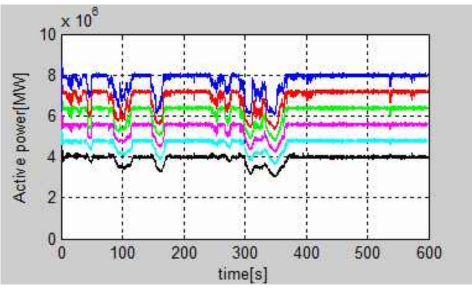

Fig. 27. Results of delta production constraint

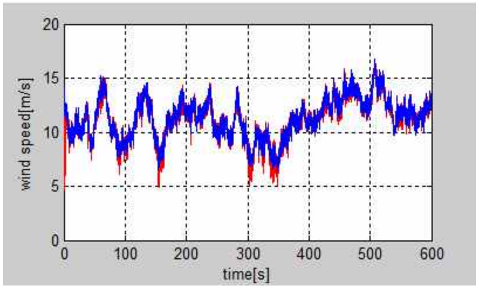

Fig. 28. Wind speed estimates

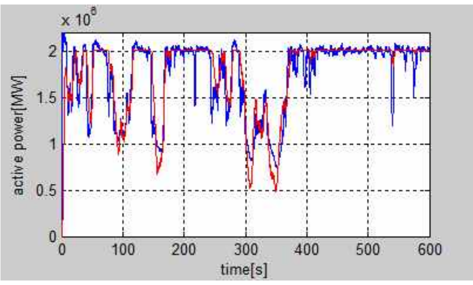

Fig. 29. Estimates of available active power

5.4 System two-stage protection

Fig. 26 shows the simulation results for system two-stage protection, which has the highest priority in the active power control regulations. A simulation was performed assuming that a grid accident occurred at 150 s, 200 s, 250 s, and 300 s. The power reduction amount, stop time, and gradient were changed. In system two-stage protection, the power reduction amount, stop time, and gradient must be set according to the grid operator's request. In the results of the simulation, it can be seen that the power for protecting the system satisfied the regulations.

5.5 Delta production constraint

The wind farm's delta production constraint for ensuring reserve power is required by a high-functioning pitch controller. It is controlled through available power estimates made by estimating the wind speed. Fig. 27 shows the wind farm's active power graph when the delta ratio is changed between 50% and 100%. Fig. 28 shows the instantaneous wind speed at wind turbine hub height, which was estimated for the delta production constraint.

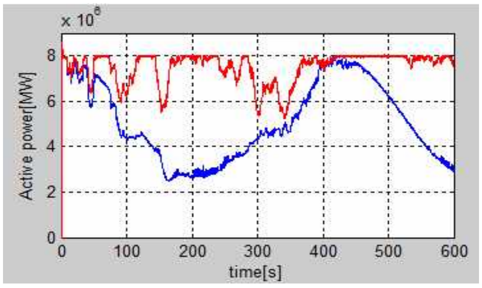

Fig. 30. Result of frequency regulation

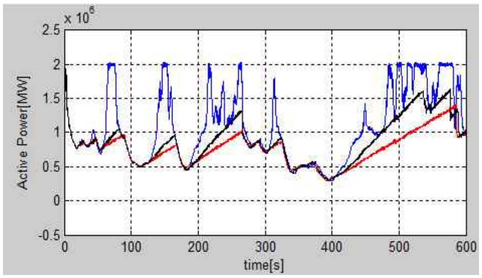

Fig. 31. Result of power gradient constraint

In the figure, the blue line is the actual wind speed, which is the input of wind turbine; the red line is the wind speed calculated from estimated aerodynamic torque using a Kalman filter. This calculated wind speed goes through a low pass filter with a regular time constant and estimates the available active power through the maximum power curve. The blue line of Fig. 29 shows the actual available power. The red line shows the estimated available active power.

5.6 Frequency regulation

Fig. 30 shows the result of active power control of the wind turbine according to changes in frequency. When the grid frequency was changed to a 50~50.8 Hz sine waveform, the wind farm's power responded to the intended frequency changes and the active power was controlled to the set ratio. The active power rate of change according to changes in frequency can be controlled.

5.7 Power gradient constraint

Fig. 31 shows the results of performing the power gradient constraint. The power gradient constraint not only suppresses sudden increases in power, it can also simultaneously perform the role of compensating the overall power quality. In [20], an algorithm was presented for controlling the ramp rate of a wind turbine level with an added offset, and Fig. 32 shows the simulation results when this was used at the wind farm level.

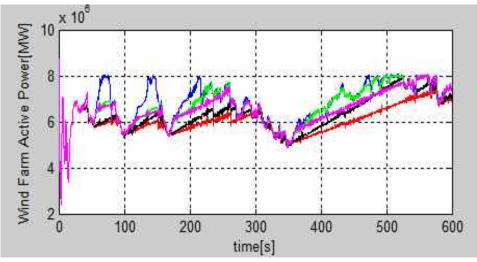

Fig. 32. Result of offset ramp rate control

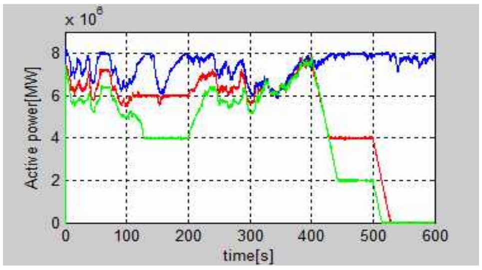

Fig. 33. Result of priority logic

In Fig. 32, at 150 s and 350 s, the wind farm's power increases from the lowest value along a continuous gradient. However, setting a fixed offset and implementing a gradient constraint has the advantage of reducing active power loss in the range where it does not have negative effects on the frequency change.

5.8 Priority logic control

When two functions are performed at the same time, they are controlled according to the priority order in the wind farm's active power regulation. Fig. 33 shows the active power wave according to the priority control logic. When a delta production constraint is being used, if a balance control demand is sent in the 100 s, the wind farm performs balance control. If a balance control demand is canceled in the 200 s, the delta production constraint is performed again. In the 300 s, the delta production constraint is canceled, and normal operation occurs according to the power curve of wind turbines in the wind farm. In the 400 s, system two-stage protection is performed. In the simulation, two scenarios were performed with each different control demand and setting, and control was executed according to the control logic priority.

6. Conclusion

In this article, power control capabilities were verified with reference to active power control regulations of Energinet.dk in Denmark. Frequency control and the six active power control regulations which are made clear in the Energinet.dk were introduced. Wind farm and wind turbine control algorithms for satisfying the active power regulations were presented. Because the performance of wind farm control is greatly affected by the performance of wind turbine control, proper modification of wind turbine control algorithm is necessary. Therefore, the wind turbine control algorithm for active power control was introduced and modified in terms of:

- Power control by a variable torque limit.
- Power control by speed demand change.

The key points of two control algorithms are power control loop as a limiter in the torque control loop and multi-power gain scheduling in the pitch control loop.

The wind farm controller uses dispatch function and priority logic to create power demands for each wind turbine. Because a closed loop control system is required for wind farm control, a wind speed estimates algorithm was added as a function of wind turbine controller. For the simulations, several scenarios were implemented in order to verify the wind farm control performance, including the six active control regulations, frequency control, and priority logic and evaluate the simulation results.

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