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Wind farm control to meet grid requirements

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Summary

This paper shows the results of a wind farm controller, designed to trade-off the grid requirements against the operators need to for optimal utilisation of their assets, by using the Power Adjusting Controller (PAC). For the development of the wind farm controller a complete wind farm model has been developed. The wind farm controller allows the operator to increase or decrease the total power output of a wind farm by requesting an increase or decrease of power production from selected wind turbines. The wind farm controller was developed based on a wind farm consisting of 10 5MW wind turbines. To allow more realistic representation of offshore wind farms, simulations of a wind farm with 40 wind turbines will be illustrated.

Abstract

This paper describes the design and development of a wind farm controller to trade-off the grid requirements against the operators need for optimal utilisation of their assets, by using the Power Adjusting Controller. The PAC was developed by A. Stock and W. Leithead for the 5MW Supergen Exemplar wind turbine [1]. It allows for the manipulation of the power outcome of each individual wind turbine, and consequently can be used to alter the power output of the wind farm. The PAC can be used to increase or decrease the power output of a wind farm, whilst keeping its operation within a safe operational region.

The development of an accurate wind farm model is essential. The wind farm model needs to include the wind field representation, the wake interactions between the wind turbines and the wind turbine model. The initial model consists of 10 wind turbines; for a more realistic representation of an offshore wind farm, a wind farm consisting of 40 wind turbines has also been developed. The wind turbine model used is the Supergen 5MW Exemplar wind turbine model [2], [3].

1. Introduction

Wind energy is one of the most widely used renewable energy sources. At present, wind farms are utilised in a simple way, as they simply output all the extracted energy from the wind. However, future scenarios for UK power generation envisage a substantial penetration of offshore wind energy. Hence, it will no longer be appropriate to operate wind farms in this simple manner.

That is, wind farms will need to provide ancillary services to the grid such as voltage and frequency support, spinning reserve and support to matching of supply to demand. The wind farms are also required to maximise the return on investment. To achieve that, ensuring that each wind turbine is operated with the appropriate trade-off between loading and power production is essential. For both cases, a more flexible wind farm operation is required.

The development of a suitable wind farm model is prerequisite for the design of a wind farm controller. This paper shows the developments to the date of the wind farm model, illustrated by simulation results.

2. Controller Overview

As mentioned in the introduction, the development of a wind farm controller is essential to provide additional flexibility to wind farm operation. The wind farm controller will allow for improved wind farm utilization and will ultimately allow wind farms to be operated as conventional power plants.

2.1 Power Adjusting Controller Overview

A brief overview of the PAC is presented in this section. The PAC is a generic type of controller, which allows the generated power of an individual wind turbine to be modified. This is achieved by regulating the difference between the generated power and the power available in the wind, to track an externally provided set point. By adjusting this set point (ΔP), the power output of each wind turbine can be manipulated as the operator requires [4].

The PAC is configured as a jacket around the existing full envelope controller without any modification to the wind turbine's full envelope controller or converter's design. Hence, the PAC can be used on a large range of wind turbines. An illustration of the power adjusting controller is shown in Figure 1 [5].

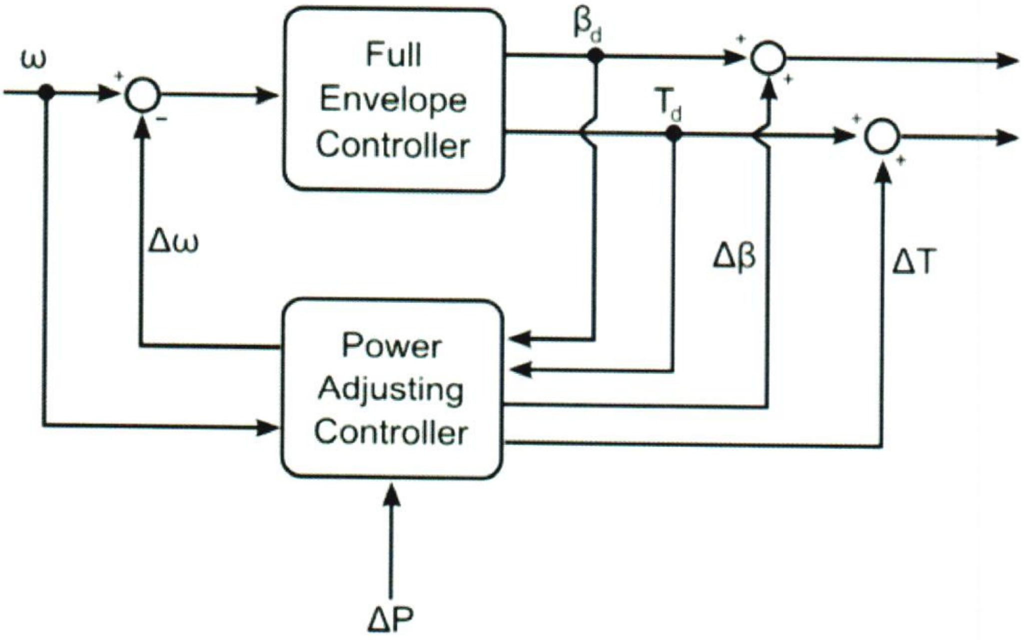

Figure 1: The power adjusting controller

The PAC alters the power output of a wind turbine by a set point ΔP. The input ΔP is provided externally allowing the values of Δω, ΔT and Δβ to be independent from the current state of the wind turbine. This means that the controller does not contain any feedback.

To achieve the change in power output, the wind turbine needs to move away from the normal operating curve. In above rated operation this is achieved by adjusting the adjusting the torque demand by an increment (ΔT). The full envelope controller regulates the rotor speed through pitch action, so the change ΔT is counteracted by a change in pitch angle. This allows for the power output to be altered whilst the rotor speed is controlled [5].

In below rated operation, the generator torque demand is used by the central controller to regulate the rotor speed. Changes in wind speed which cause deviations in rotor speed are thus handled by changes in the torque demand. The implication of this is that an external attempting to take power out of the rotor by adjusting the torque demand must ensure that its effect on the rotor speed is hidden, so that the central controller takes no action. For this, the PAC produces a dummy signal, Δω. Δω is the change in generator speed caused by the use of the PAC. For decreasing the power output, pitching the blades results in a reduction in aerodynamic torque, which consequently reduces the generated power. Hence, a value for the change in pitch angle Δβ is produced. For increasing the power output, there is no pitch angle that will allow the aerodynamic torque to match the generator torque. Hence, positive ΔP values can only be provided for a limited period of time as there is a limit to the minimum speed of the generator.

Assuming a constant wind speed, an example of the reduction of power in below rated operation is illustrated in Figure 2 [5]. The generator torque is reduced by ΔT from point A to point B. This creates a difference between the aerodynamic torque of the rotor and the generator torque. Hence, the rotor speed increases towards point D while the generator torque speed increases towards point C. A change Δβ in the pitch angle allows the aerodynamic operating point to return back to point B.

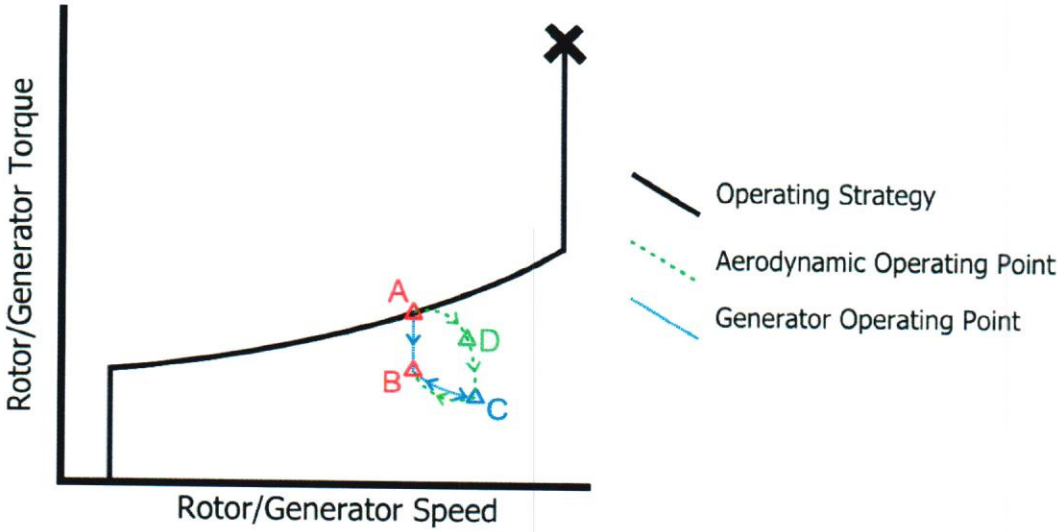

Figure 2: Movement of the operating point on the Torque-Speed plane

The PAC is not specifically designed for the 5MW Supergen wind turbine; it has also been validated on the 2MW Supergen wind turbine [6].

2.2 Wind Farm Controller Overview

The wind farm controller under development is a highly decentralised controller. This type of controller has many advantages, the most important of which is simplicity of implementation and design since the different tasks are separated. An illustration of the wind farm controller is shown in Figure 3 [7].

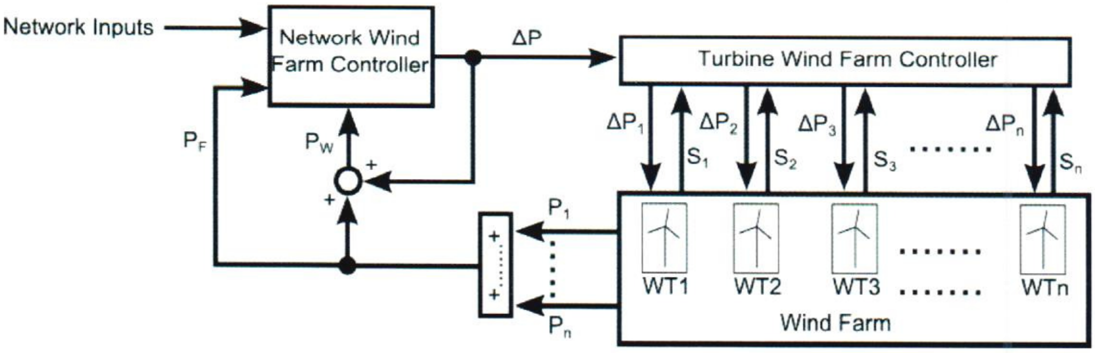

Figure 3: Wind farm controller overview

The wind farm controller presented in this paper acts in response to network inputs. The network wind farm controller is designed to mimic the response of a synchronous generator to changes in the grid frequency. A simple Simulink model has been used for the grid representation. A synchronous generator is connected to an infinite bus. At a given time the circuit breaker will open creating an island, leaving the synchronous generator to provide power for the loads. Changing values of the loads changes the response of the generator. The network controller calculates the percentage change in produced power from a synchronous generator after a change in frequency occurs (i.e. the circuit breaker opens). This allows for a direct calculation of ΔP as a percentage of the total power production of the wind farm which mimics the response of the synchronous generator. The change in power is only requested when the frequency of the system moves below 49.9Hz or above 50.1Hz, in order to avoid excessive application of the PAC.

The turbine wind farm controller reacts to two types of inputs. The first is the total ΔP requested from the network wind farm controller and the second is the wind turbine inputs. The turbine inputs are PAC flags related to the condition and status of the wind turbine. The PAC is designed in such way to keep the wind turbine operation within a safe operational region. The safe region is divided into three zones, the green zone, the amber zone and the red zone. The green zone is safe so while the turbine operates within the green region no additional action is needed. If the turbine moves at the amber zone the flag changes and the controller knows that the wind turbine is moving away from the "safe region". To avoid overloading the wind farm controller will reduce the requested ΔP for this turbine and will redistribute it to another turbine. The red zone is the final zone, which informs the operator that the turbine is far away from its "safe region". In this case the wind farm controller will either drastically reduce the requested ΔP for this wind turbine, or if that is not possible it will set the requested ΔP equal to zero and will ask the turbine to recover. The final limit is the black limit, which is the outer boundary of the red zone. If the turbine reaches the black limit then the turbine will be asked to recover. This will override any information given by the wind farm controller as the safety of the assets (i.e. wind turbines) is the top priority of the PAC. An illustration of the PAC zone definition for the Supergen 5MW wind turbine is illustrated in Figure 4 [5].

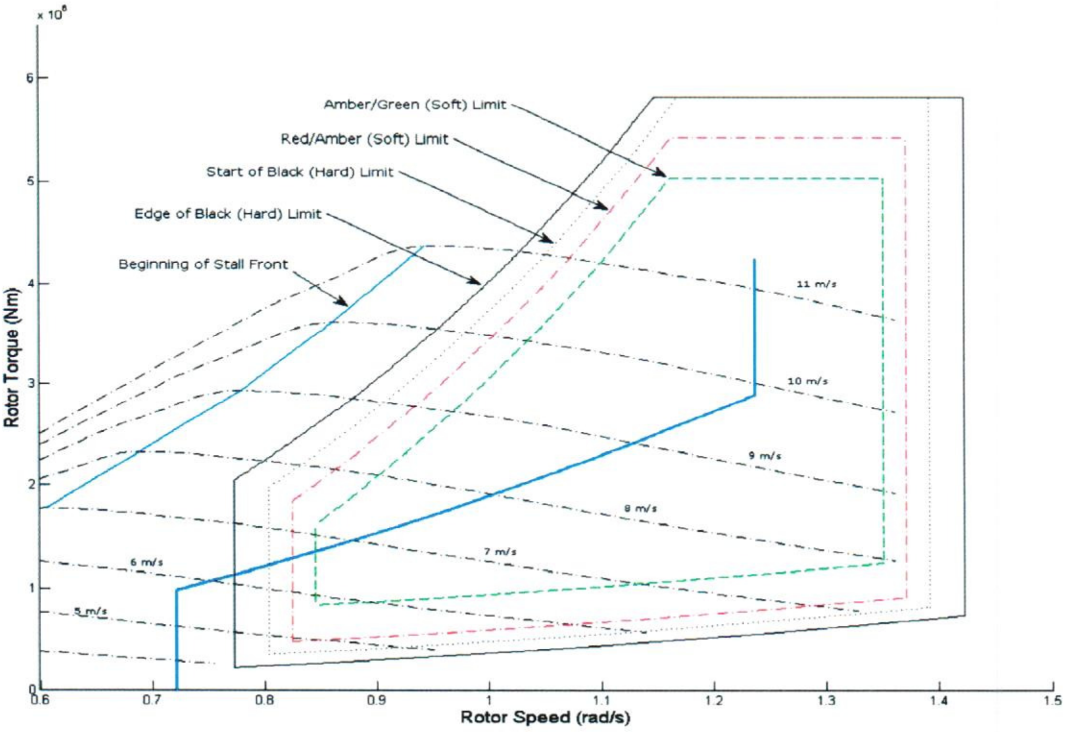

Figure 4: Operational strategy and PAC limits for the Supergen 5MW wind turbine

The decentralised structure illustrated in Figure 3 ensures that the wind farm controller does not impede the operation of the individual turbine controllers. A wind farm controller with this structure enables each turbine to be operated completely flexibly.

3. Wind Farm Model Overview

As mentioned in the introduction, an accurate wind farm model is essential for the development of a wind farm controller. The wind farm model should be able to represent the wind and wake interaction between the turbines.

3.1 SimWindFarm Toolbox Overview

SimWindFarm (SWF) toolbox is a Simulink based, open source wind farm simulation model developed in the EU-FP7 project (Aeolus). The SWF toolbox provides a publicly available wind farm simulation package for researchers developing wind farm level control solutions [8].

The SWF toolbox consists of four main components:

- Wind turbine dynamics,
- Wind field interactions,
- Wind farm controller and
- Electrical network.

The SWF model generated by the toolbox is illustrated in Figure 5. The toolbox allows the user to define the turbine position. It also allows the user to choose whether Taylor's frozen turbulence hypothesis for the ambient wind field is valid or not. If the user assumes that Taylor's frozen turbulence hypothesis is valid then the wake deficit model used is the Park (Jensen) model [9]. If the user chooses that Taylor's frozen turbulence hypothesis is invalid, then the wake deficit model used is the analytical model of wind speed deficit in large wind farms [10].

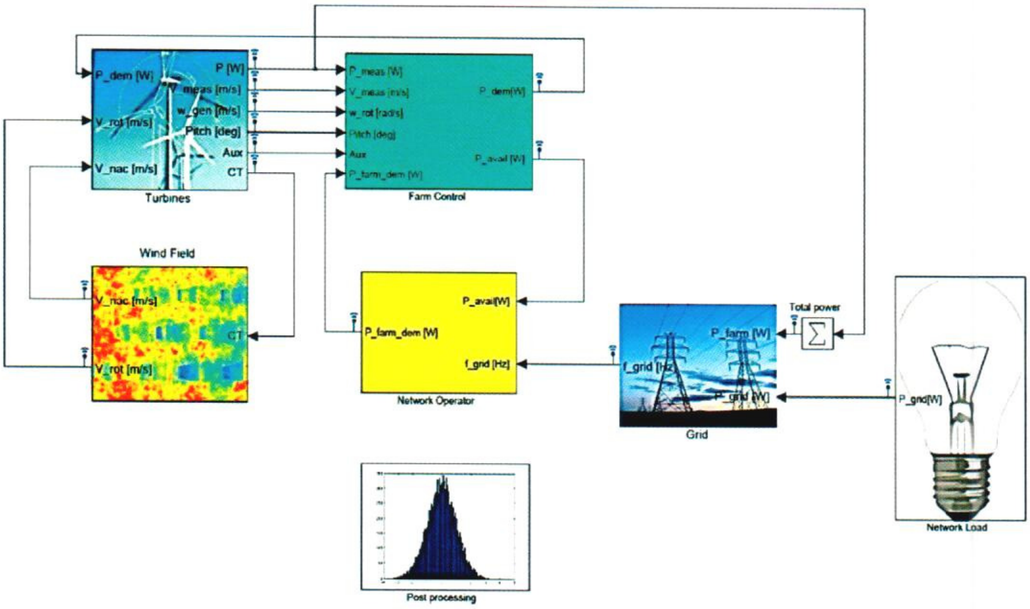

Figure 5: SWF Simulink model overview

For the developed wind farm model presented in this paper the only component that will be used from the SWF toolbox is the wind field interactions block.

3.2 Wind Turbine and Wind Farm Model Overview

The wind turbine model used for all simulations is a Simulink model of the Supergen 5MW exemplar wind turbine [11]. The operational strategy of the Supergen 5MW turbine is illustrated in Figure 4. This turbine achieves rated power at a wind speed of approximately 11.31m/sec.

The wind farm model presented in this paper is illustrated in Figure 6, and consists of the following components:

- The Supergen 5MW wind turbine model,
- The wind field interactions (i.e. SWF toolbox),
- The turbine wind farm controller and
- The network wind farm controller.

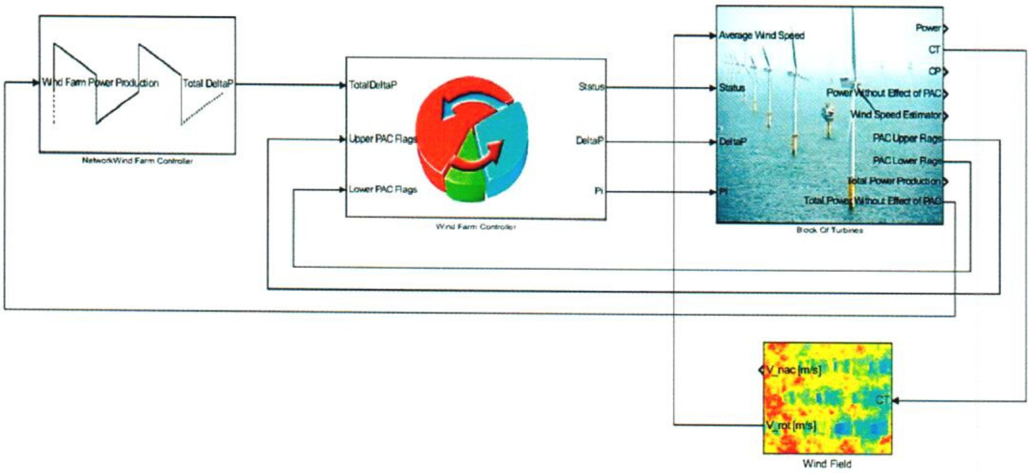

Figure 6: Wind Farm Simulink model overview

4. Results and Discussion

All simulation results presented in this paper are performed in Simulink. Two wind farms have been used. The first wind farm consists of 10 wind turbines and the second wind farm consists of 40 wind turbines. The wind farm consisting of 10 wind turbines is illustrated in Figure 7. It has four rows and three columns. The first and third columns consist of three wind turbines (turbines 1, 4, 7 and 3, 6, 9 respectively), while the second column consists of four wind turbines (turbines 2, 5, 8, 10). The wind farm consisting of 40 wind turbines has five rows and eight columns. In both wind farms the lateral distance between the turbines in a row is 400m and the longitudinal distance between the turbines in a column is 800m. For both wind farms the wind is blowing in the direction of the wind farm's length.

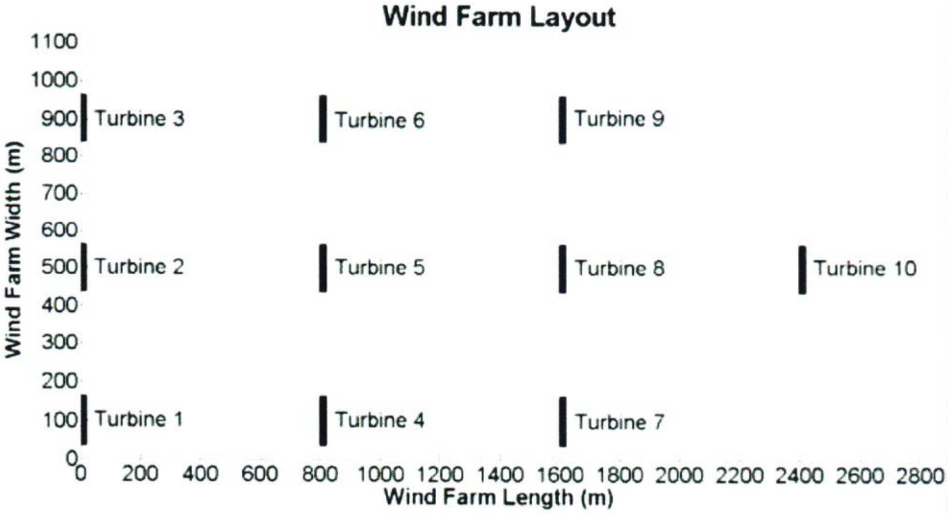

Figure 7: Wind farm with 10 turbines layout

The wind farm controller takes into consideration the operational status of each wind turbine, as illustrated in Figure 4. The controller makes sure that the total ΔP is distributed between all the available wind turbines, by making sure that all turbines are operating within the "green/safe" region. For the wind farm consisting of 10 wind turbines, it is assumed that only 7 turbines are available to alter their power output. The rest are unavailable to alter their power outcome. This restriction was used to show that the controller considers real life cases, where some turbines are unavailable (i.e. turbines under maintenance). For the wind farm consisting of 40 wind turbines, it is assumed that only 28 turbines are available to alter their power output.

For both wind farm models, a time varying wind speed was used, with the mean wind speed interacting with the first row of wind turbines equal to 9m/sec (i.e. below rated operation) and the turbulence intensity equal to 10%. For both simulation models the simulation time is 600 seconds. To avoid any transient effects, the plotting time starts at 50 seconds. For both simulation models the controller is requested to reduce the total power production by 10% for a total of 200 seconds (i.e. between 150sec and 350sec) and then increase the power production by 10% for a total of 20 seconds (i.e. between 480sec and 500sec). The results for the 10 turbine wind farm (i.e. 50MW rated capacity) are illustrated in Figure 8, and the results for the 40 turbine wind farm (i.e. 200MW rated capacity) are illustrated in Figure 9.

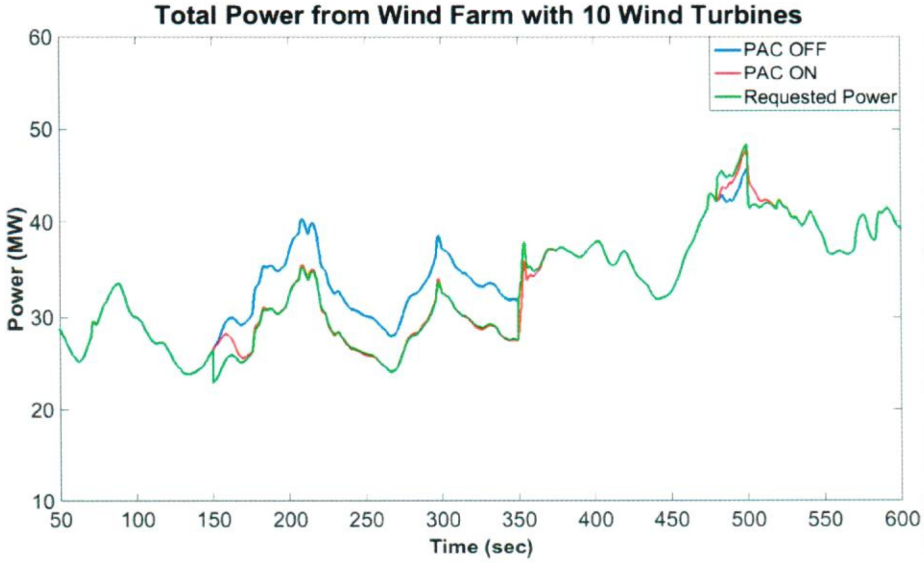

Figure 8: Simulation results for the wind farm consisting of 10 wind turbines

As can be seen in Figures 8 and 9 when the controller is asked to alter the total power outcome of the wind farm, the requested power change is immediately requested from the available turbines. It should be noted that the PAC has a restriction on the ramp rate of change of power in order to minimise the loads on the drive-train components. For negative ΔP values the wind farm controller can impose the reduction for large periods of time; for positive ΔP values, when bellow rated operation, the wind farm controller can impose the reduction for limited periods of time.

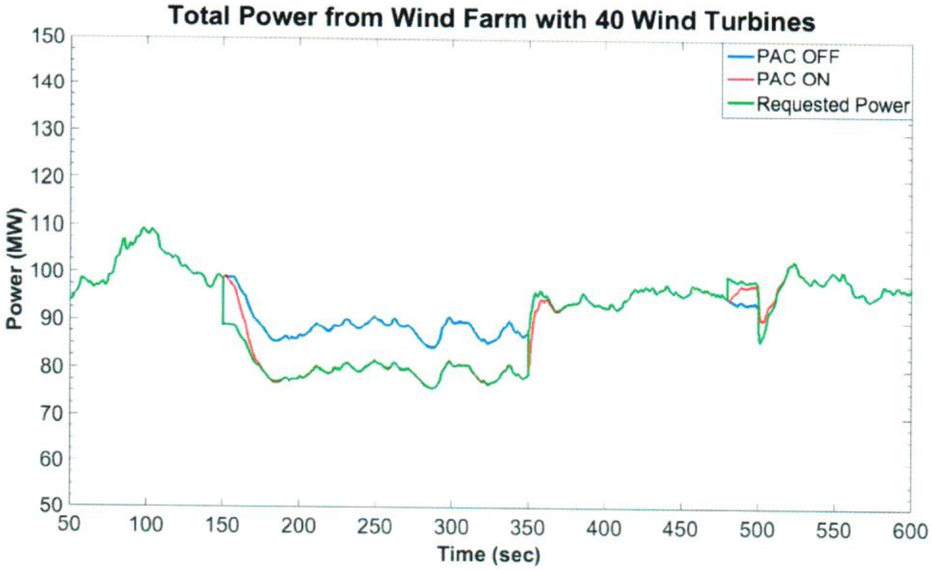

Figure 9: Simulation results for the wind farm consisting of 40 wind turbines

5. Conclusions

This paper illustrates the ability of the PAC to be utilised by a wind farm controller to alter the total power outcome of a wind farm. The simulation models developed are able to include wind and wake interactions between the turbines, allowing for a realistic representation of wind farms. The PAC allows the operator to have increased controllability over the wind farm, allowing for a much more flexible operation.

Future work is going on further developing the turbine and network wind farm controller. The turbine wind farm controller is going to be designed to keep track of a predefined power outcome. The ΔP is going to be changing all the time with respect to the difference between the requested power output and the available energy in the wind. This will allow the wind farm operator to utilise the wind farm as a conventional power plant. A more realistic representation of the power system is also essential for further development of the network wind farm controller.

The development of wind farm consisting of more wind turbines is also essential, in order to allow for more realistic representation of large wind farms. In addition to that, future wind farm models will make use of a more realistic wind field model which will consider dynamic movement of the wake through the wind farm [11].

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