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Control Based Power Smoothing for Aggregated Vertical Axis Wind Turbines

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Abstract:

Recently there has been renewed interest in the potential of vertical axis wind turbines (VAWTs), particularly, at very large scale of 10 MW or above owing to their structural simplicity. A significant disadvantage for many types of VAWTs is that the generated power is inherently periodic in nature. This power quality issue is exacerbated as the turbines increase in size and are aggregated requiring the transmission system to withstand large transients.

These periodic perturbations in power can be smoothed out by permitting the rotor speed to vary; however, operation in this manner results in a poor capacity factor. A new approach to smoothing the power fluctuations from aggregated VAWTs is proposed, whereby a controller for a small group of turbines is used to adjust the relative phase of the periodic power output from individual machines while maintaining the overall performance of the turbines in a group.

Simulation of this control scheme demonstrates that the fluctuations in the aggregated power can be significantly reduced without affecting the mean aggregated power output. The control strategy has been tested by simulation for a range of farm configurations at various wind speeds. The results indicate that the proposed control scheme becomes more effective for increased number of turbines.

Keywords: *VAWT, wind farm control, periodic power, phase-shifting.*

1 Introduction

A major challenge over the next decade will be how to effectively harness the potential of offshore wind speeds resource that tends to be larger but is of course inaccessible and in hostile environments. Horizontal axis wind turbines (HAWTs) are the preferred technology for the onshore sector due to their high efficiency in capturing energy from the wind. Another type of wind turbine is the vertical axis wind turbine (VAWT), which has certain key advantages over HAWTs that may make them the preferable candidate for harnessing wind offshore such as less constraints on the weight and size of drive-train components which can be housed near the base of the turbine [1].

The wind speed relative to the rotor aerofoils of a VAWT is periodic in nature because the axis of rotation is transverse to the direction of the wind flow. For straight blade, fixed pitch rotors, each blade has optimal aerodynamic efficiency at one azimuthal position, it will be sub-optimal at most other positions. This characteristic causes torque to be periodic in nature, and hence also generated power [2]. Skewed or helical blades are one way of providing some smoothing of the periodic power generated by a single turbine. This is unlikely to be economical at the multi-megawatt scale due to the increase in length required, complexity of manufacture and loss of aerodynamic performance. Instead, this paper investigates a control based approach to smooth power output from a group of aggregated VAWTs.

When VAWTs are aggregated there is a risk of peaks in generated power overlapping and causing very large power transients in the wind farm network. To handle this problem with multiple VAWTs, a control scheme is introduced that aims to control the drive-train torque demand to an individual VAWT in order to manipulate the phase of the power output cycle. Therefore, when multiple VAWTs are aggregated, they can be controlled with the objective of maintaining the necessary phase difference between each power output cycle in order to smooth the aggregated power output from the wind farm.

When operated according to a constant speed stall strategy, the periodic torque perturbations can be absorbed by allowing the rotor speed to vary relative to the constant speed set point [3], [4]. Unfortunately, the capacity factor for a turbine operated in this manner is low. The alternative is to operate the turbine according to the variable speed strategy as shown in Figure 1. However, since the dynamics in the stall region are unstable, the controller needs to regulate the rotor speed more tightly and it is no longer possible to absorb the periodic torque perturbations by allowing the rotor speed to vary. In this paper, a novel method of controlling a group of VAWTs with the objective of reducing the fluctuations in aggregate power is proposed.

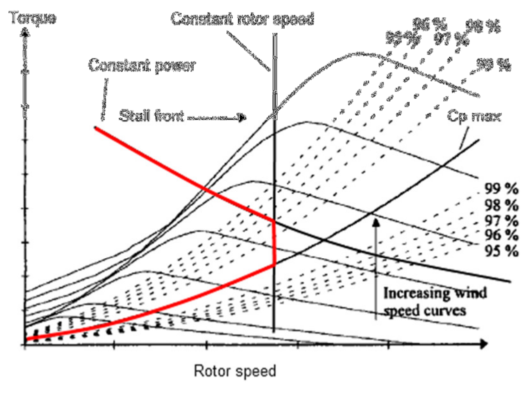

Figure 1: The operating regions of a variable speed stall regulated wind turbine [5].

A model of a multiple vertical axis wind turbine farm is developed which is used to design the controller and assess its performance. The individual turbines are two bladed 5 MW, stall controlled, variable speed VAWTs. The fixed-pitch rotor aerodynamics for a turbine are determined from a double multiple stream-tube (DMS) momentum model [6]. Since the controller for the group of VAWTs is very slowly acting, a simple lumped parameter ODE model of the turbine dynamics would suffice. A stochastic wind speed model is used in the farm model.

The remaining of the paper is organised as follows. In Section 2 the operation and control of the individual VAWT is described. Section 3 explains the VAWT farm model and the novel controller. Section 4 discusses the performance of the control strategy, estimated using a simulation of a wind farm. First, a three turbine farm is examined for a range of wind speeds, and then the addition of more turbines is investigated in the case of a medium wind speed. The conclusions and suggestions for further work are provided in Section 5.

2 VAWT model and control

2.1 Periodic power output

The effective wind incident on the blades, denoted by *W* in Figure 2, is the vector sum of the apparent wind due to blade rotation, $-\omega r$, and the wind field at the blades, *U*. For an unpitched blade, $-\omega r$ is always along the chord line but the angle between U and the chordline varies with azimuthal angle, *θ,* leading to a time varying angle of attack *α(t)*.

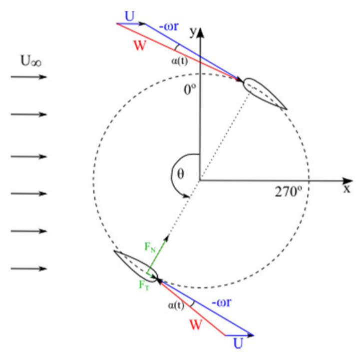

Figure 2: Plan view of a two blade VAWT. Components of effective wind on each aerofoil are highlighted.

The periodic nature of *α* leads to a periodic torque and hence periodic power output because the lift and drag forces on the blades are functions of *α,* and the torque coefficient varies with *α* [2].

2.2 V rotor VAWT

The wind turbine considered in this study is a 5MW V-VAWT. The blades are tapered and untwisted. The turbine parameters are provided in Table 1.

Number of blades	2
Length of blade	100 m
Blade chord at root	10.5 m
Blade chord at tip	3.8m
Inclination to the vertical	36 degrees
Radius at rood	23 m
Rated Power	5MW

Table 1: Parameters of the V rotor VAWT used in this study.

A simple lumped parameter ODE Simulink model, incorporating a DMS model for the rotor aerodynamics, is employed to simulate the turbine. The dynamics of the turbine is simply

$$J\frac{d\Omega}{dt} = T_A - T_{DT} \quad (1)$$

where Ω is the rotation speed of the rotor, J is the inertia of the rotor, T_A is the aerodynamic torque produced by the rotor, and T_{DT} is the drive train torque, essentially the scaled generator reaction torque.

The DMS model of the aerodynamics is employed to determine the aerodynamic performance of the rotor, that is, the power, torque and forces for a range of operating conditions. The induction factors are obtained by finding the intersections of blade element forces and momentum forces [7].

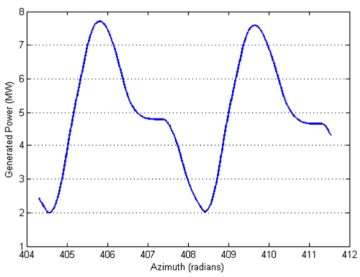

Figure 3: One power output cycle from an individual VAWT at a mean wind speed of 16 ms^{-1}.

The power output from one of these VAWT models with a mean wind speed of 16 ms^{-1}is presented in Figure 3. At this wind speed, the VAWT model exhibits periodic power fluctuations with amplitude of almost 3 MW. One of the blade azimuthal positions is used to indicate the azimuthal position of the rotor. However, the second blade is positioned exactly π rads out of phase causing symmetry in the power output produced upstream and downstream. The periodic nature of the generated power is apparent and for every half cycle there is a peak in power output. For two bladed VAWTs, these peaks occur at multiples of (n+1)π/2 when one of the blades is close to $\theta = 90^{o}$ as shown in Figure 2. Energy extraction on the upstream pass reduces the wind field strength incident on blades downstream significantly reducing the angle of attack α and leads to a much lower torque contribution from each blade downstream [8]. With the two blade configuration the total power waveform repeats twice for every cycle of the rotor.

2.3 Individual turbine control

The controller for the VAWT has a hierarchical structure with inner and outer controllers. Each individual VAWT has its own inner controller, consisting of a feedback loop with a simple PI controller. Its primary purpose is to regulate the turbine speed by adjusting the generator torque or equivalently power. The outer controller interacts with all wind turbines in the farm and attempts to maintain a certain difference in the phase of the periodic power output by each turbine in order to smooth the aggregated power output.

The objective of the inner control system in a variable speed, stall regulated wind turbine depends on the wind speed. The operating strategy has four modes [5]:

i) The rotor speed is held constant in very low wind speeds;
ii) The drive train torque tracks the Cp max curve for low winds;
iii) The rotor speed is held constant in intermediate wind speeds;
iv) The aerodynamic torque tracks constant power for high winds.

Modes ii), iii) and iv) are depicted on the torque/rotor speed diagram, Figure 1. The controller aims to maximize energy capture by tracking the Cp max curve in low wind speeds. However, in high wind speeds the turbine must operate in the stall region to limit the power.

The inner controller has the task of controlling the turbine in each of the above three different operating regions. Since the focus here is on the VAWT wind farm control, the details of the wind turbine controller are not discussed here.

3 Farm model and control

3.1 Phase-shifting control concept

The basic concept for the outer controller is the following. When the aerodynamic torque is greater/less than the drive-train torque, the rotor speed increases/decreases according to equation (1), changing the azimuthal angle of the rotor relative to the wind speed direction. Hence, the phase of a VAWT power output cycle can be adjusted by manipulating the drive-train torque as illustrated in Figure 4.

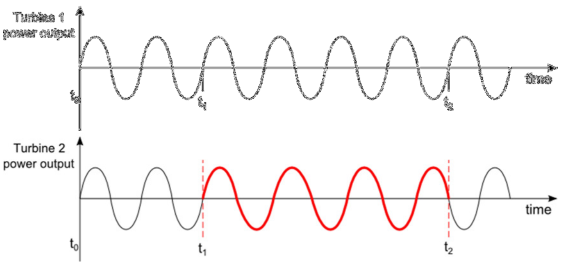

Figure 4: Simplistic view of resultant sinusoidal power output from two VAWT models. Turbine 2 has a higher drive train torque demand between times t_1 and t_2.

Figure 4 depicts the non-physical situation where the power cycles are exact sinusoids. Initially, there are two turbines with the peaks in power output in-phase. The period of one rotor cycle is $t_1 - t_0$. At time t_1, the drive-train torque of turbine 2 is increased to reduce its rotor speed. By time t_2, turbine 2 is π/2 out of phase relative to turbine 1. The drive-train torque is then reduced to its original setting so that the peaks in the power output remain π/2 out of phase. The aggregated power from the two turbines has fluctuations at t_1 which can be twice the maximum fluctuation of each individual turbine, whereas by t_2 the aggregated power fluctuations are eliminated because the individual turbine power fluctuations are out of phase.

Aggregating wind turbines essentially sums the power outputs [9]. Thus aggregation of multiple VAWTs has the potential of producing power flows with current transients exceeding safety levels in the power lines. The idea of the proposed phase-shifting control is to combine multiple identical VAWTs in such a way that the aggregated power output is smoothed.

3.2 Farm control scheme

A farm with three VAWTs is demonstrated in Figure 5. The u_i are the effective wind speeds, θ_i are the rotor azimuthal positions and, T_{DTi} are drive train torque demands and δT_{DTi} are the increments to drive train torque demand. The subscript i refers to the i^{th} turbine. ϕ_i is the phase difference between azimuthal position of rotor 1 and rotor i. The outer controller determines an adjustment to the inner feedback loops set points by comparing the azimuthal positions of the rotors relative to one another.

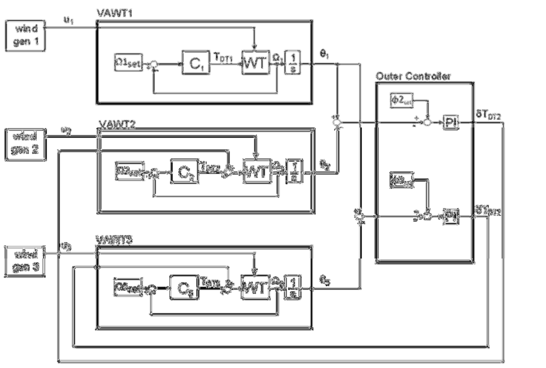

Figure 5: Structure of the wind farm control system.

The objective of the outer controller is to regulate the relative phases so that the overlapping of peaks in the generated power from individual machines is avoided. The speed of this phase-shifting controller for the group of wind turbines is much slower than the individual wind turbine central controllers due to the large inertia of the rotors. The two controllers are, thereby, effectively decoupled.

An example farm consists of three VAWTs. The objective of the outer controller is to maintain a π/3 phase difference between the first and second turbine and a 2π/3 phase difference between the first and third turbine. This can be interpreted as a disturbance rejection problem. For turbine 2, the outer controller must reject the phase of turbine 1 as a disturbance while attempting to control the phase of turbine 2. The difference between the target phase difference and the actual phase difference at each instance is feedback to a PI controller and the controller output increments the reference set point of the inner controller.

4 Simulation and results

In this section, the performance of the VAWT farm controller is discussed. The performance for a three-turbine wind farm is investigated at three different mean wind speeds; 8 ms^{-1}, 16 ms^{-1} and 22 ms^{-1}. The performance for a twelve-turbine farm is also investigated at a mean wind speed of 16 ms^{-1}.

4.1 Three-turbine wind farm

For the three-turbine farm, the simulation is run with the farm controller operating at three different wind speeds; a low wind speed of 8 ms^{-1}, a medium wind speed of 16 ms^{-1}, and a high wind speed of 22 ms^{-1}. The performance is compared to the situation when the simulation is run for the same wind speed inputs without the farm controller operating.

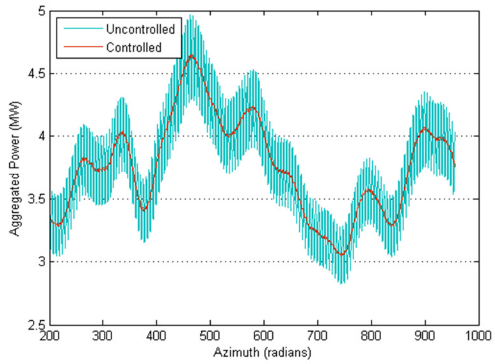

Figure 6: Aggregated power output from a three VAWT model at a mean wind speed of 8 ms^{-1} with and without the phase-shifting outer controller.

Figure 6 shows the aggregated power output for a three-turbine farm at a mean wind speed of 8 ms^{-1}. The average aggregated power fluctuates about 3.75 MW. At this low wind speed, stochastic variation of the wind speed still has a strong influence on the average power output once the azimuthal fluctuations have been smoothed. The phase shifting controller has reduced fluctuations in aggregated power. However; power transients are not significant because the aggregated power is low.

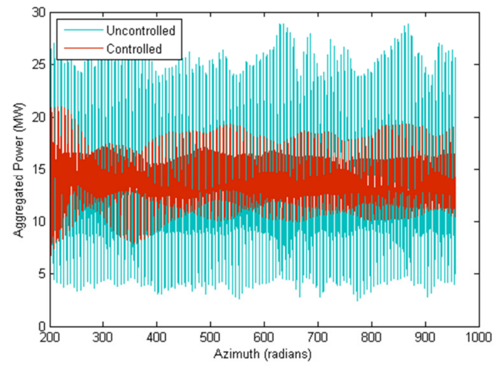

Figure 7: Aggregated power output from a three VAWT model at a mean wind speed of 16 ms^{-1} with and without the phase-shifting outer controller.

Once the wind speed rises above rated, each individual turbine adopts constant power tracking control and the power fluctuations become significant. Figure 7 demonstrates the effectiveness of the outer controller when the mean wind speed is 16 ms^{-1}. Fluctuations exceeding 10 MW above the average aggregated power output are reduced to 3 MW without affecting the average aggregate power output of 15 MW.

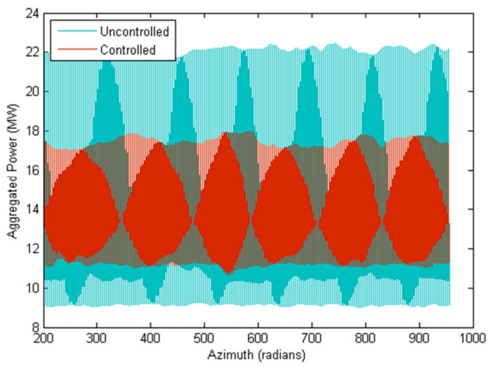

Figure 8: Aggregated power output from a three VAWT model at a mean wind speed of 22 ms^{-1} with and without the phase-shifting outer controller.

At very high wind speeds the control strategy remains effective. This is evident from Figure 8 where the uncontrolled aggregate power deviates from the mean by approximately 7 MW while the controlled output has maximum power fluctuations of 3 MW. A closer inspection of the individual power output at very high wind speeds reveals why the periodicity of the power fluctuations appear to have increased.

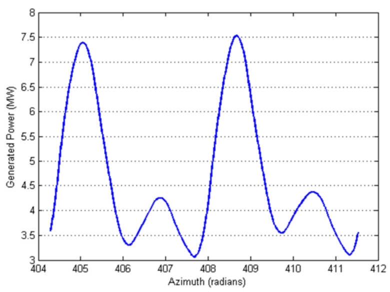

Figure 9: One power cycle from an individual VAWT in a mean wind speed of 22 ms^{-1}.

Figure 9 presents the power output from an individual VAWT at a mean wind speed of 22 ms^{-1}. Compared with Figure 3, it can be observed that each peak in power output has developed into a double peak, with the appearance of a secondary smaller peak. This is due to the rotor stalling over an increased range of azimuth angles. Nevertheless, the controller remains effective and there is no requirement to modify the controller in these high wind speed conditions.

4.2 Generalisation of control scheme for additional turbines

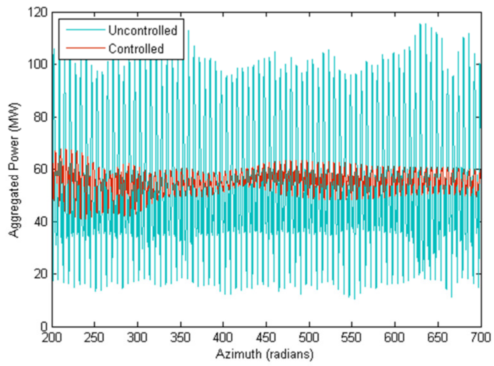

Figure 10: Aggregated power output from a twelve VAWT model at a mean wind speed of 16ms^{-1} with and without the phase-shifting outer controller.

The aggregated power output for a twelve-turbine VAWT farm is shown in Figure 10 for a mean wind speed of 16 ms^{-1}. The average power is 60 MW. The outer controller is required to phase shift each turbine power cycle by $\pi/12$ relative to its neighbouring turbine. The outer controller is particularly effective in this case. The uncontrolled output shows power fluctuations of 50 MW around the average value while the outer controller reduces these to roughly 8 MW. As might be expected, the more wind turbines aggregated, the greater the benefit.

The initial case considered is a three-turbine farm with each turbine having two blades. The objective for the phase-shifting controller is to adjust the three phases of the power cycles to be 0, $\pi/3$ and $2\pi/3$ relative to the first turbine. For the twelve-turbine farm the objective is to maintain a phase difference of $2\pi/(12 \times 2)$. For an *n*-turbine each with *m* blades, the relative phase difference would be $2\pi/(n \times m)$. However, the number of turbines grouped together needs to be constrained to reduce the size of the network connecting them and to ensure that the wind speed conditions for each are not too dissimilar. It is unlikely that the number would be as large as twelve but that needs to be explored further. The phase-shifting controller should then be applied to groups of turbines within the wind farm.

5 Conclusions

The potential through wind farm control to reduce the peak transients in power generated by a wind farm of large VAWTs is demonstrated. The wind farm controller acts to adjust the relative phase of the periodic perturbation of the power generated by the individual wind turbines and thereby smooth the peaks and troughs. Avoiding unsafe power transients should reduce the cost of the wind farm transmission system. With offshore farms consisting of hundreds of turbines, aggregated power smoothing could contribute to improved safety and cost.

A model of a stall regulated, variable speed VAWT farm with three turbines is briefly described. Combining three 5 MW turbines, each with power variations of 4 MW, has the potential risk of aggregated power output peaking at 27 MW. However, the control scheme presented here demonstrates that using drive-train torque to control the phase of the periodical generated power can keep power fluctuations for a farm of three aggregated VAWTs to less than 4 MW without altering the mean generated power of 15 MW and the aggregate power less than 19 MW.

For the more general situation with farms containing a larger number of VAWTs, the control strategy becomes more effective.

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