# Yaw Control for 20MW Offshore Multi Rotor System

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## Abstract

A Simulink model of a 20MW multi rotor system (MRS) is built containing all the necessary detail to demonstrate yaw control for a novel yawing technique. The aerodynamics of each rotor are based on blade element momentum theory summed across a single actuator with the rotor and power conversion system modelled as a lumped mass model. A yaw controller is designed which operates by manipulating the thrusts of the rotors. The feasibility of this yaw mechanism is demonstrated by implementing it at wind speeds of 8m/s, 11m/s and 15m/s. At each wind speed the system remained stable with the yaw error kept within a maximum of 5 degrees over a two hour period.

**Keywords:** Multi Rotor System, Yaw Control

## 1 Introduction

Large scale offshore wind turbines of up to 20MW offer substantial reductions in cost due to minimising the number of offshore foundations required per unit of power produced. Multi rotor systems have great potential as a solution to building turbines of such scale without incurring structural penalties while also reducing cost of energy (CoE) [2].

There are many fundamental reasons as to why MRS produces a compelling case for turbines of the 20MW scale. MRS will have less weight in comparison to turbines of fewer rotors resulting in a reduction in the cost. Analysis based on scaling with similarity [1] shows that the ratio of mass of a set of small rotors to that of a single rotor, with the same swept area and therefore power, is $1/\sqrt{n}$ where n is the number of rotors. It is estimated that the MRS presented has an 80% reduction in blade material alone compared to that of a single rotor [2].

MRS will also benefit from standardisation. With numerous identical components needed in the manufacturing of the MRS, production will become cheaper through the reduction in construction time [3]. With the rotors already much smaller than the largest produced by industry currently, the making of components will become more efficient, resulting in a reduction in cost and increase in reliability.

The MRS design has the significant advantage that a failure in one Rotor and Power Conversion (RPC) system will only result in the loss of 1/45th of the capacity. Even if several RPC systems fail, it is still preferable to losing 100% of the power. Potentially the most cost effective solution to maintenance would be to only have only scheduled maintenance. No reactive maintenance would be required. The MRS also benefits from the fact that the component parts are smaller. Time taken to fix individual outages will be shorter as the smaller parts are easier to fix and replace. At the 444kW scale many of the components will also be manageable for a person to carry.

Recent simulations indicate potential benefit for both power production and loading on the turbine. It is hypothesised that the MRS will have benefits in power production as smaller rotors will have a more complete spatial coverage over a swept area [2]. Smaller rotors also respond faster and so can extract high frequency energy from the turbulent wind field. Initial tests at turbulence intensity of around 5-6% at a wind speed of 9m/s indicate 2% gains in energy. Gains in power

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are also predicted through the aerodynamic interaction of the rotors. Using CFD and vortex models an 8% power gain is predicted due to acceleration between rotors. Due to the rotors all running at varying speeds in turbulent wind, an averaging effect is noted whereby structural loads are reduced.

In addition to these advantages it is proposed that further reduction in cost can be obtained through removing the yaw actuator. Instead, a novel yawing technique is put forward whereby the yaw angle is controlled through adjusting the thrust on the individual rotors. The resulting yaw moment created acts to reduce yaw error. The feasibility of implementing such a yaw control is examined.

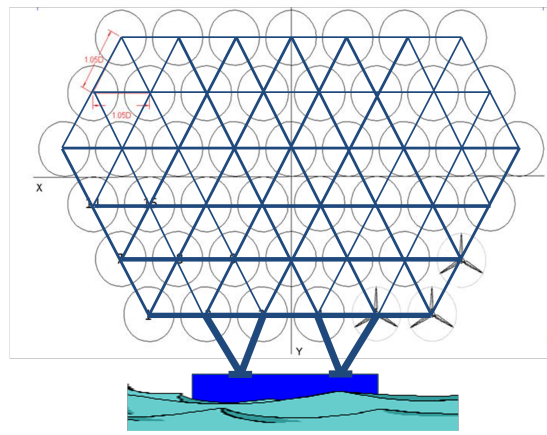



Figure 1: Rotor layout of the MRS

# 2 MRS Design and Power Adjusting Controller

Developed in the European InnWind project alongside work in [3], the MRS design is an optimised design for a next generation 20MW offshore wind turbine [2]. A rotor design is established with 45 rotors set in a plane supported by a steel structure as shown in Figure 1. The RPC systems are rated at 444kW with direct drive power conversion system to increase reliability. Structural considerations of the design are discussed in [4]. The rotor spacing is $1.05D$, where $D$ is the diameter, with the rotors arranged symmetrically about the yaw axis and to avoid a high centre of thrust. The yawing axis is shown as the y axis in Figure 1 and is placed in the same plane as the rotors.

The novel yawing technique applied is to adjust the thrust of the individual rotors. For example, if a clockwise motion is required to reduce the yaw error, the thrust of the rotors on the right hand side of the yaw axis, as shown in Figure 1, may be reduced. This is done using a Power Adjusting Controller (PAC) [5]. The PAC is designed to act as an augmentation to the Full Envelope Controller (FEC) of a wind turbine. The FEC acts to maximise power output below rated wind speeds, maintain rated power above rated wind speeds and reduce loads on the turbine. The PAC consists of a feed foward controller jacketed around the FEC. No prior knowledge of the FEC is needed and the operation of the full envelope controller remains unaffected. It is a generic controller which can be applied to any horizontal axis variable speed pitch regulated turbine.

The PAC alters the power output of the wind turbine by a value $\Delta P$ set by the operator. This will also cause a change in the thrust force, inducing a yaw moment. The only degree of freedom considered is the yawing direction. The MRS is considered to be built upon a stable jacket structure with no stabilisation required due to wave dynamics.

# 3 Model Implementation

## 3.1 Generation of Effective Wind Speeds

The model of the rotor requires an effective wind speed time series. The effective wind speed time series is found by initially generating a field of point wind speeds and converting the point wind speeds at each RPC system hub into effective wind speeds. The effective wind speeds are then used as inputs to the RPC system models, which in turn calculate key parameters such as the thrust and power output.

A Matlab script (adapted from [6]) using the Sandia method [7] is used to create the wind field across the entire structure. Point wind speeds are created in a plane perpendicular to the mean wind direction. The Sandia method uses Taylor's frozen wake theory where

under certain conditions turbulent structures move as frozen entities transported by a mean wind speed. With a turbulent wind field in place the effective wind speed is found using a model based on the method described in [8]. The model is used to generate an effective wind speed given an input of a point wind speed.

The model is simplified in order to reduce the complexity of the control strategy, as well as to reduce the computational time. The rotors are gathered in 17 clusters as shown in Figure 2. The clustering is designed such that each cluster consists of no more than three rotors, and all rotors in a cluster are located next to one another. Larger clusters would result in less accurate approximations as the large area would result in great variation in wind speeds. The model would therefore risk becoming over simplified. Conversely, if the clusters are made too small then the processing time increases such that controller design becomes impractical.

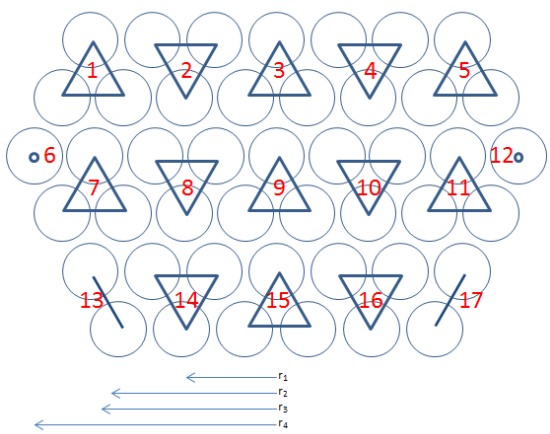



Figure 2: Arrangement of clusters

Where it is not possible to cluster together three rotors one or two rotors are clustered. It is advantageous for rotors 22 and 30 to not form part of a cluster as they are furthest from the yaw axis and so have the greatest contribution to the yaw moment. The effective wind speed for a cluster is taken to be the average of the effective wind speed of each rotor within that cluster. The relevant outputs, such as thrust and power, are found by feeding this averaged speed through the RPC system model and multiplying by the number of rotors in the cluster. Although not mathematically equivalent, this simplification is a reasonable approximation for the controller design for the MRS.

## 3.2 Rotor and Power System Model

A lumped parameter model is used to model each rotor and power conversion system. The model consists of drivetrain dynamics, 3P and 6P loadings, blade edge and flap frequency dynamics, dynamic inflow effects and actuator dynamics. Figure 3 shows the dynamic relationship of the lumped parameter model.

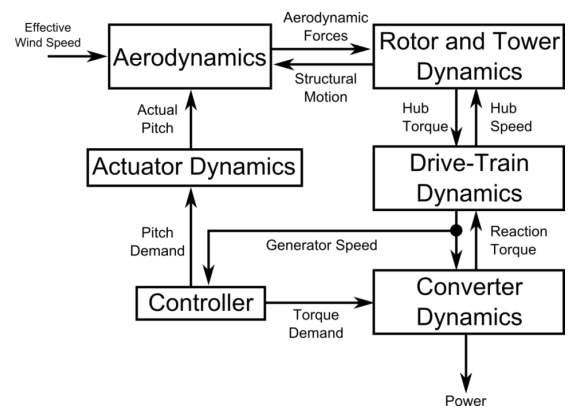



Figure 3: Dynamic Relationship of the control model

Ordinary differential equations are used in the lumped parameter model. The aerodynamics are based on blade element momentum theory summed across the actuator disc with a single stream tube [5]. Rotor dynamics are also included, however as the model considers the entire rotor and not each individual blade. This is dealt with using a derivation from Lagrange's equations [9] [8]. The drivetrain and generator are modelled as a two lumped mass model. The model contains enough detail on the rotational loads for controller design. Specifically the model contains cyclic components of the dynamics at multiples of the rotor speed (nP) up to 3P.

The mass and moment of inertia for the full structure have been calculated with yaw dynamics approximated using a second order dynamic system:

$$\frac{\phi}{M} = \frac{1}{J_{yaw}s^2 + B_{yaw}s} \tag{1}$$

$J_{yaw}$ is the inertia of the system, $B_{Yaw}$ is the damping, $M$ is the moment about the y axis, and $\phi$ is the error in yaw angle (assuming a constant wind direction). Damping losses are approximated to be 1% of the torque.

# 4 Control Design

A hierarchical structure is implemented for control of the MRS. The MRS controller is shown as two separate elements in Figure 4. The aggregate controller utilises feedback from the RPC systems to request a total change in power $\Delta P$. This action does introduce additional feedback throughout the system, however the feedback introduced around each RPC is very weak due to it being divided by 45 rotors. It is therefore vital to the operation of the PAC that this structure is maintained in order that no strong feedback loops are introduced.

The aggregate controller estimates the total change in power, $\Delta P$, required to reduce the yaw error to zero. The reduction in power of a sub-set of rotors will reduce the thrust on these rotors altering the yaw moment on the structure and acting to reduce the yaw error.

The dispatch controller acts to distribute the total change in power between the RPC systems, accounting for the state of each system from information provide by the flags ($S_{1-45}$).

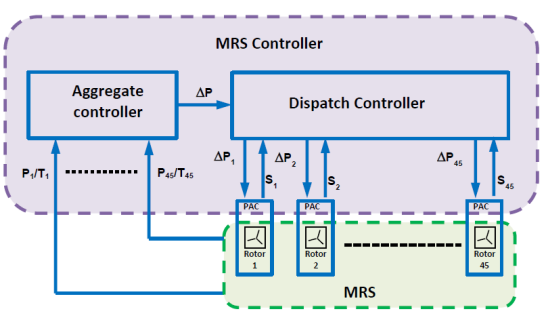



Figure 4: Hierarchical structure of the MRS controller

The simplest possible solution for the distribution of power, $\Delta P$, is to reduce power of every RPC system equally on one side of the MRS, as shown in Figure 5, depending on whether the yaw angle is positive or negative. However, with yaw angle as the only feedback signal sent to the MRS controller, finding adequate gain and phase margins whilst also keeping the gain crossover frequency high is demanding and requires a large derivative gain. In effect, a phase lead term has to be introduced. This type of controller would require large amounts of power reducing the energy being supplied to the grid through high amounts of control action.

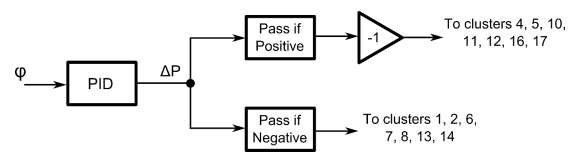



Figure 5: Element of the Dispatch controller

Instead a double control loop system is used with the control diagram shown in Figure 6. The first inner loop, working at a faster rate, acts to reduce the yaw rate whilst the slower outer loop acts to reduce the yaw error. The switch marked with a cross corresponds to the distribution of power shown in Figure 5 and so will dictate on which side of the MRS the power will be reduced. The switch in the inner loop will have an input of $\dot{\phi}$ rather than $\phi$ shown in Figure 5. For the left hand side of the MRS (as seen in Figure 2), a reduction in power will therefore be requested if the yaw angle is negative or the yaw rate is negative (clockwise). The diagram therefore only represents one side of the MRS.

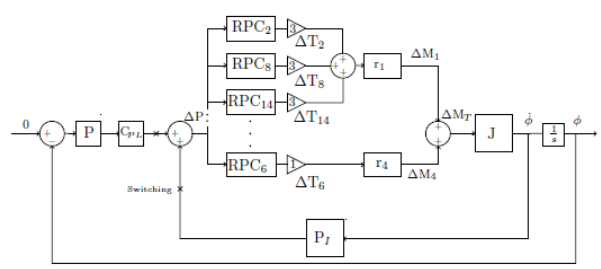



Figure 6: Double feedback loop

The control diagram corresponds with both the numbering of the groups and the distance from yaw axis of each group shown in Figure 2. The numbers in Figure 6 correspond to the clusters on the left hand side of Figure 2. The RPC blocks are the transfer functions from $\Delta P$, requested by the PAC, to the change in thrust for one rotor. A gain is applied to the output thrust of each RPC block to represent the number of rotors in that cluster. Clusters located at the same distance from the yaw axis are then summed together and multiplied by this distance to find a moment. The moments are then summed together and the total change in moment is found. The plant $J$ is simply the transfer function for the yaw dynamics shown in equation 2, with the input the overall change in moment, $M$, of the MRS (the moment produced on one side subtracted by the moment produced on the other side).

$$\frac{\dot{\phi}}{M} = \frac{1}{J_{yaw}s + B_{yaw}} \tag{2}$$

The controller is tuned using the open loop transfer function of the system. In order to obtain this the transfer function for the RPC block at each wind speed is required. An empirical approach is taken to finding the transfer function of the RPC plant from $\Delta P$ to $\Delta T$. A negative step is supplied to the PAC on a single RPC system and the thrust response of the RPC system is analysed. By modelling the RPC as a second order system, an approximation of the dynamics is estimated. Given an input of -20kW; the overshoot and frequency are read from the graph, resulting in values for the gain, natural frequency and damping ratio for the transfer function. At each wind speed this response differs and so a transfer function is found across the operational wind speeds of the turbine.

The open loop transfer function for the inner loop is tuned first. The inner loop only requires proportional control as the value for $B_{yaw}$ is small and so the transfer function $J$ effectively acts as an integrator. The inner loop is then closed, with the closed inner loop transfer function combined with the integrator $(\frac{1}{s})$ now forming the open loop transfer function for the whole system. Again with an integrator naturally occurring in the yaw dynamics, integral control is unnecessary and so no integral term is used for the outer loop. With proportional control alone large phase margins were obtained. A phase lead is therefore added which acts to reduce the phase margin whilst also increasing the crossover frequency.

The proportional controller of the inner feedback loop as well as the proportional and phase lead controllers of the outer loop are effectively the aggregate controller. The inner and outer loop switches as well as the equal division of the power between all the RPC systems combine to make up the dispatch controller.

# 5 Results

As a baseline simulation the model is left to run with no additional controller, the system is clearly unstable as shown in Figure 7. The yaw angle is held at zero until it reaches 100 seconds in order that any transient start up effects are neglected. Within 100 seconds a yaw error over 30 degrees is reached.

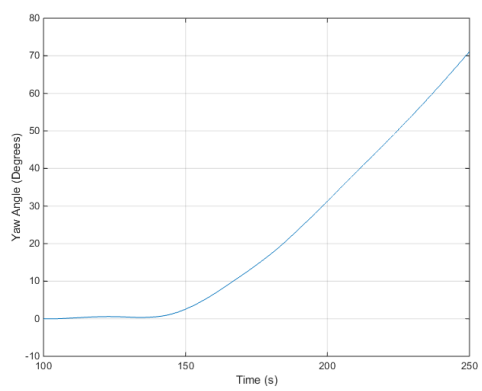
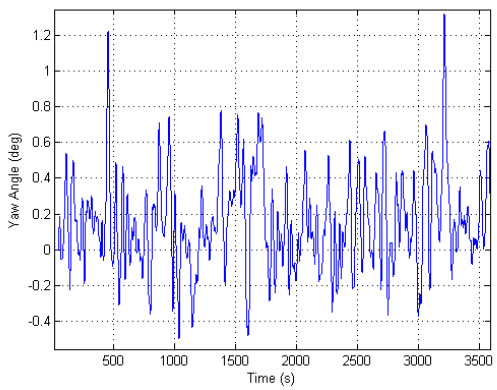
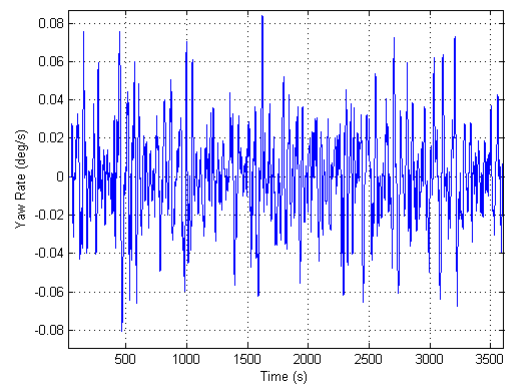



Figure 7: Controller layout

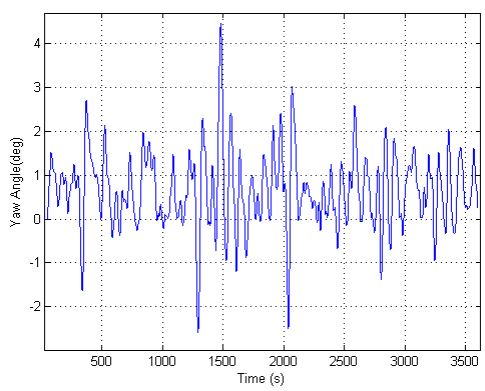
Figure 8a shows that the yaw error of MRS at 8m/s. The structure remains stable over a long period of time (2 hours), staying within 1.3 degrees. Figure 8b shows the low yaw rate at 8m/s with yaw rate rarely exceeding +/- 0.08 deg/s. These low figures are expected as when one side of the MRS swings into the wind the relative speed which a rotor experiences will increase. Below rated, this will result in a higher thrust acting to naturally reduce the yaw error.



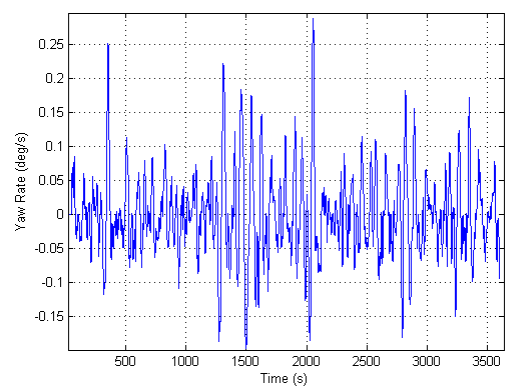

(a) Yaw error over two hour period at average wind speed of 8m/s



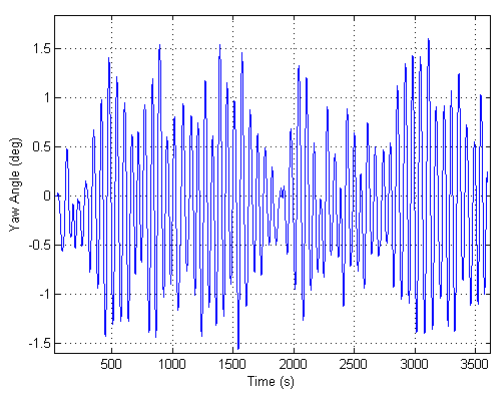

(b) Yaw rate over two hour period at average wind speed of 8m/s



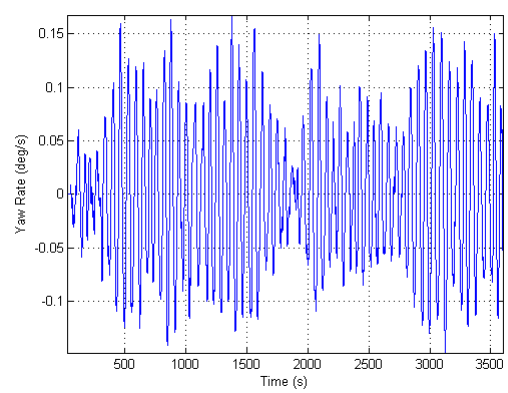

(c) Yaw error over two hour period at average wind speed of 11m/s




(d) Yaw rate over two hour period at average wind speed of 11m/s




(e) Yaw error over two hour period at average wind speed of 15m/s




(f) Yaw rate over two hour period at average wind speed of 15m/s

Figure 8: Yaw error and yaw rate across operational wind speeds

Simulations are also conducted at rated (11m/s) and above rated (15m/s) wind speeds. Figure 8c and Figure 8d show the yaw error and yaw rate respectively at an average wind speed of 11 m/s. The results show greater variation in the yaw angle than in the below rated wind speed simulation, keeping the yaw angle within +/-5 degrees. This is due to a lower crossover frequency at this wind speed. In order to have sufficient gain and phase margins the crossover frequency is required to be lower than that the below rated wind speed scenario. There is also no natural damping through the increases in relative wind speed that occurs below rated. However the MRS does remain stable over this two hour period. Figure 8e and Figure 8f show the results at 15 m/s where a maximum yaw error 1.5 degrees is obtained.

Further simulations conducted over a one hour time period monitor the power lost in comparison to the scenario where there is zero yaw error. The energy lost at 8 m/s, 11m/s and 15 m/s over this period are 213MJ, 870MJ and 3.18GJ respectively. As a percentage this equates to 0.84%, 1.5% and 4.49% of the energy obtained with zero yaw error. The larger percentage loss is expected at higher wind speeds due the lower gain values of the transfer function from $\Delta P$ to $\Delta T$. This means that a higher gain is needed for the proportional controllers above rated, resulting in a larger reduction power for a given reduction in thrust.

# 6 Conclusion and Future Work

With a model built of an MRS on a stable platform, the feasibility of using a novel yawing technique has been demonstrated. With the yaw error remaining stable over a period of two hours over a range of operational wind speeds the ability of this yaw technique is shown. However, further analysis must be done over a wider range of wind speeds and at varying turbulence intensities in order to further validate the yawing technique. Further innovation in the control at rated wind speed is also needed in order to decrease the yaw error to within two degrees. It may be however, that an alternative control strategy will yield an increase in power and therefore significantly decrease the cost of energy. Simulations need to be conducted where the thrust of the rotors are adjusted only after the MRS exceeds a certain minimum yaw error. This may result in a reduction in power lost. It is also possible for the dispatch controller to have a secondary function. The dispatch controller currently only allocates power in order to yaw the system however it is possible, at a slower time scale, for it to also act to increase the power output. This may be done by letting the outer rotors reduce the yaw error whilst letting the inner rotors operate to maximise energy output. Furthermore, the yawing technique has only been proven to work when all the rotors are operational and yaw control is the sole purpose of the controller. The technique must be proven to work where a proportion of the RPC systems are out of operation. As well as this, proving that this technique is possible whilst also stabilising a floating platform would allow the MRS concept to be developed for deeper offshore sites.

Despite this the feasibility of the yawing technique deems it unnecessary for an MRS system to have a yawing actuator. In a short space of time yaw angle has been controlled through adjusting rotor thrust for a multi rotor system. Further development will lead to improved control with further research needed into optimising the control strategy for minimum power loss and failure scenarios.

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