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Wind Farm Optimization Using ORTO Agents

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Abstract

A wind farm is a group of wind turbines, usually spread uniformly across one location, onshore or offshore. They vary in size from a small number of turbines to several thousand covering hundreds of square kilometers. Variable speed wind turbines (VSWTs) commonly make up a wind farm, with power produced by a single VSWT dependent upon prevailing environmental conditions e.g., wind speed and air density. Power generated may also be adversely impacted by air turbulence caused by upstream objects. Wake effects, resulting from the action of a turbine as air flow passes through the sweep area of its blades, can also be a source of turbulence and adversely impact downstream turbine operation. Wake effects not only impact power generated, but they may also result in increased and uneven mechanical stress on downstream turbines, potentially reducing their operational life. This paper describes how ORTO agents can also be used to optimize wind farm operation, increasing total power generated by over 5%. This is achieved by reducing wake impacts caused by neighboring turbines, through the adjustment of each turbine's yaw angle.

Keywords: *Real-time Optimization; Wind Farm; Wake Steering, ORTO Agents*

1 Introduction

1.1 Wind Farm Overview

A wind farm is a group of wind turbines, usually spread uniformly across one location, onshore or offshore. Each turbine generates electrical power which is exported collectively to an electrical grid system. Wind farms vary in size from a small number of turbines to several thousand covering hundreds of square kilometers. Many of the largest are in China, India, and the United States. The largest onshore wind farm presently is Gansu wind farm in China (https://en.wikipedia.org/wiki/Gansu_Wind_Farm), having over 4000 turbines and a capacity of almost 8GW. Hornsea 2 (https://orsted.com/en/media/newsroom/news/2022/08/20220831559011), off the east coast of England, having 165 turbines and a capacity of almost 1.4GW, is presently the largest offshore wind farm.

Variable speed wind turbines (VSWTs) commonly make up a wind farm, with power produced by a single VSWT dependent upon prevailing environmental conditions e.g., wind speed and air density. For a single VSWT, yaw angle is controlled to keep the turbine perpendicular to the wind direction and ORTO agents can then be used to manipulate blade pitch angle and tip speed ratio to maximize power generated (*Oram, 2022*).

Power generated may also be impaired by air turbulence caused by upstream objects. Wake effects, resulting from the action of a turbine as air flow passes through the sweep area of its blades, can also be a source of turbulence for downstream turbines. Figure 1 illustrates the effect turbines have on air flow, with the impact on downstream turbines clearly visible. Wake effects may also result in increased and uneven mechanical stress on the turbine, potentially reducing its operational life. To model wake effects accurately is a highly complex task, and an area of intensive research. Computational Fluid Dynamics (CFD) is one technique often used e.g., *Castellania et al, 2013*. Such modeling helps to improve turbine design and their citing within a wind farm e.g., *Schmidt and Bernhard Stoevesandt, 2015.*

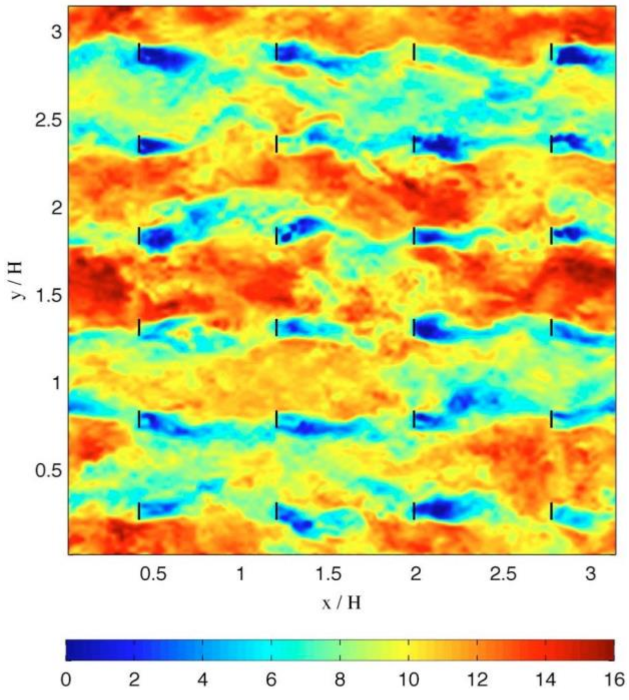

Figure 1: Modelled air flow through a wind farm (*Creech & Früh, 2016*). Colours depict wind speed in m/s.

The impact of wake on downstream turbines can be mitigated by altering the yaw angle of the upstream turbine. As depicted in figure 2, changing yaw angle steers the wake path away from the downstream turbine, lessening its impact, allowing total power generated to be increased. *Kanev, 2019* demonstrated how total power can by yaw angle adjustments, as depicted in Figure 3.

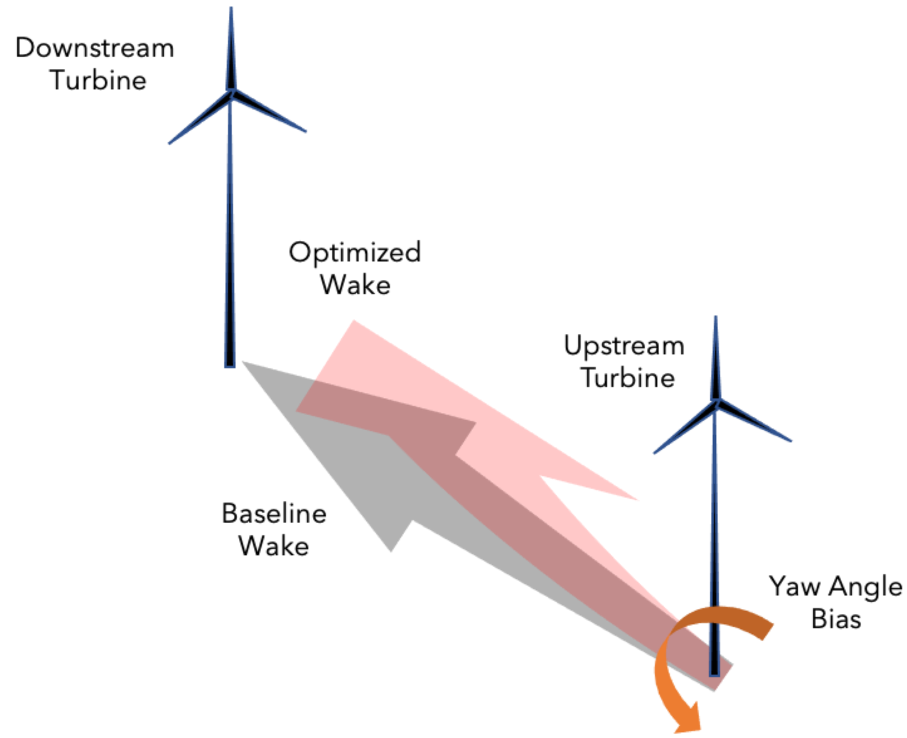

Figure 2: Wake Direction Change Using Upstream Yaw Angle

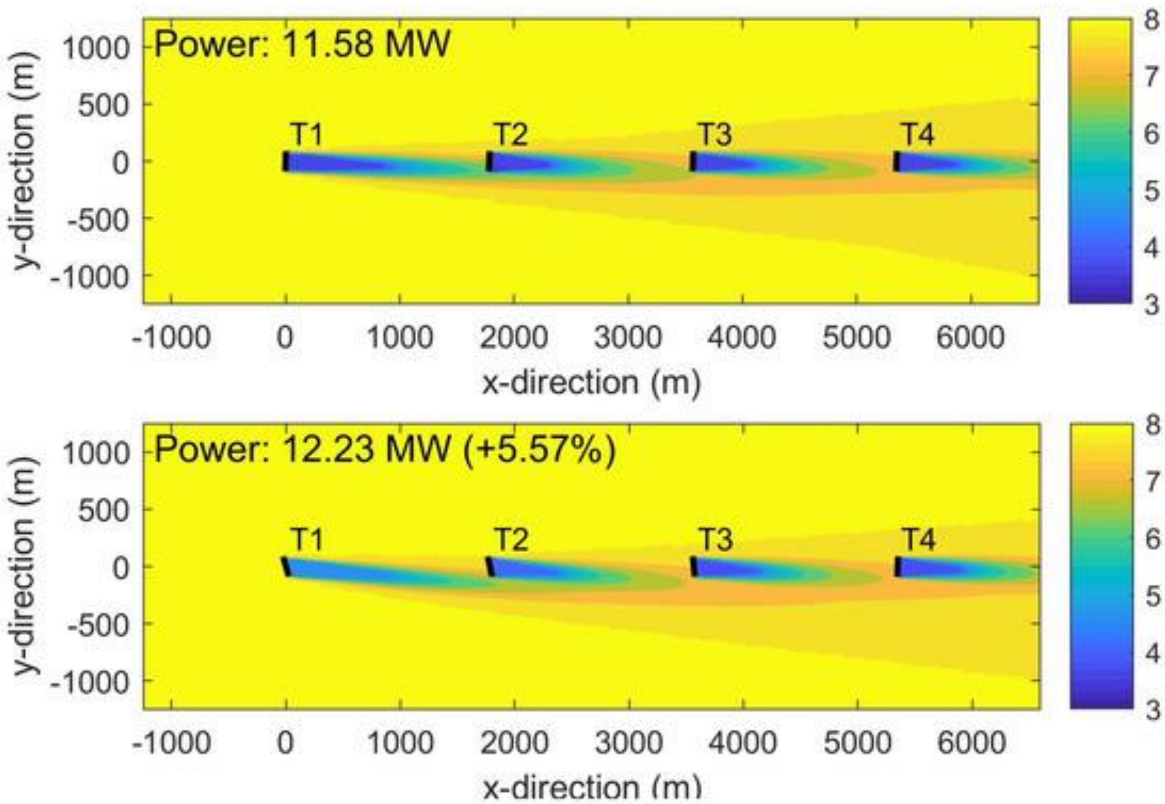

Figure 3: Impact of Wake Steering (*Kanev 2019*)

Reducing wake effects increases the power being generated by turbines impacted by the wake. However, changing the yaw angle of the upstream turbine to achieve this, may sacrifice some of the power it generates. A 'sweet spot' therefore will exist, where total power generated by all turbines is maximized i.e., the difference in increased power and sacrificed power across the whole wind farm is maximized.

1.2 ORTO Overview

ORTO (Oram Real-time Optimization) is a proprietary novel model-free real-time optimization approach, developed by Ortomation Ltd. ORTO offers distinct advantages over traditional RTO technologies. These advantages include greater flexibility, a more intuitive design procedure and straightforward implementation. ORTO also automatically tracks non-stationary (time dependent) optima, e.g., caused by a change in operating philosophy, discrete system modifications, or changes in process dynamics over time. In addition, optima are found, whether constrained or unconstrained. An ORTO scheme is built using independent ORTO agents, each manipulating one system variable. Being model free, ORTO agents have no prior knowledge of the optimization n-dimensional plane. The 'ORTO agent principle' ensures agents learn from each other and work together, to move to and then track the desired optimum value.

2 Wind Farm Modelling Modeling

2.1 Wind Farm Array

The operation of a wind farm is firstly modelled, to facilitate the design and testing of an ORTO wind farm power optimization scheme. To reiterate, ORTO agents are model-free. The model is only required in lieu of a real wind farm!

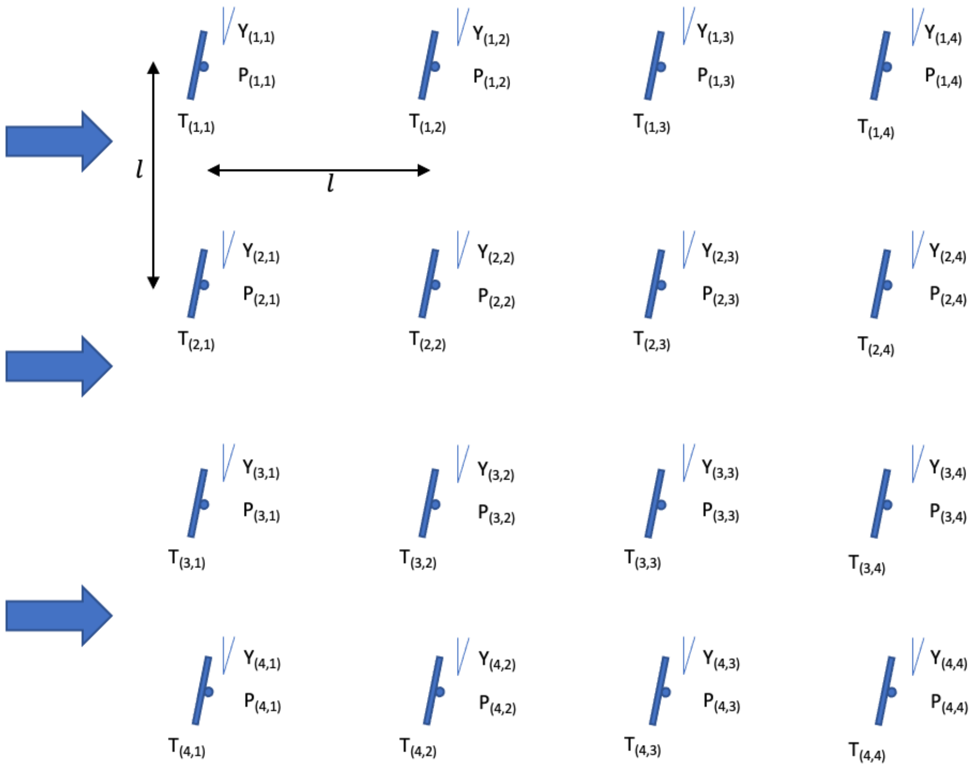

Figure 4: 4x4 Turbine Array

Consider the 4x4 turbine array $T_{(1,1)}$ to $T_{(4,4)}$, shown in figure 4. The turbines are separated by l meters, both horizontally and vertically. It is assumed that a regulatory PID controller controls yaw angle, such that the turbines are kept perpendicular to the wind direction, which, for the case shown in the figure is easterly. A yaw bias, $Y_{(r,c)}$, can be added to the SP of the yaw controller. Each turbine generates power, $P_{(r,c)}$[1], thus, total power generated by the array is given by:

$$P_{Tot} = P_{(1,1)} + P_{(1,2)} + \cdots . + P_{(4,4)} \qquad ...[1]$$

2.2 Wake Effect Modelling

A pragmatic approach to modelling wake effect interaction between turbines, having sufficient complexity and fidelity to demonstrate adequately ORTO's ability to optimize the system, is now described. The approach has no mechanistic basis, it has been devised simply to mimic the observed impact of wakes on downstream turbines. The assertion is that the model is sufficiently complex e.g., non-linear, to demonstrate ORTO's ability to optimize such systems.

Firstly, an approximate nonlinear interpretation of wake impact is assumed, where the wake effect magnitude, from an upstream turbine on power generated by the impacted turbine, is a bimodal function of the upstream yaw angle $\mathrm{Y}_{(r,c)}$:

$$\phi = \max\left[0.033\left[\frac{90-\mathrm{Y}_{(r,c)}}{90}\right]^3, 0.1\left[\frac{20-\mathrm{Y}_{(r,c)}}{20}\right]^3\right] \qquad ...[2]$$

A graph of this function is detailed in figure 5.

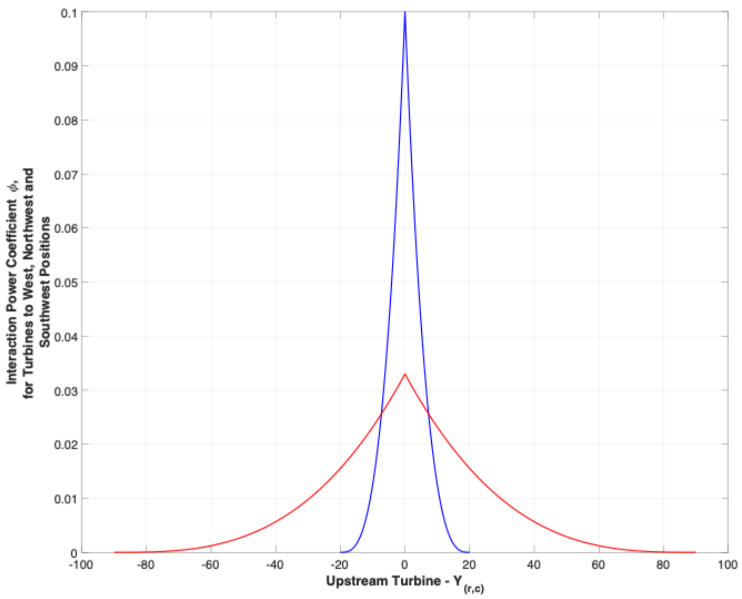

Figure 5: Wake 'Interaction Coefficient'

[1] For modelling and optimization purposes, power can be simply instantaneous power generated by the turbine, or power, normalized for current wind speed and air density.

The 0.033 gain in [2] is chosen to provide a reduced impact outside of the main wake effect. The 0.1 gain in [2] is chosen to deliver a ~10% downstream turbine power loss, when wake effect is at a maximum, for example when:

$$Y_{(1,1)} = Y_{(1,2)} = 0^{o} \qquad ...[3]$$

This model extends to the diagonal pairings. For example, if we consider the impact of turbines $T_{(1,1)}$, $T_{(2,1)}$ and $T_{(3,1)}$ on $T_{(2,2)}$, then the respective interaction coefficients are as follows:

$$\phi_{(1,1)} = \max\left[0.033\left[\frac{90-|(Y_{(2,1)}-45)|}{90}\right]^{3}, 0.1\left[\frac{20-|(Y_{(2,1)}-45)|}{20}\right]^{3}\right] \qquad ...[4]$$

$$\phi_{(2,1)} = \max\left[0.033\left[\frac{90-Y_{(2,1)}}{90}\right]^{3}, 0.1\left[\frac{20-Y_{(2,1)}}{20}\right]^{3}\right] \qquad ...[5]$$

$$\phi_{(3,1)} = \max\left[0.033\left[\frac{90-|(Y_{(3,1)}+45)|}{90}\right]^{3}, 0.1\left[\frac{20-|(Y_{(3,1)}+45)|}{20}\right]^{3}\right] \qquad ...[6]$$

Wake effects caused by a single turbine, beyond those immediately affected downstream, are assumed to be negligible. For example, if the wind is coming from an easterly direction and the turbines are orientated in a square grid pattern as shown in figure 4, then only downstream turbines directly to the east, northeast and southeast are impacted.

Now, we assume that power generated by $T_{(2,2)}$, when there is zero upstream turbulence present, is related to its yaw angle as follows:

$$P_{gen(2,2)} = P_{\max(2,2)}\cos(Y_{(2,2)}) \qquad ...[7]$$

Where $P_{\max(2,2)}$ is the maximum power achievable and a function of how the turbine is being operated e.g., for any given tip speed ratio or blade pitch. Again, the power generated, $P_{gen(2,2)}$, is at a maximum, $P_{\max(2,2)}$, when the yaw angle is maintained at 0^{o} i.e., when the turbine is kept perpendicular to the wind direction. Introducing losses incurred from the upstream turbines, using the interaction coefficients described in [4]. [5] and [6], gives the full wake effect model for turbine $T_{(2,2)}$:

$$\begin{aligned} P_{gen(2,2)} = {} & P_{\max(2,2)}\cos(Y_{(2,2)}) - P_{\max(2,2)}\phi_{(2,1)}\cos(Y_{(2,2)}) - \cdots \\ & P_{\max(2,2)}\phi_{(1,1)}\cos(45 - Y_{(2,2)}) - \cdots \\ & P_{\max(2,2)}\phi_{(3,1)}\cos(45 + Y_{(2,2)}) \end{aligned} \qquad ...[8]$$

Equation [8] can be repeated for each turbine across the whole wind farm, to provide a full wake effect model. For turbines on the peripheries, then equation [8] can be reduced accordingly. For example, turbine $T_{(1,2)}$ is impacted by $T_{(1,1)}$ and $T_{(2,1)}$ only, therefore [7] reduces to:

$$\begin{aligned} P_{gen(1,2)} = {} & P_{\max(1,2)}\cos(Y_{(1,2)}) - P_{\max(1,2)}\phi_{(1,1)}\cos(Y_{(1,2)}) - \cdots \\ & P_{\max(1,2)}\phi_{(2,1)}\cos(45 + Y_{(1,2)}) \end{aligned} \qquad ...[9]$$

2.3 System Dynamics

The wake effect modelling developed in section 2.2 describes steady state relationships between yaw angles and power generated. To describe the associated turbine dynamics, assumed to be the same for each turbine across the wind farm, the following first order plus time delay Laplace transfer functions are used as approximations and assumed to hold true over the respective operating ranges.

Yaw closed loop control: $$\frac{Y_{pv(r,c)}(s)}{Y_{sp(r,c)}(s)} = \frac{e^{-5s}}{30s+1}$$ ...[10]

Generated power to a change in yaw angle: $$\frac{P_{gen(r,c)}(s)}{Y_{pv(r,c)}(s)} = \frac{e^{-5s}}{100s+1}$$ ...[11]

In addition, there are time delays for air to travel from the upstream turbines to the impacted downstream turbine. If we assume an average wind velocity of v_{wind} , with the turbines separated by l m, then:

Delay from directly adjacent turbine: $$\frac{P_{gen(r,c+1)}(s)}{Y_{pv(r,c)}(s)} = e^{-\left[\frac{l}{v_{wind}}\right]s}$$ ...[12]

Delay from upstream diagonal turbines $$\frac{P_{gen(r,c+1)}(s)}{Y_{pv(r\pm1,c)}(s)} = e^{-\left[\frac{\sqrt{2l^2}}{v_{wind}}\right]s}$$ ...[13]

3 ORTO Optimization Scheme

3.1 Optimization Objective Function

The optimization objective function can be easily expressed as follows:

Maximize:

- Total normalized power, P_{Tot}, from a windfarm **Optimization Variable (OV)**

By manipulating:

- Yaw angles, $Y_{(r,c)}$ **Manipulated Variables (MVs)**

Subject to:

- $-15^0 < Y_{(r,c)} < +15^0$ **MV Constraints**

Each MV has an associated ORTO Agent (OA), thus for the modelled array shown in figure 4, sixteen OAs are required. The manipulation of yaw angle by each OA is restricted to within $\pm 15^o$**.** Some further explanation on why normalized power is selected as the OV is required. We note that both wind speed, v_{wind}, and air density, ρ, are wild 'feed-through' disturbance variables i.e., they affect power output directly, irrespective of yaw angle. Now:

$$P_{(r,c)} \sim \propto \mathrm{v}_{wind}^3$$ ...[14]

And:

$$P_{(r,c)} \sim \propto \rho$$ ...[15]

Hence, to help reject external disturbances and improve optimization performance, a superior OV is the ratio of power output to wind speed cubed multiplied by air density [16]. This ratio is directly proportional to the turbine's efficiency i.e., maximizing this ratio will implicitly maximize the power generated.

$$\mathrm{OV} = \frac{P_{(r,c)}}{\rho v_{wind}^3}$$ ...[16]

The obvious scheme structure to adopt, to achieve the above objective function, is simply to install the sixteen OAs, each using total normalized power generated, P_{Tot}, as the OV. However, summing all sixteen power outputs to calculate P_{Tot}, also sums all associated signal noise. Consequently, power improvements made by one OA may be difficult to distinguish from the noise, impairing optimization performance. Alternatively, we can subdivide the optimization problem into constituent parts.

3.2 Optimization Scheme Structure: Adjacent Pairing Strategy

Consider the turbines $T_{(1,1)}$ and $T_{(1,2)}$. The objective function for this pairing, fulfilled using a single agent $OA_{(1,1)}$, is as follows:

Maximize:

- $P_{\text{pairing}(1,1)} = P_{(1,1)} + P_{(1,2)}$ **Optimization Variable (OV)**

By manipulating:

- Yaw angle, $Y_{(1,1)}$ **Manipulated Variables (MVs)**

Subject to:

- $-15^0 < Y_{(1,1)} < +15^0$ **MV Constraints**

We observe that to achieve the above, $OA_{(1,1)}$ needs to sacrifice some of $P_{(1,1)}$, by adjusting $Y_{(1,1)}$ thereby reducing downstream wake effects, to maximize $P_{\text{pairing}(1,1)}$. Similarly, the objective function for the turbine pairing $T_{(1,2)}$ and $T_{(1,3)}$ is as follows:

Maximize:

- $P_{\text{pairing}(1,2)} = P_{(1,2)} + P_{(1,3)}$ **Optimization Variable (OV)**

By manipulating:

- Yaw angle, $Y_{(1,2)}$ **Manipulated Variables (MVs)**

Subject to:

- $-15^0 < Y_{(1,2)} < +15^0$ **MV Constraints**

This pairing arrangement can be repeated across the whole wind farm. For the turbine at the end of each row, the associated OA simply takes the power generated by it alone as the OV. We note that there is coupling between OA pairings. For example, $OA_{(1,1)}$ is continually chasing a moving optimum, because of the action of $OA_{(1,2)}$, etc. Diagonal interactions e.g., the wake from $T_{(1,1)}$ impacting both $T_{(1,2)}$ and $T_{(2,2)}$, etc. are implicitly handled within the optimization pairing framework. The overall objective of maximizing P_{Tot}, as defined in [1], is also implicitly achieved through the OA coupling.

A disadvantage of this strategy is that pairings need to change, increasing the configuration complexity, as the wind direction crosses the 45^0, 135^0, 225^0 and 315^0 axis lines. For example, a move from an easterly to northerly wind will require the first northeast pairing to change from $T_{(1,1)}$ and $T_{(1,2)}$ to $T_{(1,1)}$ and $T_{(2,1)}$, etc. However, if the OAs are performing well, the switch should be seamless.

3.3 Optimization Scheme Structure: Star Cluster Strategy

To negate the need to switch turbine pairings, an alternative strategy is to select a 'star cluster' of turbines, to the north, east, south and west, around the turbine whose yaw angle is being adjusted by an OA. Consider turbines $T_{(2,2)}, T_{(1,2)}, T_{(2,3)}$, $T_{(3,2)}$ and $T_{(2,1)}$, The objective function for the agent $OA_{(2,2)}$, is as follows:

Maximize:

- $P_{star(2,2)} = P_{(2,2)} + P_{(1,2)} + P_{(2,3)} + P_{(3,2)} + P_{(2,1)}$ **Optimization Variable (OV)**

By manipulating:

- Yaw angle, $Y_{(2,2)}$ **Manipulated Variables (MVs)**

Subject to:

- $-15^0 < Y_{(2,2)} < +15^0$ **MV Constraints**

To achieve the above, $OA_{(1,1)}$ needs to sacrifice some of $P_{(2,2)}$ to maximize the total $P_{star(2,2)}$. Similarly, for turbines $T_{(2,3)}, T_{(1,3)}, T_{(2,4)}$, $T_{(3,3)}$ and $T_{(2,2)}$:

Maximize:

- $P_{star(2,3)} = P_{(2,3)} + P_{(1,3)} + P_{(2,4)} + P_{(3,3)} + P_{(2,2)}$ **Optimization Variable (OV)**

By manipulating:

- Yaw angle, $Y_{(2,3)}$ **Manipulated Variables (MVs)**

Subject to:

- $-15^0 < Y_{(2,3)} < +15^0$ **MV Constraints**

This star cluster arrangement can be repeated across the whole wind farm. For the turbine at the end of each row, the associated OA simply takes the power generated by it and those turbines remaining in the cluster. As with the adjacent pairing strategy, the overall objective of maximizing P_{Tot}, as defined in [1], is implicitly achieved.

A disadvantage of this strategy is that at least two turbines within a cluster are unaffected by the OA yaw movements of the central turbine, at any one time, dampening the OA response. Also, as OV noise increases, performance of the star strategy may deteriorate faster than that of the adjacent pairing strategy.

4 ORTO Agent Implementation

For both the adjacent pairing and star cluster strategy, each turbine has an associated OA. As depicted in figure 6 for the adjacent pairing strategy, the OA reads the total normalized power as the OV. The yaw controller typically has a setpoint of zero degrees written to it within the SCADA system. When engaged, the OA writes a bias to this setpoint to maximize the OV.

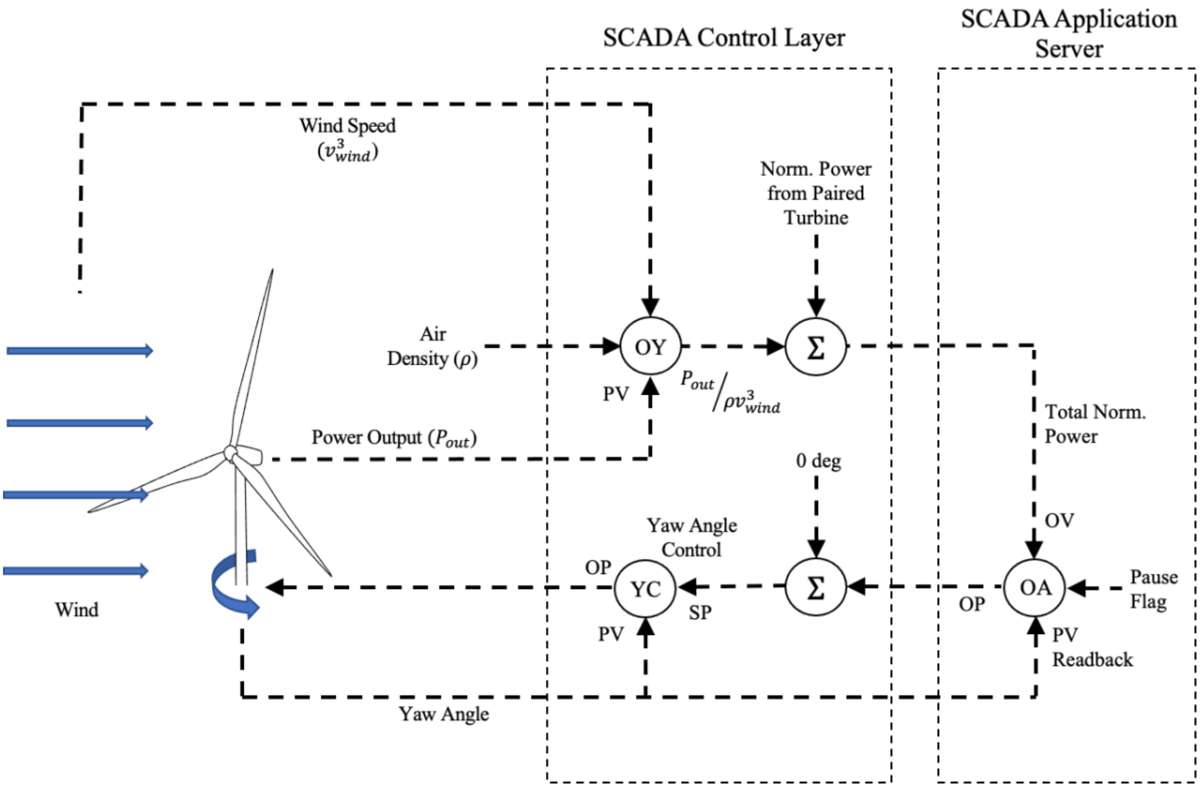

Figure 6: Single ORTO Agent Implementation (Adjacent Pairing Strategy)

There are periods when wind speeds dictate that optimization should be paused. Consider the distinct regions of wind turbine operation, as depicted in figure 7. In region 1, below a cut-in speed, there is no power generation as wind speeds are too light. In region 2, the wind turbine can generate power within a range of wind speeds but below a maximum rated power. In region 3, the wind speed is between the rated and cut-out speed. Rotor rotation is controlled to a nominal speed, until region 4 is reached upon which power generation is cut to zero, to protect against machinery damage during periods of severe weather.

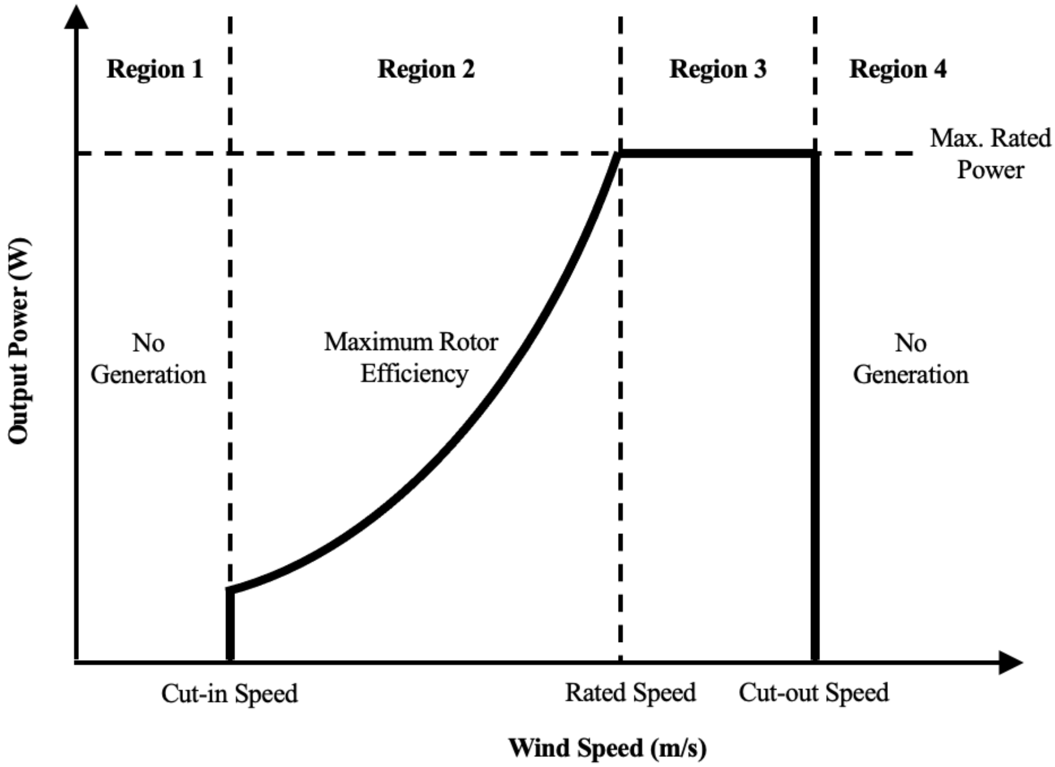

Figure 7: Wind Turbine Regions of Operation *(Apata & Oyedokun, 2020)*

Thus, power generation can only be maximized whilst operating in region 2. ORTO agents should therefore be paused when wind speed is below the cut-in speed and above the rated speed. Obviously, whilst the agents are paused, wind direction may change. Agents will then need to alter the yaw angle accordingly, to return to the optimum, once active again.

5 ORTO Agent Configuration

The chosen set-up parameters for each ORTO agent are detailed in Table 1. The rationale for each the agent settings is as follows:

- **Optimization Objective:** Power is to be maximized; hence the optimization objective is set to 'maximize' for all agents.
- **OV Engineering Range:** Set to the expected change in normalized power over the MV constraint bounds. So, over a $\pm 15^o$ change in yaw angle, expected change in total power is ~3000000W, giving an approximate normalized power change of $3000000/(20^3 * 1.204) \approx 310$. The specified OV range is therefore set to [310 0].
- **MV Engineering Range:** Set to $\pm 15^o$
- **Output Update Time:** Set approximately in line with process dynamics. Adjacent ORTO agents should also be asynchronous. Different update times are therefore set across the array diagonals.
- **Max Move Size:** After some initial tuning, set to 1.0 for all OAs.
- **MV Upper and Lower Constraint Bounds:** Set to MV engineering range, $\pm 15^o$.
- **Initial Push Direction:** We assume that each turbine yaw angle will need to be offset from the initial 0^o starting position, so defined as positive.

Appendix A provides a summary of the general design philosophy with appendix B providing a deeper overview of how ORTO agent configuration parameters should be set.

ORTO agents on $T_{(1,1)}, T_{(2,2)}, T_{(3,3)}$ & $T_{(4,4)}$	Optimization Objective	Maximize
	OV Engineering Range	[310 0]
	MV Engineering Range	[15 -15]
	Output Update Time (Secs)	137
	Max. Move Size	1
	MV Upper and Lower Constraint Bounds	[15 -15]
	Initial Push Direction?	+ve
ORTO agents on $T_{(1,2)}, T_{(2,3)}, T_{(3,4)}$ & $T_{(4,1)}$	Optimization Objective	Maximize
	OV Engineering Range	[310 0]
	MV Engineering Range	[15 -15]
	Output Update Time (Secs)	149
	Max. Move Size	1
	MV Upper and Lower Constraint Bounds	[15 -15]
	Initial Push Direction?	+ve
ORTO agents on $T_{(1,3)}, T_{(2,4)}, T_{(3,1)}$ & $T_{(4,2)}$	Optimization Objective	Maximize
	OV Engineering Range	[310 0]
	MV Engineering Range	[15 -15]
	Output Update Time (Secs)	157
	Max. Move Size	1
	MV Upper and Lower Constraint Bounds	[15 -15]
	Initial Push Direction?	+ve
ORTO agents on $T_{(1,4)}, T_{(2,1)}, T_{(3,2)}$ & $T_{(4,3)}$	Optimization Objective	Maximize
	OV Engineering Range	[310 0]
	MV Engineering Range	[15 -15]
	Output Update Time (Secs)	167
	Max. Move Size	1
	MV Upper and Lower Constraint Bounds	[15 -15]
	Initial Push Direction?	+ve

Table 1: ORTO Agents Configuration

6 Simulink Model

To test ORTO's performance, two Simulink models, consisting of the sixteen turbines and sixteen overlying ORTO agents, are used. The first simulates the adjacent pairing optimization arrangement, as described in section 3.2, the second the star cluster optimization arrangement, as described in section 3.3. Figure 8 details the top level of the adjacent pairing Simulink model.

A turbine power output, when subjected to no wake effects, of 10MW is assumed, giving a theoretical maximum output from the wind farm of 160MW. An average wind velocity, v_{wind}, of 20 m/s, an average air density, ρ, of 1.204 kg/m^3 and an orthogonal turbine separation, l, of 1.5km are also assumed. Wind direction remains from an easterly direction throughout.

To reiterate, ORTO agents have no prior knowledge of the model. They must work together to navigate and find the maximum possible power output. Four case studies are now presented.

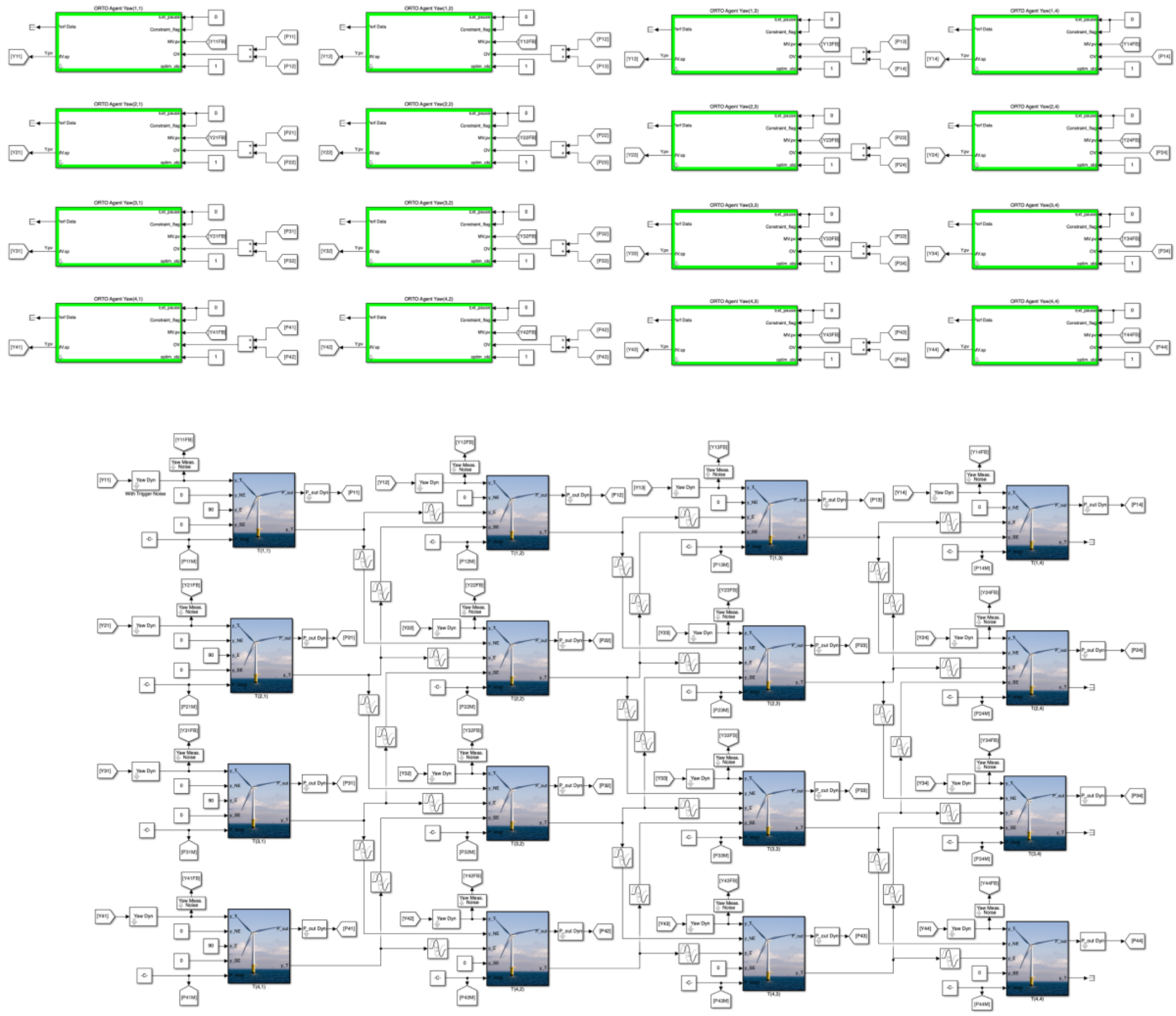

Figure 8: Simulink Winds Farm Modelling with Overlying ORTO Agents (Adjacent Pairing Strategy)

7 Simulation Analysis

To analyze ORTO's performance, both the adjacent pairing and star cluster arrangements are now tested, with and without noise on the normalized power OV. Throughout each simulation run, all turbines are operating in region 2, allowing for continuous optimization. Each run simulates 72 hours of operation, starting with all turbines perpendicular to the general wind direction i.e., having a 0^{o} yaw angle. All ORTO agents are engaged simultaneously at the start of each run.

For each test case, two trend plots are presented. The first details yaw angle movements made by the ORTO agents, subdivided on a turbine row basis to improve readability. The second details total power generated by the wind farm array, between a minimum trend line, where no action is taken to reduce wake effects and a theoretical maximum trend line, when all wake effects are removed. Observations drawn from the results are also presented.

7.1 Case 1: Wind Farm Power Optimization: ORTO Agent Adjacent Pairing Strategy

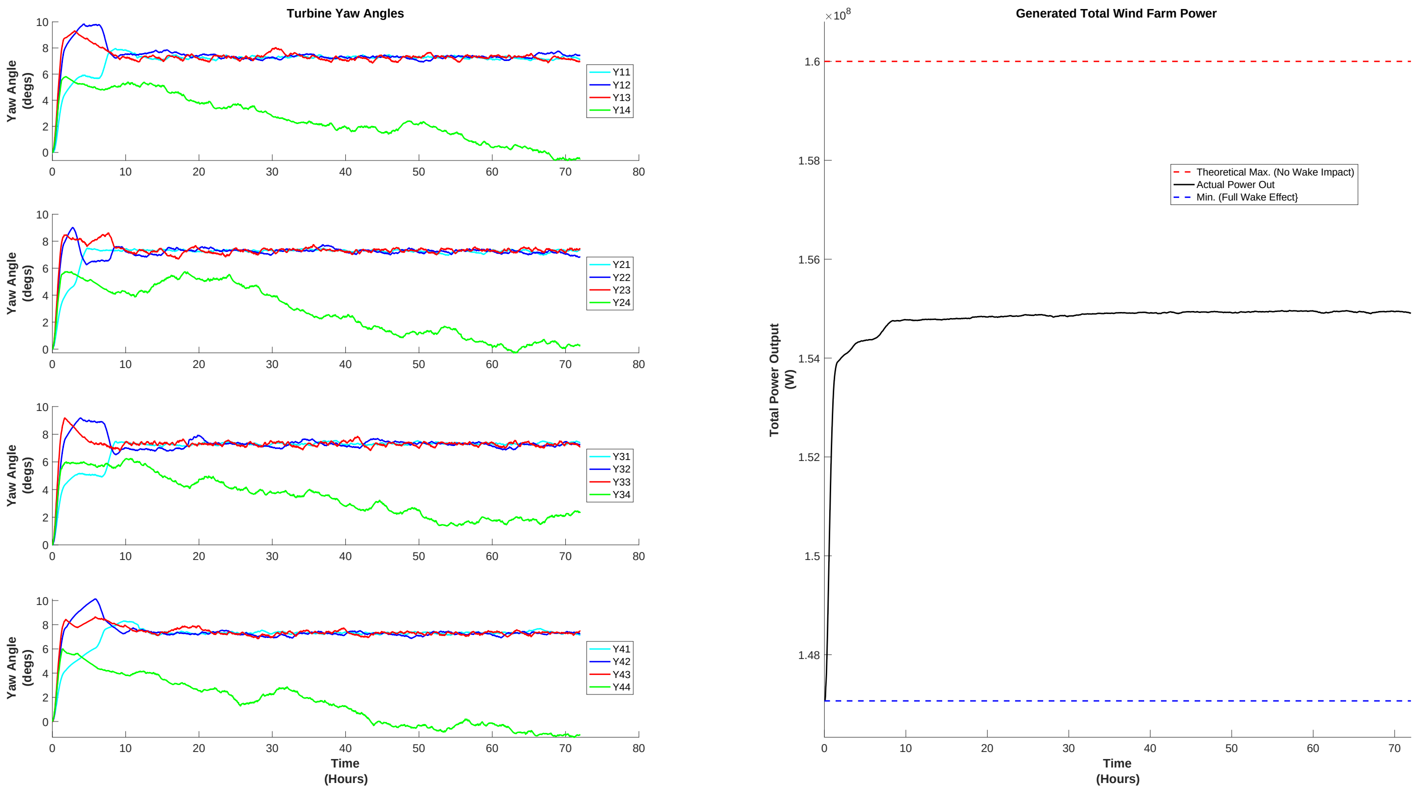

Figure 9: Wind Farm Power Optimization: ORTO Agent Adjacent Pairing Strategy.

Key Observations:

- All yaw angles are immediately adjusted by all sixteen ORTO agents, increasing total power generated by ~4.7% within the first two hours of operation.
- Over the following hours, the ORTO agents make further adjustments, increasing total power generated by 5.3%.
- Yaw angles of the turbines in the first three columns, settle at ~7.3deg.
- The yaw angles of the final column of turbines are slowly reduced back to zero, incrementally improving power generated yet further.
- Total additional power generated, through wake reduction, is ~7.2MW, equivalent to adding ~75% output from an additional turbine.

7.2 *Case 2: Wind Farm Power Optimization: ORTO Agent Star Cluster Strategy*

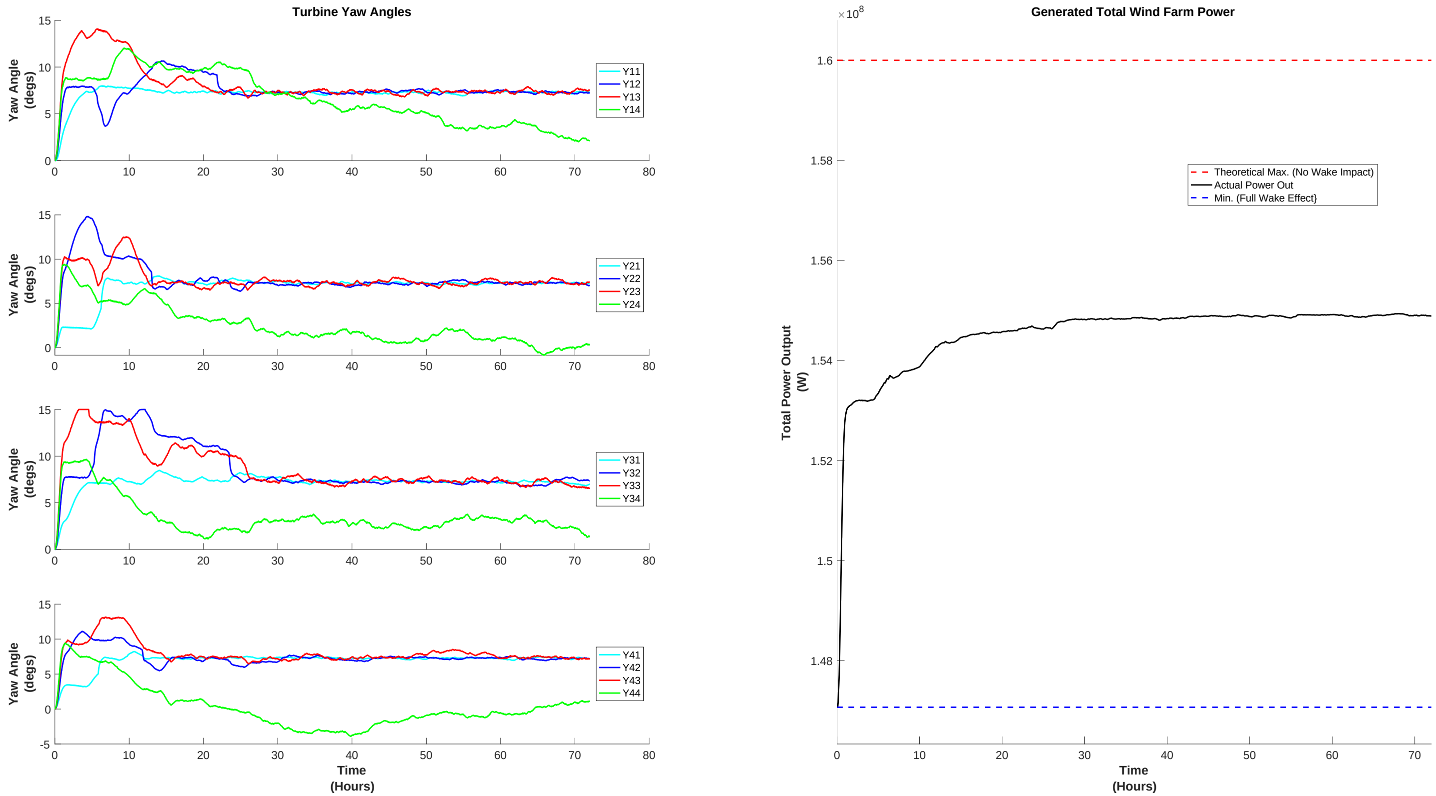

Figure 10: Wind Farm Power Optimization: ORTO Agent Star Cluster Strategy.

Case Description:

- Case 1 is now repeated, but with a star cluster arrangement around each ORTO agent.

Observations:

- Total power generated is increased again by ~5.3%, at the end of the test run. However, unlike case 1, the power increase achieved in the first two hours is reduced to ~4%.
- Yaw angles of the turbines in the first three columns again settle at ~7.3deg.
- The yaw angles of the final column of turbines are marginally quicker to zero, incrementally improving power generated.

7.3 Case 3: Wind Farm Power Optimization: ORTO Agent Adjacent Pairing Strategy with +/- 1.5% OV Noise

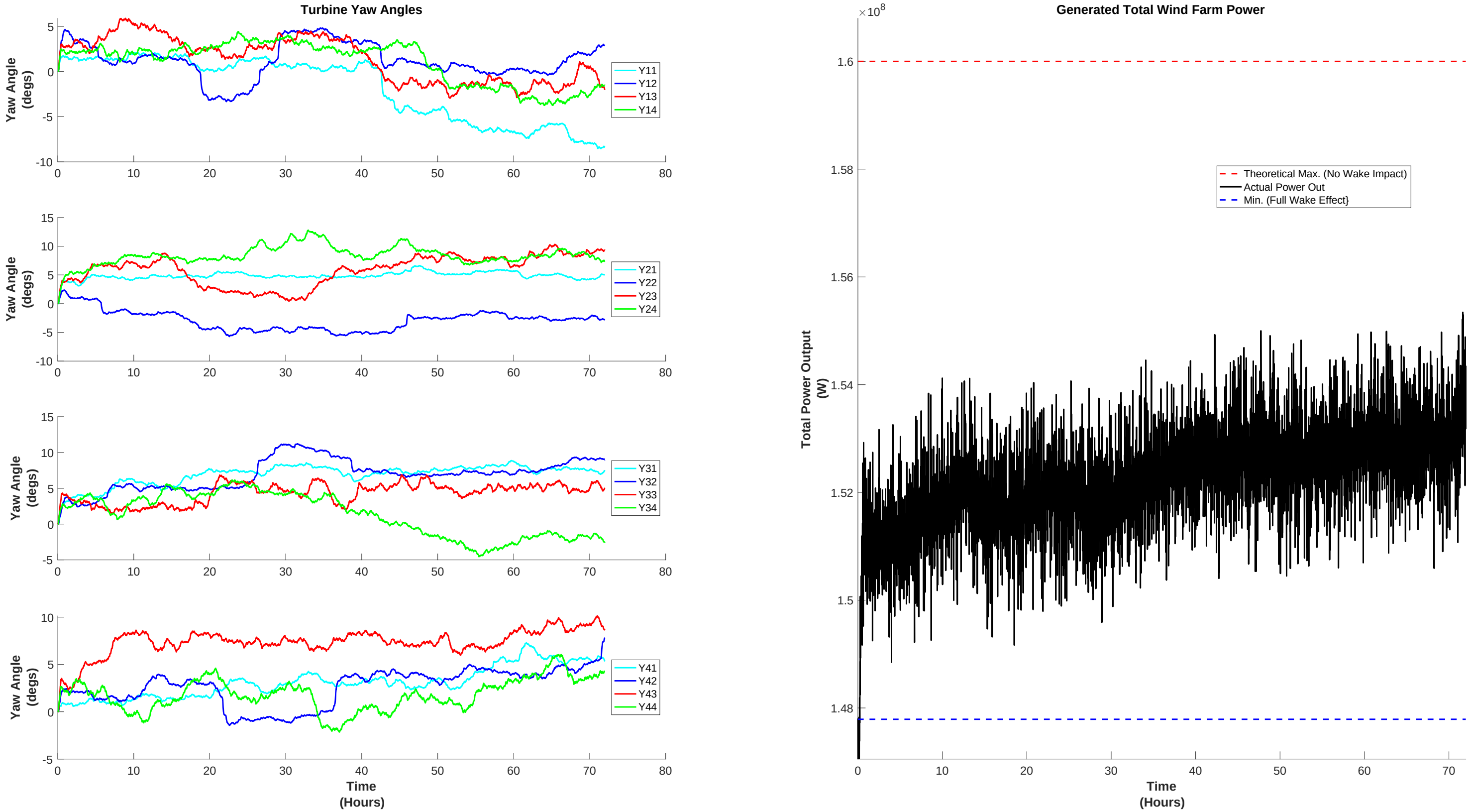

Figure 11: Case 3: Wind Farm Power Optimization: ORTO Agent Adjacent Pairing Strategy with +/- 1.5% OV Noise

Case Description:

- Case 1 is again repeated, but with 3% peak-to peak random noise added to each turbine output power signal, the aim being to replicate natural movement and measurement error in the normalized power calculations.

Observations:

- Comparing results achieved in case 1, noise does adversely affect optimization performance.
- The ORTO agents immediately increase power by ~3%. Further improvements are then made very gradually over the full duration of the test run. The final increase in power achieved is ~4%.

7.4 *Case 4: Wind Farm Power Optimization: ORTO Agent Star Cluster Strategy with +/- 1.5% OV Noise*

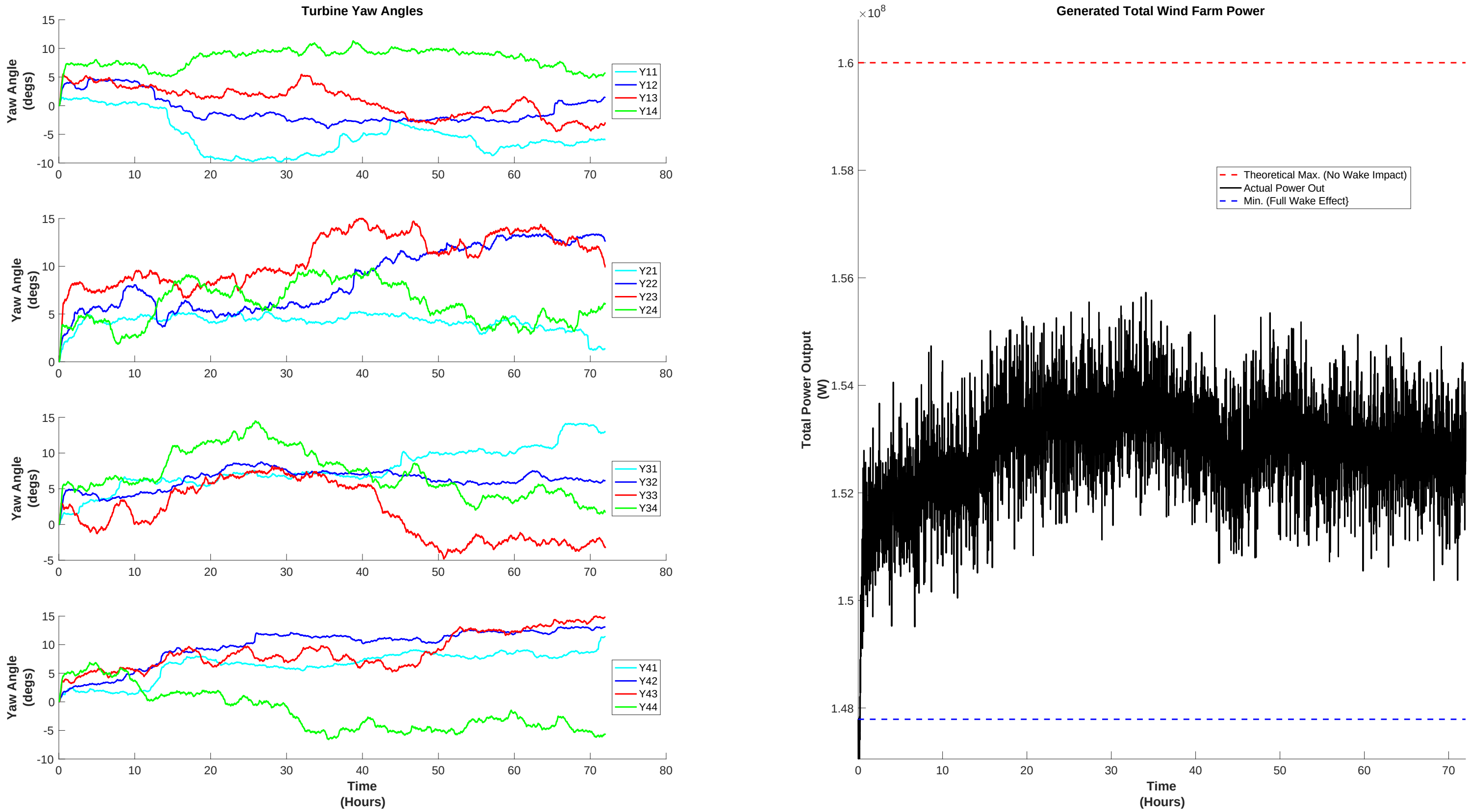

Figure 12: Case 4: Wind Farm Power Optimization: ORTO Agent Star Cluster Strategy with +/- 3% OV Noise.

Case Description:

- Case 2 is again repeated, but with 3% peak-to peak random noise added to each turbine output power signal, the aim being to replicate natural movement and measurement error in the normalized power calculations.

Observations:

- Comparing results achieved in case 2, noise does adversely affect optimization performance.
- The ORTO agents immediately increase power by ~3%. However, further improvements thereafter are less than those achieved in case 3.

8 Conclusions

Using a pragmatic approach to model wake effect interaction between turbines, this paper has described how ORTO agents can be employed to maximize generated power from a wind farm. It is believed such maximization of total power, an unconstrained optimum, by wake effect reduction in real time, has never been demonstrated before.

Two optimization strategies have been presented, each with advantages and disadvantages over the other. The 'adjacent pairing' strategy has the advantage of faster convergence to the maximum but adopting this strategy would result in greater design and configuration complexity to accommodate wind direction changes. The 'star cluster' strategy inherently accommodates wind direction changes, but convergence is slightly slower and performance degradation is slightly greater as OV noise grows. Both strategies could be built and commissioned incrementally. Once operational, individual turbines can easily be removed from each strategy e.g., to accommodate maintenance outages. Although a wind farm having an orthogonal grid pattern was chosen for modelling and testing purposes, each optimization strategy could easily be adapted to suit any geographical siting of wake impacted turbines, onshore or offshore.

For the interpreted wake impacts, both strategies delivered a maximum ~5.3% increase in generated power, whilst operating in figure 7's region 2. This is equivalent to the adding ¾ of a turbine to the array. It is expected that similar results would be attained by applying ORTO agents to an operational wind farm.

Finally, this application has demonstrated how a complex optimization problem can be solved by subdividing the system into an overlapping set of constituent parts and then applying ORTO agents to these parts. This approach can be applied to any complex system.

9 Further Work

Although the application of ORTO proved successful, further agent tuning could improve convergence speed. Additional optimization overlapping strategies across the turbine array should also be evaluated.

As illustrated, the noise level on the OV adversely impacts performance. The proposed ORTO approaches need to be validated using real wind speed, air density and power out data to calculate actual normalized power (used as the OV). The impact of excessive movement in normalized power, notably as wind speed changes rapidly, needs to be assessed.

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Appendix A. ORTO Scheme General Design Methodology

The procedure to design and build an ORTO scheme, for any given process or system, is as follows:

- **Step 1**: Review business objectives. Identify the key commercial, environmental or safety variable to be optimized (OV).
- **Step 2**: Identify all manipulated variables (MVs) which have an influence on the optimization objective and define the range within which an ORTO agent can safely move them within. The number of MVs identified equals the number of ORTO agents required.
- **Step 3**: Identify any wild 'feed-through' variables (WVs) which directly impact the optimization variable, irrespective of MV action. If required, modify the OV to take account of the WVs accordingly.
- **Step 4**: Identify any external constraint variables (CVs) that the optimization must respect e.g., product quality variables.
- **Step 5**: Implement each ORTO agent, with outputs cascaded to each respective MV and with OV, MV readback and CV logic inputs configured.
- **Step 6**: Configure each ORTO agent by setting the parameters, as listed and described in Appendix B.
- **Step 7**: Switch each ORTO agent on, monitoring OV improvements. Adjust maximum move sizes and / or search space, as confidence grows in optimization performance. Remove any ORTO agents making a negligible contribution. Add further ORTO agents as additional MVs are identified.

Appendix B. ORTO Agent Configuration Parameters

Optimization Objective	Set to 'Maximize' or 'Minimize'. All ORTO agents must have the same optimization objective within an optimization scheme.
OV Engineering Range (EU)	Knowing the OV and MV ranges helps ORTO to calibrate its MV moves.
MV Engineering Range (EU)	
Output Update Time (Secs)	Set as a function of system dynamics. Combined with maximum move size, sets the speed of optimization.
Max. Move Size (EU)	The maximum acceptable net move across the defined output update time. Setting maximum move size too low will slow down optimization. Setting it too high may cause excessive movement of MV around the optimum value.
MV Hi-Lo Constraint Bounds (EU)	The bounds within which the MV can be moved.
Initial Push Direction	Set to 'Positive', 'Negative' or 'Not Sure'. Direction is a function of the initial condition i.e., starting point.