Optimal power dispatching in offshore wind farms ensuring power reserve for frequency control and load mitigation

Michel KINNAERT, Younes OUDICH
Université Libre de Bruxelles
Department of Control Engineering and System Analysis
CP 165/55, 50 Av.F.D. Roosevelt, B-1050 Bruxelles, Belgium
Emails: `michel.kinnaert@ulb.ac.be, younes.oudich@ulb.ac.be`

1 Introduction

In the last two decades, increasing interest is brought to control the output active power of wind farms in order to meet power set-points sent to the wind turbines and fulfill the power demand. However, the ability to participate in the frequency regulation and provide ancillary services to the TSO (Transmission System Operator) is one of the present offshore wind farm challenges. The goal of this research project is to further investigate how wind farms can achieve this goal at best by taking into account wake effects, load mitigation and active power reserve in the dispatching of the active power set points to the individual turbines. The control strategy will be based on three modules. A module estimating the total power available in the immediate future, a module deducing the plant wide power reserve needed to ensure proper frequency regulation, and a module performing the optimal power dispatching including load mitigation. The developed control strategy will be implemented and validated in simulation using software like FAST.Farm and SOWFA.

2 The control strategy

The present control strategy in the Belgian offshore wind farms is based only on controlling the output power in order to dispatch the demand from ELIA (the Belgian TSO) as displayed in **Figure.1** by following the blue dots. Indeed, thanks to measurements and historical data inputs, the available power of the wind farm is predicted one day ahead. On this basis, ELIA decides on a power reference that goes through a power controller dispatching the power needed for the demand. Finally, the wind farm gives back new SCADA measurements as input to the power prediction algorithm. Our contribution is to assess the opportunity for offshore wind farms to participate in the utility grid. Indeed, by following the orange dots **Figure.1**, the wind farm power is predicted in the immediate future then converted to know the immediate future power reserve at hand. If a fault is detected, a frequency controller overcomes this disturbance by appropriate action on the wind farm power set-points.

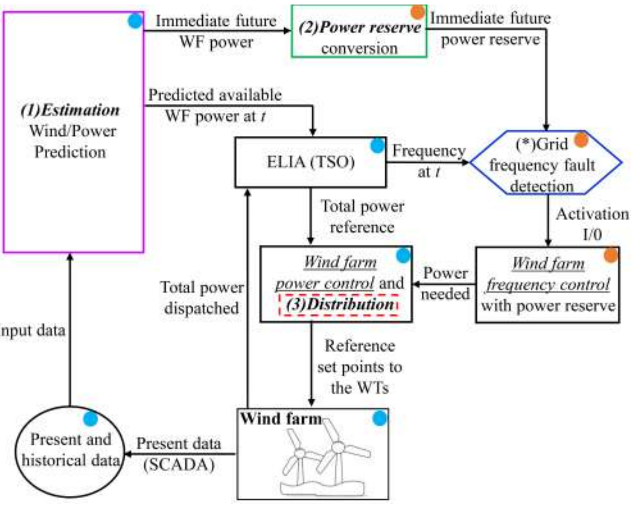


Figure 1: The control strategy of the belgian offshore wind farms (blue dots in the top right corners), and our contribution (orange dots in the top right corners

3 Future work

The research project will focus on the three following modules that are also displayed in **Figure.1**:

1. Estimation: predict the total power available now and in the immediate future.
2. Power reserve: determine the plant-wide power reserve level needed to provide frequency regulation.
3. Distribution (Control): Determine the optimal power set points to distribute to the wind turbines.

4 Acknowledgement

This research is part of the Belgian PhairywinD project, which aims to develop the current and the future offshore wind farms in a multi-disciplinary framework. It is funded by the Belgian Energy Transition Fund (FPS Economy).

References

[1] Jan-Willem van Wingerden, Lucy Pao, Jacob Aho, Paul Fleming, ”Active Power Control of Waked Wind Farms” IFAC-PapersOnLine,Volume 50, Issue 1, 2017.

ULB UNIVERSITÉ LIBRE DE BRUXELLES

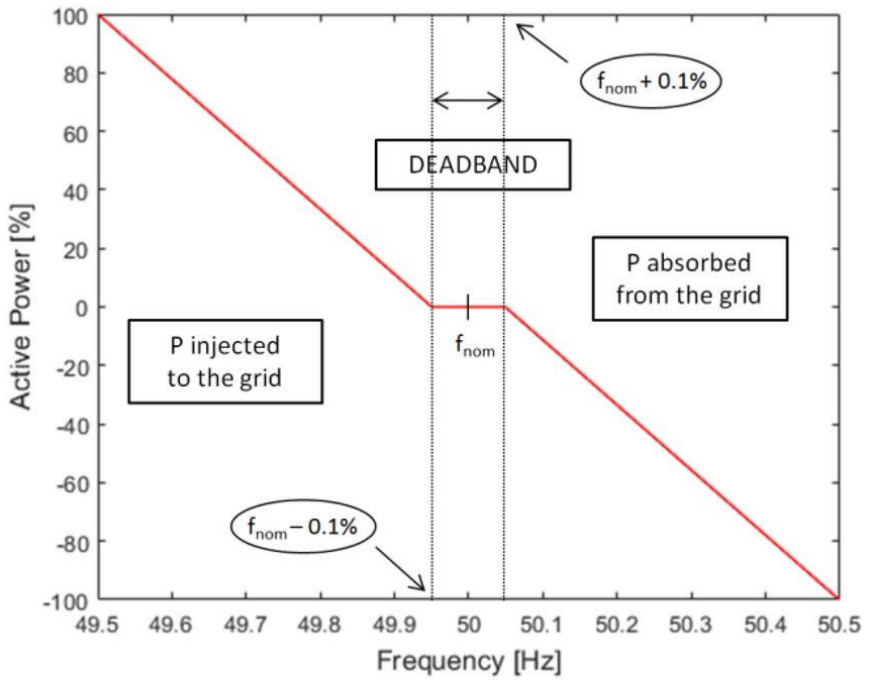
Optimal power dispatching in offshore wind farms ensuring power reserve for frequency control and load mitigation

- Younes Oudich : Depart. SAAS - ULB
- Michel Kinnaert : Depart. SAAS - ULB
- Johan Gyselinck : Depart. BEAMS - ULB
- Frederik De Belie : Depart. ESME - UGENT

PhairywinD
Belgian Offshore PhD Expertise

Power balance in a power system

Balance between **Production** power and **Consumption** power must be controlled.

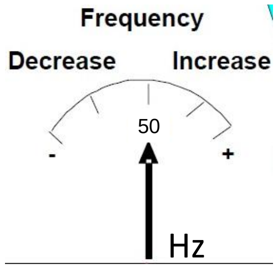


[2]

- How to measure this balance?

➔Frequency is the global indicator of consumption-production balance !

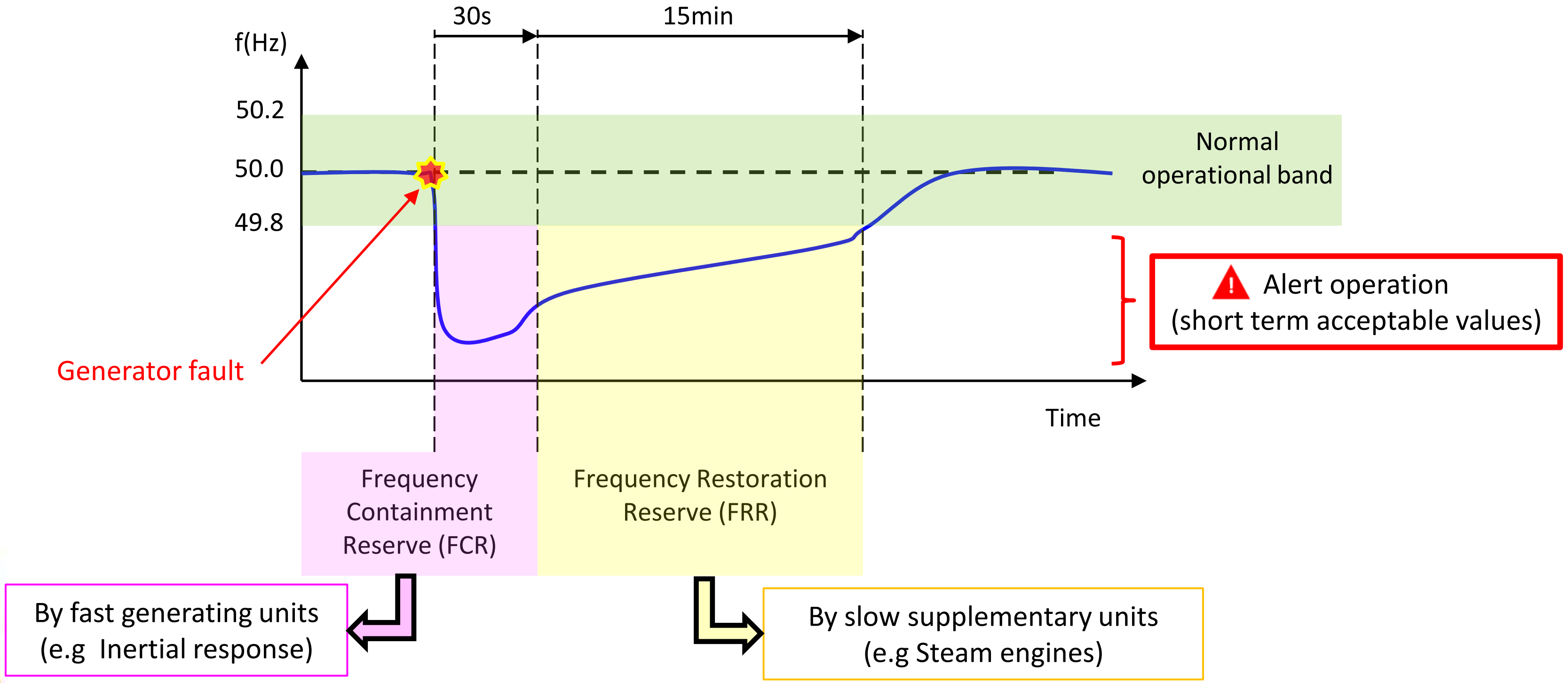
- **ELIA (TSO)** requirement 1: The grid frequency must be: 50 Hz +/- 0.2 Hz



[2] ANN-based grid voltage and frequency forecaster, Alessandro.M et Al.

Power balance in a power system

ELIA (TSO) requirements (2,3): Time to deliver primary and secondary frequency regulations



Normal operational band

Alert operation
(short term acceptable values)

Generator fault

Frequency Containment Reserve (FCR)

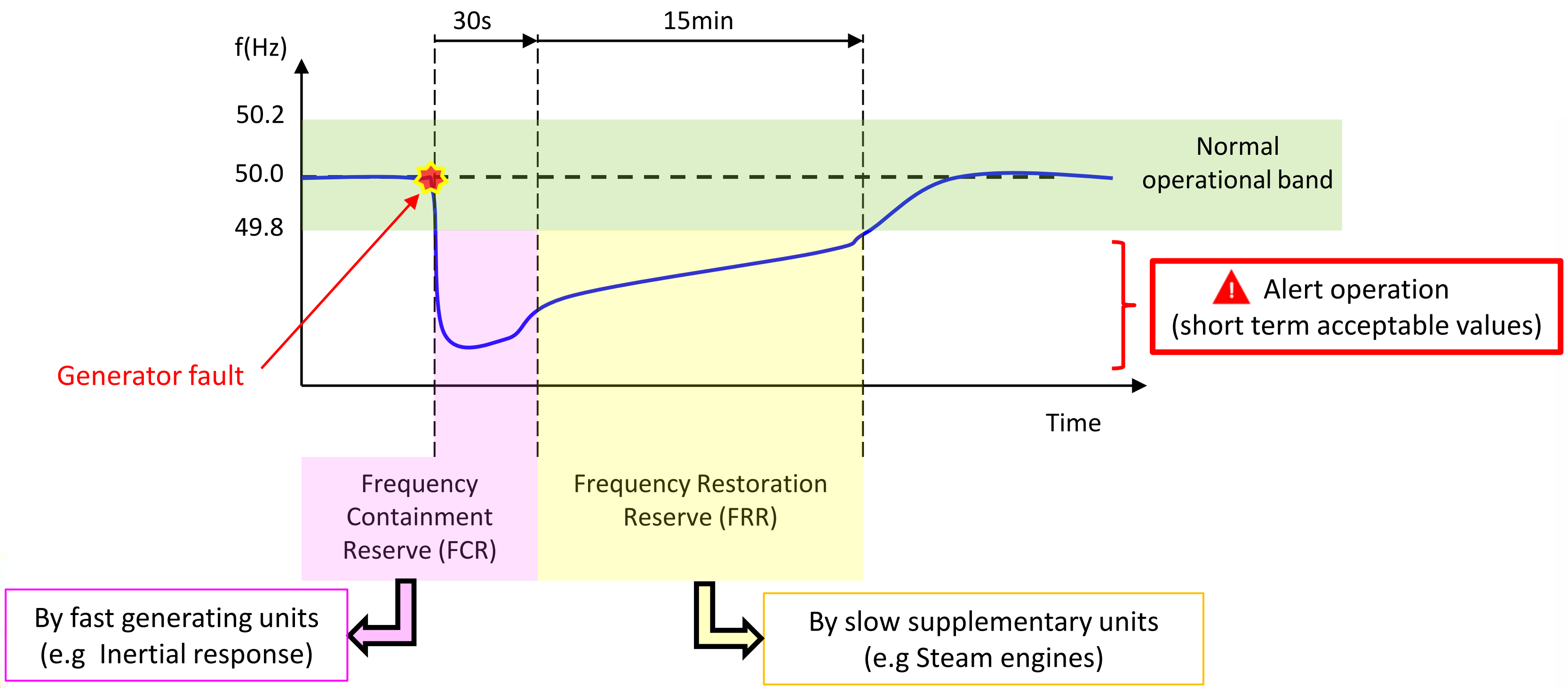
Frequency Restoration Reserve (FRR)

By fast generating units
(e.g Inertial response)

By slow supplementary units
(e.g Steam engines)

Aim of the thesis (Problem)

ELIA requirements (2,3): Time to deliver primary and secondary frequency regulations



Normal operational band

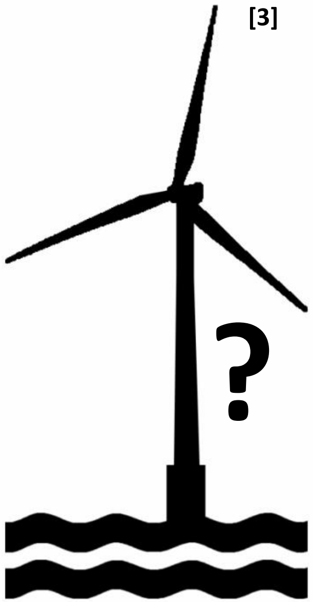
⚠ Alert operation
(short term acceptable values)

Frequency Containment Reserve (FCR)

Frequency Restoration Reserve (FRR)

By fast generating units
(e.g Inertial response)

By slow supplementary units
(e.g Steam engines)

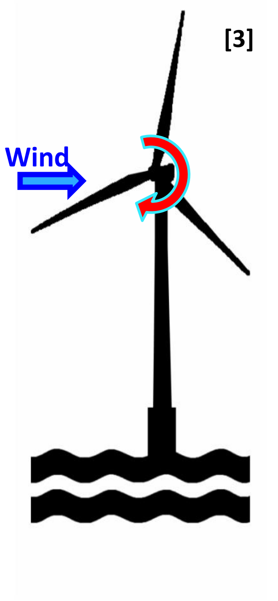


➔ **Aim of the thesis:** How wind farms can achieve at best ancillary services, FCR and FRR, in case of a fault in the grid?

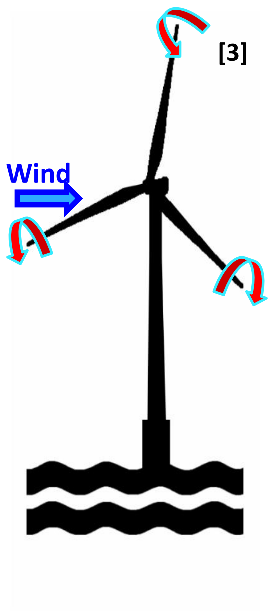
[3]: Free icons, License: Personal Use Only:https://www.vippng.com/preview/iJJoTm_marine-offshore-wind-turbine-icon-offshore-wind-turbines/

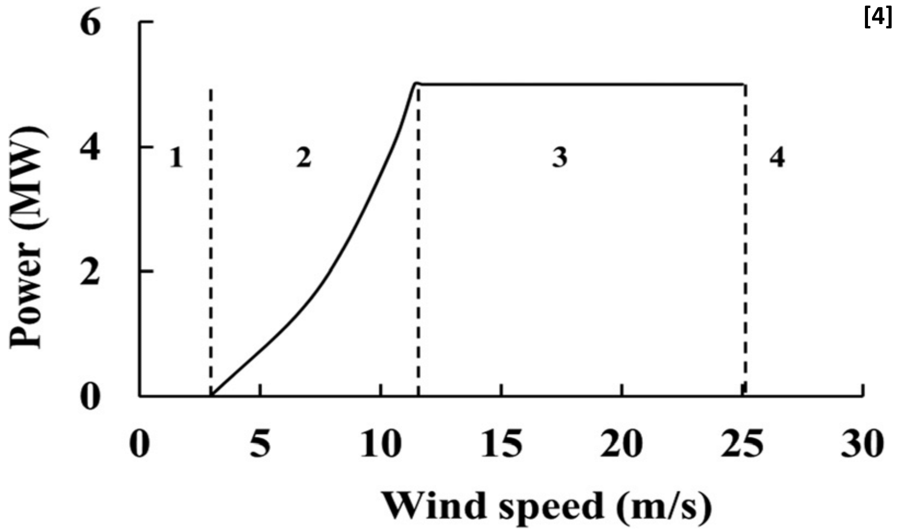
Main controls on a wind turbine

Torque control



Pitch control





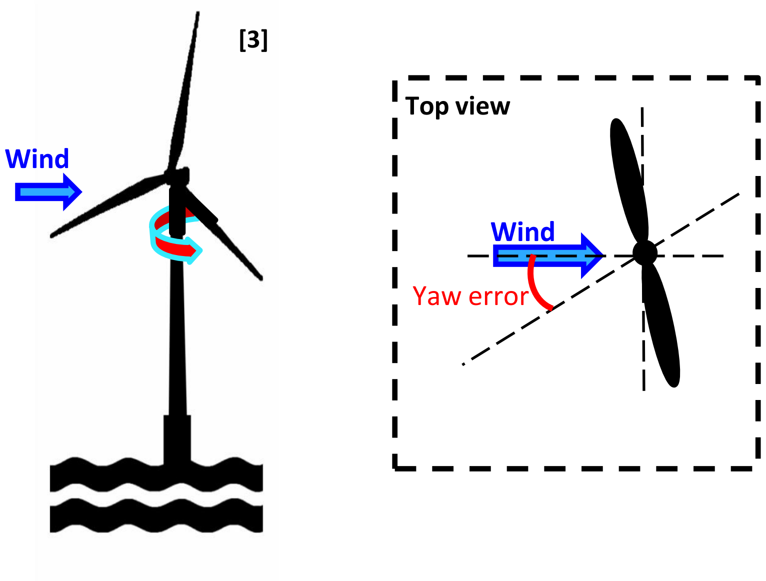
➔ Controls aim: Maximize the wind turbine power dependently from wind speed

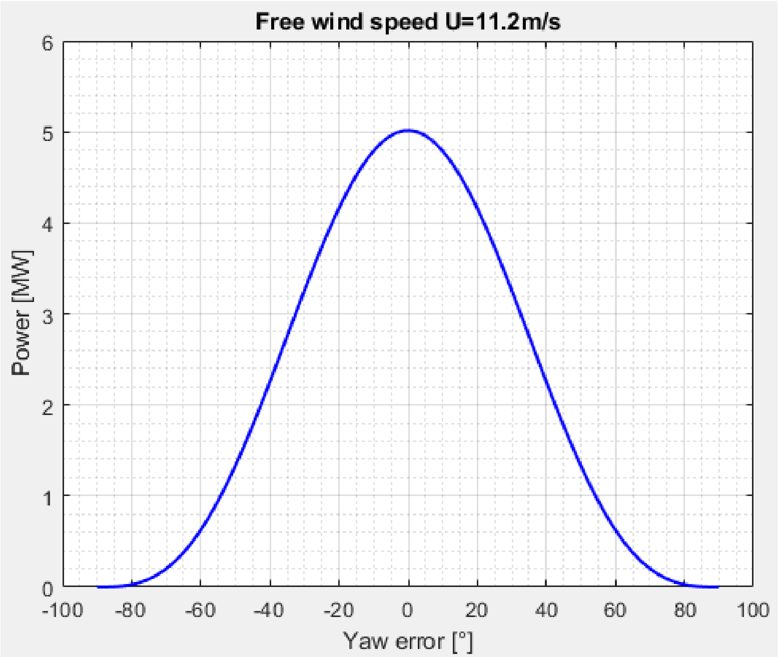
➔ Fast controls (torque rate: 15 kN.m/s | pitch rate: 8°/s)

[4]: ''Load Mitigation Using Slotted Flaps in Offshore Wind Turbines'' Silpha et Al.

Main controls on a wind turbine

Yaw control



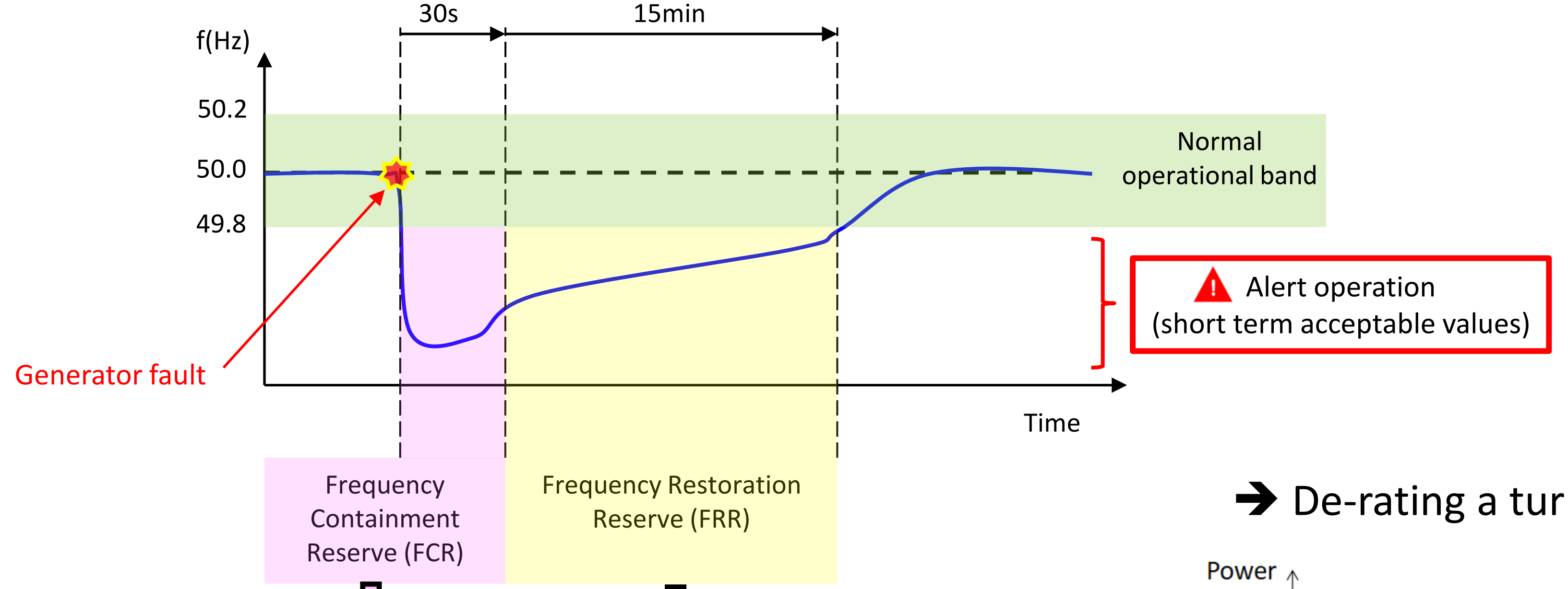


➔ Control aim: Maximize the wind turbine power by minimizing the yaw error.

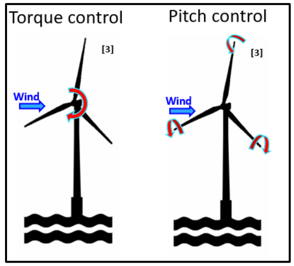
➔ Slow control (yaw rate: 0.3°/s)
27 times slower than the pitch control!

Wind farms in power system balance (state of the art)

In the literature: It has been proven that FCR or FRR can be achieved by the fast controllers: De-rating the turbines using pitch and torque controls

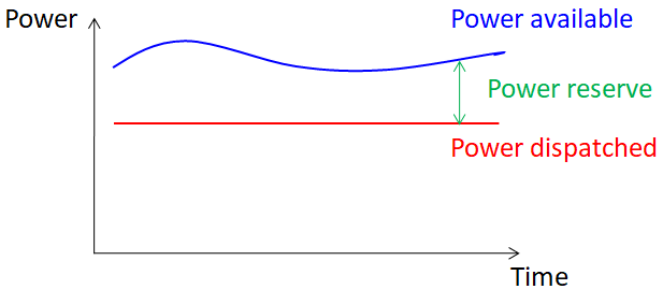


By fast generating units: Torque and Pitch controls



By slow supplementary units: Torque and Pitch controls

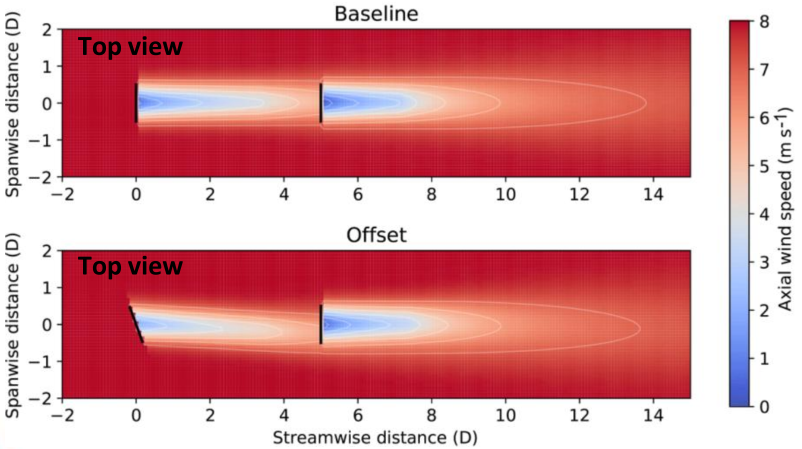
➔ De-rating a turbine:



Wind farms in power system balance (state of the art)

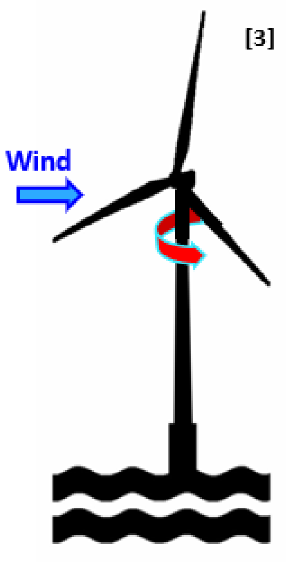
In the literature: It has been proven that a **wind farm efficiency** can be **increased by** approximately **15%** thanks to the yaw redirecting method (**yaw optimization control**)

[5]



[6]

Yaw control



[3]

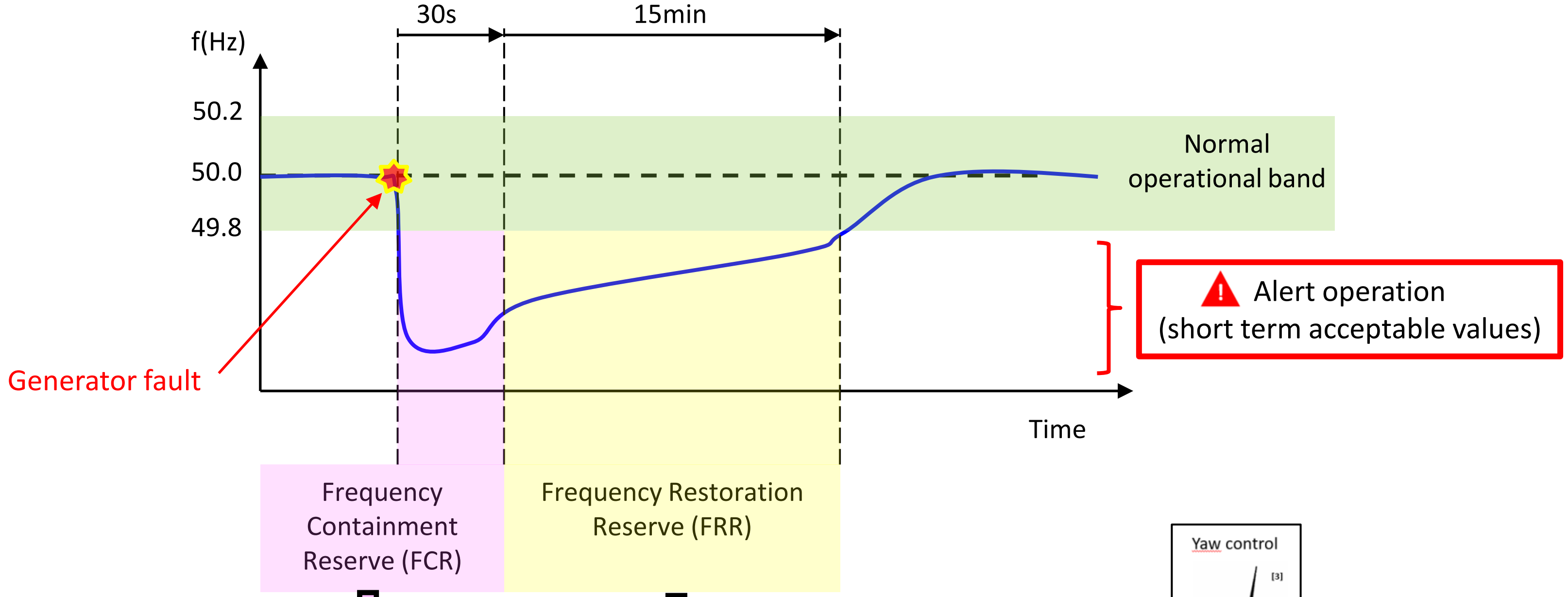
Wind farm efficiency:

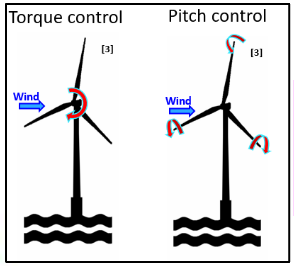
$$\eta = \frac{Annual\ production}{Wind\ farm\ capacity}$$

[5]: A light fog reveals the wake effect behind turbines at Vattenfall's Horns Rev wind farm off Denmark.Photo: Vattenfall
[6]: Design and analysis of a wake steering controller with wind direction variability; Eric et Al.

Wind farms in power system balance (Solution)

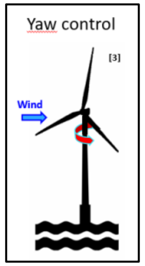
Novel approach: Acheive **FCR** and **FRR** using **torque and pitch controls** as the fast generating units, and **yaw optimization control** as the slow supplementary unit.





By fast generating units:
Torque and Pitch controls

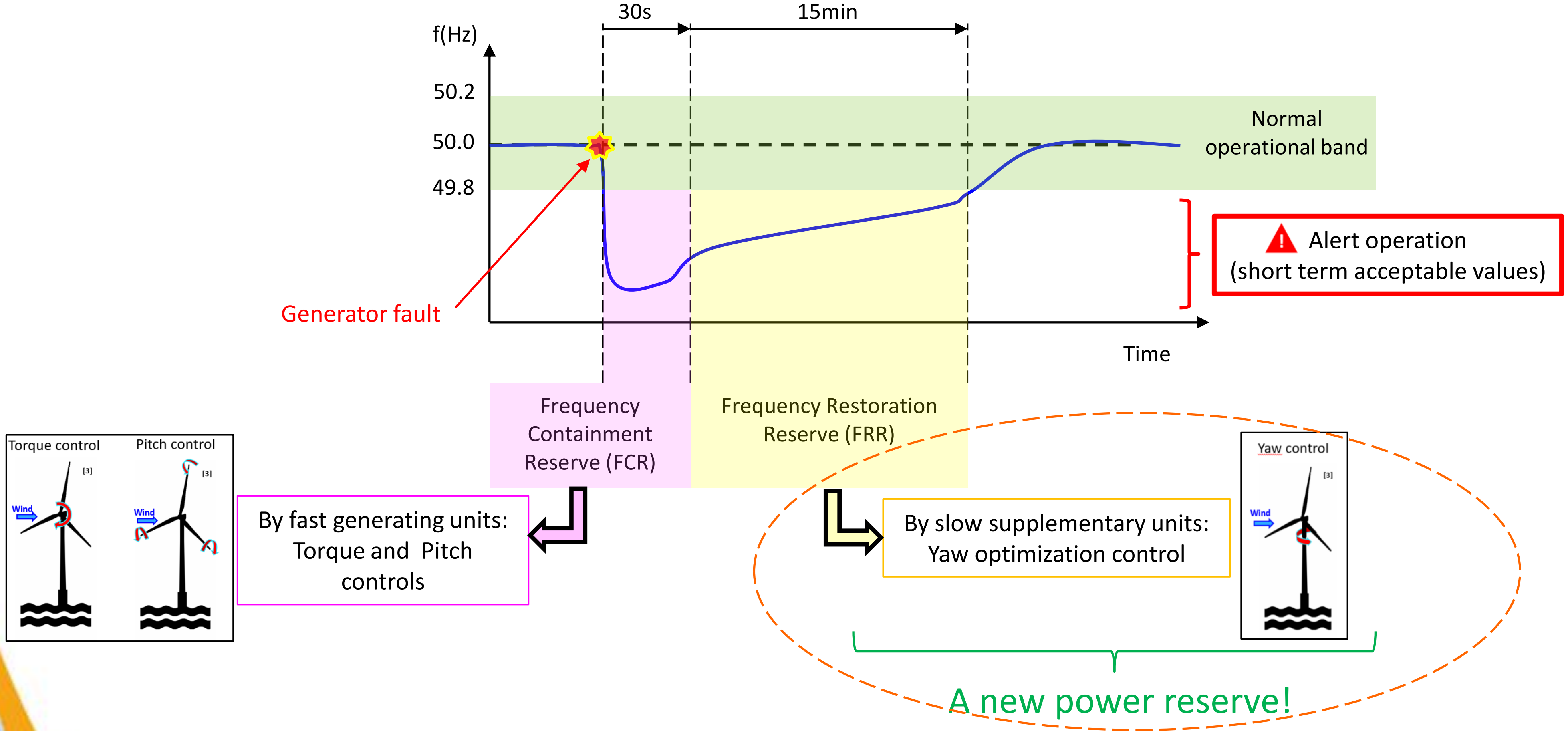
By slow supplementary units:
Yaw optimization control



A new power reserve!

Wind farms in power system balance (Solution)

Novel approach: Acheive **FCR** and **FRR** using **torque and pitch controls** as the fast generating units, and **yaw optimization control** as the slow supplementary unit.



Alert operation (short term acceptable values)

Frequency Containment Reserve (FCR)

Frequency Restoration Reserve (FRR)

By fast generating units: Torque and Pitch controls

By slow supplementary units: Yaw optimization control

A new power reserve!

What is the relationship between wake, yaw, and power within a wind farm?

Wake – yaw – power model

Wake deficit of turbine *j*:

$$u(x,r,\boldsymbol{a},\gamma_j) = \left(1 - \delta u(x,r,\boldsymbol{a},\gamma_j)\right) U_0$$

$$\delta u(x,r,\boldsymbol{a},\gamma_j) = 2\boldsymbol{a}\cos(\boldsymbol{\mu}\gamma_j)\left(\frac{R}{R+\boldsymbol{k}x}\right)^2 \exp\left(-\left(\frac{r - c(x,\boldsymbol{a},\gamma_j)}{R+\boldsymbol{k}x}\right)^2\right)$$

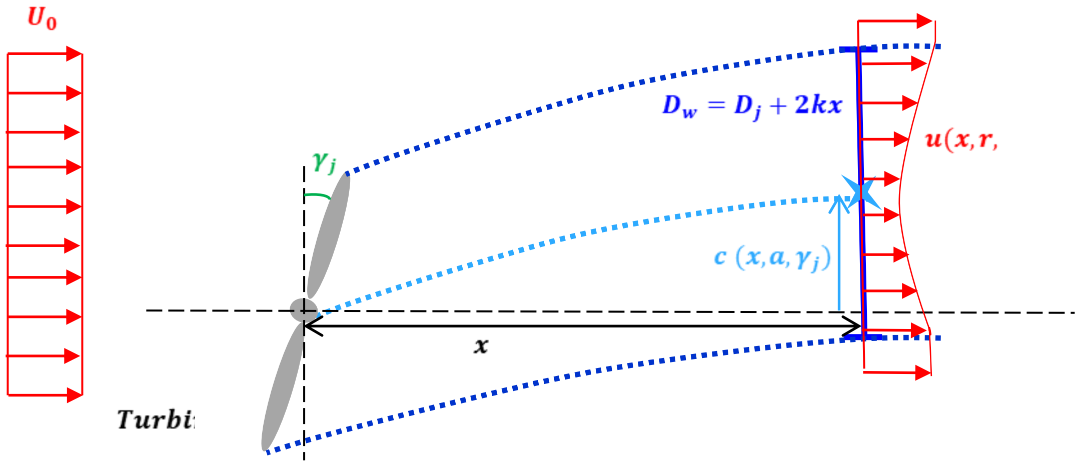
Wake center position:

$$c(x,\boldsymbol{a},\gamma_j) = \int_0^x \tan\left(\Phi(v,\boldsymbol{a},\gamma_j)\right) dv - \tau(x)$$

with:

$$\Phi(x,\boldsymbol{a},\gamma_j) \approx \frac{2\cos^2(\gamma_j)\sin(\gamma)\,\boldsymbol{a}(1-\boldsymbol{a})}{\left(1+\frac{2\boldsymbol{k_d}x}{D}\right)^2}$$

$$\tau(x) = \boldsymbol{a_d} + \boldsymbol{b_d}x$$



Wake – yaw – power model

Wake deficit of turbine *j*:

$$u(x,r,\boldsymbol{a},\gamma_j) = \left(1 - \delta u(x,r,\boldsymbol{a},\gamma_j)\right) U_0$$

$$\delta u(x,r,\boldsymbol{a},\gamma_j) = 2\boldsymbol{a}\cos(\boldsymbol{\mu}\gamma_j)\left(\frac{R}{R+\boldsymbol{k}x}\right)^2 \exp\left(-\left(\frac{r - c(x,\boldsymbol{a},\gamma_j)}{R+\boldsymbol{k}x}\right)^2\right)$$

Wake center position:

$$c(x,\boldsymbol{a},\gamma_j) = \int_0^x \tan\left(\Phi(v,\boldsymbol{a},\gamma_j)\right) dv - \tau(x)$$

with:

$$\Phi(x,\boldsymbol{a},\gamma_j) \approx \frac{2\cos^2(\gamma_j)\sin(\gamma)\,\boldsymbol{a}(1-\boldsymbol{a})}{\left(1+\frac{2\boldsymbol{k_d}x}{D}\right)^2}$$

$$\tau(x) = \boldsymbol{a_d} + \boldsymbol{b_d}x$$

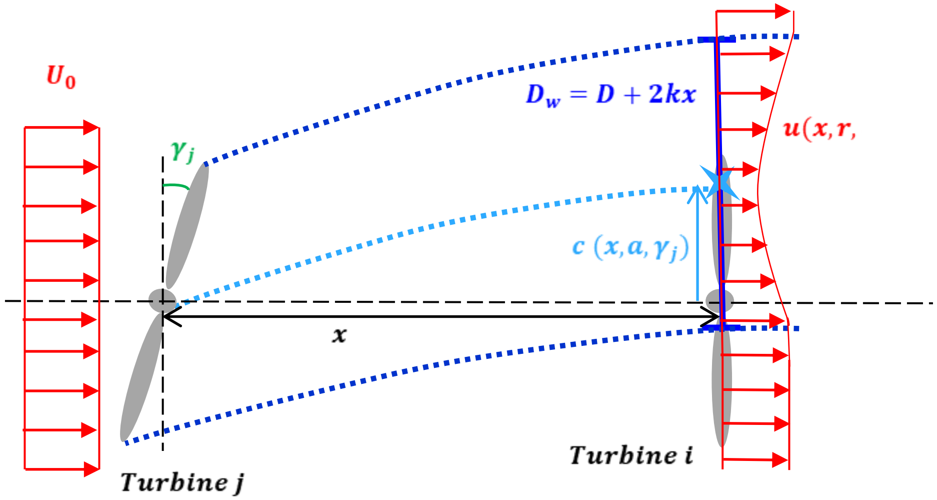
Wake deficit by all turbines {j} on turbine i:

$$\delta u_{ij}(\boldsymbol{a},\gamma_j) = \frac{1}{\pi R^2}\int_{\theta'=0}^{2\pi}\int_{r'=0}^{R} \delta u_{ij}(r',\theta',\boldsymbol{a},\gamma_j)\, r' dr' d\theta'$$

$$\delta u_i(\boldsymbol{a},\gamma_{js}) = \sqrt{\sum_{j\neq i} \delta u_{ij}^2(\boldsymbol{a},\gamma_j)}$$

Power generated by turbine i:

$$P_i(\boldsymbol{a},\gamma_i,U_0) = \frac{1}{2}\eta\rho\pi R^2 \boldsymbol{C_p}(\lambda,\beta)\left\{\left[1-\delta u_i(\boldsymbol{a},\gamma_{js})\right]U_0\right\}^3 \cos^3(\gamma_i)$$



Wake – yaw – power model

Wake deficit of turbine *j*:

$$u(x,r,\boldsymbol{a},\gamma_j) = \left(1 - \delta u(x,r,\boldsymbol{a},\gamma_j)\right) U_0$$

$$\delta u(x,r,\boldsymbol{a},\gamma_j) = 2\boldsymbol{a}\cos(\boldsymbol{\mu}\gamma_j)\left(\frac{R}{R+\boldsymbol{k}x}\right)^2 \exp\left(-\left(\frac{r - c(x,\boldsymbol{a},\gamma_j)}{R+\boldsymbol{k}x}\right)^2\right)$$

Wake center position:

$$c(x,\boldsymbol{a},\gamma_j) = \int_0^x \tan\left(\Phi(v,\boldsymbol{a},\gamma_j)\right) dv - \tau(x)$$

with:

$$\Phi(x,\boldsymbol{a},\gamma_j) \approx \frac{2\cos^2(\gamma_j)\sin(\gamma)\,\boldsymbol{a}(1-\boldsymbol{a})}{\left(1+\frac{2\boldsymbol{k_d}x}{D}\right)^2}$$

$$\tau(x) = \boldsymbol{a_d} + \boldsymbol{b_d}x$$

Wake deficit by all turbines {j} on turbine i:

$$\delta u_{ij}(\boldsymbol{a},\gamma_j) = \frac{1}{\pi R^2}\int_{\theta'=0}^{2\pi}\int_{r'=0}^{R} \delta u_{ij}(r',\theta',\boldsymbol{a},\gamma_j)\, r' dr' d\theta'$$

$$\delta u_i(\boldsymbol{a},\gamma_{js}) = \sqrt{\sum_{j\neq i} \delta u_{ij}^2(\boldsymbol{a},\gamma_j)}$$

Power generated by turbine i:

$$P_i(\boldsymbol{a},\gamma_i,U_0) = \frac{1}{2}\eta\rho\pi R^2 \boldsymbol{C_p}(\lambda,\beta)\left\{\left[1-\delta u_i(\boldsymbol{a},\gamma_{js})\right]U_0\right\}^3 \cos^3(\gamma_i)$$

Hypothesis & limits:

- Far wake model ($x \geq 3D$)
- Static model
- Valid only between cut-in and rated wind speeds

Constante values:

- $\boldsymbol{C_p = 0.48}$
- $\boldsymbol{a = 1/3}$

Wake – yaw – power model

Wake deficit of turbine *j*:

$$u(x,r,\boldsymbol{a},\gamma_j) = \big(1-\delta u(x,r,\boldsymbol{a},\gamma_j)\big)\,U_0$$

$$\delta u(x,r,\boldsymbol{a},\gamma_j) = 2\boldsymbol{a}\cos(\boldsymbol{\mu}\gamma_j)\left(\frac{R}{R+\boldsymbol{k}x}\right)^2 \exp\left(-\left(\frac{r-c(x,\boldsymbol{a},\gamma_j)}{R+\boldsymbol{k}x}\right)^2\right)$$

Wake center position:

$$c(x,\boldsymbol{a},\gamma_j) = \int_0^x \tan\big(\Phi(v,\boldsymbol{a},\gamma_j)\big)\,dv - \tau(x)$$

with:

$$\Phi(x,\boldsymbol{a},\gamma_j) \approx \frac{2\cos^2(\gamma_j)\sin(\gamma)\,\boldsymbol{a}(1-\boldsymbol{a})}{\left(1+\frac{2\boldsymbol{k_d}x}{D}\right)^2}$$

$$\tau(x) = \boldsymbol{a_d} + \boldsymbol{b_d}x$$

Wake deficit by all turbines {j} on turbine i:

$$\delta u_{ij}(\boldsymbol{a},\gamma_j) = \frac{1}{\pi R^2}\int_{\theta'=0}^{2\pi}\int_{r'=0}^{R} \delta u_{ij}(r',\theta',\boldsymbol{a},\gamma_j)\,r'dr'd\theta'$$

$$\delta u_i(\boldsymbol{a},\gamma_{js}) = \sqrt{\sum_{j\neq i}\delta u_{ij}^2(\boldsymbol{a},\gamma_j)}$$

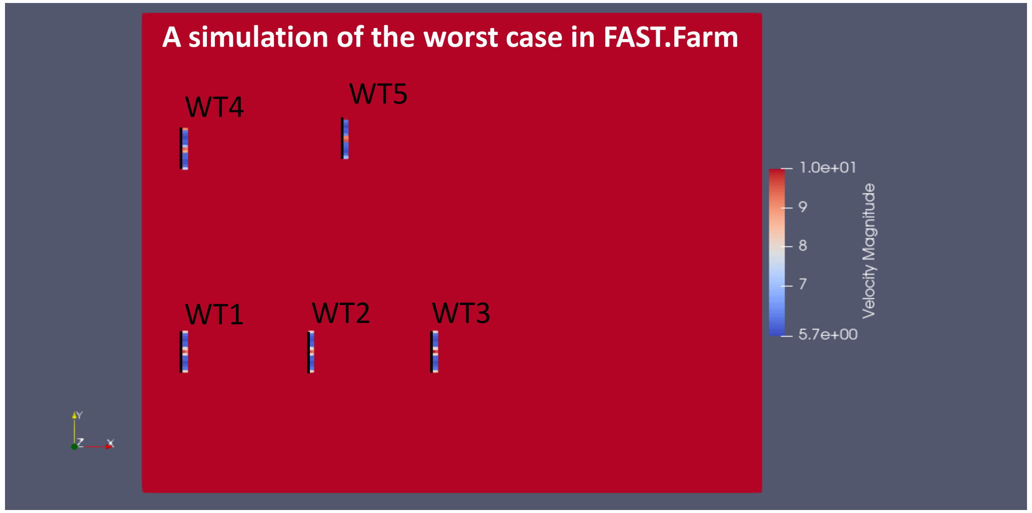
5 parameters to update:
Best guess values from literature:

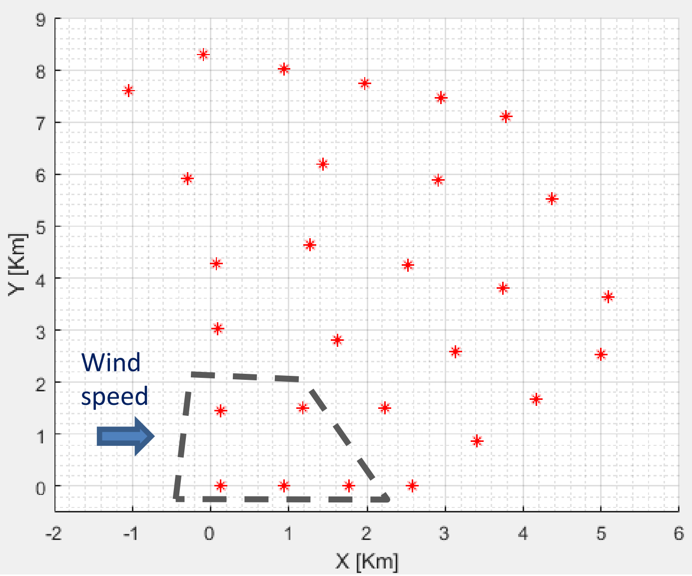
$k = 0.03$
$\mu = 1.2$
$k_d = 0.15$
$a_d = 4.5$
$b_d = 0.01$

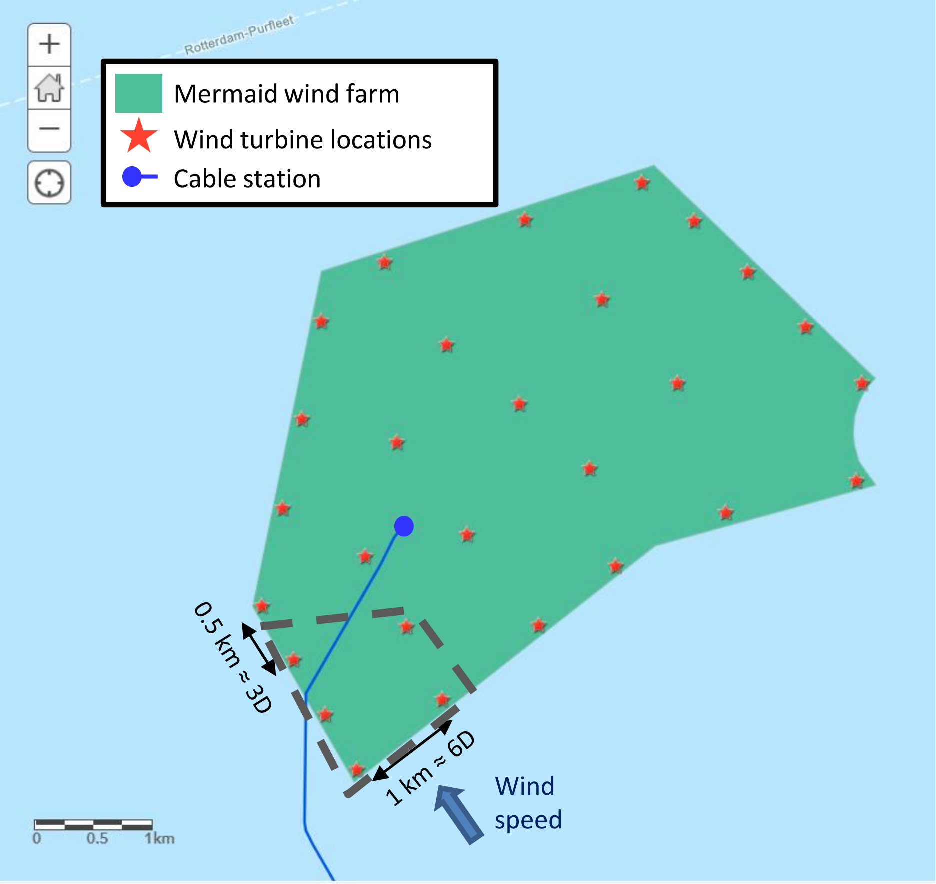
Power generated by turbine i:

$$P_i(\boldsymbol{a},\gamma_i,U_0) = \frac{1}{2}\eta\rho\pi R^2\boldsymbol{C_p}(\lambda,\beta)\left\{\left[1-\delta u_i(\boldsymbol{a},\gamma_{js})\right]U_0\right\}^3\cos^3(\gamma_i)$$

Parameters update with FAST.Farm


A simulation of the worst case in FAST.Farm





ROYAL BELGIAN INSTITUTE OF NATURAL SCIENCES
https://odnature.naturalsciences.be/mumm/en/windfarms/project/5

Parameters update with FAST.Farm

➔ Minimize the RMSE (optimization problem to find the updated parameters).

$$\min\left(\sqrt{\frac{1}{5\cdot N}\sum_{i=1}^{N}\sum_{j=1}^{5}\left(P_{model,j}(\boldsymbol{k},\boldsymbol{\mu},\boldsymbol{k_d},\boldsymbol{a_d},\boldsymbol{b_d},\boldsymbol{\gamma_j},\boldsymbol{U_{0i}})-P_{FF,j}(\boldsymbol{\gamma_j},\boldsymbol{U_{0i}})\right)^2}\right);$$

$$0 < k \leq 0.1;$$
$$0 < \mu \leq 2;$$
$$0 < k_d \leq 10;$$
$$0 \leq a_d \leq 10;$$
$$0 \leq b_d \leq 0.1;$$

- 5 turbines with individual yaw angles, and the free wind speed ➔ 6 Dimensions
- If only 10 points is taken for each dimension ➔ 10^6 points (simulations)!

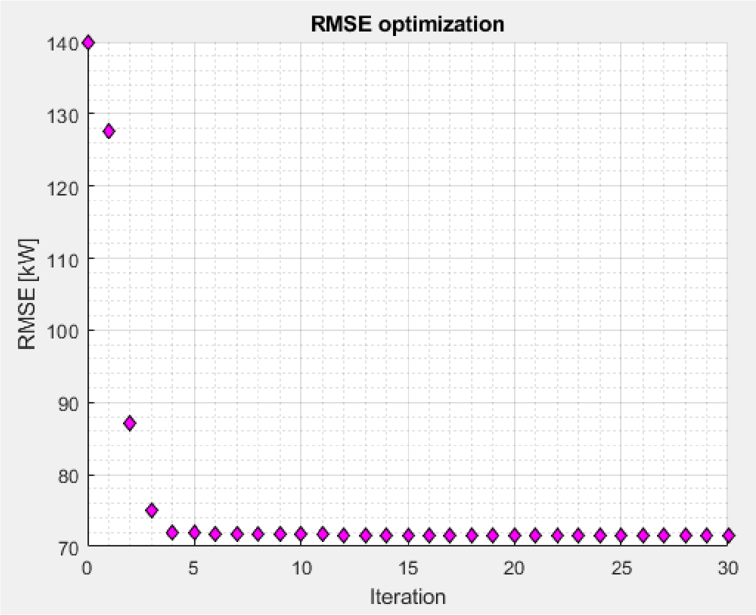
➔ Solution: **Latin hypercube sampling (LHS)**

A statistical method aiming to reduce drastically the number of runs necessary to achieve a reasonably accurate result.

ULB UNIVERSITÉ LIBRE DE BRUXELLES

Parameters update with FAST.Farm

➔ LHS for N=50 quasi-random simulations (wind speed and yaw angles)
➔ Minimize the RMSE (optimization problem to find the updated parameters).



$$\min\left(\sqrt{\frac{1}{5\cdot N}\sum_{i=1}^{N}\sum_{j=1}^{5}\left(P_{model,j}(k,\mu,k_d,a_d,b_d,\boldsymbol{\gamma_j},\boldsymbol{U_{0i}})-P_{FF,j}(\boldsymbol{\gamma_j},\boldsymbol{U_{0i}})\right)^2}\right);$$

$$\begin{gathered}0 < k \leq 0.1;\\ 0 < \mu \leq 2;\\ 0 < k_d \leq 10;\\ 0 \leq a_d \leq 10;\\ 0 \leq b_d \leq 0.1;\end{gathered}$$

$$\left.k = 3.73\cdot 10^{-2}\right\}$$ Value most recommended for offshore wind farms in literature

$$\mu = 4.99\cdot 10^{-1}$$

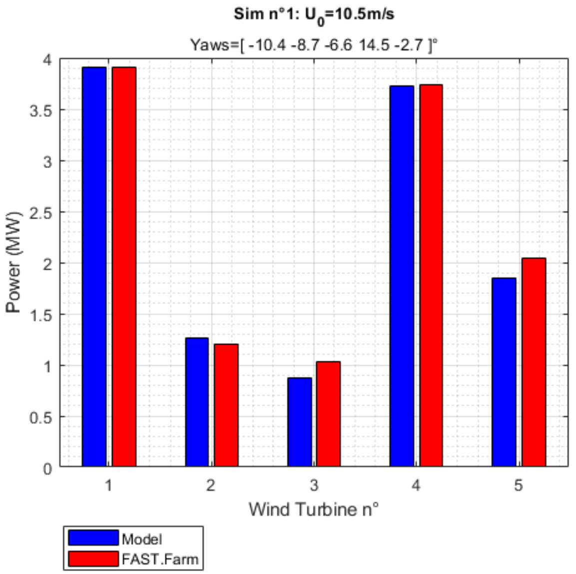
$$k_d = 9.88$$

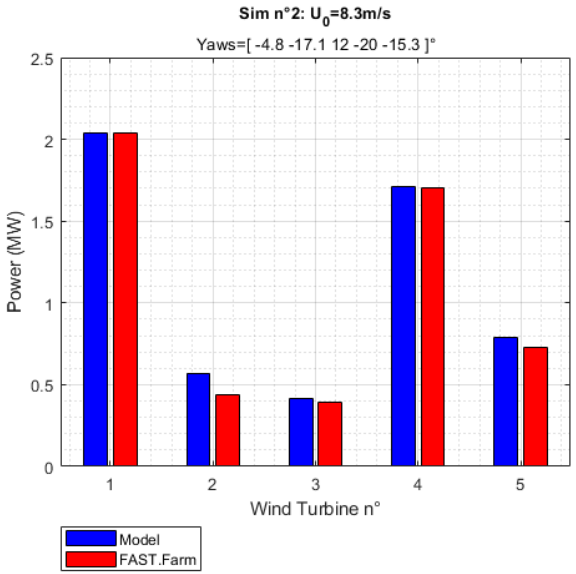
$$a_d = 2.70\cdot 10^{-3}\ m$$

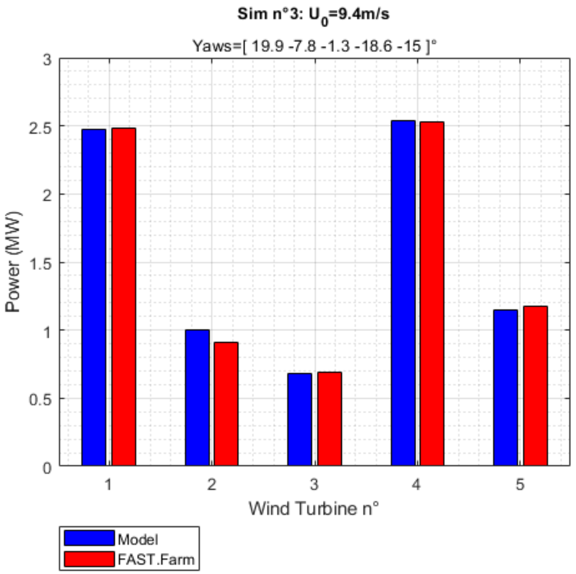
$$b_d = 6.80\cdot 10^{-3}$$

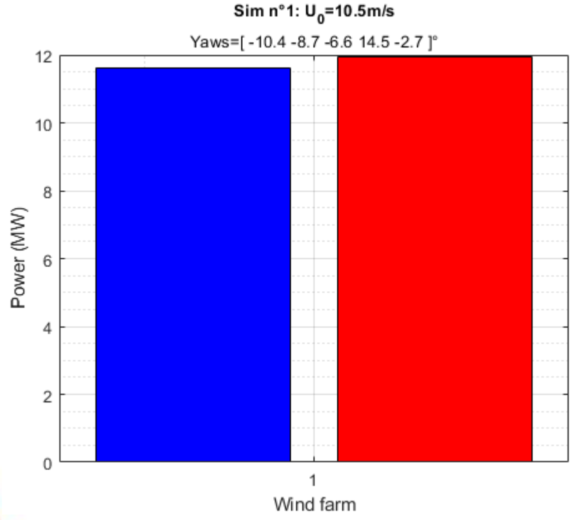
➔ The total RMSE 0,07 MW
➔ The RMSE of each simulation with the same data:
min(RMSE)=0,041 MW ; **Max(RMSE)=0,162 MW**
➔ The RMSE of each simulation with a validation data (N=50 new quasi-random simulations from LHS)
min(RMSE)=0,042 MW ; **Max(RMSE)= 0,165 MW**

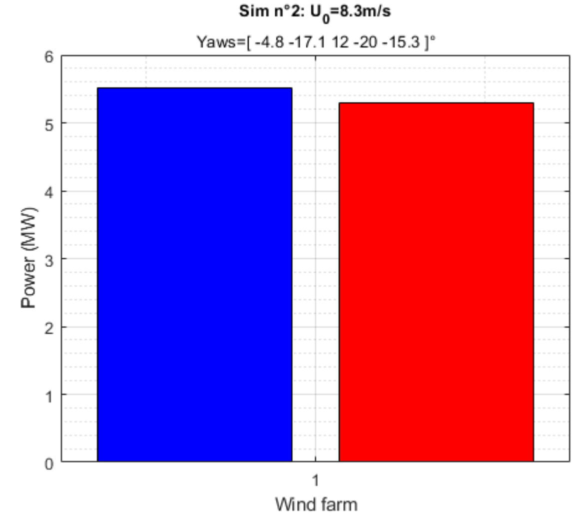
Wake – yaw – power model VS FAST.Farm

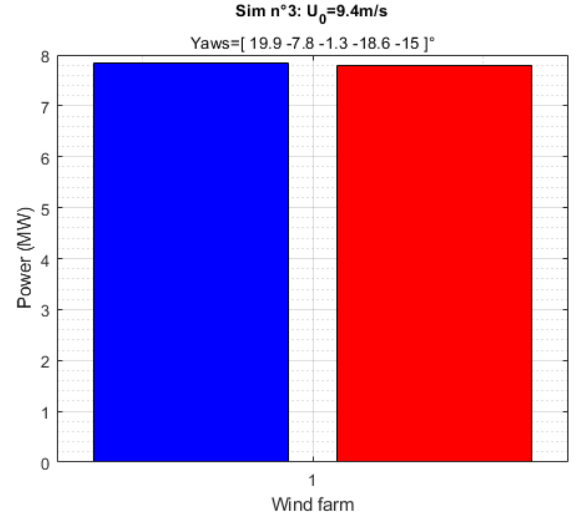






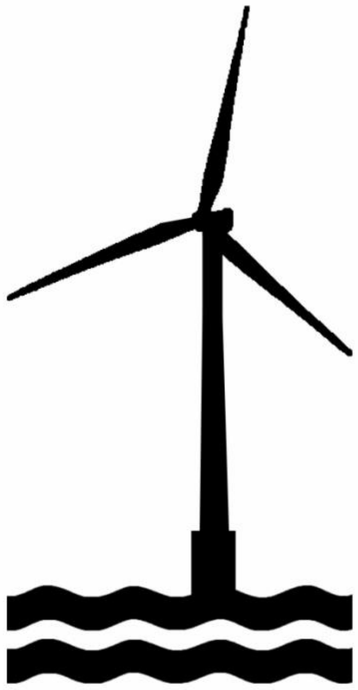






Future work

- Optimization yaw angles algorithm
- Quantify the power gained from yaw optimization control for FRR
- Set the pitch and torque controllers for power de-rating needed for FCR
- Achieve ELIA's FCR and FRR tests
- Expand the problem to higher wind speeds (higher than the rated one)
- Load mitigation



ULB UNIVERSITÉ LIBRE DE BRUXELLES

Thank you for your attention

PhairywinD
Belgian Offshore PhD Expertise

Partners

GHENT UNIVERSITY · UMONS Université de Mons · ULB UNIVERSITÉ LIBRE DE BRUXELLES · von KARMAN INSTITUTE FOR FLUID DYNAMICS · VUB VRIJE UNIVERSITEIT BRUSSEL · KU LEUVEN · LIÈGE université · Universiteit Antwerpen · UCLouvain · sirris driving industry by technology

With the support of Energy Transition Fund

economie

Younes.O : younes.oudich@ulb.be
Michel.K : michel.kinnaert@ulb.be
Johan.G : johan.gyselinck@ulb.be
Frederik.D : frederik.debelie@ugent.be