A wind farm operational strategy for primary frequency support optimization

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INNOVATIVE CONTROLS FOR RENEWABLE SOURCE INTEGRATION INTO SMART ENERGY SYSTEMS
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Introduction

In the last decades, wind power generation has experienced a significant growth worldwide, largely due to the commitment of industrialized countries to endorse global environmental concerns.

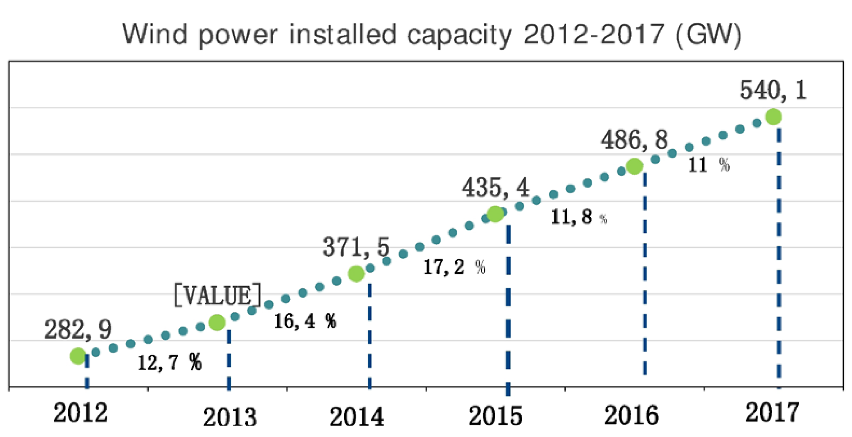


Figure 1: Statistics of wind power capacity istalled worldwide[1]

The drawbacks of this high wind power penetration in the electrical networks are

- reduction of the inertia of the system,
- deeper rates of change of frequency after a frequency event and greater steady-state frequency deviations.

Some Trasmission System Operators (TSOs) are requiring wind power plants to **participate in ancillary services**.
Advanced control strategies have been proposed for wind farms and wind turbines to provide active power for *frequency support*.

Wind turbines can reduce the fall of frequency by generating extra power. Two main approaches have been proposed so far:
1- releasing the kinetic energy stored in the rotating masses,
2- de-loading the wind turbines by keeping a ***power reserve***.

Objectives

General Objective

Design a de-loading control strategy based on model predictive control approach aimed to regulate the total power delivered to the grid while maximizing the power reserve for help in primary frequency support.

Specific Objectives

The tasks assigned to a centralized wind farm controller are,

- addressing de-loading operational strategy when the available power is higher than the power demanded by the electrical grid.
- coordinating the power contribution of each turbine, such that their power production sums to the desired amount.

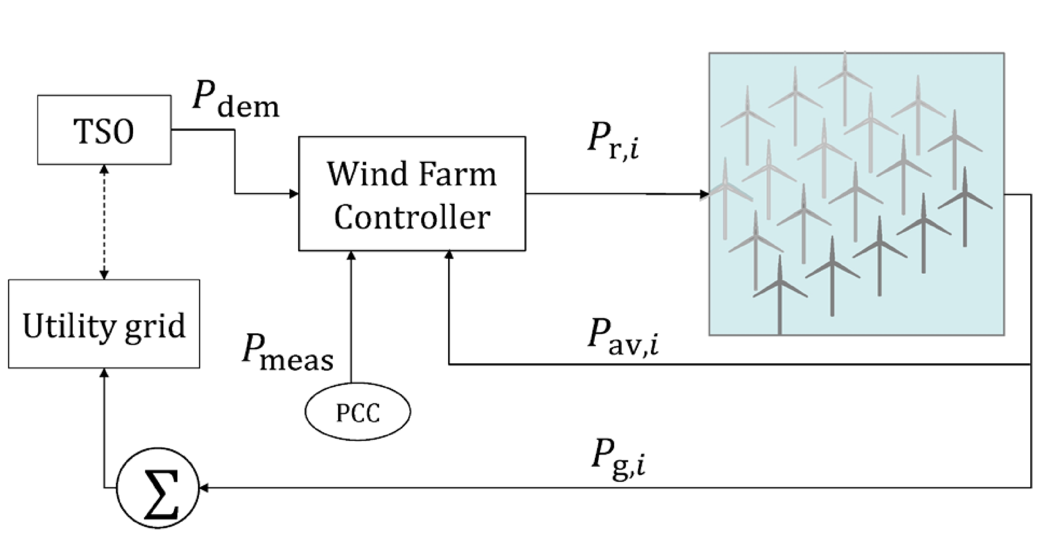


Figure 2: Block representation of the feedback control. According to the utility demands the TSO requires wind farm an amount of power demand P_{dem}, the wind farm controller based on the total available power $P_{av,i}$ and the measurements P_{meas} from the PCC addresses the power require for each wind turbine $P_{r,i}$.

Method

In de-loading operation the power set-points $P_{r,i}$ shall be chosen to maximize the power reserve,

$$P_{\text{reserve},i} = P_{\text{av},i}(v_i) - \tilde{P}_{g,i}$$

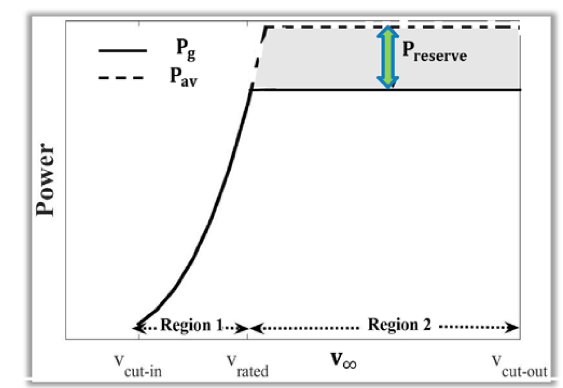


Figure 3: Power- wind speed characteristic curve.

Wind Farm Modelling

The wind turbines work mainly in two regions

- Region 1 the available power $P_{av,i}$ and generated power $P_{g,i}$ are proportional to the cube of the wind speed,
- Region 2 $P_{av,i}$ is constant and equal to the rated power.

Assuming:
1. The internal power control strategy for each turbine ensures the power curve in Figure 1.
2. The wind turbine can be modelled as a first order system generating a power

$$\tilde{P}_{g,i} = \min\{P_{r_i}, P_{av,i}\}$$

Since the available power $P_{av,i}$ depends on the wind conditions v_i faced by each turbine, the maximization of power reserve should consider the variation of the wind speed inside the wind farm.

Jensen's wake model [2]

$$v_i = f(v_\infty, \delta, \alpha, R, C_T) \qquad \delta = y_i - y_j \qquad j \in \mathbb{N}: y_j < y_i$$

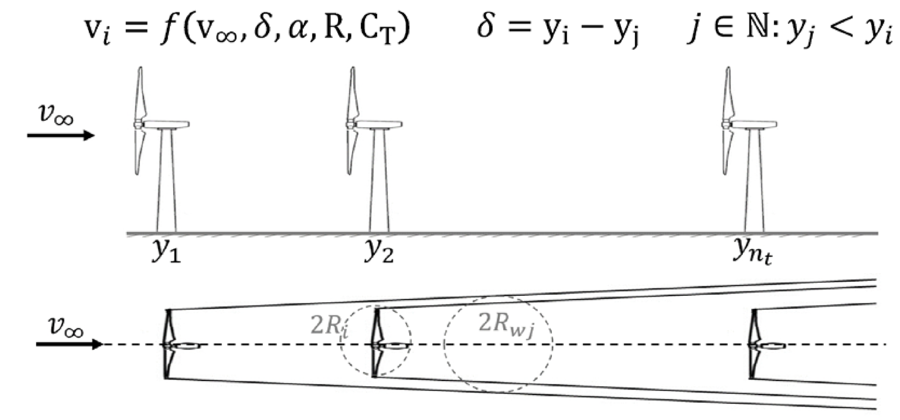


Figure 4: Wake expansion..

Model Predictive Control Strategy

Modelling the wind turbine as a first order system the state-space difference equation to be controlled is

$$\boldsymbol{x}(k+1) = \boldsymbol{A}\ \boldsymbol{x}(k) + \boldsymbol{B}_1\ \boldsymbol{P_r}(k) + \boldsymbol{B}_2\ P_{\text{dem}}(k)$$

$\mathbf{x} = [\boldsymbol{P}_g^T, \xi]^T \in \mathbb{R}^{n_x}$ ⇒ state vector $\boldsymbol{P_g} = [P_{g,1}, \dots, P_{g,n_t}]^T$, $\dot{\xi} = [P_{\text{dem}} - \sum P_{g,i}]$

$\boldsymbol{P_r} = [P_{r,1}, \dots, P_{r,n_u}]^T \in \mathbb{R}^{n_u}$ ⇒ manipulated variables vector

The MPC controller is designed by stating the following open-loop finite-horizon multi-objective optimization problem

O1: Ensure the power required by TSO
O2: Maximize the power reserve

$$\min_{\mathbf{P_r}(k)\in\mathbb{U}} J(k) \triangleq \sum_{i=0}^{H_p-1} \underbrace{\|Q\Delta\boldsymbol{x}(k+i)\|_1 + \|R\Delta\boldsymbol{P_r}(k+i)\|_1}_{O1} - \underbrace{\|\boldsymbol{P}_{\text{av}} - \boldsymbol{P_g}(k+i)\|_1}_{O2}$$

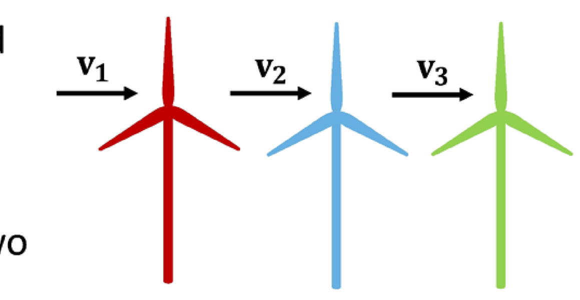
$$\boldsymbol{x}(k+j+1|k) = \boldsymbol{A}\ \boldsymbol{x}(k+j|k) + \boldsymbol{B}_1\ \boldsymbol{P_r}(k+j|k) + \boldsymbol{B}_2\ P_{\text{dem}}(k+j|k)$$

$\boldsymbol{x}(k+j|k) \in \mathbb{X}, \qquad \mathbb{X} = \{\boldsymbol{x} \in \mathbb{R}^{n_x} | \boldsymbol{x}(k) \in [\underline{\boldsymbol{x}}, \overline{\boldsymbol{x}}], \forall k\}$

$\boldsymbol{P_r}(k+j|k) \in \mathbb{U}, \qquad \mathbb{U} = \{\boldsymbol{P_r} \in \mathbb{R}^{n_u} | \boldsymbol{P_r}(k) \in [\underline{\boldsymbol{P}}, \overline{\boldsymbol{P_r}}], \forall k\}$

Results

- NREL5MW benchmark Wind Turbine [3]
- The wind turbines are described by a non-linear two mass model.



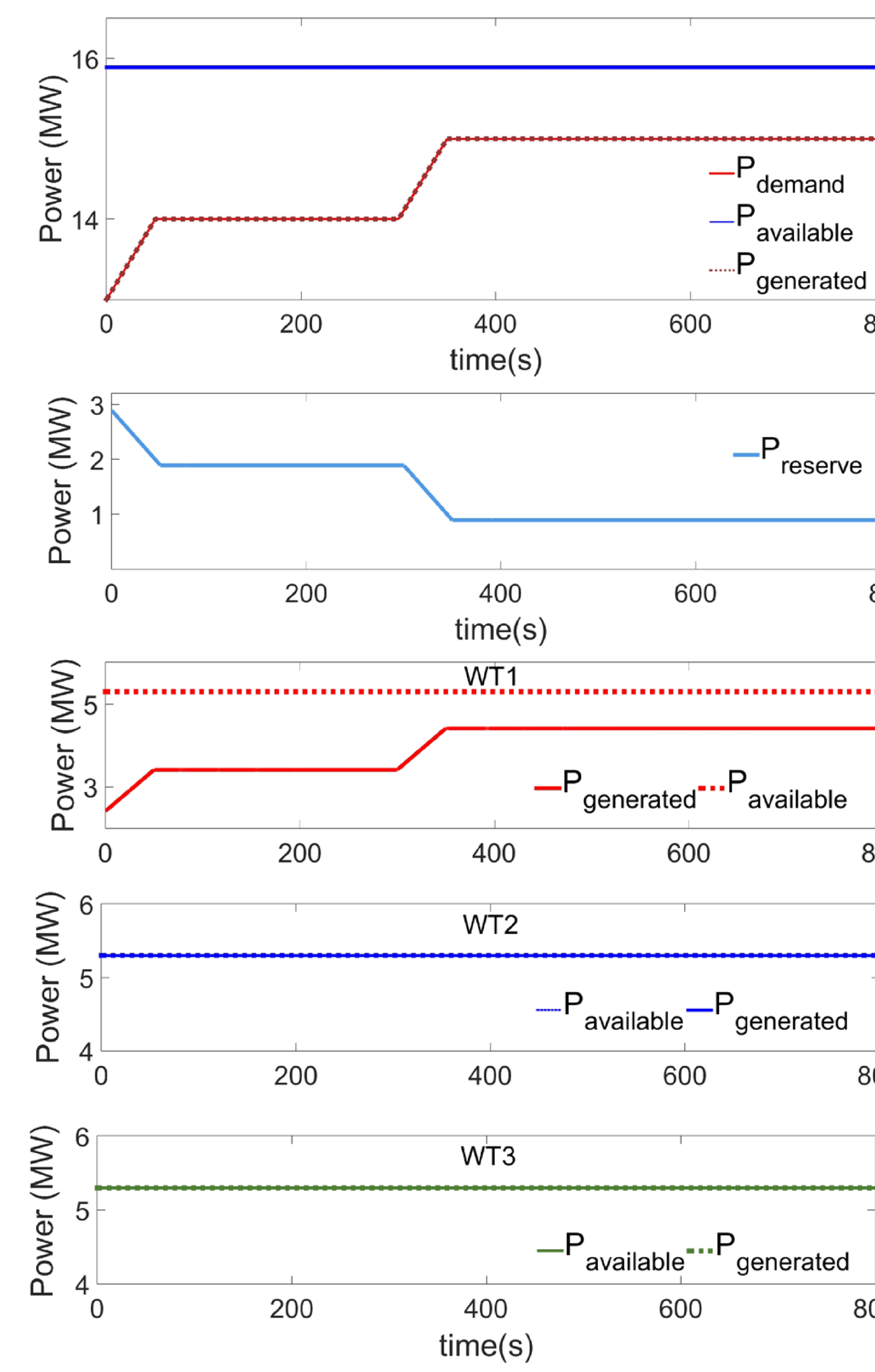


Figure 5: System response for scenario 1. Top plot: generated, available and demanded total power. Middle plot: total power reserve. Bottom plot: generated and available powers for each turbine.

Conclusions

With the aim of distributing the total power required at the wind farm control level for each wind turbine, we proposed a multi-objective model predictive control scheme able to:

1. ensures the tracking of the power demanded by the electrical grid;
2. provide primary frequency control by de-loading the wind turbines;
3. maximize the total power reserve when the available power is higher than the power demand.

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