Advanced Control for Wind Turbine Grid Connection Requirements

Nicol`o Gionfra
Supervisors: Guillaume Sandou, Houria Siguerdidjane
EDF actors: Damien Faille, Philippe Loevenbruck

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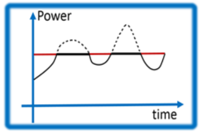
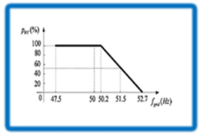
A New Grid Code



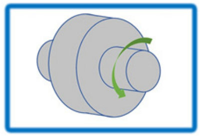
Power Curtailment

Typically imposed by the GSO. It is a valid alternative to grid reinforcement.
Modified power reference: $P_{ref} = sat_{P_{max}}(P)$



Primary frequency control

Participation at *primary* reserve for frequency control (especially downward).
Modified power reference: $\Delta P = k_1 \Delta\omega$



Artificial Inertia

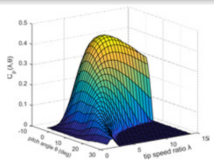
Reproduce the natural behavior of synchronous generators connected to the grid: $J\dot{\omega} = T_{mec} - T_{elec}$
Modified power reference: $\Delta P = k_2 \frac{d\omega}{dt}$

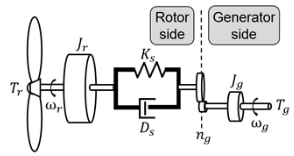
Wind Turbine Model

Two-mass model*

$$\begin{bmatrix}\dot\omega_r\\ \dot\omega_g\\ \dot\delta\\ \dot\vartheta\\ \dot T_g\end{bmatrix} = \begin{bmatrix} \frac{1}{J_r}\frac{P_r(\omega_r,\vartheta,v)}{\omega_r} - \frac{D_s}{J_r}\omega_r + \frac{D_s}{J_r n_g}\omega_g - \frac{K_s}{J_r}\delta \\ \frac{D_s}{J_g n_g}\omega_r - \frac{D_s}{J_g n_g^2}\omega_g + \frac{K_s}{J_g n_g}\delta - \frac{1}{J_g}T_g \\ \omega_r - \frac{1}{n_g}\omega_g \\ -\frac{1}{\tau_\vartheta}\vartheta + \frac{1}{\tau_\vartheta}\vartheta_r \\ -\frac{1}{\tau_T}T_g + \frac{1}{\tau_T}T_{g,r}\end{bmatrix}$$

where $P_r = \omega_r T_r = \frac{1}{2}\rho\pi R^2 v^3 C_p(\lambda,\vartheta)$, and $\lambda = \frac{\omega_r}{v}$





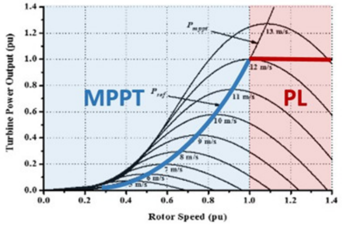
*CART turbine located at NREL's National Wind Technology

Classic Mode of Operation

- MPPT control at low wind speed, with constant ϑ.
- Power Limiting (PL) at high wind speed, by acting on ϑ.

Tipically two loops of PI control:

- ω_r controlled via $T_{g,r}$, and by inverting the static relation in the figure.
- Power limiting via ϑ, only activated when necessary.



Power curves for $\vartheta = 1^\circ$ and parametric wind.

Control Objectives

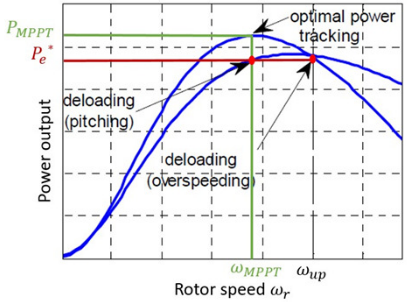
Main objective

Track a general power reference $P_e^*(\cdot)$ satisfying
$0 \leq P_e^*(t) \leq min(P_{MPPT}, P_{e,n}) \quad \forall t \geq 0$,
given by an upper control level, in particular, for:

- Downward active power reserve.
- Temporary maximum deliverable power constraints.

Choice of a Particular Reference

For a given P^*_e there might exist multiple state choices to achieve it:



State choice that maximizes the stored kinetic energy
(Žertek et al. (2012))

$$(\omega_r^*, \vartheta^*) = \arg\max_{\omega_r, \vartheta} \omega_r$$

subject to

$$P_e^* = P_r(\omega_r, \vartheta, v)$$
$$\omega_{r,min} \le \omega_r \le \omega_{r,n}$$
$$\vartheta_{min} \le \vartheta \le \vartheta_{max}$$

So that we get:

$$\Delta W_k \cong \frac{1}{2} J_r(\omega_{r,up}^2 - \omega_{r,MPPT}^2)$$

Some non linear (NL) controllers

(Thomsen (2006)),(Boukhezzar and Siguerdidjane (2011)), (Boukhezzar et al. (2007)): NL controllers conceived for either MPPT *or* Power Limiting mode of operation.

(Burkart et al. (2011)): NL controller for the whole operating envelope, but difficult to adapt to the general power reference tracking problem.

Feedback Linearization Step

Main steps

Choice of the change of coordinates (considering the output $y = \omega_r$):

$$\xi = col(\omega_r \quad \dot{\omega}_r \quad \omega_g \quad \delta \quad T_g)$$

Non linearities are concentrated in:

$$\dot{\xi}_2 = \alpha(\xi, \vartheta, v, \dot{v}) + A_2\xi + \beta(\xi, \vartheta, v)\vartheta_r$$

Choice of feedback linearizing input:

$$\vartheta_{r,FL} \text{ ¾ } \vartheta_r = \frac{1}{\beta(\xi, \vartheta, v)}(-\alpha(\xi, \vartheta, v, \dot{v}) + v_\vartheta)$$

where v_ϑ is left as a degree of freedom.

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where v_ϑ is left as a degree of freedom.

Feedback Linearization step

Linearized system

$$\dot{\xi} = A\xi + B[v_\vartheta \quad T_{g,r}]^T$$

$$= \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ a_{2,1} & 0 & a_{2,3} & a_{2,4} & a_{2,5} \\ \frac{D_s}{n_g J_g} & 0 & -\frac{D_s}{n_g^2 J_g} & \frac{K_s}{n_g J_g} & -\frac{1}{J_g} \\ 1 & 0 & -\frac{1}{n_g} & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{\tau_T} \end{bmatrix} \xi + \begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & \frac{1}{\tau_T} \end{bmatrix} \cdot \begin{bmatrix} v_\vartheta \\ T_{g,r} \end{bmatrix}.$$

Avoiding Singular Points

Proposition

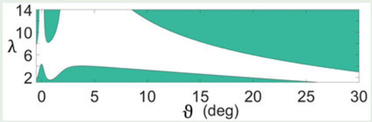
Consider a SISO system of the form

$$\dot{x} = f(x) + g(x)u, \quad x(0) = x_0$$
$$y = h(x)$$

where $x \in \Omega \subseteq \mathbb{R}^n$. *Then*
$L_g L_f^{r-1} h(x(t)) \neq 0 \ \forall t \geq 0$
iff
The system relative degree in x_0 *is well-defined and equal to* $r \leq n$.

$sign(L_g L_f^{r-1} h(x(t))) = sign(L_g L_f^{r-1} h(x_0)) \quad \forall t \geq 0.$

In our system:
$\beta(\cdot) = L_g L_f^{r-1} h(\cdot)$, which is, for the points of functioning of interest, *negative* and whose domain is *connected*.



Λ: set of (λ, ϑ) s.t. $\beta(\lambda, \vartheta) < 0$

Hence: we aim to constrain the trajectory to lie in Λ.

MPC Step

Optimization problem

At each time step j, MPC solves the following problem P:

$$\min_{\{u_{MPC}\}} \sum_{k=1}^{N_h-1} \|\tilde{\xi}(k)\|^2_{Q_\xi} + \|\tilde{u}_{MPC}(k)\|^2_R + \|\Delta u_{MPC}(k)\|^2_{R_\Delta} + \|\tilde{\xi}(N_h)\|^2_P$$

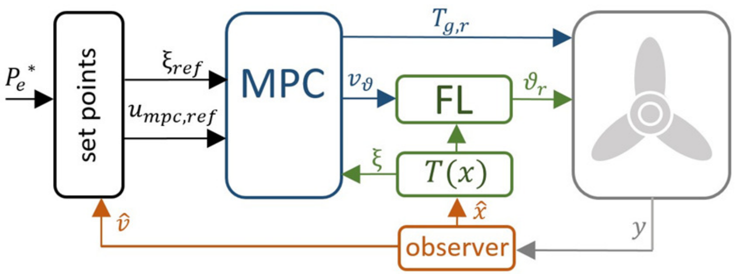
subject to

- discretization of $\dot{\xi} = A\xi + Bu_{MPC}$, $\xi(0) = \xi(j)$
- $\beta(\xi, \vartheta, v) < 0$
- $\vartheta_{min} \leq \vartheta_{r,FL} \leq \vartheta_{max}$
- $0 \leq \omega_r T_g$, and other system constraints

Note: constraints are linearized at each j to make the problem *convex*, (quadratic).

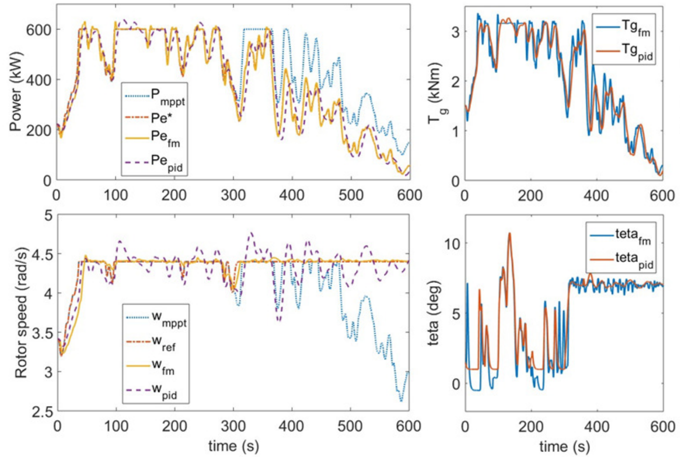
where $\tilde{\xi} \triangleq \xi - \xi_{ref}$, $\tilde{u}_{MPC} \triangleq u_{MPC} - u_{MPC,ref}$, $u_{MPC} \triangleq col(v_\vartheta \quad T_{g,r})$.

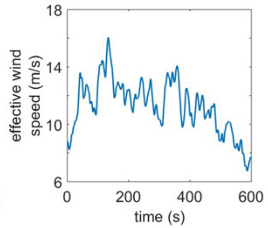
Overall Controller



where $y = col\,(\omega_r \quad \omega_g \quad \vartheta \quad T_g)$

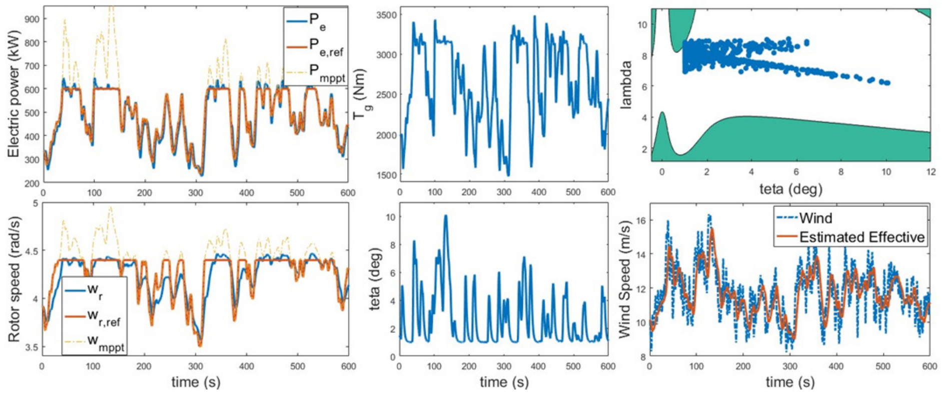
FL+MPC vs PI



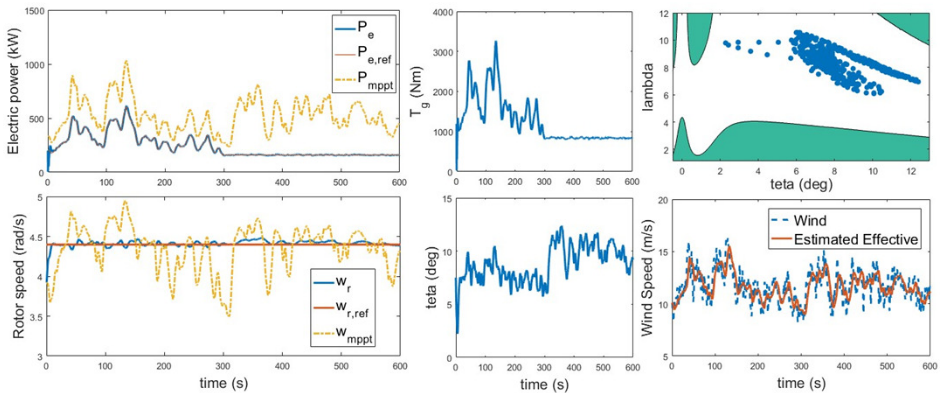


	Energy	$\overline{\lvert err_{\omega_r} \rvert}$	$\overline{\lvert err_{P_e} \rvert}$
FL-MPC	232,51 *MJ*	0,0434 *rad/s*	8,315 *kJ*
PI	231,79 *MJ*	0,1420 *rad/s*	36,884 *kJ*
FL-MPC/PI	1,0031	0,3059	0,2254

MPPT and Power Limiting

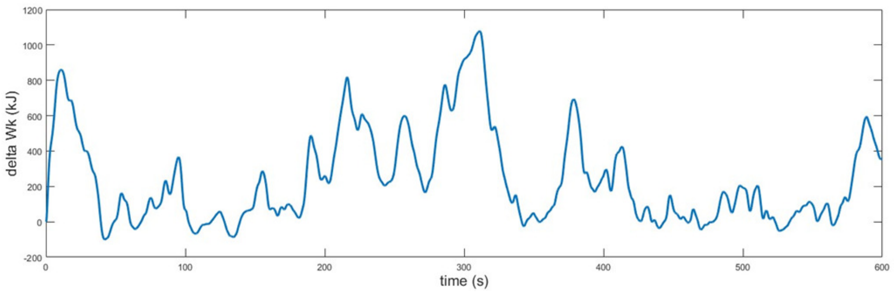


De-loaded Mode



De-loaded Mode

Surplus of stored kinetic energy during the de-loaded mode of functioning:

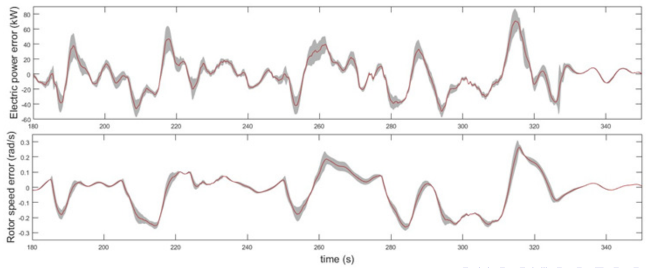


Montecarlo Simulation

100 simulations on a 600*s* time basis.

We let D_s, K_s, J_r, J_g span an interval of ± 20 % of their nominal value, according to a uniform distribution of probability.

The system is excited by a wind speed signal whose average is 12m/s.



Conclusions

The proposed control enables tracking of a general power reference. It allows to control a wind turbine in the whole operating envelope. It showed better performance with respect to a PI control.

Montecarlo simulation showed a certain inherent degree of robustness.

Future Works

Application for mechanical stress reduction via Individual Pitch Control.

Integration at the wind farm level.

Thanks for your attention!