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Adaptive PI control and active tower damping compensation of a wind turbine

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This paper deals with the control problem of a wind turbine model working in the nominal zone. This process is a nonlinear system whose dynamics vary strongly depending on the operation point. In the nominal region, the wind turbine speed is controlled by means of the pitch angle to generate the nominal power. The wind fluctuations and its non-uniform special profile act as disturbances on the power generation and the tower deflections. These oscillations must be reduced to improve the wind turbine lifetime.

In this work, an adaptive control structure operating on the pitch variable is proposed. It is composed of a gain-scheduling PI control, an adaptive feedforward compensation of the wind speed and an adaptive gain compensation for the tower damping. The tuning of the controller parameters is formulated as an optimization problem that minimizes the tower fore-aft displacements and the deviation of the wind turbine speed from its nominal value. It is resolved using genetic algorithms for different linear models that are obtained from the nonlinear model.

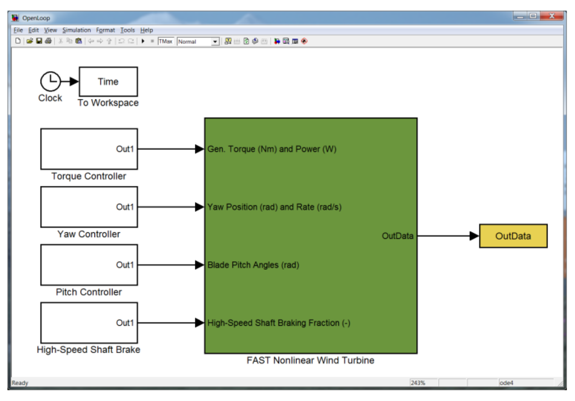
The proposed controller is compared with a classical baseline PI (Proportional-integral) controller and the simulation results show a significant improvement of the system performance when the proposed strategy is applied.

Wind turbine model

In this work, a wind turbine model is simulated using the Matlab/Simulink software with the assistance of FAST software (Fatigue, Aerodynamics, Structures and Turbulence). The 5-MW NREL turbine model has been implemented by using software FAST version 8 (v8.16.00a-bjj). Control loops and controllers are implemented in Matlab/Simulink.

An average linear model is obtained from the approximated linear models calculated at the seven operation conditions considered according to the disturbance value v_w (12, 14, 16, 18, 20, 22, 24) m/s within the nominal region (ω_g =1173.7 rpm).

The structure of the continuous model is given by the follow equations:



$$G_{\omega g}(s) = \frac{K_1}{(s+p_1)}$$

$$Gd_{\omega g}(s) = \frac{K_2}{(s+p_2)}$$

$$G_{x_t}(s) = \frac{K_3(s+z_3)}{(s+p_{31})(s+p_{32a} \pm p_{32b}j)}$$

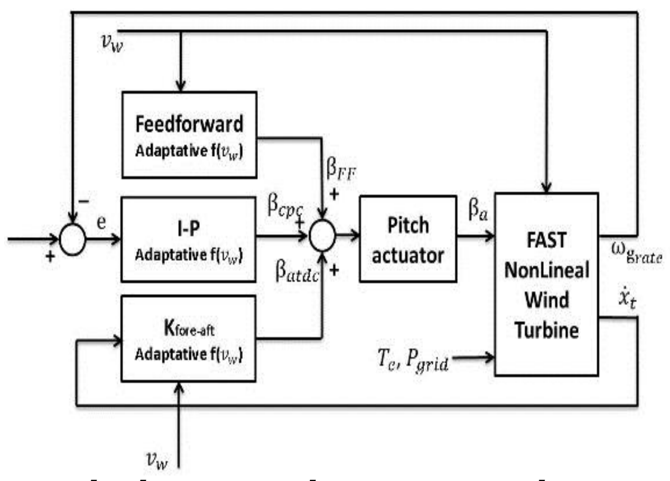
$$Gd_{x_t}(s) = \frac{K_4(s+z_4)}{(s+p_{41})(s+p_{42a} \pm p_{42b}j)}$$

where $G_{\omega g}$ (s) is the transfer function relating the angular velocity at high speed shaft (ω_g) to pitch angle (β), $Gd_{\omega g}$(s) is the transfer function relating the controlled variable ω_g to the wind disturbance variable (v_w), G_{x_t}(s) is the transfer function of the tower fore-aft displacement (x_t) from the pitch (β) and Gd_{x_t} (s) is the transfer function relating the controlled variable x_t to the wind disturbance variable (v_w).

Control methodology

The control strategy proposed in this work combines two control loops: one loop to maintain the wind turbine speed at its nominal value and other loop to reduce the f-a tower displacements. There is a gain-scheduling I-P controller regulating the turbine speed by actuating on the pitch angle. This loop also contains an adaptive feedforward compensation of the wind speed as a disturbance, that must be added to pitch control signal.

In addition, there is an adaptive proportional controller to mitigate the tower f-a oscillation that generates an extra pitch control component proportional to the tower fore-aft velocity $\dot{x}_t$. This is also added to the pitch control signal.



Pitch control system scheme

The tuning procedure of the PI controllers with fore-aft control is performed by means of a multi-objective genetic algorithm (MGA) simulating each of the seven linear models. The function to minimize is composed by the following indices: integral of time-weighted *absolute* error (ITAE) and integral of absolute error (IAE) of the controlled variable ω_g ,and the cumulative variation rate (CVR) and ITAE of the variable x_t taking as reference the stationary value for this last index.

Due to the nonlinearity of these performance indices, the PI tuning design that minimizes them must be formulated as a nonlinear optimization problem, and thus, it can be solved using MGA. The procedure is performed using the Global Optimization toolbox of Matlab. In each PI controller, there are three parameters to be tuned: Kp and Ti (PI controller) and K_{fore_aft} (ATDC).

$$IAE_{\omega g} = \int_{t_0}^{t_s} |\omega_{g_{rat}} - \omega_g(t)|\, dt$$

$$ITAE_{\omega g} = \int_{t_0}^{t_s} t\, |\omega_{g\_rat} - \omega_g(t)|\, dt$$

$$CVR_{x_t} = \int_{0}^{t_s} |x_t(t_k) - x_t(t_{k-1})|\, dt$$

$$ITAE_{x_t} = \int_{0}^{ts} t\, |x_t(t) - x_t(\infty)| dt$$

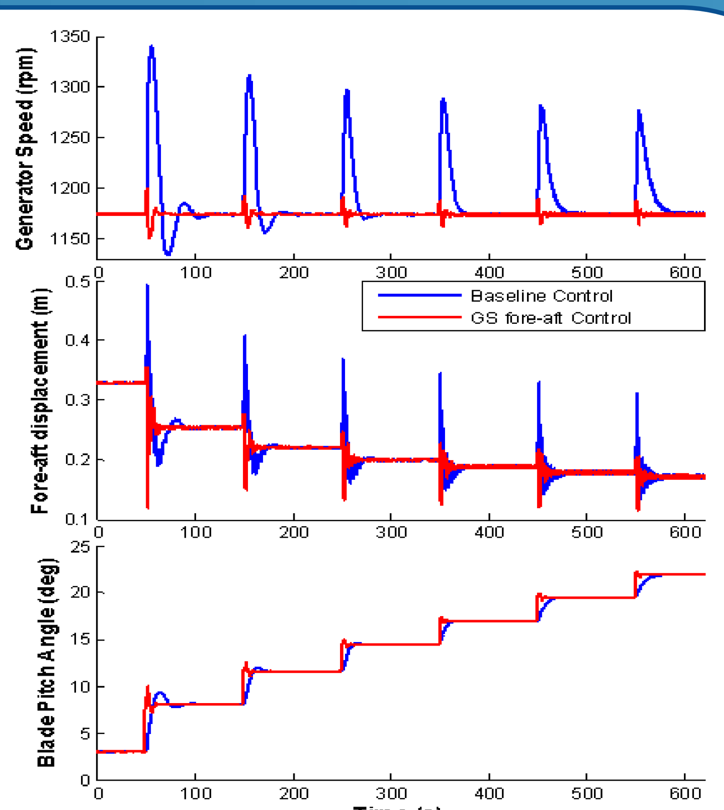
Simulation results

The designed controller is compared to a traditional gain scheduling PI controller.

The step responses for different operation points are shown in the following figure, where the first plot shows the generator speed, the second one, the tower top fore-aft displacement and the last one, the pitch angle.

Performance index values for steps wind speeds

	$IAE_{\omega g}$	$ITAE_{\omega g}$	CVR_{x_t}	$ITAE_{x_t}$	CVR_{β}
BC	8.7e3	10.1e4	7.11	2.55e3	25.6
GSC	754.2	19.2e3	4.83	1.07e3	60.5



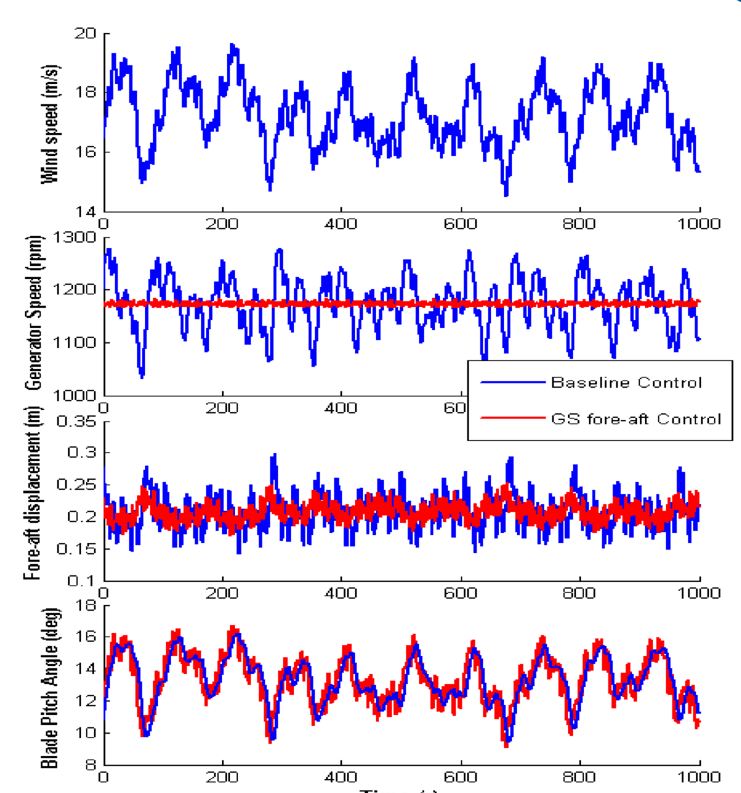
Comparative control system responses to wind steps

Next to perform a simulation with a more realistic wind speed profile, a stochastic wind speed has been used in the model.

The next figure shows the simulation results using this wind speed profile. The first plot shows the wind speed, the second the generator speed, the third one the tower top fore-aft displacement and last one the pitch angle.

Performance index values for stochastic wind speeds

	$IAE_{\omega g}$	CVR_{x_t}	CVR_{β}
BC	4.08e+04	13.14	118.76
GSC	3.18e+03	8.89	341.09



Simulation responses with a stochastic wind speed profile

Observing the qualitative and quantitative results, the following can be highlighted: the proposed controller obtains a better CVR_{x_t} index value, reducing its index in a 32.3% compared to that of the baseline controller. With respect to the $IAE_{\omega g}$ value, the designed controller reduces this index in a 92.2% in comparison with that obtained using the baseline controller.

Regarding the qualitative and quantitative results against step wind, similar conclusions can be obtained: the designed controller obtains a better CVR_{x_t} and $ITAE_{x_t}$ index values, reducing such index values in a 32.06% and 58.04%, respectively, in comparison with those of the baseline controller. With respect to the $IAE_{\omega g}$ and $ITAE_{\omega g}$ index values, the designed controller reduces these indices in a 91.3% and 81% respectively, compared to the baseline controller.

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