Predictive Control of Variable Speed Wind Turbine for Power Capture Optimization

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***Abstract*—This work presents a predictive control approach for power capture optimization of a variable speed wind turbine(WT). A two mass flexible shaft model is used for control design. Predictive constrained control of the WT associated with a Kalman filter is then proposed. The controller is tested with a real experimental wind turbine parameters under a realistic wind speed profile. The simulation results show a good performance in terms of power capture and shaft load reduction.**

I. Introduction

control design is a key factor in wind turbines performance, enhancement [1], [2]. During the last decade and until now, wind turbine control remain an active research area. Many control strategies have been proposed for this purpose [3]. Linear controllers have been intensively studied and applied in industry. From PI-PID [4], [5] to LPV controllers [6] through other well-known linear control strategies like LQ/LQG [7] controllers and robust linear controllers [8], they are based on a one or more linearized models around an operating point or across a trajectory [6]. Nonlinear controllers have also received a lot of interest for wind turbine control [9]. Nonlinear input-output feedback linearization are proposed in [10]. Sliding modes [11] and adaptive controllers [12] have also used.

In this paper, a new control scheme based on predictive control and Kalman flittering is proposed for wind power capture enhancement with a variable speed wind turbine. Predictive control encountered a lot of success in industrial environment [13]–[15]. Its success is due to its simple and direct integration of constraints on control signals and controlled variables [16]. This technique was used in classical linear controllers context for wind turbines control. The proposed works use a linearized model of the WT around an operating point [17], [18]. It is well known that these controllers have a limited performances when hard nonlinearities or large variations of the manipulated variables are encountered [19], [20]. The main result with these works are presented for constants or non realistic wind speed profiles and rarely tested with a real set of parameters of wind turbine.

The main idea of the proposed approach is to use a Kalman filter to estimate the wind turbine aerodynamic torque. This one is then considered as a measurable disturbance leading to a linear multivariable model of the WT. Considering this, it is not necessary to linearize the wind turbine around a given mean wind speed. The nonlinear behavior of the wind turbine is thus considered.

After a brief presentation of the used two mass model for control design, the objectives of a variables speed wind turbine control for low wind speed is detailed. In section III, the control scheme including the Kalman predictor and the predictive control bloc is given. Each function of the blocks is explained. The experimental wind turbine characteristics used in simulations are given in section IV. The proposed controller with predictor is then tested with a realistic wind speed profile. The simulation results are analyzed and commented. the papers ends with a conclusion and some perspectives.

II. Wind Turbine Model

A wind turbine is an electromechanical system that converts a part of wind speed kinetic power to electrical power. Many models are used in the literature for this system []. These models consists of flexible connection of a multi-mass rigid bodies. A good choice of a model is a compromise between simplicity and efficiency.

A. Two-mass model

In these work, a two-mass model is used. The scheme of the model is given in figure 1. The aerodynamic torque is a nonlinear function of the rotor speed ω_r, the wind speed v and the pitch angle β

$$T_a(\omega_r, v, \beta) = \frac{1}{2}\rho\pi R^3 C_q(\lambda, \beta) v^2 \tag{1}$$

The torque coefficient C_q is a nonlinear function of the pitch angle β and the tip-speed ratio λ

$$\lambda = \frac{\omega_t R}{v} \tag{2}$$

where ω_t is the rotor speed, R is the rotor radius and ρ is the air density.
The rotor inertia $J_r$is driven by the aerodynamic torque T_a and braked by the low-speed shaft T_{ls}

$$\dot{\omega}_t = \frac{1}{J_r}T_a - \frac{K_r}{J_r}\omega_t - \frac{1}{J_r}T_{ls} \tag{3}$$

Similarly, the generator inertia J_g is submitted to the high-

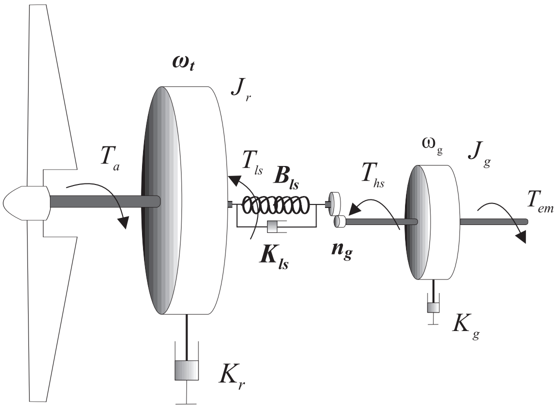

Fig. 1. Wind turbine two-mass model

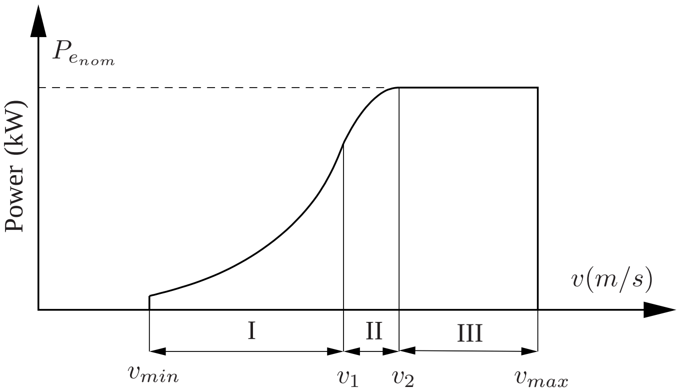

Fig. 2. Wind turbine power curve

speed shaft T_{hs} and the generator torque T_{em} that is the control input

$$\dot{\omega}_g = \frac{1}{n_g J_g} T_{ls} - \frac{K_g}{J_g}\omega_g - \frac{1}{J_g} T_{em} \tag{4}$$

A state space representation of the two-mass system is given by [10]

$$\begin{bmatrix} \dot{\omega}_t \\ \dot{\omega}_g \\ \dot{T}_{ls} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} \omega_t \\ \omega_g \\ T_{ls} \end{bmatrix} + \begin{bmatrix} b_{11} \\ b_{21} \\ b_{31} \end{bmatrix} T_a(\omega_r, v, \beta) + \begin{bmatrix} b_{12} \\ b_{22} \\ b_{32} \end{bmatrix} T_{em} \tag{5}$$

where

$$a_{11} = -\frac{K_r}{J_r} \quad ; \quad a_{12} = 0 \quad ; \quad a_{13} = -\frac{1}{J_r}$$
$$a_{21} = 0 \quad ; \quad a_{22} = -\frac{K_g}{J_g} \quad ; \quad a_{23} = \frac{1}{n_g J_g}$$

$$a_{31} = \left(B_{ls} - \frac{K_{ls} K_r}{J_r}\right) \quad ; \quad a_{32} = \frac{1}{n_g}\left(\frac{K_{ls} K_r}{J_g} - B_{ls}\right)$$
$$a_{33} = -K_{ls}\left(\frac{J_r + n_g^2 J_g}{n_g^2 J_g J_r}\right)$$

and

$$b_{11} = \frac{1}{J_r} \quad ; \quad b_{12} = 0$$
$$b_{21} = 0 \quad ; \quad b_{22} = -\frac{1}{J_g}$$
$$b_{31} = \frac{K_{ls}}{J_r} \quad ; \quad b_{22} = \frac{K_{ls}}{n_g J_g}$$

This representation is nonlinear since the aerodynamic torque is a nonlinear function of the rotor speed ω_r, the wind speed v and the pitch angle β. In order to deal with the wind turbine model as a linear system, the aerodynamic torque as measurable input disturbance including it as a state space variable. It is then estimated using a Kalman filter.

B. control objectives

The wind turbine is operational if the wind speed is situated in the interval $[v_{min}, v_{max}]$. It is divided in three areas [3] (Figure 2). In zone I, the control objective is to optimize the wind power capture. For this, the tip speed ratio λ and the pitch angle β should be fixed to their optimal values

$$\lambda = \lambda_{opt} \tag{6}$$
$$\beta = \beta_{opt} \tag{7}$$

In order to fix the tip speed ration to its optimal value, the rotor speed ω_t should track the optimal rotor speed $\omega_{t_{opt}}$ given by

$$\omega_{t_{opt}} = \frac{\lambda_{opt}}{R} v \tag{8}$$

the optimal rotor speed is proportional to the wind speed.

III. Predictive Control Using Kalman Filter

A. Kalman Aerodynamic Torque predictor

Assuming that dynamic of the aerodynamic torque is driven by a white noise ξ

$$\dot{T}_a = \xi \tag{9}$$

an augmented state-space representation of the two-mass model is then obtained [21]. Using the augmented state-space model, a Kalman filter is designed to estimate the state variables from a noisy generator torque measurement

B. Predictive control of the WT

Considering a discrete-time input-output representation of the two-mass model, with control input $u(k) = T_{em}(k)$, measurable input disturbance $T_a(k)$ and output $y(k) = \omega_r$. In order to track a optimal rotor speed reference $\omega_{r,ref}$, at instant k, a sequence $U(k)$ of control input is calculated in order to optimize a cost function $J(U_k)$.

$$U_k^T = \begin{bmatrix} T_{em}(k|k) & T_{em}(k+1|k) & \cdots & T_{em}(k+p-1|k) \end{bmatrix}$$

where p is the prediction horizon. The cost function is given by

$$J(U_k) = J_y(U_k) + J_u(U_k) + J_{\Delta u}(U_k) + J_{\varepsilon}(U_k) \tag{10}$$

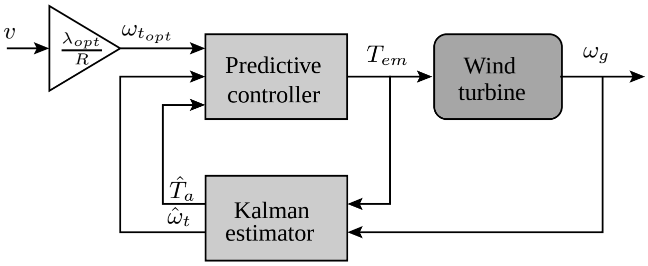

Fig. 3. Predictive controller with Kalman filter scheme

TABLE I
CART WIND TURBINE CHARACTERISTICS

Rotor diameter	43.3 m
Gear ratio	43.165
Tower height	36.6 m
Nominal power	650 kW
Nominal rotor torque	162 kN.m

Each term take into consideration a specific objective. For reference tracking

$$J_y(U_k) = \sum_{i=1}^{p} w_i \left[\omega_{r,ref}(k+i|k) - \omega_r(k+i|k)\right]^2$$

For control input move suppression

$$J_{\Delta u}(U_k) = \sum_{i=1}^{p-1} w_i^{\Delta u} \left[T_{em}(k+i|k) - T_{em}(k+i-1|k)\right]^2$$

and for constraints violation

$$J_{\varepsilon}(U_k) = \rho\varepsilon_k^2$$

The constraints are made upon the input limits. Once calculated, only the first component of U_k is applied to the system. The procedure is repeated for each sampling time.

The global controller scheme is given in figure 3

It consists of two blocks : The predictive controller and the Kalman aerodynamic torque estimator.

IV. Simulation Results

The simulations are made using Matlab 2009b with Simulink programming environnement. The wind turbine parameters corresponds to the CART 600 kW experimental wind turbine []. The parameters signification and values are given in Table I. The predictive controller with Kalman estimator is tested with a realistic wind speed profile with a mean wind speed of 7 $m.s^{-1}$ and a turbulence intensity of 25 %. The wind speed profile is represented in figure 4. It is obtained using SNwind simulator developed by NREL [22].

The predictive controller is designed using Model Predictive Control Toolbox. The discrete time model of the wind turbine is obtained with a sampling period $T_s = 0.1$ s. The prediction horizon for output and control are respectively 10 and 2. The tuning parameters are 0.0449 for input rate factor, 445.1082 for output factor and $2.0660e+005$ for the ECR. The Kalman filter covariance factors are $Q_N = 2.10^6, R_N = 0.1$ and $N_N = 1.10^{-5}$. The rotor speed ω_t is shown in figure 5 with the optimal reference. One can observe that the rotor speed track a tendency of the rotor speed reference without tracking the high speed variations due to the important turbulence. This is achieved by an appropriate choice of the tuning parameters of the predictive controller and also b filtering the control signal T_{em} with a first order low-pass filter with a constant time of 2 s. The control signal is represented in figure 6. The

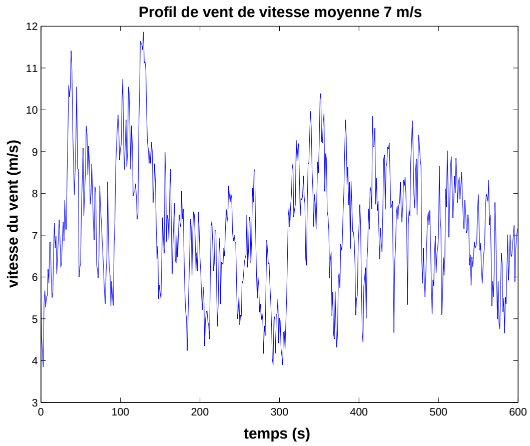

Fig. 4. Wind speed profile

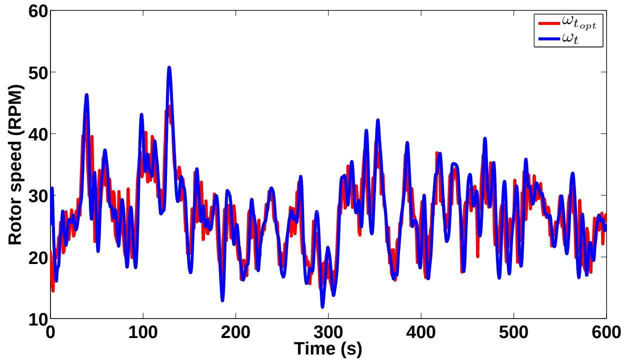

Fig. 5. Wind turbine rotor speed

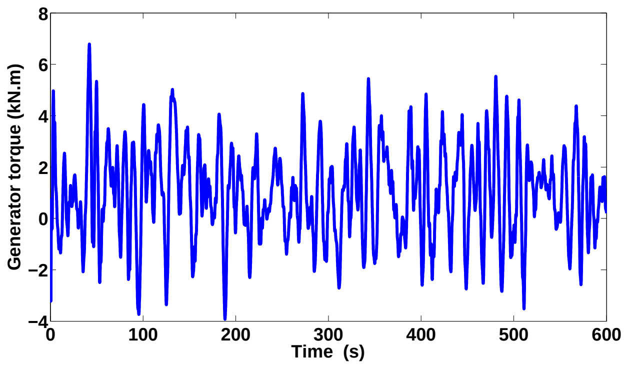

Fig. 6. Wind turbine rotor speed

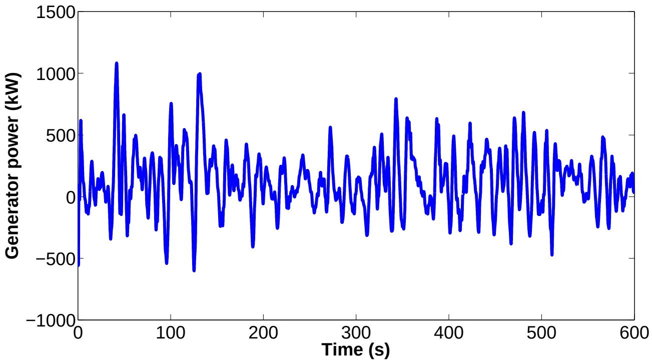

Fig. 7. Generator power

generator torque has a similar shape to the rotor speed ω_t, it is smooth signal with a maximum under the upper limit thanks to the predictive controller constraints. Figure 7 represents the electrical power. It has also a smooth shape leading to a well integration of the wind turbine to the grid.

V. Conclusion

A predictive controller associated with a Kalman filter for aerodynamic torque estimation is proposed. The use of the estimator allows to deal with the wind turbine as a linear model with the aerodynamic torque as a measurable input disturbance. The predictive controller is designed taking into consideration control variation and tracking error minimization. The test of the controller with a realistic wind speed profile using an experimental wind turbine parameters gives a satisfactory results. In perspective, the controller should be validated using a more complete wind turbine simulator.

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