Observer-Based LQR for Wind Energy Conversion Systems with Single Measurement*

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Abstract - ***The control system in wind energy conversion systems is used for tracking the optimal power via regulating the rotor speed of the generator. In this paper, we proposed a novel observer for estimating not only aerodynamic torque in wind energy conversion systems, but also d-axis and q-axis currents. Therefore, in the proposed control system, only the rotor speed of the generator is required to be measured. It should be noted that this is the first time, such a control system can do that for wind energy conversion systems. To form a complete control system, we use linear optimal control method for tracking the optimal trajectory of a generator. In this paper, the permanent magnet synchronous generator is used. In addition, on the basis of the Lyapunov theory and Sum-Of-Square technique, the conditions for observer synthesis are derived in the main theorem. The simulation results show that our control system with proposed robust observer can effectively track the speed reference in the conditions of unknown wind speed and stator currents.***

Keywords: ***Wind speed estimation, wind energy conversion systems (WECSs), linear quadratic regulator (LQR), observer***

I. INTRODUCTION

Wind energies have been installed with increasing capacity in recent years due to their sustainability and no pollutants. In wind energy conversion systems, wind speed is a key information to be known in real time [1]-[8]. It is not easy to measure it with enough precision for control systems. The measurements with anemometers [3], [4] are unable to estimate wind speed in short term. Another approach is to use the Kalman filters and Gray models [5], [6] and genetic algorithms [7]. Although these methods can estimate wind speed with high accuracy, the methods are complicated.

As aerodynamic torque is proportional to cubic of wind speed, if aerodynamic torque is known, wind speed is known. In the control systems, aerodynamic torque is considered as a disturbance. Therefore, another approach was to use observers to estimate aerodynamic torque instead of measure or estimate wind speed [1], [8]-[10]. In these techniques, the observers are combined with the controllers to form a complete control systems in order to track the optimal speed reference of the generators: in [1], a disturbance observer-based fuzzy sliding mode control method (SMC) was introduced; whereas, in [8], high-order observers with linear quadratic regulator (LQR) were presented; SMC with observer for current loops were used for [9]; an adaptive control system is proposed in [10]; These methods improved the control systems of WECSs in different aspects. However, they required the information of all state variable, i.e., the speed of the generator (or wind turbine), and stator currents of the generator.

Recently, a new method for modeling the nonlinear systems so-called the polynomial system was introduced in [11], [12]. The polynomial system can model the original nonlinear system in the format of the linear system with the system matrices being polynomial matrices. Because, in the polynomial systems, the variable is put inside the system matrices that lead to the number of the linearized terms and modeling error are decreased. Additionally, with the aid of SOS technique and SOS Tool [13] in Matlab, the controller and observer design for the polynomial system become easier and more effective. In past few years, there are a large number of studies focusing on controller and observer design for the polynomial system [11], [12], [14]-[17]. For example, a polynomial observer was synthesized for the polynomial system with unknown inputs [14] in which the effects of the unknown inputs were completely eliminated and the unmeasurable states were estimated asymptotically. Moreover, an approach to design an observer-based controller for the uncertain polynomial system was investigated in [17], where both unknown states and uncertainties were estimated and feed-backed to the controller to stabilize the system. However, on the basis of our literature review, up to now, the polynomial system has not been employed to model the WECSs and the polynomial observer is not studied for WECSs in any previous works.

Considering this fact, this paper presents a novel observer based on the polynomial form for estimating not only aerodynamic torque but also *d*-axis and *q*-axis currents. It means the only speed of the generator needs to be measured. To the best of our knowledge, this is the first time, such an observer is proposed for WECSs. Regarding the observer design, the WECSs is, firstly, modeled under the framework of the polynomial system, then the polynomial observer is synthesized for this system. The gains of the observer are obtained via the SOS toolbox. The LQR, which is both robust to noise and easy to apply, is designed for speed tracking of the generator. It is proved that the proposed observer-based control system is successfully designed and implemented. The simulation studies are carried out in the MATLAB/Simulink environment.

II. SYSTEM DESCRIPTION

The power captured by the wind turbine (WT) is expressed by

$$P_a = \frac{1}{2}\rho\pi R^2 C_p(\lambda,\beta)v^3 \quad (1)$$

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where ρ is the air density, v denotes the wind speed, R is the WT rotor radius, and $C_p(\lambda,\beta)$ is the power coefficient representing the turbine efficiency to transform the kinetic power of the wind into mechanical power. C_p is a nonlinear function of the tip-speed ratio λ and of the pitch angle β of the blades. The tip-speed ratio λ is defined as

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

where ω_t is the rotor speed of the turbine.

The aerodynamic torque T_a is given by

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

where $C_q(\lambda,\beta) = C_p(\lambda,\beta)/\lambda$ is the torque coefficient.

According to (1), the captured power is linearly promotional to coefficient C_p, which is maximized at the optimal tip-speed ratio λ_{opt}. For a given wind turbine, λ_{opt} is a constant value at a fixed blade angle; therefore, according to (2), maximum captured power is achieved by tracking the optimum reference of turbine rotor speed given by,

$$\omega_{t,ref} = \frac{\lambda_{opt}}{R} v \tag{4}$$

It should be noted that the relations between speed and torque of turbine side and generator side are given as,

$$n_{gb} = \frac{\omega}{\omega_t} = \frac{T_a}{T_{gs}} \tag{5}$$

where n_{gb} is the gearbox ratio, ω is the mechanical angular speed of the generator, and T_{gs} is the equivalent aerodynamic torque applied to the generator.

The dynamic model of a PMSG is expressed as,

$$\begin{cases} J\dfrac{d\omega}{dt} = -B_v\omega + T_{gs} - T_e \\ \dfrac{di_q}{dt} = -\dfrac{R_s}{L}i_q - P\omega i_d - \dfrac{\psi_m P}{L}\omega + \dfrac{1}{L}v_q \\ \dfrac{di_d}{dt} = -\dfrac{R_s}{L}i_d + P\omega i_q + \dfrac{1}{L}v_d \end{cases} \tag{6}$$

where i_d and i_q are the stator currents in d-axis and q-axis, respectively; v_d and v_q are the stator voltages in d-axis and q-axis, respectively; P is the number of pole pairs; R_s is the nominal stator resistance; L is the nominal stator inductances; B_v is the equivalent viscous friction coefficient; J denotes the equivalent rotor inertia; ψ_m is the magnet flux linkage, and T_e is the electromagnetic torque. The electromagnetic torque can be calculated by,

$$T_e = Ki_q \tag{7}$$

where $K = 3/2\ \psi_m P$.

From (5)-(7), we can write the dynamic equations of a PMSG as follows,

$$\begin{cases} \dfrac{d\omega}{dt} = -\dfrac{B_v}{J}\omega - \dfrac{1}{J}T_e + \dfrac{1}{J.n_{gb}}T_a \\ \dfrac{dT_e}{dt} = -\dfrac{R_s}{L}T_e - PK\omega i_d - \dfrac{\psi_m PK}{L}\omega + \dfrac{K}{L}v_q \\ \dfrac{di_d}{dt} = -\dfrac{R_s}{L}i_d + \dfrac{P}{K}\omega T_e + \dfrac{1}{L}v_d \end{cases} \tag{8}$$

Assumption 1:

1) Only ω is measurable; i_d and i_q (hence T_e) are unknown state variable and need to be estimated

2) Wind speed v and aerodynamic torque T_a are unknown;

III. LQR DESIGN

Eq. (8) can be transformed to following error dynamics,

$$\begin{cases} \dfrac{d\tilde{\omega}}{dt} = -\dfrac{B_v}{J}\tilde{\omega} - \dfrac{1}{J}\tilde{T}_e \\ \dfrac{d\tilde{T}_e}{dt} = -\dfrac{R_s}{L}\tilde{T}_e - \dfrac{\psi_m PK}{L}\tilde{\omega} + \dfrac{K}{L}(v_q - u_{qc}) \\ \dfrac{di_d}{dt} = -\dfrac{R_s}{L}i_d + \dfrac{1}{L}(v_d - u_{dc}) \end{cases} \tag{9}$$

where $\tilde{\omega}$ is the tracking error of rotor speed, $\tilde{T}_e$ is the tracking error of the electromagnetic torque of generator, and u_{qc} and u_{dc} are the compensating terms of control inputs, respectively. They are defined as follows,

$$\begin{aligned} \tilde{\omega} &= \omega - \omega_{ref}; \omega_{ref} = \omega_{t,ref}.n_{gb} = \frac{\lambda_{opt}}{R}v.n_{gb} \\ \tilde{T}_e &= T_e - T_{e,ref}; T_{e,ref} = \frac{1}{n_{gb}}T_a - B_v\omega_{ref} - J\dot{\omega}_{ref} \\ u_{qc} &= R_s K T_{e,ref} + \dot{T}_{e,ref} + \psi_m P\omega_{ref} + PL\omega i_d \\ u_{dc} &= -\frac{PL}{K}\omega T_e. \end{aligned} \tag{10}$$

where ω_{ref} is the speed reference of the generator, $T_{e,ref}$ is the reference of electromagnetic torque, and $\dot{(\cdot)}$ denotes the first time-derivative of a variable.

The system (8) can be rewritten in the following state-dependent coefficient form,

$$\dot{x} = Ax + B(u - u_c) \tag{11}$$

where

$$x = [\tilde{\omega} \quad \tilde{T}_e \quad i_d]^T, u = [v_q \quad v_d]^T, u_c = [u_{qc} \quad u_{dc}]^T,$$

$$A = \begin{bmatrix} -\dfrac{B_v}{J} & \dfrac{1}{J} & 0 \\ -\dfrac{\psi_m PK}{L} & -\dfrac{R_s}{L} & 0 \\ 0 & 0 & -\dfrac{R_s}{L} \end{bmatrix}, B = \begin{bmatrix} 0 & 0 \\ \dfrac{K}{L} & 0 \\ 0 & \dfrac{1}{L} \end{bmatrix}.$$

Let us consider the following linear quadratic performance index:

$$J(x,u) = \int_0^\infty (x^T Q x + u^T T u) \quad (12)$$

where $Q \geq 0$ is an 3×3 matrix, $T > 0$ is an 2×2 matrix. In optimal control theories, by minimizing this quadratic performance index, the optimal control law is determined.

The following control law is utilized to minimize the performance index:

$$u = u_c + K_u x \quad (13)$$

where $K_u = -T^{-1}B^T P_u$ is the gain matrix of the controller, in which P is a positive-definite solution of the following algebraic Riccati Equation:

$$P_u A + A^T P_u - P_u B T^{-1} B^T P_u + Q = 0 \quad (14)$$

Theorem 1: With the control law in (13), the state vector *x* in the system (11) exponentially converges to zero.

Proof: In order to analyze the stability, define the Lyapunov function as follows:

$$V(x) = x^T P_u x \quad (15)$$

It is obvious that *V*(*x*) is positive-definite and radially unbounded. From (11)-(15), its time derivative satisfies,

$$\begin{aligned} \dot{V}(x) &= \frac{d}{dt} x^T P_u x = 2x^T P(A + BK_u)x \\ &= 2x^T P_u (A - BT^{-1}B^T P_u) \\ &= x^T P_u (P_u A + A^T P_u - 2P_u B T^{-1} B^T P_u)x \\ &\leq -x^T Q x \end{aligned} \quad (16)$$

Equation (16) shows that the time-derivative of *V* is negative for all non-zero values of *x*. It can be inferred that *x* exponentially converges to zero.

IV. OBSERVER DESIGN

The objective of this section is to design an observer to estimate both unknown states i_d, i_q (hence T_e), and T_a, simultaneously.

Equation (8) is rewritten as follows:

$$\begin{bmatrix} \dot{\omega} \\ \dot{T}_e \\ i_d \end{bmatrix} = \begin{bmatrix} -\frac{B_v}{J} & -\frac{1}{J} & 0 \\ -\frac{\psi_m PK}{L} & -\frac{R_s}{L} & PK\omega \\ 0 & \frac{P}{K}\omega & -\frac{R_s}{L} \end{bmatrix} \begin{bmatrix} \omega \\ T_e \\ i_d \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ \frac{K}{L} & 0 \\ 0 & \frac{1}{L} \end{bmatrix} \begin{bmatrix} v_q \\ v_d \end{bmatrix} + \begin{bmatrix} \frac{1}{Jn_{gb}} \\ 0 \\ 0 \end{bmatrix} T_a \quad (17)$$

Then the system (17) is rewritten under the framework of the polynomial system

$$\begin{cases} \dot{\bar{x}} = A(y)\bar{x} + Bu + DT_a \\ y = C\bar{x} \end{cases} \quad (18)$$

where

$\bar{x} = [\omega \quad T_e \quad i_d]^T$, $u = [v_q \quad v_d]^T$, $y = \omega$

$$A(y) = \begin{bmatrix} -\frac{B_v}{J} & -\frac{1}{J} & 0 \\ -\frac{\psi_m PK}{L} & -\frac{R_s}{L} & PKy \\ 0 & \frac{P}{K}y & -\frac{R_s}{L} \end{bmatrix}, B = \begin{bmatrix} 0 & 0 \\ \frac{K}{L} & 0 \\ 0 & \frac{1}{L} \end{bmatrix}.$$

$C = [1 \quad 0 \quad 0]$ and $D = \left[\frac{1}{Jn_{gb}} \quad 0 \quad 0\right]^T$

Consider the polynomial observer form for the system (18)

$$\begin{cases} \dot{\hat{\bar{x}}} = N(y)\hat{\bar{x}} + Gu + L(y)y + F\dot{y} & (19a) \\ \hat{y} = C\hat{\bar{x}} & (19b) \\ \hat{T}_a = (CD)^{-1}\dot{y} - E(y)\hat{\bar{x}} - Ou & (19c) \end{cases}$$

where $\hat{\bar{x}}$, $\hat{y}$ and $\hat{T}_a$ are the estimation of $\bar{x}$, y and T_a, respectively. $N(y) \in \mathbb{R}^{3\times3}$, $\in \mathbb{R}^{3\times1}$, $L(y) \in \mathbb{R}^{3\times1}$, $F \in \mathbb{R}^{3\times1}$, $E(y) \in \mathbb{R}^{1\times3}$, and $O \in \mathbb{R}^{1\times2}$ are the observer gains which will be determined later.

Proposition 1 [12]: If $f(x(t))$ can be represented as the form $f(x(t)) = \sum_{i=1}^{n}[b_i(x(t))]^2$, where $b_i(x(t)$ is a polynomial in $x(t)$, then $f(x(t))$ is called a SOS. Hence, when $f(x(t))$ is a SOS, it means that $f(x(t)) \geq 0$, however, the converse is not guaranteed.

Proposition 2 [12]: Let $\Lambda(x)$ be a $n\times n$ polynomial symmetric matrix in x and $v \in \Re^n$ be a vector independent on x, then $v^T\Lambda(x)v$ is an SOS if and only if $\Lambda(x) \geq 0$ for all x.

Let us define estimation error of the states and T_a

$$e(t) = \bar{x} - \hat{\bar{x}} \quad (20)$$

and

$$e_{T_a}(t) = T_a - \hat{T}_a \quad (21)$$

Theorem 2: The estimation error of the states $e(t)$ and estimation error $e_{T_a}(t)$with the observer (19) converge to zero asymptotically if there exist the matrices $N(y)$, G, $L(y)$, F, $E(y)$, O, and symmetric matrix P such that the following conditions are satisfied

$$v_1{}^T(P - \varepsilon_1 I)v_1 \text{ is SOS} \quad (22)$$

$$-v_2{}^T(\Lambda(y) - \varepsilon_2(y)I)v_2 \text{ is SOS} \quad (23)$$

where

$$\begin{aligned} &\Lambda(y) = A^T(y)P - [D(CD)^{-1}CA(y)]^T P - C^T Q^T(y) \\ &+PA(y) - PD(CD)^{-1}CA(y) - Q(y)C \end{aligned} \quad (24)$$

$$Q(y) = PL(y) \quad (25)$$

v_1 and v_2 are the vectors that are independent on y. $\varepsilon_1$is the positive scalar and $\varepsilon_2(y) > 0$ with $y \neq 0$; $i = 1, 2, \ldots, r$

And the observer gains are computed as follows

$$F = D(CD)^{-1} \quad (26)$$
$$N(y) = A(y) - FCA(y) - L(y)C \quad (27)$$
$$L(y) = P^{-1}Q(y) \quad (28)$$
$$G = B - FCB \quad (29)$$
$$E(y) = (CD)^{-1}CA(y) \quad (30)$$
$$O = (CD)^{-1}CB \quad (31)$$

Proof: The proof is omitted due to lack of the number of pages of the paper

The observer gains of the observer (19) are obtained by solving the conditions in Theorem 2 by SOS tool in MATLAB [13].

V. RESULTS AND DISCUSSION

Consider a WECS based on a PMSG with parameters given in Table I [18]. All simulation studies are carried out via MATLAB/Simulink. Based on [19], the wind profile is chosen, with the mean value of 11.5 m/s and turbulence intensity of 15.23%; its profile is presented in Fig. 1. The power coefficient C_p is analytically estimated by a function in [18], with $\lambda_{opt} = 8.1$, and $C_{pmax} = 0.326$.

TABLE I. WECS PARAMETERS

Symbol	Parameter	Value	Unit
P_{rated}	Rated power	5	kW
P	Pole pairs	14	-
R_s	Stator resistance	0.3676	Ω
L	Stator inductance	3.55	mH
ψ_m	Magnet flux linkage	0.2867	V· s/rad
J	Mechanical inertia	7.856	kg· m^2
B	Viscous friction coefficient	0.002	kg· m^2/s
R	Rotor radius	1.84	m
ρ	Air density	1.25	kg/m^3

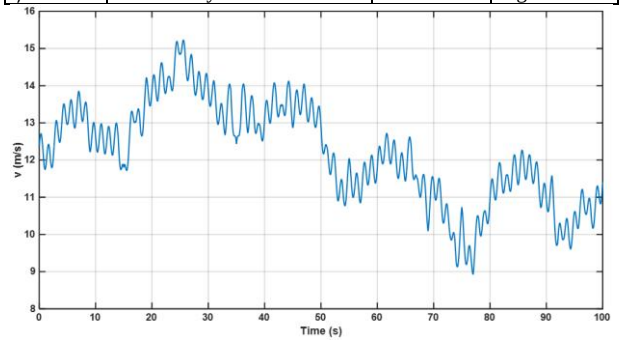


Fig. 1. *Wind speed profile*

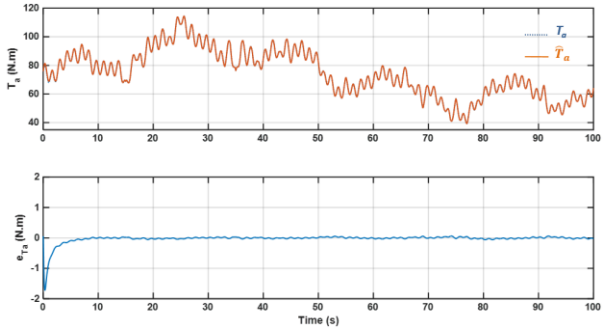


Fig. 2. *Aerodynamic torque (T_a), aerodynamic torque estimation ($\hat{T}_a$), and aerodynamic torque estimation error $e_{T_a} = T_a - \hat{T}_a$)*

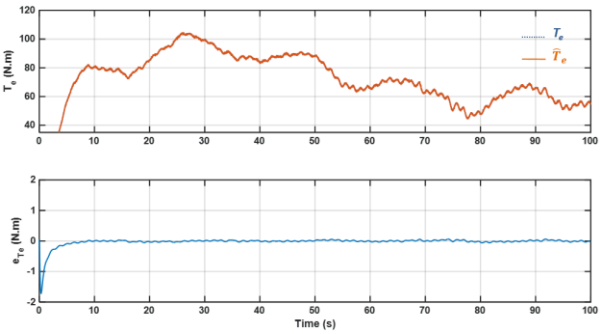


Fig. 3. *Electromagnetic torque (T_e), electromagnetic torque estimation ($\hat{T}_e$), and electromagnetic torque estimation error $e_{T_e} = T_e - \hat{T}_e$)*

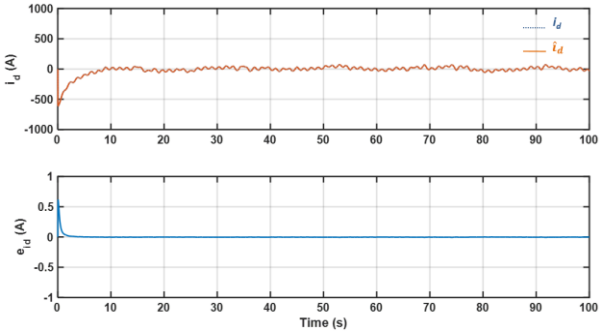


Fig. 4. *d-axis current (i_d), d-axis current estimation ($\hat{i}_d$), and d-axis current estimation error $e_{i_d} = i_d - \hat{i}_d$)*

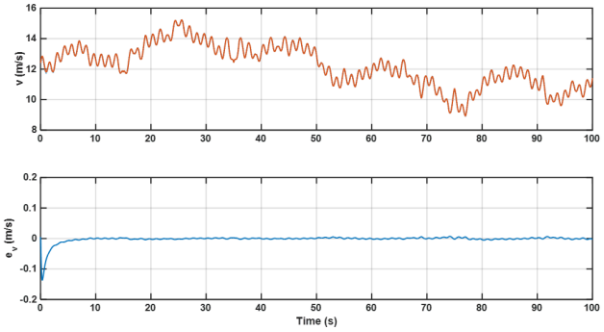


Fig. 5. *Wind speed (v), wind speed estimation ($\hat{v}$), and aerodynamic torque estimation error ($e_v = v - \hat{v}$)*

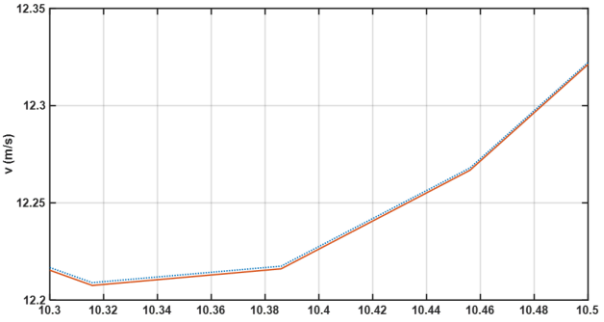


Fig. 6. Zoom-in results of *wind speed (v) and wind speed estimation ($\hat{v}$).*

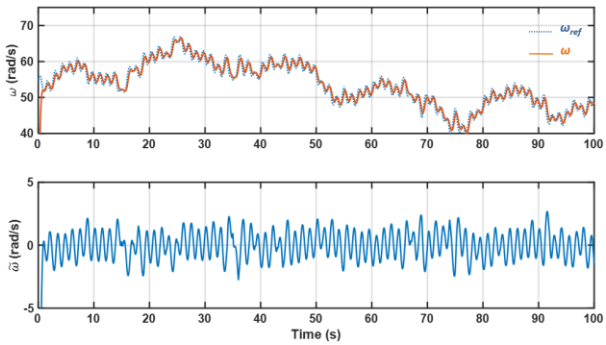


Fig. 7. *Angular shaft speed reference (ω_{ref}), angular shaft speed response (ω), and tracking error ($\tilde{\omega}$)*

The gains for observer are solved via the SOS tool in MATLAB whereas the those of controllers are selected by the procedure introduced in [20], [21].

Figs. 2-4 presents the simulation results of the responded value, estimated value, and estimation error of aerodynamic torque, electromagnetic torque, and *d*-axis current, respectively. It can be observed that the aerodynamic torque, electromagnetic torque, and *d*-axis current are precisely estimated. All the estimation errors can be considered as zero in steady-state (maximum value of steady-state errors are less than 0.1%). Fig. 5 is about the wind speed, estimated wind speed, and wind speed estimation error, whereas Fig. 6 shows the zoomed-in results of wind speed and estimated wind speed. It is easy to check that the difference between these two values is negligible. Finally, Fig. 7 illustrates generator speed reference, generator speed response, and the tracking error of the generator rotor speed. We can see that the steady-state value of tracking error is less than 4%, which is in a very precise range for controlling variable WECSs.

VI. CONCLUSION

In this paper, we presented a novel observer for WECSs. This observer estimates both the aerodynamic torque, and the stator currents. Consequently, the generator speed reference can be calculated without the measurement of wind speed. Therefore, for the proposed control system in this work, only the generator rotor speed is required to be measured. For tracking the optimal speed reference, the well-known LQR is designed and its gains are selected by via a systematic procedure. The simulation results are conducted with MATLAB/Simulink software to prove the effectiveness of our proposed observer as well as control system.

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