UDE-based Robust Control of Variable-Speed Wind Turbines

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***Abstract*—In this paper, the UDE (uncertainty and disturbance estimator)-based robust control is investigated for a two-bladed horizontal axis variable speed wind turbine in the presence of model uncertainties and external disturbances. The UDE algorithm is based on the assumption that a signal can be approximated and estimated by using a filter with the appropriate bandwidth. The most important features of the approach are that (i) the employment of UDE makes it possible to estimate the lumped uncertain term which is non-singular with respect to the system state ω_r and bounded with respect to the time t; and (ii) it does not require any knowledge (e.g., bounds) about the uncertainties and disturbances, except the information about the bandwidth, during the design process. The asymptotic stability of the closed-loop system is rigorously established and the rotor speed asymptotically tracks a reference speed that maximizes the energy captured by adjusting the armature current of the DC generator. The effectiveness of the proposed approach is demonstrated through simulation studies.**

I. INTRODUCTION

Wind energy has been regarded as an environmentally friendly alternative energy source and has attracted most of attention during the last decades. Many initiatives have been launched to increase the share of wind power in electricity generation [1], [2]. A wind turbine is a device that captures the kinetic energy of wind, which can be designed for fixed-speed or variable-speed operation. In contrast to fixed speed wind turbines, variable-speed wind turbines are designed to follow wind-speed variations in low winds to maximize aerodynamic efficiency, so have the potential to produce more energy than fixed-speed ones. Once the power is extracted, then it is important to feed it into grid. The grid integration of wind power through power electronic converters is discussed in detail in [3].

Because wind turbines are large, flexible structures operating in noisy environments, the quality of power generation strongly depends on the control techniques employed. Standard control laws [4] require that complex aerodynamic properties be well known so that the variable-speed turbine can maximize energy capture; in practice, uncertainties limit the efficient energy capture of a variable-speed turbine. To make wind power truly costly effective and reliable, the use of advanced control techniques are imperative in the presence of turbine model uncertainties and external disturbances.

The main nonlinearities in a wind turbine model come from the nonlinear aerodynamic loads on the turbine. Creating an accurate model of the dynamic characteristics of a wind turbine is expensive and extremely difficult, if not impossible. Additionally, wind turbines operate in highly turbulent and unpredictable conditions. These complex aspects of wind turbines make them attractive candidates for the application of robust control methods. Fuzzy logic control [5]–[7] and neural networks [8] have been investigated to reduce the uncertainties faced by classical control methods. Adaptive control schemes [4], [9]–[11] have been developed to eliminate some of the problems faced in wind turbine control, such as unknown and time varying model parameters in the wind turbine mode. Sliding mode control was applied to the wind energy systems in [12]–[16] to improve the robustness of the system in the presence of uncertainties.

The UDE (uncertainty and disturbance estimator) control algorithm, which was proposed in [17] as a replacement of the time-delay control (TDC) in [18], is based on the assumption that a signal can be approximated and estimated using a filter with the appropriate bandwidth. The UDE-based robust control has demonstrated excellent performance in handling uncertainties and disturbances, and has been successfully applied to robust input-output linearization [19] and combined with sliding-mode control [20], [21], and further extended to uncertain systems with state delays, for both linear systems [22] and nonlinear systems [23]. The two-degree-of-freedom nature of the UDE-based control has been revealed in [24], which enables the decoupled design of the reference model and the filters. However, the rigorous stability analysis of the closed-loop system is missing in the above works.

In this paper, the UDE-based robust control is developed for variable speed wind turbines to make the rotor speed track the desired speed by adjusting the armature current of the DC generator. The two-bladed horizontal axis wind turbine similar to the DOE MOD-0 model [10] is investigated in this paper in the presence of model uncertainties and external disturbances. One of the major contributions of this paper is to establish the rigorous asymptotic stability for variable speed wind turbines controlled by the UDE-based robust control strategy. It can be shown that the asymptotic stability of the closed-loop system is established when the UDE is chosen appropriately under very mild conditions. The most important features of the approach are that (i) the employment of UDE makes it possible to estimate the lumped uncertain term which is non-singular with respect to the system state ω_r and bounded with respect to the time t; and (ii) it does not require any knowledge (e.g., bounds) about the uncertainties and disturbances, except the information about the bandwidth, during the design process.

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The rest of the paper is organized as follows. Section II details the problem formulation. In Section III, a UDE-based controller is constructed for variable speed wind turbines. In Section IV, the stability of the closed-loop system is established. Effectiveness of the proposed approach is demonstrated through simulation studies in Section V, before the concluding remarks made in Section VI.

II. PROBLEM FORMULATION AND PRELIMINARIES

The power produced by a wind turbine can be calculated as

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

where ρ is the air density, R is the radius of the rotor, v_w is the wind speed, $C_p(\lambda, \beta)$ is the power coefficient that is dependent on the turbine design, the pitch angle β and the tip-speed ratio λ defined as

$$\lambda = \omega_r R / v_w, \quad (2)$$

where ω_r is the angular speed of the wind turbine. The tip-speed ratio plays a vital role in extracting power from wind. If the rotor turns too slowly, most of the wind passes through the gap between the rotor blades without doing any work; if the rotor turns too quickly, the blurring blades block the wind like a solid wall. Hence, wind turbines are designed to operate at optimal tip-speed ratios so that as much power as possible can be extracted.

The power coefficient C_p is a highly nonlinear function of λ and β. For wind turbines with a fixed pitch angle β, the relationship between C_p and the tip speed ration λ often has the shape shown in Figure 1. The power coefficient reaches its maximum point at the optimum tip speed ratio λ_{opt}, which depends on the number of blades in the wind turbine rotor. The fewer the number of blades, the faster the wind turbine rotor needs to turn to extract the maximum power from the wind. According to (2), the curves of C_p against different wind speeds have similar shapes, as shown in Figure 2(a), where six C_p curves are shown for six different wind speeds with $v_{w1} > v_{w2} > v_{w3} > v_{w4} > v_{w5} > v_{w6}$. The corresponding power P_m is shown in Figure 2(b). Therefore, the operational points of a wind turbine at different wind speeds are different, which are determined by the optimal tip-speed ratio λ_{opt} and the wind speed. See [25] for more details. It is worth noting that the power coefficient C_p of a wind turbine is limited by 0.593, according to the Betz law.

Combining (1) and (2) results in

$$P_m = k_\omega \omega_r^3, \quad (3)$$

where

$$k_\omega = \frac{1}{2} C_p \rho \pi \frac{R^5}{\lambda^3}.$$

Most modern wind turbines use a horizontal axis configuration with two or three blades, operating either downwind or upwind. The major components of a typical wind turbine include an aeroturbine, which converts wind energy into mechanical energy; a gearbox, which serves to increase the

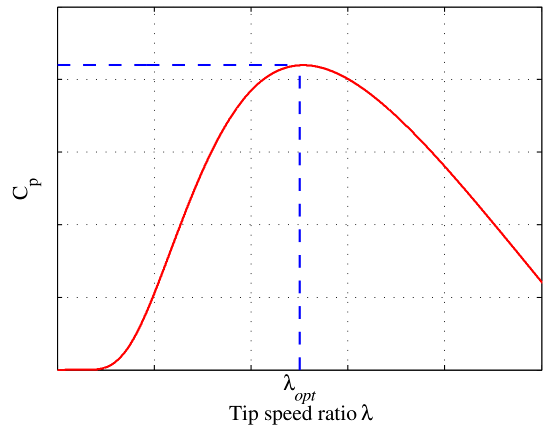
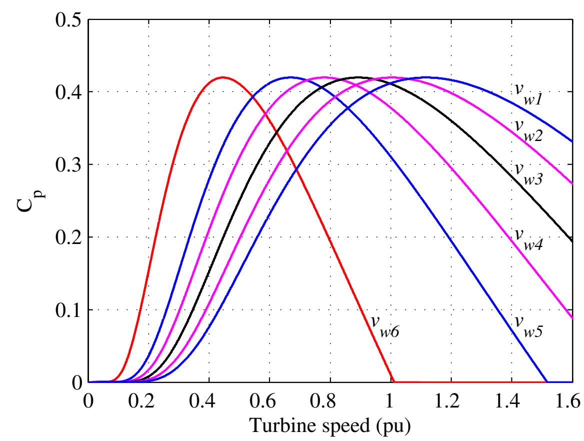
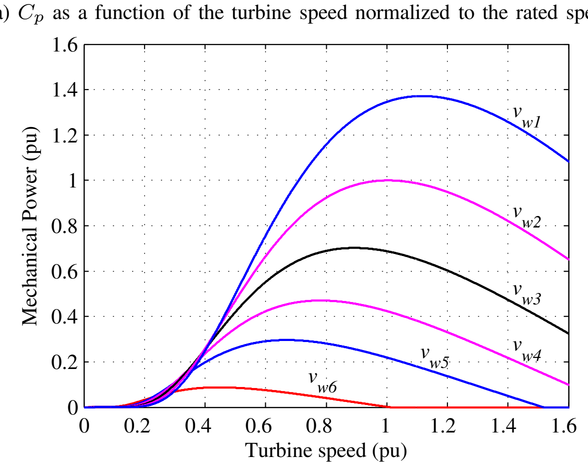


Figure 1. Power coefficient C_p as a function of the tip-speed ratio λ [3].



(a) C_p as a function of the turbine speed normalized to the rated speed



(b) Power P_m

Figure 2. Power coefficient C_p and mechanical power P_m at different wind speeds [3].

speed and decrease the torque; and a generator which converts mechanical energy into electrical energy. Figure 3 shows the schematic diagram of wind power system adopted in this work where a DC generator is considered in order to demonstrate the concept of robust control of rotor speed to achieve the MPPT (maximum power point tracking). However, the principle is also applicable to the wind power systems with Permanent Magnet Synchronous Generator (PMSG) or Doubly-fed Induction Generator (DFIG).

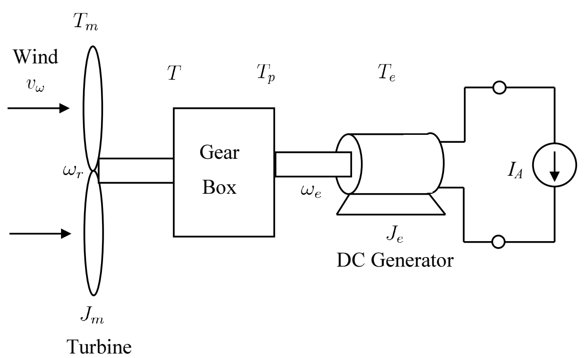


Figure 3. Schematic diagram of a wind power system.

In Figure 3, the dynamics of the system are characterized by the following equations:

$$J_m\dot{\omega}_r + B_m\omega_r = T_m - T, \quad (4)$$
$$J_e\dot{\omega}_e + B_e\omega_e = T_p - T_e, \quad (5)$$
$$T_p\omega_e = T\omega_r, \quad (6)$$

where T_m, T_e, T, T_p are the shaft torques at turbine end, generator end, before and after gear box, J_m, J_e are the moments of inertia of the turbine and the generator, B_m, B_e are the friction-related constants, ω_r, ω_e are the angular speeds of the shaft at turbine end and generator end respectively. The gearbox ratio is defined as

$$\gamma = \frac{\omega_e}{\omega_r}. \quad (7)$$

Furthermore, (4)-(7) can be combined into the following equation

$$J\dot{\omega}_r + B\omega_r = T_m - \gamma T_e, \quad (8)$$

where $J = J_m + \gamma^2 J_e$, $B = B_m + \gamma^2 B_e$. It is well known that

$$T_m = \frac{P_m}{\omega_r}, \quad (9)$$
$$T_e = \frac{P_e}{\omega_e}, \quad (10)$$

where P_m denotes the wind power given by (3) and P_e represents the electric power generated, which is related to the armature current of the generator as follows:

$$P_e = K_\phi \omega_e I_A, \quad (11)$$

where K_ϕ is a machine-related constant, I_A is the armature current of the DC generator. For the systems with PMSG or DFIG, the current source I_A can be achieved via controlling the rectifier.

Substituting (9)-(11) into (8) results in the rotor dynamics

$$\dot{\omega}_r = g(\omega_r) + bI_A \quad (12)$$

where $g(\omega_r) = (-B\omega_r + k_\omega\omega_r^2)/J$ and $b = -\gamma K_\phi/J$. The rotor dynamics (12) shows that the rotor speed of the wind turbine ω_r is controlled through the adjustment of the armature current I_A.

However, creating an accurate model of the dynamic characteristics of a wind turbine is expensive and extremely difficult, if not impossible. Additionally, wind turbines operate in highly turbulent and unpredictable conditions. Instead of the nominal model (12), the following modified model is considered:

$$\dot{\omega}_r = g(\omega_r) + bI_A + \Delta(\omega_r, t), \quad (13)$$

where the nominal values of system parameters are assumed to be known, i.e., $g(\omega_r)$ and b are known, $\Delta(\omega_r, t)$ represents the term of uncertainties and disturbances which might caused by unknown modeling parameters or poorly known operating conditions.

Assumption 1: The unknown lumped uncertain term $\Delta(\omega_r, t)$ is non-singular with respect to the system state ω_r and bounded with respect to the time t. But its bandwidth is known.

Compared with other existing robust control schemes in the literature, most of which require the boundedness of the lumped uncertain term $\Delta(\omega_r, t)$ with respect to both the state ω_r and the time t, the Assumption 1 is more relaxed and applicable to a more general class of systems.

Our objective is to design a control current I_A in (13) in the presence of model uncertainties and external disturbances such that the rotor speed ω_r of the wind turbine in (13) asymptotically tracks a reference speed ω_{rd}, i.e., the tracking error $e(t) = \omega_{rd} - \omega_r$ asymptoticially converges to zero.

The reference signal ω_{rd} can be generated by an MPPT (maximum power point tracking) controller, e.g., [26]. In this paper, we assume that the reference signal ω_{rd} is generated using the following stable linear reference model

$$\dot{\omega}_{rd} = a_m\omega_{rd} + b_m c(t) \quad (14)$$

where ω_{rd}, $c(t)$ are the state and input signal, $c(t)$ is a piecewise continuous and uniformly bounded command to the system, a_m and b_m, are chosen to meet the desired specification of the closed-loop control system.

In addition, the desired error dynamics are specified as follows

$$\dot{e}(t) = (a_m + K)e(t) \quad (15)$$

where K is an error feedback gain. Since the reference model is chosen to the stable, K may be chosen as 0. If a different error dynamics is desired or required to guarantee the stability or to meet the dynamic performance, then common control strategies, e.g., pole placement, can be used to choose K.

III. UDE-based control strategy

Combining equations (13, 14, 15), then

$$a_m \omega_r + b_m c - g(\omega_r) - bI_A - \Delta(\omega_r, t) = Ke. \quad (16)$$

In order to simplify the exposition, the arguments of functions are omitted in this paper. The control signal I_A needs to satisfy

$$bI_A = a_m \omega_r + b_m c - g - u_d - Ke, \quad (17)$$

where

$$u_d = \Delta.$$

According to the system dynamics in (13), u_d can be represented as

$$u_d = \Delta = \dot{\omega}_r - g - bI_A,$$

which indicates that the unknown dynamics and disturbances can be obtained from the known dynamics of the system and control signal. However, it cannot be directly used to formulate a control law. The UDE-based robust control strategy [17] adopts an estimation of this signal so that a control law is derived, based on the assumption that a signal can be approximated and estimated using a filter with the appropriate bandwidth. For example, if the filter has a wide enough bandwidth, the uncertainty and disturbance estimator is able to accurately and quickly estimate the lumped uncertainty term u_d.

Following the procedures provided in [17], assume that $g_f(t)$ is the impulse response of a strictly proper stable filter $G_f(s)$ with the unity gain and zero phase shift over the spectrum of u_d. Note that this can be easily achieved. Then u_d can be accurately approximated by

$$\hat{u}_d = u_d * g_f = (\dot{\omega}_r - g - bI_A) * g_f, \quad (18)$$

where $\hat{u}_d$ is an estimate of u_d, "$*$" is the convolution operator. Therefore, $\hat{u}_d = u_d$ if the bandwidth of the filter is chosen broad enough to cover the spectrum of u_d. It is achievable due to Assumption 1.

Replacing u_d with $\hat{u}_d$ in (17) results in

$$bI_A = a_m \omega_r + b_m c - g - Ke - (\dot{\omega}_r - g - bI_A) * g_f. \quad (19)$$

This brings the UDE-based control law

$$\begin{aligned} I_A = \frac{1}{b}\Bigg[& -g + L^{-1}\left\{\frac{1}{1-G_f(s)}\right\} * (a_m\omega_r + b_m c - Ke) \\ & - L^{-1}\left\{\frac{sG_f(s)}{1-G_f(s)}\right\} * \omega_r \Bigg], \end{aligned} \quad (20)$$

where $L^{-1}\{\cdot\}$ is the inverse Laplace transform operator. Therefore, the unknown dynamics and disturbances are removed from the control signal in (20).

As demonstrated in [24] , the filter $G_f(s)$ can be designed to meet desired specifications but in many cases it is enough to choose $G_f(s)$ as the following first-order low-pass filter

$$G_f(s) = \frac{1}{1+\tau s}, \quad (21)$$

of which the bandwidth is wide enough to cover the spectrum of u_d. It is worth noting that

$$\frac{1}{1-G_f(s)} = 1 + \frac{1}{\tau s},$$

and

$$\frac{sG_f(s)}{1-G_f(s)} = \frac{1}{\tau}.$$

Therefore, when the low-pass filter (21) is used, the UDE-based control law (20) satisfies

$$\begin{aligned} & I_A \\ = & \frac{1}{b}[-g + a_m\omega_r + b_m c - Ke - \frac{1}{\tau}\omega_r \\ & + \frac{1}{\tau}\int_0^t (a_m\omega_r + b_m c - Ke)dt] \\ = & -\frac{g}{b} + \frac{1}{b}(a_m\omega_{rd} + b_m c) \\ & + \frac{1}{b\tau}((1 - (a_m + K)\tau)e(t) - (a_m + K)\int_0^t e(t)dt). \end{aligned} \quad (22)$$

This simplified control law clearly demonstrates the nature of the UDE-based control strategy. It consists of three terms, which cancel the known system dynamics (the first term), introduce the desired dynamics given by the reference model (the second term) and adds a PI-like controller (the third term).

IV. Stability Analysis

The asymptotic stability of the closed-loop resulting system is summarized in the theorem below.

Theorem 1. *Consider the closed-loop system consisting of the rotor dynamics (13) satisfying Assumption 1, the reference model (14) and the UDE-based controller (20). Assume that the filter $G_f(s)$ is chosen appropriately as a strictly-proper stable filter with unity gain over the spectrum of the lumped term $u_d = \Delta$ of uncertainties and disturbances. Then the closed-loop system is asymptotically stable. Moreover, the tracking error dynamics of the state converges to*

$$\dot{e}(t) = (a_m + K)e(t) \quad (23)$$

where a_m is the stable reference model gain, and K is the designed error feedback gain.

Proof: If u_d in (17) is known, then the desired error dynamics (23) is obtained after substituting (17) into (13) and calculating the derivative of the error signal $e(t) = \omega_{rd} - \omega_r$.

When the lumped term u_d is unknown, the estimated term $\hat{u}_d$ from the UDE in (18) is adopted to estimate u_d. Then the error dynamics becomes

$$\dot{e}(t) = (a_m + K)e(t) + \tilde{u}_d, \quad (24)$$

where

$$\tilde{u}_d \triangleq u_d - \hat{u}_d$$

is the estimation error of the uncertainty and disturbance. According to (18), the estimate error is

$$\tilde{u}_d = u_d \cdot (1 - G_f(s)), \tag{25}$$

of which the equivalent structure is shown in Figure 4(a). Due to the Assumption 1, the filter G_f can be easily designed to have $G_f = 1$ over the spectrum of u_d, then

$$\tilde{u}_d \to 0$$

for any u_d. Therefore, the error dynamics in (24) converges to the desired error dynamics in (23), which is asymptotically stable by design. This completes the proof. ■

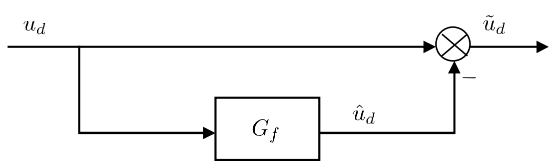
If $G_f(s)$ is chosen as the first-order low pass filter in (21), then (25) becomes

$$\tilde{u}_d = u_d \cdot \frac{\tau s}{\tau s + 1}. \tag{26}$$

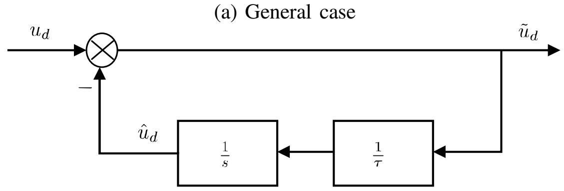
It is obvious that for any u_d with the given finite spectrum, if $\tau \to 0$ then

$$\tilde{u}_d \to 0.$$

The structure of (26) is shown in Figure 4(b).



(a) General case



(b) When $G_f(s) = \frac{1}{\tau s+1}$

Figure 4. Sketch of the UDE according to eq. (25).

V. Simulation Studies

To demonstrate the effectiveness of the proposed approach in this section, the wind power generation system given by (13) is rewritten as follows

$$\dot{\omega}_r = g(\omega_r) + bI_A + \Delta(\omega_r, t),$$

with $g(\omega_r) = (-B\omega_r + k_w\omega_r^2)/J$, $b = -\gamma K_\phi / J$. The term of uncertainties and disturbances $\Delta(\omega_r, t) = 0.1(\omega_r + \omega_r^2) + \sin(0.2\pi t) + 1(t-30)$ is used to verifiy the robustness of the proposed UDE-based control. The nominal parameters are chosen as [10]: $J = 16$ kg·m^2, $\gamma = 37.5$, $k_\omega = 3$, $B = 52$, $K_\phi = 1.7$. The reference model is chosen as

$$\dot{\omega}_{rd} = -10\omega_{rd} + 10c$$

and the error feedback gain K in the desired error dynamics in (15) is taken as -2. The reference input is set as $c(t) = 2 + \sin(0.1\pi t)$(rad/s). The initial condition is set as $\omega_r(0) = 0$ and the time constant τ of the low-pass filter in (21) is chosen as 0.001s.

The simulation results are shown in Figures 5 -7, where the UDE-based robust control (with the UDE $\hat{u}_d$) and the model-based control (without the UDE, that is, $\hat{u}_d = 0$) are conducted respectively. It can be seen that the better tracking performance is achieved with the proposed UDE-based robust control as the UDE is able to handle the system uncertainties and disturbances.

VI. Conclusion

In this paper, the UDE (uncertainty and disturbance estimator)-based robust control strategy was proposed for variable speed control of a two-bladed horizontal axis wind turbine in the presence of model uncertainties and external disturbances. The common assumptions about the uncertainties and disturbances are relaxed in our paper. It does not require any knowledge (e.g., bounds) about the uncertainties and disturbances, except the information about the bandwidth, during the design process. The asymptotic stability of the resulting closed-loop system was achieved. Though the DC generator was considered, the principle developed in this paper is also applicable to the wind power systems with PMSG or DFIG, where the current source can be achieved via controlling the rectifier.

References

[1] H.-J. Wagner and J. Mathur. *Introduction to Wind Energy Systems: Basics, Technology and Operation*. Springer-Verlag, 2009.

[2] S. Mathew. *Wind Energy: Fundamentals, Resource Analysis and Economics*. Springer-Verlag, 2006.

[3] Q.-C. Zhong and T. Hornik. *Control of Power Inverters in Renewable Energy and Smart Grid Integration*. Wiley-IEEE Press, 2013.

[4] K. Johnson, L. Fingersh, M. Balas, and L. Pao. Methods for increasing region 2 power capture on a variable speed wind turbine. *Journal of Solar Energy Engineering*, 126(4):1092–1100, 2004.

[5] R. Chedid, S. Karaki, and C. El-Chamali. Adaptive fuzzy control for wind-diesel weak power systems. *IEEE Trans. Energy Conversion*, 15(1):71–78, 2000.

[6] M. Prats, J. Carrasco, E. Galvan, J. Sanchez, L.Franquelo, and C.Batista. Improving transition between power optimization and power limitation of variable speed, variable pitch wind turbines using fuzzy control techniques. In *Proc. IECON 2000*, pages 1497–1502, Nagoya, Japan, 2000.

[7] X. Zhang, W. Wang, and Y. Liu. Fuzzy control of variable speed wind turbine. In *Proc. 6th World Congress on Intelligent Control and Automation*, pages 3872–3876, Dalian, China, 2006.

[8] F. Kanellos and N. Hatziargyriou. A new control scheme for variable speed wind turbines using neural networks. In *Proc. IEEE Power Eng. Soc. Trans. Distrib. Conf.*, pages 360–365, New York, NY, 2002.

[9] J. Freeman and M. Balas. An investigation of variable speed horizontal-axis wind turbines using direct model-reference adaptive contro. In *Proc. 18th ASME Wind Energy Symp.*, pages 66–76, Reno, NV, 1999.

[10] Y. D. Song, B. Dhinakaran, and X. Y. Bao. Variable speed control of wind turbines using nonlinear and adaptive algorithms. *Journal of Wind Engineering and Industrial Aerodynamics*, 85:293–308, 2000.

[11] K. Johnson, L. Pao, M. Balas, and L. Fingersh. Control of variable-speed wind turbines: Standard and adaptive techniques for maximizing energy capture. *IEEE Control Syst. Mag.*, 26(3):70–81, 2006.

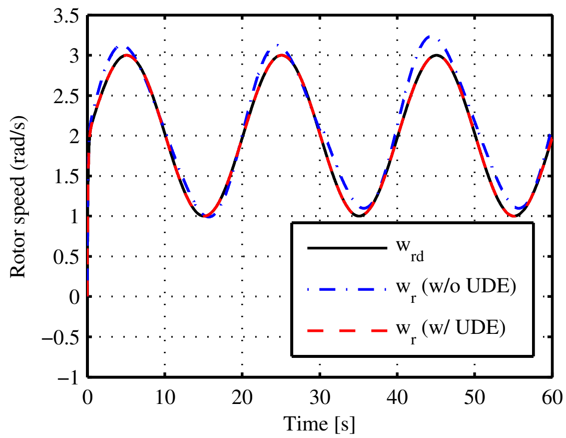


Figure 5. Comparision of rotor speed tracking performance with and without UDE

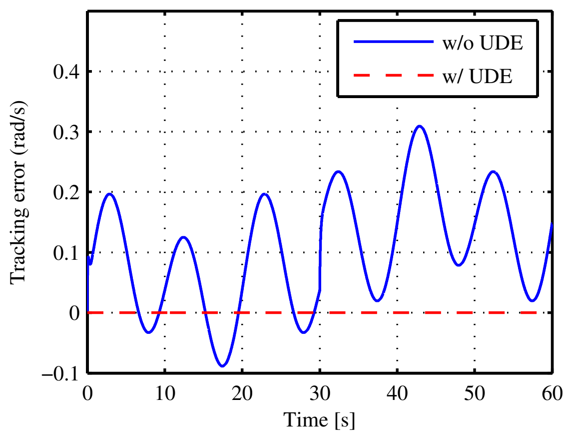


Figure 6. Comparision of rotor speed tracking error with and without UDE

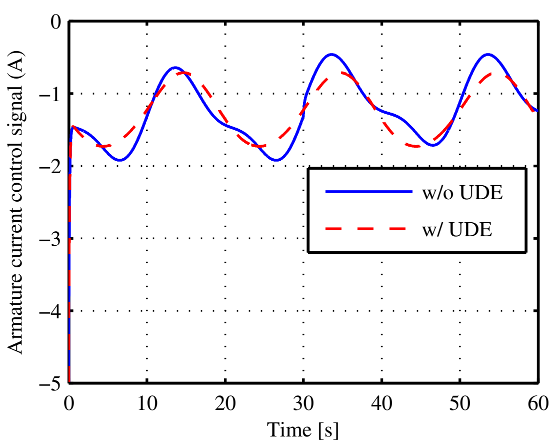


Figure 7. Comparision of armature current control signal with and without UDE

[12] H. De Battista, P.F. Puleston, R.J. Mantz, and C.F. Christiansen. Sliding mode control of wind energy systems with doig-power efficiency and torsional dynamics optimization. *IEEE Trans. Power Syst.*, 15:728–734, 2000.

[13] F. Valenciaga, P.F. Puleston, and P.E. Battaiotto. Variable structure system control design method based on a differential geometric approach: Application to a wind energy conversion subsystem. *IEE Proc. Control Theory Appl.*, 151:6–12, 2004.

[14] X. Yang, X. Liu, and Q. Wu. Integral fuzzy sliding mode control for variable speed wind power system. In *Proceedings of the IEEE International Conference on Automation and Logistics*, pages 1289–1294, Jinan, China, 2007.

[15] I. Munteanu, S. Bacha, A.I. Bratcu, J. Guiraud, and D. Roye. Energy-reliability optimization of wind energy conversion systems by sliding mode control. *IEEE Trans. Energy Convers.*, 23:975–985, 2008.

[16] O. Barambones. Sliding model control strategy for wind turbine power maximization. *Energies*, 5:2310–2330, 2012.

[17] Q.-C. Zhong and D. Rees. Control of uncertain LTI systems based on an uncertainty and disturbance estimator. *Journal of Dyn. Sys. Meas. Con.Trans. ASME*, 126(4):905–910, Dec. 2004.

[18] K. Youcef-Toumi and O. Ito. A time delay controller for systems with unknown dynamics. *Journal of Dyn. Sys. Meas. Con.Trans. ASME*, 112(1):133–142, Mar. 1990.

[19] S. Talole and S. Phadke. Robust input-output linearization using UDE. In *Proc. of International Conference on Advances in Control and Optimization of Dynamical Systems (ACODS)*, pages 79–82, 2007.

[20] S. Talole and S. Phadke. Model following sliding mode control based on uncertainty and disturbance estimator. *Journal of Dyn. Sys. Meas. Con.Trans. ASME*, 130:1–5, 2008.

[21] T. Chandrasekhar and L. Dewan. Sliding mode control based on TDC and UDE. *Int. J. of Information and Systems Science*, 3(1):36–53, 2007.

[22] R. K. Stobart and Q.C. Zhong. Uncertainty and disturbance estimator (UDE)-based control for uncertain LTI-SISO systems with state delays. *Journal of Dyn. Sys. Meas. Con.Trans. ASME*, 133(2):1–6, 2011.

[23] A. Kuperman and Q.-C. Zhong. Robust control of uncertain nonlinear systems with state delays based on an uncertainty and disturbance estimator. *International Journal of Robust and Nonlinear Control*, 21(1):79–92, Mar. 2010.

[24] Q.-C. Zhong, A. Kuperman, and R.K. Stobart. Design of UDE-based controllers from their two-degree-of-freedom nature. *International Journal of Robust and Nonlinear Control*, 21:1994–2008, 2011.

[25] S. Heier. *Grid Integration of Wind Energy Conversion Systems*. John Wiley & Sons, 2006.

[26] Jogendra Singh Thongam and Mohand Ouhrouche. Mppt control methods in wind energy conversion systems. *Fundamental and Advanced Topics in Wind Power*, pages 339–360, 2011.