EVOLUTION OF WIND TURBINE CONTROL SYSTEMS

Hoa M. Nguyen
Department of Electrical Engineering, and Measurement and Control Engineering Research Center, Idaho State University, Pocatello, USA.

D. Subbaram Naidu
Department of Electrical Engineering, and Measurement and Control Engineering Research Center, Idaho State University, Pocatello, USA.

Keywords: Wind turbine, wind energy conversion system, wind turbine control, wind turbine modeling, drive train, power electronic converters, generators, PID control, maximum power point tracking, optimal control, robust control, linear time varying control, adaptive control, model predictive control, sliding mode control, fuzzy logic control, neural network control, genetic algorithm, fusion control.

Content

Summary

This chapter presents an overview of advanced control strategies for wind turbine systems. It starts with important historical evolutions regarding wind energy that lead to the introduction of modern wind turbines. Next, the modeling of wind turbines, which is essential for the control system design, is presented. Finally, the chapter focuses on a wide variety of advanced control system techniques including hard, soft, and fusion control tools. In particular, key ideas for control methods are briefly described and reviewed.

1. Wind Energy Systems

1.1. Short History of Wind Energy

It is worth giving a brief review of wind energy so that the readers can see the path that wind energy has undergone for centuries. Wind was the primary source of energy to power sailing ships before the advent of steam engines in the 18th century (Johnson (2006),Hansen (2008)). In addition to transportation use, wind turbines often referred to as windmills; were also used for agricultural purposes such as pumping water, grinding grains, sawing wood, and powering tools (Manwell et al. (2002)). In the middle of the seventh century, Persians began transmitting stories of windmills, but it was not verified until the first recorded windmill appeared in the tenth century in Persia (Spera (2009)). Windmills at this time were vertical-axis types and so simple that they provided poor performance with low efficiency (Johnson (2006)). More sophisticated and efficient windmills were designed in Europe. At this time, people witnessed a major technological change from vertical-axis to horizontal-axis that significantly increased the conversion efficiency. The earliest horizontal-axis windmill was by the English in 1191 (Johnson (2006), Spera (2009)). After this time, windmills began to thrive and become an essential source of power in Europe for centuries. However, when the industrial revolution happened in the 18th century, the use of windmills declined, and they were rapidly replaced by steam and internal combustion engines.

Wind turbines for electricity generation were invented towards the end of the 19th century following the development of electrical generators (Manwell et al. (2002),Spera (2009)). Technological achievements of wind turbines, particularly for large-size wind turbines, took place in the middle of the 1940s. Nevertheless, much attention was not paid to wind energy generation until the oil crisis in the 1970s. Increasing awareness of the negative environmental effects of fossil fuel energy, compounded with the strong desire to be independent of oil, caused many countries in Europe and America to carry out national research programs in alternative energy resources, particularly large wind turbines. Consequently, reliable wind turbine prototypes were created. However, technological advances in the wind turbine field were not strong enough to encourage larger generation of wind power. The situation was truly changed when governments imposed regulations advocating wind energy and offered attractive incentives for wind energy producers in the 1970s and 1980s. Additionally, the cost of wind energy has continuously dropped, approaching the competitive level of conventional energy. These factors enabled a powerful re-emergence of modern wind turbines.

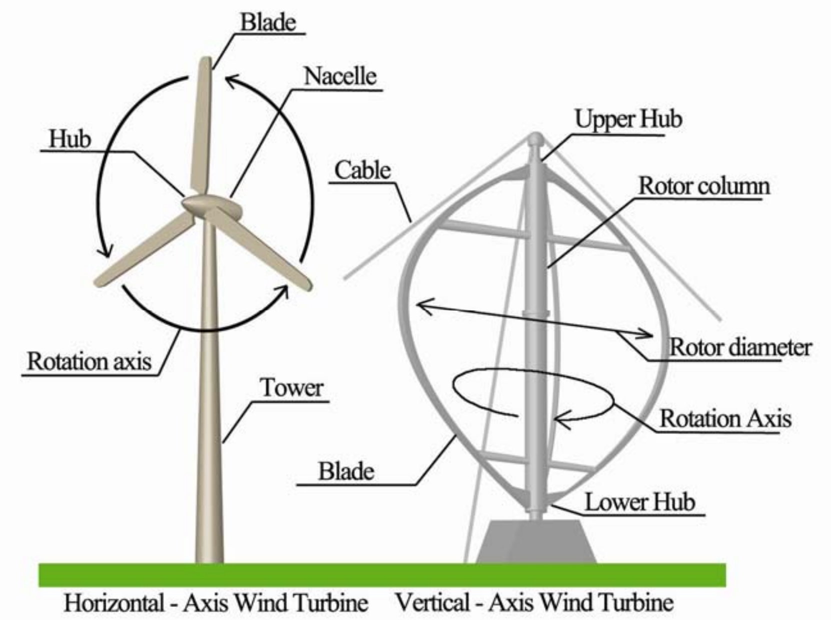

Figure 1. Two basic types of wind turbines

1.2. Wind Turbine Structures

The two basic types of wind turbines are horizontal-axis wind turbines (HAWT) and vertical-axis wind turbines (VAWT). These configurations are shown in Figure 1.

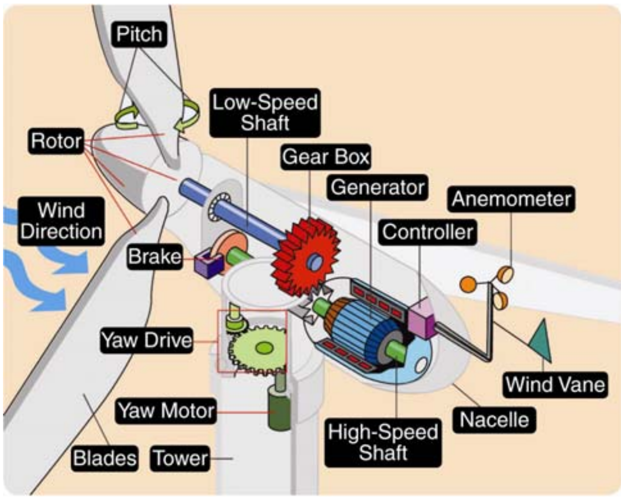

Figure 2. Basic components of a HAWT (Courtesy of the U.S. Department of Energy: http://www1.eere.energy.gov/wind/wind_how.html)

1.2.1. Horizontal-Axis Wind Turbine (HAWT) Configuration

A modern HAWT consists of different interacting sub-systems as shown in Figure 2. Basically, these sub-systems can be divided into two categories: mechanical sub-systems and electrical sub-systems.

- *Mechanical Sub-systems*: The mechanical sub-systems contain 1) the wind turbine rotor, 2) the drive train, 3) the nacelle structure, and 4) the tower.

1. *The Wind Turbine Rotor:* The wind turbine rotor converts kinetic energy from wind into mechanical energy. It is made up of blades which are all connected to a central hub, then this hub is linked to a turbine shaft. As a result, when wind goes through the blades, it causes rotation of the turbine shaft. A one-blade wind rotor operates at high speed so it allows the mechanical transmission component to be simplified. However, due to its great imbalance and static structure, weight compensation for the missing blade must be made. Moreover, the aerodynamic efficiency is much lower than that of two or three-blade HAWTs. As a result, the one-blade HAWTs were technologically successful but not commercially successful (Gipe (2009)). In similar manner, a two-blade HAWT provides for a cheaper wind rotor and transmission unit and easier installation over a three-blade HAWT. Nevertheless, the three-blade HAWT is presently common because of its superior energy efficiency. Another important aspect of the wind turbine rotor is the materials used for the blades. Blades were traditionally made of wood, steel, or aluminum. However, these materials have limitations, so their use has been in decline. Nowadays, almost all wind blades are made of a composite material called fiberglass.

2. *The Drive Train:* The drive train is responsible for transmitting the mechanical power from the wind rotor to the electric generator. The drive train consists of a turbine shaft or low-speed shaft, a gearbox, and a generator shaft or high-speed shaft. The turbine shaft must meet both structural and mechanical requirements because it needs to support the rotor weight and provide torsional damping caused by wind gusts on the wind rotor. The gearbox is to step up the rotational speed.

3. *The Nacelle Structure:* The nacelle is a bed plate that supports the drive train and the generator. Moreover, in the HAWTs, there is a yaw mechanism that turns the wind rotor to face the wind direction.

4. *The Tower:* The tower is a support for the wind turbine. The most important factors in designing a tower are height and strength. The higher the tower, the more the captured wind power. However, the height cannot be as high as possible because there is a tradeoff between the height and the cost. In addition, the tower must be strong enough to withstand wind thrust.

- *Electrical Sub-Systems:* The electrical sub-systems contain 1) the generator and 2) power electronic converter.

    1. *The Generator:* The generator transforms mechanical power into electrical power. Essentially, its operating principle is that a coil of wire (rotor) rotating

within a magnetic field (stator) will produce an output voltage and current. The amount of produced power is a function of the size of the generator and the relative movement between the rotor and the stator.

Generators are classified as direct current (DC) or alternating current (AC). The AC generators are then characterized into two types: synchronous AC generators and asynchronous or induction AC generators. Induction AC generators are widely used because they are inexpensive, simple, and capable of attenuating torsional torque. Induction generators, however, have more mechanical-electrical conversion losses than synchronous generators. Synchronous generators provide more efficiency than induction generators, but they require extra voltage controllers and are not able to mitigate torsional stresses.

2. *The Power Electronic Converter:* When the wind speed changes, the wind rotor speed changes accordingly, and hence the output voltages and frequency fluctuate. In grid-connected wind turbines, this is unacceptable. Thus, the output voltages and frequency need to be kept constant. In essence, a power electronic converter functions as a stabilizer that helps fix the output voltages and frequency under the wind speed changes.

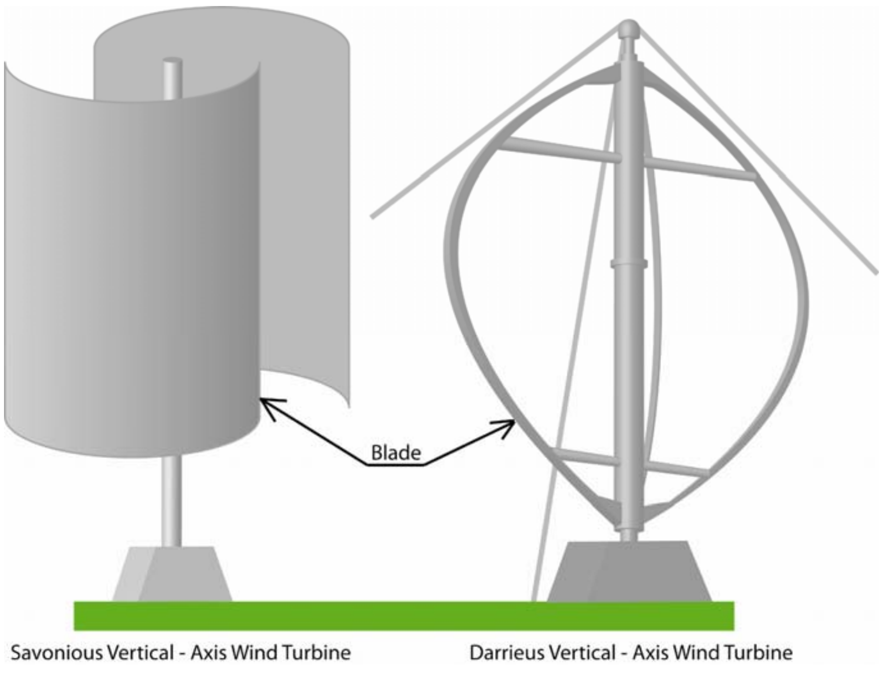

Figure 3. Two types Of VAWTs

1.2.2. Vertical-Axis Wind Turbine (VAWT) Configuration

There are several types of VAWTs. However, two popular ones are Savonius and Darrieus VAWTs as indicated in Figure 3 . Unlike HAWTs, VAWTs do not depend upon wind direction. They rotate equally in any wind direction and hence, the yaw drive systems are not necessary. This is a big advantage of VAWTs. In addition, the drive train and generating sub-systems are placed on the ground, and not necessarily located on high positions that require costly nacelle platforms for support. However, VAWTs provide low conversion efficiency. Moreover, VAWTs demand high maintenance and particularly, the Darrieus VAWT is not self-starting. These disadvantages consequently result in less use of VAWTs.

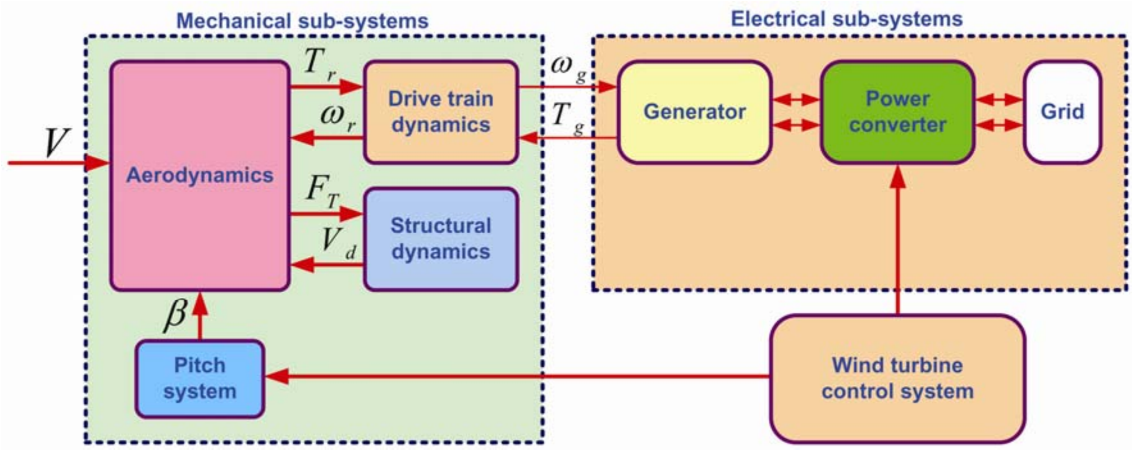

Figure 4. Wind turbine subsystem block diagram

2. Wind Turbine Modeling for Control

Wind turbines contain many physically different subsystems; so modeling of wind turbines requires a wide range of knowledge to develop suitable models for each subsystem. Certainly, designers want to achieve models as accurate as possible by using advanced available tools such as computational fluid dynamics or finite element analysis. Nevertheless, these tools increase the design time and cost. For the purpose of automatic control of wind turbines, the modeling techniques used are simply based on fundamental dynamic principles.

Figure 4 (Bianchi et al. (2007)) shows a grid-connected wind turbine block diagram for modeling. The mechanical sub-systems include the aerodynamics, the drive train dynamics, the structural dynamics, and the pitch system dynamics. The electrical sub-systems contain the generator dynamics, the power electronic converter dynamics, and the grid dynamics. Here, only models of the aerodynamics, the drive train dynamics, the structural dynamics, and the generator dynamics are given.

2.1. Wind Turbine Aerodynamics Modeling

Aerodynamics modeling is to describe how a three-dimensional wind field causes forces and rotation on wind turbines. Although more expensive computational fluid dynamics tools can be employed to build more exact models of aerodynamics, the blade element momentum (BEM) theory is commonly accepted as an essential tool to obtain aerodynamic models of wind turbines. This theory explains the development of aerodynamic forces acting on a radial blade element of infinitesimal length. Figure 5 (Gipe (2009)) shows a cut plane viewed from the blade tip. This plane describes a blade element and developed forces. It is explained that as this blade element moves in the wind flow, differential pressure around the blade element causes forces called the lift force and drag force. These two forces, which are dependent on the angle of attack α or the pitch angle β, can be resolved into two other forces called the torque τ_{r} and thrust force f_{T}. The two forces, τ_{r} and f_{T}, are integrated along the blade length, resulting in the global torque T_{r} and thrust force F_{T} acting on the wind turbine.

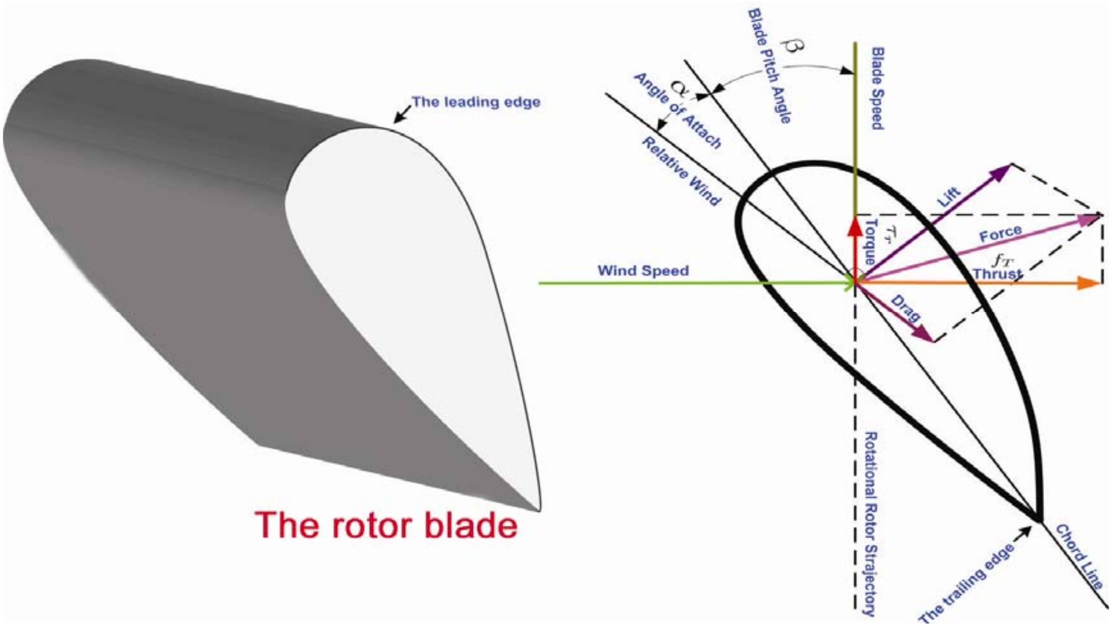

Figure 5. Aerodynamic principle of HAWTs

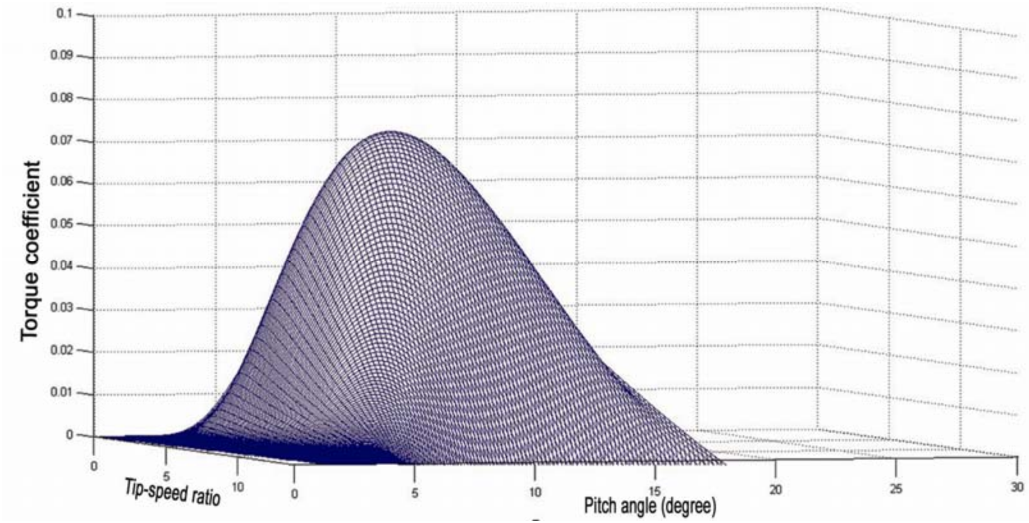

Figure 6. Torque coefficient is a function of the tip-speed ratio and pitch angle

It is observed from Figure 4 that the inputs of the aerodynamic model are the wind speed *V*, the pitch angle β, the rotor speed ω_{r}, and the total axial speed of the tower and blades V_{d}. The outputs are the torque T_{r} and a thrust force F_{T}. The relationships between the inputs and the outputs are given as (Bianchi et al. (2007))

$$\begin{cases} F_{\mathrm{T}} = \frac{1}{2}\rho\pi R^2 C_{\mathrm{T}}\left(\lambda_{\mathrm{e}},\beta\right)V_{\mathrm{e}}^2, \\ T_{\mathrm{r}} = \frac{1}{2}\rho\pi R^3 C_{\mathrm{Q}}\left(\lambda_{\mathrm{e}},\beta\right)V_{\mathrm{e}}^2, \end{cases} \tag{1}$$

where ρ is the air density, R is the radius of wind rotor, $\lambda_{\mathrm{e}} = \dfrac{\omega_{\mathrm{r}} R}{V_{\mathrm{e}}}$ is the tip-speed ratio, β is the pitch angle, C_{T} and C_{Q} are the torque coefficient and the power coefficient, respectively. These coefficients are the functions of the tip-speed ratio and the pitch angle (see Figure 6), and

$$V_{\mathrm{e}} = V - V_{\mathrm{d}}, \tag{2}$$

where $V_{\mathrm{d}} = \dot{z} + r\dot{\delta}$, r is the lumped force distance, and z and δ are the axial displacement of the tower and the blades caused by the tower bending and blade flapping phenomena which are defined in the mechanical modeling section.

2.2. Mechanical Sub-Systems Modeling

Mechanical sub-systems are simpler in modeling than any other subsystems of wind turbines (Moriarty and Butterfield (2009)). Multi-body dynamics or finite element analysis are advanced options to analyze the dynamics of blades and tower, but they are too complicated and expensive for control modeling. Instead, modal representations are used. Movements imposed on blades and the tower are modeled in two directions (one is perpendicular or axial, and the other is parallel to the rotational plane.)

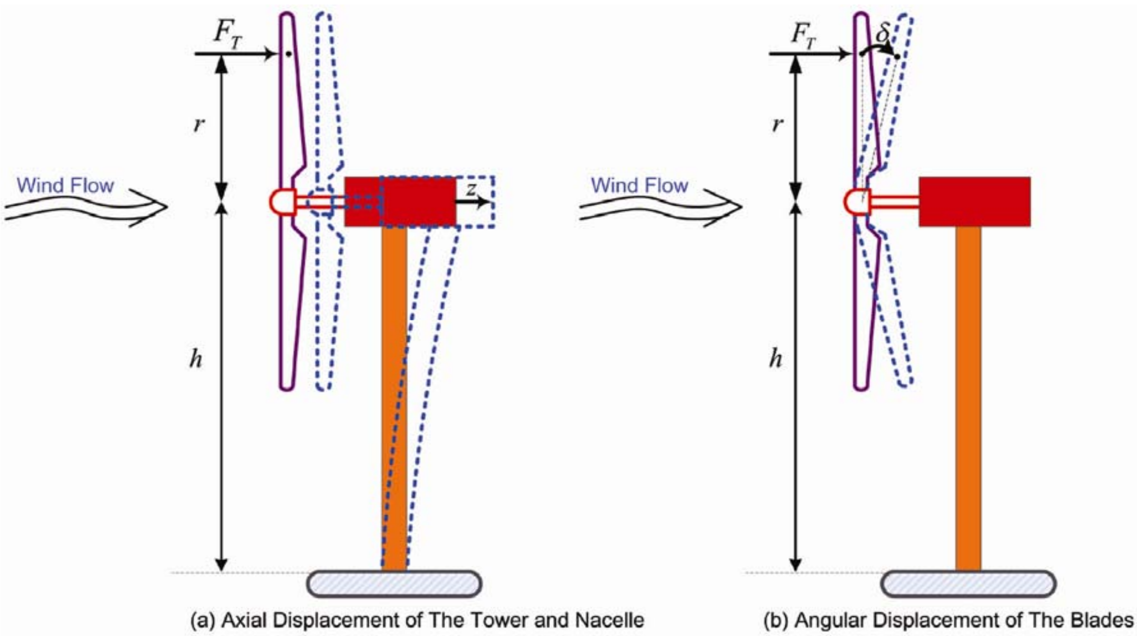

Figure 7. Structural dynamics of HAWTs

2.2.1. Structural Modeling

Here, the flapping dynamics of blades and the bending dynamics of the tower are presented as shown in Figure 7 (Bianchi et al. (2007)). Distributed thrust forces acting along each blade are lumped as the force F_{T} at distance *r*. This lumped force causes an angular displacement δ of each blade and an axial reflection *z* of the nacelle. Using the Lagrangian theory, a state space model in terms of $\dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{Bu}$ with parameters defined as (Bianchi et al. (2007)).

$$\underbrace{\begin{bmatrix} \dot{\mathbf{x}}_1 \\ \dot{\mathbf{x}}_2 \end{bmatrix}}_{\dot{\mathbf{x}}} = \underbrace{\begin{bmatrix} \mathbf{0}_{2x2} & \mathbf{I}_{2x2} \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{C} \end{bmatrix}}_{\mathbf{A}} \underbrace{\begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \end{bmatrix}}_{\mathbf{x}} + \underbrace{\begin{bmatrix} \mathbf{0}_{2x2} \\ -\mathbf{M}^{-1} \end{bmatrix}}_{\mathbf{B}} \underbrace{\mathbf{Q}}_{\mathbf{u}}, \tag{3}$$

where

N : The number of blades

r : The lumped force distance

m_{t} : Total mass of the tower and nacelle

m_{b} : Mass of each blade

K_{t} : Stiffness coefficient of the tower

K_{b} : Stiffness coefficient of each blade

B_{t} : Damping coefficient of the tower

B_{b} : Damping coefficient of each blade

$$\mathbf{x} = \begin{bmatrix} x & \delta & \dot{z} & \dot{\delta} \end{bmatrix}^{\mathrm{T}}, \ \mathbf{Q} = \begin{bmatrix} NF_{\mathrm{T}} & NF_{\mathrm{T}}r \end{bmatrix}^{\mathrm{T}}, \ \mathbf{0}_{2x2} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}, \ \mathbf{I}_{2x2} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix},$$

$$\mathbf{M} = \begin{bmatrix} m_{\mathrm{t}} + Nm_{\mathrm{b}} & Nm_{\mathrm{b}}r \\ Nm_{\mathrm{b}}r & Nm_{\mathrm{b}}r^2 \end{bmatrix}, \ \mathbf{C} = \begin{bmatrix} B_{\mathrm{t}} & 0 \\ 0 & NB_{\mathrm{b}}r^2 \end{bmatrix}, \ \mathbf{K} = \begin{bmatrix} K_{\mathrm{t}} & 0 \\ 0 & NK_{\mathrm{b}}r^2 \end{bmatrix},$$

and the output equation is given as

$$y = V_{\mathrm{d}} = \dot{z} + r\dot{\delta} = \underbrace{\begin{bmatrix} 0 & 0 & 1 & r \end{bmatrix}}_{\mathbf{C_o}} \mathbf{x}. \tag{4}$$

Notions	Descriptions
N	The number of blade
r	The lumped force distance
m_t	Total mass of the tower and nacelle
m_b	Mass of each blade
K_t	Stiffness coefficient of the tower
K_b	Stiffness coefficient of each blade
B_t	Damping coefficient of the tower
B_b	Damping coefficient of each blade

Table 1. Parameter descriptions for the modeling of the structure of HAWTs

2.2.2. Drive Train Modeling

In essence, the drive train system includes the turbine shaft or low-speed shaft, a gearbox, and the generator shaft or high-speed shaft. The process of deriving a mathematical model of the drive train requires some assumptions. First, the wind rotor and generator are considered two masses and the low-speed shaft and high-speed shaft are represented by two spring elements. Second, the gearbox is regarded ideal when the transmission efficiency is one hundred percent and constant over the operating range. Moreover, the impact of internal structures and phenomena such as gear type, gear backlash, etc. is ignored.

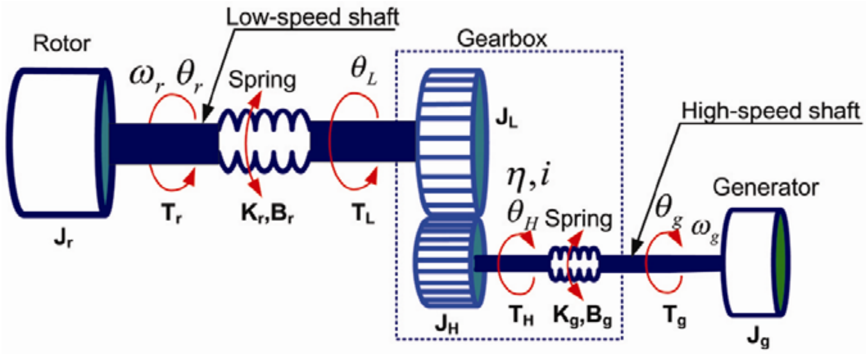

Figure 8. Flexible drive train of HAWTs

Notions	Descriptions
θ_r	The rotational angle of the wind rotor
θ_L	The rotational angle of the low-speed shaft
θ_H	The rotational angle of the high-speed shaft
θ_g	The rotational angle of the generator
ω_r	The rotational speed of the wind rotor
ω_L	The rotational speed of the low-speed shaft
ω_H	The rotational speed of the high-speed shaft
ω_g	The rotational speed of the generator
T_r	The torque of the wind rotor
T_L	The torque of the low-speed shaft
T_H	The torque of the high-speed shaft
T_g	The torque of the generator
J_r	The inertia of the wind rotor
J_L	The inertia of the low-speed shaft
J_H	The inertia of the high-speed shaft

J_g	The inertia of the generator
K_r	The stiffness coefficient of the wind rotor side
K_g	The stiffness coefficient of the generator side
B_r	The damping coefficient of the wind rotor side
B_g	The damping coefficient of the generator side
i	The gearbox ratio
η	The transmission efficiency of the gearbox

Table 2. Parameter descriptions for the modeling of the drive train of HAWTs

The drive train system is shown in Figure 8 (Munteanu et al. (2008b)) and model parameters are given in Table 2. Similar to the structural modeling described above, the Lagrangian theory can be applied to derive the model of the above drive train system (Note that coordinates here are angular motions). The state space model in terms of $\dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{Bu}$ is obtained as

$$\underbrace{\begin{bmatrix} \dot{\mathbf{x}}_1 \\ \dot{\mathbf{x}}_2 \end{bmatrix}}_{\dot{\mathbf{x}}} = \underbrace{\begin{bmatrix} \mathbf{0}_{4x4} & \mathbf{I}_{4x4} \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{C} \end{bmatrix}}_{\mathbf{A}} \underbrace{\begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \end{bmatrix}}_{\dot{\mathbf{x}}} + \underbrace{\begin{bmatrix} \mathbf{0}_{4x4} \\ \mathbf{M}^{-1} \end{bmatrix}}_{\mathbf{B}} \underbrace{\mathbf{Q}}_{\mathbf{u}}, \tag{5}$$

where $\mathbf{x} = \begin{bmatrix} \theta_r & \theta_L & \theta_H & \theta_g & \omega_r & \omega_L & \omega_H & \omega_g \end{bmatrix}^T$, $\mathbf{0}_{4x4} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$,

$$\mathbf{I}_{4x4} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$\mathbf{M} = \begin{bmatrix} J_r & 0 & 0 & 0 \\ 0 & J_L & 0 & 0 \\ 0 & 0 & J_H & 0 \\ 0 & 0 & 0 & J_g \end{bmatrix}, \quad \mathbf{C} = \begin{bmatrix} B_r & -B_r & 0 & 0 \\ -B_r & B_r & 0 & 0 \\ 0 & 0 & B_g & -B_g \\ 0 & 0 & -B_g & B_g \end{bmatrix},$$

$$\mathbf{K} = \begin{bmatrix} K_r & -K_r & 0 & 0 \\ -K_r & K_r & & \\ & & K_g & -K_g \\ & & -K_g & K_g \end{bmatrix},$$

and $\mathbf{Q} = \begin{bmatrix} T_r & -T_L & T_H & -T_g \end{bmatrix}^T$.

If only angular speeds are of interest, the output equation will be

$$\mathbf{y} = \underbrace{\begin{bmatrix} \mathbf{0}_{4x4} & \mathbf{I}_{4x4} \end{bmatrix}}_{\mathbf{C_o}} \mathbf{x}, \tag{6}$$

where $\mathbf{y} = \begin{bmatrix} \omega_r & \omega_L & \omega_H & \omega_g \end{bmatrix}^T$.

Note that the above drive train model can be simplified by transforming the gearbox mass and inertia into the wind rotor and the generator. The reduced model of the drive train becomes

$$\underbrace{\begin{bmatrix} \dot{\mathbf{x}}_1 \\ \dot{\mathbf{x}}_2 \end{bmatrix}}_{\dot{\mathbf{x}}} = \underbrace{\begin{bmatrix} \mathbf{0}_{2x2} & \mathbf{I}_{2x2} \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{C} \end{bmatrix}}_{\mathbf{A}} \underbrace{\begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \end{bmatrix}}_{\mathbf{x}} + \underbrace{\begin{bmatrix} \mathbf{0}_{2x2} \\ \mathbf{M}^{-1} \end{bmatrix}}_{\mathbf{B}} \underbrace{\mathbf{Q}}_{\mathbf{u}}, \tag{7}$$

where $\mathbf{x} = \begin{bmatrix} \theta_r \, \theta_g \, \omega_r \, \omega_g \end{bmatrix}^T$, $\mathbf{0}_{2x2} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$, $\mathbf{I}_{2x2} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$, $\mathbf{M} = \begin{bmatrix} J_r & 0 \\ 0 & J_g \end{bmatrix}$, $\mathbf{C} = \begin{bmatrix} B_r & 0 \\ 0 & B_g \end{bmatrix}$, $\mathbf{K} = \begin{bmatrix} K_r & 0 \\ 0 & K_g \end{bmatrix}$, and $\mathbf{Q} = \begin{bmatrix} T_r & -T_g \end{bmatrix}^T$

The output equation is given as

$$\mathbf{y} = \underbrace{\begin{bmatrix} \mathbf{0}_{2x2} \; \mathbf{I}_{2x2} \end{bmatrix}}_{\mathbf{C_o}} \mathbf{x}, \tag{8}$$

where $\mathbf{y} = \begin{bmatrix} \omega_r \, \omega_g \end{bmatrix}^T$.

-

-

Bibliography

References

[1] Agarwal V., Aggarwal R.K., Patidar P., Patki C (2010). A novel scheme for rapid tracking of maximum power point in wind energy generation systems. *IEEE Transactions on Energy Conversion,*

25(1), 228–236. [This presents a method of fast maximum power point tracking control irrespective to wind speeds for a WECS].

[2] Astrom K.J.,Hagglund T. (2008). *Adaptive Control*. Dover Publications Inc., Mineola, N.Y., U.S., 2nd Edition. [A standard textbook which presents basic adaptive techniques for linear systems].

[3] Astrom K.J., Wittenmark B. (1995). *PID controllers: Theory, Design, and Tuning*. Instrument Society of America, Research Triangle Park, NC, U.S., 2nd Edition. [A comprehensive textbook which describes methods of designing and tuning of PID controllers].

[4] Bayat M., Karegar H.K. (2009). Predictive control of wind energy conversion system. In *Proceedings of the 1st International Conference on the Developments in Renewable Energy Technology (ICDRET)*, pp. 1–5. [This is a case study reporting the application of predictive control scheme in maximizing the power conversion of a DFIG-based WECS under disturbances and noises].

[5] Bianchi F.D., Battista H.D., Mantz R.J. (2007). *Wind Turbine Control System: Principles, Modeling, and Gain Scheduling Design*. Springer-Verlag, London, UK. [This is a research monogragh reporting modeling and control for WECS based on the linear parameter varying gain scheduling method].

[6] Brahmi J., Krichen L., Ouali A. (2009). Sensorless control of PMSG in WECS using artificial neural network. In *Proceedings of the 6th International Multi-Conference on Systems, Signals and Devices*, pp. 1–8.. [This is a case study showing the application of artificial neural networks to estimate the wind speed for a PMSG-based WECS's control system].

[7] Buehring I.K., Freris L.L. (1981). Control policies for wind-energy conversion systems. In *Proceedings of the Conference on Generation, Transmission and Distribution*, vol.128, No.5, pp. 253–261. [This is one of early reports addressing control strategies in maximizing the power conversion of WECS].

[8] Calderaro V., Galdi V., Piccolo A., Siano P. (2007). Design and implementation of a fuzzy controller for wind generators performance optimisation. In *Proceedings of the European Conference on Power Electronics and Applications*, pp. 1–10. [A report that suggests a fusion of fuzzy logic and genetic algorithm for WECS].

[9] Camacho E.F., Bordons C. (1999). *Model Predictive Control*. Springer-Verlag London Limited. [A book that covers different types of model predictive control techniques].

[10] Chen G., Pham T.T. (2001). *Introduction to Fuzzy Sets, Fuzzy Logic, and Fuzzy Control Systems*. CRC Press LLC. [A readable book that presents basic concepts of fuzzy control].

[11] Dang D.Q., Wang Y., Cai W. (2008). Nonlinear model predictive control of fixed pitch variable speed wind turbine. In *Proceedings of the IEEE International Conference on Sustainable Energy Technologies (ICSET)*, pp. 29–33. [This study reports the application of model predictive control based on multiple direct shooting methods and sequential quadratic programming to maximize the power conversion of WECS].

[12] Dang D.Q., Wang Y., Cai W. (2009). A multi-objective optimal nonlinear control of variable speed wind turbine. In *Proceedings of the IEEE International Conference on Control and Automation (ICCA)*, pp. 17–22. [This study also reports the application of model predictive control based on multiple direct shooting methods and sequential quadratic programming to maximize the power conversion of WECS].

[13] De Battista H., Puleston P.F., Mantz R.J., Christiansen C.F. (2000). Sliding mode control of wind energy systems with DOIG-power efficiency and torsional dynamics optimization. *IEEE Transactions on Power Systems*, 15(2), 728–734. [A sliding mode control which compromises the maximum power conversion and the torque reduction for a DFIG-based WECS].

[14] Dinghui W., Lili X., Zhicheng J. (2009). Fuzzy adaptive control for wind energy conversion system based on model reference. In *Proceedings of the Chinese Control and Decision Conference (CCDC)*, pp. 1783–1787. [A fusion of fuzzy and adaptive control based on the model reference scheme for a variable speed SCIG-based WECS].

[15] Gipe P. (2004). *Wind Power: Renewable Energy for Home, Farm, and Business*. Chelsea Green Publishing Company, VT, U.S. [A practical book of wind power].

[16] Hansen M.O.L. (2008). *Aerodynamics of Wind Turbines*, 2nd Edition. Earthscan. [A book presenting aerodynamics theories of wind turbines].

[17] Hui J., Bakhshai A. (2008a). Adaptive algorithm for fast maximum power point tracking in wind energy systems. In *Proceedings of the 34th IEEE Annual Conference on Industrial Electronics (IECON)*, pp. 2119–2124. [A report of maximum power point tracking control based on HCS search with an intelligent memory for a PMSG-based WECS].

[18] Hui J., Bakhshai A. (2008b). A new adaptive control algorithm for maximum power point tracking for wind energy conversion systems. In *Proceedings of the IEEE Conference on Power Electronics Specialists (PESC)*, pp. 4003–4007. [Another report of maximum power point tracking control based on HCS search with an intelligent memory for a PMSG-based WECS].

[19] Jianlin L., Honghua X. (2008). Research on control system of high power DFIG wind power system. In *Proceedings of the International Conference on MultiMedia and Information Technology (MMIT)*, pp. 669–672. [This presents an LQR controller for the pitch system of a WECS].

[20] Johnson G.L. (2006). *Wind Energy Systems*, Electronic Edition. Prentice-Hall. [An introductory book of wind and WECS components].

[21] Kalantar M. and Sedighizadeh M. (2005). Adaptive-neural PID control of wind energy conversion systems using wavenets. In Intelligent Control, 2005. In *Proceedings of the 2005 IEEE International Symposium on, Mediterrean Conference on Control and Automation*, pp. 219–224. [This presents a PID control whose parameters are tuned by a wavenet for a WECS].

[22] Kazmi S.M.R., Goto H., Guo H.J., Ichinokura O. (2011). A novel algorithm for fast and efficient speed-sensorless maximum power point tracking in wind energy conversion systems. *IEEE Transactions on Industrial Electronics*, 58(1), 29–36. [A report on maximum power point tracking control based on the HCS search with an intelligent and faster tuning scheme for a WECS].

[23] Khalil H.K. (1996). *Nonlinear Systems*. 2nd Edition. Prentice-Hall. Inc., Upper Saddle River, New Jersey, U.S. [A well-known textbook on nonlinear control techniques].

[24] Lavanya V., Gounden N.A., Rao P.M. (2006). A simple controller using line commutated inverter with maximum power tracking for wind-driven grid-connected permanent magnet synchronous generators. In *Proceedings of the International Conference on Power Electronics, Drives and Energy Systems (PEDES)*, pp. 1–6. [This report proposes a maximum power point tracking PI controller for the power electronic converter of a PMSG-based WECS].

[25] Li H., Shi K.L., McLaren P.G. (2005). Neural-network-based sensorless maximum wind energy capture with compensated power coefficient. *IEEE Transactions on Industry Applications*, 41(6), 1548–1556. [A report presenting the use of neural network as an estimator for the controller of a PMSG-based WECS].

[26] Manwell J.F., McGowan J.G., Rogers A.L. (2002). *Wind Energy Explained: Theory, Design, and Application*. John Wiley & Sons Ltd. [A good reference book for many aspects of a WECS].

[27] Mashaly H.M., Sharaf A.M., El-Sattar A.A., Mansour M. (1994). A fuzzy logic controller for wind energy utilization. In *Proceedings of the 3rd IEEE Conference on Control Applications*, pp. 221–226. [This report proposes a maximum power point tracking fuzzy logic controller for the power electronic converter of a PMSG-based WECS].

[28] Mayosky M.A., Cancelo I.E. (1999). Direct adaptive control of wind energy conversion systems using Gaussian networks. *IEEE Transactions on Neural Networks*, 10(4), 898–906. [A fusion of neural network and adaptive control for a WECS where a neural network is used to adapt the controller].

[29] Molina M.G., Sanchez A.G., Lede A.M.R. (2010). Dynamic modeling of wind farms with variable-speed direct-driven PMSG wind turbines. In *Proceedings of the IEEE/PES Transmission and Distribution Conference and Exposition: Latin America*, pp. 816–823. [This presents a comprehensive dynamic model and control structure of a wind farm including direct-drive PMSG-based WECS].

[30] Moriarty P.J., Butterfield S.B. (2009). Wind turbine modeling overview for control engineers. In *Proceedings of the* American Control Conference (ACC), pp. 2090–2095. [A good overview presenting the modeling of different dynamics for both onshore and offshore wind turbines].

[31] Munteanu I., Bacha S., Bratcu A.I., Guiraud J., Roye D. (2008a). Energy-reliability optimization of wind energy conversion systems by sliding mode control. *IEEE Transactions on Energy Conversion*, 23(3), 975–985. [A report of the application of sliding model control for the maximum power conversion of a DFIG-based WECS].

[32] Munteanu I., Bratcu A.I., Cutuluslis N.A., Ceanga E. (2008b). *Optimal Control of Wind Energy Systems: Toward a Global Approach*. Springer. [A good research reference book for modeling and controlling of variable-speed and fixed-pitch WECS].

[33] Naidu D.S. (2003). *Optimal Control Systems*. Chapman and CRC Press. [A nice graduate textbook of optimal control techniques].

[34] Naidu D.S., Rieger C.G. (2011). Advanced control strategies for HVAC&R systems-An overview: part II: Soft and fusion control. *HVAC&R Research*, 17(2), 144–158. [An overview of soft and fusion control of HVAC&R systems].

[35] Nguyen H.M., Naidu D.S. (2011a). Advanced control strategies for wind energy systems: An overview. In *Proceedings of the Power Systems Conference and Exposition (PSCE)*, pp. 1–8. [A comprehensive overview of advanced control methods for WECS].

[36] Nguyen H.M., Naidu D.S. (2011b). A survey on advanced control strategies for wind energy conversion systems. *Technical report*, Idaho State University, 921 S. 8th Avenue, Pocatello, ID, USA. [An updated version of a comprehensive overview of advanced control methods for WECS].

[37] Nguyen H.T., Prasad N.R., Walker C.L., Walker E.A. (2003). *A First Course in Fuzzy and Neural Control*. Chapman & Hall/CRC. [A good introductory book of fuzzy and neural control].

[38] Norgaard M., Rawn O., Poulsen N.K., Hansen L.K. (2000). *Neural Networks for Modeling and Control of Dynamic Systems*. Springer-Verlag London Limited. [A good book that covers many different modeling and control techniques based on neural networks].

[39] Ostergaard K.Z., Stoustrup J., Brath P. (2009). Linear parameter varying control of wind turbines covering both partial load and full load conditions. *International Journal of Robust and Nonlinear Control*, 19, 92–116. [A report that proposes a controller for both regions of a WECS based on the gain scheduled LPV].

[40] Ovaska S.J., VanLandingham H.F., Kamiya A. (2002). Fusion of soft computing and hard computing in industrial applications: an overview. *IEEE Transactions on Systems, Man, and Cybernetics, Part C: Applications and Reviews* 32(2), 72–79. [This is one of the first overviews addressing the fusion of soft and hard control for dynamical systems].

[41] Pena R., Sbarbaro D. (1999). Integral variable structure controllers for small wind energy systems. In *Proceedings of the 25th IEEE Annual Conference of Industrial Electronics Society (IECON)*, vol. 3, pp. 1067 –1072. [A report of sliding mode control for WECS].

[42] Perruquetti W., Barbot J.P. (2002). *Sliding Mode Control In Engineering*. Marcel Dekker, Inc., New York, U.S. [A collection of topics covering different aspects of sliding model control].

[43] Qi J., Liu Y. (2010). PID control in adjustable-pitch wind turbine system based on fuzzy control. In *Proceedings of the 2nd International Conference on Industrial Mechatronics and Automation (ICIMA)*, vol. 2, pp. 341–344. [A fusion of PID and fuzzy control for a WECS].

[44] Qin Z., Su S., Lei J., Dong H. (2008). Study on intelligent control of three phase grid-connected inverter of wind power generation. In *Proceedings of the International Conference on Intelligent Computation Technology and Automation (ICICTA)*, vol. 1, pp. 1149–1152. [A report of an adaptive PID control based on neural networks for the inverter of a WECS].

[45] Raza K.S.M., Goto H., Guo H.J., Ichinokura O. (2008). A novel speed-sensorless adaptive hill climbing algorithm for fast and efficient maximum power point tracking of wind energy conversion systems. In *Proceedings of the IEEE International Conference on Sustainable Energy Technologies (ICSET)*, pp. 628–633. [Another report on maximum power point tracking control based on the HCS search with an intelligent and faster tuning scheme for a WECS].

[46] Ren Y.F., Bao G.Q. (2010). Control strategy of maximum wind energy capture of direct-drive wind turbine generator based on neural-network. In *Proceedings of the Asia-Pacific Power and Energy*

Engineering Conference (APPEEC), pp. 1–4. [A study that reports an application of neural networks as estimator for the maximum power conversion control of a PMSG-based WECS].

[47] Rocha R., Filho L.S.M., Bortolus M.V. (2005). Optimal multivariable control for wind energy conversion system - A comparison between H_2 and H_∞ controllers. In *Proceedings of the 44th IEEE Conference on Decision and Control and European Control Conference (CDC-ECC)*, pp. 7906–7911. [A report that studies the performance of both H_2 and H_∞ robust controllers for a WECS].

[48] Sedighizadeh M., Harris D. A., Kalantar M. (2004). Adaptive PID control of wind energy conversion systems using RASP1 mother wavelet basis function networks. In *Proceedings of the IEEE Region 10 Conference (TENCON)*, vol. C, pp. 524–527. [A report of fusion of PID and adaptive control for a WECS where PID parameters are tuned via neural networks].

[49] Sedighizadeh M., Rezazadeh A., Khatibi M. (2008). A self-tuning PID control for a wind energy conversion system based on the Lyapunov approach. In *Proceedings of the 43rd International Universities Power Engineering Conference (UPEC)*, pp. 1–4. [A report of fusion of PID and adaptive control for a WECS where PID parameters are tuned based on Lyapunov approach].

[50] Senjyu T., Sakamoto R., Urasaki N., Funabashi T., Sekine H. (2006). Output power leveling of wind farm using pitch angle control with fuzzy neural network. In *Proceedings of the IEEE Power Engineering Society General Meeting*, pp. 8-16. [A report of fusion of fuzzy and neural networks control for the pitch control systems of a wind farm].

[51] Shepherd W., Zhang L. (2011). *Electricity Generation Using Wind Power*. World Scientific Publishing Co.Pte.Ltd, Singapore. [A reference book for wind power].

[52] Simoes M.G., Bose B.K., Spiegel R.J. (1997). Design and performance evaluation of a fuzzy-logic-based variable-speed wind generation system. *IEEE Transactions on Industry Applications*, 33(4), 956–965. [A power converter control scheme based on fuzzy logic for a WECS].

[53] Simon D. (2006). *Optimal State Estimation: Kalman, H_∞, and Nonlinear Approaches*. John Wiley & Sons, Inc. [A good graduate textbook for stochastic optimal control systems].

[54] Soliman M., Malik O.P., Westwick D.T. (2010). Multiple model MIMO predictive control for variable speed variable pitch wind turbines. In *Proceedings of the American Control Conference (ACC)*, pp. 2778–2784. [A report of predictive control using multiple models for a WECS].

[55] Spera D.A. (2009). *Wind Turbine Technology: Fundamental Concepts of Wind Turbine Engineering*, 2nd Edition. ASME Press. [An introductory book for different aspects of wind turbines].

[56] Tan K., Islam S. (2004). Optimum control strategies in energy conversion of PMSG wind turbine system without mechanical sensors. *IEEE Transactions on Energy Conversion*, 19(2), 392–399. [A report of maximum power point tracking control based on the DC power-DC voltage characteristic for a PMSSG-based WECS].

[57] Thongam J.S., Bouchard P., Ezzaidi H., Ouhrouche M. (2009). Artificial neural network-based maximum power point tracking control for variable speed wind energy conversion systems. In *Proceedings of the IEEE Conference on Control Applications (CCA) and Intelligent Control (ISIC)*, pp. 1667–1671. [This study makes use of neural networks as an estimator for the maximum power point tracking control of a PMSG-based WECS].

[58] Valenciaga F., Puleston P.F., Battaiotto P.E. (2004). Variable structure system control design method based on a differential geometric approach: application to a wind energy conversion subsystem. In *Proceedings of the Conference on Control Theory and Applications*, 151(1), 6–12. [A report of sliding mode control for a hybrid standalone PMSG-based WECS].

[59] Wang C., Weiss G. (2006). Self-scheduled LPV control of a wind driven doubly-fed induction generator. In *Proceedings of the 45th IEEE Conference on Decision and Control*, pp. 1246–1251. [A report of robust LPV control devoted to a DFIG of a WECS].

[60] Wang L. (2009). *Model Predictive Control System Design and Implementation Using MATLAB*. Springer-Verlag London Limited. [A useful reference book for model predictive control].

[61] Wang Y., Fu Y., Li D. (2009). Synthesized power and frequency control strategies based on fuzzy neural networks for wind power generation systems. In *Proceedings of the International Conference on Energy and Environment Technology (ICEET)*, vol. 1, pp. 869–872. [A report of fusion of fuzzy neural networks and adaptive control using a fuzzy neural network as a tuner for the adaptive control of a WECS].

[62] Wu K. C., Joseph R.K., Thupili N.K. (1993). Evaluation of classical and fuzzy logic controllers for wind turbine yaw control. In *Proceedings of the 1st IEEE Regional Conference on Aerospace Control Systems*, pp. 254–258. [A report that studies the performance comparison of PID and fuzzy control for a yaw system of a wind turbines].

[63] Xing Z., Li Q., Su X., Guo H. (2009). Application of BP neural network for wind turbines. In *Proceedings of the 2nd International Conference on Intelligent Computation Technology and Automation (ICICTA)*, vol. 1, pp. 42–44. [A report of fusion of PID and adaptive control using a back-propagation neural network to adapt PID's parameters for a wind turbines].

[64] Yang X., Liu X., Wu Q. (2007). Integral fuzzy sliding mode control for variable speed wind power system. In *Proceedings of the IEEE International Conference on Automation and Logistics*, pp. 1289–1294. [A report of fusion of sliding mode and fuzzy control for a large-scale wind turbine].

[65] Yao X., Guo C., Xing Z., Li Y., Liu S., Wang X. (2009a). Pitch regulated LQG controller design for variable speed wind turbine. In *Proceedings of the International Conference on Mechatronics and Automation (ICMA)*, pp. 845–849. [This presents an application of LQG optimal control for the pitch system of a wind turbine].

[66] Yao X., Liu Y., Guo C. (2007a). Adaptive fuzzy sliding-mode control in variable speed adjustable pitch wind turbine. In *Proceedings of the IEEE International Conference on Automation and Logistics*, pp. 313–318. [A report of fusion of sliding mode and adaptive fuzzy control where an adaptive fuzzy scheme was used to reduce chattering caused by the sliding model controller for the pitch system of a DFIG-based WECS].

[67] Yao X., Su X., Tian L. (2009b). Pitch angle control of variable pitch wind turbines based on neural network PID. In *Proceedings of the 4th IEEE Conference on Industrial Electronics and Applications (ICIEA)*, pp. 3235–3239. [A report of fusion of PID and adaptive control where a neural network was used to tune the PID controller for the pitch system of a wind turbine].

[68] Yao X., Wen H., Deng Y., Zhang Z. (2007b). Research on rotor excitation neural network PID control of variable speed constant frequency wind turbine. In *Proceedings of the International Conference on Electrical Machines and Systems (ICEMS)*, pp. 560–565. [A report of fusion of PID and adaptive control for the DFIG of a wind turbine].

[69] Zhang L., Li H., Chunliang E., Li J., Xu H. (2008). Pitch control of large scale wind turbine based on fuzzy-PD method. In *Proceedings of the 3rd International Conference on Electric Utility Deregulation and Restructuring and Power Technologies (DRPT)*, pp. 2447–2452. [A report of fusion of PID and fuzzy control for the pitch system of a WECS].

[70] Zhou K., Doyle J.C. (1998). *Essentials of Robust Control*. Prentice-Hall. Inc., Upper Saddle River, New Jersey, U.S. [A widely used textbook for robust control].

Biographical Sketches

Hoa Minh Nguyen was born in Tra Vinh, Vietnam. He received his B.E. degree in electrical and electronics engineering and M.E. degree in control engineering from Ho Chi Minh City University of Technology, Vietnam in 2002 and 2005, respectively. He joined the faculty of Tra Vinh University, Vietnam in 2002, and became the interim Dean of the College of Engineering and Technology, Tra Vinh University, from 2006 to 2009. From 2009-present, he is studying as a Ph.D. student at the Department of Electrical Engineering, Idaho State University, USA. His research interests include advanced control, nonlinear control, optimal control, adaptive control, intelligent control, and wind energy control systems.

Desineni Subbaram Naidu, PhD, PE, Fellow IEEE, did his graduate work at Indian Institute of Technology (IIT). Professor Naidu held various positions with IIT, NASA Langley Research Center, US Air Force Research Laboratory, Norwegian University of Science and Technology (NTNU), Swiss

Federal Institute of Technology (ETH). Professor Naidu's primary areas of teaching and research include electrical engineering, circuits, signals and systems, control systems, optimal control, intelligent control, order reduction via singular perturbations and time scales, digital flight control systems, biomedical engineering, aerobraking, orbital transfer, unmanned aerial vehicles, guidance and control of aerospace vehicles, gas metal arc welding . He has over 200 publications including 6 books. Professor Naidu has been on the Editorial Boards several journals including the *IEEE Transaction on Automatic Control*, the *International Journal of Robust and Nonlinear Control*, and *Optimal Control: Applications and Methods.* Professor Naidu is an elected Fellow of the Institute of Electrical and Electronics Engineers (IEEE), and an elected Fellow of the World Innovation Foundation , UK and a member of several other professional organizations. More information is available at *http://engr.isu.edu/~naiduds.*