A Tutorial on the Dynamics and Control of Wind Turbines and Wind Farms

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Abstract— **Wind energy is currently the fastest-growing energy source in the world, with a concurrent growth in demand for the expertise of engineers and researchers in the wind energy field. There are still many unsolved challenges in expanding wind power, and there are numerous problems of interest to systems and control researchers. In this paper, we first review the basic structure of wind turbines and then describe wind turbine control systems and control loops. Of great interest are the generator torque and blade pitch control systems, where significant performance improvements are achievable with more advanced systems and control research. We describe recent developments in advanced controllers for wind turbines and wind farms, and we also outline many open problems in the areas of modeling and control of wind turbines.**

I. Introduction

Wind energy is a fast-growing interdisciplinary field that encompasses many different branches of engineering and science. According to the American Wind Energy Association, the installed capacity of wind grew at an average rate of 29% per year over the years 2002-2007 [1]. At the end of 2007, the installed capacity in the United States was nearly 17,000 megawatts (MW) and the worldwide installed capacity was over 94,000 MW (see Fig. 1). Wind is recognized worldwide as a cost-effective, environmentally friendly solution to energy shortages. Although the U.S. receives only about 1% of its electrical energy from wind [1], that figure in Denmark is more than 15% [2]. A comprehensive report by the U.S. Department of Energy [3] lays the framework for achieving 20% of the U.S. electrical energy generation from wind by the year 2030. This report covers technological, manufacturing, transmission and integration, market, environmental, and siting factors.

Despite the amazing growth in the installed capacity of wind turbines in recent years, engineering and science challenges still exist. Because larger wind turbines have power capture and economical advantages, the typical size of utility-scale wind turbines has grown dramatically over the last three decades (see Fig. 2). Modern wind turbines are large, flexible structures operating in uncertain environments and lend themselves nicely to advanced control solutions. Advanced controllers can help achieve the overall goal of decreasing the cost of wind energy by increasing the efficiency, and thus the energy capture, or by reducing structural loading and increasing the lifetimes of the components and turbine structures. Our goal in this tutorial is to introduce control engineers to the technical challenges that exist in the wind industry and to encourage new control systems research in this area.

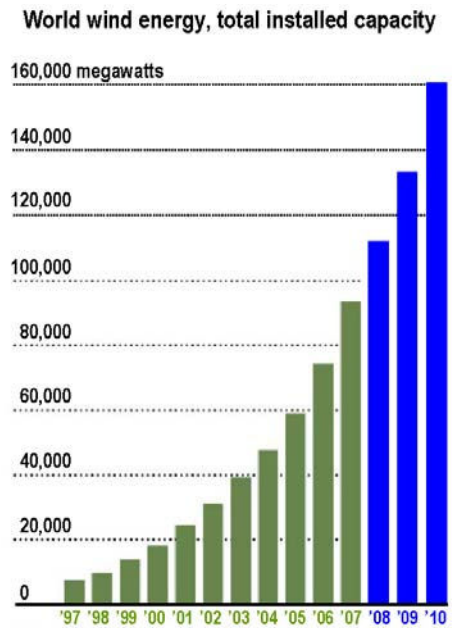

Fig. 1. The installed wind energy capacity worldwide has grown significantly over the last decade. Capacities for 2008-2010 are projections. [Graph reproduced from data in [4]]

Although wind turbines come in both vertical-axis and horizontal-axis configurations, as shown in Fig. 3, we will focus on horizontal-axis wind turbines (HAWTs) in this tutorial because HAWTs are the most commonly produced utility-scale wind turbines today. HAWTs have an advantage over VAWTs in that the entire rotor can be placed atop a tall tower, where it can take advantage of larger wind speeds higher above the ground. Some of the other advantages of HAWTs over VAWTs for utility-scale turbines include pitchable blades, improved power capture and structural performance, and no need for guy wires (which are tensioned cables used to add structural stability). VAWTs are much more common as smaller turbines, where these disadvantages become less important and the benefits of reduced noise

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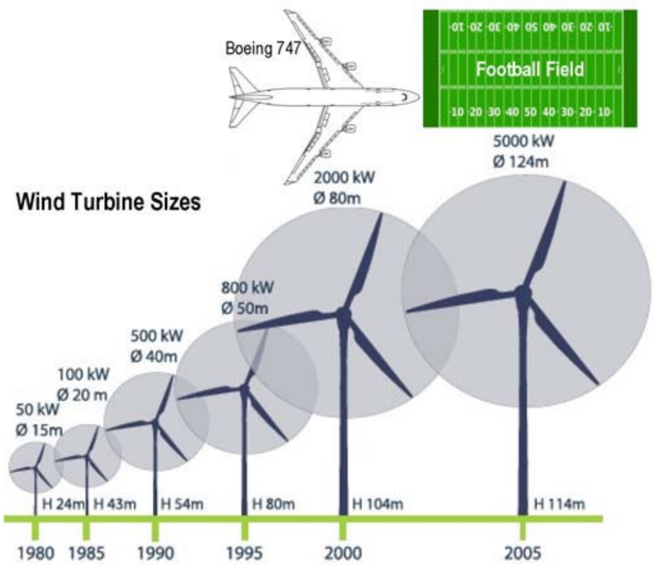

Fig. 2. Modern utility-scale wind turbines are very large flexible structures. Schematics of a Boeing 747 and an American football field are included on the same scale for comparison. Advanced control methods can be used to improve power capture and power quality while reducing structural loading (and hence decreasing maintenance requirements and/or extending lifetime) on wind turbines. This diagram shows the progression of ever larger turbines being introduced commercially over the last three decades. [Diagram and schematics from [5], [6], [7]]

and omni-directionality become more pronounced. The generating capacity of modern commercially-available turbines ranges from less than 1 kilowatt (kW) to several MW. Active control is most cost-effective on larger wind turbines, and therefore this tutorial will focus on wind turbines with capacities of 600 kW or more.

The rest of this paper is organized as follows. Section II describes the configurations and basic operation of wind turbines. Section III explains the layout of a wind turbine control system by taking the readers on a "walk" around the wind turbine control loop, including wind inflow characteristics and available sensors and actuators for use in control. Section IV describes the current state of wind turbine control, which is then followed by a discussion of the issues and opportunities in wind turbine and wind farm control in Sections V, VI, VII, and VIII. Concluding remarks are given in Section IX.

II. Wind Turbine Basics

The main components of a horizontal-axis wind turbine that are visible from the ground are its tower, nacelle, and rotor, as can be seen in Fig. 4. The nacelle houses the generator, which is driven by the high-speed shaft. The high-speed shaft is in turn usually driven by a gear box, which steps up the rotational speed from the low-speed shaft. The low-speed shaft is connected to the rotor, which includes the airfoil-shaped blades. These blades capture the kinetic energy in the wind and transform it into the rotational kinetic energy of the wind turbine.

(a) (b)

Fig. 3. vertical-axis and horizontal-axis wind turbines. (a) vertical-axis turbines spin like tops and are advantageous because they don't need to turn into the wind and their heavy components, like generators, can be located on the ground. [Figure from [8]] (b) horizontal-axis turbines are usually placed on tall towers to catch more of the wind at higher levels above the ground. [Figure courtesy of Lee Jay Fingersh of the U.S. National Renewable Energy Laboratory]

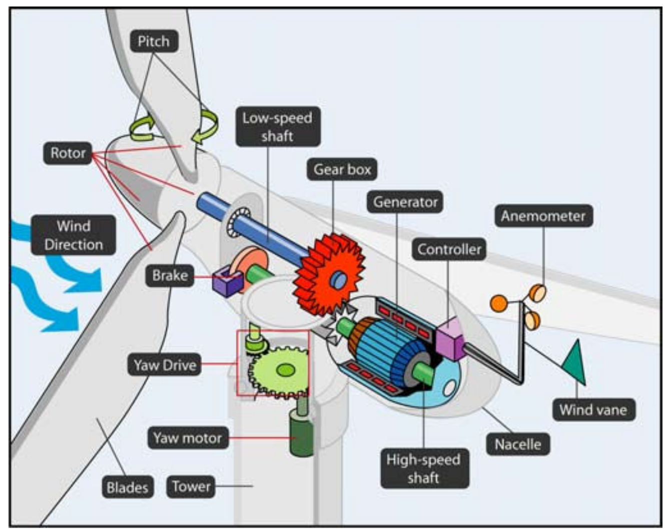

Fig. 4. Wind turbine components. The wind encounters the rotor on this upwind horizontal-axis turbine, causing it to spin. The low-speed shaft transfers energy to the gear box, which steps up in speed and spins the high speed shaft. The high speed shaft causes the generator to spin, producing electricity. Also shown is the yaw system, used to turn the nacelle so that the rotor faces into the wind. (Figure courtesy of the U.S. Department of Energy [9].)

Wind turbine control goals and strategies are affected by turbine configuration. HAWTs may be "upwind," with the rotor on the upwind side of the tower, or "downwind." The choice of upwind versus downwind configuration affects the choice of yaw controller and the turbine dynamics, and thus the structural design. Wind turbines may also be variable pitch or fixed pitch, meaning that the blades may or may not be able to rotate along their longitudinal axes. Although fixed-pitch machines are less expensive initially, the reduced ability to control loads and change the aerodynamic torque means that they are becoming less common within the realm of large wind turbines. Variable-pitch turbines may allow all or part of their blades to rotate along the pitch axis.

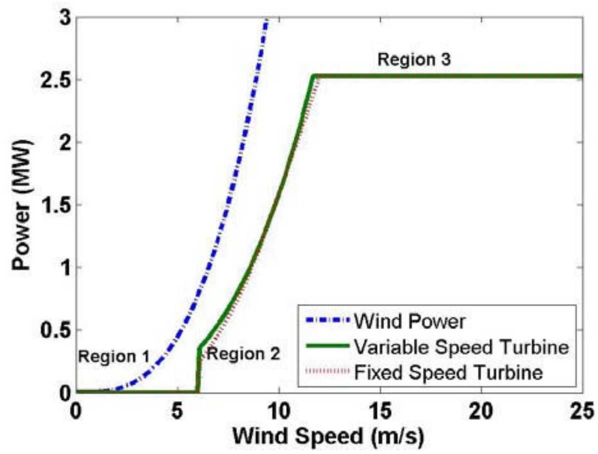

Fig. 5. Example power curves. The "Wind Power" curve shows the power available in the wind for a turbine of the same size as the two example turbines. Note that the example turbines produce no power in low winds because they are not turned on until the wind speed reaches a certain level. Further, power is limited to protect the electrical and mechanical components of both turbines in high wind speeds. Both turbines produce the same power at the design point for the fixed speed turbine, but the variable speed turbine produces more power over the rest of Region 2.

Moreover, wind turbines can be variable speed or fixed speed. Variable-speed turbines tend to operate closer to their maximum aerodynamic efficiency for a higher percentage of the time, but require electrical power processing so that the generated electricity can be fed into the electrical grid at the proper frequency. As generator and power electronics technologies improve and costs decrease, variable-speed turbines are becoming more popular than constant-speed turbines at the utility scale.

Fig. 5 shows example power curves for a variable-speed and a fixed-speed wind turbine, as well as a curve showing the power available in the wind for this 2.5 MW example turbine. For both turbines, when the wind speed is low (in this case, below 6 m/s), the power available in the wind is low compared to losses in the turbine system so the turbines are not run. This operational region is sometimes known as Region 1. When the wind speed is high, Region 3 (above 11.7 m/s in this example), power is limited for both turbines to avoid exceeding safe electrical and mechanical load limits.

The main difference in Fig. 5 between the two types of turbines appears for mid-range wind speeds, Region 2, which encompasses wind speeds between 6 and 11.7 m/s in this example. Except for one design operating point (10 m/s in this example), the variable-speed turbine captures more power than the fixed-speed turbine. The reason for the discrepancy is that variable-speed turbines can operate at maximum aerodynamic efficiency over a wider range of wind speeds than fixed-speed turbines. The maximum difference between the two curves in Region 2 is 150 kW. For a typical wind speed distribution with a Weibull distribution [10], [11] having a shape parameter $k = 2$ and scale parameter $c = 8.5$, the variable-speed turbine captures 2.3% more energy per year than the constant-speed turbine, which is considered to be a significant difference in the wind industry.

Not shown in Fig. 5 is the "high wind cut-out," a wind speed above which the turbine is powered down and stopped to avoid excessive operating loads. High wind cut-out typically occurs at wind speeds above 20 - 30 m/s for large turbines, with many factors determining the exact value.

Even a perfect wind turbine cannot fully capture the power available in the wind. In fact, actuator disc theory shows that the theoretical maximum aerodynamic efficiency, which is called the Betz Limit, is approximately 59% of the wind power [12]. The reason that an efficiency of 100% cannot be achieved is that the wind must have some kinetic energy remaining after passing through the rotor disc; if it did not, the wind would by definition be stopped and no more wind would be able to pass through the rotor to provide energy to the turbine.

The aerodynamic efficiency is the ratio of turbine power to wind power and is known as the turbine's power coefficient, C_p. C_p can be computed as

$$C_p = \frac{P}{P_{wind}}, \tag{1}$$

where P is the power captured by the turbine and P_{wind} is the power available in the wind for a turbine of that size. The power P_{wind} is given by

$$P_{wind} = \frac{1}{2}\rho A v^3, \tag{2}$$

where ρ is the air density, A is the 'swept area' of the rotor, and v is the instantaneous wind speed. The swept area is the circle described by the blade tip, or πR^2, where R is the rotor radius. In (2), the wind speed v is assumed to be uniform across the rotor swept area.

References [10] and [11] are excellent sources for more detailed information about many aspects of wind turbines.

III. A Walk Around the Wind Turbine Control Loops

In designing controllers for wind turbines, it is often assumed (as in (2)) that the wind speed is uniform across the rotor plane. However, as shown by the "instantaneous wind field" in Fig. 6, the wind input can vary substantially in space and time as it approaches the rotor plane. The deviations of the wind speed from the expected nominal wind speed across the rotor plane are considered disturbances for control design. It is virtually impossible to obtain a good measurement of the wind speed encountering the blades because of the spatial and temporal variability and also because the rotor interacts with and changes the wind input. Not only does turbulent wind cause the wind to be different for the different blades, but the wind speed input is different at different positions along each blade.

Utility-scale wind turbines have several levels of control, which can be called 'supervisory control,' 'operational control,' and 'subsystem control.' The top-level supervisory control determines when the turbine starts and stops in response to changes in the wind speed, and also monitors the health of the turbine. The operational control determines

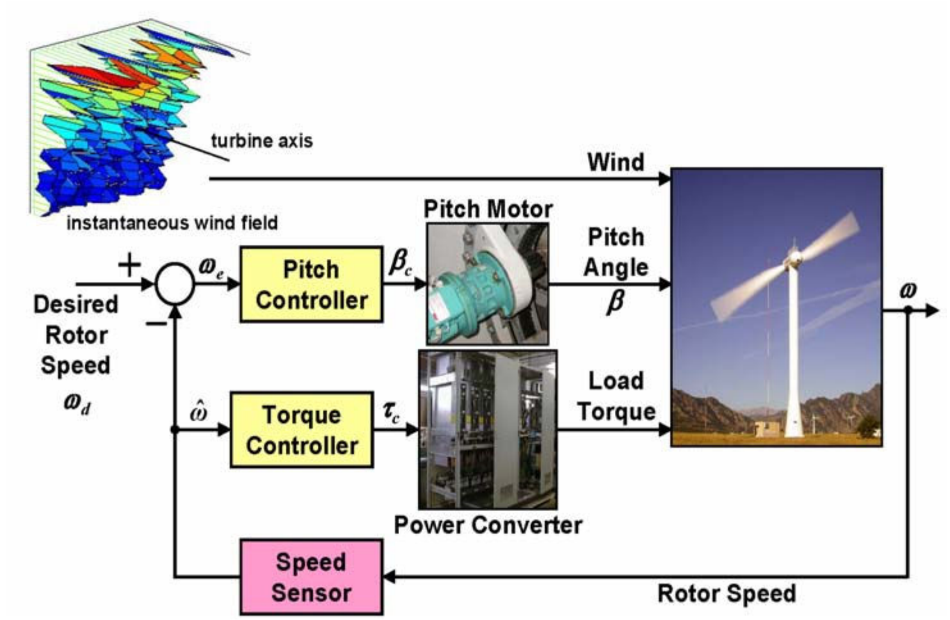

Fig. 6. A Wind Turbine Control Block Diagram. The diagram shows that the speed of the wind that hits the turbine can vary significantly across the rotor plane. Rotor speed measurements are usually the only measurements used in the feedback loops for both the generator torque control and the blade pitch control.

how the turbine achieves its control objectives in Regions 2 and 3. The subsystem controllers cause the generator, power electronics, yaw drive, pitch drive, and other actuators to perform as desired. In this section, we will move through the operational control loops shown in Fig. 6, describing the wind inflow, sensors, and actuators in more detail while treating the subsystem controllers as black boxes. The pitch and torque controllers in Fig. 6 will be discussed further in Section IV. The details of the subsystem controllers are beyond the scope of this paper, and the reader is referred to [10], [11] for an overview of these lower-level controllers.

A. *Wind Inflow*

The differential heating of the earth's atmosphere is the driving mechanism for the earth's winds. Numerous atmospheric phenomena, such as the nocturnal low-level jet, sea breezes, frontal passages, and mountain and valley flows, affect the wind inflow across a wind turbine's rotor plane [10]. From Fig. 2, the rotor plane of modern megawatt utility-scale wind turbines span from 60 m to 180 m above the ground. Given this large size of wind turbine rotor planes, and the variability of wind, it is virtually impossible to obtain a good measurement of the wind speed encountering the entire span of the blades from in situ sensors mounted on the nacelle or turbine blades. Current and future technologies for measuring wind inflow to a turbine will be discussed in Sections III-B and VI, respectively.

The available wind resource is often characterized by the average wind speed, the frequency distribution of wind speeds, the temporal and spatial variation in wind speed, the most frequent wind direction (i.e., prevailing wind direction), and the frequency of other wind directions [10]. How consistently the wind blows above the rated wind speed for a given turbine will determine how often the turbine will be operating in Region 3 at its maximum rated power generation capacity. The *capacity factor* is the ratio of a wind turbine's (or wind farm's) energy output over a period of time to the amount of energy the turbine would have produced if it had run at full capacity for the same amount of time:

$$\text{Capacity Factor} = \frac{\text{actual energy output over time period}}{\begin{array}{c}\text{energy output if turbine operated}\\ \text{at max output over same time period}\end{array}}$$

To accurately predict capacity factors and maintenance requirements for wind turbines, it is important to be able to understand wind characteristics over long (multi-year) as well as short (second and sub-second) time scales. The ability to measure and predict the available wind resource at a particular site is important in determining whether that location is suitable and economically advantageous for siting wind turbines. Significant variations in seasonal average wind speeds are common and affect a local area's available wind resource over the course of each year. Large wind speed and direction variations also occur on a diurnal (or daily) time scale. Diurnal wind variation is caused by the differential heating of the earth's surface during the daily solar radiation cycle. Being able to accurately predict hourly wind speed variations is important for utilities to properly plan their energy resource portfolio mix of wind energy with other sources of energy. Finally, knowledge of short-term wind speed variations, such as gusts and turbulence, is important in both turbine and control design processes so that structural loading can be mitigated during these events.

Although wind inflow characteristics are dynamic and

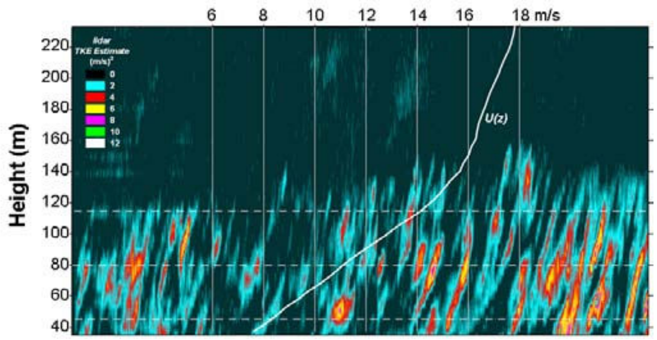

Fig. 7. High-resolution Doppler Lidar measurements showing coherent turbulent kinetic energy (TKE), which may cause excessive loading on a wind turbine. Note that the majority of the TKE occurs between 40 - 120 m, which is a typical range for a utility-scale turbine rotor. Reproduced with permission from [13].

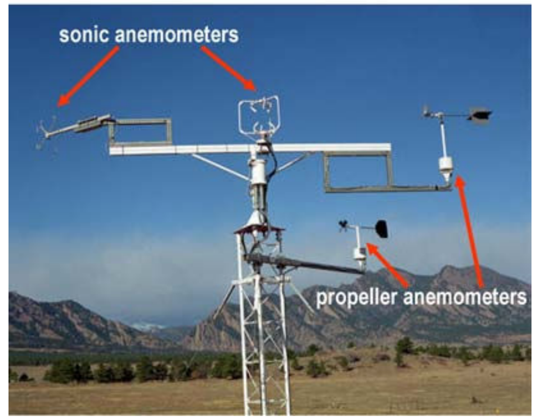

Fig. 8. Several types of sonic and propeller anemometers on a meteorological tower at the National Renewable Energy Laboratory's (NREL's) National Wind Technology Center (NWTC) near Boulder, Colorado. Anemometers on commercial wind turbines are typically placed on the nacelle.

variable across the turbine's rotor plane, nearly all modeling, design, and control is based on assumptions of uniform and constant wind across the rotor plane, including equations (1)-(2) above (as well all other equations in the remainder of this paper). While this assumption simplifies models and hence the design and control of wind turbines, as wind turbines become larger, the variability of the wind across the rotor plane makes this uniform wind assumption more and more erroneous. This assumption is leading to poor predictions of both the available wind power and loading and wear on the turbine due to the wind. This latter is becoming especially problematic as realistic nocturnal low-level jets (which are non-uniform winds) are leading to much higher levels of maintenance and repair on significantly large numbers of commercial turbines than predicted based on uniform wind assumptions.

Random turbulent structures have always existed in the wind resource throughout history. In past decades, when turbines were smaller and placed atop shorter towers, the effects of these structures hitting the turbines was either not well understood, or was less significant than it is becoming with more modern turbines. Today's larger turbines are often hit with turbulent structures that are comparable or smaller in size than turbine rotor planes, and recent analysis indicates that turbulent structures smaller than the rotor cause more damage than those larger than the rotor. This effect may stem from the fact that smaller structures cause very different wind conditions to "hit" different blades of a large turbine, causing serious fatigue and extreme loading issues that can cause excessive wear or damage to the turbine structure [14]. Better capabilities for measuring and predicting turbulent events are needed [15], and this is an active area of research among atmospheric scientists. Fig. 7 shows measurements of coherent turbulent kinetic energy (TKE) in a low-level jet, a common atmospheric feature in some parts of the US. There are significant energetic structures located between 40 - 120 m above ground level, the typical height for modern utility-scale turbine rotors. Turbulent structures may take many forms, with one example being wind velocity appearing like a log rolling toward the turbine (higher velocity at the top, and lower or even negative velocity at the bottom). Controllers designed to alleviate structural loading in response to turbulent structures are described in [16].

B. Sensors

A typical commercial wind turbine has surprisingly few sensors for its size and complexity. As shown in Fig. 6, only rotor speed measurements are typically used in feedback for basic control in both Region 2 and Region 3. Since the gear box ratio is known, speed can be measured on either the high speed (generator) or low speed (rotor) shafts.

In addition to rotor speed measurements, wind turbines usually have anemometers for supervisory control purposes, in particular to determine if the wind speed is sufficient to start turbine operation. Fig. 8 shows sonic and propeller anemometers on a meteorological tower. Most turbines have an anemometer and a wind vane located on top of the nacelle (at approximately hub height) for measuring wind speed and wind direction. This anemometer provides limited measurements of wind speed only at hub height. Moreover, because of the interaction between the rotor and the wind, this usual placement of anemometers on nacelles leads to inaccurate wind speed measurements. In fact, the interaction extends both upwind and downwind of the rotor, so good wind measurements cannot be achieved during operation on either upwind or downwind turbines.

Further, nearly all utility-scale wind turbines also have power measurement devices. Power measurement is necessary for keeping track of a turbine's energy generation. Other sensors that are sometimes found on wind turbines and whose measurements have been used in more advanced wind turbine controllers include:

- strain gauges on the tower and blades,
- accelerometers,
- position encoders on the drive shaft and blade pitch actuation systems, and
- torque transducers.

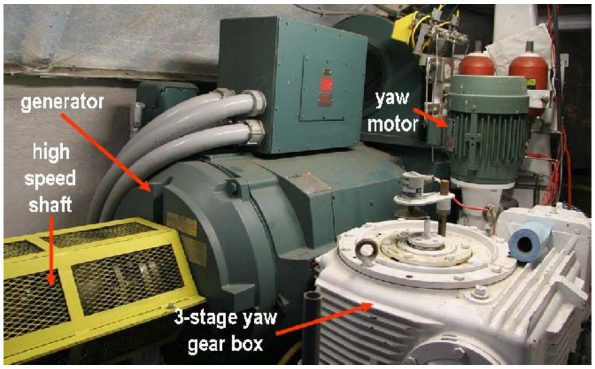

Fig. 9. Photo of the inside of the 3-bladed Controls Advanced Research Turbine (CART3) nacelle, showing the high-speed shaft (inside the yellow cage at left), the generator (large green unit in the middle), the yaw motor (smaller green unit toward the right), and the 3-stage yaw gear box (large white box in lower right). Another gear box connects the high-speed shaft on the left to the low-speed shaft and rotor (not shown here). Photo courtesy of Lee Jay Fingersh of NREL.

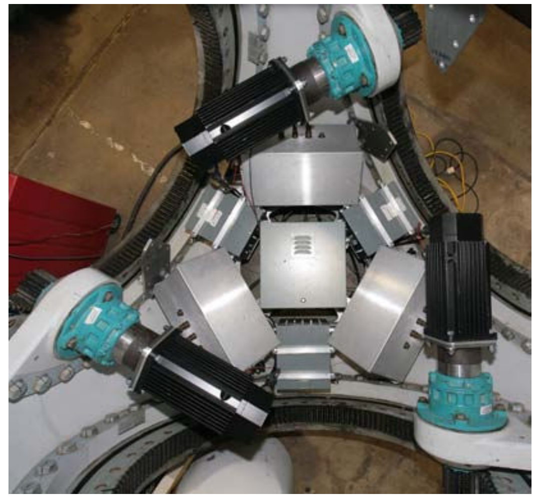

Fig. 10. This photo of the three pitch motors on the CART3 was taken from inside the turbine's hub prior to installation of the blades. The view is looking "upwind" from the turbine, and the control circuitry boxes and gears are also visible. Like many modern utility-scale turbines, CART3 is equipped with independent blade pitch capability. Photo courtesy of Lee Jay Fingersh of NREL.

When selecting sensors for use in wind turbine control, sensor reliability is of critical importance. A faulty sensor can reduce turbine availability, especially if the sensor is required for control. As discussed in [17], sensor failures can be difficult to diagnose. Calibration drift is a common problem, for example, so controllers that rely on sensors prone to drifting must be robust to calibration errors. Control solutions to sensor reliability problems may include the need for small mechatronic systems, auto-calibration techniques, adaptive control, and other procedures.

C. Actuators

Modern utility-scale wind turbines typically have up to three main types of actuators. A yaw motor, which turns the wind turbine to align it with the wind, is nearly always included on large turbines, resulting in active yaw control. However, due to dangerous gyroscopic forces, it is not usually desirable to yaw the turbine at a high rate. Most large turbines yaw at rates of less than 1 deg/s. Thus, investigation of advanced controllers for yaw control is not of as much interest as advanced controllers for other actuators.

Small turbines are often either designed with the rotor downwind of the tower or designed with a fan-like tail, either of which can allow passive yaw motion into the wind. Because they are much smaller than utility-scale turbines, gyroscopic loading is not much of a concern and yaw can occur more frequently with each wind direction change.

The second common actuator on modern turbines is the generator, which, depending on type of generator and power processing equipment, can be forced to 'command' a desired torque or load. Although the net torque on the rotor always depends on the input torque from the wind and the load torque from the generator, the generator torque can be used to affect the acceleration and deceleration of the rotor. The generator torque can usually be changed very quickly, with a time constant an order of magnitude or more faster than that of the rotor speed. Thus, generator torque can be an effective control actuator. The generator inside the 3-bladed Controls Advanced Research Turbine (CART3) located at the National Renewable Energy Laboratory's (NREL's) National Wind Technology Center (NWTC) can be seen in Fig. 9. CART3 is a 600 kW turbine with a 40 m rotor diameter that is used as an experimental test bed for advanced controllers.

The last actuator that we discuss is the blade pitch motor. Fig. 10 shows the three pitch motors of CART3. Like CART3, most modern utility-scale wind turbines have three blades and thus three pitch motors. Two-bladed turbines typically use a teetering hinge to allow the rotor to respond to differential loads when the blades are in a vertical position [11], [18]. This teeter hinge allows one blade to move upwind while the other moves downwind in response to differential wind loads, much as a teeter totter allows one child to move up while another moves down. For a turbine with an even number of blades placed symmetrically around the rotor, when one blade is at the uppermost position, another blade will be in the slower wind caused by tower "shadow" behind the tower or the "bow wake" in front of the tower. This discrepancy is even more pronounced in typical wind shear conditions, which result in larger wind speeds higher above the ground. Three-bladed turbines tend to experience more symmetrical loading, but the cost of the third blade can be substantial.

Fig. 11 shows operational blade pitch angle data from CART2, a 2-bladed, 600 kW wind turbine with a 43 m diameter rotor at NREL's NWTC. Data collection was performed during a normal shut down event caused by the wind speed decreasing into Region 1. In this case, the pitch rate is restricted to approximately 5 deg/sec. The lag between the commanded and actual pitch angle can be represented by a first-order filter.

Wind turbine blades may be controlled to all turn *collec-*

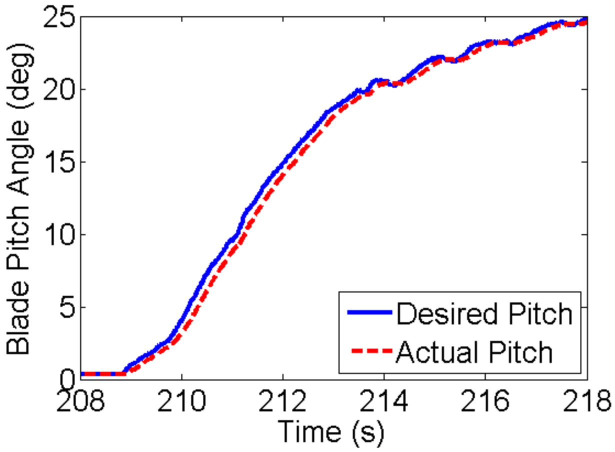

Fig. 11. The data shown in this figure is operating data from the CART2, the 2-bladed Controls Advanced Research Turbine at NREL's NWTC. The commanded (desired) pitch and actual pitch angles are shown during a normal shut down event as the blades are pitched from -1 to 90 deg, although only the first 10 s of the shut-down event are plotted. The lag between the two signals can be represented by a first-order filter.

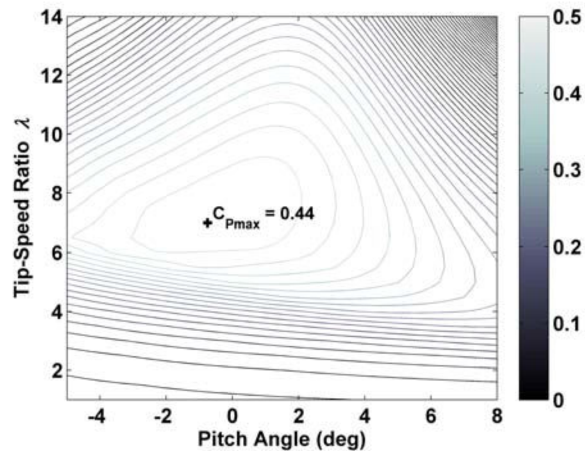

Fig. 12. C_p surface for CART3. The peak power coefficient $C_{p_{max}} = 0.4438$ for CART3 occurs at a tip-speed ratio $\lambda_* = 7.0$ and a blade pitch angle $\beta_* = -0.75$ deg.

tively or to each turn *independently* or *individually*. Pitch motors can be used to change the aerodynamic torque from the wind input, and are often fast enough to be of interest to the control community. Typical maximum pitch rates range from 18 deg/s for 600 kW research turbines down to 8 deg/s for 5 MW turbines.

Variable-pitch turbines can limit power either by pitching to "stall" or to "feather," and fixed-pitch turbines typically limit power by entering the aerodynamic stall regime above rated wind speed. A blade in full feather is one in which the leading edge of the blade points directly into the wind. A discussion of the benefits of pitching to feather versus pitching to stall is outside the scope of this paper, but more information is provided in [10], [19].

D. Control Loops

The primary Region 2 control objective for a variable-speed wind turbine is to maximize the power coefficient C_p. For modern HAWTs, this power coefficient is a function of the turbine's tip-speed ratio λ, which is defined as

$$\lambda = \frac{\omega R}{v}. \tag{3}$$

In (3), ω is the rotational speed of the rotor, and R and v are the rotor radius and instantaneous wind speed, respectively. Thus, the tip-speed ratio is the ratio of the linear (tangential) speed of the blade tip to the wind speed, where R is fixed for a given turbine, v is always time-varying, and ω is time-varying for a variable-speed turbine. For modern HAWTs, the relationship between the power coefficient C_p and the tip-speed ratio λ is a turbine-specific nonlinear function. C_p also depends on the blade pitch angle in a nonlinear fashion, and these relationships have the same basic shape for most modern HAWTs. The C_p surface is shown in Fig. 12 for one specific turbine, the CART3 at NREL's NWTC.

As shown in Fig. 12, the turbine will operate at its highest aerodynamic efficiency point, $C_{p_{max}}$, at a certain pitch angle and tip-speed ratio. Pitch angle is easy to control, and can be reliably maintained at the optimal efficiency point. However, tip-speed ratio depends on the incoming wind speed u and therefore is constantly changing. Thus, Region 2 control is primarily concerned with varying the turbine speed to track the wind speed. Section IV-A will explain how this control objective can be achieved.

On utility-scale wind turbines, Region 3 control is typically performed via a separate pitch control loop, as shown in Fig. 6. In Region 3, the primary objective is to limit the turbine power so that safe electrical and mechanical loads are not exceeded. Power limitation can be achieved by pitching the blades or by yawing the turbine out of the wind, both of which can reduce the aerodynamic torque below what is theoretically available from an increase in wind speed. Note that the power P is related to rotor speed ω and aerodynamic torque τ_{aero} by

$$P = \tau_{aero}\omega. \tag{4}$$

If the power and rotor speed are held constant, the aerodynamic torque must also be constant even as wind speed varies. It is desirable to produce as much power as the turbine can safely produce, the limit of which is known as the turbine's rated power. In Region 3, the pitch control loop regulates the rotor speed ω (at the turbine's "rated speed") so that the turbine operates at its rated power.

IV. Feedback Control

In this section, we will provide further information regarding what control algorithms are typically used for the "Torque Control" and "Pitch Control" blocks of Fig. 6. As depicted in Fig. 6, both control loops typically only use rotor speed feedback. The other sensors and measurements discussed in Section III-B are usually only used for supervisory control and fault detection purposes. Interested readers may

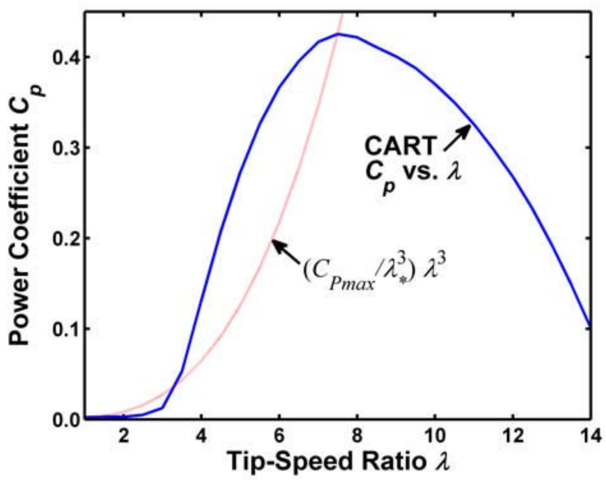

Fig. 13. C_p versus λ curve for the CART3 when the blade pitch angle β = -0.75 deg. The turbine accelerates toward the optimal tip-speed ratio λ_* when the red curve (representing (8)) is less than the blue curve ("CART C_p vs. λ"), and decelerates when the opposite is true.

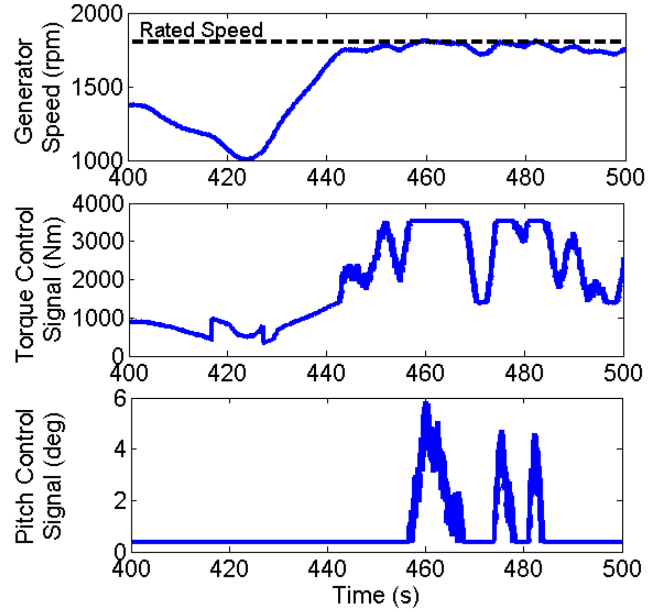

Fig. 14. Experimental generator speed and torque and pitch control signals for the CART2 in normal operation. The rated speed for CART2 is 1800 rpm; when this rated value is reached, the torque control signal is saturated at its maximum value and pitch control is used to limit turbine power.

refer to [19] for a more detailed description of wind turbine control, especially for the four combinations of variable and fixed pitch together with variable and fixed speed.

A. Generator Torque Control

There are numerous generator torque controllers in use by the wind industry, and most of these are proprietary. Here, we present one type of generator torque control in use on CART2 at NREL's NWTC. For the remainder of this paper, we will refer to this controller as the "standard" torque controller. The (nonlinear) control is achieved by setting the generator (control) torque τ_c as

$$\tau_c = K\hat{\omega}^2, \tag{5}$$

where $\hat{\omega}$ is the measurement of the rotor speed, and K is given by

$$K = \frac{1}{2}\rho\pi R^5 \frac{C_{p_{max}}}{\lambda_*^3}, \tag{6}$$

where $C_{p_{max}}$ is the maximum power coefficient achievable by the turbine, and λ_* is the tip speed ratio at the maximum power coefficient.

Assuming $\hat{\omega} = \omega$ (perfect measurements), the torque control given by (5) and (6) can be shown to achieve $C_{p_{max}}$ by examining the dynamics of a single degree-of-freedom rotational system. In this case, we relate net torque and angular acceleration by

$$\dot{\omega} = \frac{1}{J}\left(\tau_{aero} - \tau_c\right), \tag{7}$$

where J is the rotational inertia of the system. Combining (7) with (1)-(6), we find that

$$\dot{\omega} = \frac{1}{2J}\rho\pi R^5\omega^2\left(\frac{C_p}{\lambda^3} - \frac{C_{p_{max}}}{\lambda_*^3}\right).$$

Thus,

$$\begin{array}{lcll} & \dot{\omega} < 0 & \text{when} & C_p < \frac{C_{p_{max}}}{\lambda_*^3}\lambda^3 \\ \text{and} & \dot{\omega} > 0 & \text{when} & C_p > \frac{C_{p_{max}}}{\lambda_*^3}\lambda^3 \end{array} \tag{8}$$

and we see that the control law given by (5) and (6) causes the turbine to accelerate toward the desired set point when the rotor speed is too slow and decelerate when the rotor speed is too fast. The representation of (8) can be seen graphically in Fig. 13.

Fig. 14 shows operational data from the CART2 of the measured high speed shaft (generator) speed, the control torque signal given by (5), and the pitch control signal. For the first 50 seconds, the wind speed is low enough that control is based on (5). After that time, wind speeds have increased and the rated speed of 1800 rpm is reached, upon which the torque control signal is saturated and pitch control takes over to limit turbine power. The two very steep sections of the torque control signal at approximately 417 s and 427 s are due to a tower resonance avoidance controller described further in [17].

For additional information about this Region 2 standard torque controller, as well as an adaptive torque controller, please see [20].

B. Pitch Control

In commercial wind turbines, pitch control in Region 3 is frequently performed using a proportional-integral-derivative (PID) collective pitch control:

$$\beta_c(t) = K_P\omega_e(t) + K_I\int_0^t \omega_e(\tau)d\tau + K_D\frac{d\omega_e(t)}{dt} \tag{9}$$

where $\omega_e = \omega_d - \hat{\omega}$ is the rotor speed error, the difference between the desired rotor speed ω_d and the measured rotor speed $\hat{\omega}$. Because of its sensitivity to measurement noise, the derivative term is often combined with a low-pass filter, or the term is sometimes omitted altogether (i.e., $K_D = 0$) leaving just a PI pitch controller. The PI gains on most modern utility-scale wind turbines are gain scheduled because the pitch authority is nonlinear in Region 3. The output signal can be either blade pitch angle or rate of change. A nice summary of Region 3 pitch control for speed regulation is provided in [21]. A systematic method for selecting the PID pitch control gains is presented in [22].

Fig. 14 also shows Region 2 and 3 operational pitch angle data from the CART2 in its third plot. Shown is the desired blade pitch angle, which changes from its nominal value only in Region 3, when it is used to limit rotor speed and power. As mentioned previously, the 600 kW CART2 has a higher maximum pitch rate (18 deg/s) than most modern (and often larger) utility-scale turbines.

While collective blade pitch only requires a single-input, single-output (SISO) controller, many modern utility-scale turbines allow the blades to be pitched independently of one another. Assuming more sensors/measurements are available for feedback, multi-input, multi-output (MIMO) individual blade pitch controllers can be designed for increased performance [23], [24]. Additional discussion on MIMO pitch feedback control is provided in [25].

V. Issues in Wind Turbine Control

The increasing dimensions of wind turbines have led to the relative increase in the loads on wind turbine structures. Because of the increasing rotor size and the spatial load variations along the blade, it is necessary to react to turbulence in a more detailed way, with each blade separately controlled. Additional pitch control loops are sometimes included for damping fore-aft tower motion or other structural vibrations in Region 3, and the individual pitch control loops are sometimes considered and developed separately.

Given the complexity of the wind turbine system, the stability of the complete control system is often difficult to fully establish. The multiple control loops interact, as do the multiple degrees of freedom of the turbine (especially as wind turbines become larger and have lower natural frequencies). The coupling across degrees of freedom becomes even more pronounced in floating offshore wind turbines; Section VIII will discuss additional issues in offshore wind turbines. A unified multi-input, multi-output (MIMO) framework for individual blade pitch control can be beneficial and has been shown to achieve significant load reductions [23], [24].

Because wind turbine control is often achieved using two distinct control loops for Regions 2 and 3, the transition between regions can be problematic. In fact, for some turbines, the maximum structural damage occurs due to extreme and fatigue loads during this transition. Often, the act of switching between Region 2 and Region 3 controllers contributes to the problem.

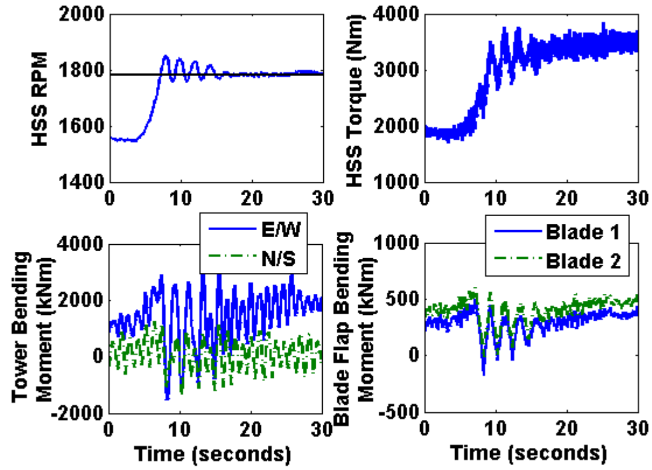

Fig. 15. These plots show high speed shaft velocity (HSSV), high speed shaft torque, tower bending moment, and blade flap bending moments for the CART2 operating during a poor Region 2 to Region 3 transition. The "E/W" and "N/S" designations indicate tower bending directions in the East-West and North-South directions. More sophisticated control techniques may reduce the oscillatory behavior.

The CART2 baseline controller, for example, uses an additional control region called "Region 2.5" to switch between Region 2 and Region 3 control. The Region 2.5 control strategy is described in [25] and [26], and its primary objective is to connect the Regions 2 and 3 controllers linearly in the generator torque vs. generator speed plane. Unfortunately, this linear connection does not result in smooth transitions, and the discontinuous slopes in the torque control curve can contribute to excessive loading on the turbine. CART2 uses a saturation block on pitch angle in Region 2, and pitch control becomes active (unsaturated) when rotor speed is greater than 99% of rated speed. A poor CART2 transition is shown in Fig. 15.

Wind turbines can also be damaged when they are stopped as a result of supervisory control action, either due to high winds or fault conditions. However, very little active control is usually done when the turbine is stopped, although the yaw angle may be changed to accommodate changes in wind direction.

In addition to the possibility of improving control when the turbine is stopped, advanced fault detection and turbine protection schemes are of interest to the wind industry. Stopping the turbine in the case of emergency, which may entail pitching the blades to the desired stop position at maximum pitch rate and setting the rotor brake(s), can also cause damage to the machine and should only be done when there is reason to suspect a turbine failure.

Finally, the performances of controllers depend upon modelling accuracies. For instance, it has been shown that a very common 5% modeling error in the optimal tip speed ratio λ_* alone can cause an energy loss of around 1% - 3% in Region 2 [27]. This can be a significant loss in this industry, since for example, a wind farm rated at 100 MW and operating with a reasonable 35% capacity factor can produce about 307 gigawatt-hour (GWh) of energy in a given year. If the cost of energy is \$0.04 per kilowatt-hour (kWh), each GWh is worth about \$40,000, meaning a 1% loss of energy on this wind farm is equivalent to a loss of \$123,000 per year [28]. Even if model errors are extremely small, the dynamical behavior of a wind turbine will change over time due wear, debris build up on the blades, environmental conditions, etc. As such, adaptive methods have been investigated to tune controllers to ensure "optimal" performance over all time [29], [30], [28], [20], [31].

Common practice in the wind industry is to model the dynamics using first principles. Efficient methods to obtain mathematical models from measurements also exist, and recent work has included developing closed-loop identification methods for determining accurate linear parameter-varying (LPV) models [32]. Such models then lend themselves naturally to existing advanced control synthesis techniques within the robust control framework. Wind turbines are highly nonlinear systems, and control techniques must keep this fact in mind. Modeling of wind turbines, as well as wind farms, are further discussed in [33].

VI. Advanced Control of Wind Turbines

There are many aspects of wind turbine performance that can be improved with more advanced control development. Researchers have developed methods for using adaptive control to compensate for unknown or time-varying parameters [34], [29], [31]. A few researchers have also begun to investigate the addition of feedforward control to improve the disturbance rejection performance when the incoming wind profile deviates from that expected [35], [36], [37], [38]. Most of these feedforward controllers use estimates of the disturbance (or wind deviation).

New sensing technologies will enable various avenues of advanced control research. For instance, there has been recent interest in evaluating the potential of lidar (which stands for "light detection and ranging") sensors for wind turbine control [35], [36]. Lidar is a remote optical sensing technology that has been used since the 1970s for meteorology for measuring wind speed profiles for monitoring hurricanes and wind conditions around airports. New lidar systems based on solid-state sources and off-the-shelf telecommunications equipment allow for inexpensive deployment, modularity, and improved reliability [39].

Depending on the particular type of technology used, lidar sensors can provide quantities representing the wind speed and direction and various wind turbulence and shear parameters. An accurate measurement of the wind profile over the entire rotor plane in Fig. 6 can enable feedforward pitch control and feedforward torque control to improve performance dramatically. Advanced wind turbine controllers are further discussed and compared in [25].

As turbines get larger and blades get longer, it is possible that turbine manufacturers will build turbines that allow for different pitch angles at different radial positions along the blades relative to the standard blade twist angle. In this case, separate actuators and controllers may be necessary, opening up even more control opportunities [40].

Fig. 16. Wind turbines at a wind farm in Galicia, Spain. Aerodynamic and electrical interaction among turbines on a wind farm can result in energy capture losses. Better modelling and coordinated control of such arrays of multiple turbines can recover some of these losses. Photo from [42].

Turbine manufacturers and researchers are also investigating actuators other than a pitch motor to change the aerodynamics of the turbine blade. For example, micro-tabs and tiny valves to allow pressurized air to flow out of the blade may change the flow of the air across the blade, thus affecting the lift and drag coefficients and providing another possibility for control. Advanced rotor concepts fall in two categories [41]: devices to alter the local blade aerodynamic properties and geometry control via extendable blades. Controllers are based on linear state-space methods with individual blade pitch control and MIMO control of devices, and the effect of each on cost of energy is also discussed in [41].

We note that initial concepts for wind turbine modeling, design, and control were borrowed from the helicopter industry. Although the basic idea of rotating, pitchable blades is a unifying theme, the significantly faster rotational speed of a helicopter rotor leads to noticeable differences in the dynamics and aerodynamics that drive the design and control.

VII. Modeling and Control of Wind Farms

Wind turbines are often located with other turbines in wind farms to reduce costs by taking advantage of economies of scale. Fig. 16 shows turbines in a line at a farm in Galicia, Spain. Turbines on wind farms can be located along a single line, in multiple lines, in clusters, in grids, and in nearly any configuration imaginable based on geographical features, prevailing wind direction, and other factors. These other factors may include

- access requirements,
- turbine noise,
- environmental effects,
- safety,
- prior and future land use (wind farms are sometimes used as ranchland), and
- visual impacts.

The noise, safety, visual, and environmental effects are typically more pronounced in wind farms with multiple turbines than they are for individual turbines.

From a control systems perspective, wind farm research is focused mainly on two areas: control of the electricity generated by the turbines and coordinated control of the power produced by individual turbines in the farm to minimize the negative effects of turbine aerodynamic interaction. Of these, the electrical interconnection of turbines on a wind farm has been more extensively studied. Standards governing the wind farm's interconnection to the utility grid vary by location, but in general wind farms should not contribute to grid faults, should not be damaged by grid faults, and should have voltage control strategies. More information about existing standards can be found in [43].

In this section, we provide a sampling of some of the recent results in wind farm electrical system control. Many of the following papers study wind turbines equipped with doubly-fed induction generators, which are increasingly common in wind turbines. A survey of types of generators used in wind turbines is given in [11], and a good overview of wind farm electrical system concerns can be found in [10].

A comparison of three wind farm-based control strategies for control of active and reactive power is provided in [44], which incorporates controllers for three regimes: power optimization, power limitation, and down power regulation. A dual-level controller with both centralized and turbine-based controllers is presented in [45]. The turbine-based controllers ensure that reference commands provided by the centralized controller are achieved.

Damping of the network electromechanical oscillations of a wind farm power system is the focus of [46], which uses a strategy derived from Lyapunov theory. Only local measurements are required for the proposed strategy. In [47], a wind farm level optimization strategy for wind turbine commitment and active and reactive turbine control is described. The strategy assumes that short-term wind forecasts are known for each turbine in the farm.

Voltage stability and the uninterrupted operation of a wind farm connected to an electric grid during a grid fault is the focus of [48]. The focus of [49] is coordinated control of wind farms over three control levels: central control, wind farm control, and individual turbine control. Under-load tap changing transformers and convectional mechanical switched capacitors are used to implement the control strategies, which can be implemented on both fixed- and variable-speed turbines.

A discussion on the experiences with the first wind farm equipped with advanced control of both active and reactive power, Denmark's Horns Rev, can be found in [50]. Finally, wind farm modeling from the electrical perspective has been a topic of research at NREL, and more information about these models can be found in [51], [52].

The aerodynamic interaction of turbines on a wind farm is not as well understood as the electrical interconnection, though some research in this area includes [53], [54], [55], [56]. While wind farms help reduce the average cost of energy due to economies of scale, aerodynamic interaction among turbines can decrease the total energy converted to electricity compared to the same number of isolated turbines operating under the same wind inflow conditions. Turbines on a wind farm are typically spaced farther apart in the direction parallel to the prevailing wind direction ("downwind spacing") than in the perpendicular direction ("crosswind spacing"), as shown in Fig. 17. Downwind spacing may be approximately 8-10 rotor diameters, and crosswind spacing may be approximately half that, although the exact distances chosen vary significantly with geography and other factors. Shorter crosswind spacing distances can reduce land costs and are most beneficial at locations where the wind is in the prevailing direction a large percentage of the time.

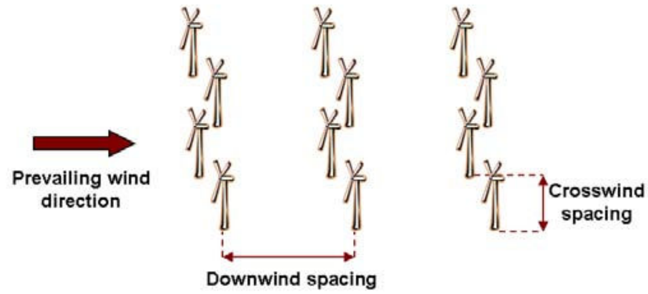

Fig. 17. Wind turbines in a farm arranged with larger distances between turbines in the prevailing wind direction ("downwind spacing") than in the perpendicular direction ("crosswind spacing"). Although the shorter crosswind spacing reduces land use by the wind farm, energy capture can be compromised when the wind comes from a direction other than the prevailing one.

The efficiency of a wind farm, called the array efficiency η_A, is given by

$$\eta_A = \frac{E_A}{E_T * N}, \tag{10}$$

where E_A is the annual energy of the array, E_T is the annual energy of one isolated turbine and N is the number of turbines in the wind farm. Array efficiencies of greater than 90% have been shown to be achievable when downwind spacings of 8-10 rotor diameters and crosswind spacings of 5 rotor diameters are used [57].

Since wind turbines can slow the wind for a distance of 5-20 km [58], it is nearly impossible to eliminate the aerodynamic interaction of turbines on a wind farm. Due to this aerodynamic interaction, coordinated control of all the turbines on a farm is important. It can be shown that the strategy of having each wind turbine in an array extract as much power as possible does not lead to maximal total overall power capture across the entire array, because the turbines on the upwind side of the farm extract too much power, slowing the wind too much before it reaches other turbines on the farm. The spatial variation of turbines on a wind farm often result in "power smoothing," wherein the standard deviation of the power produced by multiple turbines is less than the standard deviation of the power produced by each individual turbine [10]. This effect makes sense, as different wind gusts and lulls hit different turbines on the farm at different times. More discussion of the modeling of the aerodynamic interaction among turbines in

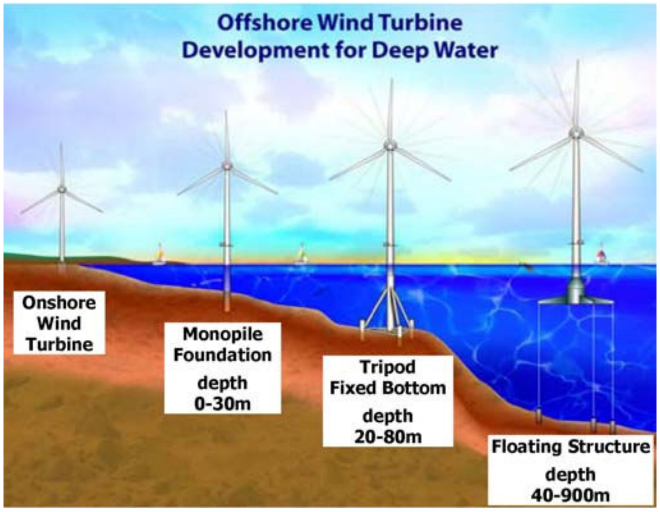

Fig. 18. The natural progression of wind turbine substructure designs for use onshore, in shallow water, and in deepwater. [Image courtesy of NREL.]

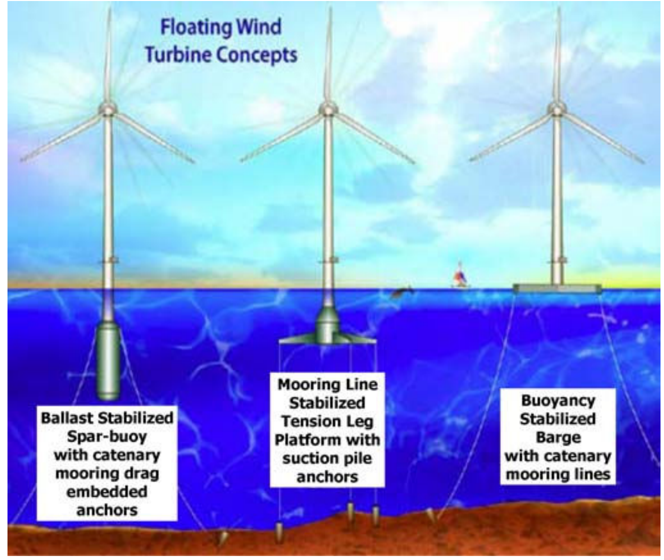

Fig. 19. Different floating platform configurations have been proposed for deepwater offshore wind turbines. [Image courtesy of NREL.]

an array, and the coordinated control of such turbine arrays, can be found in [33] and [59].

VIII. Offshore Wind Turbines

While wind resources are abundant over land, there is a vast offshore wind resource that can power much of the world with renewable energy through the use of offshore wind turbines [60], [61]. There are a number of advantages of installing wind energy offshore over land-based wind farm installations. First, wind tends to blow stronger and more consistently offshore, with less turbulence and smaller shear at sea than on land. Second, the sizes of offshore wind turbines are not limited by road or rail logistical constraints. Third, the visual and noise annoyances of wind turbines can be avoided if the turbines are installed a sufficient distance from shore. Furthermore, vast expanses of uninterrupted open sea are available and the installations will not occupy precious land.

Even non-floating offshore turbines present special control challenges, as the flexible tower is continually excited by ocean waves. Particular care must be taken to ensure that waves do not excite any significant tower bending modes, either through the initial turbine design or via advanced control techniques.

However, for many countries such as the U.S., most of the offshore wind resource potential is in deep water ($>$ 30m) [62]. This precludes using the same type of offshore wind turbine technology that exists commercially today: fixed-bottom shallow water ($<$ 20 m) installations where monopiles are driven into the seabed or where concrete gravity bases are used. These existing fixed-bottom technologies are economically infeasible in deeper waters. At some depth, floating support platforms are the most economical (see Fig. 18). Numerous floating platform configurations are possible, including a variety of configurations already used in the offshore oil and gas industries (see Fig. 19). Recent work includes evaluating a number of floating support platform configurations, deriving models of the fully coupled aeroelastic and hydrodynamics responses of offshore wind turbines, and developing comprehensive simulation tools [62], [63].

Much work remains to determine if any of these floating offshore concepts are technically or economically feasible when used as a support for offshore wind turbines. Fundamental issues of controllability and observability of offshore wind turbines need to be investigated. Are deepwater offshore wind turbines stabilizable and/or controllable using the typical control systems (pitch control, generator torque control, and yaw control) that already exist in land-based wind turbines? If not, what additional actuators/motors are needed to enable stabilizability and controllability? What sensors are required to observe the critical parameters to enable effective feedback control performance? These are fundamental questions that must be answered before deepwater offshore wind turbines can be successfully designed and deployed. Initial studies have explored the extent to which individual blade pitch control can simultaneously regulate both the rotor speed and the floating platform angle (the angle of the platform relative to horizontal) [64], [65].

IX. Conclusions

In this tutorial, we have examined the control of wind turbines and wind farms from a systems and control engineering point of view. A walk around the wind turbine control loops discusses the goals of each traditional loop and overviews the typical actuation and sensing available on commercial turbines. We have built upon an earlier tutorial paper [66] to provide an updated and broader perspective by covering not only the modeling and control of individual wind turbines, but also outlining a number of areas for further research, including MIMO control, combined feedforward/feedback control, coordinated control of arrays of wind turbines on wind farms, control of floating offshore wind turbines, and anticipating new sensing capabilities that can open up new paradigms for advanced control approaches.

In summary, wind energy is a fast growing industry, and this growth has led to a large demand for better modeling and control of wind turbines and wind farms. The uncertainties and difficulties in measuring the wind inflow to wind turbines and wind farms makes the control challenging, and more advanced modeling via system identification techniques and a number of advanced control approaches should be explored to reduce the cost of wind energy. By enabling this clean renewable energy source to provide and reliably meet the world's electricity needs, we will be helping to meet the tremendous challenge of solving the world's energy requirements in the future. The wind resource available worldwide is large, and much of the world's future electrical energy needs can be provided by wind energy alone if the technological barriers are overcome. The application of advanced controls for wind energy systems is still in its infancy, and there are many fundamental and applied issues that can be addressed by the systems and control community to significantly improve the efficiency, operation, and lifetimes of wind turbines.

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