Chapter 1

Wind Turbine Components

I Introduction

Wind Turbines can be classified in two categories based on rotor structure. Vertical axis wind turbines have a main shaft that stands perpendicular to the direction of the wind stream. Horizontal axis wind turbines have a main shaft that lies along the direction of the wind stream. The experiments and theories contained in this handbook generally pertain to horizontal axis wind turbines. Several wind turbine emulators are used in these experiments, including full-system, lab-scale wind turbines, electric generators, and various measurement systems. Experiments will use sensor-based measurements to illustrate theories regarding turbine operation and enhance understanding.

A wind turbines is a system of systems. Each has a particular function, and can be generally classified according to Table 1.1.

Table 1.1: Subsystems of a typical wind turbine generator

System	Function
Yaw	Track incoming wind direction
Pitch	Control blade position
Drivetrain	Shift torque and speed characteristic
Generator	Convert from mechanical to electrical energy
Power system interconnection	Interface generator with load or power grid
SCADA	Monitor performance, control set-points, human interface

Each system has dependency on the others. Therefore, it is necessary for the turbine to have a system-wide controller to communicate with and coordinate control of various turbine components. Based on information from various sensors, the main controller can set operating conditions, verify performance metrics, and communicate with external parties, including a park-wide supervisory control and data acquisition (SCADA) system. The remainder of this chapter is devoted to an overview of the subsystems.

II Yaw

To keep the wind turbine pointed into the wind, signals from a wind vane (or other wind direction measuring device) are monitored to check incoming wind direction. With this information, the controller can actuate yaw motors to turn the nacelle as necessary. However, many turbine designs are restricted in their yaw movement. Cables that carry power and/or control signals from down-tower to up-tower are generally bundled together, and allowed to twist a specified amount as the nacelle rotates. If those cables are twisted too much, they can be pulled off of their anchors resulting in extreme damage. A limit switch is useful to notify the controller when the twist limit has been reached. Even with this limitation in place, cables can still wear out due to repetitive movement. Yaw system components of a utility-scale wind turbine are pictured in Fig. 1.1.

Figure 1.1: Components around the yaw system of a MW-class turbine.

Another yaw system composed of one motor and one gear-set is shown in Fig. 1.2.

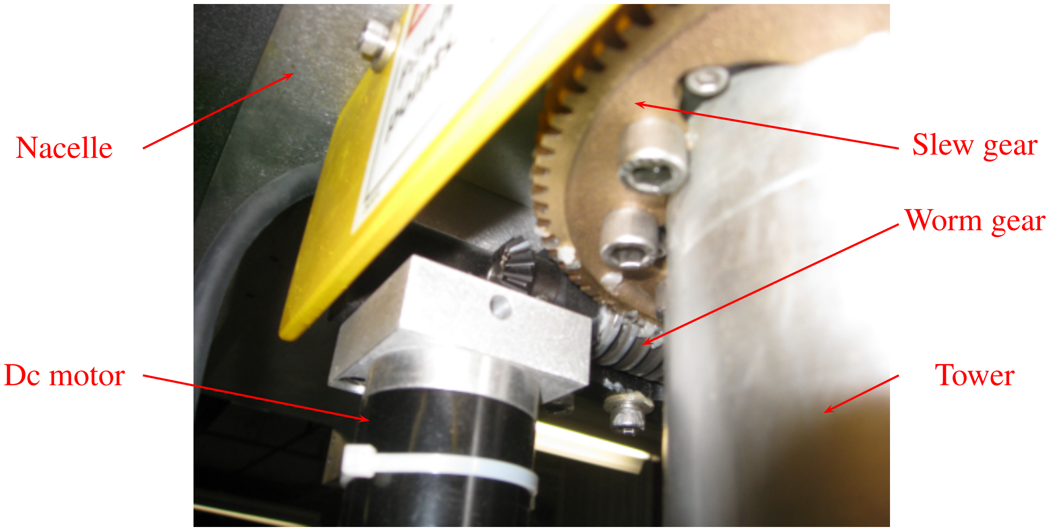

Figure 1.2: Yaw system drive of a kW-class turbine.

III Pitch

Wind turbine blades provide lift and drag forces, similar to an airplane. As air passes around the blades a torque is applied to the main shaft making it accelerate. If no energy were extracted from the system via the generator, and the entire system were lossless, the turbine shaft would accelerate indefinitely. In a real system, turbulence is created around the blades as they cut through the flowing airmass. As the rotor speed increases, the blades will begin to cut into the turbulent air created by the previous blade, causing it to "stall".

Interestingly, stall provides a means of mechanical speed limitation; blades can be designed to stall at specific speeds and rates. More complex turbine designs include individual pitch control, via electric motors or hydraulic cylinders. These systems rely on feedback of blade angle measurements; this can be from proximity sensors on the blade-connecting bolts or encoders on actuating devices. Some of the internal hub components of a hydraulic pitch system are pictured in Fig. 1.3.

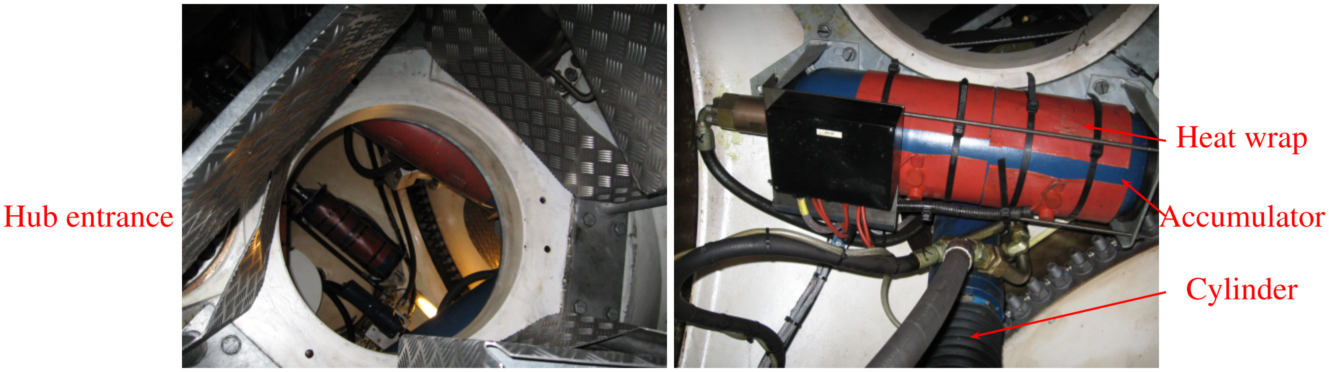

Figure 1.3: Pitch system components; a hydraulic system in a harsh environment.

Pitch angle directly impacts performance coefficient, a measure of turbine efficiency. Variable pitch angle allows maximization of energy capture and limitation at high-wind. Maximum energy extraction is obtained by operating the blades at a specific aerodynamic condition and the generator at a specific torque and speed condition; both are impacted by the tip-speed ratio. The tip-speed ratio is the steady-state speed at which the blades rotate for a given wind speed. It is defined as

$$\lambda = \frac{v_{\text{tip}}}{v_{\text{wind}}}. \tag{1.1}$$

The tip-speed ratio and corresponding performance coefficient sets the torque vs. speed curve for the wind turbine. By defining the desired tip-speed ratio, a specific toque vs. speed curve can be created; notably, one that maximizes performance. Experiments will be performed later in this handbook to measure performance coefficient across the desired wind speed range to find a desired tip-speed ratio.

The performance coefficient, C_p, is a measure of how much energy is extracted from the turbine compared to how much is available. This measure has a theoretical limit, the Betz limit; $C_{p,\,\text{max}} = 13/27$; derivation is provided in your class notes. Do not confuse this with the "capacity factor", which is a merit of the wind resource. Performance coefficient varies with pitch angle and operating speed; this will be observed in a later experiment. It is defined as

$$C_p(\lambda, \theta) = \frac{P_{\text{gen}}(\lambda, \theta)}{0.5 \rho A v_{\text{wind}}^3}, \tag{1.2}$$

where P_{gen} is the generator terminal power after consideration of all losses and which varies with pitch angle, θ, and tip-speed ratio, λ. A is the swept area and v_{wind} is the velocity of the incoming wind stream. A typical relationship of performance coefficient over a range of pitch angle and tip-speed ratio is plotted in Fig. 1.4.

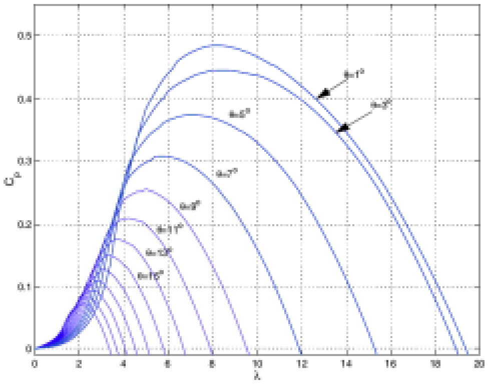

Figure 1.4: Variation of performance coefficient over tip-speed ratio and rotor speed.

To operate with maximum power extraction, the turbine should operate with the tip-speed ratio and blade angle that maximizes extraction. When operating at high-wind conditions so the blades are pitched back, the tip-speed ratio is adjusted to maintain maximum extraction with the new blade angle. From the plot of Fig. 1.4 it's easy to see that the performance coefficient for the turbine that resulted in that data has its performance maximized when $\lambda = 8$ with the blades pitched to $1°$.

IV Drivetrain

The drivetrain consists of all components attached to energy-transmitting shafts. This includes the main bearing and low-speed shaft, all gearbox shafts and bearings, and the generator shaft assembly which includes a flexible coupling to allow slight shaft misalignment.

The gearbox increases the speed of the shaft connected to the generator. The generators torque and speed characteristics will influence the choice of gear ratio, so that the desired operating wind speed range aligns with a desired generator operating speed range. For doubly-fed induction generators (DFIGs) the gearbox ratio is generally chosen so the DFIG experiences a specific slip-range. For squirrel-cage induction generators, the gear ratio is chosen so that wind speed range is beyond the synchronous speed, putting the squirrel-cage machine in the power generating slip region. For permanent magnet generators, the gear ratio can be chosen to increase the speed of the shaft, which has a direct influence on the operating voltage and efficiency of the generator. Alternatively, wind turbines with permanent magnet generators can be operated in a direct-drive configuration, in which the gearbox is omitted and the generator shaft is directly coupled to the hub, reducing the size and weight of the nacelle, increasing overall efficiency, and reduce the number of moving parts and potential for failure.

Shaft couplings usually include at least one joint which offers flexibility. Without a flexible shaft coupling, vibrations caused by misalignment are transferred through the rigid coupling and into the connected equipment. The result is increased stress on bearing races and rollers. Increased harmonic content is also noticed when operating without a flexible coupling. Imagine gears meshing, causing small impulses, which in turn lead to an impulse response. Unstable nodes can more easily be excited when damping (flex of the coupling) is removed. For these reasons, it is important to take care in ensuring shaft alignment, component integrity, and ample damping.

V Generator

Wind turbines are classified by the type of generator. Although there is a range of machines that can do the job, each offer different advantages and disadvantages. Some machines require precise control of the terminal voltages and currents, while others do not. Some are capable of operating over a wide range of conditions, while others are quite limited. In general, the use of power electronic converters is essential to maintaining efficient operation of the generator. The four types of wind turbine generators are as follows:

Type 1) Squirrel-cage induction machine (nearly fixed-speed).
Type 2) Wound-rotor induction machine with variable resistance (wider speed/torque range).
Type 3) Wound-rotor induction machine with power electronics (Doubly-fed, widest range).
Type 4) Full-converter interfaced machine (typically PMSG or other synchronous constructions).

An example of each type is pictured in Fig. 1.5. Note use of the term “machine”; each of these machines can be operated as either a motor or generator. The difference is whether power is applied to the shaft, or extracted from it; the gear-ratio is such that the desired torque/speed characteristic is reached, or in the case of controlled interfaces, the power converter is programmed to follow a desired torque/speed curve.

The generator supplied with the wind turbine simulator (WTS) illustrating this handbook is an external-field synchronous machine (basically a car alternator). It is a type 4 configuration with the power converter interface being made of a simple rectifier circuit; a boost converter circuit can be added to the output to control generator torque. This is a common machine, and is very popular among amateur wind turbine enthusiasts for its durability and ease of use. However, it is interesting to note that performance of the turbine is greatly affected by the way the generator is operated. The WTS generator is configured to run in an uncontrolled manner, with the stator terminals rectified to provide a dc voltage and current; this generator has a voltage range of 6 – 25 V, depending on the speed and field strength. Several experiments are included later in this handbook to illustrate performance dependence on control technique.

VI Power system interconnection

Wind turbines can be operated as part of an existing power distribution network or in a standalone island power system. Both require use of controllers, transformers, filters, relays, and other sensors and protective devices. A portion of a DFIG power system interface, including overcurrent and synchronization hardware, is pictured in Fig. 1.6.

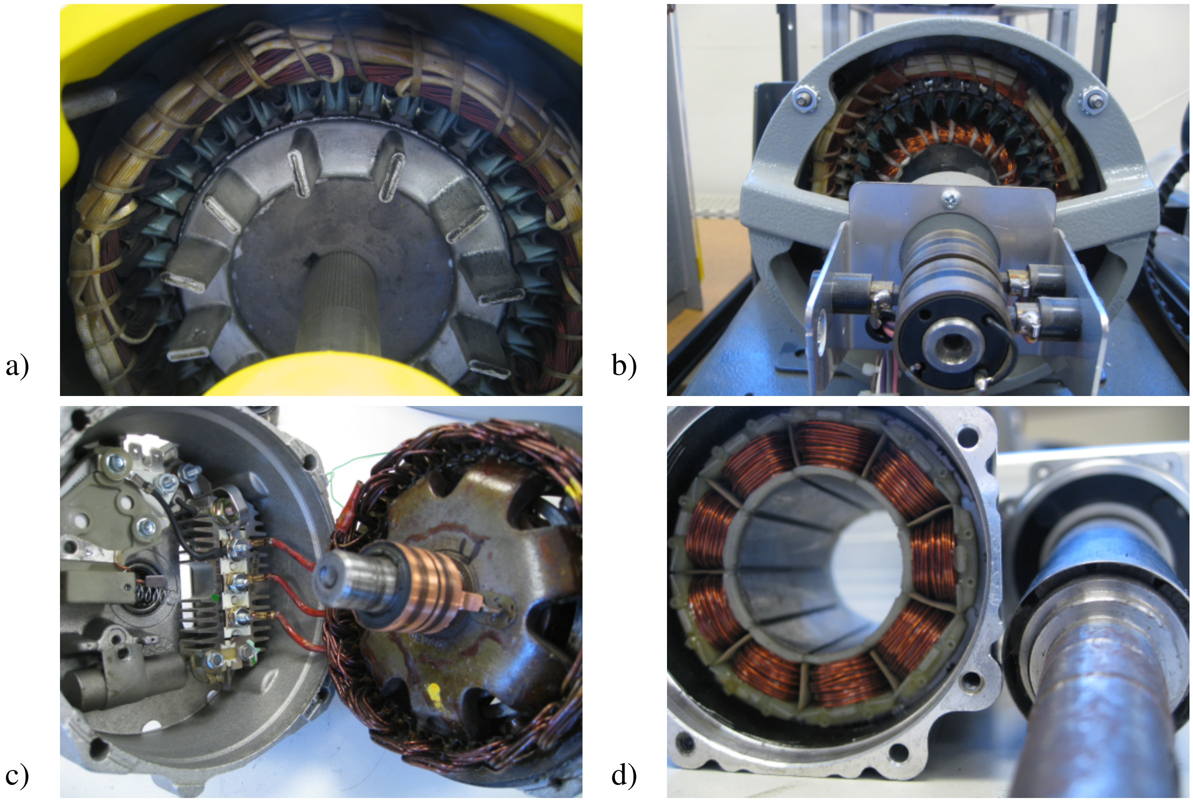

Figure 1.5: Types of machines used in wind turbines. (a) Type 1 squirrel-cage machine. (b) Type 2 and 3 wound-rotor induction machine. (c) Type 4 external-field synchronous machine. (d) Type 4 permanent magnet machine.

When used in an island mode, the wind turbine plays a large role in stability of the power system. Frequency and voltage can be regulated by the wind turbine or auxiliary systems. Such ancillary services provide reactive power for voltage support, and inertia emulation for frequency regulation. Experiments are performed later in this handbook using a doubly-fed induction generator to illustrate power system interconnection.

The wind turbine must also be capable of limiting its power output, and must have the capability of withstanding various fault conditions. For instance, when connecting a wind turbine to an existing power distribution network, it is required that the terminal voltage and frequency match that of the power system, and that harmonic currents are limited. Filters are useful for harmonic mitigation, and controllers provide automated synchronization.

VII Supervisory control and data acquisition

Supervisory control and data acquisition (SCADA) systems are an important item to consider. SCADA systems collect information from wind turbines, substations, loads, and system operators, and can control turbine set-points to maintain reliable operation. When power generation signals are provided by a system operator, such as Mid-Continental Independent Service Operator (MISO), the SCADA system receives those and adjusts set-points of individual turbines. It can also shut down turbines in case of excess energy production and emergency operations.

SCADA systems also provide the operator with visual information regarding turbine status

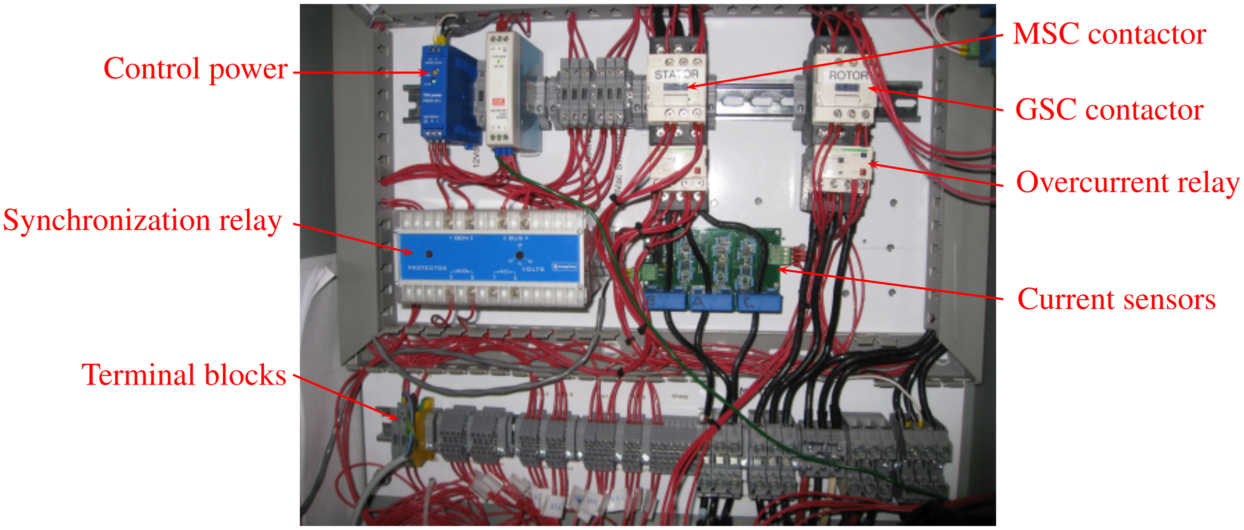

Figure 1.6: Circuit breakers and other interconnection hardware for a kw-class DFIG; power converters and filters not shown.

and component health. Interfaces are usually provided to visualize system details and provide remote control the wind turbine. An example SCADA screen is shown in Fig. 1.7.

Rotor Speed 29.6 RPM
1 min. Wind Speed 3.0 m/s
10 min. Wind Speed 3.4 m/s
Total Energy Produced 318149 kWh
Time Available 31592 Hr
Yaw Position 222.1 deg
Yaw Turns 1.6

Wind Turbine Controls
Enabled
Dispatch Enabled
Base Switch Run
Nacelle Switch Run
Yaw OK

Wind Turbine Status
Turbine State Running
Inverter State Active
Warnings No Warnings
Faults No Faults

Operating Conditions
Wind Speed Low
Temperature OK
External Conditions OK
Grid OK

Ambient Temp 24.8 °C

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Figure 1.7: SCADA interface of the 100 kW wind turbine on the Iowa State University campus. Interact online at https://smartview.northernpower.com/fleet.php; “studentview@iastate.edu, isuwind”.

Experiment 1.1: Component identification and operation

For this exercise, open the machine and dissect the subsystems. identify and discuss components on the Wind Turbine Simulator (WTS) and observe system interaction using measurements from various sensors.

Goals: Inspect wind turbine components and observe system interactions. Understand major components of the pitch, gearbox, and generator systems. Operate the turbine at a variety of torque and speed conditions, observing time and frequency-spectrum data.

Procedure:

1. Setup the wind turbine simulator (WTS) in a location conducive to operating the machine; beware of the hub while rotating. Setup the control and data acquisition system to measure the main shaft torque and speed, main bearing radial acceleration, and synchronous generator stator voltage. Ensure a variable electric load is connected, and that a generator rotor magnetic field dc supply is available as well.
2. Remove the hub cover and inspect the pitch system. Identify pitch actuators and sensor feedback mechanisms.
3. Remove the gearbox covers; remove the lid from the parallel-stage case, as well as the front face of the planetary set. Identify bearings and sprockets and forces they may experience while operating.
4. Compare the different types of synchronous and asynchronous generators using the open-face models available, and discuss concepts of electromechanical energy conversion.
5. Assemble the turbine and run the machine. Observe measured variables using the oscilloscope and network analyzer.

Deliverables:

1. Choose a wind turbine subsystem that interests you, and sketch a diagram of it. Be sure to include sensors, actuators, controllers, and other physical structures. You do not need to provide advanced operating details, but please do provide a description of how the subsystem operates, where it fits in the overall turbine design and its purpose for being. Your subsystem does not need to be based on any particular design; imagine the subsystem as you see it on the type of turbine you imagine it, large or small.
2. What benefits does the subsystem provide to meeting turbine objectives? What problems do you think the subsystem could experience during prolonged operation and transient events? What other wind turbine subsystems and components do you expect are vulnerable to failure, and why?
3. Describe how variables observed on lab instruments are related to eachother and the operating condition of the machine. What do you find interesting about your observations?

Experiment 1.2: Wind turbine operation

Goals: Control the towered wind turbine simulator by manual manipulation of the system, including actively pitching, yawing, and changing the electrical load. Understand interaction of wind turbine subsystems and complexity of control system operation.

Procedure:

1. Move the wind turbine simulator into a natural wind stream. Keep the blades pitched to 90 to prevent the machine from accelerating out of control
2. Yaw the turbine into the wind and pitch the blades to zero degrees. As the rotor accelerates, adjust the generator field and electrical load to make the machine operate at a steady-state condition.
3. Pitch the blades to 10 and see how your control action changes. Try to keep the speed between 200 and 400 rpm.

Deliverables:

1. Create a desired power vs speed curve for this turbine, assuming an ideal performance coefficient; be sure to measure the radius of swept area.
2. Are you able to achieve a steady-state condition? What difficulties do you encounter in controlling the turbine?
3. What do you find most difficult about controlling a wind turbine, and what do you find most interesting about controlling a wind turbine.