2009 American Control Conference
Hyatt Regency Riverfront, St. Louis, MO, USA
June 10-12, 2009

Wind Turbine Modeling Overview for Control Engineers

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Abstract—**Accurate modeling of wind turbine systems is of paramount importance for controls engineers seeking to reduce loads and optimize energy capture of operating turbines in the field. When designing control systems, engineers often employ a series of models developed in the different disciplines of wind energy. The limitations and coupling of each of these models is explained to highlight how these models might influence control system design.**

I. Introduction

WIND energy is currently the fastest growing source of energy in the world with a 45% increase in installed capacity in the United States last year alone. As the technology matures with increasing capacity, wind turbines are becoming more reliant on advanced control systems to both maximize the energy captured from the wind and also minimize the loads of these machines. The development and use of control systems to improve performance requires accurate models of the wind turbine environment and also turbine response to environmental forcing during operation.

Wind turbines are highly flexible machines operating in stochastic environments and modeling these systems requires knowledge from across a range of typical engineering and atmospheric science disciplines. Each of these disciplines typically has their own suite of design tools that analyze only a subset of the wind turbine and its surrounding environment. To model the combined physical behavior of the turbine, these tools must be combined using an overall system wide approach.

The set of models discussed in this paper are used in what the wind turbine industry terms "design codes." Designers routinely use these codes to perform thousands of calculations to determine the loads and power for a given turbine design. Thus, these codes are not necessarily the most accurate, but are balanced in terms of speed and accuracy. Often this entails a degree of empiricism to maintain this balance that limits the models applicability in certain situations. More accurate models that resolve more of the physical processes, such as computational fluid dynamics or finite element analysis, are available to the designer, but are too slow to be useful in the systems design process in which controls engineers often operate. As computational speeds increase, greater complexity models will be added to design codes, but this paper is intended to be a snapshot of the current state of the art.

The interface between different models also affects the overall accuracy of the design code. For the purposes of control system development, the models from different wind energy disciplines are often combined through a loose coupling. This means that the different models influence each other, but the coupling between them is not always fully non-linear and feedback effects are often neglected. For example, motions of the turbine itself are assumed to be small perturbations about a mean value and do not affect the aerodynamic behavior. This assumption works well, for smaller stiffer turbines, but may not reflect the behavior of modern flexible machines. The coupling between models will continue to mature as time progresses, but currently these models can be thought of independent systems as described in the sections below.

Those designing control systems should realize the limitations of these models and also their coupling, so as not to produce over-aggressive controllers that may function improperly or even become unstable in an operational system. In this paper, we will first discuss the different areas of modeling and many of the assumptions and simplifications made within these models. We will then focus attention on the events that drive wind turbine design and have some discussion as to how control systems can best improve energy capture and reduce operating loads.

II. Modeling Areas

A schematic of the different areas of turbine modeling and how they interact is shown in Figure 1. This schematic represents the typical flow of information within most wind turbine design codes for predicting power output, design loads and also control system behavior. This paper will focus mainly on NREL developed models [1]-[3], however many of the models and limitations presented here are similar, if not identical, to those in other existing codes used within the industry (e.g. Bladed [4], HawC2 [5], and FLEX5 [6]).

Generally, wind turbine modeling can be broken into six distinct, but coupled areas: turbulent inflow, aerodynamics, hydrodynamics (for offshore turbines only), foundation dynamics, structural dynamics and controls systems. Within these areas are models with their own unique set of physical equations that distinguish the areas from one another. These areas are explained in more detail below.

Manuscript received March 20, 2009. This work was supported by Contract No. DE-AC36-99-GO10337 between Midwest Research Institute, Battelle and the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy.

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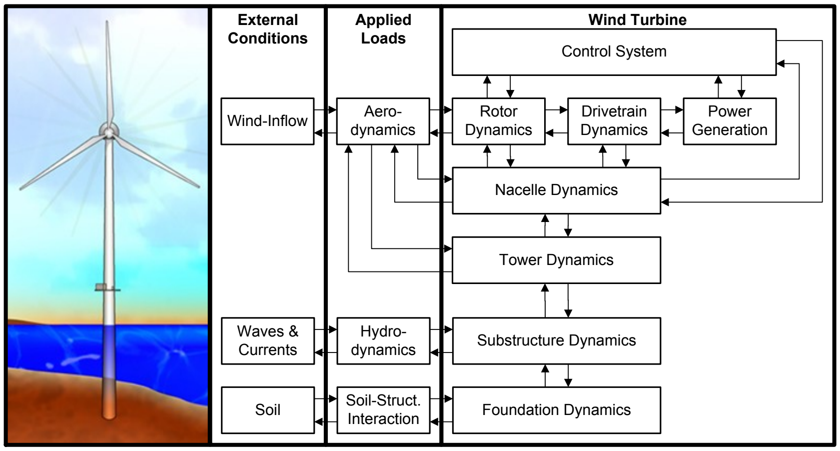

Fig. 1. Modeling hierarchy for current NREL design codes FAST and ADAMS®

A. Turbulent Inflow

The wind by nature is a highly stochastic process involving many different length and time scales, from mesoscale type processes that affect the climate to microscale processes that influence local blade aerodynamics. Scales that are on the order of the turbine size or less are usually of greatest interest to the wind turbine control engineer as these determine the power and loads. Although, larger scale phenomena, such as storm fronts, may impact the design, particularly if they produce extreme loads.

International design standards, such as the widely accepted International Electrotechnical Commission (IEC) 61400-1 [7], have sought to quantify the wind inflow in terms of both extreme events and also smaller scale stochastic variability. Traditionally these two sets of wind conditions are separated by the characteristic time scale over which these events occur. Stochastic events are considered to be those that are related to small scale turbulence and are dominant for periods under 10-minutes. The industry standard for stochastic simulation is to perform many 10-minute simulations at different mean wind speeds and turbulence intensities, dependent on the local environment. Extreme events also can happen over very short periods of time (e.g. a 10-second gust), but the probability of occurrence for these events is considered small, for example, once in 50 years. Often these discrete events are simulated only once for a given design.

When classifying a wind turbine site, the IEC standard specifies 9 possible wind class regimes for turbine design that dictate both the stochastic and extreme wind environment. These classes are based on measured annual mean wind speeds and turbulence intensities, which have been calibrated to various sites in Europe and North America. Within the IEC classes, the detailed factors that affect the behavior of local winds are not directly reflected and thus this class system is limited. These factors include: the terrain, vegetation and also the presence of the turbine within a large wind farm. Given that winds can be site specific, designers may choose more appropriate wind variables at certain sites. For example, larger than required turbulence intensities are often observed in Japan, where complex terrain is prevalent.

In addition to mean wind speed and turbulence levels, another important variable for loads production is wind shear, where the wind speed at the bottom of the rotor swept area is less than at the top. This difference in wind speed increases with rotor size. Modelers typically use a simple power law distribution to model the shear with an exponent of 0.2. However, measurements have shown that this exponent can vary significantly over the period of a day [8] and can have exponent values much greater than the standard 0.2, particularly in the American Mid-West.

Until recently, the atmosphere and local wind environment were assumed to be decoupled from the influence of the turbine or its neighbors. In reality, turbines operating within large wind farms tend to experience lower wind speeds and higher turbulence levels created by the presence of the farm. This makes them behave much differently than standalone turbines. This effect will become more prominent as turbines and farms extract a larger percentage of the energy from the local atmosphere, changing the actual inflow. Newly developed control strategies to optimize wind farm performance do account for some of these turbine interactions, but they may need to be modified as a greater understanding of the physical processes involved in these interactions arises.

B. Aerodynamics

Modeling aerodynamics is critical for predicting how the varying winds are transformed into power and loads that affect wind turbine performance. Unfortunately, aerodynamic models tend to have the greatest uncertainty of all the modeling regimes, given the potential for non-linear behavior [9]. An example of this uncertainty is shown in Figure 2, which is a comparison of design code predictions to measurements of a wind turbine operating in a wind tunnel (the darkest line). The major difference between each of these codes is how the aerodynamics are modeled. Notice

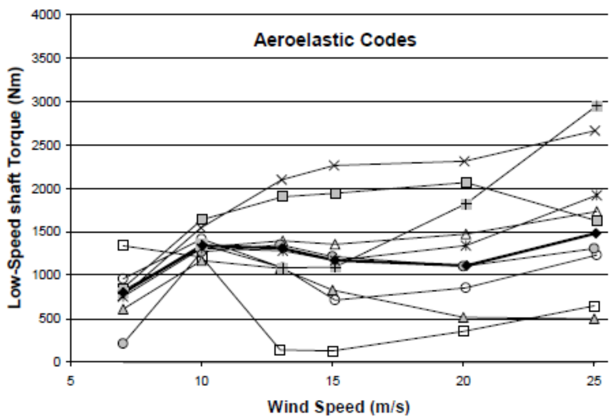

Fig. 2. Effect of aerodynamic modeling variation on low speed shaft torque calculation [9].

that at low wind speeds, the majority of aerodynamic models are within 10% of each other, but at higher wind speeds the differences are large, with a 50-100% difference between the prediction and measurement being common. At higher wind speeds, more complicated aerodynamic behavior arises that can be unsteady and three-dimensional, which is difficult to model. Similar phenomena can be also seen in highly unsteady winds. Unfortunately, the regimes where these aerodynamic models are least reliable are also where the behavior of the control systems is crucial for controlling power fluctuations.

As in the other modeling areas, aerodynamic models have a range of complexity and accuracy. More complicated aerodynamics models are based on computational fluid dynamics that are more accurate than simpler models, but have a large disadvantage in that they are computationally expensive. Design codes that include control system response often employ more basic aerodynamic models; most commonly blade element momentum (BEM) theory [3], which was developed in the mid 20th century, but is still useful today for general aerodynamic response predictions over a range of operating regimes.

Models such as BEM break the problem of aerodynamics into the behavior of the turbine wake and the behavior of the wind turbine blades. The wind turbine blades are modeled as discrete airfoil sections whose properties are derived from wind tunnel tests. Often the data from these wind tunnel tests are tuned with field validation data of operating turbines to improve predictive accuracy. Thus, the tuned models work well when a design is changed incrementally from a previous version, but drastically different design changes require more detailed and complex analysis. One of the most significant limitations is these models assume that there is no flow between sections, essentially making them two dimensional. This means that they are not valid once the flow on the blade becomes three dimensional, as is the case at high wind speeds in Figure 2.

In BEM, the wakes are modeled as a uniform set of vortices that are convected downstream with the mean wind speed. A limitation of the wake portion of BEM theory is that it assumes an instantaneous balancing of forces between the wake and the blade, which is somewhat unrealistic given there is a time lag between the wake vortices and blade forces. Some design codes have incorporated this time lag into their aerodynamic models, as this physical phenomenon greatly affects the time response of aerodynamic loading in turbulent winds.

In the case of rotor yaw (an angle between the incoming wind and rotor normal vector), the aerodynamics across a rotor can be greatly changed and also become time and blade azimuth angle dependent. Simple corrections are used in BEM to estimate this non-linear wake behavior, which work well for small yaw angles (<10°) but are not valid for larger yaw angles.

One of the more important effects seen in yaw and also highly turbulent winds is dynamic stall, which is an unsteady amplification of aerodynamic forces that varies with rotor azimuth. Dynamic stall can lead to significantly larger loads then steady models predict and are very difficult to model. Most models of dynamic stall originate in the helicopter industry, which is less concerned about the turbulent fluctuations of the incoming wind than the wind turbine industry. The applicability and best use of these models to wind turbine design remains an active area of study.

One final limitation of the aerodynamic models is that the aerodynamic forces are usually calculated independently of the turbine motion, which will lead to large errors with highly flexible machines.

C. *Hydrodynamics*

Predicting hydrodynamics loads for offshore structures will be important for future offshore wind farms and is currently an active topic of research [10]. The hydrodynamics depend largely on the foundation system chosen for the offshore turbine and also the depth of the water in which the turbines are placed. To date, most control systems offshore are extensions of their onshore cousins because the foundations are based on monopile type construction in shallow water (see Fig. 1). These foundations are nearly identical to onshore turbines, with the exception that they are designed to absorb additional loading from waves and currents. As turbines move into deeper water with more flexible or even possible floating designs, the control system strategies may be rethought.

There are no defined limits, but following trends in the offshore oil and gas industry, monopile structures are thought to be sufficient to water depths of about 30m, truss (or jacket) structures for 30-60m depths and floating structures for depths greater than 60m. European waters happen to be fairly shallow; hence the monopile has seen widespread use. As offshore turbines are erected in the US, with its deeper waters, more complicated substructures will need to be employed.

Fixed bottom structures such as monopiles and trusses are hydrodynamically less complex than floating structures. Because the turbine motions are small, the incoming wave

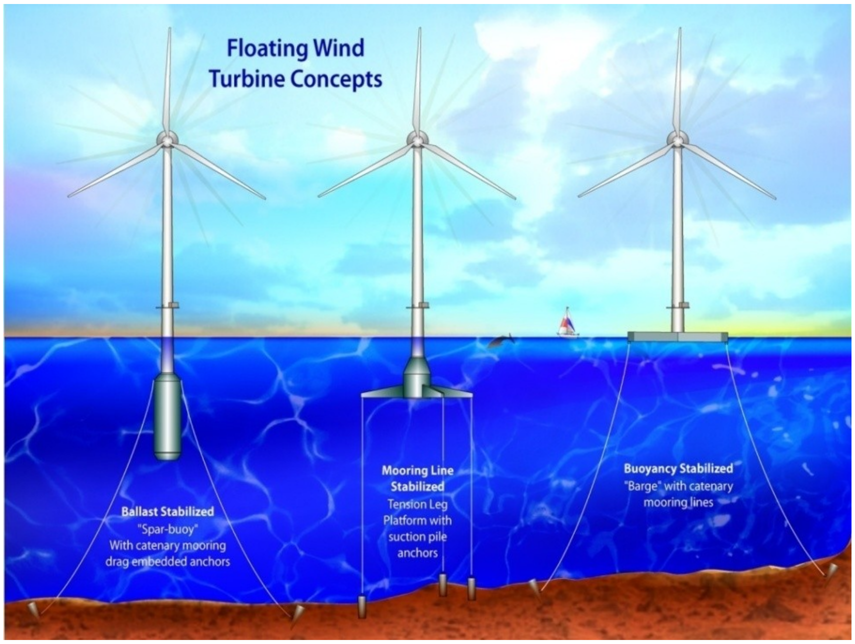

Fig. 3. Floating wind turbine stabilization concepts

spectra are not greatly affected by the structural motions and can be considered uncoupled. However, because these structures are located in more shallow waters, the forcing of nonlinear breaking waves should be considered. The current generation of wave models is linear, and breaking waves cannot be modeled stochastically. They are instead treated as extreme events, where the largest wave over a given return period is simulated as a single event. Often a large breaking wave can be a critical design load case for structures in shallow water.

In deeper waters the waves are considered linear and thus more easily modeled. But, because turbines operating in this environment are floating, the substructure and/or platform motions affect the incoming wave dynamics. This impact is modeled nonlinearly through Morrison's equation [10], which calculates buoyancy, wave scattering, the radiation (damping) terms due to platform motion and added mass effects that also introduce a damping term. These simplified equations often used in design codes assume small motion so second order dynamics are neglected. Also, any large accelerations of the foundation violate the linear wave dynamics in most models.

D. *Foundation Dynamics*

Foundation dynamics are also different depending on the turbine location. Onshore and in shallow water, the support structure is often considered rigid, such that there is little coupling between the turbine and support structure motions. In reality, the interaction of the foundation with the soil influences the overall dynamic behavior of the system, but this effect is usually considered small. It is often sufficient to model the soil interface as a rigid surface, but in softer soil areas, the non-linear soil dynamics should be included. A better soil model would require more sophisticated tools than the current generation of engineering models. The effects of earthquake loads, in contrast, can be easily modeled in most engineering design codes as excitations of the foundation.

For floating turbines offshore, the support structures are considered compliant and have large motions. Thus, the dynamic responses of the turbine and support structure are strongly coupled. The floating structure dynamics are largely driven by how the structures are stabilized: by ballast, by mooring lines, or by buoyancy (see Fig. 3). The foundation dynamics of a ballast stabilized system will depend largely on the mass and buoyancy of the design and to a lesser extent the mooring lines. The mooring line stabilized system will depend on the tension of the moorings and the buoyancy of the underwater tank. This system is the stiffest of the configurations and will have the smallest amount of platform motion. The buoyancy stabilized system dynamics are influenced by the platform configuration relative to the wave forcing and also the mooring line tension. The current generation of design tools have models [10] applicable to these different configurations, which predict the foundation motion from hydrodynamic forcing. Although, researchers have not yet validated these models due to a lack of experimental data.

E. *Structural Dynamics*

Structural dynamics involve the forcing and motion of the rotating and non-rotating parts of the wind turbine. These models tend to be the most accurate among the different modeling categories. However, as turbines have become larger and design margins have decreased, structural components have become more flexible and more difficult to model.

The most important structural components of the turbine are the blades, drivetrain and tower, but can also include the nacelle, pitch system, yaw drive, and hub. For the more flexible elements of the system, such as the blades and tower, engineering codes typically use a modal representation of the deformed shape of the structure. These shapes are derived from modal (eigenvalue) analysis of the structural properties of the blades and tower. Often blades and towers are modeled using the first couple mode shapes in perpendicular directions, e.g. motion perpendicular and parallel to the rotor plane. Some codes also include coupling of modes in both directions which is currently an active area of research.

Other codes, such as ADAMS use a multibody dynamics representation of the blade and tower. This allows for virtually unlimited degrees of freedom and easier coupling between them, but also slows the calculation time considerably. Some more advanced structural models use finite element analysis to model structural response. However, as with advanced aerodynamics models, these models tend to computationally expensive and are therefore difficult to use for control systems design.

One load control method where modeling of coupled mode shapes is vital is flap-twist coupling of blades. By optimizing the structural fiber layout of the blade, the blade twists as it bends under loading, thereby reducing the load aerodynamically. Active control systems exploiting this passive control mechanism have yet to be developed, but may be in the near future.

The stiffer elements of the structural system are usually modeled very simply. Often, the drivetrain is modeled as a single torsional mode to represent the overall dynamic behavior. Systems such as the yaw drive, pitch system, hub and nacelle are typically modeled as fully rigid. But, again as turbine systems get larger and more flexible, code designers may need to include more dynamic aspects of these systems.

An important subset of the structural dynamics modeling area is stability analysis [11]. Stability analysis seeks to indicate the dangerous operational envelopes of turbines that can be avoided using different control system designs. For example, often turbines will have at least one rotational speed within their operating range that will excite various fundamental structural modes. The traditional control strategy to avoid too much excitation is to accelerate as quickly as possible through this regime. So, it is very important to analyze the various stability regimes in this respect. This analysis is done through a process of linearization, where the dominant equations are linearized about system operating points. Using these equations, state matrices are calculated that dictate the full system modes of either an operating or stationary turbine. A Campbell diagram can then be constructed which shows the unstable operating areas for the turbine to be avoided or around which controls systems must be designed.

F. Control Systems

All engineering design codes have control system capabilities as the control system is now an integral part of the turbine design. The control schemes are most often implemented in the codes through subroutines, dynamic link libraries, or even integrated with MATLAB Simulink® [2].

Some design codes may also have routines that perform linearization about operating points to enable more efficient control design methods. Using these routines, a plant model of the wind turbine can be developed from linearized, but period state matrices. The linearization process consists of two steps: (1) computing a periodic steady state operating point condition for the DOFs and (2) numerically linearizing the models about this operating point to form periodic state matrices. The calculated state matrices can then be azimuth-averaged for time invariant controls development or periodic to determine operating point values that depend on the rotor azimuth.

Yaw, torque and pitch control are the mode most often used in industry, but some turbine use other methods such as high speed shaft brakes or tip brakes. Pitch control is usually done with identical motion among blades, but individual blade pitch may see significant use in the future, particularly to alleviate wind shear fluctuations. Eventually, more active aerodynamic control devices may also be placed on blades, which will require additional design code and control system development. More details on different control schemes can be found in [12].

III. Energy Capture

The main purpose of a wind turbine is to capture as much energy as possible for a given site. The amount of wind energy converted to electrical output is largely influenced by the aerodynamic efficiency of the blade design, but can also be greatly influenced by other factors such as gearbox, electrical conversion efficiencies and of course the control system. Many different types of control systems exist, but the one that is most relevant to energy capture is how rotor speed is scheduled. Among the different options, variable speed control has become an industry standard largely because it optimizes energy capture over a large range of wind speeds.

Most control systems are independent of turbine location and also fixed with time. In the future, more site specific design and variable control schemes may be employed to adapt to local conditions. Energy capture is dependent on the wind characteristics, e.g. more turbulent sites will produce less energy on average than another site with an identical annual average mean wind speed, but lower turbulence. Turbine output is also not constant largely because aerodynamic performance degrades with time. Control paradigms such as adaptive control [13] have been specifically developed to adjust to changing aerodynamic efficiency at the design point, thereby augmenting energy capture without increasing loads and may see widespread use in the future.

IV. Design Loads

Accurately predicting the design loads help wind energy engineers determine the operating lifetime of a machine. In the design process, engineers often rely on international design standards, such as the IEC 61400-1 [7], to determine the types of loads a turbine will encounter over a 20 year lifetime at a given site. These loads can be broken into two categories: fatigue and extreme loads. The mission of a control strategy is to reduce these loads as much as possible without decreasing energy capture or increasing loads in other components. Often this is done through active blade pitch or generator torque control.

Extreme loads and fatigue loads are not mutually exclusive; extreme loads cause a considerable amount of fatigue damage and fatigue loads can be extreme, so the break is somewhat artificial. As with the wind environment, fatigue and extreme loads are separated by probability of occurrence. Extreme loads are those that happen rarely, such as once per year or 50 years, whereas fatigue loads are thought to be smaller fluctuations that are routinely occurring when the turbine is operating.

While failures from extreme loads (such as typhoons) tend to get more attention because of their dramatic nature, fatigue loading is the more prevalent mechanism of failure in the current wind turbine fleet. This is particularly true of the gearbox failure issue that is industry wide [14], where gearboxes are routinely failing within five years of installation and short of their 20 year lifetime. Given the widespread and consistent failure rates, the loads creating these failures would be classified as fatigue dominant. Blades are also seeing a lot of failures in the field, but since they are not industry wide, manufacturing defects are thought to be the driving root cause.

A. Fatigue

Fatigue loads are the constantly varying stresses and strains that the different components experience over long periods of time. These loads are produced both by gravity; where the constant movement of the blades causes the structure to bend at consistent time intervals, and also loads from the turbulent wind input, which are more stochastic in nature. The relative contribution of gravity versus wind is dependent on the size of the turbine, where the larger turbines with heavier blades (larger than 5 MW in size) will tend to have larger fatigue loads dominated by gravity effects, while smaller turbines will be dominated by the wind input. Another common periodic fatigue load is that created by wind shear and also the tower influence, where blade loads (and hence all other structural loads) will change with azimuth angle. These periodic loads occur once per revolution for each blade and 3 times per revolution for other components on a 3-bladed turbine.

Controlling these loads is often accomplished by blade pitch control to shed loads at high wind speed and generator torque control to prevent rotor overspeed during gust events.

B. Extreme Loads

Extreme loads by definition tend to be single events caused by rare changes in the turbulent inflow or from an operational failure of the turbine itself. Controlling loads from extreme events often entails shutting down the machine completely and/or waiting for the extreme condition to pass.

Extreme loads arising from wind input are of course caused by extreme events in the wind environment. One common design driving event described in IEC standard is the extreme gust with direction change, where a 15 m/s gust over 10 seconds coincides with a 30° change in wind direction. Many engineers have found this type of extreme event to produce the highest loads in simulation and similar events have damaged turbines operating in the field.

Extreme loading events can also occur from a failure of the electrical grid or a turbine subsystem, like the pitch drive, or even a programming error in the controls system itself. To stop these types of loads from occurring, turbines will often have a watchdog control system to ensure that the turbine maintains a safe operating condition and will shut down the turbine completely before a catastrophic failure can occur.

V. CONCLUSION

Models of wind turbine behavior will continue to evolve in sophistication as better understanding of the physical mechanisms behind wind turbine operation surface. With better models of wind turbine behavior, controls engineers should be able to design control systems that better reduce loads, increasing the operating lifetime, and also augment power production, both of which will serve to lower the cost of wind energy making it more cost effective.

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