Control of Large Wind Turbines:
Review and Suggested Approach to Multivariable Design

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Abstract— **Large wind turbines of today are endowed with sophisticated control systems. This paper presents a review of the state-of-the-art of control technology used in for variable-speed, pitch-controlled horizontal axis wind turbines. A study of the state-of-the art indicates that in most prior efforts, the multivariable nature of large wind turbine behaviour has not adequately addressed. This paper proposes an approach to multivariable design of controllers which explicitly addresses specifics of large wind turbine design concerns. Problems of immediate interest to the industry are discussed.**

I. INTRODUCTION

Wind power is the fastest growing electric power industry in the world [1]. Current global installed capacity exceeds 32000 MW with a projected growth rate of 10000 MW/year for the next five years. The phenomenal growth of this industry can be attributed, primarily, to the rapid progress made in wind turbine technology. Over the last couple of decades, technological progress has led to the development of turbines with high power capture efficiency. Today, many wind farms produce electrical power at a Cost-of-Energy ($\approx$ 4-6 c/kWHr) comparable to that of coal and natural gas based power plants.

For economic reasons, much of the work on wind turbine development has focused on large wind turbines. Typical large wind turbines of today are massive structures (Fig. 1) with enormous blade spans (70-100m in diameter), tall towers (60-100m in height) with power ratings in the 1-5 MW range. Amongst the technologies that enable realization of these machines, advanced control plays a pivotal role. Modern large wind turbines are endowed with sophisticated control systems which are organized to support several modes of operation such as start-up. shut-down, power production etc.

The focus of this paper is the design of control routines for the power production mode of operation. The control objectives for this mode differ vastly depending on the wind conditions. During low wind speed operation, the goal is to maximize energy capture. However, in conditions where wind speeds are greater than the turbine's "rated" wind speed (usually around 10-12 m/s) the primary objective is to minimize fatigue loading of the turbine structure.

In this paper, we present an overview of the current state-of-the-art of control technology for large horizontal-axis wind turbines. We motivate the need for the development of multivariable control strategies and suggest an approach for the same. The paper is organized as follows. Section II discusses preliminaries. This is followed, in Section III by a review of the state-of-the-art of wind turbine control-oriented modeling and design. Finally, in Section IV we present an approach to multivariable design of control routines and mention problems of immediate significance to the wind turbine industry.

Fig. 1. Horizontal-Axis Large Wind Turbine (Courtesy: GE Energy)

II. PRELIMINARIES

In this section we focus on the background required for the reader to appreciate the discussions in the sections to follow.

A. Turbine Architecture

In this paper we deal with horizontal-axis (axis of rotation of rotor is horizontal), three-bladed, upwind (rotor points into wind), large wind turbines - the predominant architecture of today's commercial wind turbines. These turbines, almost always, support variable-speed operation. In other words, the rotor and generator speed is not rigidly coupled to that of the grid frequency as in the case of fixed-speed turbines. Many of these turbines also support independent blade pitch action - each of the blades of the turbine can

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be pitched about its longitudinal axes. Our attention will be directed at variable-speed, pitch regulated machines.

B. Power Capture in Horizontal-axis Wind Turbines

A wind turbine extracts energy by converting a part of the kinetic energy of the wind into mechanical work. The ratio of the power extracted from wind to the energy flowing through the area swept by the rotor in unit time is termed as the Coefficient-of-Power. The Coefficient-of-Power, C_p, may be expresed as:

$$C_p \quad = \quad \frac{P}{\left(\frac{1}{2}\rho A v^3\right)}$$

where, P, ρ, A and v are respectively the mechanical power captured, density of air, rotor area and free-stream wind velocity. Early last century, under assumptions of steady, homogenous, incompressible, inviscid flow conditions, Betz (see [2]) showed that the maximum achievable C_p in horizontal-axis wind turbines is $\frac{16}{27}$ (≈ 0.59). In practice, wind turbines have achieved power capture efficiencies of around 0.4.

It can be shown that C_p is a function of the tip speed ratio (λ)- the ratio of linear velocity of blade tip to that of wind velocity[2]. The variation of C_p with λ for a typical three-bladed, horizontal-axis wind turbine is shown in Fig. 2. It can be seen that for a fixed pitch angle, the maximum value of C_p occurs at a particular value, λ_{opt}, of the tip speed ratio. To maximize energy capture it is desirable that the turbine operates close to the condition corresponding to λ_{opt}.

Fig. 3 shows a typical "Design Power Curve" of horizontal-axis large wind turbines. The smallest wind speed at which useful power capture becomes possible is termed as the cut-in wind speed, V_{cut-in}. As expected, with an increase in wind speed, power captured by the turbine increases along with the mechanical loads on the turbine structure. At a pre-chosen wind speed, called as "rated" wind speed, V_{rated}, the power extracted reaches rated power of the wind turbine. Above rated wind speed, power captured by the turbine is kept limited to the rated power so that the loads on the turbine structure are kept within design limits. Due to safety considerations, the turbine is shut-down for wind speeds in excess of the cut-out wind speed, $V_{cut-out}$.

C. Wind Model

The wind field over the entire rotor area is seldom uniform. It varies both in space (across the rotor area) and in time. For the purpose of loads analysis, it is useful to consider the wind field to be composed of three components (Fig. 4).

1) A slowly varying component with a ”mean” wind speed : This component is often referred to as the nominal wind speed in the specification of turbine performance characterisitcs.

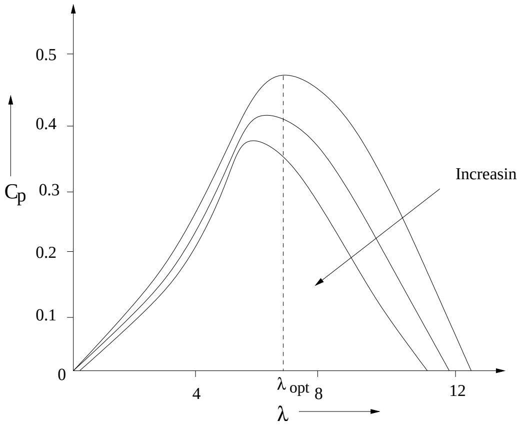

Fig. 2. Variation of the coefficient of power with tip speed ratio for a typical three bladed wind turbine

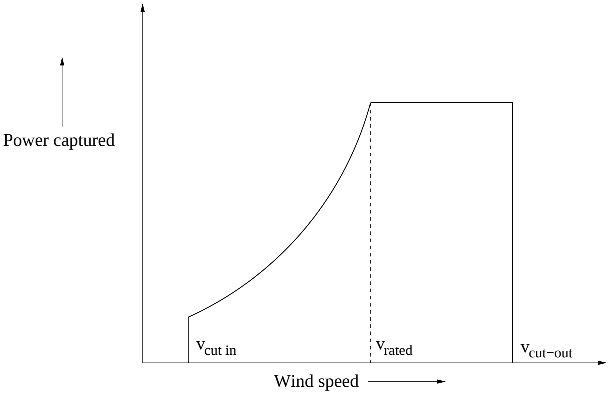

Fig. 3. Desired "Power Curve" of a typical commercial large wind turbine

2) A slowly varying ”wind shear” component: Wind velocity often increases with increase in altitude - a phenomenon known as wind shear. Close to the surface of the earth, wind velocities are smaller due to skin-friction effects. Wind shear causes rotor loading that varies with blade azimuth angle introduing periodicity in loads/power.
3) A rapidly varying ”turbulent” wind component: This component may be attributed to random motion of eddies. It is often modeled as a white noise with zero mean speed.

The resulting wind field across the rotor is obtained by superimposition of these three components.

D. Blade Aerodynamics

The aerodynamic torque responsible for power production and the structural loading of the wind turbine largely arise due to the forces and moments produced due to interaction of the blades with the wind. Here, we present the gist of the Blade Element Momentum (BEM) theory used to predict blade forces.

Fig. 5 shows a typical blade section (note the aerofoil shape). We assume that wind is incident normal to the plane

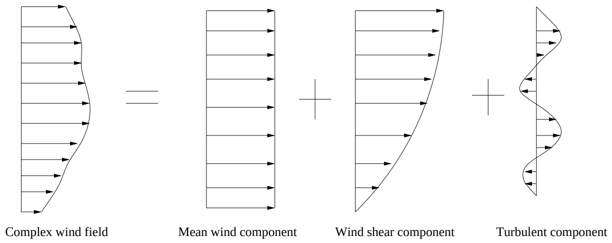

Fig. 4. Wind Model

of rotation with velocity V. Due to the rotation of the blade, the section sees a relative wind velocity W. The angle α made by the relative wind velocity with blade chord line is called the Angle-of-Attack (AoA). The angle made by the chord line with the plane of rotation is the sum of the twist angle ϕ of the blade element and the pitch angle β of the blade. The incident wind produces a "lift" force F_L and a "drag" force F_D which are, respectively, normal to and parallel to W. The resultant of these forces may be resolved into an axial component F_T and a tangential component F_r. If the blades are rigid, the sum of axial forces from all blade elements is termed as the thrust on the rotor. The tangential component of the force on the blade element contributes to aerodynamic torque.

The lift and the drag forces on the blade section can be written as:$F_L = (\frac{1}{2}\rho A W^2)C_L, F_D = (\frac{1}{2}\rho A W^2)C_D$ where C_L and C_D are the lift and drag coefficients associated with the aerofoil. It is well known that C_L and C_D depend primarily on the AoA.

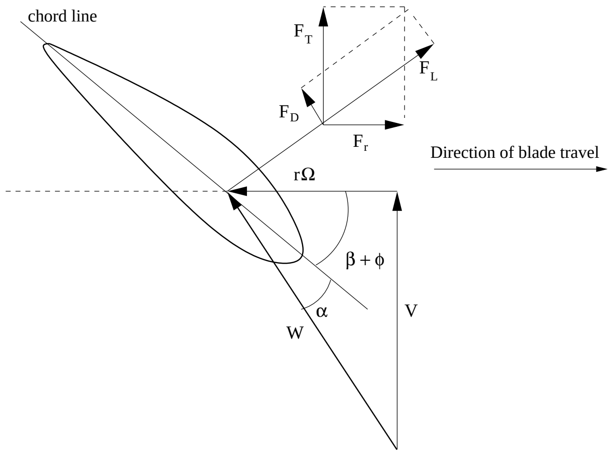

Fig. 5. Aerodynamics of Blade Section

E. Means of Control in Large Wind Turbines

As mentioned earlier, for below-rated wind speed conditions, the control objective is to maximize energy capture. If the wind speed across the rotor plane is constant, it can be seen that this objective can be achieved by maintaining the rotational speed of the turbine close to the condition when $\lambda = \lambda_{opt}$. The rotor rotational speed is often controlled by imposing an appropriate generator torque on the drive train. In wind turbine control parlance, generator torque demand variation is termed as 'torque control'.

For above-rated wind speed conditions, the primary control objective is to ensure that the mechanical loads on the turbine structure are maintained within design limits. From the expressions for lift and drag forces, it can be seen that the thrust force and rotor aerodynamic torque may be regulated by controlling the angles of attack of the wind's interaction with the blade elements. The angles of attack associated with different blade elements can be controlled, to a significant extent, by appropriate choices for the pitch angle and rotor rotational speed. The use of blade pitch action to achieve load/power control is termed as 'pitch control'.

III. STATE-OF-THE-ART IN CONTROL OF LARGE WIND TURBINES

A. Control

As mentioned earlier, the control objectives in the power production mode vary vastly depending on the prevailing wind conditions. Three-bladed large horizontal axis wind turbines often have four independent control inputs: three blade pitch inputs and a generator torque demand. The primary sensed variable is generator speed. The regulated variables of interest include power captured and mechanical loads on the turbine structure.

1) Control below rated speed: Below rated wind speed, the focus is on maximizing power capture. The loads on structure are, generally, small. In this region of operation, generator torque is, often, the only actuator input. The pitch angle is maintained constant. A strong motivation for using only generator torque as the actuation input is that power capture is maximized for a particular value of the pitch angle, referred to as *fine pitch* (see Figure 2). A widely used control law is to set the generator torque demand T_{gen} to $T_{gen} = K\omega^2$ where ω is the generator speed and the constant K is chosen so that the generator torque demand corresponds to the aerodynamic torque that would have been produced for the condition that $\lambda = \lambda_{opt}$(see [3], [4], [5], [6]). Pierce [19] discusses the behaviour of the closed-loop dynamics of large wind turbines about the operating condition $\lambda = \lambda_{opt}$.

2) Control above rated wind speed: Above rated wind speed, the primary objective is to keep power output of the turbine and associated loads on the turbine structure within design limits. A popular strategy for regulating power is to keep generator torque constant and regulate generator speed to a constant value using collective pitch control - each blade is pitched by the same amount. It should be noted that, under this control law, the limiting of loads on the turbine structure arises as a by-product. Speed regulation is often achieved through PID control [7], [8]. In addition, several model-based classical/optimal control design techniques have been used to design controllers to regulate generator speed in high wind speed conditions (see [8], [9], [10]).

3) Drive Train Damping: Along with the issues of maximizing energy capture and minimizing power/loads, damping of drive train has received considerable attention. Drive train vibrations can seriously impact gearbox life. Replacement of a failed gearbox is an expensive proposition - a situation turbine manufacturers would like to avoid.

The drive train is often modeled using a spring-mass system [11] as shown below.

$$J\ddot{\theta}(t) + K\theta(t) \quad = \quad T_{aero} - T_{gen}$$

where θ, T_{aero} and T_{gen} are the angular displacements, aerodynamic torque and the generator torque respectively, and J and K are lumped parameters representing drive train inertia and stiffness respectively. In fixed-speed turbines that use induction generators, the generator torque T_{gen} is directly proportional to the the slip and therefore the generator speed $\dot{\theta}$. As is clearly seen, this operational characterisitc of induction generators naturally aids in damping oscillations. However, active dampers are required in the case of variable-speed wind turbines. As mentioned earlier, variable-speed turbines are typically installed with doubly-fed induction drives. In such machines, the torque is no longer restricted to being proportional to slip, resulting in a loss of damping performance. A popular active damping solution is to make T_{gen} large at the drive train resonant frequency ($\sqrt{\frac{K}{J}}$) using generator speed feedback. Recent work by Suryanarayanan et al [12] suggests that generator speed information alone can be used to mitigate both drive train as well as tower side-to-side vibrations in addition to minimizing power fluctuations.

Most control schemes developed thus far suggest a dichotomous power production controller architecture. For below-rated wind speed conditions, only torque control with little or no pitch action is used, whereas for above-rated wind speeds, only pitch control is used with little or no variation in generator torque demand. The emergence of a dichotomous architecture as a standard may be attributed to several reasons. First, for a given tip speed ratio there exists a unique value of pitch angle that maximizes power capture efficiency. In the absence of reliable wind speed information, the above observation provides the merit to the argument that pitch action in below-rated wind speed condtiions can be detrimental to the achievement of the objective of maximizing power capture. Second, the implementation and tuning of the control algorithms become easier when torque control and pitch control action are largely separate. Last, but not the least, the design of control routines become simpler for such an architecture since only single-input, single-output (SISO) loops are involved.

B. Modeling of Wind Turbine Dynamics

Over the last decade or so, several wind turbine simulators such as BLADED [13], Flex5 [14], FAST [15], SymDyn [16] etc have been developed for purpose of loads simulations. More recently, the dynamics captured by these simulators are used to extract control-oriented models. The typical inputs to wind turbine simulators are three-dimensional wind field data, turbine parameters and a generator model. The output consists time series of the variables of interest which often include mechanical loads, power produced etc.

Wind turbine simulators are designed to capture the structural dynamics of turbine components as well as the aerodynamic interaction of the blades with the wind (discussed earlier). For large wind turbines, the structural dynamics become especially siginificant because of the flexible nature of its components. To model the structural behaviour of these components, one of the following three approaches is often used [17]: (a) the “Assumed Modes” method (as used, for example, in FAST and BLADED), (b) Multibody dynamics (as used in ADAMS-WT) and (c) Finite element analysis. Between these three approaches, finite element analysis is computationally the most expensive making it an unattractive option for quick loads calculations. On the other hand, the “Assumed Modes” method, also known as the modal simulation [18], is computationally the least expensive. This method is based on the observation that responses of distributed parameter systems (such as a homogenous towers, blades etc) can be approximated by a linear combination of a few dominant “modes” of the system. Utilization of such an approximation reduces the dynamics of a distributed parameter system to that of a finite degree of freedom (DOF) system - thus enabling rapid loads computations.

The dynamics of large, horizontal-axis wind turbines can often be adequately captured using a five DOF model (see Fig. 6). The dominant modes include blade flap - out-of-rotor-plane delfection of the blade, blade edge -in-plane deflection of blade, tower fore-aft, tower side-to side motions and drive train torsional deflections. As suggested in Fig. 6, the dynamics of the deflections associated with these degrees of freedom tend to be coupled. For example, that tower fore-aft motion is strongly coupled with the blade flap motion and that tower side-to-side motion is strongly coupled with blade edge and drivetrain torsion.

A survey of the past work reveals that the complexity of the model used for controller design has been chosen according to the control objective. For example, for the control objective of maximizing the energy capture below rated speed, tower and blade dynamics have often been neglected. Novak [11] has modeled only drivetrain part of wind turbine, as two inertias connected by torsional spring and damper. For a similar control objective, Hand [3] and Pierce [19] have modeled only rotor inertia, neglecting generator inertia and drivetrain torsion. If, on the other hand,

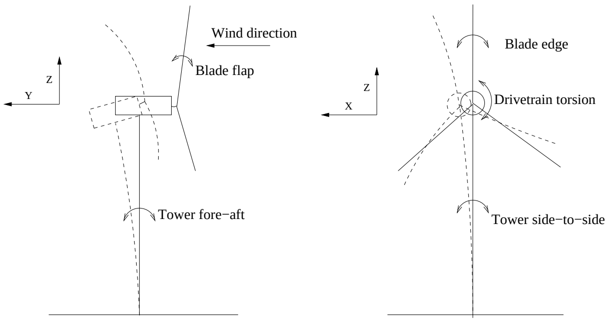

Fig. 6. Degrees of freedom of a large wind turbine

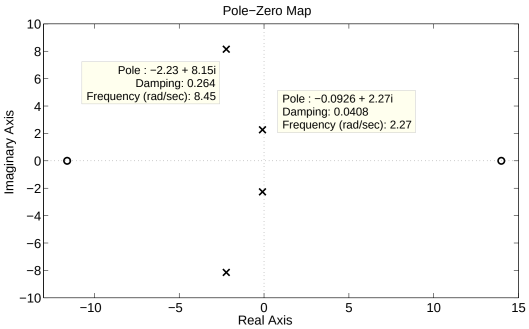

Fig. 7. Pole-zero map for the transfer function from the collective pitch to the tower top fore aft deflection for a typical 1.5 MW wind turbine

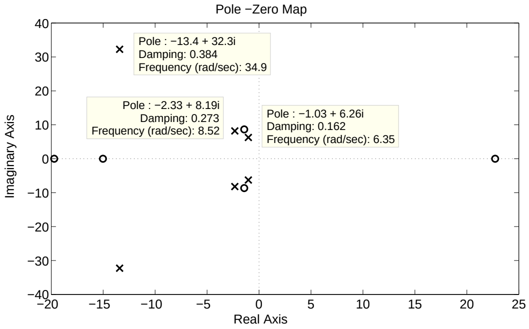

Fig. 8. Pole-zero map for the transfer function from the generator torque to power for a typical 1.5 MW wind turbine

the controller is to operate in the above rated wind region, the structural dynamics of the blade and tower have been taken into account. For example, Stol [20] has modeled tower fore-aft dynamics and blade flap to arrive at a control-oriented model for a controller eimed at minimizing blade root loads.

C. Linearized Dynamics

A linearized model representing the turbine dynamics is an essential starting point for the design of a linear controller. The dynamics are multivariable in nature and change substantially for different wind conditions and pitch angles. In the interests of brevity, we do not extensively document them here. However, to give the reader a flavour of the dynamics of large wind turbines, we present pole-zero maps of a couple of important transfer functions. Specifically, we look at the transfer functions that establish linear maps from collective blade pitch input to tower top fore-aft deflection and from generator torque to power (see Figs. 7 and 8) for a chosen operating condition. The turbine considered here is a 1.5MW turbine (see [15] for turbine parameters). The natural frequencies corresponding to the dominant modes for this turbine are as follows: tower fore-aft: 2.3 rad/s, tower side-to-side: 2.3 rad/s, blade flap: 8.5 rad/s, blade edge: 35 rad/s and drivetrain torsion: 6.4 rad/s. As suggested by the pole-zero maps, the tower fore-aft, side-to-side and blade flap motions are lightly damped. Also note the presence of right-half plane zeros. Though RHP zero situation does not occur or is not serious (RHP zero is far away from the imaginary axis) for many operating conditions, recent investigations [22] suggest that for certain operating conditions, the effects can be significant.

IV. SUGGESTED APPROACH TO MULTI-VARIABLE DESIGN OF LARGE WIND TURBINE CONTROLLERS

The control problem dealt with in this paper is truly multi-variable in nature with upto four actuator inputs, several sensed outputs and a large number of variables of interest. As discussed earlier, most attempts at solving the problem have focussed on the design of SISO control loops which use either one of pitch or torque control in different wind speed regimes. Though this paradigm has its advantages, the downside of the use shaping SISO loops alone is a resultant sub-optimal solution since the multi-variable nature of the problem is not explicitly addressed. For example, pitching action has strong impacts on power produced, blade root loads, tower base loads, hub loads etc. By considering only speed regulation, it is quite likely that we ignore important variables of interest (eg tower base loads).

Lately, several research efforts have been focussed on multivariable design. However, few of these efforts have adequately addressed the specifics of the wind turbine control problem [21]. For example, optimal control techniques such as LQG/H_∞ have been applied to the load mitigation problem without giving due attention to the signal norms of interest in the context of large wind turbine control. Consequently, the promises of multivariable control have, largely, not been realized in practice.

We now present the elements of an approach (and related problems of interest) to the design of multivariable control strategies for large wind turbine control which address the specifics of wind turbine behaviour.

1) Identify appropriate signal norms that capture fatigue loading of turbine components: Fatigue loading on turbine components is often estimated using the well-established technique of Rainflow Counting [23], [24]. For the purposes of casting the load mitigation

problem as an optimal control problem, it would be useful to identify appropriate signal norms which capture fatigue loading. Rychlik's closed-form expression for rainflow cycle counts [25] of a given time history of stress/strain can act as a starting point for such an investigation.

2) Solve the "Full Information" problem: The "Full Information" assumes that all variables of interest can be sensed. Importantly, it assumes that incident wind velocity is known ahead of time. The problem is one of determining the limits of performance of control strategies to maximize energy capture and minimize signal norms that capture fatigue loading while incorporating turbine dynamics and actuator limits As can be seen, this problem would necessitate the use of multivariable design tools. The solution of the "Full Information" problem will serve as a benchmark for wind turbine controller design.
3) Choose appropriate sensing scheme: In most large wind turbines, generator speed is the major sensed information used by real-time control routines. The industry is seeing the emergence of exciting new sensing options such as sensing of upstream wind velocity using a SONAR/LIDAR [26], tower top acceleration sensors etc. The solution to the "Full Information" problem will provide the answers to the question of achievable improvement in control performance (and therefore CoE) by incorporating information from a given sensor. These answers will go a long way in choosing the appropriate sensing architecture for future turbines.
4) Design optimal controllers for chosen sensing scheme: Based on the sensing scheme of choice, optimal multivariable controllers may be designed using established techniques. Their performance should be compared against the control that solves the "Full Information" problem..

V. SUMMARY

In this paper, we looked the problem of control of variable-speed, pitch-regulated, horizontal-axis large wind turbines. The control problem is one of maximizing energy capture while guaranteeing the structural integrity of the turbine during its life by minimzing the structural loads. The problem is truly multivariable in nature with upto four actuator inputs (for three-bladed turbines) and several controlled variables.However, in the past, this problem has often been dealt with as a pair of SISO problems arising out of a pre-imposed dichotomous controller structure. This paper made a case for using formal multivariable design tools to solve the problem. Such techniques promise to account for accordance with multiple, and often conflicting, control objectives which are often encountered in this problem for large wind turbines. Recent advances in sensing for large wind turbines, such as tower-top acceleration sensing and upwind wind velocity sensing, provide an opportunity for realizing improved controller performance. These developements can be best exploited by using multivariable design tools.

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