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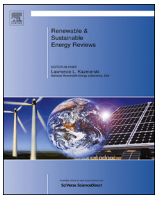

State-of-the-art in wind turbine control: Trends and challenges

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ABSTRACT

Wind energy is one of the most rapidly growing renewable sources of energy due to the fact that it has little negative impact on environment. To meet the growing demand, wind turbines are being scaled up both in size and power rating. However, as the size increases, the structural loads of the turbine become more dominant, causing increased fatigue stress on the turbine components which can lead to early failure. Another area of focus in wind energy is lowering production cost to give it a competitive edge over other alternative power sources. From the control point of view, low production cost of wind energy can be achieved by operating the wind turbine at/or near the optimum power efficiency during partial load regime, guaranteeing reliability by reducing fatigue loads, and regulating generated power to its rated value in the high wind regime. Often, it is difficult to realize a control algorithm that can guarantee both efficiency and reliability because these two aspects involve conflicting objectives. This paper reviews various control strategies that are used in wind turbine systems, both in low and high wind speed regions focusing primarily on multi-objective control schemes. Emerging trends that are likely to influence the current or future wind energy production, either positively or negatively, are also discussed.

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1. Introduction

Owing to growing environmental concerns, focus has shifted to generating power from renewable energy sources such as hydro, tidal, wind, bio-, and solar which do not emit greenhouse gases. Among these renewable energy sources, wind energy has attracted a lot of attention due to its abundance and advancement of supporting technologies among other factors. Wind energy is harnessed by wind turbines which converts wind kinetic energy into mechanical energy and finally into electrical energy.

In spite of increasing global installed wind turbine capacity and favorable future projections [1], the cost of wind power is still high compared with other conventional power sources as a result of high initial capital investment, which in turn increases the production cost per unit of power generated.

Another challenge related to wind energy harvesting is the high operation and maintenance (O&M) costs, especially in offshore wind turbines located far away from coastal line due to logistical difficulties in accessing the production sites as well as high cost of transmission lines. But with the employment of robust structural health monitoring methods in conjunction with appropriate control strategies, especially in offshore wind farms, the cost of producing wind power can be further reduced.

Due to the obvious advantages, majority of modern utility-scale wind turbines produced today have three blades with horizontal-axis configuration [2,3]. For instance, the entire rotor can be placed atop tall tower where it is able to capture higher velocity winds. Other advantages include; improved power capture efficiency, use of yaw mechanism to position rotor to face the direction of wind flow, easy installation and maintenance.

As noted in [4], wind turbines can either be manufactured with a fixed-pitch or variable-pitch blades. Although, fixed-pitch turbines are initially less expensive, their inability to adjust pitch angle make them less popular in the realm of large wind turbines where structural loads are more pronounced. Moreover, wind turbines can also be variable-speed or fixed-speed [5]. Variable-speed turbines can also be operated around their optimum power efficiency, but this requires the use of additional power electronic processing unit to couple them to grid system. The use of converters guarantee that the power generated meets certain performance requirements before it is connected to the main grid. On the other hand, fixed speed wind turbine are simple and robust, but they are not popular with Megawatt-scale turbines due to ineffectiveness in extracting energy from wind and induction of mechanical stress in drive–train during variable wind speed. Furthermore, generator speed of the fixed-speed wind turbines is fully dependent on the grid frequency making them undesirable candidates for variable-speed operations. As a matter of fact majority of Mega utility-scale wind turbines that are manufactured nowadays are variable-speed, variable-pitch, and horizontal-axis turbines.

Generally, wind turbines are inherently nonlinear and interact with wind profile which spatially varies in both speed and magnitude [2]. Due to nonlinearities in wind turbine, it is difficult to develop a perfect mathematical model that can effectively capture all its dynamics. This challenge is further compounded by the fact that the dynamic behaviors of incoming wind are usually faster than that of turbine itself, unknown, and difficult to predict. Contrastingly, unmodeled dynamics in wind turbine can be compensated for by using appropriate control methods. Over the last few decades, several simulators such as GH Bladed [6], Fatigue, Aerodynamics, Structures, and Turbulence (FAST) [7], Flex5 [8], Automatic Dynamic Analysis of Mechanical Systems (ADAMS) [9] etc., have been developed for the purpose of designing and simulating wind turbine structural dynamics. Among these simulators, FAST and GH-Bladed, which are based on the "Assumed Mode" method, are the most preferred in control design approaches because it is possible to extra control-oriented models. Compared to finite element-based models, "Assumed Mode"-based models are less computationally expensive, making them more attractive in control design applications.

Nowadays, most of utility-scale wind turbines are installed with individual blade actuation mechanism to control each blade independently. Furthermore, they are also equipped with several sensors on blades as well as on tower and nacelle, making them inherently multi-input multi-output (MIMO) systems. For this reason, standard single-input single output (SISO) controllers that are used in majority of utility-scale wind turbines are rendered ineffective in controlling such systems [10]. The additional measurements can also be used for monitoring the health status of various components in turbine and in condition-based maintenance (CBM) [11].

Unlike SISO controllers, MIMO controllers can realize multiple objectives such as elimination of structural loads and regulation of generated power at the same time. This is becoming an attractive control strategy since wind turbine maintenance cost can be lowered as well as extending operational life time. In recent years, a number of control strategies have been proposed to mitigate structural load on wind turbines and these include mitigation of loads in rotor blades [12,13], minimization of tower deflection [14–16], and reduction of drive–train vibrations [17,18].

In order to reduce the cost of energy (COE) in wind power generation, control strategies are hinged on efficiency, reliability, and safe operation of wind turbines. In this paper, a detailed review of existing and emerging wind turbine control schemes is presented, highlighting the approaches employed, and exploring their strengths and shortcomings. This paper is organized as follows: Section 2 gives a brief insight on wind turbine fundamentals, outlining control objectives and underscoring existing challenges in wind turbine control. In Section 3 various advanced methods employed in wind turbine control are discussed. Section 4, presents an analysis and discussion emanating from reviewed control methods is delineated. Finally conclusions drawn from various control strategies are summarized in Section 5.

2. Fundamentals of wind energy generation

In this section a brief summary of wind turbine operation basics is given. Challenges in the standard control methods are highlighted.

2.1. Wind turbine basics

The maximum extractable power by wind turbines is limited to 59.3% of the available wind power [19]. This limit is referred to as Betz limit, which gives the maximum achievable aerodynamic efficiency in wind turbines. The power extracted by wind turbine P_a is expressed as

$$P_a = C_p(\lambda,\beta)P_w = \frac{1}{2}\rho\pi R^2 C_p(\lambda,\beta)v^3 \tag{1}$$

where ρ denotes air density, R is the rotor radius, v represents wind speed before interacting with turbine, and $C_p(\lambda,\beta)$ is aerodynamic efficiency which is a nonlinear function of the tip-speed-ratio (TSR), λ and blade pitch angle β. The TSR is defined as

$$\lambda = \frac{\Omega R}{v} \tag{2}$$

where Ω denotes rotor angular speed, R is rotor radius, and v represents incoming wind speed. For any wind speed, there exist a rotor speed for which the value $C_p(\lambda,\beta)$ is maximum and this