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Original Research Article

Tradeoff analysis of energy harvesting and noise emission for distributed wind turbines

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ABSTRACT

Wind energy is considered one of the most promising renewable energy sources. However, the advancement of wind power generation is impeded by major challenges such as the cost of wind power, environmental impacts, and effects on power grid stability. One of the major environmental challenges hindering public acceptance for new wind power installations is the noise emission from wind turbines. Unfortunately, reducing the noise emission could lead to decreased wind energy harvesting. As a result of these conflicting goals, a tradeoff between power generation and noise emission arises.

An optimal control approach for wind turbines is presented in this paper. By controlling the electromagnetic torque of the generator and/or the blade pitch angle, an optimal operating condition that considers the tradeoff between wind turbine energy harvesting and noise emission can be obtained. Simulations were conducted to analyze the impact of the control design on power generation and noise emission in partial and full-load conditions. Additionally, a case study for a wind farm located near a residential area operating in two different wind classes is detailed.

Introduction

During the last few decades, the installation of wind turbines worldwide has grown rapidly [1]. For instance, the United States Department of Energy (DOE) has set a goal of having wind power providing 20% of the anticipated electrical power supply by the year 2030 [2]. However, the expansion of wind power is faced by major challenges such as the initial and operational cost, environmental impacts, and effects on power grid stability. One of the major environmental challenges hindering further growth of the wind energy industry is the noise emission from wind turbines [3–9]. Noise emission is of significant concerns for small (i.e. up to 100 kW) and medium (i.e. 101 kW to 1 MW) sized wind turbines installed in the vicinity of residential areas [10,11], such as those installed for distributed power generation in microgrids [12–14].

Wind turbine noise is primarily emitted from two sources: mechanical and aerodynamic sources. Mechanical noises are caused by the interaction between the moving mechanical components and their dynamics in the wind turbine drivetrain. The design improvements of drivetrain components and the implementation of advanced sound and vibration insulation techniques has led to an adequate suppression of mechanical noise in modern wind turbines [3–5]. On the other hand, aerodynamic noise, which is emitted due to the airflow around the wind turbine rotor blades, still presents a significant challenge. It is the main source of wind turbine noise [4–6,15–18], and is generally affected by many factors that include the air flow speed, rotor size, angle-of-attack, airfoil shape, and airfoil surface conditions [19,20]. Additionally, the rotor tip-speed ratio, which is a function of the inflow wind speed, rotor diameter, and rotor speed, significantly, affects the aerodynamic noise emissions [4–6].

Most of existing research effort has focused on precisely predicting and measuring the noise emission from both horizontal-axis wind turbines (HAWTs) [21–23] and vertical-axis wind turbines (VAWTs) [24–28]. A comprehensive comparison between wind turbine types can be found in [29–31]. In general, VAWTs usually operate at a lower tip-speed ratio, thus emitting less noise as compared to HAWTs [26]. However, major wind turbine manufacturers have focused on mass producing HAWTs due to their higher efficiency, thus lower electricity cost (i.e. price/kW) as compared to VAWTs [29–31]. Therefore, this work will investigate the noise emission problem for HAWTs as they are the commercially dominant type.

There are various approaches implemented for reducing the wind turbine noise emission. They can be categorized into two main groups: passive and active approaches [32]. The concept of

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Nomenclature

BET	blade element theory
HAWT	horizontal-axis wind turbine
NREL	National Renewable Energy Laboratory
VAWT	vertical-axis wind turbine
WHO	World Health Organization
B_r	frictional losses in drivetrain mechanical components (kg m^2/sec)
D_r	rotor diameter (m)
G_r	gear ratio (–)
J_r	rotor inertia (kg m^2)
L	setback distance between a wind farm and a residential area (m)
L_B	background sound pressure level at a residential area (dB(A))
L_p	overall sound pressure level at an observer location (dB(A))
L_w	sound power level of a noise source (dB(A))
P_T	power extracted from the wind by a turbine (W)
P_g	generator power (W)
R	slant distance between a noise source and a receiver (m)
T_g	generator torque (N m)
c_p	aerodynamic power coefficient (–)
v_w	wind speed (m/s)
α	cost function weighting factor (–)
β	blade pitch angle (deg.)
λ	rotor tip-speed ratio (–)
ρ_{air}	air density (kg/m^3)
σ	frequency-dependent sound absorption coefficient (dB(A)/m)
ω_r	rotor speed (rad/s)

passive approaches mainly focuses on the optimal design of blade airfoil to minimize the noise emission with minimum impact on aerodynamic performance [33–36]. Additionally, investigations were conducted to study the effect of serrated trailing edges of the blades on noise emission reduction [35,37,38]. Active methods were also developed to mitigate the noise emission during turbine operation. For a standalone wind turbine, the blade pitch angle and the generator torque can be used to adjust the rotor tip-speed and the blade angle-of-attack to reduce the wind turbine noise emission [39,40]. For a wind farm with multiple wind turbines, each wind turbine can be operated at a different blade azimuth angle to avoid noise reinforcement [32].

Among these methods, changing the airflow speed around the blades, which relates to the rotor tip-speed or tip-speed ratio, is the primary contributor to noise emissions [4–6]. Altering the rotor tip-speed to reduce noise emission might cause the wind turbine to deviate from its optimum tip-speed ratio for power generation. As a result, a tradeoff arises between minimizing noise emission and maximizing wind power generation. Therefore, it is necessary to investigate new and effective approaches to reduce the wind turbine noise emissions, while still maximizing wind power generation. The result will improve the public acceptance of future wind energy growth and maintain a high efficient operation of wind turbine systems.

As discussed previously, active approaches were investigated and implemented to minimize noise emission from wind turbines. However, in published literature, the noise emission minimization problem is formulated as a single objective optimization problem [34,39]. For instance, the noise emission is bounded by an upper limit while the energy harvesting is maximized or the allowable drop in energy harvesting is constrained while the noise emission is minimized. Alternatively, this paper presents a control methodology for wind turbine operation to actively minimize noise emission with limited effect on wind energy harvesting. A multi-objective optimal control problem will be formulated that considers the minimization of noise emission (through an active approach) and maximization of power generation simultaneously.

The organization of the paper is summarized as follows. Section Human exposure to wind turbine noise summarizes the effects of human exposure to wind turbine noise and the recommended noise thresholds worldwide. In Section System modeling, a wind turbine drivetrain dynamic model is introduced and a semi-empirical noise prediction model is then presented. Section Control and optimization methodology describes the formulation of the optimal control problem. Section Simulation results and analysis shows simulation results from the tradeoff study between noise emission and wind power generation. Finally, in Section Wind farm layout, a case study is presented to reveal the effectiveness of the proposed control approach in reducing noise emission from a wind farm and its propagation to the nearby residential area.

Human exposure to wind turbine noise

Before presenting the aforementioned tradeoff analysis, background information regarding wind turbine noise emission is given in this section. According to the World Health Organization (WHO) [41], noise is defined as any unwanted sound. In general, the effect of noise on human health can be divided into physical and non-physical effects [42]. The physical effects are associated with high sound pressure levels and frequencies leading to noise-induced physical health problems, such as Noise-Induced Hearing Loss. The non-physical effects are associated with lower sound pressure levels and frequencies in addition to predisposing factors such as noise amplitude modulation, time of day, and attitude toward the noise source. Annoyance and sleep disturbance are the major non-physical effects of noise, which if persistent, can lead to the deterioration of health, quality of life, and well-being.

The effect of noise emitted from wind turbines on human health can be categorized as a non-physical effect. Generally, there are four types of noise that can be generated by wind turbines [3–5], namely tonal, broadband, low-frequency, and impulsive noise. In most studies, annoyance is often related to only two types of noise, low-frequency [43–46] and broadband noise [8,47]. Specifically, the "swishing" or "whooshing" characteristic of the wind turbine noise has been widely cited as the most vexing in many questionnaires [8,42–47]. This "swishing" sound had been explained in [17,18,32] as the amplitude modulation of the broadband aerodynamic noise during the downward movement of the blades.

In general, noise from a wind turbine becomes noticeable and annoying when it exceeds the environmental background noise. The WHO published guidelines [41] for noise levels in residential environments as shown in Table 1. The noise limits in Table 1 are not specific to noise emitted from wind turbines. They are used as references when establishing maximum limits on the sound pressure levels measured at residential areas located near any noise source [48]. Additionally, Table 1 shows the major health problems associated with those limits being exceeded. Examples of the maximum wind turbine noise limits during day and night