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A mathematical approach to minimizing the cost of energy for large utility wind turbines

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HIGHLIGHTS

- A mathematical approach to minimizing the turbine cost of energy based on wind statistics is developed.
- The turbine cost of energy model includes the turbine rated power and the turbine rated wind speed.
- A general procedure to minimize the turbine cost of energy is presented.
- Wind sites with higher mean wind speed require higher turbine rated wind speed.
- Turbine rated wind speed has a larger influence on turbine cost of energy than turbine rated power.

ARTICLE INFO

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ABSTRACT

With the aim of reducing green gas emission, wind turbine installations worldwide have grown rapidly in recent years. Wind energy itself is free, but has costs due to the wind turbine infrastructure and maintenance. The installation size of the wind turbine at a specific location is not only determined by the wind statistics at that location, but also by the turbine infrastructure and the maintenance cost. The payback time of the turbine is determined by the turbine cost of energy (COE). In this paper, a mathematical approach is proposed to minimize the turbine cost of energy based on wind statistics. Turbine annual energy production (AEP) is calculated based on turbine output power and annual wind speed distribution. A wind turbine cost model developed by U.S. National Renewable Energy Laboratory (NREL) is used for turbine cost analysis. The turbine cost of energy model includes the turbine rated power and the turbine rated wind speed. Finally a general guideline to minimize the turbine COE is presented. Three case studies are conducted to show the effectiveness of the proposed approach.

1. Introduction

It is desired to reduce green gas emission due to increasing demand for clean and renewable energy. As one of the most important renewable energy resources, wind energy has been developed rapidly worldwide in recent years. The Global Wind Energy Council (GWEC) states that the global cumulative installed wind turbine capacity in 2017 had reached 539.58 GW, with the four leading countries in the installed capacity being China (34.9%), USA (16.5%), Germany (10.4%) and India (6.1%) [1]. A typical horizontal-axis variable speed wind turbine mainly consists of a turbine blade, capturing wind kinetic energy and converting it into rotor shaft energy, a gearbox, stepping up the low rotor shaft speed, and a generator, converting the mechanical energy into electrical energy [2].

In the last few decades, many researchers have focused their study on wind turbine optimization [3]. One research approach is to increase the turbine output power and thereby to increase the turbine annual energy production (AEP). In [4,5], the authors proposed a novel adaptive blade concept for large utility wind turbines where the blade twist distribution is optimized to increase the turbine energy production. In [6], Shen et al. combined a lifting surface model with a multi-objective optimization algorithm as an optimization method to find the trade-off between maximum AEP and minimum blade loads. In [7], a cascaded nonlinear controller has been designed for a variable speed wind turbine with doubly fed induction generator (DFIG) to track the optimal rotor speed to increase wind energy capture. In [8], Barambones presented a sliding mode control for turbine energy maximization. In [9], Wang and Stelson proposed a model predictive

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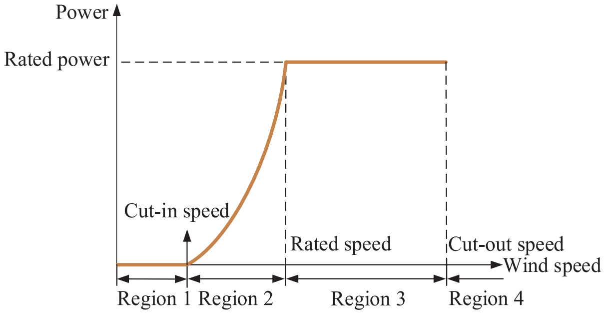


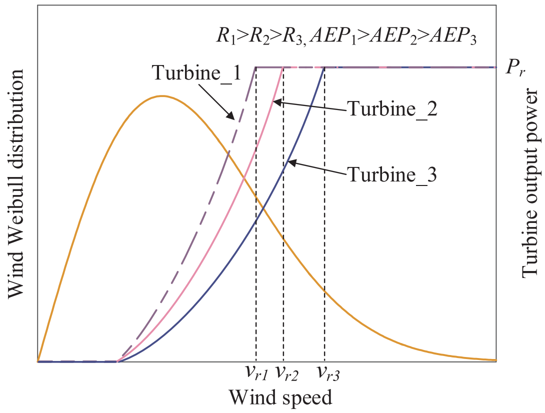
Fig. 1. Four control regions in a modern wind turbine.

control for a hydrostatic wind turbine to maximize the energy capture during the wind turbulence.

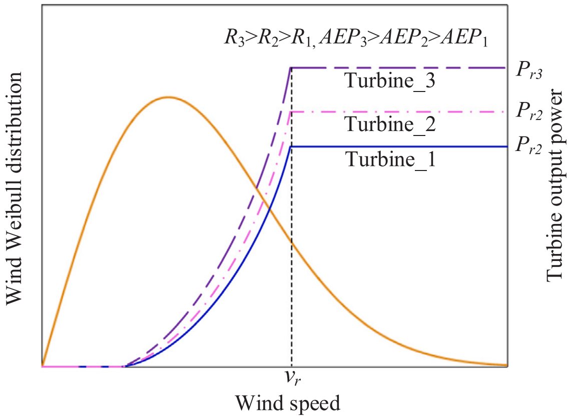
There are four control regions in a modern wind turbine based on wind speeds, as shown in Fig. 1. In region 1 where the wind speed is below cut-in speed, the power in the wind is too low for generation so the turbine is in standby mode. In region 2 where the wind speed is between the cut-in and the rated wind speed, the rotor speed is controlled to achieve maximum blade aerodynamic efficiency and therefore the turbine can capture maximum power. In region 3 where the wind speed is between the rated and the cut-out speed, the turbine output power is limited to the rated power. In region 4 where the wind speed is above the cut-out speed, the turbine is shut down to prevent damage [10]. Most studies have focused on increasing the turbine output power by improving the turbine dynamic performance in region 2. In a practical wind turbine, the turbine AEP is calculated based on the steady-state turbine output power calculated from the turbine output power curve and the wind speed distribution, usually assumed to be a Weibull distribution. The energy produced at each wind speed is the steady-state turbine output power multiplied by the time that wind speed occurs in a year. By summing the energy production at all wind speeds, the turbine annual energy production is calculated. Turbine-level optimization by matching the turbine physical parameters (e.g., turbine rated power and turbine blade size) with the turbine operating parameters (e.g., rated wind speed) has a greater impact on the turbine annual energy production than increasing the turbine output power in some control region. This is due to the fact that the turbine-level optimization takes the turbine operation within the full turbine operating region into consideration.

Matching the turbine physical and operational parameters has a large impact on maximizing turbine energy production. The turbine reaches the rated power at the rated wind speed. The turbine rated power is proportional to the cube of the rated wind speed and the square of the turbine rotor radius. With these conditions three ways of maximizing the turbine energy production can be considered. In Fig. 2(a) the turbine rated power is fixed while the rated wind speed and the turbine rotor radius vary. A turbine with lower rated wind speed can achieve higher turbine energy production, however it requires larger radius turbine rotor, resulting in higher turbine cost. Fig. 2(b) shows the case of fixed rated wind speed with the turbine rated power and turbine rotor radius varying. In this case a larger radius turbine rotor results in higher turbine rated power therefore higher turbine energy production. However the turbine cost increases due to the larger radius turbine rotor, higher power transmission, generator and power electronics. In Fig. 2(c) the turbine rotor radius is fixed while the turbine rated power and the rated wind speed vary. This creates a higher rated wind speed increasing the turbine rated power and therefore the turbine energy production. However it also increases the power level of transmission, generator and power electronics, resulting in higher turbine cost.

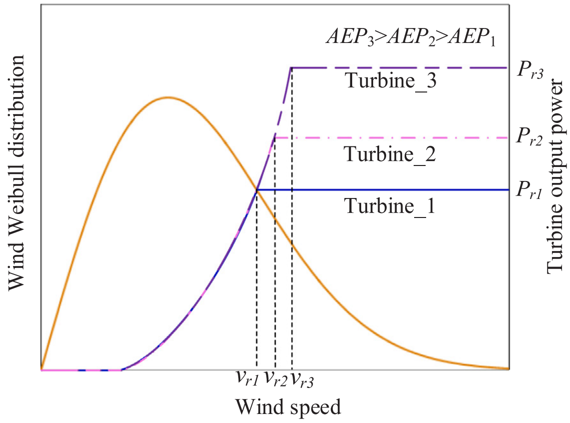
The three ways above show the ideal cases of maximizing the turbine energy production while not taking the turbine cost into consideration, an approach of little practical significance. Many studies had been carried out to investigate the economic aspects of wind turbines. Blanco [11] summarized the different costs categories of wind turbines and the factors that most influence cost. Kaplan [12] presented a review of the wind energy policies in many countries. Suitable energy policies can increase the wind turbine installation. A similar study can be found in [13]. Carroll et al. [14] analyzed the maintenance costs of offshore wind turbines with different drive train configurations. Islam et al. [15] proposed the offshore turbine cost is highly related to the weight and volume of the nacelle.



(a) P_r is fixed, v_r and R vary



(b) v_r is fixed, P_r and R vary



(c) R is fixed, P_r and v_r vary

Fig. 2. Three ways of maximizing the turbine AEP. (P_r - turbine rated power, v_r - rated wind speed, R - turbine rotor radius).

It is more meaningful and practical to minimize the turbine cost of