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Unit commitment in wind farms based on a glowworm metaphor algorithm☆

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ABSTRACT

Mechanical health and operational efficiency of a wind turbine (WT) are important to the overall cost effectiveness in a wind farm. This paper presents a unit commitment (UC) model based on fatigue damage modeling of blades and uncertainty estimation of wind power forecasting (WPF). A novel glowworm metaphor algorithm (GMA) is developed to solve the proposed UC problem. During the pheromone updating of GMA, the luminescence carrying by glowworm reflects the net improvement by agent moving. This characteristic supports GMA to find the global optima for optimization of UC problem. The proposed UC objective is minimizing the mechanical damages of WTs in the whole wind farm. Uncertain interval of wind power generation is obtained as constraint function based on relevance vector machine (RVM). Data from a wind farm in China are used to validate the feasibility and effectiveness of the proposed method. Simulation results reveal the capabilities of GMA to efficiently get the better performance than benchmark methods, in terms of minimum mechanical damage, reliability and running efficiency. The benchmark methods are particle swarm optimization (PSO) and genetic algorithm (GA). The comparison between UC with and without consideration of WPF uncertainty exhibits the superiority of the incorporation of WPF uncertainty modeling.

1. Introduction

Unit commitment (UC) in a wind farm is to determine the day ahead start-up/shut-down schedules of WTs in each operation timeslot. The goal is to minimize the wind power generation cost while satisfying the constraints of system demand and wind availabilities, etc. As the increase of wind farm scale and wind turbine (WT) capacity, UC is getting more difficult challenges to be solved. This comes from the scaling-up uncertainty from wind intermittency and computational burden on operation. Moreover, the large scale WTs bear more fatigue from variable wind, frequent on/off operation, etc., and thereby bringing down their lifespan [1]. It is significant to improve traditional operation strategy in wind farms, in terms of mechanical damages of WTs, profitability for wind farm owners, operation efficiency and quality of wind power output [2,16].

Most of the early works on the UC problem use deterministic wind power forecasting (WPF) [9–11]. However, the root square mean error (RSME) of a day-ahead WPF can be as high as 20% of the wind farm capacity and even larger in extreme conditions. When a large-scale wind farm is considered, the wake effect or topographical effect makes wind power even harder to predict. Therefore, many works consider forecasting uncertainties during operating wind farms using scenario constructing method [5], fuzzy set theory [6] or stochastic programming [7,8]. Kalantari proposed security constrained unit commitment (SCUC) based on multiple stochastic wind power scenarios to account for wind power uncertainty, and improved the computational efficiency; and the proposed SCUC was reformulated within the loadability set rather than on the larger set of generation and demand [5]. In paper [6], the 24 h ahead load forecasting uncertainty was evaluated by applying fuzzy set theory and added to the multi objective UC model; this UC was used to minimize both the supply risk and the generation cost.

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Wang formulated a stochastic price-based UC problem with chance constraints to ensure wind power utilization considering price and wind power forecasting uncertainties, and solved the optimization problem by sample average approximation method [7].

All the above UC optimizations are with high dimensional, nonlinear and mixed integer combinatorial problem. Many mathematical programming and heuristic based approaches have been utilized to solve the UC problem, for instance, dynamic programming, neural networks, simulated annealing, evolutionary programming, constraint logic programming, genetic algorithms (GA), Lagrangian relaxation, tabu search and particle swarm optimization (PSO) [12–16]. However, these methods might bear an additional computational burden or even suffer from "dimensional curve", particularly when high-dimensionally mathematical model for a large-scale wind farm with hundreds of WTs or wind farm cluster is concerned.

With the intention of developing better algorithm to solve optimal operation problems, a new searching theory-glowworm metaphor algorithm (GMA) is proposed by Krishnanand and Ghose [24]. GMA has been applied for sensor deployment in wireless sensor networks. The results prove that GSO outperforms PSO.

This paper presents three means of improving traditional UC within wind farms: (1) a unit commitment model relating to wind farm damage is established based on blade fatigue damage; (2) glowworm metaphor algorithm (GMA) is applied to solve the mechanical damage minimizing UC problem; and (3) WPF uncertainty is quantified in a UC formulation based on wind power interval forecasting. Based on the case study in a Chinese wind farm, it can be concluded that GMA approach is reliable and efficient in solving UC problem. The proposed the mechanical damage minimizing objective and uncertainty incorporated-UC model can diminish the maintenance cost and extend wind turbine lifespan in wind farms.

The remaining paper is organized as follows. In Section 2, the model for calculating fatigue damage values of the blades (FDVB) in four operational conditions is firstly established to quantify the mechanical losses of WT. With fatigue model, the objective of UC problem can be established in Section 3. Also in Section 3, the uncertainty interval of wind turbine generation forecasting are estimated and incorporated into the UC constraints. In Section 4, GMA theory is applied to solve the optimization problem. In Section 5, a wind farm in China is taken as case study to validate the proposed GMA approach and UC model, and to compare the performance to benchmark methods – PSO and GA. Conclusions are drawn in Section 6.

2. Fatigue damage value of blades (FDVB)

Blades are important and fragile components for WTs to convert wind energy into mechanical energy. From the economic perspectives, blades take up to 20% of the total cost of WTs [3]. Its maintenance cost is at least 5% of the total O&M cost for a WT in healthy conditions [4]. This cost goes much higher if the blades are in malfunction due to frequent operations. And, the profits of wind farms will be slashed. From the mechanical damage perspectives, wind loads on a WT are mostly born by blades, especially the root part of blades, and then transferred to the interconnection piece, rotor and hub. This mechanical damage potentially reduces the economic efficiency of wind farm operation or even restricts the wind power share in a power system. Therefore, it is significant to incorporate blade damage consideration in maintenance and operation strategy, especially under the context when the installation capacity of wind farm is constantly increasing.

Many studies focus on the fatigue behavior of wind turbine blades [25,26]. However, none of these works quantifies damaging model of blades in UC problem. So, the maintenance cost from the mechanical damages of a WT is not considered in many previous works, although it is the primary capital flow during running a wind farm. Therefore, it is significant to improve the traditional UC models to incorporate mechanical damage formulations for reducing the total costs of operating and maintaining all WTs in a wind farm. In this section, the fatigue damage value of blades [17] indicating the lifetime and damages of WTs is calculated based on miner cumulative fatigue damage theory [18].

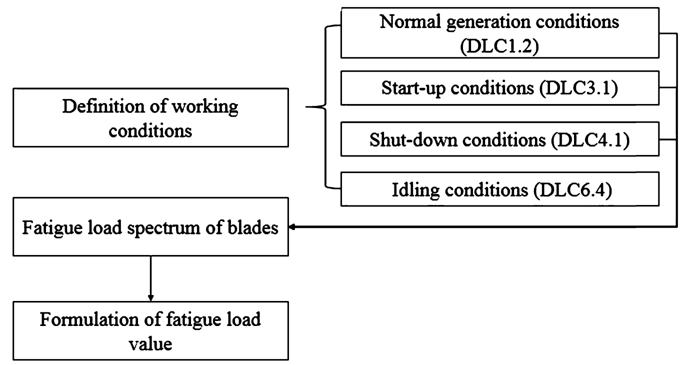

Fig. 1. The framework of deciding fatigue damage value.

2.1. WT working conditions

The framework of deciding the fatigue damage value is given in Fig. 1. First, four typical loading conditions are defined for simulating various working conditions of WTs, according to Load Assumptions in GL2003 standard released by Germanischer Lloyd (GL) [19]. Various operational conditions of WTs are considered because different external factors have variable loading effects. For example, when WTs operate in a normal generation state with normal wind conditions, particularly operating in rated power generation state, the load or damage on blade root is relatively small, while impulse loads would increase the blade damage when operating in yawing or braking process. Second, based on the modeling of blade fatigue load in typical operational conditions, loading and cycling number are calculated to establish the fatigue load spectrum of blades. And then, fatigue damage value can be calculated based on miner cumulative fatigue theory.

(i) Normal generation conditions (DLC1.2): normal turbulence model – NTM is set under different average wind speed ranging from $V_{in} < V_{hub} < V_{out}$ (V_{in}: cut in wind speed; V_{hub}: wind speed at hub height; V_{out}: cut off wind speed) to calculate shimmy moment of blade root with various wind conditions.
(ii) Start-up conditions (DLC3.1): normal wind profile model – NWP is set to calculate shimmy moment under different stable wind speed ranging from $V_{in} < V_{hub} < V_{out}$.
(iii) Shut-down conditions (DLC4.1): normal wind profile model-NWP is set to calculate shimmy moment under different stable wind speeds ranging from $V_{in} < V_{hub} < V_{out}$.
(iv) Idling conditions (DLC6.4): normal turbulence model – NTM is set under different average wind speeds to calculate shimmy moment of blade root under various wind conditions.

2.2. Fatigue load spectrum of blades

After defining four typical working conditions, the fatigue load spectrum of blades can be calculated based on GH-Bladed software. Fatigue load spectrum describes the relationship between cycling number and loading. It is the basics for analyzing the loading conditions and forecasting of fatigue lifetime [20,21].