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Maintenance strategy selection for improving cost-effectiveness of offshore wind systems

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ABSTRACT

This paper proposes approaches to determine the optimal maintenance schedules for offshore wind system such that maintenance cost is minimized. The proposed approaches aim to provide the optimal maintenance schedules for each component using a dynamic approach and for multiple components by proposing an algorithm to optimize grouping multiple maintenance schedules. To increase the accuracy of estimating the maintenance cost in the proposed approaches, a number of impacted parameters such as system reliability, cost–effective, weather condition, maintenance duration, power generation loss during maintenance, market electricity price and offshore wind system location are all considered. Firstly, a dynamic maintenance strategy is proposed to determine an optimal individual maintenance schedule for each component in an offshore wind turbine, in which the failure rate and maintenance cost are critical parameters for the cost model. Then, a grouping maintenance optimization strategy is proposed to determine the grouping maintenance schedule which groups multiple maintenance activities to a grouping maintenance activity. The results indicate that the proposed individual maintenance schedule and grouping maintenance schedule may save an average of 2.33% and 4.56% on maintenance cost over baseline maintenance schedule.

1. Introduction

Renewable energy is one of the most important solutions for many countries to achieve sustainable energy supply and environmental protection. Beside renewable energy sources such as solar energy, biomass, geothermal heat, hydropower, wave and tidal energy, offshore wind energy are increasingly attracted because of its tremendous advantages such as unlimited installation space and strong wind resources. As shown in Fig. 1, the cumulative installed offshore wind capacity increased from 801 MW in 2006 to 3.01 GW in 2010, and reached 12.63 GW in 2016 (correlatively 3589 offshore wind turbines) [1]. However, because offshore wind system is positioned far away from coastline, the installation cost and maintenance cost of offshore wind system are very high [2]. According to Kerres et al. [3], the maintenance cost of offshore wind system contributes from 18% to 23% of the total life-cycle cost, which is five times higher than maintenance cost of onshore wind system [4]. To increase cost–effective of offshore wind system, it is necessary to reduce maintenance cost by improving the efficiency of maintenance activities.

Maintenance scheduling aims to determine a detailed maintenance plan that may provide optimum system reliability with minimum maintenance cost. Maintenance scheduling for offshore wind system is complex and challenging [5]. If maintenance activities are insufficient, failure rate will be increased and the system reliability will be degraded. Otherwise, if maintenance activities are performed too often, the system reliability is guaranteed, but maintenance cost may increase to an unsatisfactory level.

Generally, there are three types of maintenance for wind system including corrective maintenance, preventive maintenance, and condition–based maintenance. In comparison with preventive maintenance and condition–based maintenance, corrective maintenance may avoid unnecessary repairs and inspections of the wind system [3], but the failure rate is higher and the system reliability is worse. Condition–based maintenance assesses actual equipment conditions by using special equipment for inspection and monitoring [6]. Condition–based maintenance usually requires complicated monitoring systems and expensive equipment [7]. Currently, corrective maintenance and preventive maintenance are the major maintenance types applying for wind system [7].

A large number of studies has been published to provide maintenance schedules for offshore wind system. Bouwer [4], Andrawus et al. [8], Besnard [9], Wang [10], Hofmann [11], Rademakers et al. [12], and El-Thalji et al. [13] reviewed different maintenance schedules for wind system. Scheu et al. [14] simulated the operating phase of a

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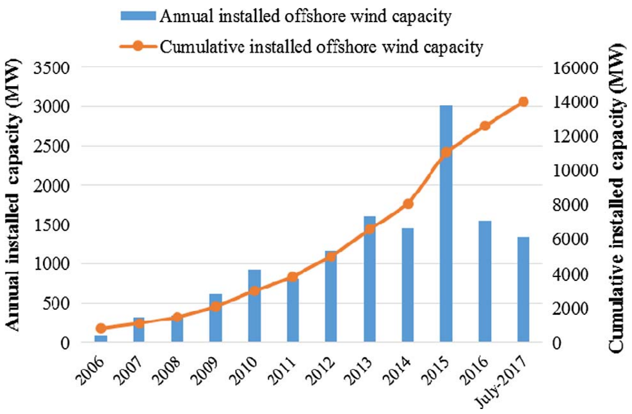

Fig. 1. European installed offshore wind energy capacity in 2006–2017.

wind farm with a special emphasis on the modeling of failures and implementing the model in Matlab, and investigated the influence of variations in maintenance fleet. The results indicated that a potential cost saving of 780 M€ in average per turbine could be achieved, due to an increase in availability values of maintenance fleet from 62% to 93%. Besnard and Bertling [15], Shafiee et al. [16], and Tian et al. [17] presented the approaches to optimize condition–based maintenance for wind turbine blades, which degradation can be classified according to the severity of the damage. A maintenance cost model for offshore wind turbine following multilevel opportunistic preventive maintenance strategy was introduced by Sarker and Faiz [18]. Zhang et al. [7] proposed an opportunistic maintenance methodology for wind turbines considering various maintenance actions based on reliability analysis. Irawan et al. [6], and Dai et al. [19] investigated the maintenance routing and scheduling for offshore wind farms to find optimal transportation cost and optimal vessel routing. Afanasyeva et al. [20], Gan et al. [21], Wu et al. [22], and Siyal et al. [23] evaluated the influence of maintenance cost on financial risks of wind projects. There are many studies considering the influence of technical parameters on the power generation [24–30]; the impact of environment such as wind speed on the power generation [31–35]; the estimation of the system reliability [36,37] or the optimal location for installing offshore wind system [38]. However, only a handful of studies use variety of parameters (system reliability, cost–effective, weather condition, power generation, market electricity price and offshore wind system location) to build a maintenance model.

In short, the existing literatures mainly focus on: (i) maintenance schedules for single wind turbine or a single component of a wind turbine [15,16,39], (ii) a review on different types of maintenance for wind turbine such as preventive maintenance, corrective maintenance, and condition–based maintenance [3,36,37,40]; (iii) maintenance schedules with the fixed maintenance interval (time threshold), where a maintenance activity is performed after the fixed maintenance interval [18]. Moreover, some existing studies propose maintenance schedules based on subjective assumptions that maintenance cost of offshore wind system does not depend on the failure rate of system [7,41]; and the maintenance duration and production loss cost can be neglected [18,42]. The existing maintenance schedules for a single component seems no longer suitable for modern wind system. In addition, the existing maintenance schedule with the fixed maintenance interval and the existing maintenance schedules with the subjective assumptions (neglecting failure rate, maintenance duration, and production loss cost) are unable to accurately assess the maintenance cost and the economic efficiency of offshore wind system.

This paper proposes approaches to determine maintenance schedules which may minimize maintenance cost while guaranteeing system reliability. The maintenance interval is dynamically adjusted to avoid the unreasonable maintenance activities. The proposed maintenance schedules could be applied for the single component or multiple components in offshore wind system. Moreover, the influences among different components are analyzed to group multiple maintenance activities to further improve the cost–effective of maintenance process. The parameters such as system reliability, weather condition, maintenance duration, power generation loss during maintenance, and offshore wind system location are carefully considered to enhance the accuracy of the proposed models.

This paper is organized in five sections of which section two describes the degradation model of offshore wind turbine. Section three shows the proposed mathematical model. The efficiency of the model applied to Taiwan will be evaluated specifically in section four. Finally, the conclusions are drawn in section five which provides a summary of this paper.

2. Degradation model of wind turbine

In the wind turbine's life cycle, a wind turbine gradually degrades and failure rates of the components of the wind turbine are increasing as the age of the components increases. A component i is considered as failure when the failure rate exceeds a failure threshold [43]. It is required that offshore wind system should be operated below a maximum allowed failure rate.It is assumed that an offshore wind system including i components in which a maintenance activity on one of the components leads to a shutdown of the whole offshore wind system. The degradation factor of component i ($i = 1,\dots,I$) has a probability density function $f_i(t)$ which is modeled in this paper by a two–parameter Weibull distribution, namely scale parameter (σ) and shape parameter (ε) (see [36]).

$$f_i(t) = \frac{\varepsilon}{\sigma}\left(\frac{t}{\sigma}\right)^{\varepsilon-1} e^{-\left(\frac{t}{\sigma}\right)^{\varepsilon}} \tag{1}$$

with Weibull mean (E_i) and variance (V_i) as shown in Eq. (2) in which Γ denotes the gamma function (see [44]).

$$E_i = \sigma\Gamma\left(1 + \frac{1}{\varepsilon}\right) \tag{2}$$

$$V_i = \sigma^2\left[\Gamma\left(1 + \frac{2}{\varepsilon}\right) - \Gamma^2\left(1 + \frac{1}{\varepsilon}\right)\right] \tag{3}$$

The degradation level increases as the time passes and it will reach its maximum at the mean time to failure of the component. The mean time to failure (*MTTF*) is defined as the average time of a failure–free operation up to a failure event under operation, and derived by (see [36]):

$$MTTF = \sigma\Gamma\left(\frac{1}{\varepsilon} + 1\right) \tag{4}$$

The Weibull failure rate function ($\chi_i(t)$) of component i ($i = 1,\dots,I$) is defined as the number of failure per unit time that is derived by Eq. (5) (see [36]).

$$\chi_i(t) = \frac{f_i(t)}{r_i(t)} = \frac{\varepsilon}{\sigma}\left(\frac{t}{\sigma}\right)^{\varepsilon-1} \tag{5}$$

in which $r_i(t)$ is the probability that a component performs its intended function over a period of time (t) under stated conditions (reliability) and $r_i(t) = e^{-(t/\sigma)^{\varepsilon}}$. The failure rate $\chi_i(t)$ has independent increments in each component i with $\chi_i(0) = 0$ and $\chi_i(t + \Delta t) > \chi_i(t)$. Because the failure rate of offshore wind turbine increases when component's age increases, the shape parameter (ε) will be greater than 1. When $\varepsilon = 1$, the failure rate is constant over time and the Weibull distribution reduces to an exponential distribution. For each component i, the failure rate $\chi_i(t)$ is used as short–term information in conjunction with cost–-effective optimization model to schedule a maintenance policy on time horizon.