Renewable Energy 85 (2016) 104–113

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Minimizing maintenance cost for offshore wind turbines following multi-level opportunistic preventive strategy

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ARTICLE INFO

Article history:
Received 27 May 2014
Received in revised form
7 May 2015
Accepted 14 June 2015
Available online 25 June 2015

Keywords:
Offshore wind farm
Wind turbines
Opportunistic maintenance
Maintenance cost

ABSTRACT

Cost of energy generated from offshore wind is impacted by maintenance cost to a great extent. Cost of maintenance depends primarily on the strategy for performing maintenance. In this paper a maintenance cost model for offshore wind turbine components following multilevel opportunistic preventive maintenance strategy is formulated. In this strategy, opportunity for performing preventive actions on components is taken while a failed component is replaced. Two kinds of preventive actions are considered, preventive replacement and preventive maintenance. In the former, components that undergo that action become as good as new (i.e., the replaced components, are not just as good as new, but are actually new), but in the latter, ages of components are reduced to some degree depending on the level of maintenance action. Total cost associated with maintenance depends on the setting of age groups that determine which component should be preventively maintained and to what degree. Through optimum selection of the number of age groups, cost of maintenance can be minimized. A model is formulated where total maintenance cost is expressed as a function of number of age groups for components. A numerical study is used to illustrate the model. The results show that total cost of maintenance is significantly impacted by number of age groups and age thresholds set for components.

1. Introduction

Sustainable energy generation system is considered to be the future of energy solution due to limited capacity of fossil fuel and concerns regarding green house gas emission. Offshore wind is considered to be one of the fastest growing sustainable energy generation systems nowadays. Due to abundance of wind potential and open space for installation, offshore wind farms have gained popularity among countries with access to open water bodies. An offshore wind farm is a power plant that consists of a number of wind turbines connected with internal grid to one or more substations and an export cable to transmit power to local grid. The principal components of an offshore wind farm include support structures, turbines, substations and electrical transmission systems. Leaded by European countries like United Kingdom, many offshore wind farms have been installed and are now operational throughout the world. Due to the fact that, this phenomenon is still developing, there is opportunity for improvement which can lead to minimize the cost of energy generated from offshore wind.

1.1. Maintenance required and components of maintenance cost

The major elements of offshore wind farm operations are the turbine and platform components and their maintenance. These principal components of an offshore wind farm include support structures, turbines, substations and electrical transmission systems, to mention a few. The external sub-components of the assembly operations of wind turbines are monopiles, jackets, tripods, and gravity foundations.

The current state of offshore wind power presents economic challenges significantly greater than onshore systems. The turbine represents just one third to one half of costs in offshore projects today, the rest comes from infrastructure, maintenance, and oversight. Larger turbines with increased energy capture make more economic sense due to the extra infrastructure in offshore systems. Offshore turbines require different types of bases for stability, according to the depth of water. To date a number of different types of offshore wind farms exists from the structural point of view, and they are:

(a) *Monopile base*, 6 m in diameter, is used in waters up to 30 m deep.

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http://dx.doi.org/10.1016/j.renene.2015.06.030
0960-1481/

(b) *Gravity Base* Structures, for use at exposed sites in water 20–80 m deep.
(c) *Tripod piled structures*, in water 20–80 m deep.
(d) *Tripod suction caisson structures*, in water 20–80 m deep.
(e) *Steel jacket structures*, as used in oil and gas industry, in water 20–80 m deep.
(f) *Floating wind turbines* are being developed for deeper water.

Transition pieces are placed on top of the foundations such that they cover the upper part of the foundation and act as connectors between foundations and turbines. They also levels horizontal inaccuracies. For monopiles, transition pieces contain boat fenders, access ladders, access deck and handrails and the gap between transition piece and foundation are filled with cement grout. For jacket and tripod foundations, transition pieces are installed at the port and do not contain various access systems as they are installed elsewhere on the foundation.

The turbine system is composed of turbine with four primary components (tower, nacelle, hub and blades) and the internal subcomponents of turbines are rotor, bearing and gearbox. The parameters of wind farm and the vessel are numerous of which a few are cited as wind farm capacity, distance from farm site to port, distance between two turbines at the farm, deck area of the vessel, vessel speed, number of parts in each turbine, lifting rate, initial assembly operation rate, pre-loading time at port, pre-loading time at turbine site, multiplier for offshore lift, number of vessel, jack up height, jacking up speed, utilization rate of vessel, vessel life, and projected life of the wind farm.

In detailed analysis or modeling, each of these components or the sub-components mentioned above is associated with either a cost of materials or operations (maintenance and/or installation) or some parametric values. The major cost structure is composed of failure replacement cost, preventive maintenance cost, fixed cost for a maintenance cycle and the turbine access cost. Though not exhaustive, the other indirect components of the maintenance costs include capital cost of vessel, financed percentage of vessel capital cost, interest rate for financed capital for vessel, daily operating cost of vessel, return on investment, daily rate of vessel, and interest rate of investment in wind farm. A vivid description of maintenance required and the components of maintenance costs are given in Faiz [14] and Hau [18] has provided a host of fundamentals, technologies and economics of wind turbines.

Offshore wind energy costs more than the cost of energy generated from onshore wind, which can be attributed to additional cost of foundation installation, high cost of turbine installation and maintenance activities. Among these costs, the latter one is most significant because of the incurring of maintenance cost throughout the operational life of the farm. In this study, maintenance cost model following an opportunistic maintenance strategy is formulated and procedure for minimization of costs has been attempted.

The research thus deals with a model to minimize the opportunistic preventive maintenance for offshore wind turbine farm. The model is formulated for determining cost of maintenance of offshore wind turbines following multi-level imperfect opportunistic maintenance strategy.

1.2. *Previous research*

Echavaria et al. [13] show how to find different functional redundancies in offshore wind turbine design. Feuchtwang and Infield [15] developed a closed form probabilistic method for calculating delays caused by sea scale in offshore wind turbine system. Arshad and O'Kelly [2] reviewed different offshore wind-turbine structures giving different ideas with respect to maintenance operation and costs. Nguyen et al. [25] proposed a framework for data integration of offshore wind farms while Shires [31] design optimization of an offshore vertical axis wind turbine. Recently Casau et al. [8] proposed a set-valued approach to FDI and FTC of wind turbines and Laura and Vincente [9] analyzed the life-cycle cost for floating offshore wind farms. Smarsly et al. [33] developed an integrated monitoring system for life-cycle management of wind turbines. Serrano Gonzalez et al. [29] proposed a new and efficient method for optimal design of large offshore wind power plants. Alshibani et al. [1] assessed the lifetime cost of permanent magnet synchronous generators for MW level wind turbines. Stankovic et al. [35] proposed a methodology for fault and delay tolerant multi-sensor control scheme. Bennouna and Heraud [3] diagnosed a real-time fault detection procedure for the monitoring of the wind turbine whereas Gucik-Derigny et al. [16] prognosticated a model-based strategy for prediction of remaining useful life of Ball-Grid-Array interconnections.

Zhou et al. [38] scheduled an opportunistic preventive maintenance for a multi-unit series system based on dynamic programming. Karyotakis and Bucknall [21] planned intervention as a maintenance and repair strategy for offshore wind turbine. Sorensen [34] proposed a framework for risk-based planning of operation and maintenance for offshore wind turbines, and Rangel-Ramirez and Sorensen [28] proposed a risk-based inspection planning optimization of offshore wind turbines. Carlos et al. [7], unlike many others, optimized the onshore wind farms maintenance using stochastic model. Hameed and Vatn [17] analyzed the role of grouping in the development of an overall maintenance optimization framework for offshore wind turbines. From another perspective, Jin et al. [19] developed a multi-criteria planning for distributed wind generator under strategic maintenance. Kahrobaee and Asgarpoor [20] showed, through a case study of wind turbines, how a hybrid analytical-simulation approach works for maintenance optimization of deteriorating equipment. Shafiee [30] recently reported a critical study on the current progress and perspectives of maintenance logistics organization for offshore wind energy. Also Ye et al. [37] developed a non-optimality detection technique for continuous processes.

Operations and maintenance costs contribute a significant portion (25–30%) of cost of energy from offshore wind turbines. Based on design of components, criteria for maintenance and maintenance strategies, there can be numerous possible decisions set which can be employed for maintenance. Several studies have been conducted to find the optimal decision set to minimize maintenance costs. Nielsen and Sørensen [24] compared two different maintenance strategies, e.g. condition-based and corrective maintenance for a generic offshore wind turbine with single component. The model is formulated as a benefits maximization problem of with constraints of design, inspection and decision rules. Influencing parameters of the model are minimum damage level to initiate repair, interval of inspection, mean time between failures of the component. A case study is presented that compared two strategies of maintenance and investigated the effects of various parameters.

Nilsson and Bertling [26] presented the effect of condition monitoring as the maintenance strategy on life cycle cost for two cases, a single turbine onshore and a wind farm offshore. According to their study, condition monitoring benefits maintenance management of offshore power systems and cost of this strategy can be covered by 0.43% increase in availability in turbines for power generation.

Besnard et al. [6], proposed an optimization model for opportunistic maintenance of offshore wind turbines. Their model suggested that, scheduling preventive maintenance when power generation potential is low can lead to minimization of cost of