Mechanical Systems and Signal Processing 104 (2018) 347–369

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Constrained non-linear multi-objective optimisation of preventive maintenance scheduling for offshore wind farms

Shuya Zhong [a,c,g], Athanasios A. Pantelous [b,c,d,g], Michael Beer [c,e,f,*], Jian Zhou [g]

[a] The Logistics Institute-Asia Pacific, National University of Singapore, Singapore
[b] Department of Econometrics and Business Statistics, Monash University, Victoria, Australia
[c] Institute for Risk and Uncertainty, University of Liverpool, Liverpool, United Kingdom
[d] Department of Mathematical Sciences, University of Liverpool, Liverpool, United Kingdom
[e] Institute for Risk and Reliability, Leibniz Universitat Hannover, Hannover, Germany
[f] School of Civil Engineering & Shanghai Institute of Disaster Prevention and Relief, Tongji University, China
[g] Department of Management Science and Engineering, Shanghai University, Shanghai China

ARTICLE INFO

Article history:
Received 28 December 2016
Received in revised form 18 September 2017
Accepted 24 October 2017

Keywords:
Reliability
Maintenance
Scheduling
Cost parameters
Offshore wind farms
Multi-objective Programming

ABSTRACT

Offshore wind farm is an emerging source of renewable energy, which has been shown to have tremendous potential in recent years. In this blooming area, a key challenge is that the preventive maintenance of offshore turbines should be scheduled reasonably to satisfy the power supply without failure. In this direction, two significant goals should be considered simultaneously as a trade-off. One is to maximise the system reliability and the other is to minimise the maintenance related cost. Thus, a non-linear multi-objective programming model is proposed including two newly defined objectives with thirteen families of constraints suitable for the preventive maintenance of offshore wind farms. In order to solve our model effectively, the nondominated sorting genetic algorithm II, especially for the multi-objective optimisation is utilised and Pareto-optimal solutions of schedules can be obtained to offer adequate support to decision-makers. Finally, an example is given to illustrate the performances of the devised model and algorithm, and explore the relationships of the two targets with the help of a contrast model.

1. Introduction - motivation

The wind energy capacity currently installed in the European Union (EU) can produce 284 TWh of electricity in an average wind year, which is enough to cover 10.2% of the EU's total electricity consumption.[1]

At present, offshore wind power accounts for almost 1.1% of the EU's *total* capacity in the electricity consumption. Obviously, offshore wind farms are emerging to be one of the driving sources of energy in the green power world. In the US in May 2014, the U.S. Department of Energy awarded three multi-million demonstration projects planned for the New Jersey, Oregon and Virginia coasts. In theory, the potential benefit and challenge are tremendous [39]. In Germany, the ambitious *Energiewende* (energy transition) programme hopes to generate at least 35% of its electricity from the green renewable

* Corresponding author at: Institute for Risk and Reliability, Leibniz Universitat Hannover, Hannover, Germany.
E-mail addresses: shuya.zhong@hotmail.com (S. Zhong), Athanasios.Pantelous@monash.edu (A.A. Pantelous), beer@irz.uni-hannover.de (M. Beer), zhou_jian@shu.edu.cn (J. Zhou).

[1] The UK remains in Europe with the largest amount of installed offshore wind capacity (45.9%), followed by Germany (29.9%), Denmark (11.5%), Belgium (6.5%), the Netherlands (3.9%) and Sweden (1.8%) (more details can be found in the EWEA's report [47]).

https://doi.org/10.1016/j.ymssp.2017.10.035
0888-3270/

energy by 2020, and by 2050 the share is expected to surpass 80%. Again, offshore wind farms in north coastal parts of Germany play a key role in this direction [42]. Last, but not least, it should also be mentioned the Chinese government is giving considerable weight to exploiting this environmentally friendly resource of energy, particularly along the south-eastern part of its coast line [7].

Maintenance is classified into two main categories: the *corrective* and the *preventive* maintenance. The former one is usually performed after a system failure or breakdown while the latter one corresponds to the scheduled actions, which are performed while the system is still operational. Generally speaking, the *preventive maintenance* (PM) is more beneficial as it may prevent serious losses due to unpredicted failures [32].

This paper is aimed at the PM scheduling of offshore wind farms. For generalised power systems, the primary goal of the PM is to *avoid* or *mitigate* failure consequences of the electrical and mechanical parts of the system caused by fatigue cumulative damages and corrosion resistance degradations. PM is able to prevent faults effectively either before they occur or before they develop into major defects. *Scheduling* means to determine the most satisfied arrangement for the downtime of elements in offshore wind farms that need to be preventively maintained. Hence, our PM scheduling of offshore wind farms is transformed to an interesting optimisation problem, which is useful to different decision-makers in the green energy world.

The rest of the paper is organized as follows. In Section 2, a discussion about the new reliability and economic criteria is provided. Section 3 introduces and reviews the algorithm used for solving our problem. A non-linear multi-objective programming model with thirteen families of constraints for the PM scheduling of offshore wind farms is formulated, as well as its contrast model using the squares of net reserves minimisation objective in Section 4. Then, the technical parts of Non-dominated Sorting Genetic Algorithm II (NSGA-II) are presented in Sections 5 and Appendix A. The effectiveness and performance of the proposed and contrast models are illustrated by presenting a numerical example in Section 6, and the results are analysed and compared from three main respects.

2. Objective functions

Reliability and economic criteria are the two most popular objectives for the maintenance optimisation models of power systems according to the literature to date. However, only a few studies have investigated the maintenance problem particularly designed for the offshore wind energy sector. In the following subsections, an analysis of the two criteria is provided.

2.1. Reliability criterion

In terms of the reliability criterion, there are commonly two mainstream definitions. The first one is related to the required net power reserves to provide the stability in meeting the customer demand, and the second one indicates the deviation of the net power reserves, i.e., the reserve margin. The net power reserve is the balance of the gross reserve after deducting the maintenance loss. For the first type of the reliability measure, Kralj and Petrović [27] suggested that the net reserve generation can be maximised as an optimality criterion. Later, Conejo et al. [6] made a further development and first defined the reliability as the net reserve being divided by the gross reserve. This formulation soon became a classical objective for the maximisation of PM scheduling models. Canto [3] employed it to solve the PM scheduling problem of power plants, and then Canto and Romero [4] extended its application to the problems associated with wind farms integrated power plants.

For the second type of reliability perspective, Egan et al. [16] first proposed that the minimisation of the sum of the *squares of the reserves* (SSR) would prevent the large variations in the net power reserves of each time period, which means the maximization of the reliability. There followed an upsurge in the use of this reliability definition by other scholars, [8,1,10,11,17,43].

In our paper, we will *adjust* the first type of the conventional reliability criterion in the PM scheduling of offshore wind farms to model the behavioral attitude of our treatment. As only the customer power demand satisfaction delineated by the power reserve ratio has been studied in the previous definitions from the demand perspective, here the reliability criterion can be better depicted if the decision-maker preferences are also taken into account over a set of choices or attitudes. Moreover, in offshore wind farms, the particularly complex and variable marine environment contributes to the effects of the maintenance and degeneration on the real power reserve which may not have such significant influence on other kinds of power plants [42]. Therefore, another factor, the *system sustainability*, which means the sustainable capability of reserving the power under the combined impacts of the maintenance work and the system degradation in each time period, is of equal importance to be considered in the reliability frame. It can reflect the actually attained power reserve ratio by exponentially adjusting the estimated power reserve ratio. Thus, we propose a novel non-linear definition of the reliability with both of the demand and supply side regards by introducing what we call the "*attainment exponent*",[2] so as to describe the decision-maker's preferences, the power demand satisfaction and the system sustainability simultaneously.

[2] This can also be seen a curvature parameter in the reliability index, see Section 4.2.1.