Energy Conversion and Management 112 (2016) 445–458

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Reliability optimization of wind farms considering redundancy and opportunistic maintenance strategy

Karim Atashgar, Hadi Abdollahzadeh *

Malek Ashtar University of Technology, Department of Industrial Engineering, Tehran 15875-1774, Iran

ARTICLE INFO

Article history:
Received 24 September 2015
Accepted 12 January 2016
Available online 29 January 2016

Keywords:
Redundancy
Opportunistic maintenance
Wind farm
Three phase simulation
Multi-objective particle swarm optimization algorithm

ABSTRACT

In this paper, a joint redundancy and imperfect block opportunistic maintenance optimization model is formulated. The objective is to determine the wind farm redundancy level and the maintenance strategy which will simultaneously minimize the wind farm loss of load probability and life cycle cost. A new opportunistic maintenance approach is developed to take advantages of the maintenance opportunities. Different reliability thresholds are introduced for imperfect maintenance of failed turbines and working turbines and preventive dispatching of maintenance teams. In addition, a simulation method is developed to evaluate the performance measures of a wind farm system considering different types of wind turbine, maintenance activation delays and durations, and limited number of maintenance teams. Sensitivity analysis is conducted to discuss the influence of the different assumption and parameters of simulation model over the wind farm performance. Pareto optimal solutions are driven based on a multi-objective particle swarm optimization algorithm. Comparative study with the commonly used maintenance policy demonstrates the advantages of the proposed opportunistic maintenance strategy in significantly reducing maintenance cost and loss of load probability.

1. Introduction

Among renewable energy sources, wind power has occupied a significant position due to higher shares of power production, lower costs, and the unlimited source of wind [1,2]. The production of wind energy deals with two major challenges: (1) reliable and stable electricity generation, and (2) economic and competitive electricity production. The electricity generated from wind power can be highly variable due to the intermittent nature of wind velocity and the uncertainties rising from unpredicted failures of wind turbine (WT) components [3]. Although, accurate prediction of wind velocity behavior as well as wind farms (WF) reliability indices can help decision makers in effective management of distribution networks [4–6], however redundancy and an appropriate maintenance strategy may provide an opportunity to reduce variability and improve competitive production.

Optimal redundancy level which is considered in designing phase of a WF affects positively the reliability term of a WF. An optimal level of redundancy is used for fault tolerance and is analyzed considering physical constraints such as land size and wake effect. Several authors such as Chen et al. [7], Morthy and Deshmukh [8], Zhang et al. [9], Turner et al. [10], Gonzalez et al. [11,12] and Chen et al. [13] contributed to the optimization of WFs redundancy level considering objectives such as WF power output and profit. Mirghaed and Roshandel [14] also developed a model to optimize sizing parameters and layout of a WF to achieve minimum levelized cost of energy. Chowdhury et al. [15] approached the unrestricted WF layout to optimize the placement and selection of turbine with respect to the cost of energy. Shamshirband et al. [16] proposed a model to determine the number of turbines for a WF considering maximization of the WF net profit based on the adaptive neuro-fuzzy inference system. To the best of our knowledge, literature indicates that no study has considered the optimal redundancy design of a WF considering reliability indices.

Using redundancy for a WF system may satisfy more than minimum required demand. However, these redundant WTs are subject to additional initial, operational and maintenance costs. Therefore, there is a trade-off between investments into system redundancy and system maintenance cost (for more details see [17–19]). In fact, reliability and life-cycle cost of a WF are highly affected by maintenance strategy. Different maintenance strategies are developed by several authors for a WF (see [20–27]).

A WT is a multi-component system and literature indicates that due to the high cost of sending maintenance facilities to the WF,

* Corresponding author. Tel./fax: +98 2122970309.
E-mail address: hadi.sangrodi@gmail.com (H. Abdollahzadeh).

http://dx.doi.org/10.1016/j.enconman.2016.01.027
0196-8904/

Nomenclature

n	index of location of wind turbine, $n = 1,2,\ldots,N_{max}$
i	index of version of wind turbine, $i = 1,2,\ldots,k$
j	index of wind turbine component, $j = 1,2,\ldots,N_i$
l	index of wind farm block, $l = 1,2,\ldots,G_{max}$
r	index of MOPSO particles, $r = 1,2,\ldots,N_{pop}$
t	index of MOPSO iterations, $t = 1,2,\ldots,Max_{it}$
d	index of each particle dimension, $d = 1,2,\ldots,2N_{max}+7$
M	vector of wind farm configuration
C_i^{int}	initial costs of wind turbine of type i
C_{int}	total initial costs of a wind farm
$C_{i,j}^{f}$	failure replacement cost of jth component of ith turbine type
$C_{i,j}^{pv}$	variable repair cost of jth component of ith turbine type
C_i^{pf}	fixed repair cost of ith turbine type
$C_{i,j}^{p}$	cost of imperfect repair of jth component of ith turbine type
C_{Access}	access cost to a wind turbine
C_{fix}	fixed cost of sending a maintenance team
$PMT_{i,j}$	repair time of jth component of ith turbine type
$CMT_{i,j}$	replacement time of jth component of ith turbine type
LT	preparation time of a maintenance team
L_{max}	maximum number of maintenance team
q	effectiveness or rejuvenation parameter
$F(\cdot)$	cumulative distribution function.
$T_{i,j}$	times between failures of jth component of ith turbine type
$\alpha_{i,j}$, $\beta_{i,j}$	Weibull scale and shape parameters
$VA_{i,j}$	virtual age of jth component of ith turbine type
v	wind velocity
v_i^{ci}	cut-in wind velocity of ith turbine type
v_i^{co}	cut-out wind velocity of ith turbine type
v_i^{r}	rated wind velocity of ith turbine type
P_i^{r}	rated power output of ith turbine type
$P_i(v)$	generated power of wind turbine of type i
RPD	reliability threshold of preventively dispatching a team
RWP	reliability threshold of perfect repair of a working turbine
RWI	reliability threshold of imperfect repair of a working turbine
RFP	reliability threshold of perfect repair of a failed turbine
RFI	reliability threshold of imperfect repair of a failed turbine
$R_{i,j}$	reliability of jth component of ith turbine type
$x_{i,l}^{n}$	equals to 1 if a wind turbine of type i is placed in position n and assign into the lth block of wind turbines. Otherwise $x_{i,l}^{n} = 0$
TC	total expected costs of design and maintenance of a wind farm
$LOLP$	loss of load probability of wind farm
$W(t)$	production rate of the wind farm
W^0	consumer demand
FS	first stage design variables
SS	second stage design variables
$P_d^r(t)$	dth dimension of rth particle position at iteration t
$V_d^r(t)$	dth dimension of rth particle velocity at iteration t
r_1, r_2	random numbers in the range [0,1]
b_1	cognitive learning factor
b_2	social learning factor
w	inertia weight
$REP_d(h)$	dth dimension of hth position in repository
$Pbest_d^r$	dth dimension of rth particle best position
CS	component state
AU	the time at which the age of a component is updated
FA	the time it takes a failure occur for a component
EPR	energy production rate of a wind turbine
TS	wind turbine state
LOM	loss of load moment
$TTOL$	total time of loss
TCM	total cost of maintenance activities
$clock$	total time of simulation
T_{max}	Maximum simulated time

there are economic dependencies among WTs and their components. Simultaneously performing several maintenance activities provide an opportunity to reduce the setup costs of a maintenance team [28–30]. It should be noted that the opportunistic maintenance studies of WFs were focused on corrective deployment of maintenance facilities. However, preventive dispatching of maintenance teams offers more effective utilization of WT components [31]. On the other hand, these studies were only focused on the minimization of maintenance cost without considering the actual characteristics of the maintenance activities such as duration of a maintenance activity, delays resulting from the preparation of a maintenance group and also their impact on the amount of energy produced. In addition, the impact of the limited number of maintenance groups on wind farm performance is an important issue that is largely ignored in the opportunistic maintenance optimization models [16,23,32].

To address the above issues, the trade-off between wind farm redundancy and maintenance strategy is analyzed simultaneously in this paper. To the best of our knowledge, this is the first time that a joint redundancy and maintenance optimization of a wind farm considering reliability indices is addressed. The attempt is to provide a comprehensive multi-objective optimization model for the cost-effective design of a WF considering different types of WT, several types of operational and maintenance costs, maintenance activation delays, maintenance activity durations and limited number of maintenance teams. Therefore, a new opportunistic maintenance approach is developed for WFs by taking advantages of the maintenance opportunities and considering imperfect maintenance efforts. Three-phase discrete event simulation is introduced to model the behavior of different entities of a WF and to evaluate main performance measures. Furthermore, to find the optimal solution of the proposed optimization model, a multi-objective particle swarm optimization algorithm is approached.

This paper is organized as follows: in Section 2 features of the problem and the proposed maintenance strategy for a WF are presented. Section 3 describes our developed mathematical optimization model. A three phase simulation method is developed to evaluate the loss of load probability and life cycle costs of a WF in Section 4.1. In Section 4.2, a multi-objective particle swarm optimization algorithm is presented and applied to solve the proposed combinatorial problem. A numerical example is analyzed comprehensively in Section 5. Finally Section 6 is allocated to our conclusion and remarks. The pseudo-codes related to the proposed simulation method are provided in Appendix A.

2. Problem definition

Assume that N_{max} denotes the maximum number of turbines allowed to install in a WF. Suppose there are k types of WT and each WT includes N_i ($i = 1,2,\ldots,k$) main component(s). In this case, it is assumed that the components of a WT are connected in series and WTs are categorized based on initial cost, component failure/