Energy 107 (2016) 172–181

Contents lists available at ScienceDirect

Energy

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

Degradation based optimization framework for long term applications of energy systems, case study: Solid oxide fuel cell stacks

Ramin Roshandel*, Tarannom Parhizkar

Department of Energy Engineering, Sharif University of Technology, Tehran, Iran

ARTICLE INFO

Article history:
Received 2 July 2015
Received in revised form
30 March 2016
Accepted 3 April 2016
Available online 26 April 2016

Keywords:
DBO (Degradation based optimization)
Degradation cost
Operating conditions
Lifetime profit
Solid oxide fuel cell

ABSTRACT

Depletion of fossil fuels has increased the pressure on energy systems to operate in the most efficient and economical mode. This tendency promotes energy systems to operate at optimum operating conditions, which maximizes the system profit over lifetime. Recently, there have been many attempts to maximize lifetime profit. Most of them concentrate on the power generation aspect without incorporating further aspects such as system degradation and profitability through lifetime. However, the main intention of the system operators is to optimize the profitability of system at the moment of operation and not the total profitability through the system lifetime. In this study a novel approach is developed which considers degradation mechanisms in optimization procedure. A DBO (degradation based optimization) framework maximizes system profit through its lifetime. The proposed framework can be applied to energy systems and the optimum operating conditions and replacement intervals can be determined. Solid oxide fuel cell is considered as the case study to validate the developed framework. The results show the value and effectiveness of DBO framework to improve the lifetime profit during system operation. Using DBO, the system lifetime profit for proposed case study is increased up to 10.45%.

1. Introduction

The major proportion of performance deterioration of energy systems result from a gradual and irreversible accumulation of damage that occurs during a system's life cycle. This process is known as degradation [1]. Degradation models attempts to characterize the evolution of degradation mechanisms [2].

DBO (Degradation based optimization) is an optimization model that considers systems degradation mechanisms in the optimization procedure. The goal of DBO is defining the optimum operating condition or design parameters of the system to maximize or minimize a specific objective function. In energy systems, mostly the optimum operating conditions lead to the minimum system total cost or maximum system profit through its operation lifetime. DBO framework consists of degradation and process modules which are added to an optimization module. Degradation and process modules, determine performance deterioration as a function of system operating conditions. Furthermore, optimization module includes an objective function as well as technical and economic constraints.

Based on the reviewed literature, the approximation of system degradation is a well-developed field and a large stream of research in energy systems area focused on component [3] and system degradation models [4] with various purposes. For instance, Guenther et al. [5] developed degradation model for batteries. Similarly, optimization of operating conditions according to plant fuel consumption or power demand regardless degradation process in power systems [6] or other energy conversion systems [7] are also available. Baldick [8] scheduled generator start-ups, shut-downs, and generation levels to minimize production and start-up/shut-down costs. In another study, Green [9] studied traditional models of optimal electricity pricing. In such studies optimization is done regardless system component degradation.

However, there are a few studies which optimize energy system based on degradation mechanisms. In this field, Wu et al. [10] developed an optimization model to minimize the total cost of degradation based maintenance by determining an optimal interval of condition monitoring. Moreover, Song et al. [11] presented a model to simultaneously minimize the total cost of the system and the capacity loss of battery over a typical China Bus Driving Cycle. In the optimization procedure, battery degradation model is

* Corresponding author.
E-mail addresses: Roshandel@sharif.edu (R. Roshandel), Parhizkar@energy.sharif.edu (T. Parhizkar).

http://dx.doi.org/10.1016/j.energy.2016.04.007
0360-5442/

Nomenclature

AV	Asset value
c	Cost
dr	Degradation rate
e	System output
F	Fuel consumption
i	Current density
J	Profit
LT	Degradation level of component
$\dot{m}$	Mass flow rate
p	Price
q	Income
u	System decision variables
V	Voltage
w	Weighting factor
x	System state variables
y	System performance index
z	Continuous variables
θ	Degraded surface
ε	Random error
λ	Random effect parameter
ω	Fixed effect parameter

Subscript and super script

0	Initial time
d	Degradation
f	Fuel
k	System outputs (heat, electricity)
l	Lifetime
m	Number of observations/tests
max	Maximum value
min	Minimum value
n	Number of components
NG	Natural gas
o	Operation

considered. Song et al. [12] developed another optimization model based on developed battery degradation model which optimizes components sizes and the system control strategy simultaneously.

In above literature, the aim of the optimization, decision variables and degradation modeling methodology are different. Mostly the objective of the optimization is maximizing energy production or minimizing system cost and decision variables are design or operating parameters. Moreover, degradation modeling methodology is data-driven or principle based. For instance, Wen et al. [13] developed a data-driven optimization model for SOFC (solid oxide fuel cell). In optimization model, the objective is maximizing generated electricity and decision variables are geometric and operating parameters. Moreover, modeling is based on system historical data and the individual data-driven degradation model is developed. The characteristic of other related researches in this area are presented in Table 1.

In recent years, degradation based optimization models consider degradation cost as a specific term in the objective function. Johnston et al. [20] consider the cost of storage degradation due to ageing effects related to cycling of charge. Fares et al. [21] introduced degradation cost in objective function which is equal to revenue reduction due to power generation deterioration.

It should be noted that the storage systems are dominant equipments in degradation analysis. In related studies the battery degradation cost is added to the system total costs. The differences are in the objective function of optimization and battery degradation models for different storage systems such as residential [22] or transportation applications [23]. In research performed by Atia et al. [24] the objective function is the minimization of the annualized cost of system. The battery degradation factor is derived as a function of temperature, SOC (State of charge) and SOC swing effect based on experimental data. Kam et al. [25] developed linear optimization model that maximize self-consumption of PV (photovoltaic) power. To give an indication of the control algorithms impact on battery lifetime they use three indicators: energy throughput, rate of charge and discharge and SOC. Song et al. [26], optimized the size of energy storage system in vehicles based on dynamic degradation model of the battery. The operation costs of different hybrid energy storage system, including the electricity and the battery degradation costs over a whole driving cycle are minimized in the optimization process. Results showed that about 50% of the operation cost of the energy storage system can be reduced.

Obviously, in energy systems there are not much literature which considers degradation cost in the objective function. Moreover, beside energy system cost, lifetime profit is another key component which must be considered in optimization of operating condition. In this work, an optimization framework is developed with the aim of maximizing lifetime profit based on degradation mechanisms. The objective of this study is to present the optimal operating conditions and replacement intervals of an energy conversion plant over a long-term horizon that maximizes lifetime profit. In this regard, the DBO framework is developed. The key components resulting from the model are the fuel cost, system degradation cost and system income. This framework is applied to a SOFC power plant as a case study and optimum operating conditions and replacement intervals are derived.

This paper is organized as follows: Section 1 presented the evolution of DBO and its literature review. In Section 2, DBO concept and its importance are introduced. The proposed DBO framework is presented in three main modules. A brief discussion

Table 1
Literature survey of degradation based optimization models.

Authors	System	Purpose	Decision variables	Methodology
Gallestey et al., 2002 [14]	Gas turbine	Minimize system cost	Production scheduling	Data-driven model
Zaidan et al., 2015 [15]	Gas turbine	Increase the fidelity of failure-time	Prediction performance, computational speed	Data-driven model
Trecate et al., 2002 [16]	Steam and gas turbine	Minimize system cost	Steam mass flow, gas turbine load	Data-driven model
Uson et al., 2010 [17]	Power plant equipment	Different targets regarding degradation	Operating conditions	Principle based and data-driven model
Rasmekomen et al., 2013 [18]	Framework development	Minimize system cost	Maintenance interval	Data-driven model
Kima et al., 2014 [19]	PEM	Maximize mean voltage	Temperature	Data-driven model