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Stochastic analysis of residential micro combined heat and power system

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ABSTRACT

In this paper the combined heat and power functionality of a fuel-cell in a residential hybrid energy system, including a battery, is studied. The demand uncertainties are modeled by investigating the stochastic load behavior by applying Monte Carlo simulation. The colonial competitive algorithm is adopted to the hybrid energy system scheduling problem and different energy resources are optimally scheduled to have optimal operating cost of hybrid energy system. In order to show the effectiveness of the colonial competitive algorithm, the results are compared with the results of the harmony search algorithm. The optimized scheduling of different energy resources is listed in an efficient look-up table for all time intervals. The effects of time of use and the battery efficiency and its size are investigated on the operating cost of the hybrid energy system. The results of this paper are expected to be used effectively in a real hybrid energy system.

1. Introduction

Distributed generation integration into micro-grids has gained more attention in the past few years, e.g. photovoltaic systems and wind turbines [1]. Using distributed generations in houses caters for the customers with electrification at a competitive price and economic use of electrical and thermal energies [2]. Use of distributed generations may have other benefits such as emissions decrease and security enhancement [3]. Thermal and electrical energies can be produced by combined heat and power (CHP) or combined cooling, heating and power systems as cogeneration systems [4]. Recently, investigation of CHP scheduling is an important issue in economic operation of systems [5]. Fuel cells (FCs) is one of the attractive devices in CHP systems, especially in houses [6]. The literature has shown that the operating costs (OCs) of FCs can be reduced by applying the optimal settings determined through a cost minimization procedure [7].

In line with the acceptable performance of CHP functionality in the hybrid energy system (HES), some studies have been carried out to investigate the FC integration to the HES and its appropriate scheduling. An intelligent control scheme based on a model-predictive strategy was applied to dispatch the micro-CHP systems in [8] and the effect of the proposed approach was evaluated in terms of energy cost reduction. In [9], it is shown that the energy optimization algorithms can play a major role at the residential level to achieve benefits. Operating cost minimization was formulated as a mixed-integer linear programming in [9]. The effects of energy storage device operation and applying of different time of use (TOU) rates on the system OC were studied in [10]. However, the OC related to the integrated energy system was not taken into consideration. In [11], the economic scheduling problem of a CHP system in the presence of wind power dynamics, PV power variations and time-varying load profile was discussed by applying chance-constrained programming.

The stochastic load effect has not been considered in the above-mentioned studies. This is a critical issue in the economic dispatch of energy resources (ERs) in HES because residential loads show sudden variations associated with the household inhabitant's lifestyles [12]. Compared with [12], in this paper, the electrical demand is considered as a stochastic variable and its effect on

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Nomenclature

Abbreviations
CHP combined heat and power
CCA colonial competitive algorithm
ER energy resource
FC fuel cell
HES hybrid energy system
OC operating cost
OF objective function
TOU time of use

Overall parameter
i indicates in the subscript of the variables and shows number of time intervals
T time interval

Utility and home parameters
P_{eL} electrical demand (kW)
P_{hL} thermal demand (kW)
C_{U_p} purchasing electricity tariff from utility ($/kW h)
$C_{U,peak}$, $C_{U,off-peak}$ cost of electricity purchased from utility in the peak and off-peak periods ($/kW h)
C_U purchased electricity cost from utility during a day ($/day)
P_U utility electrical power (kW)

Fuel-cell parameters
$\Delta P_{FC,U}$, $\Delta P_{FC,D}$ upper and lower limits of fuel cell power ramp rate (kW)
$P_{FC,\max}$, $P_{FC,\min}$ maximum and minimum limits of fuel cell generated power (kW)
η_{FC} fuel cell efficiency
γ_1, γ_2 Z startup and shutdown cost ($)
C_{FC} cost of generated power by fuel cell ($/day)
P_{hFC}, P_{eFC} heat and electrical power generated by fuel cell (kW)
r_{FC} heat to electrical power ratio of fuel cell
PLR part load ratio

Battery parameters
W energy stored in the battery (kW h)
ΔW_i battery energy change (kW h), $\Delta W_i = W_i - W_{i-1}$
η_{ch}, η_{dch} charging and discharging battery efficiency
$W_{\max}$, $W_{\min}$ maximum and minimum limits of stored energy in the battery (kW h)
C_B cost of operation of battery ($/day)
C_{B_p} operation and maintenance cost of battery per kW h ($/kW h)
$P_{Bdch\max}$, $P_{Bch\max}$ maximum discharging and charging rates of the battery (kW)
P_B electrical power absorbed or supplied by battery (kW)

Natural gas parameters
C_{gas_p} purchased natural gas cost per kW h ($/kW h)
C_{gas} cost of purchasing gas during a day ($/day)
P_{gas} directly produced heat power from gas (kW)

Colonial competitive algorithm parameters
N_{imp} number of imperialists
N_{col} number of colonies
ξ role of colonies in empire total power determining
β weight factor of colonies movement
α maximum deviation angle from the original direction

the OCs of the HES is considered. Electrical and thermal loads, a FC and a battery are integrated to the HES. In addition, natural gas resource and the electrical grid are also accessible. The economic operation of the HES is formulated by integrating the economic models of the devices. The colonial competitive algorithm (CCA) is applied to determine the optimal dispatch of ERs in the system. Random electrical load variations are modeled by applying Monte Carlo simulation as described in [13]. The effectiveness of the proposed method in HES management is shown by using a real load demand data. The results of the cost minimization problem of optimal ERs scheduling are presented as a look-up table. The amount of thermal and electrical powers produced by different ERs for each time interval is shown in this table. The minimum dispatch costs are achieved if different ERs supply thermal/electrical power according to the mentioned table in each time interval.

A HES with the same elements combination as this paper was modeled in [14] and its optimal OC was achieved by applying the harmony search algorithm. In [14] deterministic load is considered and the time-varying nature of the residential load is not modeled. In [15] stochastic nature of the residential loads is considered through the power scheduling optimization, which is carried out by applying harmony search algorithm. However, the effects of battery capacity and efficiency were not investigated. In this paper, the HES economic model is studied and the presence of stochastic residential demand is considered. In order to determine the optimal scheduling of ERs, CCA is applied as a powerful optimization algorithm. The results of this study are more realistic compared with that presented in [14] since the stochastic behavior is considered for load demand. Compared to [15], a more accurate scheduling strategy is achieved in this paper by applying a more powerful optimization algorithm. Moreover, the effects of battery parameters such as efficiency and capacity on system operating cost are investigated and the minimum efficiency of the battery to participate in the system is determined.

The rest of this paper is organized as follows. HES is introduced in Section 2 and the problem of ERs optimal scheduling is formulated. In Section 3, the CCA is explained. Section 4 discusses the simulation results and Section 5 concludes the article.

2. HES and optimization model

Fig. 1 shows the interrelations among a battery, a FC, and electrical and thermal loads as a layout of HES. As shown in this figure, the electrical load is energized by the utility grid, the battery, or FC while either the resource of natural gas or the FC recovered heat can supply the thermal load.

The energy management system determines the power supplied by different ERs in the HES at any time slot. The major part of the EMS function is to minimize the OC of supplying demand. In order to effectively use available ERs, optimal operation scheduling can be carried out for one day or more in advance. Minimization of one day-ahead OCs considering stochastic load demand is the aim of this paper. It is assumed that components integrated to the HES have been installed and installation costs are not considered, since the HES operation optimization is the aim of this paper.

2.1. Objective function

This section is presented to define an appropriate objective function. Since the objective of this paper is minimization of the