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Optimal stochastic short-term thermal and electrical operation of fuel cell/photovoltaic/battery/grid hybrid energy system in the presence of demand response program

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ABSTRACT

In this paper, cost-efficient operation problem of photovoltaic/battery/fuel cell hybrid energy system has been evaluated in the presence of demand response program. Each load curve has off-peak, mid and peak time periods in which the energy prices are different. Demand response program transfers some amount of load from peak periods to other periods to flatten the load curve and minimize total cost. So, the main goal is to meet the energy demand and propose a cost-efficient approach to minimize system's total cost including system's electrical cost and thermal cost and the revenue from exporting power to the upstream grid. A battery has been utilized as an electrical energy storage system and a heat storage tank is used as a thermal energy storage system to save energy in off-peak and mid-peak hours and then supply load in peak hours which leads to reduction of cost. The proposed cost-efficient operation problem of photovoltaic/battery/fuel cell hybrid energy system is modeled by a mixed-integer linear program and solved by General algebraic modeling system optimization software under CPLEX solver. Two case studies are investigated to show the effects of demand response program on reduction of total cost.

1. Introduction

By taking a simple look to the recent works in power system technologies, it can be understood that the upstream grid is not the only power supply resource in residential section anymore and various types of distributed energy sources are getting more and more utilized by system operators. Photovoltaic system receives solar irradiation and then generates clean energy [1]. Consuming natural gas or hydrogen, fuel cell generates heat and electric power [2]. Electrical storage systems can be also employed in power systems to store energy in peak periods and supply load in other periods [3]. So, integrated energy systems system like hybrid systems including such resources can have significant portion in handling energy demand in residential section [4].

1.1. Literature review

Due to fast-going improvement of hybrid energy systems, many researches and studies have been done by researchers. Here we have some of the important ones done recently as follows:

In [5], cost-efficient sizing of a hybrid energy system containing PV system, battery, wind turbine and fuel cell has been studied. A battery/fuel cell hybrid system generating energy without any interruption has been utilized to supply an electrical vehicle in [6]. In [7], optimal performance of a wind/PV/fuel cell/grid hybrid system supplying an electrical load and a heat pump water heater has been investigated. Optimal size of a battery/wind turbine/PV hybrid system has been found utilizing Big Bang–Big Crunch algorithm in [8]. Optimal size of a fuel cell/battery/PV hybrid system has been found with different approaches and considering several power management strategies in [9]. Economic operation of a hydrogen/battery/PV hybrid system has been evaluated and compared with diesel-PV generator and battery-PV in [10]. In [11], genetic algorithm (GA) has been employed to optimize and model a diesel/wind/PV hybrid system. In [12], different operating strategies have been utilized to evaluate performance of a hybrid energy system in residential section. In [13], with the aim of minimizing cost and CO_2, best possible size of an ESS/PV/diesel hybrid system has been found in a ship power system. In [14], several solar thermal/PV/micro-CHP hybrid systems have been designed to determine optimal economic and environmental performance of a building. Optimal performance of an off-grid wind/battery/diesel hybrid system has been evaluated in [15] using genetic algorithm (GA). Genetic algorithm and weighted Ah ageing model have been

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Nomenclature

Abbreviations
PV photovoltaic system
DRP demand response program
MIP mixed-integer linear program
GAMS general algebraic modeling system

Indices
h, s Hour and scenario indices

Parameters
H, S number of hours and scenarios
$\rho_{h,s}^{grid}$ price of procured power from upstream grid
η_e^{fc} fuel cell electrical efficiency
η^{bb} efficiency of backup burner
ρ_h^{gas} price of purchased gas
$\rho_{h,s}^{pv,sale}$ price of sold power to upstream grid by PV
M a constant number
$u_{h,s}^{grid,pur}$ binary variable; 1 if upstream grid attempts to supply load and charge battery; otherwise 0
α, β efficiency of PV system and inverter
$Prob(s)$ probability of each scenario
A area for PV installation
$R_{h,s}$ amount of solar irradiation
$u_{h,s}^{grid,s}$ binary variable; 1 if battery PV system attempts to sell power to the upstream grid; otherwise 0
$P_{capacity}^{fc}$ rated power of fuel cell
δ a small value used for considering self-discharge of battery bank
η_{ch}^{b} battery's charging efficiency
η_{dis}^{b} battery's discharging efficiency
$E_{\min}^{bat}$ minimum capacity of battery
$E_{\max}^{bat}$ maximum capacity of battery
N a constant number
$u_{h,s}^{b,ch}$ binary variable; 1 if battery storage attempts to charge; otherwise 0
$u_{h,s}^{b,dis}$ binary variable; 1 if battery storage attempts to discharge; otherwise 0
$P_{h,s}^{l}$ electrical load without considering DRP
$DRP_{\max}^{e}$ maximum amount of electrical DRP
ζ a small value used for considering loss of heat in heat storage tank
η_{in}^{st} heat storage's charging efficiency
η_{out}^{st} heat storage's discharging efficiency
$H_{capacity}^{st}$ rated capacity of heat storage tank
HE_{ratio}^{fu} heat to electricity ratio of fuel cell
$H_{capacity}^{bb}$ rated capacity of backup burner

Variables
$Cos\,t^{total}$ total cost
$Cos\,t^{grid}$ cost of power procurement from upstream grid
$Cos\,t^{gas}$ cost of gas procurement
$Sale^{pv}$ revenue from exporting power to the upstream grid by PV
$P_{h,s}^{grid,ch}$ power supplied by upstream grid to charge battery
$P_{h,s}^{grid,l}$ power supplied by upstream grid to supply load
$P_{h,s}^{fc,l}$ power supplied by fuel cell to supply load
$P_{h,s}^{fc,ch}$ power supplied by fuel cell to charge battery
$H_{h,s}^{ab}$ generated heat by backup burner
$P_{h,s}^{pv,s}$ power supplied by PV to be exported to the upstream grid
$P_{h,s}^{pv,l}$ power supplied by PV to supply load
$P_{h,s}^{b,dis}$ discharged power by battery bank to supply load
$P_{h,s}^{pv,ch}$ generated power by PV to charge battery
$E_{h,s}^{b}$ available energy of battery storage
$P_{h,s}^{l,DRP}$ electrical load with considering DRP
$P_{h,s}^{TOU}$ new load with considering time-of-use (TOU) program
$H_{h,s}^{l}$ thermal load
$H_{h,s}^{st,out}$ output heat of heat storage tank
$H_{h,s}^{st}$ available heat of heat storage tank
$H_{h,s}^{st,in}$ input heat of heat storage tank
$H_{h,s}^{fu}$ produced heat by fuel cell
$H_{h,s}^{bb}$ produced heat by backup burner

used to investigate the effect of lead-acid batteries on efficient operation of hybrid systems in [16]. In [17], performance of a fuel cell/battery/PV hybrid energy system connected to an electrolyser and H2 tank has been evaluated. Operation of a hybrid fuel cell/PV/electrolyser system for micro co-generation applications has been studied in [18]. In [19], particle swarm optimization (PSO) algorithm has been utilized to ideally size a hybrid battery/PV/H2 energy system. A fuzzy-logic based Energy management of a grid-connected fuel cell/PV hybrid system has been investigated in [20]. A complete review of techniques and methods that can be employed for optimal management of hybrid PV/battery/fuel cell system is presented in [21]. Finally, ideal sizing problem of a wind/PV/battery/diesel hybrid energy system along with minimizing CO_2 emission, dump energy and life cycle cost, has been investigated in [22]. Using energy conversion system for wind turbine and maximum power point tracking method for PV system, efficient operation of PV-wind-fuel cell hybrid energy system has been evaluated in [23]. Employing Hammersley Sequence Sampling, multi-objective model including three objective functions namely total cost, electricity efficiency and energy supply reliability is solved in [24]. Different hydrogen technologies have been used in [25] to facilitate linkage of heat and electricity for integration of renewable energy resources in various scales. Using thermo-economic based model, a hybrid fuel cell/gas turbine energy system is optimally configured in [26].

1.2. Demand response program (DRP)

Electrical loads can participate in DRP to reduce their operation costs. Participating in DRP, customers are responsible to change their energy consumption pattern to reduce their expenses. As a reward for reduction of consumption, consumers get incentives or they pay less to the utility [27]. Totally, demand response programs are divided into two groups: Incentive-Based Programs (IBPs) and Price-Based Programs (PBPs). In PBPs, dynamic pricing rates including Time of Use (TOU) rate, Critical Peak Pricing (CPP), Extreme Day Pricing (EDP), Extreme Day CPP (ED-CPP) and Real Time Pricing (RTP) are used [28,29].

IBPs are divided into market-based programs and classical programs. In these programs, customers get incentives as much as they reduce their consumption.