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A cost-emission model for fuel cell/PV/battery hybrid energy system in the presence of demand response program: ε-constraint method and fuzzy satisfying approach

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ABSTRACT

Optimal operation of hybrid energy systems is a big challenge in power systems. Nowadays, in addition to the optimum performance of energy systems, their pollution issue has been a hot topic between researchers. In this paper, a multi-objective model is proposed for economic and environmental operation of a battery/fuel cell/photovoltaic (PV) hybrid energy system in the presence of demand response program (DRP). In the proposed paper, the first objective function is minimization of total cost of hybrid energy system. The second objective function is minimization of total CO_2 emission which is in conflict with the first objective function. So, a multi-objective optimization model is presented to model the hybrid system's optimal and environmental performance problem with considering DRP. The proposed multi-objective model is solved by ε-constraint method and then fuzzy satisfying technique is employed to select the best possible solution. Also, positive effects of DRP on the economic and environmental performance of hybrid system are analyzed. A mixed-integer linear program is used to simulate the proposed model and the obtained results are compared with weighted sum approach to show the effectiveness of proposed method.

1. Introduction

Recently, due to considerable improvements in the fields of power system's planning and operation, distributed generation systems are playing a significant role in supplying energy demand. Various types of distributed generation systems are utilized by system operators in power systems like photovoltaic system [1], battery storages [2], fuel cell [3] and etc. Also, in addition to the optimal planning and operation of power systems, many efforts have been done to impel system designers and operators to consider environmental issues [4].

In order to give a better view of works done in the field of hybrid systems, the researches and works done before are reviewed. A fuel cell-battery-PV hybrid energy system is investigated through different methods and strategies to calculate the optimal size of the system [5]. Big Bang–Big Crunch algorithm is employed to calculate and find the best possible size of a battery-wind-PV hybrid energy system in [6]. Energy consumption of a building has been investigated from economic point of view with considering emission reduction in [7]. A hybrid battery-fuel cell system is used to provide a reliable and stable power for an electrical vehicle in [8]. A PV-wind-fuel cell hybrid system has been analyzed to calculate the best possible size of utilized system in [9]. A PV-diesel-battery hybrid energy system has been optimally sized in a ship power system in [10]. In order to optimize a diesel-wind-PV hybrid energy system and investigate the optimal operation of a wind-battery-diesel hybrid system, genetic algorithm is utilized in [11,12], respectively. Different strategies have been implemented to analyze behavior of a PV-fuel cell -battery hybrid system in [13]. A hybrid hydrogen-battery-PV energy system is optimally sized in [14]. Also, a grid-connected hybrid system including wind, PV, fuel cell is utilized to optimally supply a heat pump water heater and an electrical vehicle in [15]. Optimal management of a PV-battery-fuel cell hybrid energy system has been analyzed through different methods and approaches in [16]. The best possible size of a hybrid battery/PV/H2 energy system has been found utilizing particle swarm optimization (PSO) algorithm in [17]. 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 [18]. A controlling strategy has

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Nomenclature

Indices

m	index of month
h	index of time

Parameters

M	number of months in one year (months)
H	number of hours in one day (h)
λ^{e}_{base}	base payment to the upstream grid in each month ($/-month)
D	number of days in one month (days)
$\lambda^{e}_{m,h}$	price of procured power from upstream grid ($/kWh)
λ^{g}_{base}	base payment to the gas utility in each month ($/-month)
η^{fc}_{e}	fuel cell electrical efficiency (%)
η^{bb}	backup burner efficiency (%)
$\lambda^{g}_{m,h}$	price of purchased gas ($/kWh)
$\lambda^{pv}_{m,h}$	price of sold power by PV system ($/kWh)
Z	a constant number
$u^{e,pur}_{m,h}$	binary variable, 1 if power is purchased from upstream grid; otherwise 0
α	PV system efficiency (%)
β	inverter efficiency (%)
A	area in which PV system is installed (m^2)
$R_{m,h}$	solar irradiation in month m at hour h (kW/m^2)
$u^{pv,s}_{m,h}$	binary variable, 1 if the excess power of PV is sold; otherwise 0
P^{fc}_{c}	fuel cell rated capacity (kW)
δ	a small value used for considering self-discharge of battery bank (%)
η^{b}_{ch}	battery storage charging efficiency (%)
η^{b}_{dis}	battery storage discharging efficiency (%)
$E^{b}_{\min}$	minimum capacity of battery (kWh)
$E^{b}_{\max}$	maximum capacity of battery (kWh)
N	a constant number
$u^{b,ch}_{m,h}$	binary variable, 1 if battery is in charging mode; otherwise 0
$u^{b,dis}_{m,h}$	binary variable, 1 if battery is in discharging mode; otherwise 0
$P^{l}_{m,h}$	electrical load without considering DRP (kW)
$DRP^{e}_{\max}$	costumers participation in DRP in month m at hour h (%)
ζ	loss of heat in the heat storage tank (%)
η^{s}_{in}	heat storage charging efficiency (%)
η^{s}_{out}	heat storage discharging efficiency (%)
H^{s}_{c}	heat storage rated capacity (kWh)
HE^{fc}_{ratio}	fuel cell heat to electricity ratio
H^{bb}_{c}	backup burner rated capacity (kW)

Control variables

$Cost^{t}$	total cost of hybrid system ($)
$Cost^{e}_{p}$	cost of power procurement from upstream grid ($)
$Cost^{g}_{p}$	cost of gas procurement ($)
$Sale^{pv}$	benefit from selling power to the upstream grid ($)
$P^{e,ch}_{m,h}$	purchased power from upstream grid to charge battery (kW)
$P^{e,l}_{m,h}$	purchased power from upstream grid to supply electrical load (kW)
$P^{fc,l}_{m,h}$	generated power by fuel cell to supply load (kW)
$P^{fc,ch}_{m,h}$	generated power by fuel cell to charge battery (kW)
$H^{ab}_{m,h}$	generated heat by backup burner (kW)
$P^{pv,s}_{m,h}$	sold power by PV system (kW)
CO^{t}	total CO_2 emission (kg)
CO^{g}	CO_2 emission due to gas consumption (kg)
CO^{e}	CO_2 emission due to the purchased power from upstream grid (kg)
CI^{g}	city gas carbon intensity (kg/kWh)
CI^{e}	upstream grid carbon intensity (kg/kWh)
$P^{l,DRP}_{m,h}$	electrical load with considering DRP (kW)
$P^{pv,l}_{m,h}$	generated power by PV system to supply load (kW)
$P^{b,dis}_{m,h}$	discharged power by battery to supply load (kW)
$P^{pv,ch}_{m,h}$	generated power by PV system to charge battery (kW)
$E^{b}_{m,h}$	state of battery storage in month m at hour h (kWh)
$P^{l,TOU}_{m,h}$	new electrical load with considering time-of-use (TOU) program (kW)
$H^{l}_{m,h}$	thermal load in month m at hour h (kW)
$H^{s,out}_{m,h}$	output heat of heat storage tank to supply thermal load (kW)
$H^{s}_{m,h}$	state of heat storage tank in month m at hour h (kWh)
$H^{s,in}_{m,h}$	entrant heat to the heat storage tank (kW)
$H^{fc}_{m,h}$	generated heat by fuel cell in month m at hour h (kW)
$H^{bb}_{m,h}$	generated heat by backup burner in month m at hour h (kW)

been employed to improve the optimal performance of a PV-fuel cell-battery hybrid system in [19]. A PV-electrolyser-fuel cell hybrid energy system has been modeled and simulated for micro co-generation application in [20]. Energy management of a hybrid PV-fuel cell energy system has been analyzed in [21]. Finally, utilizing weighted Ah ageing model and Genetic algorithm in [22], influence of lead-acid batteries on economic operation of microgrids and hybrid energy systems has been investigated.

In this paper, a multi-objective optimization model is proposed for cost-emission performance of PV/battery/fuel cell hybrid energy system in the presence of DRP. The proposed model is solved using ε-constraint method and then many various solutions are obtained. To choose the best possible solution, fuzzy satisfying approach is employed. Also, time-of-use rate of DRP is used to flatten the load curve by shifting some percentage of load from peak (expensive) periods to other periods which leads to reduction of system's total cost.

Also, besides upstream grid, distributed energy resources are utilized to supply some percentage of load and therefore, upstream grid portion in supplying load decreases and the role of distributed energy resources becomes more notable. So, summarizing the mentioned explanations, the novelty and contributions of this paper are presented as follows:

1. Multi-objective optimization model for cost-emission performance of PV/battery/fuel cell hybrid energy system.
2. Utilization of ε-constraint method to solve the proposed multi-objective model and employing fuzzy satisfying approach to select the best possible solution.
3. Implementation of demand response program (DRP) to flatten the load curve and reduce total cost.
4. Reducing the role of upstream grid in supplying load by improving the optimal operation of distributed energy sources (PV system, battery and fuel cell).