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Optimal coordinated scheduling of combined heat and power fuel cell, wind, and photovoltaic units in micro grids considering uncertainties

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ABSTRACT

In this paper, a stochastic model is proposed for coordinated scheduling of combined heat and power units in micro grid considering wind turbine and photovoltaic units. Uncertainties of electrical market price; the speed of wind and solar radiation are considered using a scenario-based method. In the method, scenarios are generated using roulette wheel mechanism based on probability distribution functions of input random variables. Using this method, the probabilistic specifics of the problem are distributed and the problem is converted to a deterministic one. The type of the objective function, coordinated scheduling of combined heat and power, wind turbine, and photovoltaic units change this problem to a mixed integer nonlinear one. Therefore to solve this problem modified particle swarm optimization algorithm is employed. The mentioned uncertainties lead to an increase in profit. Moreover, the optimal coordinated scheduling of renewable energy resources and thermal units in micro grids increase the total profit. In order to evaluate the performance of the proposed method, its performance is executed on modified 33 bus distributed system as a micro grid.

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1. Introduction

Nowadays, the majority of the electrical energy is supplied by nuclear or large fossil fuel power plants around the world and they have high reliability and capacity. However, regarding the fact that the investment cost of these power plants is very high, in order to draw the attention of small capitals and reducing environmental emissions, Renewable Energy Sources (RESs) at small scales attract a higher interest [1]. On the other hand, increasing the use of renewable energy and Distributed Generation (DG) sources of high efficiency in power systems has provided new points of view. This new viewpoint, i.e. generation units generating power in a smaller scale, is close to consumers in the Micro Grid (MG). MGs comprise distribution networks with distributed energy resources: i.e. Wind Turbine (WT), Fuel Cells (FCs) based Combined Heat and Power (CHP), Photovoltaic (PV), etc. [2,3]. MGs can be managed in a non-autonomous mode, if interconnected to the main grid, or in an autonomous mode, if disconnected from the main grid [4]. The operation of DGs in the network can provide different benefits for the overall network performance, if optimally scheduled and coordinated [4]. One of the most important issues in MGs is optimal operation in deregulated markets by determining the best value generation of each unit to achieve the highest profit. In this regard, distributed generators that are capable of CHP production are increasingly used in MGs as well as in RESs such as solar and wind energy sources which have stochastic nature [5]. Since, the generation of RESs is uncertain, their generation should be forecasted; on the other hand, the uncertainties of load and RESs are considered in Ref. [6].

Many studies have been carried out on the performance of MG and profit maximization objective function [7–18]. The pool electricity market of MG for PV and FC units has also been investigated in Ref. [7]. In this study, the profit maximization objective function is considered and genetic optimization algorithm is used to solve the problem. In Ref. [8], the optimal operation and participation of MGs in electricity market are proposed by considering energy sources such as WT, PV, and FC, while adopting profit-maximizing

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List of abbreviations: CHP, Combined Heat and Power; MG, Micro Grid; WT, Wind Turbine; PV, Photovoltaic; MPSO, Modified Particle Swarm Optimization algorithm; DG, Distributed Generation; TH, Thermal unit; FC, Fuel Cell; RES, Renewable Energy Source.

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Nomenclature:

$C_{Buy,t,s}$	cost of buying electrical energy in *s*th scenario
cv_f	coefficient of variation
$DT_{s,s'}$	the distance between scenarios *s* and s'
$f_{TH,h}, f_{FC-CHP,l}, f_{Wind,j}, f_{PV,q}$	cost functions related to thermal, CHP, WT, PV units respectively
$H_{Boiler,l,t,s}$	the heat generated by the boiler can be parallel CHP units in *s*th scenario
$H_{CHP,l,t,s}$	heat generated by CHP units in *s*th scenario
$H_{Demand,t,s}$	thermal load demand in *s*th scenario
$Load_{t,s}$	electrical load in time *t* in *s*th scenario
N_{bus}	total number of buses
N_{FC}	total number of FCs
N_s	number of scenarios of each batch
$P_{Buy,t,s}$	amount of electrical power bought from market in *s*th scenario
$Penalty_{Market}$, $Penalty_{Demand}$	penalty factor for market and demand
$P^t_{FCj,s}$	active power generated by *FCj* during time *t* in *s*th scenario
$P^t_{Hj,s}$	equivalent electric power for hydrogen production during time *t* in *s*th scenario
PLR_j	part load ratio of *FCj* (equal to electrical generated power/maximum power)
$P_{Max,FC}$	maximum power of FC
$P^{min}_{Unit,i,t,s}$, $P^{max}_{Unit,i,t,s}$	minimum and maximum of active power produced by Unit*i* during time t in *s*th scenario
$P_{not\text{-}supplied,Market,t,s}$	not-supplied power on the market at the time t in *s*th scenario
$P_{Sell,t,s}$,$P_{H,Sell,t,s}$	electrical power and heat energy sold to market in *s*th scenario
$P^t_{thi,s}$	produced thermal by FC in bus *i* if there is a FCPP in this bus during time *t* in *s*th scenario
$P_{TH,h,t,s}$, $P_{FC-CHP,l,t,s}$, $P_{WT,j,t,s}$, $P_{PV,q,t,s}$	generated power related to thermal, CHP, WT, PV units in *s*th scenario respectively
V_{FC}	output voltage of FC
V^t_i	voltage magnitude of the bus i during time *t*
V_{Min},V_{Max}	lowest and highest voltages of each bus
V_{ref}	nominal voltage
$X^k_{mut,j}$	mutant vector of particle *j* at iteration *k*
$X^k_{new,j}$	the trial vector
$rand(.)$	random number between 0 and 1
r_{TEj}	thermal energy to electrical energy ratio
S^{max}_{exch}	maximum power exchanged with the upstream network
T	the total time
V_{con}	over voltage due to concentration
Vel^k_j, Vel^{k+1}_j	current velocity of particle *j* at iteration*k* and *k*+1
X^k_j	current position of particle *j* at iteration *k*
ρ_s	probability of each scenario
η_{act}	activation polarization
η^t_j	efficiency of FC*j* during time *t*
η_{ohm}	ohmic polarization
η_{st}	hydrogen storage efficiency
$\pi_{penalti,Market,t,s}$	penalty factor for failing to meet the power of market at the time t in *s*th scenario
$\pi_{sell,t,s}$	tariff of electrical energy selling to market in *s*th scenario
$\pi_{Tariff,s}$,$\pi_{H,sell,t,s}$	tariff of electrical and heat energy selling to customer in *s*th scenario
μ_f	mean value of the output variable *f*
σ_f	standard deviation value of the output variable *f*

strategy. In this article, uncertainties related to the market price and electrical load are also considered. In Ref. [9], the problem of coordination between PV and electrical energy storage batteries is proposed and their participation in the electricity market is solved. The energy generated by WT and PV units as well as the energy stored by means of hydrogen and their participation in short-term electricity market are investigated in Ref. [10]. In this study, the day-ahead electricity market has been simulated and the uncertainty of WT production is considered to reach the maximum profit. In Refs. [11,12], the electricity market for distribution companies with DG units and interruptible loads has been solved. Profit maximization in both the energy and reserve markets is considered as the objective function. The coordinated scheduling of WT, PV, energy storage, and pumped storage to reach the maximum profit in the power market and ancillary services have been investigated in Refs. [13,14]. The uncertainties of WT, PV generation, and market price are considered. In Ref. [15], the problem of coordinated schedule of WT and thermal units (TH) to participate in the energy and reserve market has been modeled by multi-objective optimization problem. The objective function of this problem is the profit maximization and emission minimization. Coordinated scheduling of PV and energy storage device units with CHP units in an industrial MG is described in Ref. [16]. In this paper, the profit maximization objective function is considered. In Ref. [17], the participation of MG in the day-ahead electricity market with the goal of maximizing profits has been studied and the scenario-based method is used for modeling the uncertainties. In Ref. [18], MG was scheduled for participation in day-ahead electricity market in a way to reach the maximum profit and minimum cost while considering heat consumers. Moreover, CHP plants have been investigated from diverse and different mechanical engineering points of view such as energy balance, fueled microturbine, and thermo-economic analysis [19–21].

The performance of MG and profit maximization objective function is studied in Refs. [7–18]. Furthermore, many different types of DGs such as WT unit [7,8,10,13–15]; PV unit [7–10,13,14 and 16]; FC unit [7,8 and 10]; CHP unit [16,18]; and some DGs [11,12,17 and 18] have been applied to MGs. The uncertainties of uncertain variables of MGs have been considered in Refs. [8,10,13,14 and 17] by different methods. In the above-mentioned studies, the coordinated scheduling of WT, PV, TH, and FC-CHP units are not simultaneously considered for participation in an electricity market. Furthermore, in some of the studies mentioned above, the essential uncertainties of MGs such as electrical market price, the speed of wind, and solar radiation are not considered.

In this paper, a scenario-based stochastic programming framework is used for the coordinated scheduling of CHP, PV, WT, and TH DGs by considering uncertainties of wind speed, solar radiation, and the electrical market price. The normal probability density function is used for modeling the variation of electrical and thermal loads forecasting, solar radiation, and the electrical market price. The Weibull distribution function is used for

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