Electrical Power and Energy Systems 106 (2019) 1–16

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

Stochastic multi-objective economic-environmental energy and reserve scheduling of microgrids considering battery energy storage system

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ARTICLE INFO

Keywords:
Microgrid (MG)
Energy Management System (EMS)
Distributed Generation (DG)
Battery Energy Storage System (BESS)
Differential Evaluation (DE) algorithm

ABSTRACT

Due to environmental concerns and ever-increasing fuel costs, governments offer incentives for clean and sustainable energy production from Distributed Generations (DGs) such as Wind Turbine (WT) and Photovoltaic (PV) generators. Optimal operation of Microgrids (MGs) and management of demand side are necessary to increase the efficiency and reliability of distribution networks. In this paper, the stochastic operation scheduling of a MG consisting of non-dispatchable resources including WT and PV and dispatchable resources including Phosphoric Acid Fuel Cell (PAFC), Micro-gas Turbine (MT), and electrical storage as Battery Energy Storage System (BESS) is investigated to minimize operation cost and emissions. The problem is solved by combination of Differential Evolutionary (DE) and Modified PSO (MPSO) algorithms considering Incentive-based (IB) Demand Response (DR) program and generation reserve scheduling. A stochastic model is also proposed for energy management in MGs in the grid-connected operating mode by taking into account the uncertainty of WT and PV generations and forecasted electric demands. A scenario tree is used to generate scenarios and then, representative scenarios are selected by a scenario reduction technique based on DE. The proposed method is applied on a typical MG and simulation results illustrate its efficiency in comparison to other techniques.

1. Introduction

Recently, the awareness of energy, economic, and environmental challenges like growing demand, inadequacy of fossil fuels in future, and emission pollutants has been increased across the world. Integration of small-scale DGs, mostly based on renewable resources, near consumers has introduced MGs a promising solution for environmental/economic challenges. MGs can result in higher efficiency, reduced losses, and environmental benefits due to using renewable energy sources such as wind and solar [1]. If the variability of DG powers is successfully mitigated using different technologies such as energy storage, MGs also offer acceptable power quality. If an efficient EMS is properly developed for an MG, reliability can also be improved through MG architecture especially at times of events and peak demand hours. In addition, EMS reduces MG operational cost and optimizes energy usage by exchanging power from/to the main grid depending on generations and demands under a suitable market policy. Furthermore, EMS of MG determines optimal scheduling of DGs and supplies demands using BESSs to manage uncertainty of DGs [2–7]. Literature studies have focused on different aspects of MG energy scheduling. Some researches consider single-objective optimizations mostly minimizing operation costs of MGs by economic UC of generation units, while some others have concentrated on environmental/economic energy management in MGs. The studies that are performed for MG management can be classified from different perspectives including type of formulation, the selected objective functions, considering uncertainty in the formulation, solving method, type of DR program and etc. Table 1 lists the recent references regarding the above-mentioned perspectives. In Table 1, DR programs is categorized into two main groups that are PB-DR and IB-DR programs. These programs are also classified into several sub-categorizes [8].

Some works have addressed cost as the single-objective function. For instance, authors in [9] have utilized a deterministic model of predictive control in order to minimize the cost of MG operation and BESS scheduling by dynamically modeling the BESS. Authors in [10] proposed AMFA to optimally solve stochastic single-objective MG operation cost considering uncertainties of electrical demands, WS, and SR. In [11], an algorithm for EMS based on MACO is presented to obtain energy scheduling in MGs. The aim of study is to figure out the optimum operation of micro-sources to decrease electricity production cost by hourly day-ahead and real-time scheduling to achieve optimal set points of the generation units as well as the MG optimal topology for

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https://doi.org/10.1016/j.ijepes.2018.09.037
Received 24 February 2018; Received in revised form 28 August 2018; Accepted 22 September 2018

Nomenclature

Sets

T	set of times
S	set of scenarios
N	set of DGs
D	set of industrial customers
H	set of residential customers
C	set of commercial customers
N_r	set of DGs that are allowed to participate in reserve scheduling program

Binary variables

$u^s(i, t)$	On/off status of i^{th} DG in period t and scenario s: 1 if DG is on; 0 otherwise

Continuous variables

$cost_{DG}^s$	total operation cost of DGs in scenario s ($/h)
$cost_{grid}^s$	total cost of power exchange between the MG and the main grid in scenario s ($/h)
$cost_{DR}^s$	total cost of participating in demand bidding/buyback program in scenario s ($/h)
$cost_{RS}^s$	total expected reserve cost in scenario s ($/h)
$cost_{CL}^s$	total cost of mandatory curtailed loading in scenario s ($/h)
$cost_{BESS}^s$	total cost of power exchange between the MG and the BESS in scenario s ($/h)
$SU^s(i, t)$	cost of startup or shut-down of i^{th} DG in period t and scenario s ($/h)
$C^s(i, t)$	cost of active power generation of i^{th} DG in period t and scenario s ($/h)
$P_G^s(i, t)$	active power output of i^{th} DG in period t and scenario s (kW)
$P_{grid}^s(t)$	active power of main grid in period t and scenario s (kW)
$ID^s(d, t)$	load reduction proposed by d^{th} industrial customers in period t and scenario s (kW)
$HD^s(h, t)$	load reduction proposed by h^{th} residential customers in period t and scenario s (kW)
$CD^s(c, t)$	load reduction proposed by c^{th} commercial customers in period t and scenario s (kW)
$IR^s(d, t)$	load reduced by d^{th} industrial customers to contribute in reserve program in period t and scenario s (kW)
$HR^s(h, t)$	load reduced by h^{th} residential customers to contribute in reserve program in period t and scenario s (kW)
$CR^s(c, t)$	load reduced by c^{th} commercial customers to contribute in reserve program in period t and scenario s (kW)
$R_{DG}^s(i, t)$	Generation reduced by j^{th} DG to contribute in reserve program in period t and scenario s (kW)
$ENS^s(t)$	amount of unsupplied load in period t and scenario s (kW)
$P_{ch}^s(t)$	active power at charging mode of BESS in period t and scenario s (kW)
$P_{dch}^s(t)$	active power at discharging mode of BESS in period t and scenario s (kW)
$emission_{DG}^s$	total pollutant emissions of DGs in scenario s (kg/h)
$emission_{grid}^s$	total pollutant emissions of upstream grid in scenario s (kg/h)
$SOC^s(t)$	SOC of BESS in period t and scenario s (kW)
$P_{GPV}^s(t)$	active power output of PV in period t and scenario s (kW)
$P_{GWT}^s(t)$	active power output of WT in period t and scenario s (kW)

Parameters

ρ^s	the probability of scenario s
S_h	the number of scenarios at each hour
$B^{BESS}(t)$	price of active power of BESS for both charging and discharging mode in period t ($/kWh)
η^-	efficiency of BESS in the discharging mode
$voll(t)$	cost of unsupplied load in period t ($/kWh)
$PR_{DG}(t)$	offered price by DGs for contributing in reserve program in period t ($/kW)
$B_G(i, t)$	price of active power generation of i^{th} DG in period t ($/kWh)
$SSC_{DG}(i, t)$	price of startup or shut-down of i^{th} DG in period t ($/h)
η^+	efficiency of BESS in the charging mode
$E_G(i, t)$	pollutant emitted by i^{th} DG for generation of active power in period t (kg/kWh)
$E_{grid}(t)$	pollutant emitted by upstream grid for generation of active power in period t (kg/kWh)
$CO_{2_{DG}}(i, t)$	CO_2 emitted by i^{th} DG for generation of active power in period t (kg/kWh)
$SO_{2_{DG}}(i, t)$	SO_2 emitted by i^{th} DG for generation of active power in period t (kg/kWh)
$NO_{x_{DG}}(i, t)$	NO_x emitted by i^{th} DG for generation of active power in period t (kg/kWh)
$CO_{2_{grid}}(t)$	CO_2 emitted by the main grid for generation of active power in period t (kg/kWh)
$SO_{2_{grid}}(t)$	SO_2 emitted by the main grid for generation of active power in period t (kg/kWh)
$NO_{x_{grid}}(t)$	NO_x emitted by the main grid for generation of active power in period t (kg/kWh)
$B_{Grid}(t)$	price of active power of the main grid in period t ($/kWh)
$IO_{DR}(t)$	offered price by industrial customers for load reduction in period t ($/kWh)
$HO_{DR}(t)$	offered price by residential customers for load reduction in period t ($/kWh)
$CO_{DR}(t)$	offered price by commercial customers for load reduction in period t ($/kWh)
$IO_{RS}(t)$	offered price by industrial customers for contributing in reserve program in period t ($/kWh)
$HO_{RS}(t)$	offered price by residential customers for contributing in reserve program in period t ($/kWh)
$CO_{RS}(t)$	offered price by commercial customers for contributing in reserve program in period t ($/kWh)
$L^s(t)$	total electric demand of MG in period t and scenario s (kW)
PG_i^{min}	minimum active power limit of i^{th} DG (kW)
PG_i^{max}	maximum active power limit of i^{th} DG (kW)
UR_i	ramp up rate limit of i^{th} DG (kW/h)
DR_i	ramp down rate limit of i^{th} DG (kW/h)
Δt	time interval (h)
SOC_{max}	maximum SOC of BESS (kW)
SOC_{min}	minimum SOC of BESS (kW)
P_{dch}^{max}	maximum discharging rate of BESS (kW)
P_{ch}^{max}	maximum charging rate of BESS (kW)
$P_{forcast}^{PV}(t)$	forecasted active power output of PV in period t (kW)
$P_{forcast}^{WT}(t)$	forecasted active power output of WT in period t (kW)

Abbreviations

AMFA	Adaptive Modified Firefly Algorithm
AMPSO	Adaptive Modified Particle Swarm Optimization
BESS	Battery Energy Storage System
CQGA	Chaotic Quantum Genetic Algorithm
DB	Davies – Bouldin
DG	Distributed Generation
DE	Differential Evolutionary
DER	Distributed Energy Resource
DiG	Diesel Generator