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A decentralized robust model for optimal operation of distribution companies with private microgrids

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ABSTRACT

With the integration of microgrids (MGs) in future distribution networks (DNs), it is essential to develop a practical model for the distribution company (DISCO). Optimal operation of MGs is not generally consistent with DISCO, especially when they are operated by private owners. To this end, a decentralized robust model for optimal operation of DISCO with private MGs (PMGs) is proposed in this paper. The objective is to minimize the total operation cost of the system including DN and PMGs through coordinated operation of them. The enforced operational uncertainties are handled using an adaptive robust optimization (ARO) approach, enabling the operators of DISCO and PMGs to adjust different conservation levels during operating horizon. To respect the ownership of PMGs, a decentralized algorithm based on alternating direction method of multipliers (ADMM) is proposed to efficiently solve the resulting ARO model in which the operating problems of DISCO and PMGs are optimized independently. Case studies of a test system including modified IEEE 33-bus distribution network with three PMGs is used to demonstrate the effectiveness of the proposed model.

1. Introduction

In deregulated power systems, a distribution company (DISCO) as a private entity involves in the wholesale market to procure electricity needs of its customers within their territories. Recently, integration of distributed energy resources (DERs) (e.g. micro turbines, wind turbines, photovoltaic systems, and battery energy storage systems) into distribution networks (DN) has enabled the DISCO to perform a bi-directional power exchange, i.e. selling or purchasing power, with wholesale market and DERs. To operate the DISCO more efficiently, integrated DERs into the DN could be clustered in form of microgrids (MGs). MG is a cluster of DERs that supply electricity to the load in a localized area on the DN. MG may be operated by private owners with different utility functions. The private MG (PMG) is an independent entity which negotiates with the DISCO and schedules its DERs with the purpose of achieving higher profit while technical limits are not sacrificed. Therefore, coordinated operation of DN and multiple PMGs is challenging for the DISCO, especially when the uncertainties of renewable generations and wholesale market are considered.

A lot of studies have been focused on the optimal operation of DISCO and MGs considering economic and technical issues. In [1], a two-level decision making model for a DISCO in day-ahead electricity market is proposed considering interruptible loads (ILs) and distribution generations (DGs). In [2], a stochastic framework for short-term operation of DISCO is presented considering day-ahead and real-time markets. Authors of [3], integrate price-based demand response (DR) in short-term operation model of a DISCO. A real-time procurement strategy for a DISCO with DR aggregators is presented in [4] to maximize the profit of the company. In [5], a two-level decision-making scheme for a DISCO is proposed in which a competition is formed between DISCOs to purchase power from day-ahead market. In [6], an energy and reserve scheduling model is presented for optimal operation of MGs considering renewable generation and DR programs. The proposed model is formulated as a two-stage stochastic programing optimization problem. Authors of [7] have presented an optimal bidding strategy for MGs in both day-ahead and real-time market using robust/stochastic optimization method. In [8], an agent-based model is used for energy management of MGs and uncertainties of wind power generation and energy consumption are modeled in form of prediction intervals. Authors of [9] have proposed an optimal schedule for MGs using chance-constrained method in which islanding constraints are considered.

With high integration of DERs into DNs, it is expected that multiple MGs are organized in DNs. In the literature, several models have been

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Nomenclature

Indices and sets

d	index of interruptible load
$DG_{(n)}$	set of DGs connected to bus n
e	index of battery of energy storage
i	index of microgrid
$IL_{(n)}$	set of interruptible loads connected to bus n
j	index of DG
k	index of ADMM iteration
n, m	index of distribution network buses
$MG_{(n)}$	set of microgrids connected to bus n
r	index of renewable resource
s	index of step of price-quantity offer
t	index of time
w/pv	index of wind turbine/photovoltaic

Parameters

α, β, γ	cost function coefficients of DG
α', β', λ'	cost function coefficients of micro turbine
C^{PV}/C^{WT}	cost of maintenance and operation of photovoltaic/wind turbine
C_{OM}^{BS}	maintenance cost of battery energy storage
$\varepsilon_{(i,t)}/\varepsilon'_{(i,t)}$	self-elasticity of responsive load indicating its variation during hour t to the price during that hour/cross-elasticity of responsive load indicating its variation during hour t to hour t'
δ	offer of interruptible load at each step
η^{Bd}/η^{Bc}	discharge/charge efficiency of battery energy storage
$\Gamma_0/\Gamma_{(t)}$	uncertainty budget of wholesale price/renewable generation
I_{sub}	current flow allowed at substation
k_{SOC}	a scalar parameter related to minimum state of charge of battery
L_0^{MG}	initial demand of responsive load in microgrids
Lp/Lq	active/reactive load demand at each bus
Lp^{DN}/Lq^{DN}	active/reactive load demand at each bus of distribution network
π_0^{MG}	based electricity price offered to microgrids
π^{IL}	price of interruptible load at each step
π^{WS}	forecasted price of wholesale market
r_L/x_L	resistance/reactance of feeders of distribution network
SDC	shut-down cost of DG
u	commitment state of DG
SUC	start-up cost of DG
u^{ON}/u^{OFF}	start-up/shut-down status of DG
UR/DR	ramp up/down of DG
UT/DT	minimum up/down time of DG
ν, η, yp, yw	auxiliary variables in robust approach
ζ^{WS}/ζ^{REN}	degree of wholesale price/renewable generation uncertainty

Variables

bsc/bsd	charge/discharge status of battery energy storage
CIL	compensation cost of interruptible loads
CMG	operation cost of microgrid
l/v	auxiliary variables introduced in the AC power flow equations
L^{MG}	responsive load demand of microgrids
P^{Bd}/P^{Bc}	discharge/charge power of battery energy storage
P^{DG}/Q^{DG}	active/reactive power generation of DGs
P^{flow}/Q^{flow}	active/reactive power flow thorough feeders of distribution network
P^{IL}/Q^{IL}	active/reactive power interuption of interruptible load
$P^{MG-\mathrm{Im}}/P^{MG-Exp}$	power imported/exported from distribution network to microgrid
P^{MT}	power generation of micro-turbine
P^{REN}	total power generation of wind turbines and photovoltaic systems
P^{WT}/P^{PV}	power generation of wind turbine/photovoltaic system
P^{WS}/Q^{WS}	active/reactive exchanged power with wholesale market
π^{MG}	time varying prices offered by microgrids to their responsive loads
SOC	state of charge of battery energy storage
V	voltage of distribution network busses.

Symbol

$\bar{(\cdot)}/\underline{(\cdot)}$	maximum/minimum bounds of $(\cdot)$
$\widehat{(\cdot)}$	deviation of $(\cdot)$ from forecasted value
$\widetilde{(\cdot)}$	uncertain value of $(\cdot)$

proposed to operate multiple MGs systems optimally. Authors of [10] present a stochastic energy management system in which daily optimal scheduling of networked MGs are performed. In this paper, a centralized operator is the main entity responsible for coordination of MGs. In [11], a distributed robust energy management system scheme for multiple interconnected MGs is developed to minimize total operation cost of MGs. Based on [11], authors of [12] have presented an optimal energy and reserve scheduling model for a system of multiple MGs. In [13], a centralized model is proposed for optimal operation of interconnected MGs in which network reliability is considered. Ref. [14] solves the optimal power dispatch problem of multiple MG system in which total cost of power generation in each MG as well as the total cost of exchanged power between MGs and the main grid is minimized. A stochastic model has been adopted to model uncertainties in load and renewable energy sources.

The above-mentioned studies assumed that MGs trade power among themselves without considering the role of DISCO. However, since MGs are connected to DN through electrical network and exchange power with it, the operating strategies of DISCO and MGs affect their operating costs. Therefore, the operation of DISCO and MGs needs to be coordinated during the operating horizon. In [15], a multi-objective bi-level optimal operation model for DN with grid-connected MGs is explained. In the same work, the uncertainties are ignored and a genetic algorithm is used to optimize the proposed model. In [16] an agent-based energy management system is introduced to schedule a DN with MGs considering a transactive market. DR actions and energy storage devices are also utilized to manage energy imbalances of MGs. In [17], a system of systems model is proposed for hourly operation scheduling of active DNs including multiple MGs. In the proposed model, active DN and MGs are considered autonomous systems, which are coordinated using a hierarchical optimization algorithm.

In DNs with multiple MGs that might have private owners, the optimal operation of the whole system including the DISCO and the PMGs becomes more complicated. In this regard, a centralized coordination model may violate the ownership of entities. Meanwhile, centralized models may increase computational complexity of operating model and possibility of congestion in communication networks. Furthermore, in DN with multiple MGs operation uncertainties can be intensified especially if MGs are located in the same geographical area. The above-mentioned studies have considered the operation uncertainties using the scenario-based methods, which their optimality depends on the accuracy of the probability distribution function (PDF) and the number