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Optimal bidding strategy for microgrids in joint energy and ancillary service markets considering flexible ramping products ☆

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HIGHLIGHTS

- Flexible ramping products are modelled in the framework of a microgrid.
- Microgrids' optimal bidding model is proposed in energy and ancillary service markets.
- A hybrid stochastic and robust optimization approach is adopted.
- The effectiveness of the proposed bidding model is verified based on real-world data.

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ABSTRACT

Due to the volatile nature of wind and photovoltaic power, wind farms and solar stations are generally thought of as the consumers of ramping services. However, a microgrid (MG) is able to strategically integrate various distributed energy resources (DERs) to provide both energy and ancillary services (ASs) for the bulk power system. To evaluate the ramping capabilities of an MG in the joint energy and AS markets, an optimal bidding strategy is developed in this paper considering flexible ramping products (FRPs). By aggregating and coordinating various DERs, including wind turbines (WTs), photovoltaic systems (PVs), micro-turbines (MTs) and energy storage systems (ESSs), the MG is able to optimally allocate the capacities for energy, spinning reserve and ramping. Taking advantage of the synergy among DERs, the MG can maximize its revenues from different markets. Moreover, the flexibility of the MG for the bulk power system can be fully explored. To address the uncertainties introduced by renewable generation and market prices, a hybrid stochastic/robust optimization (RO) approach is adopted. Case studies based on a real-world MG with various DERs demonstrate the market behavior of the MG using the proposed bidding model.

1. Introduction

1.1. Motivation

The development of renewable energy has been drawing attention across the world in the past decade. California, for example, announced its ambitious goal of achieving a 50% renewable portfolio standard by 2030 [1]. While the use of renewable energy contributes to a more sustainable future, the variabilities and uncertainties of the renewable sources pose great challenges to the economic and reliable operations of the power system [2]. With the increasing penetration of renewable energy, rapid ramping of generation resources may be insufficient to smooth out the huge fluctuations in renewable energy production. Thus, it is critical to facilitate the accommodation of renewable generation while economically and reliably operating the power system.

The concept of the microgrid (MG) assumes a cluster of loads and distributed energy resources (DERs) operating as a single controllable system [3]. Taking advantage of the synergy among various DERs, the renewable generators can cooperate with controllable energy resources to provide both energy and ancillary services (ASs) for the bulk power system [4]. For example, in a

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Nomenclature

Indices and sets

t	time index
s	price scenario index
Φ^B	set of decision variables
Φ^U	set of random variables
E	superscript for energy
RES	superscript for spinning reserve service
$RAMPU$	superscript for upward FRP service
$RAMPD$	superscript for downward FRP service
WT	superscript for wind turbines
PV	superscript for photovoltaic systems
MT	superscript for micro-turbines
ESS	superscript for energy storage systems

Parameters and constants

$\hat{P}_t^{WT}$	point forecast of historical wind power (Unit: MW) in the MG at time slot t
$\hat{P}_t^{PV}$	point forecast of historical solar power (Unit: MW) in the MG at time slot t
Γ_t^{WT}	robustness parameter of wind power
Γ_t^{PV}	robustness parameter of solar power
$P_{\max}^{WT}$	total wind power capacity (Unit: MW) in the MG
$P_{\max}^{PV}$	total solar power capacity (Unit: MW) in the MG
N^{MT}	number of MTs in the MG
N^{ESS}	number of ESSs in the MG
γ_s	weight of price scenario s
N^S	number of price scenarios
$\lambda_{t,s}^{(\cdot)}$	day-ahead market price (Unit: \$/MW h) at time slot t in scenario s
h	time interval
$\beta^{(\cdot)}$	expectation of real-time deployment ratio of ancillary services
c_i^{MT}	operation cost per unit energy production (Unit: \$/MW h) of MT i
$P_{i,\max}^{MT}$	maximal power (Unit: MW) of MT i
$P_{i,\max}^{MT,RAMPU}$	Maximal ramping-up capacity (Unit: MW/h) of MT i
$P_{i,\max}^{MT,RAMPD}$	maximal ramping-down capacity (Unit: MW/h) of MT i
$P_{i,\alpha,\max}^{ESS}$	maximal charging power (Unit: MW) of ESS i
$P_{i,\beta,\max}^{ESS}$	maximal discharging power (Unit: MW) of ESS i
$\eta_{i,\alpha}^{ESS}$	charging efficiency of ESS i
$\eta_{i,\beta}^{ESS}$	discharging efficiency of ESS i
$SOC_{i,\min}^{ESS}$	minimal state of charge of ESS i
$SOC_{i,\max}^{ESS}$	maximal state of charge of ESS i
C_i^{ESS}	capacity (Unit: MW h) of ESS i
$E_{i,0}^{ESS}$	initial stored energy (Unit: MW h) of ESS i in scenario s
P_t^D	load demand (Unit: MW) of the MG at time slot t

Variable

P_t^{AWT}	random variable of available wind power (Unit: MW) at time slot t
P_t^{APV}	random variable of available solar power (Unit: MW) at time slot t
ε_t^{WT}	normalized error between actual and point forecast wind power
ε_t^{PV}	normalized error between actual and point forecast solar power
$R_s^{(\cdot)}$	revenue (Unit: \$) in scenario s from the day-ahead markets
C^{OP}	operation costs (Unit: \$) of the MG
$P_t^{(\cdot)}$	bidding capacity (Unit: MW) of the MG or DER for energy or ASs at time slot t
$\alpha_{i,t}^{ESS}$	binary variable of ESS i at time slot t representing the status of charging
$\beta_{i,t}^{ESS}$	binary variable of ESS i at time slot t representing the status of discharging
$E_{i,t}^{ESS}$	stored energy (Unit: MW h) of ESS i at time slot t

stand-alone mode, a wind farm must deviate from its maximum power output status and leave a margin to provide ramping services for the system. However, in an MG, the wind farm is able to leave the ramping margin by charging a Na/S battery without deviating from its maximum power. Hence, an MG can stably provide both energy and ASs by integrating various DERs [5]. From the system point of view, MGs show the advantages of low investment costs, low pollutant emission and high operational flexibility. The flexibility of the MGs provided by the DERs can be aggregated for power system operations, thereby replacing high-cost centralized units and deferring the generation expansion. In addition, the MGs are located at the demand side, efficiently offering capacities to meet the local requirements [6]. Compared with centralized thermal units, MGs can achieve localized energy balance without the loss accompanied with long-distance power transmission and difficulties caused by transmission congestions. Therefore, the concept of the MG provides new insights for exploring the grid-friendly manner of DERs [7].

In most electricity markets across the world, ASs play a critical role in the reliable operation of power systems. In California, for example, the reserve and regulation services are co-optimized with the energy in the day-ahead market. With the increasing penetration of solar energy, the variability and uncertainties in net load demands will become more severe in the real-time operation. As illustrated in Fig. 1, the steep rise of the system net loads from 17:00 to 18:00 as the sun sets requires over 5500 MW of generating capacity to come online, which poses great challenges to the secure operation of the power system.

To cope with the inadequacy of the system's ramping capacities, the flexible ramping product (FRP) has been introduced into the California market recently to improve the dispatch flexibility and address the operational challenges [8,9]. FRPs are flexible generation capacities dispatched by the independent system operator (ISO) to deal with energy imbalances and satisfy the load following requirements in the real-time operation. The energy imbalances

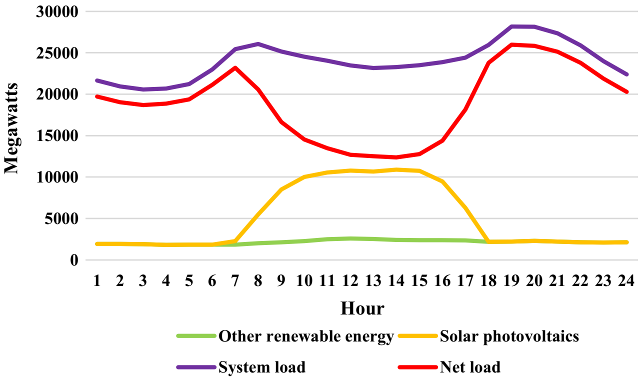

Fig. 1. Hourly renewable energy and electric load demands on March 1, 2017 in California.