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Bidding strategy of microgrid with consideration of uncertainty for participating in power market

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ABSTRACT

Microgrid is commonly regarded as an efficient way for integration of distributed generation (DG) in low voltage network. However, the integration method of microgrid in power system for maximum benefit needs to be further promoted. In this paper, a stochastic bidding strategy of microgrid in a joint day-ahead market of energy and spinning reserve service is proposed taking into account of uncertainty of renewable DG units' output power and load. The stochastic bidding strategy is modeled as bi-level optimization problem and can be divided into two steps. First, Latin Hypercube Sampling (LHS) is utilized for generating microgrid uncertain net power scenarios according to day-ahead uncertain power scenario models, and then reduced by backward scenario reduction technique for less computation. Second, the upper level total bidding profit including bidding revenue, expected imbalance and operation cost is optimized by interior point algorithm in MATLAB for making optimal bids. The expected imbalance and operation cost is calculated by iteratively invoking lower level deterministic unit commitment under each microgrid uncertain net power scenario. The lower level deterministic unit commitment is coded and solved by mixed integer nonlinear programming (MINLP) solver DICOPT in GAMS. Finally, the optimal energy and spinning reserve bids are given by solving the bi-level bidding model. The model is applied to a modified typical low-voltage microgrid and the effectiveness and excellence of proposed strategy is proven by comparing simulation results with traditional deterministic bidding strategy.

1. Introduction

The worldwide trend of exploitation of distributed generation (DG) as the alternative to traditional generation keeps on increasing. Distributed generation is small scale generation units installed close to the consumers. In this way, transmission losses and network congestion can be mitigated. Moreover, the renewable DG units are widely utilized among the different types of DG units due to green, sustainable and free energy source. However, the intermittent and the uncertain power output of isolated renewable DG units adversely impact power quality and system stability and the problem becomes especially severe with high penetration of renewable DG units. To solve the problem, microgrid is promoted as an active control method to aggregate DG units and provides heat and power to local consumers [1]. Generally, energy storage system (ESS) is included in the microgrid for balance between power production and consumption. More friendly and efficient DG integration can be achieved by microgrid with the benefit of carbon emissions reduction, power quality improvement, reliability enhancement, energy supply cost reduction and mitigation of power network expansion pressure [2].

Even though microgrid has many benefits, the integration of microgrid into the traditional distribution system imposes technical challenges of system operation in several aspects, such as energy management strategy, protection design and so on, that have to be comprehensively investigated. So far, many investigations have been conducted in the aspect of power control strategy of DG units [3–7], microgrid energy management strategy [8–12], protection design [13,14], optimal sizing and placement [15–17], reliability and stability assessment [18–20] and so on. Among these issues, research of interaction paradigm between microgrid and traditional system is crucial for maximizing potential benefits of microgrid and ultimately encouraging DG or microgrid adoption. In consideration of free-market conditions, optimal operation of microgrid in energy or ancillary service market has been investigated in [21–26]. These research or practical application would facilitate integration of microgrid with more effectiveness and profitability. However, uncertainty including renewable DG units' power output, market price, and lines/units reliability is lack of consideration in these models. Therefore, probabilistic energy

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Nomenclature

t, k	index for time interval and uncertain net power scenario of microgrid
S_i^t	status of DG unit i at hour t (on = 1, off = 0)
u_i^t, d_i^t	start-up or shut-down decision for DG unit i at hour t
n	number of preserved scenarios
p_k	probability of preserved scenario k
m	number of dispatchable DG units
d_T	duration time of bidding interval, e.g. 1 h
C_i^t	generation cost function of DG unit i at hour t (cents)
C_L^t	payback cost function of curtailed load at hour t (cents)
C_{bes}^t	operational cost of battery energy storage system at hour t (cents)
$C_{u,i}^t, C_{d,i}^t$	C start up and shut down costs of DG unit i at hour t (cents)
S_{DG}	set of other dispatchable DG units
$E_{Grid,\max}$	the maximum exchanging power between microgrid and the upstream grid (kW)
$E_{bes,\max}$	installed capacity of battery energy storage (kW h)
$L_{curt,\max}$	upper limit for curtailing on interruptible load (kW)
$M_{SR,i}$	ramping capacity of DG unit i for providing spinning reserve (kW/min)
$M_{UT,i}$, $M_{DT,i}$	minimum up and down time limits of DG unit i (h)
$P_{i,\min}$, $P_{i,\max}$	lower and upper limits on generation of DG unit i (kW)
$r_{u,i}$, $r_{d,i}$	ramping up and ramping down limit of DG unit i (kW/h)
$r_{ch,\max}$, $r_{dis,\max}$	maximum charge and discharge rate of battery energy storage (kW)
$T_{on,i}^t, T_{off,i}^t$	number of hours for which DG unit has been on/off at hour t
η_{ch}, η_{dis}	charge and discharge efficiency of battery energy storage system
$\xi_{bes,\min}$	the lower limit of state of charge of battery energy storage system
AR_{MG}	adequacy reserve maintained by microgrid (kW)
ρ_E^t, ρ_R^t	price of energy and spinning reserve market at hour t (cents/kW h)
ρ_L^t	retail energy rate of microgrid at hour t (cents/kW h)
$\rho_{Eimb}^t, \rho_{Rimb}^t$	imbalance price of energy and spinning reserve market at hour t (cents/kW h)
$\rho_{Eimbp}^t, \rho_{Eimbn}^t$	imbalance price of energy market in positive and negative imbalance at hour t (cents/kW h)
$\rho_{Rimbp}^t, \rho_{Rimbp}^t$	imbalance price of spinning reserve market in positive and negative balance at hour t (cents/kW h)
$\rho_{Load,f}^t, \rho_{MG,f}^t$	forecasted load and net power of microgrid at hour t (kW)
$P_{load,t}^t, P_{loadcurt}^t$	served and un-served load of microgrid at hour t (kW)
$P_{WT,f}^t, P_{PV,f}^t$	wind power and photovoltaic power forecast at hour t (kW)
$P_{MG,k}^t, P_{Load}^t$	microgrid net power and load demand in scenario k (kW)
P_i^t	power generation of DG unit i at hour t for energy market (kW)
P_{bes}^t	charged/discharged power of battery energy storage system at hour t (kW)
E_{bes}^t	the storage energy of battery energy storage system at hour t (kW h)
E_{MGd}^t, E_{MGs}^t	bids of microgrid in energy market at hour t under deterministic and stochastic bidding strategy (kW)
R_i^t, R_L^t	bids of DG unit i and interruptible load in spinning reserve market at hour t (kW)
R_{MGd}^t, R_{MGs}^t	bids of microgrid in spinning reserve market at hour t under deterministic and stochastic bidding strategy (kW)
$E_{MG,k}^t, R_{MG,k}^t$	the exchanging power and provided spinning reserve of microgrid at hour t in scenario k (kW)

manage strategy were proposed under uncertainty environment in [27–30]. Furthermore, the uncertainty is actually inevitable and bound up with maximum benefit of microgrid in competitive power market. The bidding strategy of microgrid with consideration of uncertainty in power market has not been specially studied yet.

Therefore, this paper focuses on the paradigm of microgrid participating in power market for providing energy and spinning reserve taking into account of uncertainty. The uncertainty in wind speed, solar irradiance and load during each operation period of next day is implemented through multi-scenario technique. The main contributions of the work are as follows:

1. Presenting a stochastic bidding strategy for microgrid participating in energy and spinning reserve market in consideration of uncertainties of load and available output power of wind and photovoltaic units.
2. Backward scenario reduction method is employed to decrease the computation time.
3. In the stochastic bi-level optimization bidding model, the imbalance and operation cost is supposed to be minimized in each scenario. It implies that integration of renewable DG units in microgrid would not only maximize utilization of renewable power but also mitigate the uncertainty of renewable power. In this way, the potential benefit of renewable power and microgrid is expected to be maximized in power market.

2. Control strategy and market framework

In general, small modular generation units (wind turbines, photovoltaic arrays, fuel cells, micro-turbines, diesel engines, etc.), storage devices and loads are connected into microgrid together. In islanded mode, power balance must be maintained continuously for frequency stability. The intermittence and randomness of renewable power output (wind turbines, photovoltaic arrays) should be managed by efficient dispatch of dispatchable generation units, energy storage units and controllable load. In interconnected mode, the power can be exchanged between microgrid and upstream grid by interconnection line. The capacity is generally adequate compared to the local demands even though with the physical limit of interconnection line. However, under deregulated energy environment, microgrid may be a participant of power market for maximizing its own profit. Regardless of the operation mode, it is obvious that the control strategy is vital for secure and economic operation.

Significant researches have been carried out on control strategy of microgrid, ranging from centralized control [8] to decentralized control [6,12]. In centralized control, the DG units and responsive loads in the whole microgrid are coordinated via the microgrid central controller (MGCC). The MGCC is responsible for the maximization of the microgrid revenues for participating in power market and optimization of its operation. Advance information and communication infrastructure is required to collect system frequency, real-time production/consumption, energy and ancillary