A TWO-STAGE OPERATING STRATEGY OF MICROGRIDS WITH CONSIDERATION OF UNCERTAINTY FOR PARTICIPATING IN POWER MARKET

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ABSTRACT

In this paper, a two-stage strategy is proposed for the microgrid to optimize the energy bids for the day-ahead (DA) and real-time (RT) balancing market, respectively. The uncertainty of the energy prices in DA and RT market, the output power of renewable energy resources and the load demand are considered and modeled in this paper. In the first stage, the microgrid simultaneously optimizes the energy bids in both the DA and RT market. After the DA market clearing, the cleared energy quantity and energy price are known. The microgrid re-optimizes the bids for RT market during the DA rebidding period. Comprehensive case studies based on the codes and data of PJM power market show that the proposed strategy can minimize the total cost of the microgrid.

NOMENCLATURE

α_p	The probability of scenario p
α_ω	The probability of scenario ω
$C_{i,t,p,\omega}$	The operating cost of unit i in scenario $p\,\omega$ during period t
$P_{i,t,p,\omega}$	The output power of unit i in scenario ω during period t
$s_{i,t,\omega}$	Binary variable. 1 if unit i is scheduled on in scenario $p\,\omega$ during period t and 0 otherwise.
$C^{up}_{i,t,p,\omega}$	The startup cost of unit i in scenario $p\,\omega$ during period t
$C^{bes}_{t,p,\omega}$	The charging/discharging cost of the battery energy storage in scenario $p\,\omega$ during period t
$P^{bes}_{t,p,\omega}$	The charging/discharging power of the battery energy storage in scenario $p\,\omega$ during period t
$C^{L}_{t,p,\omega}$	The cost of load curtailment in scenario $p\,\omega$ during period t
$P^{lc}_{t,p,\omega}$	The load curtailed in scenario $p\,\omega$ during period t
$P^{da}_{t,p}$	The bid power in the DA energy market in scenario p
$P^{rt}_{t,p}$	The bid power in the RT energy market in scenario p
Δt	Time interval
$p^{da}_{t,p}$	The energy price in the DA market during period t in scenario p
$p^{rt}_{t,p}$	The energy price in the RT market during period t in scenario p
$P^{load}_{t,p,\omega}$	The forecast load demand in scenario $p\,\omega$ during period t
$P^{w}_{t,p,\omega}$	The forecast output power of wind turbine in scenario $p\,\omega$ during period t
$P^{p}_{t,p,\omega}$	The forecast output power of photovoltaic arrays in scenario $p\,\omega$ during period t
$P_i^{\min}/P_i^{\max}$	The minimum/maximum output power of of unit i
r_i^u/r_i^d	The ramping up and ramping down limit of unit i during period t
$r_{ch}^{\max}/r_{dc}^{\max}$	The maximum/minimum charging/dis-charging power of the battery energy storage
$E^{bes}_{t,p,\omega}$	The energy content of the battery energy storage in scenario $p\,\omega$ during period t
$E^{bes}_{\max}/E^{bes}_{\min}$	The maximum/minimum energy content of the battery energy storage
η^{ch}/η^{dc}	The charging/discharging efficiency of the battery energy storage
$L_{\max}$	The maximum load curtailment
$P^{\max}_{grid}$	The maximum exchanging power between microgrid and the upstream grid

1. INTRODUCTION

The microgrid paradigm is a promising power system configuration for the utilization of distributed energy resources. Generally, a microgrid can be defined as a low voltage distribution network comprising various distributed generations (DGs), battery storage systems (BESs), and responsive loads that can be operated in both grid-connected and islanded modes [1].

Connected to the main distribution network, a microgrid can import or export power to the main distribution network under different market tariffs and microgrid operational conditions [2-3]. From the point of view of the power grid, a microgrid can be considered to be a controllable element and be able to exchange energy with the upstream grid [4-6]. The interaction paradigm between microgrid and the power grid is crucial for maximizing potential benefits of microgrid and ultimately encouraging DG or microgrid adoption. In general, a microgrid can participate in the energy markets to buy or sell energy from or to the upstream grid. In consideration of free-market conditions, optimal operation of microgrid in energy has been investigated in [7-8]. These researches facilitate integration of microgrid with more effectiveness and profitability. However, the uncertainty of the output power of renewable energy resource is not considered in these papers. Probabilistic energy management strategy are proposed considering the uncertainty environment in [9-10].

In this paper, we propose a two-stage strategy for a microgrid to participate in the day-ahead (DA) and real-time (RT) balancing energy market for cost minimization. The uncertainty of the energy prices in both the DA and RT market, the forecast load, the output power of renewable energy resources is considered. The energy bids in both the DA and RT market are optimized in the power market. In the first stage, the microgrid optimizes the energy bids for the DA and RT market, considering the uncertainty of the energy price, the output power of the renewable resource and the load demand. After the DA market clearing, in the RT balancing market, the microgrid re-optimizes the bids for RT market during the DA rebidding period.

2.MARKET PARTICIPATION OF THE MICROGRID

The microgrid aggregates DG units and provides power to local consumers. In addition, BES and renewable resources are included in the microgrid. The Microgrid can exchange power with upstream grid by interconnection line, as shown in Fig. 1.

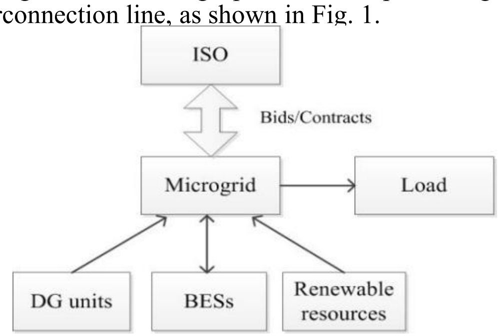

Fig. 1. The operation model of the microgrid.

We assume that the microgrid behaves as a price-taker since its limited capacity is hard to affect the market prices. The microgrid submits nonpriced energy bids for the DA and RT energy market, which are assumed to be cleared in the market. In the DA bidding period, the microgrid optimizes the energy bids for the DA and RT market. In the rebidding period, the microgrid can re-optimize the energy bids for the RT market at the rebidding period.

3. UNCERTAINTY MODELING

The bidding decisions in the DA market must be made one day in advance and for all the hours of the following day. At that time, the output power of the renewable energy resources is unknown because it is hard to forecast. In order to make the optimal bidding decisions, it is necessary to represent the uncertainty in these variables. In this paper, the uncertainty of forecast errors of the market prices, the renewable power and load demand is considered and modeled for microgrid participating in the DA and RT energy market. The DG units' unreliability uncertainty is not taken into consideration in this paper. The uncertainty of future market prices, wind power, photovoltaic (PV) power and load demand are modeled as multiple different scenarios. Thereby the stochastic optimization of microgrid bidding strategy can be solved by comprehensively executing different deterministic scenario optimization. The objective of the bidding strategy is to find the optimal bids considering all the probability of microgrid uncertain net power scenarios.

We assume that data concerning accuracy of the forecast are known. Wind speed forecast is also available for the microgrid. We use the autoregressive moving average series (ARMA) to simulate the scenarios of the wind speed forecast errors. Similar to wind power uncertainty modeling, the PV power output is mainly determined by solar irradiance. Hence, the uncertainty of PV power in this paper is derived from solar irradiance uncertainty. Detail information can be found in [4]. Moreover, the uncertainty of load demand and market price is modeled based on the load and price forecast errors. In this paper, a Gaussian distribution with specific lower and upper limits is used to model the probability density function of the hourly load and price forecast errors.

4.THE PROPOSED TWO-STAGE STRATEGY

In this section, we propose a two-stage strategy for the microgrid to minimize its total operating cost. In the DA market, the microgrid simultaneously optimizes the DA and RT energy bids, considering the uncertainty of the market price, the output power of the renewable resources and load demand. In the second stage, the microgrid re-optimize the energy bids for the RT energy market at the rebidding period, considering the DA cleared results.

The objective of the first stage is to minimize the total cost, including the energy cost in both the DA and RT market, the total generation cost of DG units, the discharging cost and the cost of demand response.

$$\begin{aligned}\min \sum_{p} \alpha_p \{ \sum_{t} \{ & (-P_{t,p}^{da} p_{t,p}^{da} - P_{t,p}^{rt} p_{t,p}^{rt}) \\ & + \sum_{\omega} \alpha_\omega (\sum_{i} [C_{i,t,p,\omega}(P_{i,t,p,\omega}) s_{i,t,p,\omega} + C_{i,t,p,\omega}^{up}] \\ & + C_{t,p,\omega}^{bes}(P_{t,p,\omega}^{bes}) + C_{t,p,\omega}^{L}(P_{t,p,\omega}^{lc})) \} \}\end{aligned} \quad (1)$$

$$C_{i,t,p,\omega}(P_{i,t,p,\omega}) = a_i (P_{i,t,p,\omega})^2 + b_i P_{i,t,p,\omega} + c_i \quad (2)$$

$$C_{t,p,\omega}^{bes}(P_{t,p,\omega}^{bes}) = a^{bes} \left| P_{t,p,\omega}^{bes} \right| + b^{bes} \quad (3)$$

$$C_{t,p,\omega}^{L}(P_{t,p,\omega}^{lc}) = a^{L} P_{t,p,\omega}^{lc} \quad (4)$$

s.t.

$$P^{da}_{t,p} + P^{rt}_{t,p} + \sum_i P_{i,t,\omega} + P^{bes}_{t,\omega} = P^{load}_{t,\omega} - (P^{w}_{t,\omega} + P^{p}_{t,\omega}) \quad \forall t \forall \omega \forall p \tag{5}$$

$$P_i^{\min} \le (P_{i,t,p,\omega} + R_{i,t,p,\omega}) s_{i,t,p,\omega} \le P_i^{\max} \quad \forall i \forall t \forall \omega \forall p \tag{6}$$

$$P_{i,t+1,p,\omega} - P_{i,t,p,\omega} \le r_i^u \quad \forall i \forall t \forall \omega \forall p \tag{7}$$

$$P_{i,t,p,\omega} - P_{i,t+1,p,\omega} \le r_i^d \quad \forall i \forall t \forall \omega \forall p \tag{8}$$

$$P^{bes}_{t,p,\omega} \le \min(r_{ch}^{\max}, r_{dc}^{\max}) \quad \forall t \forall \omega \forall p \tag{9}$$

$$\begin{cases} E^{bes}_{t+1,p,\omega} = E^{bes}_{t,p,\omega} + P^{bes}_{t,p,\omega} \Delta t \eta^{ch}, & \text{charged} \\ E^{bes}_{t+1,p,\omega} = E^{bes}_{t,p,\omega} + P^{bes}_{t,p,\omega} \Delta t / \eta^{dc}, & \text{discharged} \end{cases} \tag{10}$$

$$E^{bes}_{\min} \le E^{bes}_{t,p,\omega} \le E^{bes}_{\max} \quad \forall t \forall \omega \forall p \tag{11}$$

$$0 \le P^{lc}_{t,p,\omega} \le L_{\max} \quad \forall t \forall \omega \forall p \tag{12}$$

$$-P^{\max}_{grid} \le P^{da}_{t,p,\omega} \le P^{\max}_{grid} \quad \forall t \forall \omega \forall p \tag{13}$$

$$-P^{\max}_{grid} \le P^{rt}_{t,p,\omega} \le P^{\max}_{grid} \quad \forall t \forall \omega \forall p \tag{14}$$

Where $a_i / b_i / c_i$, a^{bes} / b^{bes} and a^L are parameters of the cost of the units, BES and responsive load, respectively.

In (1), the first term represents the total profit from bidding in market, which is the total energy cost in the DA and RT market. The second term denotes the total generation and start-up cost of the DG units. The operating cost of the units is shown in (2). The third term is the operational cost of energy storage system. It is assumed be to a linear function of the absolute value of charged/discharged capacity, as shown in (3). The last term is the cost of the demand response and modeled as a linear function of load curtailment, as shown in (4).

Constraints (5) represents the supply-demand balance. The technical limits of the DG units, including the upper and lower generation constraints, the ramp-up and ramp-down constraints, are shown in (6)-(8). Constraints (9)-(11) show the maximum charging/dis-charging power limits, minimum and maximum energy stored of the energy storage system. The load curtailment should be less than the maximum percentage of the load specified by the consumers, as shown in (12). The energy transferred between microgrid and upstream grid is limited by the capacity of tie lines, as shown in (13) and (14).

In the second stage, on the one hand, the cleared energy quantity and prices in the DA market are known, which are parameters rather than the valuables in this stage. On the other hand, the forecast prices of the RT market and the forecast output power of the DG generators can be updated. Hence, in the rebidding period, the microgrid can re-optimize the bids for the RT markets.

5. CASE STUDY

The microgrid consists of a wind turbine, PV panel, fuel cell, microturbine, diesel generator, and BES, as shown in Fig. 2. The DG units' data is adopted from [12] and listed in Table 1. All DG units are supposed to produce active power at unity power factor.

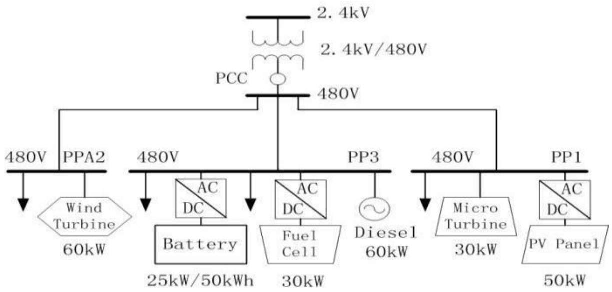

Fig. 2. The microgrid test system..

Table 1 DG units in microgrid.

DG units	Min power (kW)	Max power (kW)	b_i($/ kWh)	C_i ($)	Start up cost ($)
Diesel	20	60	0.0304	1.30	3
Micro-turbine	10	30	0.0397	0.40	2
Fuel Cell	10	30	0.0267	0.38	1.5

Based on the wind speed forecast result, 10 wind speed scenarios are generated and the corresponding wind generation power outputs are calculated, as shown in Fig.3. The maximum power and generation cost of the wind turbine are 60 kW and 0, respectively. The standard deviations of forecast errors of solar irradiance are assumed to be 10%. Ten scenarios of solar irradiance are generated and the corresponding PV output power is calculated. The capacity of the battery is 50 kWh with a maximum charging/discharging power of 25 kW and the battery efficiency is assumed to be 0.9.

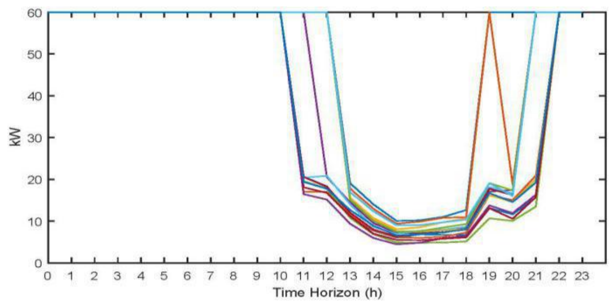

Fig. 3. Ten wind power scenarios.

The forecast DA and RT energy prices are hourly prices of December 31, 2017 in PJM market, as shown in Fig. 4. Fig. 5 shows the ten DA market price scenarios.

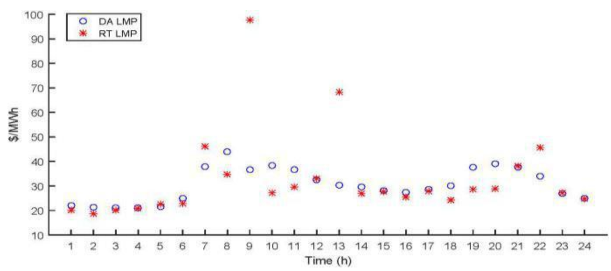

Fig. 4. Forecast DA market price.

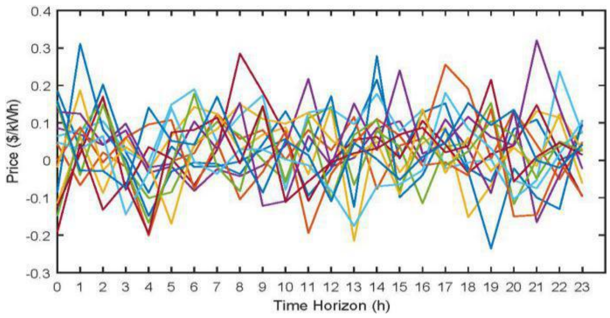

Fig. 5. Ten DA market price scenarios.

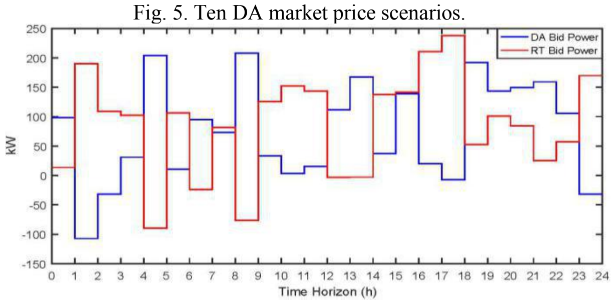

Fig. 6. The optimal results of the proposed strategy.

Fig. 6 illustrates the optimal results including DA bid power and RT bid power. Remarkable difference can be found between the DA bid power curve and the RT one. As shown in Fig. 4 and Fig. 6, when the DA LMP is higher than RT LMP the microgrid is inclined to buy less energy (or sell energy) in the DA market (e.g., 1:00-3:00, 10:00-12:00),.

As seen in Fig. 7, because the energy price minus the production cost of DG units is smaller than zero. Therefore, the DG units are not economic to be on and operate at the minimum level. When the RT LMP is higher than the production cost of DG units, the DG units are on and sells power to energy market as much as possible (e.g., 12:00-13:00, 8:00-9:00). At thses periods, the BES is generally discharged to supply energy. The quantity of load curtailment is zero during the whole periods because the payback prices are too high.

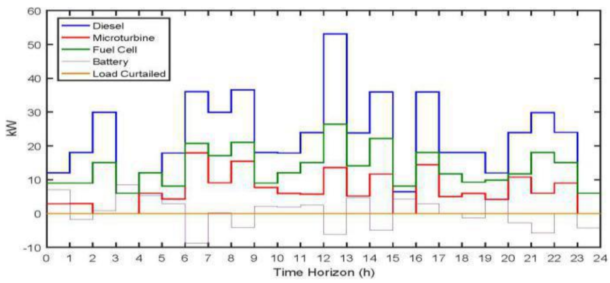

Fig. 7. Allocated power of DG units, battery and interruptible load to energy market.

6. CONCLUSION

We propose a two-stage strategy for the microgrid that participates in both the DA and RT energy markets. The uncertain of market prices, the output power of intermittent renewable resources and load demand are modeled via scenarios based on forecasts. In the first stage, the microgrid simultaneously optimizes the energy bids for DA and RT market in the DA market bidding period. After the DA market clearing, the microgrid re-optimizes the bids for RT market during the DA rebidding period. The proposed strategy can help the microgrid to minimize its total operating cost when participating in the energy market.

REFERENCES

[1] (2003). CERTS Microgrid Concept. [Online]. Available: http://certs.lbl.gov/certs-der-micro.html
[2] Pei, Wei, et al. "Optimal Bidding Strategy and Intramarket Mechanism of Microgrid Aggregator in Real-Time Balancing Market." IEEE Transactions on Industrial Informatics 12.2(2016):587-596.
[3] Liu, Guodong, Y. Xu, and K. Tomsovic. "Bidding Strategy for Microgrid in DA Market Based on Hybrid Stochastic/Robust Optimization." IEEE Transactions on Smart Grid 7.1(2015):227-237.
[4] Shi, L., Y. Luo, and G. Y. Tu. "Bidding strategy of microgrid with consideration of uncertainty for participating in power market." International Journal of Electrical Power & Energy Systems 59.7(2014):1-13.
[5] Zakariazadeh, Alireza, S. Jadid, and P. Siano. "Smart microgrid energy and reserve scheduling with demand response using stochastic optimization." International Journal of Electrical Power & Energy Systems 63.12(2014):523-533.
[6] Mohan, Vivek, et al. "An efficient two stage stochastic optimal energy and reserve management in a microgrid." Applied Energy 160(2015):28-38.
[7] Zhang, Dong, et al. "Optimal Microgrid Control and Power-Flow Study With Different Bidding Policies by Using PowerWorld Simulator." IEEE Transactions on Sustainable Energy 5.1 (2014): 282-292.
[8] Correa, Carlos Adrian, R. A. Bolaños, and A. Garces. "Optimal Operation of Microgrids in the Colombian energy market." Transmission and Distribution: Latin America Conference and Exposition IEEE, 2012:1-5.
[9] Mohammadi, Sirus, et al. "An Adaptive Modified Firefly Optimisation Algorithm based on Hong's Point Estimate Method to optimal operation management in a microgrid with consideration of uncertainties." Energy 51(2013):339-348.
[10] Niknam, Taher, F. Golestaneh, and A. Malekpour. "Probabilistic energy and operation management of a microgrid containing wind/photovoltaic/fuel cell generation and energy storage devices based on point estimate method and self-adaptive gravitational search algorithm." Energy 43.1(2012):427-437.
[11] PJM Manual 11: Energy & Ancillary Services Market Operations, Feb. 2017. [Online]. Available: http://www.pjm.com//media/documents/manuals/m11.ashx
[12] Logenthiran, Thillainathan, et al. "Multiagent System for Real-Time Operation of a Microgrid in Real-Time Digital Simulator." IEEE Transactions on Smart Grid 3.2(2012):925-933.