

# Dispatch and bidding strategy of active distribution network in energy and ancillary services market

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**Abstract** The active distribution network (ADN) is able to manage distributed generators (DGs), active loads and storage facilities actively. It is also capable of purchasing electricity from main grid and providing ancillary services through a flexible dispatching mode. A competitive market environment is beneficial for the exploration of ADN's activeness in optimizing dispatch and bidding strategy. In a bilateral electricity market, the decision variables such as bid volume and price can influence the market clearing price (MCP). The MCP can also have impacts on the dispatch strategy of ADN at the same time. This paper proposes a bi-level coordinate dispatch model with fully consideration of the information interaction between main grid and ADN. Simulation results on a typical ADN validate the feasibility of the proposed method. A balanced proportion between energy market and ancillary services market can be achieved.

**Keywords** Active distribution network (ADN), Energy market, Ancillary services market, Optimal dispatch, Bidding Strategy

## 1 Introduction

Distributed energy resources (DERs) such as distributed generators (DGs), active loads and storage devices are effective ways for the sustainable development of energy resources. With the integration of DERs into distribution networks, the active distribution network (ADN) is presented [1–4]. ADN is defined as the distribution network with the system controlling a combination of DERs [1]. ADNs are entitled with high dispatch autonomy right, making it possible to provide ancillary services such as spinning reserve service and peak regulation.

Various factors should be considered when making an ADN dispatch plan. The scheduling of DERs as well as the exchanged power between ADN and main grid should be made for dispatch strategy. In addition, the bid price and volume need to be decided for bidding strategy. Lots of researches on the strategy of ADN have been carried out in recent years. A coordinated method is presented to manage ADN concerning the cost of DGs and purchasing electricity in [5]. The scheduling procedure [6] is composed of two stages: a day-ahead scheduler to reduce cost and an intra-day scheduler to meet the operation requirements. Dynamic optimal power flow is applied in active network management [7]. An optimal schedule model is proposed for ADN to minimize the operation cost of a complete dispatch cycle [8]. A decentralized decision-making framework is presented to determine a secure and economical schedule in [9]. The technical and economic effects of active management on distribution network are evaluated in [10].

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Most of the researches focus on the scheduling of DERs and purchasing electricity when the market clearing price (MCP) is given. However, few efforts have been made to study the coordination between main grid and distribution network. In fact, bidding strategy of ADN can influence the MCP as well. Therefore, the information interaction should be taken into consideration when making an ADN strategy.

Although research work has been seldom conducted on the market participation mechanism of ADN, there are many existing researches focusing on the related concepts, such as power plant, micro-grid and plug-in electric vehicles (PEVs), which are of great meaning. Bidding strategy is solved as a bi-level optimization problem in most researches [11–13]. The upper level is a market clearing problem, and the lower level is a dispatch model. Micro-grid resembles ADN in many aspects and the market participation mechanism is widely studied [14, 15]. When ADN takes part in energy and ancillary services markets at the same time, the balance between the two markets should be considered [16–18].

This paper proposes an optimal dispatch and bidding strategy of ADN considering the combination of energy and ancillary services market. The scheduling of DERs and bid volumes is determined to minimize the total cost. Finally, the proposed method is applied to a typical ADN and the impact of DERs on ancillary services market is investigated.

The remaining sections of this paper are organized as follows. The market framework is presented including energy and ancillary services market clearing problem and the bidding strategy is discussed in Section 2. Then, an ADN dispatch model is proposed in Section 3. A case study is tested to illustrate the validity of the proposed method in Section 4. Section 5 concludes this paper.

## 2 Market framework

Though a fixed electricity market mechanism for ADN does not exist, a competitive market environment can be helpful to the exploration of ADN activeness in optimizing dispatch and bidding strategy. This paper utilizes a pool based bilateral electricity market mechanism, which enables ADN to schedule in response to price signals. Compared with traditional power systems, ADN has more flexibility in dispatch. ADN can not only purchase electricity in energy market, but also provide ancillary services. Specifically, conventional load, storage devices and intermittent resources such as wind energy can participate in energy market, while active load can be utilized in

ancillary services market. Controllable DGs such as micro-turbine can be applied in both markets.

### 2.1 Energy market

In the bilateral electricity market environment, buyers and suppliers both offer bid volume and price to independent system operator (ISO). MCP is the uniform marginal cost represented as  $\lambda t$ . The objective of energy market clearing problem is to maximize the surplus of buyers and suppliers considering the security of power systems. Mathematically, it can be formulated as

$$\max \sum_{t=1}^T \left( \sum_{j=1}^{N_b} C_{bj}^t P_{bj}^t + C_{DN}^t P_{DN}^t - \sum_{i=1}^{N_s} U_i^t C_{si}^t P_{si}^t \right) \quad (1)$$

$$\text{s.t.} \quad \sum_{i=1}^{N_s} U_i^t P_{si}^t = \sum_{j=1}^{N_d} P_{bj}^t + P_{DN}^t \quad (2)$$

$$U_i^t P_{si}^{\min} \leq P_{si}^t \leq U_i^t P_{si}^{\max} \quad (3)$$

$$0 \leq P_{bj}^t \leq P_{bj}^{\max} \quad (4)$$

where  $T$  is the total numbers of hours;  $N_b$  and  $N_s$  are the numbers of buyers and suppliers, respectively;  $C_{bj}^t$ ,  $C_{DN}^t$  and  $C_{si}^t$  are the bid prices of  $j^{\text{th}}$  buyer, ADN and  $i^{\text{th}}$  supplier;  $P_{bj}^t$ ,  $P_{DN}^t$  and  $P_{si}^t$  are the bid volume of  $j^{\text{th}}$  buyer, ADN and  $i^{\text{th}}$  supplier;  $U_i^t$  is the status of  $i^{\text{th}}$  supplier (0 is OFF, 1 is ON);  $P_{si}^{\min}$  and  $P_{si}^{\max}$  are the lower and upper bound of  $i^{\text{th}}$  supplier's bid volume;  $P_{dj}^{\max}$  is the upper bound of  $j^{\text{th}}$  buyer's load demand.

### 2.2 Ancillary services market

With the deregulation of power systems, competition mechanism is introduced into the ancillary services market [19, 20]. The ancillary services market mechanism proposed in this paper is a bid-based auction model, and the reserve market is taken into account. The participants of reserve market submit two types of bids: capacity bids and energy bids. All bidders are paid capacity price whether reserve capacity is dispatched or not. However, only the dispatched part will be paid energy price. Ancillary services market clearing problem aims to achieve social cost minimization subject to the required reserve capacity and limits of suppliers.

$$\min \sum_{t=1}^T \left[ \sum_{i=1}^{N_s} U_i^t (C_{r,i}^t + xC_{e,i}^t) R_{si}^t + (C_{r,DN}^t + xC_{e,DN}^t) R_{DN}^t \right] \tag{5}$$

$$\text{s.t.} \quad \sum_{i=1}^{N_s} U_i^t R_{si}^t + R_{DN}^t \geq R_t \tag{6}$$

$$0 \leq R_{si}^t \leq \min\{U_i^t P_{si}^{\max} - P_{si}^t, R_{ui}\} \tag{7}$$

where  $C_{r,i}^t$  and  $C_{e,i}^t$  are reserve capacity and energy bid price of  $i^{\text{th}}$  supplier, respectively;  $C_{r,DN}^t$  and  $C_{e,DN}^t$  are bid reserve capacity and energy price of ADN, respectively;  $R_{si}^t$  and  $R_{DN}^t$  are reserve capacity bid volume of  $i^{\text{th}}$  supplier and ADN;  $R_t$  is the required reserve capacity of the system;  $R_{ui}$  is the limit of ramp-up rate;  $x$  is the probability that reserve capacity is assumed to be 20 % in this paper. ISO presets the probability  $x$  and informs ancillary services market participants in advance.

### 2.3 Bidding strategy of ADN

ADN can provide ancillary services in addition to purchasing energy. In day-ahead market, ADN submits purchasing electricity bid to ISO in energy market and reserve capacity bid in ancillary services market. The market framework is shown in Fig. 1.

Load demand would be satisfied if the bid price is slightly higher than the MCP in energy market. Similarly, bid volume would be accepted if the bid price is marginally lower than the MCP in ancillary services market. Therefore, only bid volumes need to be determined when designing the strategy of ADN. In order to obtain the MCP, other bidding strategies of market participants are required

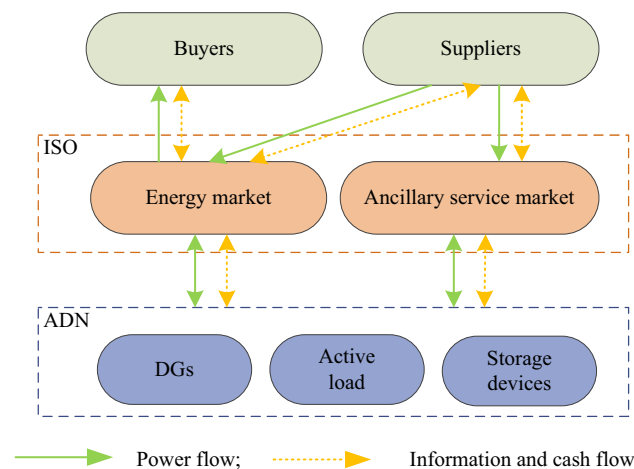


Fig. 1 Market framework

in advance. It is assumed that there is a simple linear relationship between the bid price and bid volume, i.e.,  $C_i = \alpha_i P_i + \beta_i$ , where  $\alpha_i$  and  $\beta_i$  are bidding coefficients which can be estimated based on historical data [21].

## 3 Dispatch strategy of ADN

### 3.1 Objective function

The optimal dispatch problem is defined as the sum of electricity purchasing cost, ancillary services market revenues and cost of DGs. The objective function can be formulated as

$$f = \sum_{t=1}^T \lambda_t P_{DN}^t - (C_r^t + xC_{e,DN}^t) R_{DN}^t + \sum_{i=1}^{N_{DG}} \left[ (1-x) F_i(P_i^t) + x F_i(P_i^t + R_{gi}^t) \right] \tag{8}$$

$$F_i(P_i^t) = U_i^t \left[ a_i (P_i^t)^2 + b_i P_i^t + c_i + C_{si} (1 - U_i^t) \right] \tag{9}$$

where  $N_{DG}$  is the total number of DGs;  $P_i^t$  and  $R_{gi}^t$  are the output and reserve capacity of  $i^{\text{th}}$  DG in the  $t^{\text{th}}$  period, respectively;  $a_i$ ,  $b_i$  and  $c_i$  are the coefficients of production cost function;  $C_{si}$  is the start-up cost of  $i^{\text{th}}$  DG.

### 3.2 Constraints

#### 1) Power balance

If reserve capacity is not dispatched, Eq. (10) should be satisfied. Otherwise, Eq. (11) holds.

$$P_{DN}^t + \sum_{i=1}^{N_{DG}} P_i^t U_i^t + P_w^t + P_{dis}^t - P_{ch}^t = P_L^t \tag{10}$$

$$P_{DN}^t + \sum_{i=1}^{N_{DG}} (P_i^t + R_{gi}^t) U_i^t + P_w^t + P_{dis}^t - P_{ch}^t = P_L^t - R_{shift}^t \tag{11}$$

where  $P_w^t$  is the wind power;  $P_{ch}^t$  and  $P_{dis}^t$  are the charge and discharge power of storage device, respectively;  $P_L^t$  is the load demand of ADN;  $R_{shift}^t$  is the shiftable load (positive and negative indicate shifting out and shifting in).

#### 2) DGs constraints

$$P_i^{\min} \leq P_i^t \leq P_i^{\max} \tag{12}$$

$$P_i^{t-1} - R_{Di} \leq P_i^t \leq P_i^{t-1} + UR_i \tag{13}$$



$$T_i^{on} \geq X_i^{on}, T_i^{off} \geq X_i^{off} \tag{14}$$

where  $P_i^{min}$  and  $P_i^{max}$  are the minimum and maximum power output of  $i^{th}$  DG;  $R_{Ui}$  and  $R_{Di}$  are the limits of ramp-up and ramp-down rates, respectively;  $T_i^{on}$  and  $T_i^{off}$  are the continuous up and down time, respectively;  $X_i^{on}$  and  $X_i^{off}$  are the minimum continuous up and down time, respectively.

3) Constraints for active load

Active load can fulfill the target of peak load shifting and hence achieve considerable electricity purchasing cost reduction. Equation (15) ensures that total load demand over the scheduling horizon is satisfied.

$$\sum_{t=1}^T R_{shift}^t = 0 \tag{15}$$

$$R_{shift}^{min} \leq R_{shift}^t \leq R_{shift}^{max} \tag{16}$$

where  $R_{shift}^{min}$  and  $R_{shift}^{max}$  are the minimum and maximum bounds of shiftable load; respectively, and  $R_{shift}^{min} < 0$ .

4) Constraints for storage units

Equation (21) ensures that the state of storage units at the end of scheduling period remains the same with that at the beginning.

$$0 \leq P_{dis}^t \leq P_{dis}^{max} \tag{17}$$

$$0 \leq P_{ch}^t \leq P_{ch}^{max} \tag{18}$$

$$S_{min} \leq S_t \leq S_{max} \tag{19}$$

$$S_t = S_{t-1} + P_{ch}^t \eta_{ch} - P_{dis}^t \eta_{dis}^{-1} \tag{20}$$

$$S_1 = S_T \tag{21}$$

where  $P_{ch}^{max}$  and  $P_{dis}^{max}$  are the maximum charging and discharging power, respectively;  $S_t$  is the storage state at time  $t$ ;  $S_{min}$  and  $S_{max}$  are the lower and upper bounds of storage capacity, respectively;  $\eta_{ch}$  and  $\eta_{dis}$  are the charge and discharge efficiency, respectively.

5) Reserve constraints

DGs and active load are utilized for energy and ancillary market.

$$R_{DN}^t = R_{gi}^t + R_{shift}^t \tag{22}$$

$$0 \leq R_{gi}^t \leq \min\{U_i^t(P_i^{max} - P_i^t), R_{ui}\} \tag{23}$$

6) Security constraints

Voltage levels and line limits are taken into account.

$$V_i^{min} \leq V_i^t \leq V_i^{max} \tag{24}$$

$$|S_i^t| \leq S_i^{max} \tag{25}$$

where  $V_i^t$  is the voltage amplitude at bus  $i$ ;  $V_i^{min}$  and  $V_i^{max}$  are the maximum and minimum voltage amplitude, respectively;  $S_i^t$  is the power flow of brunch  $i$ ;  $S_i^{max}$  is the transmission capacity.

Security constraints are satisfied by adding penalty terms to the objective function in this paper.

$$Pen_v = \sum_{i=1}^{N_{bus}} \frac{\Delta V_i^t}{V_i^{max} - V_i^{min}} \tag{26}$$

$$Pen_s = \sum_{i=1}^{N_{bran}} \frac{\Delta S_i^t}{S_i^{max}} \tag{27}$$

where  $N_{bus}$  and  $N_{bran}$  are the number of buses and branches, respectively.

$\Delta V_i^t$  and  $\Delta S_i^t$  can be computed by

$$\Delta V_i^t = \begin{cases} 0 & \text{satisfy (24)} \\ \max\{V_i^{min} - V_i^t, V_i^t - V_i^{max}\} & \text{else} \end{cases} \tag{28}$$

$$\Delta S_i^t = \begin{cases} 0 & \text{satisfy (25)} \\ |S_i^t| - S_i^{max} & \text{else} \end{cases} \tag{29}$$

Therefore, the original objective function is modified into  $f_{new}$ .

$$f_{new} = f + \omega_v Pen_v + \omega_s Pen_s \tag{30}$$

where  $\omega_v$  and  $\omega_s$  are the penalty factors and are assumed to be  $10^7$  in this paper.

## 4 Case study

### 4.1 Solution procedure

The solution procedure of ADN strategy is shown in Fig. 2. The behaviors of other participants are estimated and the initial values are set in advance. Then bid volume and price, which are obtained by solving the ADN dispatch model, are applied to market clearing problem to get the updated value of MCP. This iterative process ends till the convergence of MCP. The ADN dispatch model is a non-linear mixed integer program, and particle swarm

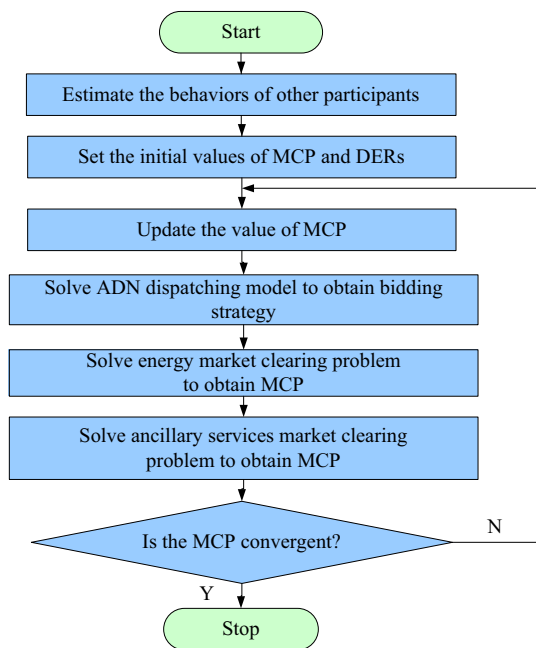


Fig. 2 Solution procedure of ADN strategy

optimization (PSO) algorithm is applied to solve the problem. Simulation process shows that the algorithm has a fast convergence speed.

4.2 Results and analysis

The method proposed in this paper is tested on a system comprised of four suppliers, a buyer and an ADN. The bidding information of market participants is shown in Table 1. The maximum and minimum output of Supplier 1 and 3 are 200 MW and 15 MW, respectively. The maximum and minimum output of Supplier 2 and 4 are 300 MW and 25 MW, respectively. The ratio of required reserve capacity to system load demand is 20 %. Reserve energy bid price is assumed to be the same with energy market.

As shown in Fig. 3, the proposed ADN consists of two DGs at Bus 2 and Bus 5, a wind turbine at Bus 6 and a

Table 1 Bidding information

Participant	Energy market		Ancillary services market	
	$\alpha_i$ (\$/MW)	$\beta_i$ (\$)	$\alpha_i$ (\$/MW)	$\beta_i$ (\$)
Supplier 1	0.20	4	0.5	6
Supplier 2	0.12	5	0.3	4
Supplier 3	0.25	4	0.4	4
Supplier 4	0.10	6	0.3	5
Buyer	-0.15	30		

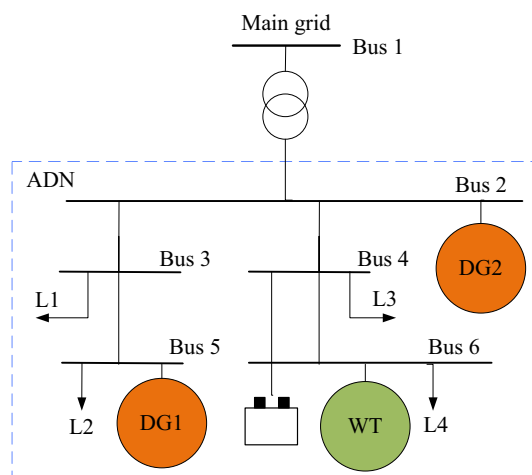


Fig. 3 Distribution network

storage device at Bus 6. Four active loads are connected to ADN through Bus 3, Bus 4, Bus 5 and Bus 6. The load percent of L1, L2, L3 and L4 are 20 %, 30 %, 40 % and 10 %, respectively. Load power factor is assumed to be 0.95. The distribution network is connected to main grid through an interconnecting line with a maximum capacity of 200 MW. Voltage limits are taken to be  $\pm 10\%$  of nominal.

The parameters of distribution network and DGs are shown in Table 2 and Table 3. The minimum up/down time are 2 h. The limit of ramp up/down is 30 MW/h. It is assumed that 3 % load can be shifted and additional 10 % load can be accepted. The upper and lower bounds of storage capacity are 100 MWh and 10 MWh, respectively. The maximum charging and discharging power are 5 MW and 10 MW, respectively, and the efficiency is 90 %. The hourly load demand and wind power output of a typical day are shown in Fig. 4.

Accordingly, the schedule of DERs, bidding strategy and MCP can be obtained through the solution procedure above. This paper fully considers the coordination between the main grid and ADN. A case study is carried out to show the effectiveness of the coordinate dispatch model, compared with dispatch model without information interaction. If ADN makes dispatch and bidding strategy independently

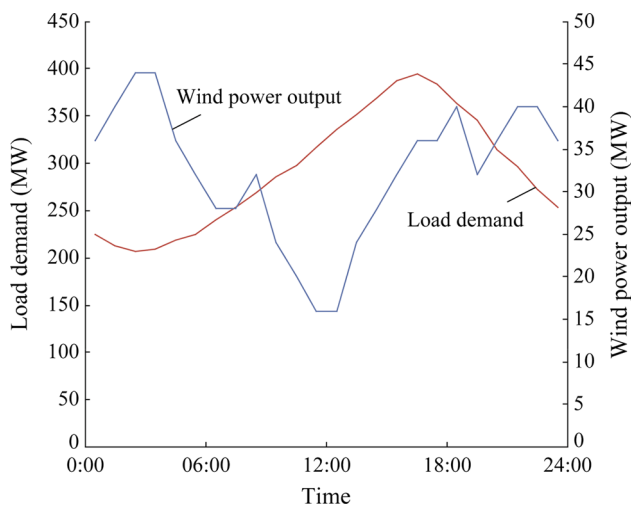
Table 2 Parameters of distribution network

From	To	Resistance	Reactance	Flow limit (MW)
Bus 1	Bus 2	0.02	0.08	200
Bus 2	Bus 3	0.04	0.15	120
Bus 2	Bus 4	0.03	0.12	120
Bus 3	Bus 5	0.03	0.09	80
Bus 4	Bus 6	0.04	0.12	100



**Table 3** Parameters of DGs

DG	Upper limit of output (MW)	Lower limit of output (MW)	$a_i$ (\$/MW <sup>2</sup> )	$b_i$ (MW)	$c_i$ (\$)	Start cost (\$)
1	70	10	0.18	4	100	120
2	110	30	0.12	3	70	150



**Fig. 4** Load demand and wind power output for one day

**Table 4** Cost and benefit of ADN under different cases

Case	Electricity purchasing cost (\$)	Ancillary services market revenues (\$)	Generation cost (\$)	Total Cost (\$)
1	84447	6088	39084	117443
2	74591	3214	47217	118594
3	96259	6717	28537	118079

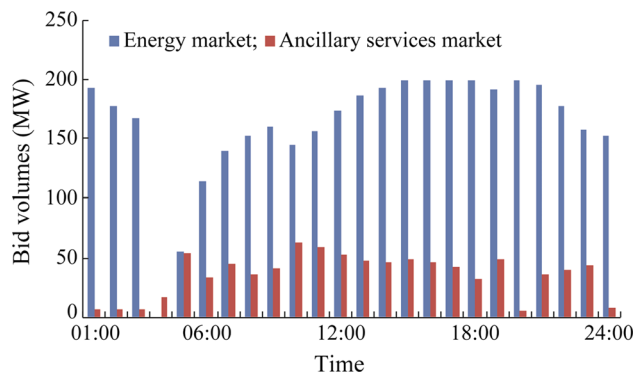
**Table 5** Cost and benefit of ADN under different cases

Case	Electricity purchasing cost (\$)	Ancillary services market revenues (\$)	Generation cost (\$)	Total cost (\$)
1	84447	6088	39084	117443
2	85745	5459	38022	118308
3	84844	5467	38353	117730

without consideration of market clearing process, electricity price needs to be forecasted in advance. The analyzed cases are as follows.

Case 1: Coordinate dispatch model proposed in this paper.

Case 2: Dispatch model without information interaction, and forecasted electricity price is 1.2 times of MCP.



**Fig. 5** Bids for energy market and ancillary services market

Case 3: Dispatch model without information interaction, and forecasted electricity price is 0.8 times of MCP.

The cost and benefit of ADN under different cases are shown in Table 4, from which we can see the proposed coordinate dispatch model costs the least. The forecasted electricity price of Case 2 is relatively higher, so ADN prefers to generate electricity using DGs rather than purchase from main grid. As a consequence, generation cost increases and DGs spare less capacity for ancillary services market. Instead, a lower forecasted electricity price will lead to the increase of electricity purchasing cost as shown in Case 3. Above all, optimal economic benefit can be achieved through information interaction between main grid and distribution network.

In order to analyze the impact of DERs on the economic efficiency of ADN, three different cases are considered as follows.

Case 1: ADN with active load and storage device.

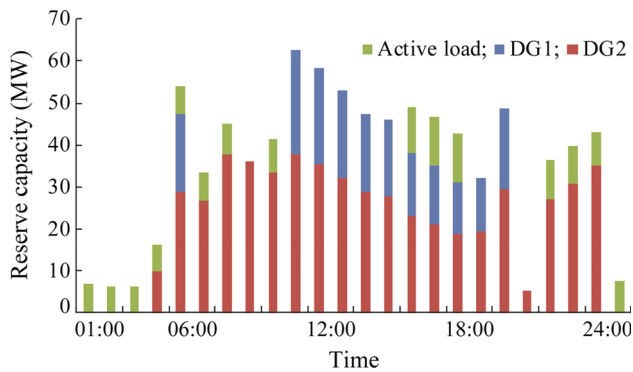
Case 2: ADN only with storage device.

Case 3: ADN only with active load.

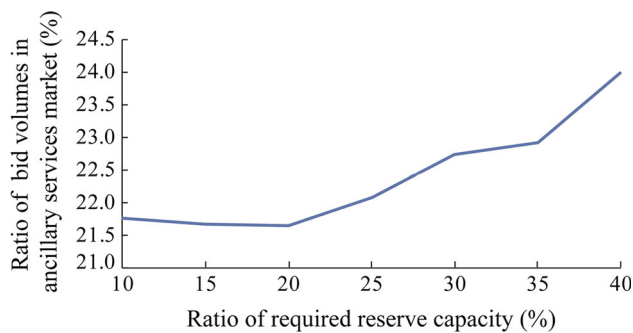
Table 5 shows the cost and benefit of ADN in three different cases. The results show that DERs are beneficial to cost reduction. Electricity purchasing cost reduction can be achieved through load shifting from high price period to low price period by active load and storage device. Additionally, benefit can be made through providing reserve capacity in ancillary services market.

The bid volumes in energy and ancillary services market are shown in Fig. 5. It can be observed that the trend of bid volume in energy market and load demand is roughly consistent. Hence ADN bidding strategy is mainly





**Fig. 6** Component of reserve capacity



**Fig. 7** Relationship between bids and required reserve capacity

determined by energy market. Bid volume is relatively higher during 1:00–3:00, because DGs are shut down due to low economic efficiency, making purchasing electricity become the only energy source. The bid volume in ancillary services market is influenced by the limit of dispatchable reserve capacity as well as MCP. DGs are in the state of nearly full capacity operation during peak hours, so the corresponding bid volume is relatively less.

The component of reserve capacity is shown in Fig. 6. The total demand of reserve capacity is supplied by DGs and active load. It can be found that DG2 with a larger capacity works as the main source of reserve capacity. Active load mainly provide reserve capacity during 1:00–9:00 and 21:00–24:00, when MCP and load demand are low.

The bid volume in ancillary services market is proportional to system required reserve capacity shown in Fig. 7. This is mainly because MCP increases with the reserve capacity demand when other conditions keep constant. Therefore, ADN would adjust the ratio of bid volume between two markets to achieve benefit maximization accordingly.

## 5 Conclusion

In this paper, a dispatch and bidding strategy of ADN in energy and ancillary services market is introduced to enhance economic efficiency. A typical ADN is studied to

demonstrate the effectiveness of the proposed model. Results show that ADN can reduce electricity purchasing cost in energy market and get revenue from ancillary services market through flexible dispatch of DERs. In addition, the obtained strategy can proportion the bid of the two markets according to MCP and security constraints.

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