Bidding Strategy of Virtual Power Plant for Participating in Energy and Spinning Reserve Markets—Part II: Numerical Analysis

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***Abstract*—This paper is to evaluate the presented model in part I for bidding strategy of virtual power plant (VPP) with centralized control in a joint market of energy and spinning reserve service. Two test VPPs are introduced and different scenarios are considered for markets prices. At first, the participation of VPP in only energy market is studied. Then, the spinning reserve market is taken into consideration and the bids of VPP in a joint market of energy and spinning reserve service is studied under different scenarios of markets prices and the results are analyzed. In all cases, the results show the effectiveness and the quality of the procedure and validate the proposed model.**

***Index Terms*—Bidding strategy, energy market, spinning reserve market, virtual power plant.**

I. INTRODUCTION

DUE to several supportive regulations worldwide [1]–[8], the share of distributed energy resources (DER) in the distribution network is increasingly grown up. As the penetration of DER in the distribution network increases, several issues related to technical, commercial and regulatory barriers of reliance of these units remain to be solved. Many researchers try to solve some of these problems by integrating these units into virtual power plants (VPPs) [9]–[15]. VPP is a concept to aggregate DER either for the purpose of trading electrical energy or to provide system support services [11]. Devising a good bidding strategy is very important for VPP to maximize its potential profit when it participates in energy and ancillary service markets. The bidding problem of VPP in a day-ahead joint market of energy and spinning reserve service is investigated in part I of this paper [16] and a non-equilibrium model based on the deterministic price-based unit commitment (PBUC) is presented for bidding strategy of VPP. The presented model takes the supply-demand balancing constraint and security constraints of VPP itself into account. In this paper, the numerical results of participating two test VPPs in only energy market and also in a joint market of energy and spinning reserve service under different scenarios of markets prices are presented and analyzed.

The rest of the paper is organized as follows. Section II introduces two test VPPs, i.e., VPP1 and VPP2. The presented bidding strategy model is investigated for VPP1 and VPP2 under different scenarios of markets prices in Sections III and IV, respectively. Execution time and convergence characteristic of the presented model are discussed in Section V. Discussion and conclusions are presented in the final section.

II. TEST SYSTEMS

In this section, two test systems are studied. At first, a small VPP, i.e., VPP1, is used to evaluate the proposed model. Then VPP2 is applied to show the effectiveness of the proposed model for larger VPP with multi DER. These systems are introduced in the following.

A. VPP1

The single line diagram of VPP1 is shown in Fig. 1(a). It contains a DG at node 121 and an electrochemical storage at node 122. The forecasted load of VPP1 is shown in Fig. 1(b). It should be mentioned that a part of load (up to 25 KW) may curtail during hours 7–8 and 11–18 if necessary. The cost of curtailing paid to consumer is assumed to be calculated by a quadratic polynomial function as $C(P)=0.01P^2+P$ in which P is the amount of un-served load. The retail energy rate for the end consumers of VPP1 is as shown in Fig. 1(c). The price of wholesale energy market regarding the usage cost of distribution network and also two scenarios for the price of spinning reserve market are shown in Fig. 2(d). It is assumed that DG and interruptible load can provide spinning reserve service. The ramping capability of DG for providing spinning reserve service is 3 KW/min. It is assumed that at the beginning of the scheduling period, DG has been off for 2 h.

B. VPP2

The single line diagram of VPP2 and its forecasted load are shown in Fig. 2(a) and (b), respectively. The load of nodes 4 and 7 can be curtailed up to 30 KW and 40 KW, respectively, during hours 7–22 if necessary. The costs of curtailing paid to consumers are assumed to be calculated as $C(P)=0.01\times P^2+3\times P$ for node 4 and as $C(P)=0.01\times P^2+1.5\times P$ for node 7 in which P is the amount of un-served load. The retail energy rate for the end consumers of VPP2 is as shown in Fig. 2(c). The price of wholesale energy market regarding the usage cost of distribution network and the price of spinning reserve market are shown in Fig. 2(d). It is assumed that DG1, DG4, DG8, and interruptible loads at nodes 4 and 7 can be used to provide spinning reserve service. The ramping capabilities of DG1, DG4, and DG8 for providing spinning reserve service are 3 KW/min, 2.5 KW/min, and 3.5 KW/min, respectively.

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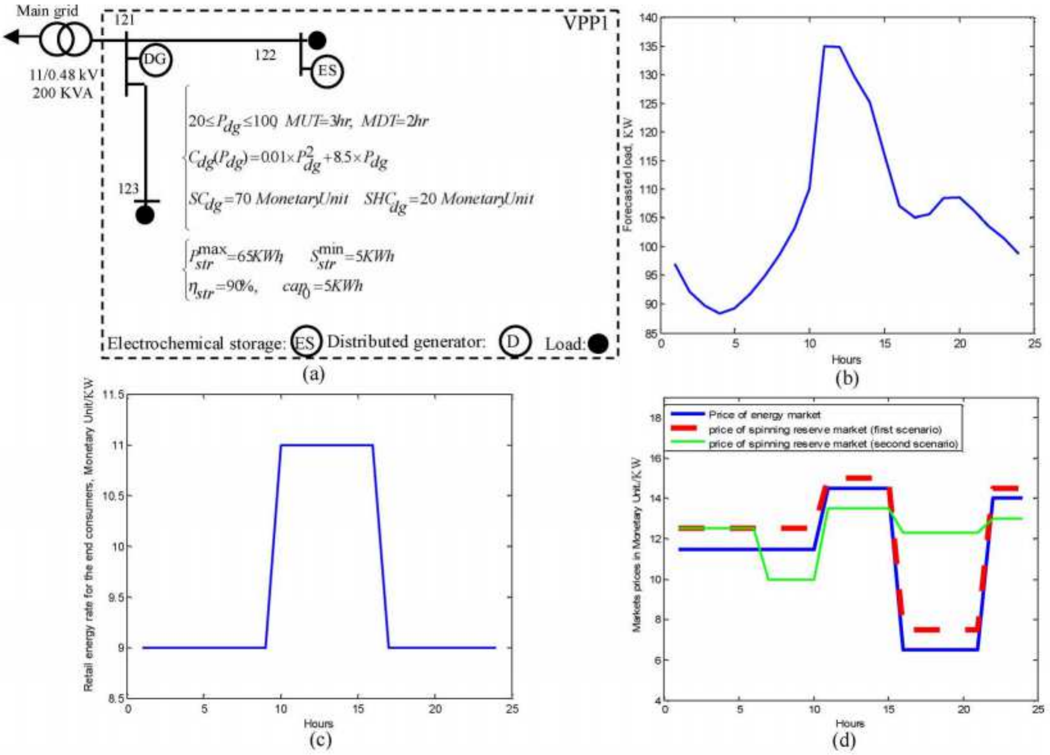


Fig. 1. VPP1. (a) Single line diagram. (b) Forecasted daily load curve. (c) Retail energy rate for the end consumers of VPP1. (d) Prices of energy and spinning reserve markets.

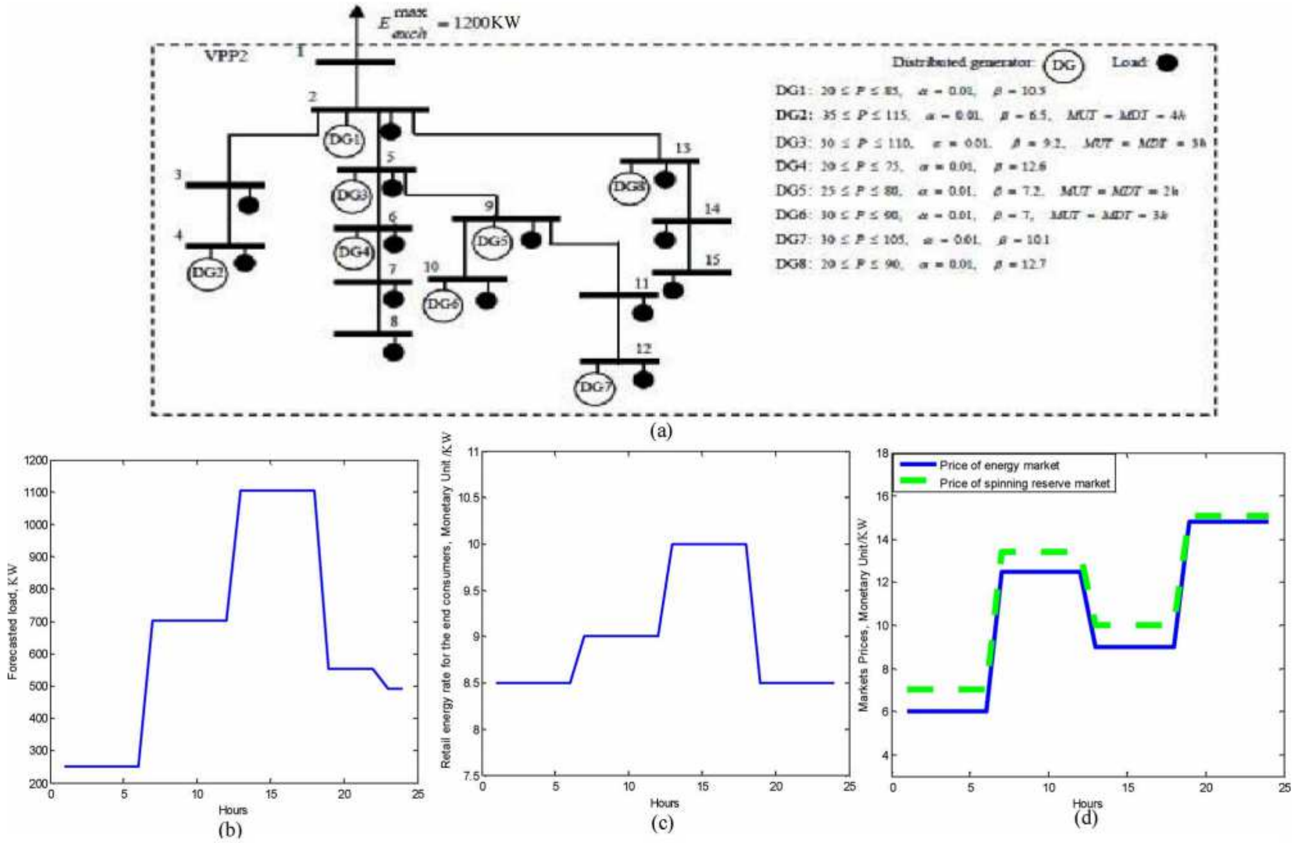
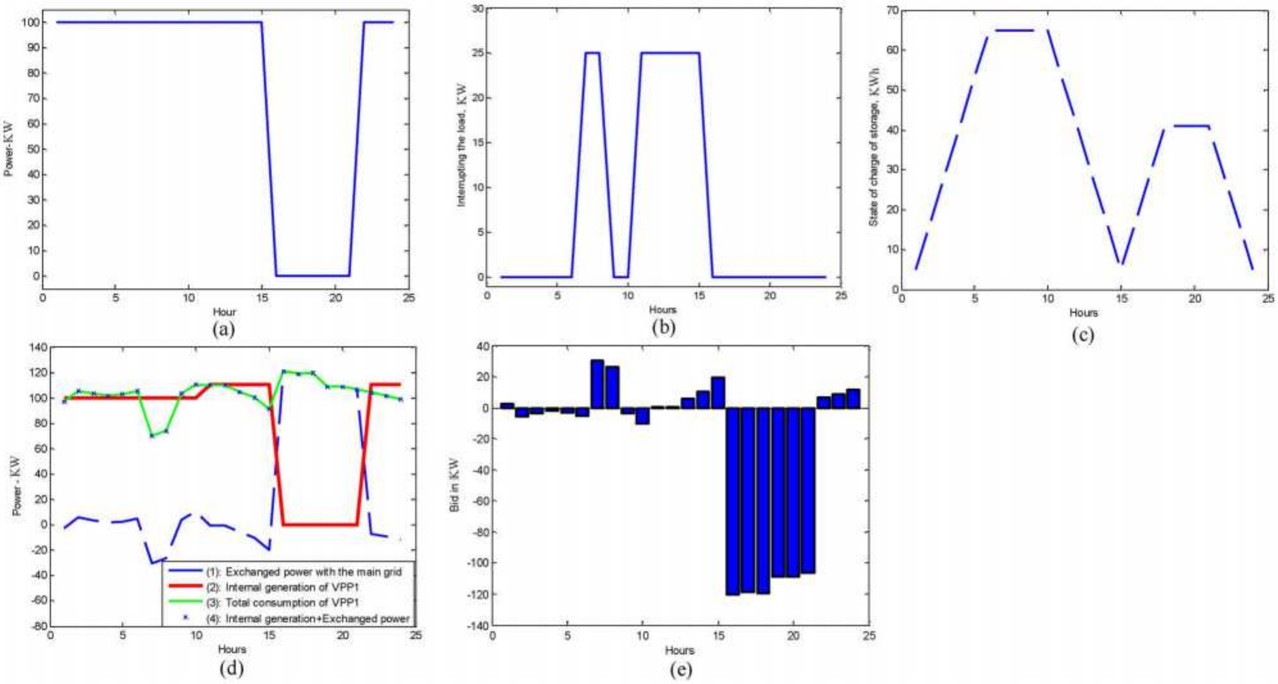


Fig. 2. VPP2. (a) Single line diagram. (b) Forecasted daily load curve. (c) Retail energy rate for the end consumers of VPP2. (d) Markets prices.



(a) (b) (c) (d) (e)

Fig. 3. Results of bidding problem for VPP1 when only energy market is considered. (a) Allocated capacity of DG unit for energy market. (b) Load interrupting options. (c) Charging and discharging behaviors of electrochemical storage. (d) Total generation, consumption, and exchanging power of VPP1. (e) Bids for energy market.

III. EVALUATING THE BIDDING PROBLEM FOR VPP1

A. Considering Only the Energy Market

In this case, it is assumed that VPP1 exchanges power with the energy market and it cannot provide spinning reserve service. The results of solving bidding problem in this case are shown in Fig. 3.

During hours 1–15 and 22–24, the price of energy market is greater than the production cost of DG; therefore, DG is on and operated at the upper level, and it is off during hours 16–21; see Fig. 3(a).

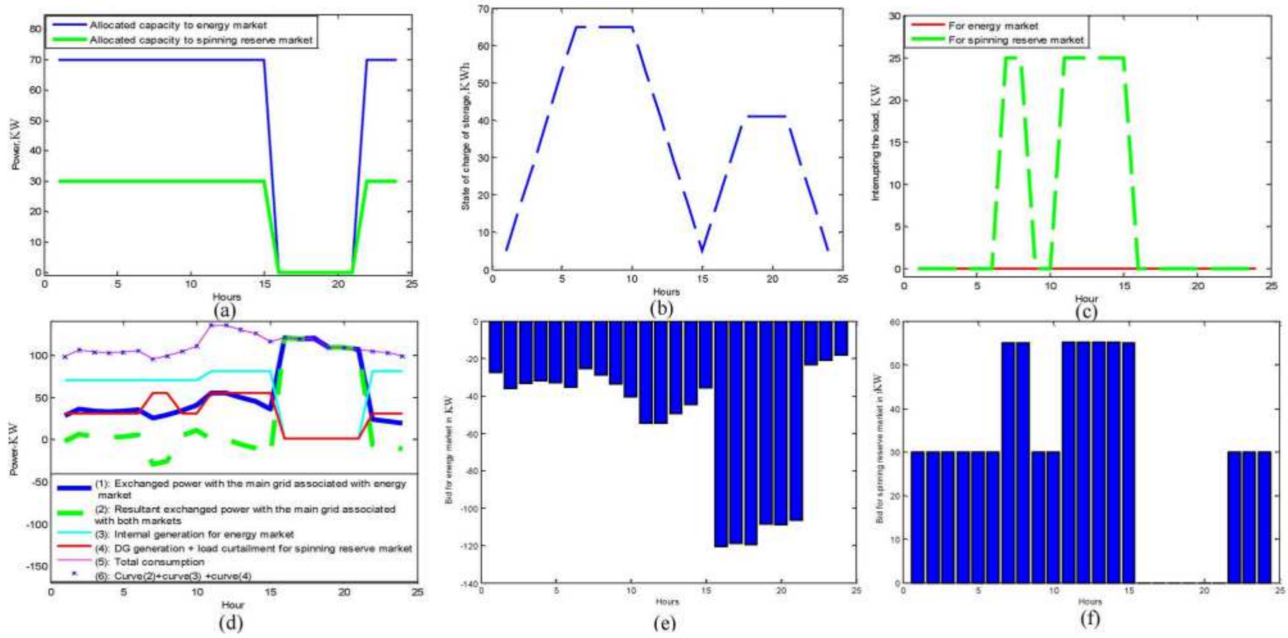
During hours 7–8 and 11–15, the retail energy rate of VPP1 is lower than the price of energy market; therefore, during hours 7–8, more profit is made by curtailing the load, and selling power to the energy market. Moreover, during hours 11–15, the purchased power from the market at a high price is reduced by curtailing the load. During hours 16–18, DG is off and total consumption of VPP1 is purchased from the main grid (energy market) at a low price (lower than the retail energy rate of VPP1), for which curtailing the load is unnecessary; see Fig. 3(b).

Fig. 3(c) shows the storage is fully charged during hours 1–8, in which the load is low—see Fig. 1(b)—and the market price is 11.5 Monetary Unit/KW. Then, it is discharged during hours 11–14, in which the load is high and the market price is 14.5 Monetary Unit/KW. The storage is again charged up to 40 KWh during hours 16–18 in which the load and the market price are low and it is discharged during hours 21–24.

Fig. 3(d) shows the optimal generation and consumption of VPP1 as well as the power exchanged with the main grid. The internal generation of VPP1 includes the generation of DG and discharged capacity of storage. The total consumption of VPP1 includes its supplied load, the power losses and charged capacity of storage. Moreover, the sign of power exchanged with the main grid shows the direction of exchanged power. The positive value indicates the power is absorbed by the VPP1 and the negative value means the power of VPP1 is injected into the main grid. In Fig. 3(d), it is observed that during hours 2–6, 9–10 and 16–21, VPP1 absorbed power from the main grid, that is, VPP1 is a consumer of main grid or energy market. But at hour 1, and during hours 7–8, 11–15 and 22–24, VPP1 acts as a producer in energy market. Fig. 3(e) illustrates the bids of VPP1 for energy market. Here, in order to better understand, the negative values show the bids for purchasing power, and positive values denote the bids for selling power to energy market. Table I shows the costs, revenues and benefits of VPP1 in this case. The maximum expected benefit of VPP1 researches to 2015.20 Monetary Unit.

B. Considering the First Scenario for the Price of Spinning Reserve Market

The bidding problem is solved considering the first scenario for spinning reserve market in Fig. 1(d). The results of solving the bidding problem are illustrated in Fig. 4. In this scenario, the price of spinning reserve market is greater than the price of energy market, and during hours 1–15, and 22–24, the price of energy and spinning reserve markets are higher than the production cost of DG. Therefore, during these hours, the maximum capability of DG for providing spinning reserve (i.e., $3\,\mathrm{kW/min}\times 10\,\mathrm{min} = 30\,\mathrm{kW}$) is applied and 70 KW of the capacity of DG is allocated to energy market. Moreover, during hours 16–21 in which the price of energy and spinning reserve market is lower than the production cost of DG, it is off; see Fig. 4(a). From



(a) (b) (c) (d) (e) (f)

Fig. 4. Results of bidding problem for VPP1 considering first scenario for the price of spinning reserve market. (a) Allocated capacity of DG unit for energy and spinning reserve markets. (b) Charging and discharging behaviors of electrochemical storage. (c) Load interrupting options. (d) Total generation, consumption, and exchanging power of VPP1. (e) Bids for energy market. (f) Bids for spinning reserve market.

Fig. 4(b), it can be concluded that the electrochemical storage is charged during hours 1–8 in which the load of VPP1 is low and the price of energy market is 11.5 Monetary Unit/KW; then, it is discharged during hours 11–14 in which the load is high and the energy market price is 14.5 Monetary Unit/KW. The storage is again charged up to 40 KWh during hours 16–18 in which the load and the energy market price are low and it is discharged during hours 21–24.

During hours 7–8, the price of spinning reserved market is 12.5 Monetary Unit/KW and the retail energy rate of VPP1 is 9 Monetary Unit/KW. Therefore, considering the cost of curtailing, more profit can be obtained by curtailing the maximum permitted value of the interruptible load and selling associated power to spinning reserve market. Also, during hours 11–5, the price of spinning reserve market is 15 Monetary Unit/KW and the retail energy rate of VPP1 is 11 Monetary Unit/KW. Therefore during these hours, the maximum permitted value of load is curtailed for providing spinning reserve service. During hours 16–18, the retail energy rate of VPP1 is greater than the markets prices, and the load is not curtailed; see Fig. 4(c). Fig. 4(d) illustrates the optimal generation, consumptions, and exchanging power of VPP1 considering both markets. It should be noted that curve (3), i.e., internal generation of VPP1 for energy market, includes the generation of DG and discharged capacity of storage. Its total consumption, i.e., curve (5), includes the supplied load, the power losses, and the charged capacity of storage. Curve (1) in Fig. 4(d) shows the exchanged power with the main grid associated with the energy market, and its sign shows the direction of exchanged power. The positive value indicates the power is absorbed by VPP1. Curve (2) in Fig. 4(d) shows the resultant exchanged power with the main grid considering both energy and spinning reserve markets. The difference between curve (2) and curve (1) is equal to the total value of spinning reserve provided by VPP1 that is measured at the connection point of the VPP1 and the main grid. During hours 16–22, curve (2) is exactly on curve (1), and the spinning reserve provided by VPP1 is equal to zero. From curve (1), it can be concluded that during 24 h, the main grid injects power to the VPP1, that is, the VPP1 is a consumer of main grid or energy market. Therefore, providing spinning reserve service by VPP1 means that the value of resultant absorbed power from the main grid will be decreased. By comparison of curve (2) with curve (1), it is observed that during hours 2–6 and 9–10, the resultant values of absorbed power from the main grid are decreased due to providing spinning reserve service. Moreover, at hours 1 and during hours 7–8, 11–15, and 22–24, the resultant exchanged power with the main grid is negative (the power is injected to the main grid), since the value of spinning reserve provided by VPP1 is greater than the injected power from the main grid associated with the energy market. Fig. 4(e) and (f) shows the bids of VPP1 for energy and spinning reserve markets, respectively. For better understanding, bids for purchasing powers from the energy market in Fig. 4(e) are illustrated by negative bars.

Table I shows the costs, revenues, and benefits of VPP1. In this case, the maximum expected benefit of VPP1 increases to 2548.51 Monetary Unit due to providing spinning reserve service by it.

C. Considering the Second Scenario for the Price of Spinning Reserve Market

The results of solving the bidding problem are shown in Fig. 5(a)–(d). Here, during hours 1–15 and 22–24, the price of energy market is greater than the production cost of DG, so it is on. During hours 1–6, the price of spinning reserve market is greater than the price of energy market, so the maximum

TABLE I
COST, REVENUES, AND BENEFIT OF VPP1

Hour	The cost of DG production + the interrupting cost paid to the interrupted consumer + the operation cost of the electrochemical storage (Monetary Unit)	Revenue of selling power to the ordinary end consumers(Monetary Unit)	Revenue of selling power to the interruptible end consumer (Monetary Unit)	Considering only energy market		Considering the first scenario for the price of spinning reserve market		
				Cost(-) or revenue(+)from exchanging power with the energy market (Monetary Unit)	Net benefit (Monetary Unit)	Cost(-) or revenue(+)from exchanging power with the energy market (Monetary Unit)	Revenue from selling power to spinning reserve market (Monetary Unit)	Net benefit (Monetary Unit)
1	1020.00	648.48	225.00	30.03	-116.49	-314.97	375.00	-86.49
2	951.55	604.43	225.00	-67.31	-189.43	-412.31	375.00	-159.43
3	951.55	582.62	225.00	-39.25	-183.18	-384.25	375.00	-153.18
4	951.55	569.39	225.00	-22.22	-179.38	-367.22	375.00	-149.38
5	951.55	577.95	225.00	-33.24	-181.84	-378.24	375.00	-151.84
6	951.55	600.77	225.00	-62.60	-188.38	-407.60	375.00	-158.38
7	981.25	628.58	0.00	344.83	-7.84	-289.37	689.35	47.31
8	981.25	662.30	0.00	301.53	-17.42	-332.75	689.43	37.73
9	950.00	704.37	225.00	-41.87	-62.51	-386.87	375.00	-32.51
10	950.00	936.50	275.00	-121.51	139.99	-466.51	375.00	169.99
11	982.80	1210.00	0.00	6.18	233.38	-794.40	828.18	260.98
12	982.80	1208.10	0.00	8.70	234.00	-791.87	828.18	261.60
13	982.80	1150.02	0.00	85.80	253.02	-714.65	828.05	280.62
14	982.80	1101.48	0.00	150.22	268.90	-650.12	827.94	296.49
15	982.80	1000.56	0.00	284.09	301.85	-516.06	827.74	329.45
16	21.55	902.50	275.00	-785.55	370.41	-785.55	0.00	370.41
17	1.55	720.64	225.00	-772.61	171.48	-772.61	0.00	171.48
18	1.55	726.17	225.00	-776.64	172.99	-776.64	0.00	172.99
19	0.00	750.09	225.00	-706.94	268.16	-706.94	0.00	268.16
20	0.00	751.65	225.00	-708.07	268.58	-708.07	0.00	268.58
21	0.00	731.63	225.00	-693.50	263.13	-693.50	0.00	263.13
22	1021.55	707.85	225.00	95.30	6.60	-324.70	435.00	21.60
23	951.55	688.78	225.00	125.15	87.39	-294.85	435.00	102.39
24	951.55	663.30	225.00	165.05	101.80	-254.95	435.00	116.80
Total	17503.55	18828.18	3925.00	-3234.43	2015.20	-12525.00	9823.87	2548.51

capability of DG for providing spinning reserve service (30 KW) is allocated for trading in spinning reserve market and the rest capability of DG (70 KW) is allocated to energy market; see Fig. 5(a). During hours 16–21, the price of energy market is very low, but the price of spinning reserve market is sufficiently high so that it is economically profitable for DG to be on and operated at its lower level in order to use its capability for providing spinning reserve service. In this case, the cost of producing 20 KW for energy market and providing 30 KW spinning reserve by DG is equal to 450 Monetary Unit at each hour of this time interval. Moreover, the value of decreased purchased power from the energy market (20 KW) at energy market price (6.5 Monetary Unit/KW), is equal to 130 Monetary Unit. Furthermore, the revenue from providing 30 KW spinning reserve is equal to 369 Monetary Unit. Therefore, operating DG at its lower level and providing 30 KW spinning reserve services leads to an increase of the expected benefit of VPP1 equal to 49 Monetary Unit at each hour of time interval of 16–21.

Fig. 5(b) illustrates the interrupting options. During hours 7–8 and 11–15, the price of energy market is greater than the price of spinning reserve market and it is very greater than the retail energy rate of VPP1 so that interrupting the maximum permitted value of load is economically profitable regarding the cost of curtailing.

Fig. 5(c) and (d) shows the bids of VPP1 for energy and spinning reserve markets, respectively. In this scenario, the maximum expected benefit of VPP1 researches to 2689.36 Monetary Unit.

IV. EVALUATING THE BIDDING PROBLEM FOR VPP2

Fig. 6 shows the results of bidding problem for VPP2. Here, the price of spinning reserve market is greater than the price of energy market all the time. During hours 1–6, the prices of

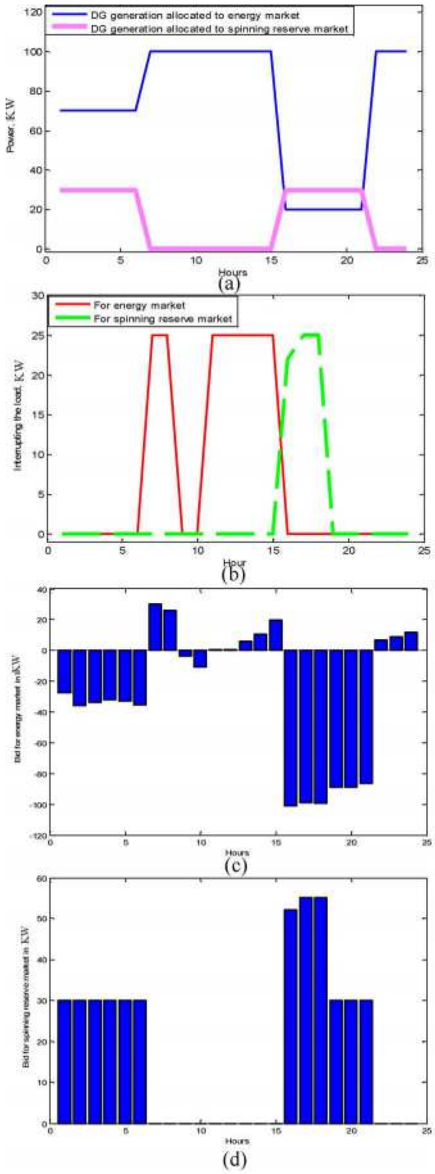


Fig. 5. Results of bidding problem for VPP1 considering second scenario for the price of spinning reserve market. (a) Allocated capacity of DG unit to energy and spinning reserve markets. (b) Load interrupting options. (c) Bids for energy market, negative (purchasing) and positive (selling). (d) Bids for spinning reserve market.

both markets are very low so that all DG units are off and VPP2 is a consumer of energy market. During hours 7–18, the total demand of the VPP2 is supplied by a combination of DGs productions and the main grid power. During hours 19–24, VPP2 injects power to the main grid. The capacities of DG units allocated to both markets are illustrated in Fig. 6(a) and (b). During hours 7–12, in which the price of energy market is relatively high, all DG units are operated at their maximum level unless DG1, DG4, and DG8. DG1 is a cheap unit so that its maximum capability for providing spinning reserve service (30 KW) is applied and the rest of its capacity (55 KW) is allocated to energy market. DG4 and DG8 are expensive units, however, since the prices of spinning reserve market during these hours are relatively high (13.4 Monetary Unit/KW), these units are on and operated at minimum level, so that makes it possible to use their capability for providing spinning reserve service. It should be

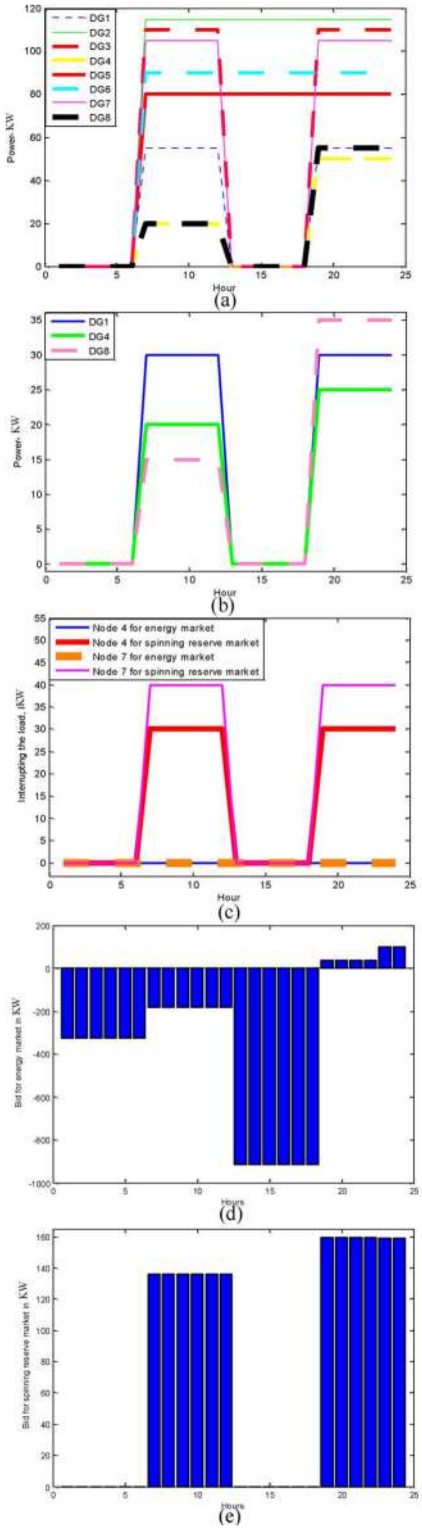


Fig. 6. Results of bidding problem for VPP2. (a) Allocated capacity of DG unit for energy market. (b) Allocated capacity of DG unit for spinning reserve market. (c) Load interrupting options. (d) Bids for energy market, negative (purchasing) and positive (selling). (e) Bids for spinning reserve market.

mentioned that since the price of spinning reserve market is not sufficiently high during these hours, it is not economically profitable to use their full capability for providing spinning reserve service. In this case, only 20 KW of the capacity of DG4 and

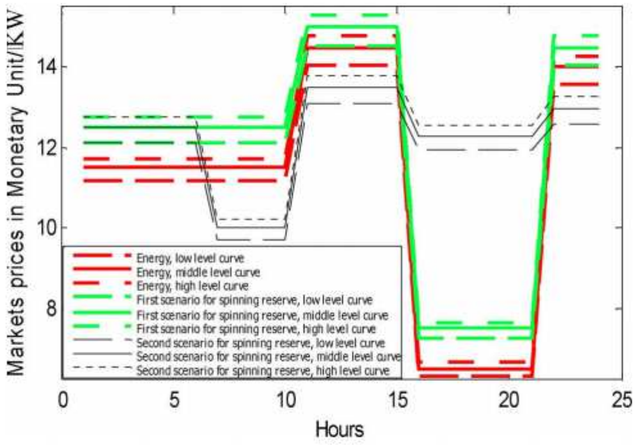


Fig. 7. Three levels of prices curves of energy and spinning reserve markets.

15 KW of the capacity of DG8 are allocated to spinning reserve market. During hours 13–18, the energy market price is falling and DG units (whose production costs are greater than the market price, i.e., DG1, DG3, DG4, DG7, and DG8) are off. During hours 19–24, in which the energy market price is high, all DGs are on. During these hours, since the price of spinning reserve market is sufficiently high, the full capability of DG units (30 KW of capacity of DG1, 25 KW of the capacity of DG4, and 35 KW of the capacity of DG8) are allocated to provide spinning reserve service. The rest of the capacities of these units are allocated to energy market. Fig. 6(c) shows the interrupting options. Here, since the price of spinning reserve market is greater than the price of energy market, the load is interrupted for providing spinning reserve service. Fig. 6(d) and (e) shows the bids of VPP2 for energy and spinning reserve markets, respectively. The maximum expected benefit of VPP2 is 7009.21 Monetary Unit.

V. SENSITIVITY ANALYSIS

In order to evaluate the impact of markets prices on the solution of the proposed bidding model, VPP1 is studied considering two cases, where each case includes three levels for the prices of energy and spinning reserve markets, i.e., low level, middle level, and high level prices curves; see Fig. 7. It should be mentioned that the prices curves shown in Fig. 1(d) are considered as middle prices level in Fig. 7.

A. Considering the First Scenario for the Price of Spinning Reserve Market

In this case, three levels of price curves of spinning reserve market are associated with the first scenario for the price of spinning reserve market defined in Fig. 1(d). The profit of VPP1 obtained from solving the proposed bidding problem for three levels of prices of energy and spinning reserve markets are shown in Table II. It should be mentioned that the detail results concerned with the middle level prices for energy and spinning reserve markets are the same as those reported in case B of Section III. From Table II, it is seen that when the markets prices are low, the profit of VPP1 is high; however, it is decreased by increasing the markets prices. This is because, in this case, VPP1 is ever a consumer of the energy market—see Fig. 4(e)—and increasing the market prices leads to decreasing its potential profit.

TABLE II
COMPARISON OF THE PROFITS OF VPP1 CONSIDERING THREE LEVELS FOR THE MARKETS PRICES

Scenario ID for the price of spinning reserve market	Profit of VPP1 (Monetary Unit)		
	Low level prices	Middle level prices	High level prices
First scenario	2629.42	2546.51	2492.67
Second scenario	2664.47	2689.36	2706.54

B. Considering the Second Scenario for the Price of Spinning Reserve Market

In this case, three levels of price curves of spinning reserve market are associated with the second scenario for the price of spinning reserve market defined in Fig. 1(d). The detail results concerned with the middle level prices for energy and spinning reserve markets are the same as those reported in case C of Section III. Here, when the markets prices are low, the profit of VPP1 is low; however, it is increased by increasing the markets prices; see Table II. This is because, in this case, VPP1 is sometimes a consumer of energy market and it is a producer of energy market in other times; see Fig. 5(c). Since the producing role of VPP1 prevails over its consuming role regarding the increasing of the market prices, its potential profit is increased by increasing the markets prices.

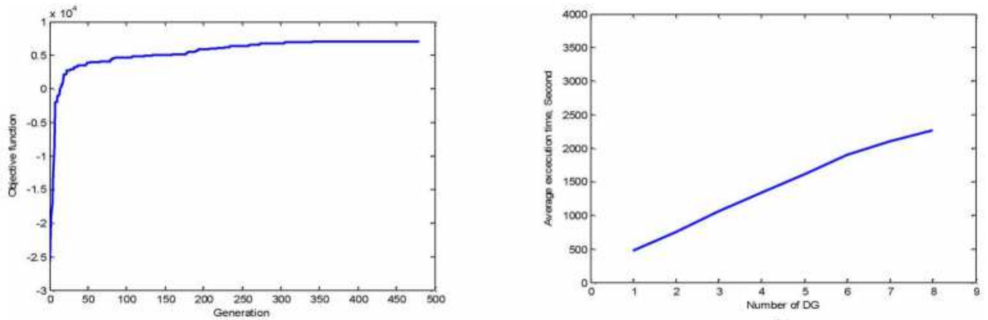
VI. EXECUTION TIME AND CONVERGENCE

The presented bidding problem is simulated in Matlab environment and tested on a laptop computer with a 2.5-GHz processor. Fig. 8(a) shows GA trace for maximizing the benefit of VPP2 with 10 DER, i.e., two interruptible loads and 8 DG units. The number of decision variable is 384 (360 real variable and 24 integer variable). The GA reaches the optimal solution after 480 generations. The average execution time calculated in 10 times execution of algorithm is 2269 s.

In order to evaluate the variation of simulation time with respect to the number of DG units, the bidding problem is solved for different scenarios of DG units in the VPP2, i.e., presence of one DG, two DGs, ... and 8 DGs. Fig. 8(b) shows the average execution times for these scenarios. It is seen that when the number of DG units in the VPP2 is increased, the average execution time is increased. The slope of increment of average execution time, however, is decreased by increasing the number of DG units.

The obtained average execution times are acceptable for day-ahead bidding problem of the VPP, which is an offline program with limited time.

Matlab is a high-level language and it is supported by many functions which help it to be efficiently and simply applied in academic research. This is the reason that the authors used Matlab for evaluating their model. Its computational speed, however, is very low in comparison with the languages which are closer to the machine language, such as C++/C# and also JAVA. Although, the calculated average execution times are satisfactory, in practical applications, these times can be



(a) (b)

Fig. 8. Execution time and convergence of GA. (a) GA trace for maximizing the benefit. (b) Changes of execution time of algorithm for presence of different numbers of DGs in VPP2.

considerably decreased by using C++/ C# or Java software for simulating the program and also applying multi-trading programming.

VII. Conclusion

This paper presents the numerical analysis for the proposed bidding model in part I of this paper for VPPs with centralized control in a joint market of energy and spinning reserve service. A small test VPP, i.e., VPP1, is applied to evaluate the presented model, and then VPP2 is studied to demonstrate the effectiveness of the presented model for larger VPP with multi DER. At first, participation of VPP in only energy market is studied. The results show that VPP may export power to the main grid or power may be injected to the VPP regarding both economical and technical aspects. In other words, VPP can participate in energy market as an entity with dual role including producer and consumer based on the direction of exchanged power with the main grid. Then, spinning reserve market is taken into consideration and the biding problem is solved under different scenarios of markets prices. The results show that VPP can provide spinning reserve service, regardless of its role in energy market. When VPP is a consumer of energy market, providing spinning reserve service means that the value of resultant absorbed power from the main grid will be decreased. The results show that when the VPP is a consumer in energy market, increasing the markets prices leads to decreasing its potential profit; however, when its producing role is dominant, increasing the market prices leads to increasing the potential profit of VPP. In the presented model, DERs are aggregated so that they can be visible for the system operator. In this aggregation model, network constraints, technical constraints of DER, and also economical aspects are taken into consideration. The obtained average execution times of algorithm are acceptable for day-ahead bidding problem of VPP, which is an offline program with limited time. However, in practical application, the execution time can be considerably decreased by using C++/C# or Java software for simulating the program and also applying multi-trading programming. In all cases, the results show the effectiveness and quality of the procedure and validate the proposed model.

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