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Article

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Energy Reports

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Suggested Citation: Huy Nguyen-Duc; Nhung Nguyen-Hong (2020) : A study on the bidding strategy of the Virtual Power Plant in energy and reserve market, Energy Reports, ISSN 2352-4847, Elsevier, Amsterdam, Vol. 6, Iss. 2, pp. 622-626, https://doi.org/10.1016/j.egyr.2019.11.129

This Version is available at:
http://hdl.handle.net/10419/243942

Available online at www.sciencedirect.com
ScienceDirect
Energy Reports 6 (2020) 622–626
www.elsevier.com/locate/egyr

The 6th International Conference on Power and Energy Systems Engineering (CPESE 2019), 20–23 September 2019, Okinawa, Japan

A study on the bidding strategy of the Virtual Power Plant in energy and reserve market

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Received 7 October 2019; accepted 23 November 2019

Abstract

This paper studies the bidding strategy of a Virtual Power Plant (VPP) in a market of energy and regulation service. The operation of distributed energy resources (DER) and battery energy storage inside the VPP is analyzed. A bidding strategy of the VPP including the spinning reserve contract and day-ahead offering/bidding contract is investigated. A two-stage robust optimization model is proposed to determine the VPP's purchasing/sell power in each contract to maximize the VPP's profit. The uncertainty in the DER and demand is considered in the optimization framework. The proposed model is applied to a small VPP including the photovoltaic (PV) system, battery energy storage (BESS) equipped in a customer.

Peer-review under responsibility of the scientific committee of the 6th International Conference on Power and Energy Systems Engineering (CPESE 2019).

Keywords: Electricity market; Energy storage; Robust optimization; Spinning reserve; Virtual Power Plant

1. Introduction

Nowadays, the distributed energy resources (DER) such as photovoltaic (PV) systems installed on the consumer side are becoming increasingly popular. Besides, the battery storage system (BESS) is also equipped to take full advantage of DERs power output. These systems not only supply electricity to consumers but also can sell the excess power to the main grid or provide regulation reserve service. Therefore, the concept of the Virtual Power Plant (VPP) is developed. Each VPP includes both DER and demand so that it can participate in the wholesale electricity market as a supplier or a consumer to sell or purchase its total net power. Besides, the VPP can provide regulation services to the Independent System Operator (ISO). In literature, there are several studies on the offering/bidding strategies or spinning reserve contract of the VPP [1–4]. However, in these studies, the spinning reserve is decided as a real-time problem while in the actual operation of the power system, the contract of regulation service must be decided several days before the operating date. Implementing the reserve contract at the same time with the day-ahead bidding contract may be easier but can lead to a less meaningful result.

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https://doi.org/10.1016/j.egyr.2019.11.129

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In this study, a two-stage robust optimization model is proposed to determine two contracts of the VPP: (i) the spinning reserve contract between VPP and ISO, which must be decided one week before the operating date; (ii) the offering/bidding contract between VPP and the day-ahead market (DAM) which is decided on the previous day. This model will be applied to a test system including end consumer, the PV system and BESS. Besides, the PV power output and demand are treated as uncertain parameters.

2. Problem description

In this study, the VPP includes a distribution network with the PV and ESS system equipped in each end consumer. The VPP can play both roles of a supplier and a consumer: selling electricity if there is an excess capacity from the PV system; buying electricity when the PV system does not operate, or when electricity prices are low. The installation of ESS systems can help increase the energy produced from the PV system.

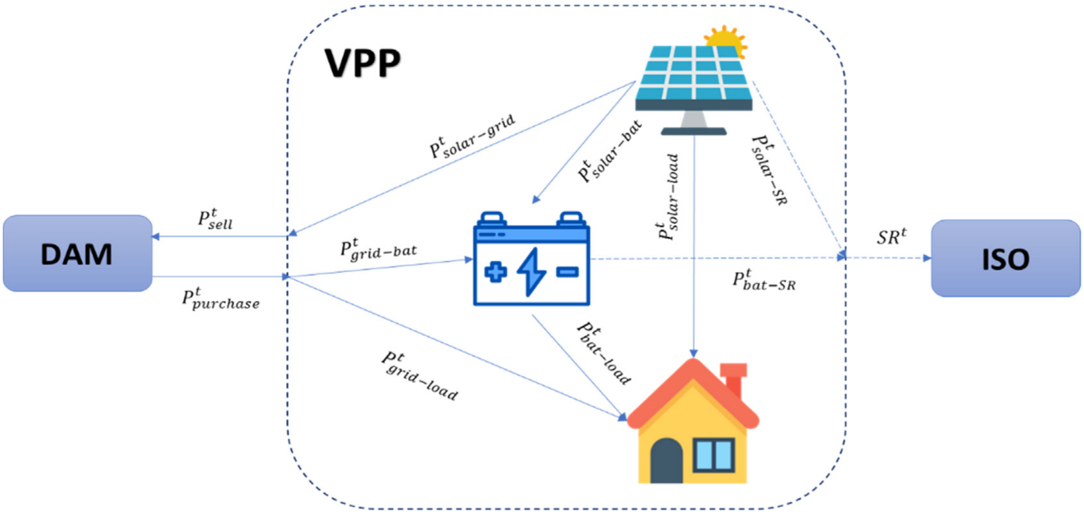

Fig. 1. Description of the VPP operation in ISO and DAM.

The VPP trading in ISO and DAM includes two services and the operation inside the VPP can be described as in Fig. 1:

- Spinning reserve service: at least one week before the operating day, the VPP signs a contract to provide spinning reserve SR^t in each time t. In actual operation, each time ISO call spinning reserve, the VPP must provide this regulation higher than a certain value and maintain over the duration τ_{iON}. After this duration, this service will be stopped within at least τ_{iOFF} before a new regulation duration. The spinning reserve can be provided by both the PV system ($P^t_{solar-SR}$) and the BESS (P^t_{bat-SR}).
- In DAM, the VPP determine to provide P^t_{sell} or purchase $P^t_{purchase}$ in each hour interval t on an operating day. This contract must be implemented before 10:00 a.m on the previous day. The electricity sold to main grid P^t_{sell} is the excess power of the PV system $P^t_{solar-grid}$. By contrast, at the night time or the off-peak price hours, the VPP will purchase electricity from the main grid to supply to demand ($P^t_{grid-load}$) or store in the BESS ($P^t_{grid-bat}$) for the peak load hours.

It is easy to see that, at the time the VPP must decide the trading contract, the information about the demand and the PV power output is limited. For this reason, a two-stage robust optimization model is applied to maximize the profit from the electricity trading contract and make sure that all consumer is supplied fully.

2.1. Objective function

The objective function includes two components: the first-stage cost is the benefit from spinning reserve bidding while the second-stage cost is related to the purchase/sell bidding in DAM.

$$\max_{SR^t} c_{sr} \sum_{t=1}^{24} SR^t + \max_{\xi} \min_{P^t_{purchase}, P^t_{sell}} \left(c^t_{purchase} \sum_{t=1}^{24} P^t_{purchase}(\xi) - c^t_{sell} \sum_{t=1}^{24} P^t_{sell}(\xi) \right) \tag{1}$$

where ξ is uncertain parameters include forecasted value of demand and the available PV power output; SR^t is spinning reserve at hour t; c_{sr} is the price of the spinning reserve bidding; $P^t_{purchase}(\xi)$ and $P^t_{sell}(\xi)$ are the electricity purchased or sold at hour t, which is corresponding to the forecasting value of ξ; $c^t_{purchase}$ and c^t_{sell} are the price of the electricity purchase or sell bidding at hour t respectively.

2.2. Constraints

- The purchase/sell bidding between the VPP and DAM: In these constraints, u^t_{grid} is a binary variable which is equal to 1 if the VPP purchase electricity from the main grid and M is a sufficiently large number.

$$0 \le P^t_{purchase} = P^t_{grid-bat} + P^t_{grid-load} \le u^t_{grid} M \tag{2}$$

$$0 \le P^t_{sell} = P^t_{solar-grid} \le (1 - u^t_{grid}) M \tag{3}$$

- The spinning reserve contract between the VPP and ISO: In these constraints, u^t_{SR} is a binary variable which is equal to 1 if the VPP decide to sell the spinning reserve. In this case, the VPP will not purchase any electricity from the main grid. u^t and v^t are binary variables which describe the begin and the end of the spinning reserve duration.

$$0 \le SR^t = P^t_{solar-SR} + P^t_{bat-SR} \le u^t_{SR} M \tag{4}$$

$$u^t_{grid} + u^t_{SR} \le 1; \sum_{k=t-\tau_{iON}}^{t} u^k \le u^t_{SR}; \sum_{k=t-\tau_{iOFF}}^{t} v^k \le 1 - u^t_{SR} \tag{5}$$

- The PV system operation: The PV power output is smaller than the forecasted value of the available PV power $Solar^t_f$ with the forecasting error $Solar^t_{error}$

$$P^t_{solar-bat} + P^t_{solar-load} + P^t_{solar-grid} + P^t_{solar-SR} \le Solar^t_f + Solar^t_{error} \tag{6}$$

- Demand constraint: The total electricity provided from the PV system, BESS and the main grid must be equal to the forecasted value of demand D^t_f in each hour considering forecasting error D^t_{error}

$$P^t_{grid-load} + P^t_{solar-load} + P^t_{bat-load} = D^t_f + D^t_{error} \tag{7}$$

- The BESS constraints: In these constraints, u^t_{BESS} is a binary variable which is equal to 1 if the BESS discharge at time t. The parameter η is charging/discharging efficiency of the BESS. The charging and discharging power of the BESS must be smaller than the actual power rating of the storage device P_{SSmax}. The energy stored in the BESS E^t_{SS} must be smaller than its rated capacity E_{ssmax} at all times. Besides, constraint (11) make sure that if the spinning reserve service start at time t, the BESS has enough energy to provide this service within τ_{iON}.

$$0 \le P^t_{grid-bat} + P^t_{solar-bat} = \left(1 - u^t_{BESS}\right) M \tag{8}$$

$$0 \le P^t_{bat-load} + P^t_{bat-SR} \le u^t_{BESS} M \tag{9}$$

$$\begin{cases} 0 \le E^t_{SS} = E^{t-1}_{SS} + \eta \left(P^t_{grid-bat} + P^t_{solar-bat}\right) - \left(P^t_{bat-load} + P^t_{bat-SR}\right)/\eta \le E_{ssmax} \\ E^{t=0}_{SS} = E^{t=24}_{SS} \end{cases} \tag{10}$$

$$0 \le E^{t-1}_{SS} - \sum_{k=t}^{t+\tau_{iON}-1} P^k_{bat-SR}/\eta \le E_{ssmax} \tag{11}$$

3. Numerical application and results

The proposed model is tested on a small VPP system including a customer, a PV system having the capacity of 4 kW and a BESS. The forecasting value of available PV power output and demand are described in Fig. 2a. We assumed that the maximum forecasting errors are equal to 15% for both solar power and demand. In purchase bidding, electricity price is illustrated in Fig. 2b with the peak-load price is 2908VND/kWh. Besides, the electricity price is 1024VND/kWh for off-peak hours and 1581VND for normal hours. These prices are public on the website of Vietnam Electricity (EVN) [5]. Until now, all PV systems in Vietnam have not yet joined to the electricity market, so we assume that the reserve trading price is 3000VND/kWh while the excess power of the PV system can be sold with 1800VND/kWh. The VPP is required to provide at least 1 kW for spinning reserve and maintain it for four hours.

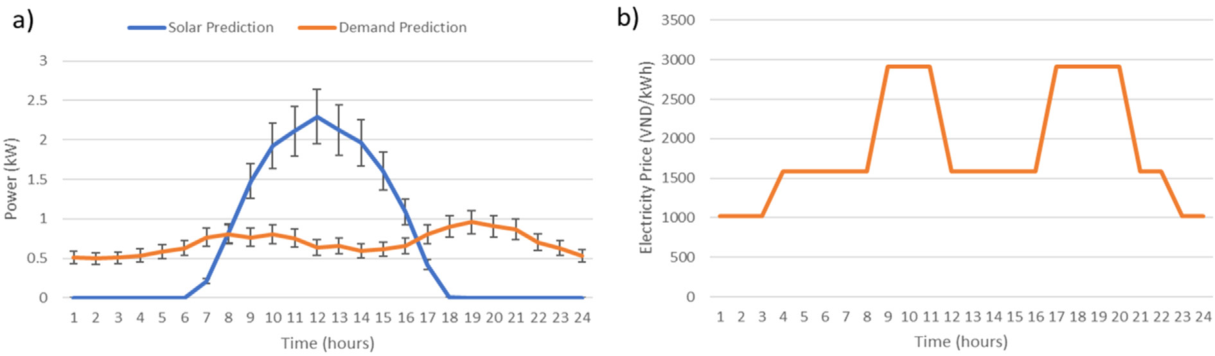

Fig. 2. (a) Forecasted available solar power and demand; (b) A typical daily price of the purchase bidding.

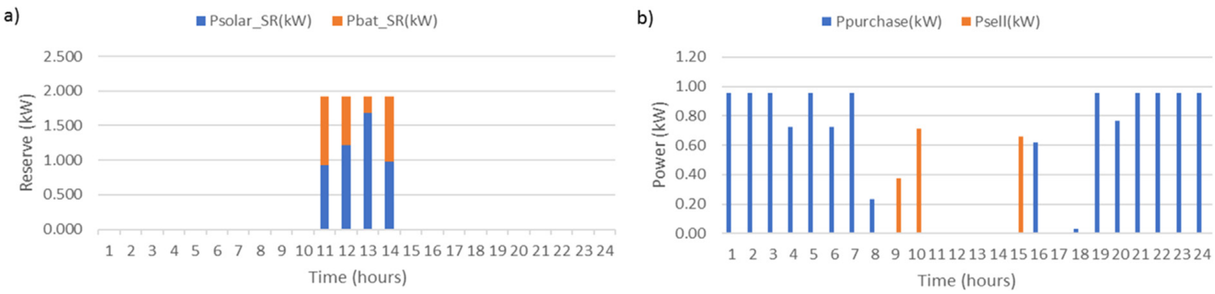

Fig. 3. Case 1: BESS 1 kW/4 kWh. (a) Reserve power provided the PV system and the BESS; (b) Purchase/sell bidding in DAM.

We implemented the proposed model in three cases of the BESS capacity: 1 kW/4 kWh, 2 kW/4 kWh, and 2 kW/8 kWh. The results including the reserve power and purchase/sell power are presented in Figs. 3–5. In case the BESS sizing is 1 kW/4 kWh, the VPP can provide spinning reserve only one time with 4 h interval. In Case 2, the VPP can provide this service two times with a larger BESS inverter rating. By contrast, the selling power in Case 2 will be decreased in comparison to Case 1. It can be explained that with a small inverter rating, the excess power from the PV system must be curtailed or sold to the main grid instead of storing in the BESS (Fig. 3b). Consequently, the VPP can only provide spinning reserve within the PV's peak hours.

On the other hand, if the BESS' capacity increases, both spinning reserve and selling power also increase. The results in Fig. 5 show that if the BESS' capacity increases to 8 kWh, almost spinning reserve is provided by the BESS. Note that the electricity price at the off-peak hours is significantly smaller than the price of spinning reserve so that in this duration, the VPP buys and stores electricity in the BESS for spinning reserve.

4. Conclusion

This study implemented a two-stage robust optimization problem to maximize the VPP's profit in both spinning reserve contract and day-ahead offering/bidding contract. The available PV power and demand are considered as

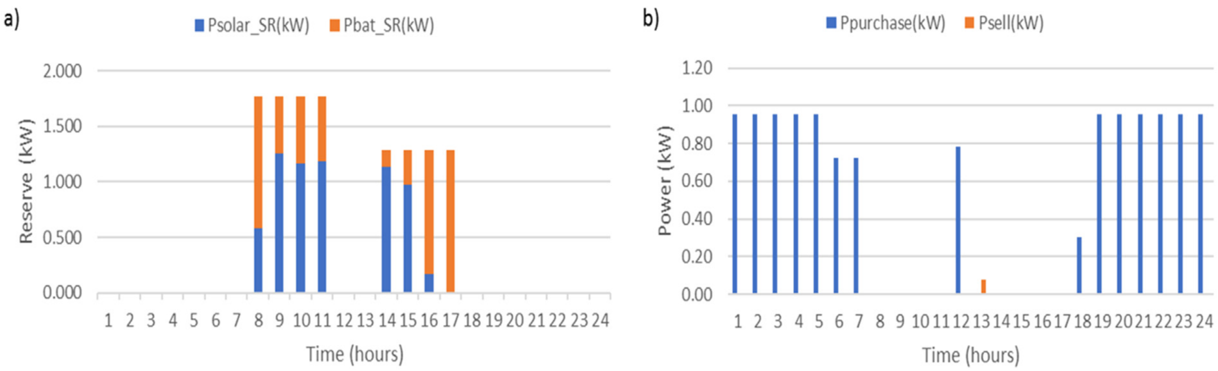

Fig. 4. Case 2: BESS 2 kW/4 kWh. (a) Reserve power provided the PV system and the BESS; (b) Purchase/sell bidding in DAM.

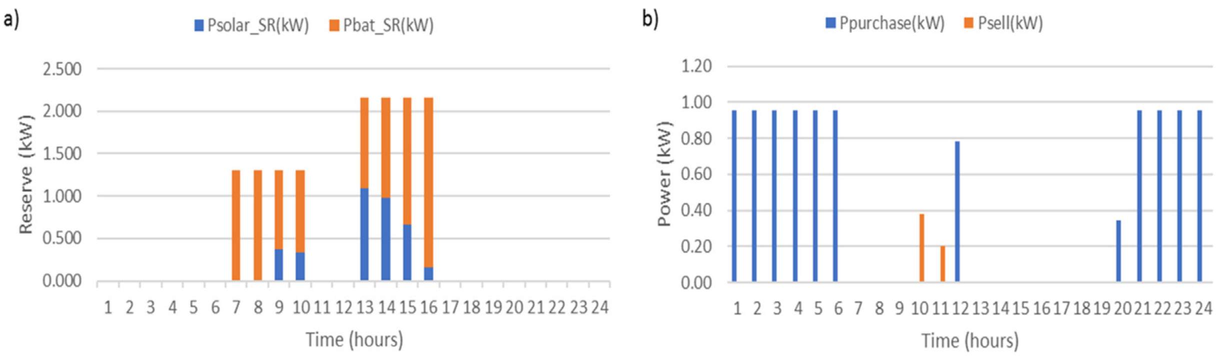

Fig. 5. Case 3: BESS 2 kW/8 kWh. (a) Reserve power provided the PV system and the BESS; (b) Purchase/sell bidding in DAM.

uncertain parameters. The results in three cases of the BESS sizing are obtained and analyzed to show the impact of the BESS inverter rating on the number of times that VPP can provide reserve service within a day.

Acknowledgment

This work was supported by the Hanoi University of Science and Technology research fund, Viet Nam under grant number T2018-PC-056.

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