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A price-droop trading strategy for residential photovoltaic-battery systems

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A price-droop trading strategy for residential photovoltaic-battery systems

Yayang Lin[1,3], Weiyi Gu[1], Feng Yan[1], Feilong Fan[2], Jun Tang[1] and Chuan Sun[1]

[1] Nantong Electric Power Company of Jiangsu Power Grid Co., Ltd., Nantong 226006, China;
[2] School of Electronic Information and Electrical Engineering, Shanghai Jiao Tong University, Shanghai 200240.

[3] Email: yayang_ling@163.com

Abstract. Residential photovoltaic-battery systems (RPBSs) are widely applied to improve the controllability and predictability of rooftop solar photovoltaic systems (RSPSs). High investments of the RPBSs demand new trading strategies to promote their applications. A price-droop trading strategy is proposed in this paper to satisfy the investors' demands. The RPBSs are formulated as virtual power plants (VPPs) in the price-droop trading strategy. The electricity price of the VPPs is adaptive to their output power. The object of the price-droop trading strategy is VPPs' daily profit maximization, which can be solved as a convex quadratic optimization problem. The price-droop trading strategy is validated by two RPBSs with time-varying electricity price. Results show that the price-droop trading strategy ensures more controllable and predictable RPBSs' output power. Its extra economic profit will encourage more residents to invest the RPBSs. Increments of RPBSs will promote the utilization of the photovoltaic resources.

1. Introduction

Solar photovoltaic resources become more popular to residential customers, due to their super environmental friendliness [1-3]. It has been reported that the total worldwide capacity of residential PV units will rise to 1.8 TW by 2040[4]. As the speed of residential PV adoption continues to accelerate, high photovoltaic penetration occurs in part of the low-voltage distribution networks. The high photovoltaic penetration will probably result in overvoltage, frequency fluctuation and back feeding flow [5-8]. Residential PV-battery systems (RPBSs) are widely utilized to deal with those challenges [9-11]. Detection and control facilities are also necessary in the management of the RPBSs. A data-driven approach for detection and estimation of residential PV installations is proposed in [8]. A dynamic operation scheme for residential PV smart inverters is presented in [12]. Auto inspection and permitting with a PV utility interface for residential plug-and-play solar photovoltaic unit are designed in [13]. The above researches focus on the technical performance rather than the economic analysis of the detection and control system. The economic competitiveness of continuous monitoring of residential PV systems is discussed in [14], which proposes a model of the costs and benefits for both the system owner and the maintenance service provider. The existed researches on the RPBSs are mostly concentrated on a single area, such as technical performance or economic analysis. Strategies combining the technical performance and economic analysis are in need.

Virtual power plant (VPP) is a suitable way to combine the technical performance and economic analysis. Plenty of researches based on VPP have been done. An optimal bidding strategy for a commercial VPP is proposed in [15] to maximize the day-ahead profit. A stochastic adaptive robust optimization approach is proposed in [16] for the VPP participating in the day-ahead and the real-time energy markets. Research in [17] proposes the control and bidding strategy for virtual power plants with renewable generation and inelastic demand in electricity markets. The existed works on the VPP focus on the bidding and control strategy for large-scale distributed renewable generations and energy storage systems. The implement of the agent center for bidding and control strategy will be complicated. As the capacity and economic profit of a single residential PV unit is low, investment of the complicated agent center is impossible. A self-manage system is more reasonable for the residential PV unit. Application of adaptive trading strategy in the self-manage system is necessary.

A price-droop trading strategy is proposed in this paper to satisfy the technical and economical demand of the self-mange RPBSs. Each RPBS is regarded as a VPP. The electricity price of the RPBSs are related to their output power. A linear droop model is established to describe the relationship between the electricity price and the output power. Based on the linear droop model, RPBSs' daily profit maximization is considered in the price-droop trading strategy. The daily profit maximization can be simplified as a convex quadratic optimization problem and solved according to the Karush-Kuhn-Tucker optimality conditions. The price-droop trading strategy is validated by two nearby RPBSs with time-varying electricity price.

The rest of this paper is organized as follows. Section II provides the price-droop trading strategy for RPBSs. In section III, daily profit maximization of RPBSs is described. The testing system and testing results are presented in section IV. Finally, Section V provides the conclusion.

2. Price-droop trading strategy for RPBSs

Each RPBS consists of a PV unit, a battery, a distributed management system and several residential loads, as shown in Figure 1. The PV unit and battery are co-managed by the DMS. The power of the DMS and the loads are monitored by the energy router.
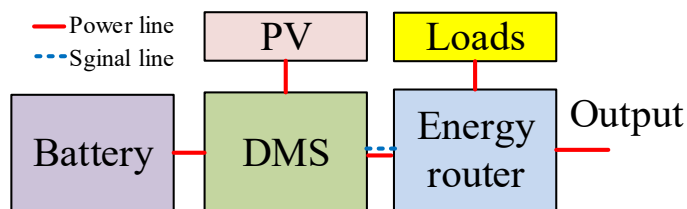
Figure 1. Main facilities of the RPBS.
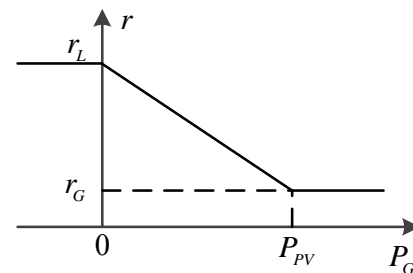
Figure 2. Liner droop model for the equivalent price of the VPP.

The VPP model of each RPBS varies upon three types: the pure power generation model, the pure load model and the mixed generation-load model. The equivalent price of the VPP is the average electricity price of the VPP model. The VPP's equivalent price in the pure power generation model is equal to the electricity price of the thermal power generation. The VPP's equivalent price in the pure load model is equal to the electricity price of the users. The VPP's equivalent price in the mixed model is the average value of the different electricity prices according to different models, as shown in (1).

$$r = \frac{r_G P_G + r_L P_L}{P_{PV}} \tag{1}$$

where $P_G + P_L = P_{PV}$, P_G means the output power, r_G means the electricity price of the pure power generation, P_L means the load power, r_L means the electricity price of the users. P_{PV} means the maximum output power of the rooftop solar PV. r means the equivalent price of the VPP.

The equivalent price of the VPP has the linear droop characteristic, as shown in Figure 2.

The linear droop characteristic in Figure 2 can be defined in (2).

$$r = \begin{cases} r_G, P_G \geq P_{PV} \\ r_L + kP_G, 0 < P_G \leq P_{PV} \\ r_L, P_G \leq 0 \end{cases} \tag{2}$$

where $k = -\dfrac{(r_L - r_G)}{P_{PV}}$

Based on the linear droop model, the profit of the VPP during each dispatching period can be defined in (3).

$$S_G = \begin{cases} r_G P_G \Delta T, P_G \geq P_{PV} \\ r_L P_G \Delta T - (r_L - r_G)\dfrac{P^2{}_G}{P_{PV}}\Delta T, 0 < P_G \leq P_{PV} \\ r_L P_G \Delta T, P_G \leq 0 \end{cases} \tag{3}$$

where ΔT means the time span of each dispatching period.

3. Daily profit maximization of the RPBSs

The daily profit maximization focuses on maximization of the RPBSs' diurnal profit. In order to optimize the RPBSs' diurnal profit, the output power P_G should be restrained from 0 to P_{PV}. The diurnal profit of each RPBS based on the VPP model can be defined in (4).

$$T_G = r_L \Delta T \sum_{i=1}^{N} P_G(i) - \frac{(r_L - r_G)\Delta T}{P_{PV}(i)} \sum_{i=1}^{N} P^2{}_G(i) \tag{4}$$

where $0 < P_G \leq P_{PV}$, i means the sequence number of each dispatching period. N means the maximum sequence number of the dispatching period.

The diurnal dispatching strategy shouldn't affect the residents' self-usage of the batteries at night. Hence, the batteries' states of charge (SOCs) at the end of the dispatching period should be equal to the SOCs at the beginning of the dispatching period. The sum of the batteries' diurnal output power should be a constant value, as defined in (5).

$$consp = \sum_{i=1}^{N} P_G(i) = \sum_{i=1}^{N} P_{PV}(i) - \sum_{i=1}^{N} P_{load}(i) \tag{5}$$

The maximization of each RPBS's daily profit can be simplified in (6).

$$\max T_G = r_L \Delta T consp - \min H \tag{6}$$

where H is defined in (7).

$$H = \frac{(r_L - r_G)\Delta T}{P_{PV}(i)} \sum_{i=1}^{N} P^2{}_G(i) \tag{7}$$

The minimization of H can be solved as a convex quadratic optimization. The convex quadratic optimization can be solved by the infeasible path-following algorithms. The results of its application on the practical RPBSs are presented in section IV.

4. Case study

The proposed price-droop trading strategy is applied on two nearby RPBSs. The structure of each RPBS is shown in Figure 3.
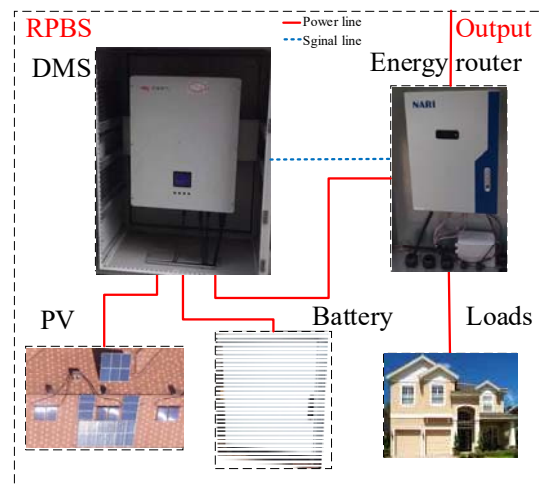
Figure 3. Structure of the RPBS.

As can be seen in Figure 3, each RPBS consists of an energy router, a DMS, a PV generation, a battery and residential loads. The energy router analyzes the data from the DMS and gives the optimal instructions to the DMS. The DMS controls the PV unit and the battery to implement the optimal instructions. The energy router figures out the optimal instructions according to the price-droop trading strategy.

The two nearby testing RPBSs have different loads' hourly power and identical PV units' hourly output power, as shown in Figure 4. The PV unit's daily total power production of each RPBS is 35.52 kWh. The loads' diurnal power consumption of each RPBS is 19.42 kWh.
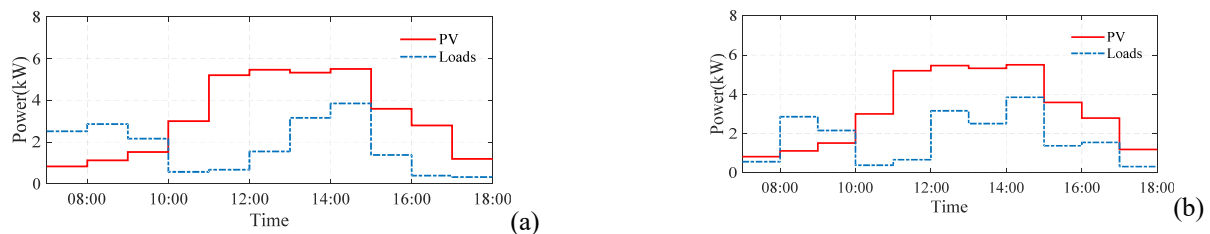

Figure 4. Power curves of the testing RPBSs. (a) Power curve of RPBS 1(b) Power curve of RPBS 2

4.1. Controllable and predictable output power

Coordinated with some extra subsidy policies, RPBSs' common trading strategy purchases the PV units' power production according to the electricity price of the thermal power generation. Compared to the common trading strategy, the merits of the price-droop trading strategy are discussed as follows.

The output power of the RPBSs using different strategies is presented in Figure 5.
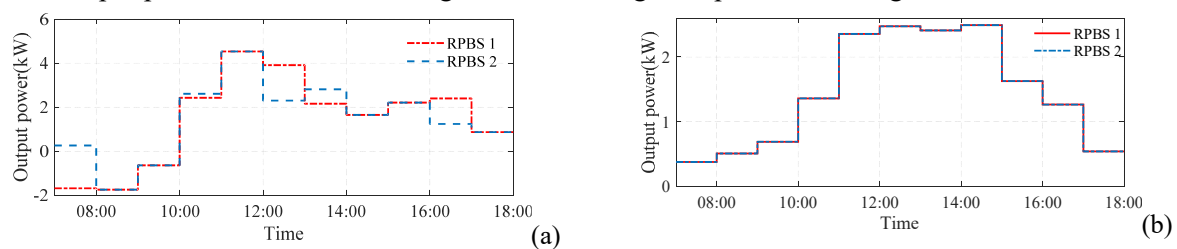

Figure 5. RPBSs' output power using different strategies. (a) Common trading strategy (b) Price-droop trading strategy.

As shown in Figure 5, the RPBSs' output power using the price-droop trading strategy are smoother than the RPBSs' output power using the common trading strategy. The variance of the RPBSs' output power using the common trading strategy is 3.96, whereas the variance of the RPBSs' output power using the price-droop trading strategy is 0.74. Besides, based on the price-droop trading strategy, the RPBSs can be simplified as continuous power sources, which are more controllable.

Results in Figure 5 also indicate that the output power of RPBSs using the price-droop trading strategy will not be affected by the loads' variable hourly power consumption. RPBSs' output power using the price-droop trading strategy is only related to the loads' diurnal power consumption and the predictable output power of the PV units. As the loads' diurnal power consumption is less variable than the loads' hourly power consumption, the output power of the RPBSs will be more predictable.

The RPBSs' controllable and predictable output power results from the unification of the local utilization rates, as shown in Figure 6.

| (a) | (b) |
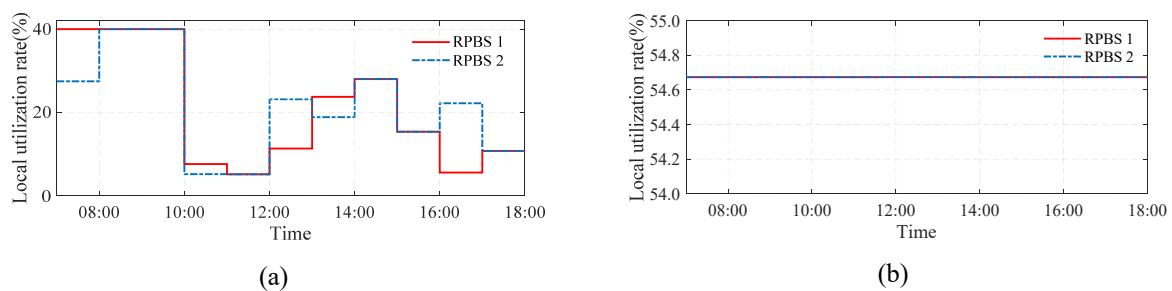
Figure 6. Unification of the local utilization rate. (a) Common trading strategy (b) Price-droop trading strategy.

As can be seen in Figure 6, the local utilization rates of the different RPBSs using the common trading strategy are different, whereas the local utilization rates of the different RPBSs using the price-droop trading strategy are identical. The unifications of the local utilization rates are implemented by the regulating of the batteries. The regulating results of the batteries are shown in Figure 7.

| (a) | (b) |
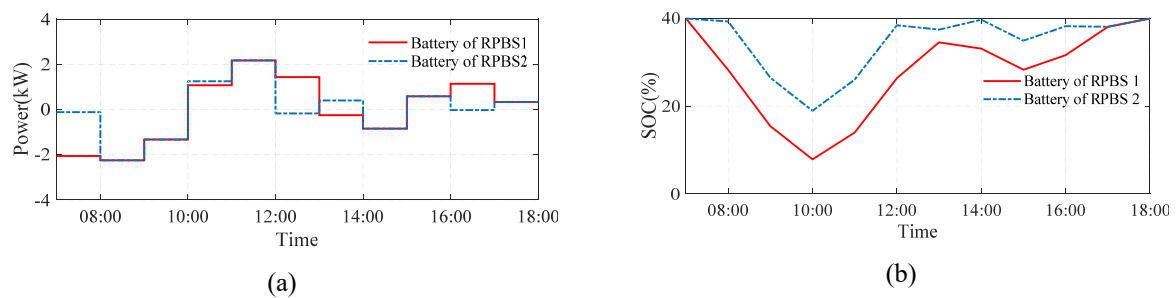
Figure 7. Power and SOCs of the batteries using the price-droop trading strategy. (a) Power of the batteries (b) SOCs of the batteries.

As presented in Figure 7, the power and SOCs of the batteries are different upon different RPBSs. The conventional time-varying RPBSs' local utilization rates are united to an identical value by the batteries' regulations.

4.2. Improvement of the economic profit
The economic profit of RPBSs decides the investors' interest to the RPBSs. The calculation of the each RPBS's economic profit is based on the time-varying electricity price, as shown in Table 1.

Table 1. Time-varying electricity price.

Price of thermal power generation (RMB)	Price type	RMB
0.4155	Off-peak price (22:00-06:00)	0.541
1	Peak price (06:00-22:00)	1.095

Based on the common trading strategy, the annual profit brought by the battery can be defined in (8).

$$G_c = N_d q_e (r_P - r_O) \tag{8}$$

where q_e means the maximum energy capacity of the battery, which values 7 kWh. r_P means the peak electricity price and r_O means the off-peak electricity price. N_d means the equivalent days of the annual operation, which values 365.

Based on the price-droop trading strategy, the annual extra profit is presented in (9).

$$G_P = N_d (q_{PVm} - q_{ld})(r_L - r_G) u_P \tag{9}$$

where q_{PVm} means PV unit's daily power production, which values 35.52 kWh in this paper. q_{ld} means the daily loads power consumption in the daytime, which values 19.42 kWh in this paper. r_L means the loads' time-varying electricity price. r_G means the electricity price of thermal power generation. u_P means the local utilization rate. N_d means the equivalent days of the annual operation, , which values 365.

The annual total profit of each RPBS based on the price-droop trading strategy is defined in (10). The economic profits based on different trading strategies are shown in table 2.

$$G_t = G_P + G_c \tag{10}$$

where G_c means the annual profit brought by the battery, G_P means extra profit related to the local utilization rate.

Table 2. Electricity price economic analysis of different trading strategy.

Strategy	Common trading strategy	Price-droop trading strategy
Battery's fixed cost(RMB)	20000	20000
Annual extra profit (RMB)	1415.47	3195.30
Theoretical lifetime(Year)	10	10
Payback period(Year)	14.13	6.26
Lifetime extra profit (RMB)	-5845.30	11953.96

The extra profit shown in Table 2 will encourage more residents to invest the RPBSs.

5. Conclusions

This paper proposes a price-droop trading strategy to promote the application of the RPBSs. Each RPBS is formulated as a typical VPP. Linear droop model of the electricity price is utilized in the VPPs to achieve more controllable and predictable output power. The proposed strategy is validated by two nearby RPBSs. Test results show that the proposed price-droop trading strategy will not only improve the RPBSs' controllability and predictability, but also bring extra profit to the residents. Due to its merits, the proposed strategy will promote the utilization of photovoltaic resources and decrease the impact of the intermittent resources.

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