Smart Home Energy Scheduling with Photovoltaic System

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Abstract

The integration of Photovoltaic (PV) system into home increasing the complexity of energy scheduling in smart home. But most of current papers concentrate on reducing the payment of the customer. There are few papers studying improve the consumption of PV energy to lead to environment advantages. This paper presents a new method for household energy management with PV system. This work address the PV energy consumption by the household compared to the existing works. The appliance model is given in mathematic model. The time-of-using pricing(TOUP) is used to solve the optimal problem. The objective function is a linear programming problem with absolute value. By introducing auxiliary variables, the objective function is changed to a typical linear programming problem that is easy to be solved.

Keywords

Smart home, household energy management, PV system.

1. Introduction

House/home energy management is an important means for Demand Side Management(DSM). The optimal energy schedule for appliances in household can greatly reduce the payments for customer and fluctuate of the load curve.

There are many literatures study the house/home energy management. An optimal strategy for operation of household appliances with price signal-based demand respond has been discussed in [1-2]. In recent years, the integration of PV systems to the household has been made [3]. PV system as a promising energy source for end users, it would change the operation mode of the household appliance. This impacts can be overcome as in [4]. In [5], a PV based demand side energy management is explored. Castillo-cagigalet al. proposed the man-agement method of washing machines and so on to realizeself-consumption enhancement in battery-PV house[6].However, the proposed papers do not consider the PV power consumption which is import in the world now.

This paper proposes an optimal household energy scheduling with PV system to maximize consumption the PV energy.

2. System model

2.1 Household appliance

Let $\mathcal{A}$ denote the set of appliances in a residential unit that may contains refrigerator-freezer, electric stove, dishwasher, PHEV, etc. Let H denote the scheduling horizon in number of hours. For example, $\mathrm{H} = 24$ or $\mathrm{H} = 48$. For each appliance $a \in \mathcal{A}$ in each hour $h \in [1, H]$, we define an energy consumption scheduling variable x_a^h. But the appliance is “off” and “on” respectively in the process of operation. So we define y_a^h as an auxiliary binary variable such that $y_a^h = 1$. if the appliance a is "on" and $y_a^h = 0$ otherwise for each appliance a at each hour. Let P_a denote the power rating of each appliance a. Given the power rating level for each appliance a, x_a^h can be derived as follows:

$$x_a^h = P_a y_a^h \tag{1}$$

Let E_a denote the total energy consumption in the scheduling horizon H for each appliance $a \in \mathcal{A}$. For example, in the case of a PHEV, we have $E_a = 16\text{kWh}$ to charge the battery for a 40-mi driving range[2]. Let $a_a \in [1, H]$ and $\beta_a \in [1, H]$ denote the beginning and end of a time interval in which the scheduled energy consumption is valid for each appliance a. If $h \notin [a_a, \beta_a]$, then we have $x_a^h = 0$. Given the predetermined parameters E_a, a_a and β_a, the total energy E_a in the interval $[a_a, \beta_a]$ is as follows:

$$E_a = \sum_{h=\alpha_a}^{\beta_a} x_a^h \tag{2}$$

Further to constrains (2), it is required that the time span need to be larger than or equal to the time duration required to finish the normal operation for appliance a.

There is usually a limit denoted by $E^{\max}$ set by the utility grid on total energy consumption at each hour, so we have

$$\sum_{a \in \mathcal{A}} x_a^h \leq E^{\max} \qquad \forall h \in [a_a, \beta_a] \tag{3}$$

2.2 Time-of-using pricing

There are many pricing models, such as real-time pricing(RTP), day-ahead pricing(DAP), time-of-using pricing(TOUP), critical-peak pricing(CPP), which are to replace the current used flat rate tariffs. As it has been shown in [5], real-time pricing with inclining block rates can better respond to time-varying prices than others. However, we select TOUP which is widely adopt by utility grid because we focus our study on application of the PV system in China.

There are three time intervals for TOUP shown in Table 1.

Table 1 TOUP Pricing Model in China

Time Interval (hour)	Electricity price (¥/kWh)
0:00-8:00	0.398
8:00-21:00	0.528
21:00-24:00	0.398

2.3 PV Generation and Feed in Tariff(FIT)

We assume that a photovoltaic energy source was installed on the rooftop of houses as shown in Fig.1. However, we note that the PV system can not fully meet the load demand of the household one day. The household must be connected to the main grid. So the operation mode is self-use for the PV power generation and power on the main grid for the surplus energy in Fig.1. There are two meters in Fig.1. The meter 1 is a two-way meters for bidirectional charging while the meter 2 is one-way meter for metering PV power generation. There are two operation scenarios corresponding different benefits under the power policy.

One is the scenario when the amount of PV power generation is larger than that of all appliances. The PV power generation is metering by meter 2. The surplus energy is exported to the distribution network except the energy meet the needs of household.

Fig.1 Smart distribution grid with PV system

Different countries have different FIT for PV power generation. Here, we take FIT as example. The household incomes is expressed under this FIT as follows:

$$Incomes = S_{PV} x_{m2}^{h} + P_{ds}\, x_{m1}^{h} \tag{4}$$

Where S_{PV} denotes state subsidies in China. x_{m2}^{h} denotes the meter reading for meter 2 at hour h. P_{ds} denotes desulfurization price. x_{m1}^{h} denotes meter reading for meter 1 at hour h.

The other scenario is when the amount of PV power generation is less than that of all appliances. The PV power generation is also metering by meter 2. The PV power generation meets the load demand in household and not exported to the distribution network. The household incomes is expressed as:

$$Incomes = S_{PV} x_{m2}^{h} - P x_{m1}^{h} \tag{5}$$

Where P denotes the electricity price at hour h.

We have $S_{PV} = 0.423$ ￥/kWh, $P_{ds} = 0.378$ ￥/kWh, $P = 0.528$ ￥/kWh in the pricing structure.

2.4 Problem Formulation

Unlike [7-9], the optimization of this work to minimize his/her PV power generation that exported to the utility company within the scheduling horizon. We formulate the energy consumption scheduling problem with PV system as the following optimization problem:

$$\text{minimize } \sum_{h=1}^{H} \left| \sum_{a\in\mathcal{A}} P_a y_a^h - x_{m2}^{h} \right| \tag{6}$$

By introducing auxiliary variables $u^h$and v^h for all h, we can rewrite (6) as:

$$\text{minimize} \sum_{h=1}^{H} (u^h + v^h) \tag{7}$$

$$\sum_{a\in\mathcal{A}} P_a y_a^h - x_{m2}^{h} + u^h - v^h = 0,\ \ h = 1,2,\dots,H \tag{8}$$

$$u^h \geq 0, v^h \geq 0, h = 1,2,\dots,H \tag{9}$$

Eq.(6) is equal to (7),(8) and (9) and this has been proved in [10]. Unlike (6), (7),(8) and (9) are linear and differentiable. They can be solved by linear programming techniques.

3. Simulation Results

To evaluate the performance of proposed load demand scheme, we consider a single house with eleven appliances and a rooftop PV system whose rating power is 5 kW. A household appliances using data obtained from [10].

In a typical scenario, the PV power generation is higher and the customers are required to consume the PV energy to reduce their bills according to (6). Compared to the conventional custom where the customers prefer to operate the appliance at the lower price intervals, the new mode where the customers prefer to consume PV energy increase the incomes of the customer from 13.13￥to 13.76￥. The PV energy consumption by the PV system owner increases by 10.2kWh. Fig.2 shows the PV energy consumption between the optimal scheduling of the appliances or not for the customers.

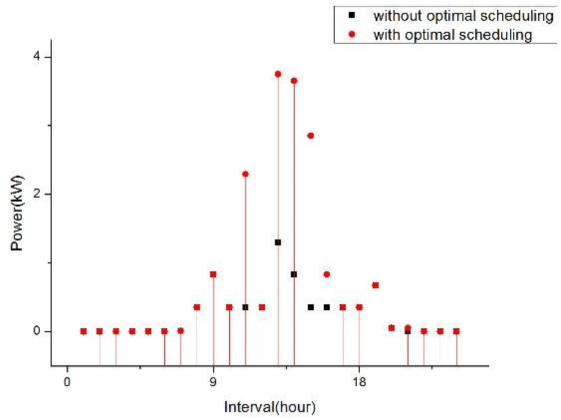

Fig.2 PV power consumption with optimal scheduling or not

It is clear that PV energy consumption with optimal scheduling of appliances by the owner is larger than that without optimal scheduling at each hour in Fig.3.

Fig.3 shows the hourly incomes comparisons between the optimal scheduling of the appliances or not for the customers.

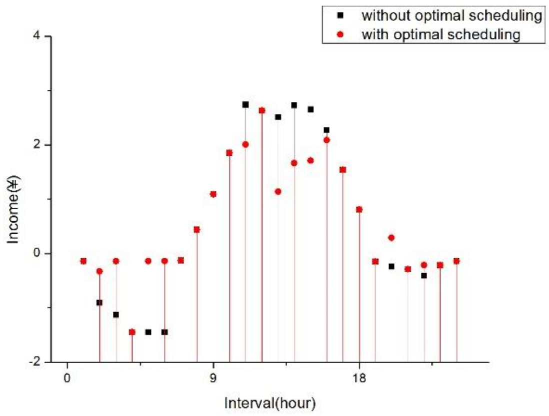

Fig.3 A residential incomes with optimal scheduling or not

The income of the customer with optimal scheduling is larger that without optimal scheduling at time 2AM, 3AM,5AM, 6AM, 20AM and 22AM. This is due to the reason that operation time of some appliance changes from these time to the time interval at noon when the PV power generation is larger. On the other hand, as most PV energy without optimal scheduling is exported to the utility grid at time 11AM, 1PM, 2PM,3PM and 4PM, the customer get more incomes by desulfurization fees than that with optimal scheduling. The total income in a sunshine day with optimal scheduling increases by 0.63¥.

4. Conclusion

By applying the proposed method to a example, we conclude that the more PV energy consumption then more incomes the end users obtained. This encourage the users to participate in the residential load control program.

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