Novel Scheduling Method to Reduce Energy Cost by Cooperative Control of Smart Houses

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Abstract—A smart house which equips power generators, power storage systems, and a smart meter which controls those equipments to utilize renewable energy efficiently has attracted attentions. Smart house is expected to reduce energy cost of residential by efficient usage of energy resources. Scheduling methods of the equipments to reduce energy cost have been proposed. However, since they focus on only one house, the effect of the scheduling decreases due to the imbalance of the equipments and the concentration of selling energy to power grid at same time. This paper proposes a new scheduling method to operate multi smart houses totally by virtually sharing their equipments. The proposed method can improve the imbalance of the equipments and reduce the amount of disposal energy. By computer simulation, it is shown that the proposed method can reduce over 16% the energy cost to the conventional method.

Index Terms—Smart Grid, Smart House, Home Energy Management System, EVNO

I. INTRODUCTION

Recently, the efficient usage of renewable energy has attracted attentions because of the environmental problems. Smart house [1][2] which has renewable power generation systems such as photovoltaic cells(PV), batteries as an energy storage system, and controllable home electronics has been proposed.

To reduce the total energy cost of the house, scheduling methods which provides optimal operation of the power generators and the storage systems based on forecast of demand and amount of power generated by renewable energy sources [3]-[5]. These methods enable users to reduce the amount of energy purchased from a power grid by managing power consumption in the house and this realizes energy cost reduction.

However, there are two problems in the conventional methods. First, it only focuses on ideal houses which have moderate amount of power generators, storage systems and demands. If imbalance of them occurs, the efficiency of equipments decreases. There are many types or circumstances among houses, ideal scheduling effect may not be introduced. Therefore, it is unrealistic to consider only ideal houses.

Second, amount of selling energy excessively concentrates in daytime because they do not know the circumstances of other houses. Excessive concentration of selling energy raises voltage of the power grid. When the voltage reaches the upper limit, there will be a surplus energy that can’t be sold and thus it will be discarded. This discarded energy is called “disposal energy” in this paper.

To solve two problems, we propose a scheduling method which manages distributed energy sources to virtually share them among multi-houses. The proposed scheduling method leads more reduction of energy cost by efficient usage of equipments with solving imbalance of them and reducing the disposal energy. An energy virtual network operator (EVNO), newly proposed business model, controls energy trading among smart houses to virtually share their equipments. EVNO makes a contract with smart houses to control their facilities and manages them totally. EVNO determines batteries rental rate among smart houses and own tariff of energy trading between houses which is used when trading surplus energy and free capacity of batteries. To minimize energy transmission loss between smart houses, an efficiency of the energy transmission which is determined by the distance between houses is newly introduced as an optimization parameter.

This paper is organized as follow: the smart house is defined in section II and EVNO is introduced in section III. In section IV, the proposed optimization method is explained and in section V, simulation results are provided to evaluate the performance of the proposed method. Finally, in section VI summarized the paper.

II. SMART HOUSE

The smart house has been proposed to realize low carbon society in recent years. Figure 1 shows an overview of the smart house. The smart house has renewable energy sources, batteries, intelligent home electronics, and smart meter which is connected to a communication network and controls equipments totally.

The smart meter collects a forecast of the power consumption demand, the power generation, and the tariff of the day from a power company. The smart meter schedules the usage of the battery based on the information from a power company and its own demand to minimize energy cost. For example, the smart house which has small demand in daytime and large demand in nighttime charges surplus energy in daytime and uses them in nighttime. It can realize reduction of the energy cost by self-sufficient energy usage.
III. EVNO (ENERGY VIRTUAL NETWORK OPERATOR)

EVNO makes a contract with houses to control their facilities and manages them efficiently with using existing power grid. Figure 2 shows an overview of EVNO. EVNO exchanges necessary information with houses and then accommodates energy between houses. When energy trading between houses happens, logical energy transmission from an energy seller to and energy buyer arises. Actual energy transmission is done by a company which manages the power grid. This means that each house just sends energy to power grid or consumes energy at the time designated by EVNO. As a result, the electric power is effectively used as if electric power is exchanged between sellers and buyers.

EVNO pays charge to the power grid company according to the amount of the transmission energy. EVNO can reduce energy cost by minimizing energy transmission loss and, self discharge of the battery, by rising usage efficiency of facilities. As a result, EVNO takes a part of the profit as a fee. In this way, the power grid management companies, EVNO, and also users can get benefit: the management companies do not need to control of distributed energy sources and get rental rate of the power grid with no efforts. EVNO does not need to own a huge infrastructure. Therefore, EVNO can start up with little initial investment and get a part of profit from contractors i.e. the power grid company. Users can reduce energy cost by operation of EVNO.

IV. PROPOSED SCHEDULING METHOD

A. Overview

A new scheduling method, which virtually sharing equipments to maximize the usage efficiency of them, will be proposed. The proposed method is executed in following steps.

1) Each smart house sends its demand and supply information to the EVNO server. The demand information includes hourly demand of the day. The supply information includes hourly forecast of output of the generator (PV)[6].

2) The EVNO server calculates schedules by matching of demands (buyers) and supplies (sellers).

3) The EVNO server sends each house’s calculated schedules to each house.

Figure 3 shows an example of matching demand and supply. EVNO server determines the matching by considering the transmission loss between houses. The value on a link in topology indicates a metric for the transmission loss. As the metric increases, the transmission loss becomes bigger and energy cost becomes high. In this example, at 12:00, house A and B request 10kW demand (-10) and house C and D report 10kW supply (+10). At that time, EVNO server matches house A, D and house B, C to minimize the transmission loss. Furthermore, EVNO server considers the shift of using or supplying energy by controlling batteries of houses. When house C and D request -10 demands, and house A and B report +10 supplies at 13:00, EVNO server instruct house B and C to change the schedule at 12:00 for that at 13:00. It means that house B hastens the start of discharging battery and house C continues to charge its battery until 13:00. This change enables to match house A, B and house C, D at 12:00 and 13:00 and the transmission loss is additionally reduced.

As described above, the proposed method enables houses to cooperate with minimum transmission loss by the total control via EVNO. In fact, other than the transmission loss, tariff, conversion efficiency and self discharging of battery of battery, are considered in the proposed scheduling method.

The proposed method has the following two merits. First
merit is that usage efficiency of the equipments is increased by virtually sharing them. The proposed method can utilize surplus energy and free capacity of batteries which cannot be used by the conventional method. For example, house A whose PV is too large compared to its demand and battery disposes surplus energy because it does not have sufficient amount of battery. On the other hand, house B whose battery is too large compared to its power generator and demand cannot utilize free capacity of its battery because the battery has no occasion to store the energy. The proposed method introduces the battery rental rate to encourage house B to use free capacity of its battery for charging surplus energy from house A.

Second merit is that disposal energy is reduced by peak shifting of the selling energy. In the conventional method, timing of selling energy tends to concentrate too much in daytime when PV generate large amount of surplus energy. This is because, houses do not know the other houses conditions. This causes the increase of the disposal energy because the capacity of the power grid is limited. If houses know their conditions each other, they can shift the timing of selling energy by using their batteries even so there are losses of charging and discharging of batteries. Figure 4 shows an example of the peak shift. This enables the voltage of the power grid to be under the upper limit and reduce the disposal energy. These features reduce energy cost compared to the conventional method.

B. Optimization Model
We take into account the scheduling problem of multi-smart houses based on the forecasting of the demand and the amount of the power generated by PV. As a matter of solution policy, we minimize total energy cost and distribute profits to the house according to the degree of contribution.

1) **Optimization objective:**
\[
\begin{align*}
\text{Min} & \sum_{n \in N} \left( \sum_{t=0}^{T} S_{n}^{out}(t) - \sum_{t=0}^{T} S_{n}^{in}(t) \right) \\
\end{align*}
\]

Where:
\[
S_{n}^{out}(t) = C^{ph}(t) \cdot P_{n}^{ph}(t) + C^{ga} \cdot P^{fl} + C^{se-evno}(t) \cdot \sum_{m \in N, m \neq n} P_{mn}^{se-evno}(t)
\]
\[
S_{n}^{in}(t) = C^{se}(t) \cdot P_{n}^{se}(t) + C^{ph-evno}(t) \cdot \sum_{m \in N, m \neq n} \frac{1}{\alpha_{nm}} P_{mn}^{ph-evno}(t)
\]

Where:

- \( T \): total number of time intervals
- \( N \): total number of houses
- \( \alpha_{nm} \): transmission loss rate between house \( n \) and \( m \)
- \( P_{n}^{ph}(t) \): power from the power grid to \( n \) at interval \( t \) (kW)
- \( P_{n}^{se}(t) \): power from \( n \) to the power grid at interval \( t \) (kW)
- \( P^{fl} \): power from fuel cell at interval \( t \) (kW)
- \( P_{mn}^{ph-evno}(t) \): power from \( m \) to \( n \) at interval \( t \) (kW)
- \( P_{n}^{se-evno}(t) \): power from \( n \) to \( m \) at interval \( t \) (kW)
- \( C^{ph}(t) \): cost for purchasing from power grid at interval \( t \) (yen/kW)
- \( C^{se}(t) \): cost for selling to power grid at interval \( t \) (yen/kW)
- \( C^{ga} \): cost of gas (yen/kW)
- \( C^{ph-evno}(t) \): cost for purchasing to EVNO at interval \( t \) (yen/kW)
- \( C^{se-evno}(t) \): cost for selling from EVNO at interval \( t \) (yen/kW)
2) Power balance: \( n \in N, \forall n, t \in T, \forall t \)
a) When battery is charging
\[
P_{n}^{ds} (t) = (P_{n}^{ph} (t) + P_{n}^{pv} (t) + P_{n}^{fl} + \sum_{m \in N, m \neq n} (P_{hm}^{n} - evno (t) + P_{mn}^{re (t)} (t) + \frac{1}{\beta} P_{n}^{ch} (t))
- (P_{n}^{se (t)} + P_{n}^{se - evno (t)}) + \sum_{m \in N, m \neq n} \frac{1}{\alpha_{nm} \beta} P_{mn}^{bo} (t) + D_{n} (t))
\] (4)
b) When battery is discharging
\[
P_{n}^{ds} (t) = (P_{n}^{ph} (t) + P_{n}^{pv} (t) + P_{n}^{fl} + \sum_{m \in N, m \neq n} (P_{hm}^{n} - evno (t) + P_{mn}^{re (t)} (t) + \beta \cdot P_{n}^{ch} (t))
- (P_{n}^{se (t)} + P_{n}^{se - evno (t)}) + \sum_{m \in N, m \neq n} \frac{1}{\alpha_{nm} \beta} P_{mn}^{bo} (t) + D_{n} (t))
\] (5)
3) Constraints of trading power between power grid and houses: \( n \in N, \forall n, t \in T, \forall t \)
\[
\{P_{n}^{ph} (t) + \sum_{m \in N, m \neq n} (P_{mn}^{re (t)} + \frac{1}{\beta} P_{mn}^{bo} (t) + P_{hm}^{n} - evno (t))\}
- (P_{n}^{se (t)} + \sum_{m \in N, m \neq n} \frac{1}{\alpha_{nm} \beta} P_{mn}^{re} (t))
+ P_{mn}^{se - evno} + \sum_{n \in N, n \neq m} \frac{1}{\alpha_{nm} \beta} P_{mn}^{bo} (t)) \leq p_{inmax}
\]
\[
\sum_{n \in N, n \neq m} \{P_{n}^{se (t)} - P_{n}^{ph (t)} + \sum_{m \in N, m \neq n} (P_{mn}^{se - evno} - P_{hm}^{n} - evno (t))\} \leq p_{outmax}
\] (7)
4) Constraints of battery: \( n \in N, \forall n, t \in T, \forall t \)
\[
0 \leq W_{n}^{ch} (t) + W_{n}^{le} \leq W_{n}^{max}
\]
\[
p_{dismax} \leq P_{n}^{ch} (t) + \sum_{m \in N, m \neq n} (P_{mn}^{bo} (t)) - \frac{1}{\alpha_{nm} \beta} P_{mn}^{re} (t)) \leq p_{chmax}
\]
\[
5) Constraints of trading power between houses:
\] (9)
\[
6) Constraints of fuel cell: \( n \in N, \forall n, t \in T, \forall t \)
\[
P_{hm}^{n} - evno (t) = \alpha_{nm} \cdot P_{mn}^{se - evno (t)}
\]
\[
0 \leq P_{n}^{fl} (t) \leq p_{flmax}
\]
\[
p_{flmax} \leq P_{n}^{fl} (t) - P_{n}^{fl} (t - 1) \leq p_{flu}
\]
Where:
\[D_{n} (t): \text{power demand at interval } t \text{ (kWh)}\]
\[P_{n}^{pv} (t): \text{power from } n's \text{ PV at interval } t \text{ (kWh)}\]
\[P_{n}^{ch} (t): \text{power of } n's \text{ own battery at interval } t \text{ (kW)}\]
\[P_{n}^{se (t)} + \text{ power which } n \text{ uses from } m's \text{ battery at interval } t \text{ (kWh)}\]
\[P_{n}^{ds} (t): \text{amount of disposal energy in } n \text{ at interval } t \text{ (kWh)}\]
\[P_{inmax}^{max}: \text{maximum limit of come in each house (kW)}\]
\[P_{outmax}^{max}: \text{maximum limit of go out to the power grid (kW)}\]
\[P_{dismax} \text{ : maximum limit of battery discharging rate(kW)}\]
\[P_{outmax}^{max}: \text{maximum limit of battery charging rate(kW)}\]
\[\text{ maximum limit of fuel cell(kW)}\]
\[P_{flu}: \text{upper limit of ramp rate of fuel cell (kW/h)}\]
\[W_{n}^{ch} \text{ : total capacity of } n's \text{ battery charging to itself at interval } t \text{ (kWh)}\]
\[W_{n}^{le} \text{ : total capacity of } n's \text{ battery lending to other houses at interval } t \text{ (kWh)}\]

V. PERFORMANCE EVALUATION

Effectiveness of the proposed method rather than the conventional method [3] is evaluated on the following points.

- Energy cost fluctuation associated with the difference of the combination of facilities and demands.
- Average energy cost fluctuation and disposal energy fluctuation associated with differences of the selling energy upper limit.

The selling energy upper limit means the amount of selling energy which the power grid can keep its voltage under the upper limit. In this simulation, elements and the tariff are assigned shown in table I, II, III. 1 km square area of houses is used and total number of houses \(N=10\) houses are allocated. The size of power generation, storage systems and demand are
configured randomly according to the actual common equipment size. The tariff is determined by referring the grid company’s tariff [7]. We simulate the power consumption for 24-hours (0:00 - 23:59).

<table>
<thead>
<tr>
<th><strong>TABLE I</strong></th>
<th><strong>SIMULATION ELEMENTS</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Area of houses</td>
<td>1km square</td>
</tr>
<tr>
<td>PV(kWp)</td>
<td>Average 3 (Normal Distribution, Dispersion 1)</td>
</tr>
<tr>
<td>Fuel cell (kWh)</td>
<td>0.7 Penetration 20%</td>
</tr>
<tr>
<td>Battery (kWh)</td>
<td>Average 3 (Normal Distribution, Dispersion 1) penetration 60%</td>
</tr>
<tr>
<td>Demand(kWh)</td>
<td>Average 10 (Normal Distribution, Dispersion 1)</td>
</tr>
<tr>
<td>Peak of demand</td>
<td>Morning 6<del>9 Night 17</del>23 (Normal Distribution, Dispersion 1)</td>
</tr>
<tr>
<td>Transmission loss rate (/km)</td>
<td>0.05</td>
</tr>
<tr>
<td>Conversion efficiency</td>
<td>0.9</td>
</tr>
<tr>
<td>Self discharging rate (/h)</td>
<td>0.01</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>TABLE II</strong></th>
<th><strong>TARIFF</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>8<del>22 1</del>7 23~24</td>
</tr>
<tr>
<td>Purchase price from power grid (yen / kWh)</td>
<td>30 10</td>
</tr>
<tr>
<td>Sale price to power grid (yen / kWh)</td>
<td>15 5</td>
</tr>
<tr>
<td>Trade price by EVNO (yen / kWh)</td>
<td>23 7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>TABLE III</strong></th>
<th><strong>SIMULATION PARAMETERS</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>24</td>
</tr>
<tr>
<td>C_{0}</td>
<td>20</td>
</tr>
<tr>
<td>p_{max}</td>
<td>2</td>
</tr>
<tr>
<td>p_{max}</td>
<td>0.18</td>
</tr>
</tbody>
</table>

A. The fluctuation of energy cost associated with the difference of the combination of facilities and demand

Figure 5 shows the energy cost fluctuation associated with the difference of the combination of facilities and demand. The horizontal axis indicates scenario number and the vertical axis indicates energy cost. Scenario means a combination of 10 houses which have different size of power equipments and demands. As shown in Fig.5, the proposed method reduced energy cost compared to the conventional method in every scenario and the average of the reduction of energy cost was over 16% over 13 Yen per day (nearly 4000 Yen(53 USD) per month). We can conclude that the proposed method is effective regardless the circumstance of equipments and demands.

B. The fluctuation of average energy cost and the disposal energy associated with the difference of the upper limit of the selling energy

Figure 6 and Figure 7 show the average energy cost fluctuation and the disposal energy fluctuation associated with the difference of the selling energy upper limit respectively. The horizontal axis indicates the upper limit of the selling energy per one house and the vertical axis indicates energy cost and disposal energy.

From Fig.6 and Fig.7, it is shown that the reduction of energy cost and disposal energy increases according to the decrease of the horizontal value when the upper limit is higher than 1.5 kWh. This result indicates that the proposed method reduces the disposal energy by shifting the peak of selling energy.

The effect of the proposed method decreases when the upper limit is lower than 1.5 kWh. The amount of selling energy in daytime exceeds the capacity of the power accommodation and the disposal energy increased.

Fig. 5. The energy cost fluctuation associated with the difference of the combination of facilities and demands.

Fig. 6. The fluctuation of average energy cost associated with the difference of the upper limit of the selling energy.
VI. CONCLUSION

The smart house which equipped power generators and power storage systems is expected to reduce energy cost by efficient usage of equipments. Scheduling methods of equipments in the smart house to minimize energy cost have been discussed. There are two problems in the conventional methods. First, the effect of reduction of energy cost decreases when the introduction of equipments is imbalance. Second, disposal energy increases because of the excessive concentration of selling energy. We proposed a new scheduling method which virtually shares facilities through EVNO. EVNO totally controls equipments of contracted houses and takes a part of the profit as a fee. This realizes utilization of the surplus energy and free capacity of batteries and reduction of the disposal energy by selling energy peak shifting. We showed that our method could reduce over 16% the energy cost compared to the conventional method by computer simulation.

VII. REFERENCES
