

Supply and Demand Management System based on Consumption Pattern Analysis and Tariff for Cost Minimization

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Abstract—In this paper, we propose a supply and demand management system based on information on the power consumption pattern analysis and the tariff for HEMS(Home Energy Management System) of KEPCO(Korea Electric Power COrporation) for cost minimization. The scheduler of a supply and demand management system decides the curtailment level for the dropped appliances based on information about the predicted power consumption amount, the predicted renewable energy generation amount, and the tariff. We get the effect of the cost minimization on power consumption for home area user using constraints to decide the optimal curtailment level.

Keywords—supply and demand management, cost optimization, curtailment, tariff, pattern analysis, HEMS

I. INTRODUCTION

The modern world has been facing on the environmental problems such as the increment of energy consumption and global warming by economic development in all countries of the world. The method which resolves the increment of energy consumption and global warming through the renewable energy use is receiving worldwide attention.

The feature of renewable energy is eco-friendly as well as safely. However, the power generation by renewable generators such as photovoltaic power generator is intermittent in accordance with the weather condition. Smart Grid technology has resolved the problem on renewable generators through using ESS(Energy Storage System) [1] – [3].

The electric power for the supply which composes the renewable generators and the power grid is used to correspond to the demand in Smart Grid. The supplied electric power is decided by the market or the provider about electric power. Even though existing authors proposed the methods to minimize the electric cost, the intermittent problem of renewable generators is not solved because of no using ESS [4] – [6].

Authors of [7] – [10] proposed the method to minimize the electric cost using ESS. Also, Authors [11] – [13] proposed the method to minimize the electric cost using ESS in HEMS. Even though authors of [11] proposed the method to minimize the electric power, the cost optimization is limited because authors of [11] didn't use information on the demand of

appliances by privacy. Even though authors of [12] proposed the method to minimize the electric cost in HEMS, the method has a problem which the kind of smart appliance is limited for the portable device. Authors of [13] proposed the method to minimize the electric cost based on the tariff for KEPCO. Although the proposed method for the curtailment of dropped appliance based on the tariff for KEPCO, the method for the curtailment of dropped appliance is limited on the minimization of the electric cost because the method didn't presented criterion except for a condition of the maximal curtailment.

In this paper, we propose supply and demand management system based on electric power consumption pattern analysis and the tariff for KEPCO for minimization on the electric cost. The system consists of the module on the power consumption prediction, renewable energy prediction, and supply and demand scheduler. The module on power consumption prediction implements the prediction of electric power consumption amount using history data. The module on renewable energy implements the prediction on the renewable energy amount. The module on supply and demand scheduler decides the curtailment level for the electric power use from power grid based on information on the predicted power consumption amount, the predicted renewable energy amount, and the tariff for KEPCO.

The rest of the paper is organized as follows. Section II briefly reviews the hierarchical clustering algorithm for the pattern analysis of electric power consumption data. In section III, The proposed supply and demand management system is described. In section IV, optimization formulation to minimize the electric cost is described and the performance analysis about the proposed method is implemented in section V. We conclude the proposed method in section VI.

II. RELATED WORK

A. Clustering the Consumption Data [14]

Data about electric power consumption is clustered to group an original electric power consumption pattern in the proposed method. All clusters have the probability density function of a Gaussian distribution. The probability density

function of a Gaussian distribution is gotten as the following equation (1).

$$\phi(x; \mu, \sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{1}{2\sigma^2}(x - \mu)^2\right) \quad (1)$$

Where μ and σ^2 are the mean and the variance of the distribution, respectively.

Clustering method requires a measure of distance between the objects to be clustered, and the choice of the distance has an influence on the result of cluster analysis. Authors of [14] used the hierarchical clustering algorithm to merge the probability density function of a Gaussian distribution.

In this paper, we use the clustering method to group an original electric power consumption pattern. To cluster, we focus the probability density function of a Gaussian distribution.

B. Hierarchical Clustering Algorithm [15]

The Hierarchical clustering algorithm can be described as the following steps.

- 1) Compute the proximity matrix containing the distance between each pair of patterns. Treat each pattern as a cluster.
- 2) Find the most similar pair of clusters using the proximity matrix. Merge these two clusters into one cluster. Update the proximity matrix to reflect this merge operation.
- 3) If all patterns are in one cluster, stop. Otherwise, go to step 2.

Based on the way the proximity matrix is updated in step 2, a variety of algorithms can be designed. Hierarchical algorithms start with a single cluster of all the given objects and keep splitting the clusters based on some criterion to obtain a partition of singleton cluster.

In this paper, we focus the hierarchical clustering algorithm to merge the probability density functions of a Gaussian distribution.

III. SUPPLY AND DEMAND MANAGEMENT SYSTEM

A. Environment and architecture of proposed system

Fig. 1 shows an environment of the proposed supply and demand management system in HEMS. Supply and demand management system collect information on the demand for smart appliance, the supplied electric power of the renewable generator, and the tariff for using electric power from power grid. Also, the system collects history data of electric power consumption, the weather for the prediction of the renewable energy amount, and the spec of the PV panel.

Smart appliances send DB server information on electric power consumption using home gateway. Information on the generation of renewable energy generators is sent supply and

demand management system using solar energy gateway. The electric power by the renewable energy generator is supplied to ESS through solar inverter from DC to AC. The electric power from power grid is sent ESS in the home area. Information on the tariff is sent supply and demand management system by the provider of the electric power.

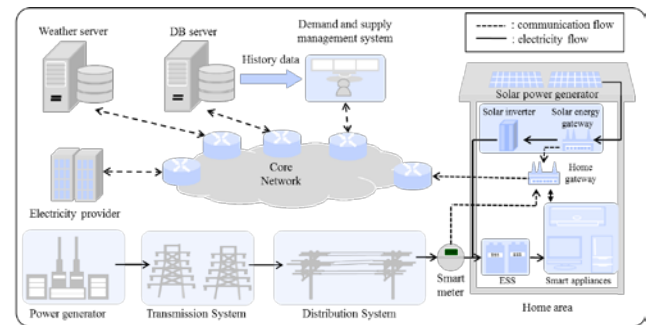


Figure 1. An environment of the proposed system

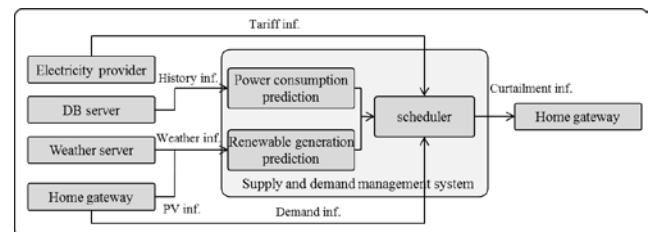


Figure 2. The block diagram about the proposed system architecture

Fig. 2 shows the block diagram of the proposed supply and demand management system. Supply and demand management system consists of the module on the power consumption prediction, the renewable energy amount prediction, and scheduler.

The module on the power consumption prediction implements the pattern analysis the electric power consumption based on data of electric power consumption by the smart appliance. Data of electric power consumption by the smart appliance are sent from DB server to supply and demand management system.

The module on the renewable energy power prediction implements the prediction about the electric power amount by the PV power generator. Supply and demand management system collects information on the weather and the specification of PV power generator for the prediction of the power generation.

The module on scheduler controls supply and demand amount to minimize the electric cost using information on the predicted electric power consumption amount, the renewable energy generation amount, and the tariff for KEPCO. The lacked electric power is supplied from the power grid by the value of the difference between information on the predicted renewable electric power amount and the predicted demand amount. When the tariff is used by the electric power amount of the power grid, operation for dropped appliance is decided by the curtailment level according to the tariff.

B. Pattern Analysis for Smart Appliance

Smart appliance consists of must-run appliance, controllable appliance, and dropped appliance. Must-run appliance is operated by consuming the required electric power amount at required time slot. Controllable appliance consists of time-shiftable appliance and power-shiftable appliance. Time-shiftable appliance can shift operating time by consuming the electric power during required time slots. Power-shiftable appliance can distribute a variety of power consumption time because they can receive the electric power during required time slots. Dropped appliance can be dropped by the policy for the management in spite of the demand for the electric power consumption.

Information on the consumed electric power by smart appliance in the past years has been collected by DB server. Information on the consumed electric power is sent the module on power consumption prediction of supply and demand management system for the prediction of the power consumption. The module on power consumption prediction implements clustering of electric power consumption data every time slots based on electric power consumption data in past years.

Fig. 3 shows the value of mean and variance based on clustering of the consumed electric power every time slots during a day in past three years. Hierarchical clustering algorithm is used to predict electric power consumption each time slots through the merger the clusters about the electric power consumption of two smart appliances.

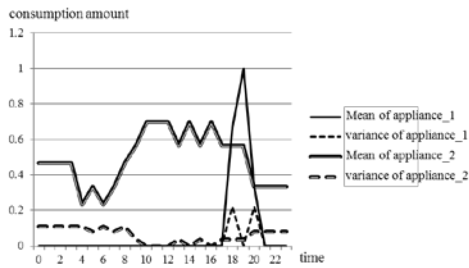


Figure 3. Mean and variance on power consumption of two appliances

Fig. 4 shows distribution of the merged cluster between two appliances at time slot t through the electric power consumption amount in past three years. The distribution of the cluster has mean and variance. Fig. 5 shows that the distribution of the cluster has mean and variance.

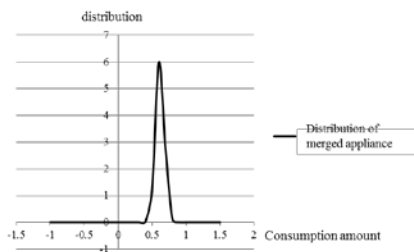


Figure 4. Distribution of merged cluster between two appliances at time t

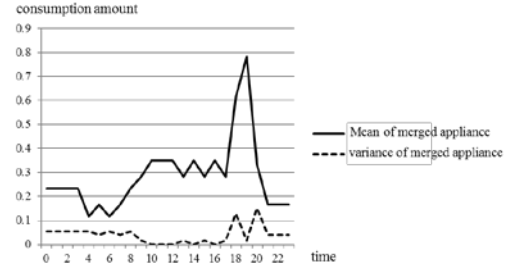


Figure 5. Mean and variance on merged cluster at time t

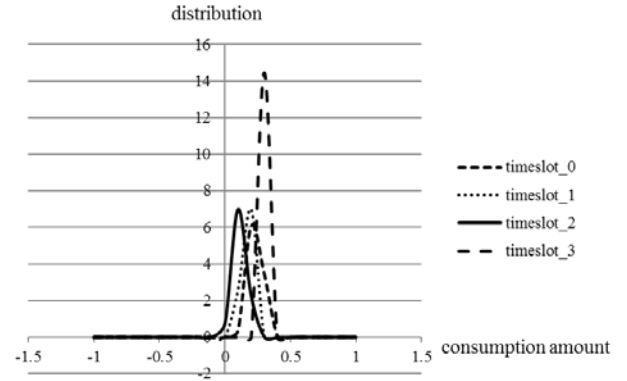


Figure 6. Distribution of merged clusters during four hours

Fig. 6 shows the graph on the distribution of the consumed electric power amount through the merged clusters of two appliances based on electric power consumption at each time slot in past three years.

C. Supply-side Policy

The supply of the electric power consists of renewable energy using PV panel and the electric power from power grid.

1) Renewable Generator Side

Information on the weather, the latitude, the longitude, and the PV panel is used [13].

The electric power generation amount of PV panel is decided by the weather, the incident angle, the air mass. The electric power generation amount of PV panel is decided by the following equation (2)

$$S_{sol,t} = \begin{cases} w_f \cdot p_p \cdot \cos\left[\frac{\pi}{12h}(t-12h)\right] \cdot e^{\frac{\delta t}{\mu}}, & 6h \leq t \leq 18h \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

w_f , p_p , $\cos\left[\frac{\pi}{12h}(t-12h)\right]$, and $e^{\frac{\delta t}{\mu}}$ mean information on the predicted weather, the peak value of a time during a day, hourly angle, and the air mass respectively. Information on the weather has the value of mean and variance because of the

prediction process. The condition of peak value means the following equation (3).

$$P_p = P_{pn} \cdot S_{pn} \cdot \cos(90^\circ - \varphi + \delta) \quad (3)$$

P_{pn} , S_{pn} , φ , and δ mean the peak power of PV panel, the area of PV panel, the latitude, and the longitude.

2) Power Grid Side

The policy of power grid consists of the tariff for KEPCO of power grid and the curtailment condition to decide the supply of the electric power to dropped appliance.

TABLE 1. TARIFF FOR HEMS OF KEPCO [13]

	Electric quantity (kWh)	Price (\$/kWh)
Step 1	0 ~ 100	0.05
Step 2	100 ~ 200	0.11
Step 3	200 ~ 300	0.16
Step 4	300 ~ 400	0.24
Step 5	400 ~ 500	0.35
Step 6	500 ~	0.62

Table.1 shows the tariff for HEMS of KEPCO. The electric cost of the tariff increases according to the increment of the consumed electric power amount step by step. If the consumed electric power amount is included in step 1 or step 2 (q_{low} : low level electric quantity), curtailment condition (θ_t) of equation (4) maintains minimum curtailment state ($\theta_{min,t}$) and the supplied electric power amount maintains high level according to $d_{grid,t} = d_{grid,t} - \theta_t$.

If the consumed electric power amount is included in step 3 or step 4 (q_{med} : medium level electric quantity), curtailment condition (θ_t) of equation (4) maintains medium curtailment state ($\theta_{med,t}$) and the supplied electric power amount maintains middle level according to $d_{grid,t} = d_{grid,t} - \theta_t$.

If the consumed electric power amount is included in step 5 or step 6 (q_{high} : high level electric quantity), curtailment condition (θ_t) of equation (4) maintains maximum curtailment state ($\theta_{max,t}$) and the supplied electric power amount maintains low level according to $d_{grid,t} = d_{grid,t} - \theta_t$.

Also, the curtailment condition has a constraint with $0 \leq \theta_t \leq d_d$.

$$\theta_t = \begin{cases} \theta_{max,t}, & q_{low} = d_{grid,t} \\ \theta_{med,t}, & q_{med} = d_{grid,t} \\ \theta_{min,t}, & q_{low} = d_{grid,t} \end{cases} \quad (4)$$

The curtailment condition calculates the value of the difference between the demand of the predicted electric power amount and the renewable energy generation amount. The demand of the predicted electric power amount and the renewable energy generation amount have the value of mean($d_{a,t}$, $S_{sol,t}$) and variance($V_{a,t}$, $V_{sol,t}$). The electric power amount from power grid is decided by the following three cases.

Case 1. When curtailment state = θ_{min} , $S_{grid,t}$ is can described as below equation (5)

$$d_{a,t} + |V_{a,t}| = S_{sol,t} + S_{grid,t} \quad (5)$$

Case 2. When curtailment state = θ_{med} , $S_{grid,t}$ is can described as below equation (6)

$$d_{a,t} + |V_{a,t}| = S_{sol,t} + |V_{sol,t}| + S_{grid,t} \quad (6)$$

Case 3. When curtailment state = θ_{max} , $S_{grid,t}$ is can described as below equation (7)

$$d_{a,t} = S_{sol,t} + |V_{sol,t}| + S_{grid,t} + |V_{d,t}| \quad (7)$$

IV. OPTIMIZATION FORMULATION

Equation (8) is optimization problem on the electric cost based on the curtailment condition through the scheduling of supply and demand management system.

Objective function of optimization problem is the minimization for the electric cost from power grid. The supply of the electric power uses the electric power from the renewable energy generator and power grid. The demand is required by smart appliances such as must-run appliance, controllable appliance, and dropped appliance. Must-run appliance is operated by consuming the required electric power amount at required time slot. Controllable appliance consists of time-shiftable appliance and power-shiftable appliance. Time-shiftable appliance can shift operating time by consuming the electric power during required time slots. Power-shiftable appliance can distribute a variety of power consumption time because they can receive the electric power during required time slots. Dropped appliance can be dropped by the policy for the management in spite of the demand for the electric power consumption.

The electric power generation amount of PV panel is decided by the weather, the value of the peak at that day, the incident angle, and the air mass. Also, PV panel generates the electric power from 6 a.m. to 6 p.m.

The curtailment condition is used to reduce the supplied electric power to dropped appliance and is decided by using electric power amount from power grid at time slot t . If the consumed electric power amount is low level, the curtailment

level becomes low level. If the consumed electric power amount is medium level, the curtailment level becomes medium level. Also, if the consumed electric power amount is high level, the curtailment level becomes high level. Therefore, the curtailment level changes according to the consumed electric power amount from power grid.

TABLE 2. NOTATION FOR OPTIMIZATION FORMULATION

Notation	mean
$S_{grid,t}$	Supply amount from power grid at time t
$S_{sol,t}$	Amount electricity supplied from PV at time t
$S_{m,t}$	Supply amount for must-run appliance at time t
$S_{c,t}$	Supply amount for controllable appliance at time t
$S_{d,t}$	Supply amount for dropped appliance at time t
$P_{grid,t}$	electricity price from power grid at time t
$d_{a,t}$	energy consumption of appliance at time t
$d_{m,t}$	Energy consumption of must-run appliance at time t
$d_{c,t}$	Energy consumption of controllable appliance at time t
$d_{d,t}$	Energy consumption of dropped appliance at time t
$\dot{d}_{m,t}$	Demand amount for must-run appliance at time t
$\dot{d}_{c,t}$	Demand amount for controllable appliance at time t
$\dot{d}_{d,t}$	Demand amount for dropped appliance at time t
θ_t	Curtailment amount at time t
$V_{a,t}$	Variance of energy consumption at time t
$V_{sol,t}$	Variance of amount electricity supplied from PV at time t
q_{low}	Low level electric quantity
q_{med}	Medium level electric quantity
q_{high}	High level electric quantity

$$\begin{aligned}
& \min S_{grid,t} \cdot P_{grid,t}, \quad \forall t \in T \\
& \text{s.t. } d_{a,t} = S_{grid,t} + S_{sol,t}, \quad \forall t \in T, \quad \forall a \in A \\
& \quad d_{a,t} = d_{m,t} + d_{c,t} + d_{d,t}, \quad \forall t \in T, \forall m \in M \\
& \quad d_{m,t} = \dot{d}_{m,t}, \quad \forall t \in T, \forall m \in M \\
& \quad d_{c,t} = \min\{R_{c,t-1} + S_{c,t}, \dot{d}_{c,t}\} + \lambda \cdot \max\{0, \dot{d}_{c,t} - R_{c,t-1} + S_{c,t}\} \quad \forall t \in T, \forall c \in C \\
& \quad d_{d,t} = \min\{R_{d,t-1} + S_{d,t}, \dot{d}_{d,t}\}, \quad \forall t \in T, \forall d \in D \\
& \quad S_{sol,t} = w_f \cdot P_p \cdot \cos\left[\frac{\pi}{12h}(t-12h)\right] \cdot e^{\frac{\delta t}{\mu}}, \quad 6h \leq t \leq 18h, \quad \forall t \in T, \forall d \in D \\
& \quad \theta_{min,t} = 0, \quad q_{low} = S_{grid,t} \\
& \quad \theta_{med,t} = |V_{sol,t}|, \quad q_{med} = S_{grid,t} \\
& \quad \theta_{max,t} = |V_{a,t}| + |V_{sol,t}|, \quad q_{high} = S_{grid,t} \\
& \quad P_{grid,t} = P_{lowprice}, \quad q_{low} = S_{grid,t} \\
& \quad P_{grid,t} = P_{medprice}, \quad q_{med} = S_{grid,t} \\
& \quad P_{grid,t} = P_{highprice}, \quad q_{high} = S_{grid,t} \\
& \quad S_{grid,t} = d_{a,t} + |V_{a,t}| - S_{sol,t}, \quad \theta_t = \theta_{min,t} \\
& \quad S_{grid,t} = d_{a,t} + |V_{a,t}| - S_{sol,t} - |V_{sol,t}|, \quad \theta_t = \theta_{med,t} \\
& \quad S_{grid,t} = d_{a,t} - |V_{a,t}| - S_{sol,t} - |V_{sol,t}|, \quad \theta_t = \theta_{max,t}
\end{aligned} \tag{8}$$

V. PERFORMANCE ANALYSIS

We analyses the using proposed method and the no using proposed method. Smart appliance divides up into the group of must-run appliance, controllable appliance, and dropped appliance. The tariff for HEMS of KEPCO is used [13].

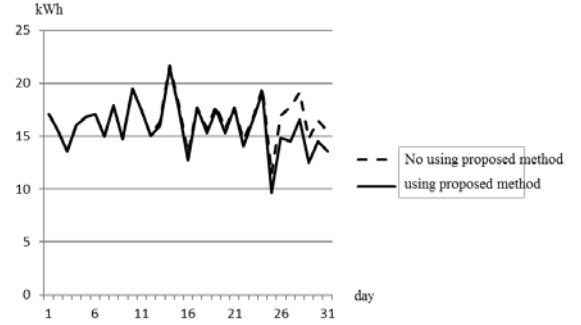


Figure 7. Comparison of no using proposed method and proposed method about power consumption during one month

Fig. 7 compares the consumed electric power amount between the using proposed method and the no using proposed method. The consumed electric power amount of the using proposed method and the no using proposed method is similar nearly during from 1 day to 12 day. However, the consumed electric power amount of the using proposed method and the no using proposed method is different during from 13 day to 24 day because the using proposed method implements the medium curtailment condition. Also, the consumed electric power amount of the using proposed method and the no using proposed method is different during from 25 day to 31 day because the using proposed method implements the high curtailment condition.

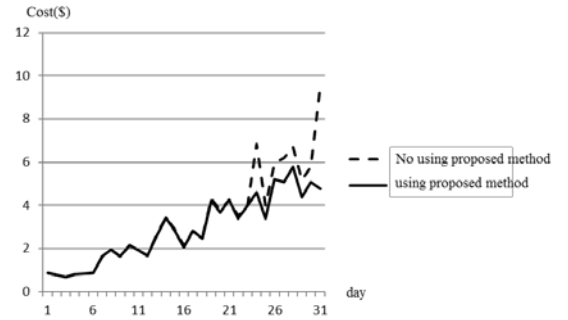


Figure 8. Comparison of no using proposed method and proposed method about cost during one month

Fig. 8 compares the electric cost amount between the using proposed method and the no using proposed method. The electric cost amount of the using proposed method and the no using proposed method is similar nearly during from 1 day to 12 day. However, the electric cost amount of the using proposed method and the no using proposed method is different during from 13 day to 24 day because the using

proposed method implements the medium curtailment condition. Also, the electric cost amount of the using proposed method and the no using proposed method is different during from 25 day to 31 day because the using proposed method implements the high curtailment condition.

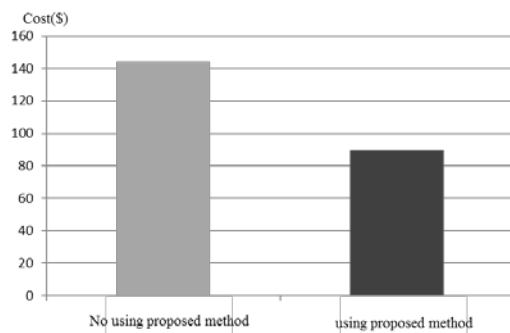


Figure 9. Comparison of no using proposed method and proposed method about cost amount during one month

Fig. 9 shows the electric cost amount of the using proposed method and the no using proposed method. The electric cost of the using proposed method during a month is 89.62\$. The electric cost of the no using proposed method during a month is 102.29\$. The different value of the using proposed method and the no using proposed method is 12.67\$.

VI. CONCLUSION

We proposed a supply demand management system based on information on the power consumption pattern analysis and the tariff for HEMS of KEPCO for cost minimization. The scheduler of a supply and demand management system decided the curtailment level for the dropped appliances based on information about the predicted power consumption amount, the predicted renewable energy generation amount, and the tariff. We got the effect of reduced 12.67\$.

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