Scheduling Method for Electric Heater in HEMS Considering User's Comfort

Yong-Sung Kim, Je-Seok Shin, Ho-Jun Jo Jin-O Kim

Abstract**—**Home Energy Management System (HEMS), which makes the residential consumers, contribute to the demand response is attracting attention in recent years. An aim of HEMS is to minimize their electricity cost by controlling the use of their appliances according to electricity price. The use of appliances in HEMS may be affected by some conditions such as external temperature and electricity price. Therefore, the user's usage pattern of appliances should be modeled according to the external conditions, and the resultant usage pattern is related to the user's comfortability on use of each appliances. This paper proposes a methodology to model the usage pattern based on the historical data with the copula function. Through copula function, the usage range of each appliance can be obtained and is able to satisfy the appropriate user's comfort according to the external conditions for next day. Within the usage range, an optimal scheduling for appliances would be conducted so as to minimize an electricity cost with considering user's comfort. Among the home appliance, electric heater (EH) is a representative appliance, which is affected by the external temperature. In this paper, an optimal scheduling algorithm for an electric heater (EH) is addressed based on the method of branch and bound. As a result, scenarios for the EH usage are obtained according to user's comfort levels and then the residential consumer would select the best scenario. The case study shows the effects of the proposed algorithm compared with the traditional operation of the EH, and it represents impacts of the comfort level on the scheduling result.

Keywords**—**Load scheduling, usage pattern, user's comfort, copula function, branch, bound, electric heater.

I. Introduction

RECENTLY, demand management in the end user aspect has received attention in future smart grids. As renewable resources with uncertainty are adopted, the demand management is more important in end user side. However, it has been difficult for the residential customers to take part in the power system, since technologies for smart grid are not prevalent yet.

The development of smart grid technologies, which are smart meters, network sensor, and controllable appliances, has changed the aspect of electricity market. Especially, the automatic metering systems (AMI) are used at the residential household side. Each residential household equipped with an AMI is connected to the power supplier. It is trigger for consumers and suppliers to interact with each other. These developed technologies enable the power system operators to improve energy efficiency and stabilize their power system. The end user customers are able to behave more actively than before. It means that consumers play an important role in the present electricity market [1]. Therefore, it is possible to control and monitor the operation of the appliances wirelessly with a home energy management system (HEMS) because of developing smart grid technologies. For example, a heating, ventilating and air conditioning with the thermostat setting (HVAC) can be scheduled automatically. In this paper, heating appliances is used in study as an example. The temperature models made by using copula are used to schedule. Through these models based on the residential customers' life pattern, the optimal scheduling is implemented.

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The object of this paper is to minimize electricity cost while preserving consumers' comfort as much as possible. Thus, it can lead to the active participation of consumers unlike other HEMS algorithm and load scheduling that have been used with the conventional paper. As a result, in the power system operator position, it achieves load reduction and minimizes their electricity bills with comfort preservation as much as possible in the residential customers' position.

This paper describes the thermal dynamic model of the electric heater, the scenario of outdoor temperature and room temperature, and comfort constraints. The case study of the scheduling method is discussed and compared with the conventional method.

II. Methodology for an Optimal Operation of the EH

The appliances in household are classified into three groups; controllable appliances with thermostat which can be controlled, non-controllable appliances without thermostat and base appliance which cannot be scheduled, since base appliance does not depend on electricity costs and operate only for a short period of time [2]. Thus, they are modeled by a load profile based on historical data. Non-controllable appliances without thermostat is can be scheduled easily. Because of their discontinuous characteristic, it is simple to turn on/off according to consumers' choices. Typical controllable appliances with thermostat are HVAC, and are the major reason to cause peak load due to their high power consumption and high frequency. In this paper, electric heater (EH) is used as an example to explain the scheduling method of the HVAC.

In order to schedule the electric heater, thermal dynamic models are required to describe the operation of the electric heater, outdoor temperature influencing room temperature and room temperature reflecting the comfort of consumers [3].

International Journal of Electrical, Electronic and Communication Sciences
ISSN: 2517-9438
Vol:9, No:10, 2015

In this paper, outdoor temperature and room temperature models are made by copula based on the historical data in order to represent the costumers' comfortability with probability.

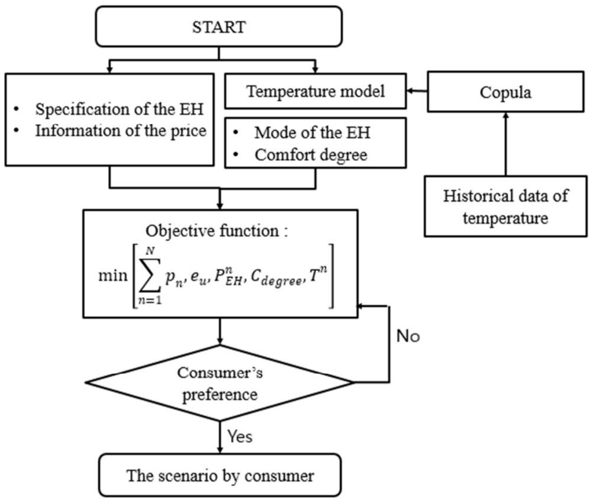

Fig. 1 Entire flowchart of formulation

The algorithm is described in detail in Fig. 1 where the time-varying set point temperature is created to select by consumers. Based on the set point temperature, a range of the room temperature is defined by comfort zone which is tolerated by consumers.

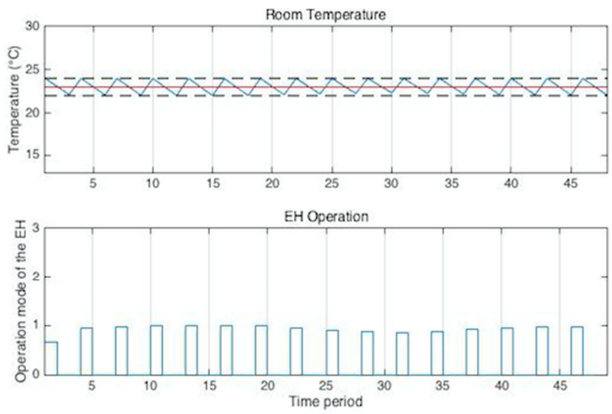

Fig. 2 Typical thermal behavior and operation of the EH (case 1)

A. Thermal Dynamic Model of the EH

The scheduling of an EH requires a thermal dynamic model that accounts for heat exchange between room temperature and outdoor temperature [5]. Fig. 2 depicts the normal behavior of the EH over time steps. The rising and falling parts represent that the EH is 'on' and 'off', respectively. 'Off' state is cooling down by outdoor temperature. As the EH operates, the room temperature rises and falls repeatedly. In this way, the room temperature is maintained within the constant boundary, where minimum and maximum limits are expressed as comfort zone.

The EH thermal model is featured by air inertia, thermal conductivity and coefficient of the EH performance. These coefficients can be estimated with statistical techniques by adjusting the performance data. The thermal dynamic behavior of an EH can be described as,

$$RT_{n+1} = \varepsilon_{air} \cdot RT_n + (1 - \varepsilon_{air}) \cdot \left(T_n^{out} + \lambda_{EH} \cdot \frac{P_{EH}^n}{\rho_{air}}\right) \quad (1)$$

where, ε_{air} is the factor of inertia of the air, RT_n is the room temperature (°F), T_n^{out} is the outdoor temperature, λ_{EH} is the coefficient of the electric heater performance, P_{EH}^n is rated power of the EH and ρ_{air} is the thermal conductivity (kW/°F). The first term is the room temperature at time T^n and the second term the amount of the increased temperature by the operation of the EH. Summation of the first and second terms is the room temperature at time T^{n+1}.

In this study, the comfort is defined as a degree which is close to the set point temperature. For example, if comfort level increases, the EH operates closely to the set point to meet the temperature. The residential consumers have their own comfort level depending on the each consumers' conditions. Therefore, we need to consider a set point temperature as possible scenarios that satisfy the convenience of the most of people in order to cover customers' demands as much as possible. While minimizing the electrical charge through the scenarios, a customer can select a set point temperature scenario for preserving the maximum comfort. Based on this set point, it is assumed that ±1.5°C, which is regarded as maximum tolerance, is added to this set point. The set temperature added ±1.5°C is defined as comfort band in this paper. Only within this range, the electric heater is assumed to be operated.

B. Usage Pattern Modeling using Gaussian Copula

Copula function used in this paper is a way to identify relationships between two or more random variables with a respective peripheral and present it to the joint probability distribution [6]. Nonlinear relationships between the variables can also be expressed more precisely than the Gaussian distribution. When a joint cumulative probability distribution $F(x_1, \cdots, x_n)$ has the n-dimensional distribution function with a peripheral cumulative probability distribution which is $F_1(x_1), \cdots, F_n(x_n)$, copula function C is expressed as [7]:

$$F(x_1, \cdots, x_n) = C(F_1(x_1), \cdots, F_n(x_n)) \quad (2)$$

In this paper, we apply the Gaussian copula function (GCF) which is given by

$$C^n(u_1, \cdots, u_n; Rho) = \phi_n(\phi^{-1}(u_1), \cdots, \phi^{-1}(u_n); Rho) \quad (3)$$

where ϕ is a standard normal distribution, ϕ^{-1} is inverse function of the standard normal distribution. *Rho* is the parameter matrix of the GCF representing a correlation between variables. It has a relationship as follows by rank correlation coefficient such as *Kendall's* τ, *Spearman's* ρ.

$$Rho = \sin\left(\frac{\tau\pi}{2}\right) = 2\sin\left(\frac{\rho\pi}{2}\right) \quad (4)$$

Based on the historical data, the data sampling is conducted by GCF about the external temperature $T_{n=N}^{out}$ and room temperature $RT_{n=N}$. Fig. 3 (a) includes distributions of the external temperature and room temperature. Through these variables, the Rho is estimated. Using the GCF, sampled data with Rho are created as shown in Fig. 3 (b). Data, which is similar to the external temperature and room temperature of the day after the last measurement are extracted among these sampled data. Fig. 4 shows the extracted results. The case study is simulated by the extracted results considered about consumer's pattern.

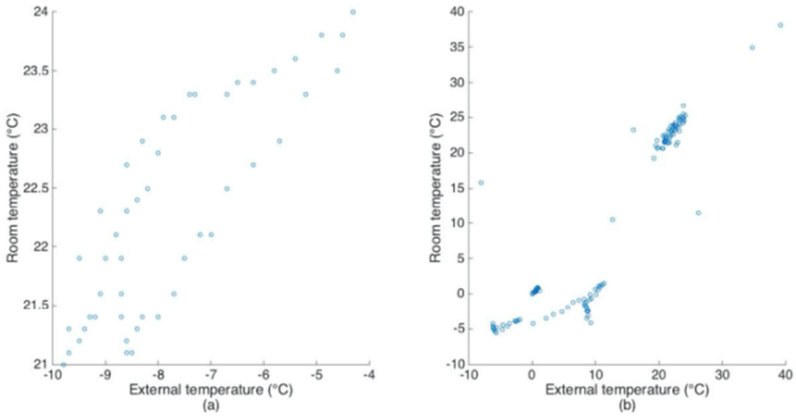

Fig. 3 Sampled results of the Gaussian copula function

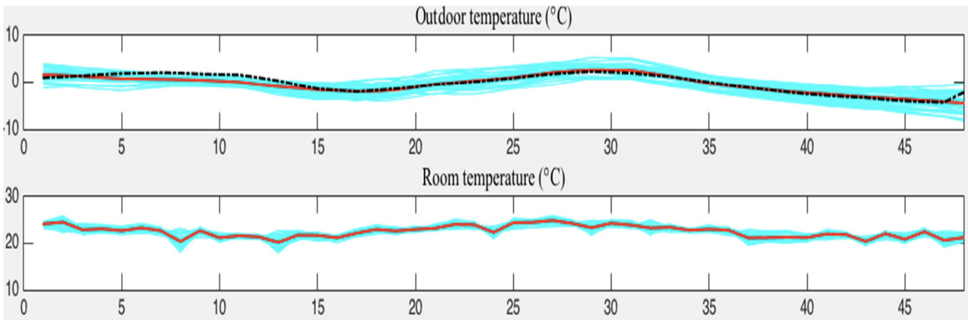

Fig. 4 Temperature models by copula

C. Scheduling Algorithm based on Branch and Bound

It is assumed that the EH load is scheduled over a 24-h period which is divided into 48 intervals. The objective function is to minimize consumers' electricity cost under comfort constraints while comfort is preserved as much as possible [4]. It is rewritten as a function of the external conditions such as the electricity price, p_n, status of the EH, e_u, comfort degree, C_{degree}, which is close from the set point temperature and time steps, $[T^n, T^{n+1}]$. The objective function can be formulated as [8]

$$\min[\sum_{n=1}^{N} p_n, e_u, P_{EH}^{n}, \Delta T] \quad (5)$$

subject to the following constraints

$$RT_n^{min} \leq RT_n \leq RT_n^{max} \quad (6)$$

$$RT_n = f(RT_{n-1}, \varepsilon_{air}, \lambda_{EH}, T_{out}, P_{EH}, e_u, T) \quad (7)$$

$[RT_n^{min}, RT_n^{max}]$ in (6) is the minimum and maximum values of the sampled data of the room temperature. Equation (7) is the temperature bounds reflected by consumer's comfort and the thermal dynamics of the EH. Therefore, the scheduling of the electric heater can be expressed as a nonlinear optimization problem. Optimization is proceeded with the outside temperature, room temperature and operation mode of the electric heater [9] in detail in Fig. 5. In this method, the optimal temperature is obtained by the thermal dynamics of the EH on each node. Since there are three modes (on, power saving, off), each node produces multitudinous nodes. In order to calculate fast, the each node is divided 48 intervals into four sections at first. If the temperatures gained by this method are over the constraints, the values are deleted. The optimal temperature is obtained through this procedure.

III. Case Study

The parameters of the EH is shown in Table I. Under real time pricing in Fig. 6, the case study is carried out based on the models obtained by copula with the historical data, which is SMP and temperature of 2011 winter day.

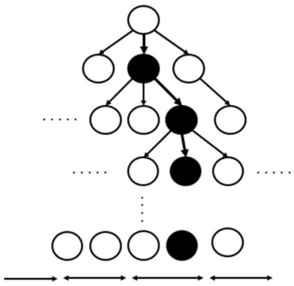

Fig. 5 Modified branch and bound

TABLE I
PARAMETERS OF THERMAL DYNAMIC MODEL

	ε_{air}	λ_{EH}	P_{EH}(kW)	ρ_{air}(kW/°F)
Values	0.96	5	4	0.19

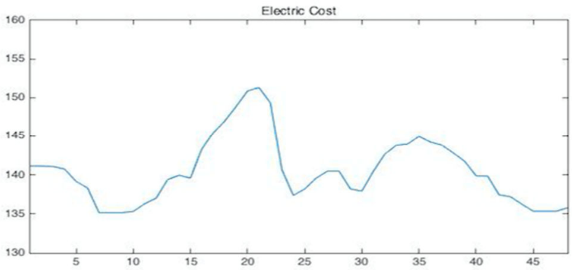

Fig. 6 Prices of winter in 2011

In Fig. 7, set point temperature is the one of the room temperature scenarios influenced by the outdoor temperature and thus, is time-varying shape. It leads to reduce electricity cost more than normal behavior case (case 1) in Fig. 2. Case 2 with the time-varying set point temperature is not considered about comfort level so that the EH operates between minimum and maximum limits.

Consequently, the operation mode is decided according to this operation as shown in Fig. 7.

The scheduling of the EH in Fig. 8 (case 3) is conducted by manipulating the comfort degree, where the objective function includes comfort degree. When the comfort level is established at high degree, the behavior of the EH operates close to the set point temperature. So, as shown in Fig. 8, the operation of the EH runs more frequently than case 2. Thus, case 3 have more convenience than other cases. However, case 3 is expensive because of frequent operation. According to customers' preference, one of three cases can be selected. As shown in Table II, this scheduling algorithm shows better typical algorithm without consideration of customers' life pattern of the room temperature. The more increasing comfort degree is, the more cost savings can be obtained.

The benefits of this scheduling algorithm can be applied automatically by various customers' life patterns and therefore, the residential consumers do not have to take care of their room temperature without adjusting their room temperature time by time.

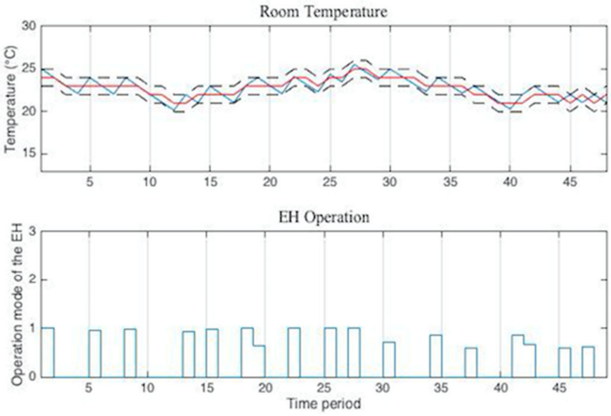

Fig. 7 Time-varying thermal behavior and operation of the EH by the proposed method (case 2)

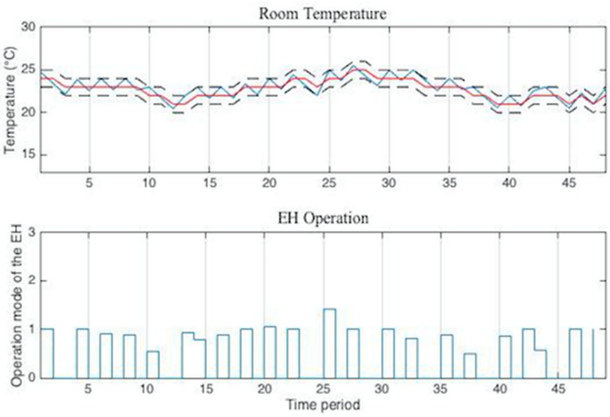

Fig. 8 Time-varying thermal behavior and operation with comfort preservation of the EH by the proposed method (case 3)

TABLE II
RESULTS OF THE SIMULATION

Case	Comfort degree	Cost
Case1	0	1045
Case2	0	1011
Case3	100	1410

IV. CONCLUSION

This paper is designed to induce active participation from consumers in HEMS environment. Because this scheduling method gives automatically the selective scenarios considered in pattern, the consumers can choose the reasonable options more easily according to their own conditions and preference. As a result, the benefits from HEMS can be greater than ever. Also, it can be applied to building energy management system as well as home energy management system.

ACKNOWLEDGMENT

This research was supported by Korea Electric Power Corporation through Korea Electrical Engineering & Science Research Institute (Grant Number: R14XA02-35).

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