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Study on Application Usage Scheduling considering Usage Pattern in HEMS

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Abstract. In HEMS, a residential power consumer can use power efficiently and participate the demand response according to an electricity price or other conditions. An optimal usage scheduling for appliances is the main function of HEMS, which generally attempts to minimize the expense on power consumption. However, user's convenience should be considered in determining when an appliance is used, or how much power is consumed. User's convenience is related with the usage pattern, and this paper introduce a methodology for modelling the usage pattern using copula function. From cumulative data for the appliance usage, a dependence between the appliance usage and factors affecting the usage is represented by copula function. By copula function with the dependence, a usage pattern for the next day is obtained. And, the modelled pattern is reflected to a scheduling problem as the constraint. In order to explain the methodology and its application, as an example, modelling the pattern and scheduling for an electric heater are carried out.

Key words

Home Energy Management System, Appliance Usage Scheduling, Usage Pattern, Copula Function, Electric Heater.

1. Introduction

In recent years, introduction of smart grid technology and many kinds of the demand response (DR) programs make a role of energy management at demand-side more important. Energy management systems (EMSs) are being developed for diverse power consumers; Home, Building and Factory, etc. Since individual residential user's power consumption is relatively low but the number of the user is so many, the residential consumers has a high potential for DR. So, this paper deals with home energy management system (HEMS). Generally, users in EMSs monitor and control their power consumption in response to external information such as electric price, outside temperature and DR signals. Typical aim of EMSs is to minimize an electricity expense or to obtain economic benefits from the participation to DR programs [1]. However, in case of residential users, it is difficult to monitor and control their power consumption in real time. This drawback can be improved by applying a day-ahead real time price (DARTP) [2, 3]. Under DARTP, HEMS would plan the schedule for appliance usage at the next day, in advance and notify a scheduling result to a user so as to be used as a guide line for appliance usage. Here, user's usage pattern per appliance should be considered when determining when an appliance, or how much power is utilized [4]. As the scheduling result is closer to the usage pattern, the convenience would become higher [5]. In the previous many studies [6-8], the usage pattern was applied by the way a user sets up time or temperature ranges in person. However, it cannot reflect the usage pattern properly, which varies with electricity price, outside temperature and etc. Therefore, this paper introduces a methodology for modelling the time-varying usage pattern using copula function. From cumulative data of the appliance usage, a dependence between the appliance usage and factors affecting the usage is estimated, and then sample data which is similar to the estimated dependency is generated by copula function. Under the factor for the next day, the range which represents the usage pattern is obtained. And, the modelled pattern is reflected to a scheduling problem as the constraint condition. In order to explain the methodology, as an example, modelling the pattern and scheduling are performed on an electric heater.

The rest of this paper is organized as follows. In Section II, appliance categories classified by factors affecting usage, and the basic concept for a usage pattern are introduced. In Section III, a methodology for modelling the usage pattern is described briefly with a usage pattern for setting inner temperature as an example. And then, Section IV shows how the modelled usage pattern to a scheduling problem for an electric heater (EH). The conclusions are summarized in section V.

2. Usage Pattern Modelling Methodology

A. Main Categories of Appliances in HEMS

This paper considers DARTP and an outside temperature as the factor which affects to appliance usage, and appliances are classified into three types [5, 8].

- Base Loads (BL): Appliances of which hours of use is short, or which are not affected by the factors, such as a microwave, TV, PC and etc.

- Curtailable Loads (CL): Appliances which are affected by an outside temperature, such as an electric heater, and electric water heater and etc. A scheduling problem of CLs is to determine a proper amount of power within the given temperature range, as shown Fig. 1. The time-varying range means that it reflects user's usage pattern.

- Deferrable Loads (DL): Appliances which are affected by DARTP, such as dishwasher, dryer, washing machine, clothes dryer and etc. A scheduling problem of DLs is to determine the time to be used within the given time range. A user may want use an appliance when an electricity price is lower, or the convenience is higher according to usage pattern.

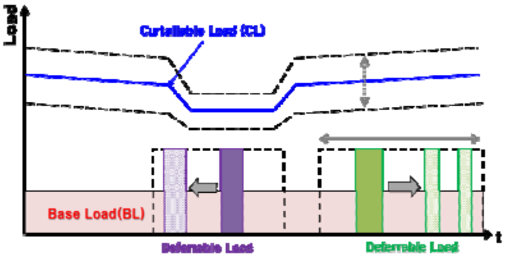

Fig. 1. Three Categories of Appliances

B. *Usage Pattern Modelling based on Copula Function*

Copula function is a way to identify dependence between two or more random variables which have individual distributions and to present it as the joint probability distribution. When a joint cumulative probability distribution (cdf), $F(x_1,...,x_n)$ has the n-dimensional distribution function with a marginal cdf which is $F(x_1)$, … , $F(x_n)$, copula function C is expressed as the following equation [4, 9].

$$F(x_1,...,x_n) = \mathrm{C}(F(x_1),...,F(x_n)) \qquad (1)$$

If the marginal cdf is continuous, copula function is unique and can be re-expressed such as Eq (2).

$$C(u_1,...,u_n) = F(F^{-1}(u_1),...,F^{-1}(u_n)), \quad (u_n = F(x_n)) \qquad (2)$$

where, $u_n \in [0,1]$, F_n^{-1} is an inverse function of F_n.

Among diverse copula functions, this paper applies the Gaussian copula function (GC) which is given by

$$C(u_1,...,u_n; Rho) = \phi_n(\phi^{-1}(u_1),...,\phi^{-1}(u_n); Rho) \qquad (3)$$

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

$$Rho = \sin\left(\frac{\tau\pi}{2}\right) = 2\sin\left(\frac{\rho\pi}{6}\right) \qquad (4)$$

Using GC, a procedure of modelling the usage pattern is shown in Fig. 2, and each stage is briefly explained quoting an electric heater (EH) as an example.

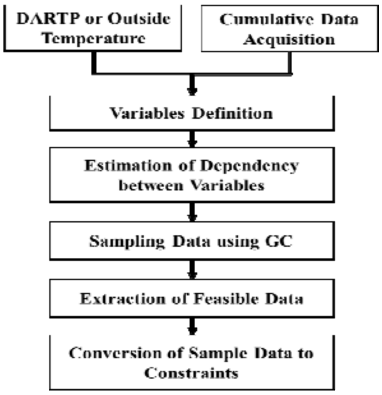

Fig. 2. Procedure of Modeling Usage Pattern

The usage pattern of EH is related to an inner temperature according to an outside temperature. Cumulative data for the inner/outside temperature is given as Fig. 3 and 4, respectively.

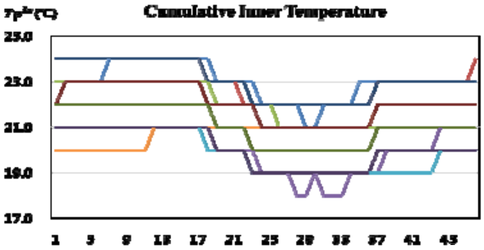

Fig. 3. Cumulative Inner Temperature

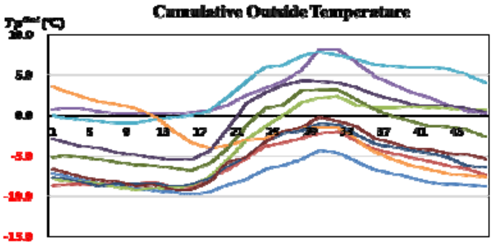

Fig. 4. Cumulative Outside Temperature

1) Variable Definition

Variables related to a usage pattern of EH, are the inner and outside temperature, which are defined as in Table I. Since a usage of EH is influenced by the outside temperature, in particular, the temperature is named as the reference variable. And, since the inner temperature is reflected as a constraint in a scheduling problem, it is named as the constraint variable.

Table I. – Definition of Variables

Reference Variable			Constraint Variable		
$Tp^{Out}(1)$	…	$Tp^{Out}(t)$	$Tp^{In}(1)$	…	$Tp^{In}(t)$

where, $Tp^{Out}(t)$ and $Tp^{In}(t)$ are the outside/inner temperature at time t, respectively.

2) Estimation of the Dependency between Variables Definition

By Eq (4), the dependency between the defined variables is estimated. If an inner temperature is higher as the outside temperature is lower, the parameter Rho has a negative value. In the opposite case, Rho become positive. Rho is closer to one as the impact of outside temperature on an inner temperature is higher. Figs. 5 (a), (b) show the dependence between $Tp^{Out}(36)$ and $Tp^{In}(38)$ at an original and uniform domain, respectively. Rho of two variables is estimated as -0.9498.

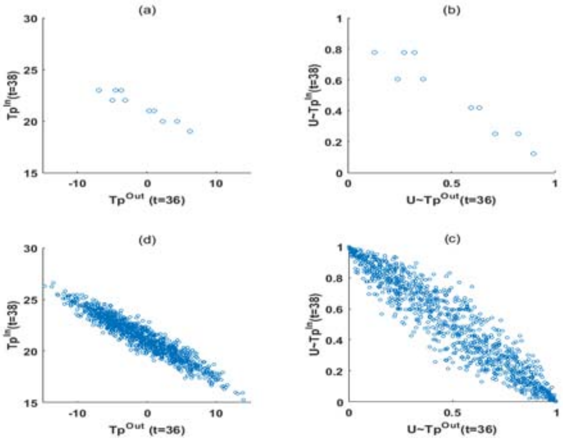

Fig. 5. Process of Sampling Data

3) Sampling Data using GC

Using Rho obtained at previous stage, GC generates sample data while maintaining the dependencies between all variables. Fig. 5(c), (d) show the result of data sampled as many as 1000, at uniform/original domain, respectively.

4) Extraction of Feasible Sample Data

After that dependencies between all variables are estimated using cumulative data, and the sample data is obtained under the dependencies, feasible data is extracted considering the outside temperature for the next day. Fig 6 shows extracted sample data for the reference variables, where lines represent all of the extracted sample data, a thicker dotted lines means the outside temperature for the next day and a thicker line means the most similar sample data to the reference.

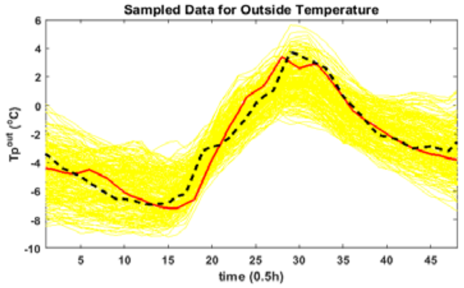

Fig. 6. Extracted Sample Data and $Tp^{Out}(t)$ of Next Day

5) Conversion of Sample Data to Constraints

Corresponding to the extracted data of reference variables, sample data of the constraint variable is also extracted as the feasible data, as in Fig. 6. The extracted data of constraint variables is converted to the constraint condition. The most similar data among data of the constraint variables line becomes a reference temperature. And, on the basis of the average of feasible sample data, a range of an inner temperature can be defined by Eq (5), and this equation would be applied in a scheduling problem of EH as a constraint.

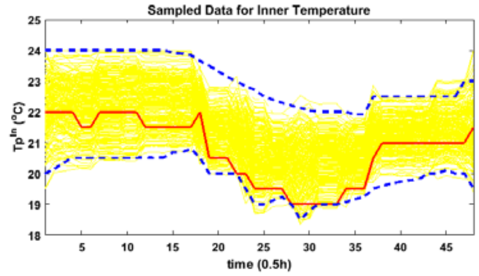

Fig. 7. Inner Temperature Range as a Constraint

$$ave\left[Tp^{In}{}_{S}(\mathrm{t})\right]-\delta \le \overline{Tp}^{In}(\mathrm{t}) \le ave\left[Tp^{In}{}_{S}(\mathrm{t})\right]+\delta \qquad (5)$$

where, $Tp^{In}{}_{S}$ is feasible sample data for an inner temperature, $ave[\bullet]$ means an average function, δ is a constant which may be a multiples of the deviation, $\overline{Tp}^{In}$ is an actual inner temperature by EH operation plan.

3. Scheduling Problem for Electric Heater

In order to show an application of the modelled temperature range, a scheduling of EH is carried out where an objective function is represented as in Eq (6).

$$\min \sum_{\forall t} \alpha\cdot\left(\pi(t)\cdot \mathrm{P}_{EH}\cdot \mu_{EH}(t)\right)+\beta\cdot\sqrt{\left(\overline{Tp}^{In}(\mathrm{t})-{}^{R}Tp^{In}(\mathrm{t})\right)^{2}} \qquad (6)$$

where, π is an time-varying electricity price announced at day-ahead, P_{EH} (=2kW) is a rated power of EH, μ_{EH} is an operating mode of EH which has a discontinuous value between 0 and 1. ${}^{R}Tp^{In}$ is a reference temperature shown in Fig. 6. α,β are weighting constants.

According to operating modes of EH, a resultant inner temperature is calculated by the modified Eq (7) [10].

$$\overline{Tp}^{In}(t+1)=\varepsilon\cdot\overline{Tp}^{In}(t)+(1-\varepsilon)\cdot(\overline{Tp}^{Out}(t)-\overline{Tp}^{In}(t))+\frac{P_{EH}\cdot\mu_{EH}(t)}{k} \qquad (7)$$

where, ε (=0.99) is a constant which represents a ratio of between remaining and lost actual inner temperature by a difference with an outside temperature $\overline{Tp}^{Out}$, k (=2) is a power required for raising 1℃.

The scheduling of EH was performed twice according to the weighting constants α, β. In case 1, α, β are 1, 0, respectively, that means the cost minimization mode. In order to emphasizes user's convenience, α, β in case 2 are applied as 0, 100, respectively. So, case 2 is the comfort mode to follow the reference temperature. The following Figs 7 & 8 indicate the results of two cases, where a histogram represents a result of EH output with a time-varying electricity price. And, a line with star means a resultant actual inner temperature. Compared with two Figs, it is indicated that EH in case 1 is more operated when an electricity price is low, so there is a high difference in two temperature. On the other hand, case 2 is operated regardless with the price in order to follow the reference. These detailed results are observed by Table II.

Table II. – Detailed Results for Two Cases

	Case1	Case2
Daily Cost	\$2.69	\$3.17
Daily Power Consumption	19 kWh	22.3kWh

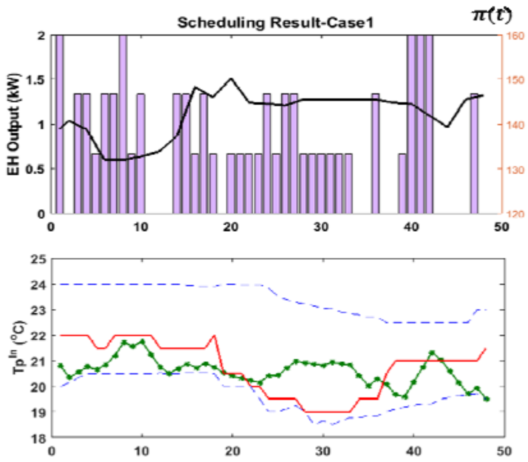

Fig. 8. Scheduling Result of Case1

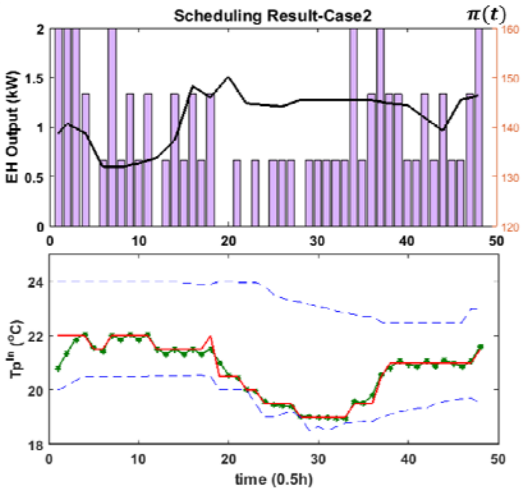

Fig. 9. Scheduling Result of Case2

From Table II, it is indicated that the expense is increased as a user wants more comfort mode of EH usage. According to the weighting constants, adobe results of cases, it is required to set the weight constants, a user can select a more preferred EH usage schedule for the next day.

4. Conclusion

In order to reduce inconvenience and develop automated HEMS, it is required to model the usage pattern for appliances. Therefore, this paper introduces a methodology to model the usage pattern using copula function. As an example, an inner temperature pattern related with the usage of EH was modeled. Applying modeled pattern, an optimal usage scheduling of EH for the next day was performed. According to the weight constants, a user can establish a preferred usage plan which may be a cost minimization mode and a comfort mode. At D-day, a user would avoid to monitor and to react power consumption according to external information in real time. If the methodology would be applied to other appliances in HEMS, it would be useful to develop an automated and customized HEMS.

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