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インテリジェント宅内エネルギー管理システムのためのエネルギー安定性認識機構

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宅内エネルギー管理システム(HEMS)は、家電機器作動の監視および管理を担っており、一連の要求に応じたエネルギーの負荷配分を行う。家電機器の増加 に伴い、宅内電力消費の逼迫による停電リスクが増し、その結果、HEMS は不安定なものとなる。本論文では、エネルギー供給および要求をリアルタイムで計 測するスマートメータ(SM)導入による HEMS を対象としたエネルギー安定性認識機構を提案する。

Energy Stability-aware Scheme for Intelligent Home Energy Management System

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Home energy management system (HEMS) is responsible for monitoring and managing the operation of in-home appliances, and providing load shifting according to a set of requirements. As more and more in-home appliances are increased, the energy consumption in home leads an increase in the risk of power blackout. Consequently, the HEMS become an unstable system. In this paper, we propose an energy stability-aware modeling scheme for the HEMS by introducing smart meter (SM) to measure energy supply and energy demand in real time.

1. Introduction

The real time monitoring of energy consumption by home appliances is a key and an integral part of future intelligent home where Intelligent home is dedicated to the seamless infusion of technology with day-to-day living within the home to create a lifestyle totally unique to each individual [1]. As more and more home appliances and consumer electronics are deployed, the power consumption in home area (1) tends to grow and (2) leads an increase in the risk of power blackout. Therefore balancing the energy use in home is a very challenging issue. The technology to manage and balance the home energy use is well-known as a home energy management system (HEMS) [2]. The HEMS is a networked system which is responsible for monitoring and managing the operation of in-home appliances, and helps residences in order to reduce power consumption according to the specific set of requirements [3]. The need for electricity has been growing rapidly in recent years as a result of addition of home appliances at home to make life comfortable for the user. These technological advances allow the shortage of electricity. Additionally, the electricity consumed varies significantly over time. Over the past several decades, HEMS have encountered more frequent stress due to ever-increasing energy demand by appliance [4]. Energy supply and energy demand has been envisioned to deal with such unexpected events by selectively curtailing system loads, whereby regaining balance between energy supply and energy demand [5]. Therefore, HEMS needs to continuously balance or monitor the energy levels for home appliances continuously. In real time application, HEMS will be installed so that the suppliers and the consumers could both have the real time information [6], Smart Meter (SM) is an advanced energy meter that measures the energy consumption of a consumer and provides added information compared to a conventional energy meter [7]. SM can read real-time energy consumption information including the values of voltage, phase angle and the frequency and securely communicates that data. A SM system includes a smart meter, a communication infrastructure and control devices. SM can communicate and execute control commands remotely as well as locally. SM can be used to monitor and also to control all home appliances and devices at

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the user's premises. They can also collect diagnostic information about home appliances and also can communicate with other smart meters in their reach. SM needs to play a very important role in reducing the energy consumption [8]. By using SM, a communication technology for HEMS is expected to be significantly improved via smart meter implementation. The specific smart metering modeling structure that we will study in this paper is based on smart meter location at suitable places in HEMS offering communication between home appliances and SM about the energy levels which are continuously changing over time, according to the desire of the user to turn ON specific device at particular time span. The proposed modeling structure would help us to conclude the effect of energy consumption of one device to the other device by checking the energy levels of home appliances connected with one hub connection in real time. In particular, we study the effect of a smart meter with real time monitoring of energy supply and demand by home appliances in HEMS. In this paper, we will interchange the word of "energy available" with "energy supply" and "energy consumed" with "energy demand" frequently.

This paper established an energy stability-aware modeling approach consisting of SM and home appliances attached with the SM. In this modeling approach, we studied the effect of energy consumption of one home appliance to the other home appliance through SM. We also discussed the cases when the energy supply for home appliance is greater than or equal to the energy demand of home appliance and also when the energy supply is less than the energy demand of home appliance. In this way, we tried to calculate the energy available for home appliances and demand and also discuss the issues related to this phenomenon. For simple consideration, we assume one SM with two home appliances. After calculating the energy available for both appliances and energy demand, we further discussed two cases (1) when the appliance is intelligent enough to behave by itself after having the idea of energy consumed of other appliances attached with the hub through SM (2) when the SM is enough intelligent to control device by providing the appliance exact amount of energy for the working according to the desire of the user. We placed the SM with hub and measured energy levels of all home appliances attached with hub. In this paper, our main objective is to propose a model based on one SM and two home appliances to prove stability analysis for the future work [9]. The proposed modelling approach tries to give an overview that how appliance will behave after introducing SM in HEMS and what are the contributions of SM in proposed modelling in both cases mentioned above. The home appliance can be any electronic devices which are going to be turn OFF and ON according to the desire of the user.

The rest of this paper is organized as follows. Research background and motivation that are related to this paper summarized in Section 2. In Section 3, we described the modelling approach with two cases; in first case each appliance will determine its own energy demand level. The Mathematical representation of calculation of energy supply and energy demand also explained with behaviour of appliance. In second case, SM is responsible to calculate energy demand for each appliance attached. Finally, we conclude our research and future works in Section 4.

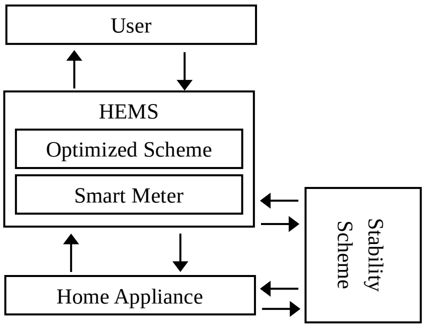


Fig. 1: Concept of HEMS

2. Research Background and Motivation

2.1 Home Energy Management System (HEMS)

As stated in [10], HEMS consists of a group of functions that facilitate remote monitoring, controlling, planning and repairing of operations and provide information on the status of installed devices and the network. In particular, the HEMS have following four functions:

- Auto configuration: auto-configuration is the most important function for user of home network services because many homes have a wrong configuration.
- Easy monitoring: comfort and easy access to real-time information in energy consumption help the user in paying attention to energy saving.
- Remote controlling: online access to a customer's usage pattern and device status enables appliances to be controlled remotely.
- Smart planning: automatic peak load management provides smart planning for reducing energy consumption.

2.2 Smart Meter

As stated in [11] SM has following functionalities to help owner in following ways:

- Outage Management
- Automatic meter reading
- Pre-payment
- Active load control
- Sub metering
- Revenue Protection

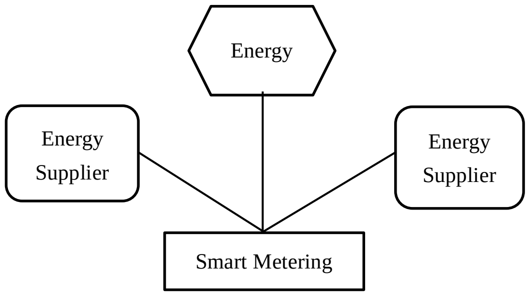


Fig. 2: Smart Metering of HEMS

SM is a subject that attracts much more attention. Smart metering is obtaining many benefits in a lot of aspects. Many benefits are available, especially on improving the energy efficiency. The smart metering is the combination of power system, telecommunication and several technologies. SM has countless benefits like it can enhance reliability, remotely read interval meeting, with the meter capable of daily reads, quality of supply and outage detection to improve consumer supply services, ability to control connection and disconnection remotely and apply supply capacity limits to manage emergency situations and quicker restoration. It can give customers more control over their everyday energy usage, opportunity for lower bills and can improves customer service and allows for a more proactive workforce.

A SM system employs several control devices, various sensors to identify parameters and devices to transfer the data and command signals. In future electricity distribution grids, smart meter would play an important role in monitoring the performance and the energy usage characteristics of the load. Collection of energy consumption data from all consumers on a regular basis allows managing electricity demand more efficiently and also to advise the consumers about the cost efficient ways to use their appliances. In light of this, smart meters can be used to control light, heat, air conditioning and other appliances [12]. SM can be programmed to maintain a schedule for operation of the home appliances and control operation of their devices accordingly. In addition, integration of smart meters helps utility companies in detecting unauthorized consumption and electricity theft in view of improving the distribution efficiency and power quality [13].

2.3 Research Motivation

The need for electricity has been growing rapidly in recent years as a result of addition of home appliance at home to make life comfortable for the user. These advances are becoming the cause of energy shortage. As the consumed energy increased the available energy limit for HEMS decreased, which makes the HEMS susceptible to outage [14]. A HEM is facing energy consumed peak hours in which HEMS should be stable all the time. For this purpose, it is necessary to monitor all the appliances through SM in real time to ensure that HEMS is working properly. The main motivation is that this work has not been studied yet by the community of Home networks. The proposed modeling approach will help us in future to prove stability of HEMS during peak hours of energy consumption which would be the milestone in the history for HEMS with increase in home appliances to keep the user comfort at the first priority. The purpose of this research is to correctly model the energy supply and energy demand levels of home appliances through SM continuously in HEMS as depicted in Fig. 1. It underlines the following tasks: (i) to calculation of energy available and energy consumed for the home appliances, (ii) to propose a model for home appliances and SM , and (iii) Discuss possibilities in which SM and home appliances can determine energy demand of home appliances for HEMS.

3. Energy management between appliance and smart meter (Case-1)

3.1 Modeling approach

Consider a SM connected with two home appliances App1 and App2 and is responsible for monitoring the energy available and energy consumed for App1 and App2 respectively in real time.

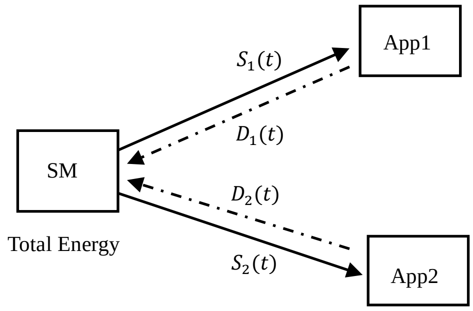


Fig. 3: Modelling structure for SM and Home Appliance

Total Energy	Energy which SM has to serve appliances
$S_1(t)$	Available energy for App1
$S_2(t)$	Available energy for App2
$D_1(t)$	Consumed energy by App1
$D_2(t)$	Consumed energy by App2
$D_{1original}(t)$	Energy level used for best performance of App1
$D_{2original}(t)$	Energy level used for best performance of App2

In this case, each appliance will determine its own energy demand and SM help the home appliance to provide the measured energy demand of other appliance attached.

Energy supply for appliance1

$$S_1(t) = D_1(t) + remaining\ power$$
$$S_1(t) = D_1(t) + Total - \left(D_1(t) + D_2(t)\right)$$
$$S_1(t) = Total - D_2(t) \qquad (1)$$

Energy supply appliance2

$$S_2(t) = D_2(t) + remaining\ power$$
$$S_2(t) = D_2(t) + Total - \left(D_1(t) + D_2(t)\right)$$
$$S_2(t) = Total - D_1(t) \qquad (2)$$

From equations (1) and (2), we can conclude that the energy supply for appliance 1 would be affected by energy consumed by appliance 2 and energy supply for appliance 2 is affected by energy consumed by appliance 1 respectively. Where, the remaining power denotes the energy left after energy is consumed by appliance from available energy. There are two possibilities about who will decide D(t) depending on $S(t)$. One possibility is that each appliance will determine its own D(t), the other possibility is that SM will determine D(t) for each appliance. We will discuss the former first as case-1 and then the later as case-2.

Energy demand for appliance1

$$D_1(t) = \begin{cases} D_{1original}(t) \ \ if \ \ S_1(t) \geq D_{1original}(t) + margin \\ \alpha_1 . D_{1original}(t) \ \ if \ \ S_1(t) < D_{1original}(t) + margin \end{cases}$$

Energy demand for appliance2

$$D_2(t) = \begin{cases} D_{2original}(t) \ \ if \ \ S_2(t) \geq D_{2original}(t) + margin \\ \alpha_2 . D_{2original}(t) \ \ if \ \ S_2(t) < D_{2original}(t) + margin \end{cases}$$

Energy demand for appliance 1 and 2 are denoted by $D_1(t)$ and $D_2(t)$ which describe two further cases when the energy supply is greater than or equal to the energy demand of the appliance with best performance. Here, best performance represents the energy level used for maximum output of each home appliance. Where, α_1 and α_2 represent the amount for decrement in the best energy performance energy level of appliance1 and 2 with the decrement in energy supply.

3.2 Linearization

This mathematical representation of non-linear system, we will move to linear system because in nonlinear system situation would be more complex and difficult to solve. The superposition principle does not hold any longer, and analysis tools involve more advanced mathematics. Because of the powerful tools we know for linear systems, the first step in analyzing a nonlinear system is usually to linearize it, if possible about some nominal operating point and analyze the resulting linear model [15]. Let energy demand $D_1(t)$ Decrease when $S_1(t)$ decrease and $D_1(t)$ approaches to $D_{1original}(t)$ when $S_1(t)$ be constant or increase.

Energy behavior for home appliances

Appliance 1:

$$\dot{D_1}(t) = \gamma_1 . \dot{S_1}(t) + \beta_1 (D_{1original}(t) - D_1(t))$$

$$\dot{D_1}(t) = -\beta_1 . D_1(t) + \beta_1 . D_{1original}(t) + \gamma_1 . \dot{S_1}(t) \qquad (3)$$

Appliance 2:

$$\dot{D_2}(t) = \gamma_2 . \dot{S_2}(t) + \beta_2 (D_{2original}(t) - D_2(t))$$

$$\dot{D_2}(t) = -\beta_2 . D_2(t) + \beta_2 . D_{2original}(t) + \gamma_2 . \dot{S_2}(t) \qquad (4)$$

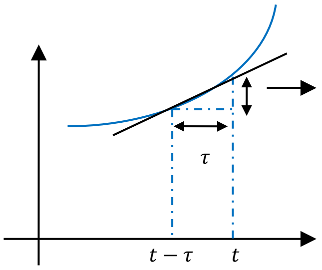
where, β_1 and β_2 Shows how fast the state changes of energy consumed of home appliance 1 and appliance 2 . The value of β depends on the particular appliance type attached with SM and its value is constant for each appliance type which is very important characteristic for each appliance. γ_1 and γ_2 shows how fast the state changes of energy supply for attached appliances 1 and appliance 2. If $\gamma = 1$ both increase /decrease in energy supply and energy demand have same increase/decrease. If $\gamma < 1$ means speed of change in energy demand of perticular appliance is slower than the energy supply which can be considered as good criteria for stability that any sudden change in energy supply will not effect the appliance with the same rate of change in energy. If $\gamma > 1$ means speed of change in energy demand of perticular appliance is faster than the energy supply which can be considered as a sensitive system in which sudden increase/decrease would effect the system with the same rate of change in energy supply.

By taking derive of equation (1) and (2), we get equation (5) and (6).

$$S_1(t) = Total - D_2(t) \qquad (1)$$
$$S_2(t) = Total - D_1(t) \qquad (2)$$

$$\dot{S_1}(t) = -\dot{D_2}(t) \qquad (5)$$
$$\dot{S_2}(t) = -\dot{D_1}(t) \qquad (6)$$

For $\dot{D}(t)$, we have to take approximation of t and $t - \tau$.



Equations (5) and (6) can be written as

$$\dot{S_1}(t) = -\dot{D_2}(t) \qquad (5)$$
$$\dot{S_2}(t) = -\dot{D_1}(t) \qquad (6)$$

$$\dot{S_2}(t) = -\frac{D_1(t) - D_1(t-\tau)}{\tau}$$
$$\dot{S_1}(t) = -\frac{D_2(t) - D_2(t-\tau)}{\tau}$$

Energy behavior equations (3) and (4) for appliance and 1 and 2 can be written as

$$\dot{D_1}(t) = -\beta_1 . D_1(t) + \beta_1 . D_{1original}(t) + \gamma_1 . \dot{S_1}(t) \qquad (3)$$

$$\dot{D_2}(t) = -\beta_2 . D_2(t) + \beta_2 . D_{2original}(t) + \gamma_2 . \dot{S_2}(t) \qquad (4)$$

$$\dot{D_1}(t) = -\beta_1 . D_1(t) + \beta_1 . D_{1original}(t) - \gamma_1 . \frac{D_2(t) - D_2(t-\tau)}{\tau} \qquad (7)$$

$$\dot{D_2}(t) = -\beta_2 . D_2(t) + \beta_2 . D_{2original}(t) - \gamma_2 . \frac{D_1(t) - D_1(t-\tau)}{\tau} \qquad (8)$$

where, $D_1(t)$, $S_1(t)$, $D_2(t)$, and $S_2(t)$ are variables and $D_{1original}(t)$, $D_{2original}(t)$ would be constant for one type of device otherwise variable. In order to make appliance responsible for calculating its own energy demand by itself, the appliance should know the energy consumed by other appliances through SM. In this way SM will get this information from appliance 2 with some delay d_1 and then send this information to appliance 1 with another delay d_2. Whenever, appliance1 want to get the earliest latest information about energy consumed of appliance 2 in time "t", both delay would occur change. The overall delay can be stated as, $d = d_1 + d_2$. $D_1(t)$ and $D_2(t)$ denotes actual energy demand level of appliance 1 and 2 at time t.

As both home appliances would work independently, we need SM to get information energy level of other device in order to calculate energy consumed level of its own. $D_{original}(t)$ is the system input which may change time-to-time by the operation of user (ON/OFF, tune volume, etc.) and/or embedded program in each appliance. Equations (7) and (8) with considering communication delay can be represented as

$$\dot{D_1}(t) = -\beta_1 . D_1(t) + \beta_1 . D_{1original}(t) - \frac{\gamma_1}{\tau}\left(D_2(t-d) - D_2(t-d-\tau)\right)$$

$$\dot{D_2}(t) = -\beta_2 . D_2(t) + \beta_2 . D_{2original}(t) - \frac{\gamma_2}{\tau}\left(D_1(t-d) - D_1(t-d-\tau)\right)$$

Matrix Notation of delay occurrence can be represented as

$$\begin{bmatrix} \dot{D_1}(t) \\ D_2(t) \end{bmatrix} = \begin{bmatrix} -\beta_1 & 0 \\ 0 & -\beta_2 \end{bmatrix} \begin{bmatrix} D_1(t) \\ D_2(t) \end{bmatrix} + \begin{bmatrix} 0 & -\frac{\gamma_1}{\tau} \\ -\frac{\gamma_2}{\tau} & 0 \end{bmatrix} \begin{bmatrix} D_1(t-d) \\ D_2(t-d) \end{bmatrix} + \begin{bmatrix} 0 & \frac{\gamma_1}{\tau} \\ \frac{\gamma_2}{\tau} & 0 \end{bmatrix} \begin{bmatrix} D_1(t-d-\tau) \\ D_2(t-d-\tau) \end{bmatrix} + \begin{bmatrix} \beta_1 . D_{1original}(t) \\ \beta_2 . D_{2original}(t) \end{bmatrix}$$

Hence, the above proposed model gives us the mathematical representation of the system consists of SM and appliances. This could be the one of the possibility of communication and we need to evaluate the system stability based on this system equation and also we need to optimize the system parameters as a future work.

3.3 Modeling Approach (Case-2)

In this case, we will consider that SM will calculate the energy demand level for each appliance. The information which is provided by the appliance 1 and 2 to SM is $D_{1original}(t)$ and $D_{2original}(t)$. In this model, SM will determine $D_1(t)$ and $D_2(t)$ by collecting $D_{1original}(t)$ from appliance 1 and $D_{2original}(t)$ from appliance 2.

So, the available information in SM is the delayed one like ($D_{1original}(t-d_1)$).

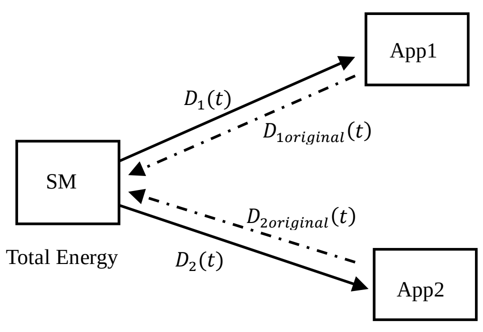


Fig. 4: Modelling structure for SM and Home Appliance

The system can be represented mathematically by

$$\dot{D_1}(t) = -\gamma_1 . \dot{D_2}(t) + \beta_1 \left(D_{1original}(t-d_1) - D_2(t)\right)$$

$$\dot{D_2}(t) = -\gamma_2 . \dot{D_1}(t) + \beta_2 \left(D_{2original}(t-d_1) - D_1(t)\right)$$

In this situation, we further have two cases, (1) $D_{original}(t)$ is purely user input and independent of $D(t)$. So, it cannot take serious part in the stability of the system (2) $D_{original}(t)$ depends on $D(t)$, then we need to add interaction between $D_{original}(t)$ and $D(t)$ to complete our system equation to prove stability analysis of HEMS.

4. Concluding Remarks

In this paper we have addressed the modeling approach consisting of SM and attached home appliances in HEMS. HEMS have encountered more frequent stress due to increasing energy demand by home appliances. To deal with such situations, energy supply and energy demand should be measured through SM which was the main objective for this paper. We presented the mathematical representation of energy levels which are continuously changing and tried to map a linear model of system from non-linear dynamics of the system. After achieving linear model, we derived the behavior of appliance in mathematical notation. This achieved mathematical model then observed under two cases that who will calculate the energy demand of home appliance whether the SM or home appliance. Under two cases we formulated the system equation in matrix notation on the basis of state variables of the system. This model can be the one example of communication between SM and home appliances. Our next target for future is to test this model in real time on HEMS and revise again to add more system parameters. This modeling approach would help us to apply stability analysis in future by considering the system equation and parameters of appliance energy level.

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