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Description	

Priority Based Maximum Consuming Power Control in Smart Homes

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***Abstract*—Due to an increase in home appliances (HAs) the overall power consumption in home tends to grow and leads an increasing risk of losing stability. In this paper, we propose a system model for smart homes to control maximum power consumption by HAs based on HA priority. The proposed system consists of smart electric sensors (SESs), power provisioning controller (PPC) and HAs. The role of PPC is to gather ON/OFF status from each HA and instantaneous consuming power level from SES, and to send control signal back to each HA. After gathering information, along with HA priority, computes a final target power level for each HA is not a hard task. However, when ON/OFF status of HAs change, we may need to reassign an amount of consuming power from one HA to another, and the transient behavior due to such reassignment of power is not simple. This paper proposes a system to control the maximum total power consumption in detailed transient behavior considering heterogeneous HAs with different time constants. In order to guarantee the maximum power limit, we will compute the remaining power, and reassign it to HAs as their temporal target power levels. Simulation results show the effectiveness of our system in managing maximum power consumption.**

I. INTRODUCTION

Smart home system is a concept that assists control of numerous different systems in a household (e.g. air conditioning, heating, security, and lighting or audio/video systems) is acknowledged under the term smart homes [1]. The smart homes concept consists of several home appliances (HAs) with their attractive features in a household that a home user likes to control [2]. The objective of moving to the smart homes is enhancing comfortable and environment-friendly unique lifestyle for each individual. But in this way, we have to face the worst situation of energy shortage. The high power required by HAs makes our home one of the most critical areas for the impact of power consumption. As the residential areas are one of the major power consumers today, reducing power in home would contribute greatly to the environment [3]. The reliability, efficiency and stability of the smart homes are expected to be significantly improved via power provisioning controller (PPC) and smart electric sensor (SES) is the most essential part of the energy system used to connect individual HA to the energy management system [4].

A smart power management system is a networked system which is responsible for monitoring and managing the working operation of in-home appliances, according to the specific set of requirements [5]. The introduction and availability of SES technologies have introduced a paradigm shift in the analysis of power system [6]. The real time management of instantaneous consuming power of the HAs through SES is a key factor of overall power management. SESs are gradually adopted due to multiple benefits like the extraction of useful information from SES readings can lead to intelligent decision making in power consumption analysis [7]. As more and more HAs and consumer electronics are used, the overall power consumption in smart homes (1) inclines to grow and (2) leads an increase in the risk of power blackout [8]. In this paper, we propose a system model to control maximum power consumption with considering HA priority.

In our proposed scenario of smart power management system the HAs considered to have different priority levels. The high priority HAs are always allowed to use power until their maximum consuming power levels. Conversely, the low priority HAs have to restrict their operation according to the remaining power. Though, with the change in ON/OFF status of HAs, we need to reassign a part of consuming power from one HA to another HA, as a result the transient behavior due to reassignment of power is not simple. This paper offers a system to control the maximum total power consumption in detailed transient behavior considering different HAs with different time constants. In order to guarantee the maximum power borderline, we will calculate the remaining power, and reassign it to HAs as their temporal target power levels. Simulation results show the efficiency of our system in managing maximum power consumption.

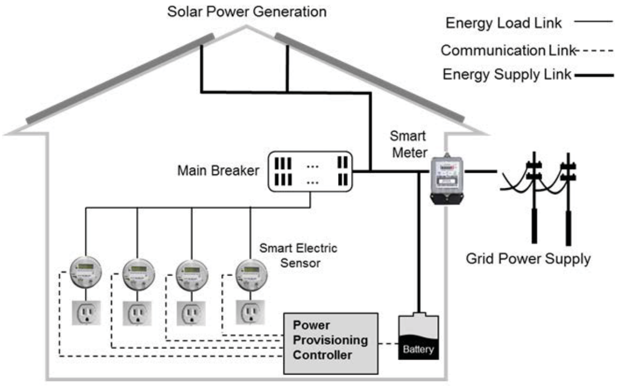

Fig. 1. A sustainable house with source and loads.

The rest of this paper is organized as follow. Research background and motivation that are related to this paper summarized in Section II. In Section III, system model is proposed followed by its novelty and key features. System control for maximum consuming power is presented in Section IV. Section V presents outcomes from simulation of proposed model with discussion of system parameters in detail. Finally, we conclude our research in Section VI.

II. Research Background and Motivation

The future smart homes are self-motivated homes with continual real-time communication between HAs, PPC and SES. Embedding intelligence in the form of energy management system in smart homes to meet the challenges of improved reliability, security, efficiency and system dynamics is a challenging task.

Electricity is the basic need for daily life and its failure will possibly paralyze the individual home to the whole city depending on the scale of the failure. The severe accidents by large scale failure have been recognized and many efforts have been done for preventing such a failure [9]-[11]. Conversely, when total power consumption of the HAs is more than the power supply limit is also a critical problem, but no research study has been done to control this situation. It causes mental stress for the home users and also damages to the HAs. The future home should be smart enough to maintain its stability all the times. So, we need to introduce a smart power management system that plays a vital role in obtaining reduction in maximum consuming power by the HAs. PPC is a complete system that includes all the important elements to achieve reduction of power consumption [12]. However, to attain the goal of stability of energy management system for home, we need a check and balance system for instantaneous consuming power of HAs. In order to reduce maximum consuming power, it is first important to know how power is consumed. Therefore, power consumption monitoring is needed. The real time monitoring of instantaneous consuming power of the HAs can be successfully achieved by SES [13]. Secondly, it is necessary to manage and control the HAs to apply power reduction strategies. For controlling and managing the HAs, a number of home energy management systems (HEMS) were proposed and developed [14]-[15]. The previous HEMS monitors and controls the home devices, and display home energy consumption information. HEMS in [16], is explained in detail with its overall goals that must be fulfill by HEMS and also provide guidelines for the system development to reduce power consumption at home efficiently. In general, priority of the HAs is also an important study in HEMS [17], but transient behavior issues for detailed analysis are neglected in many papers. To control and maintain stability the detailed behavior analysis is very important. So, we try to consider priority issue in our system to control maximum power consumption below the certain power limit. Communication delay and communication interval between SES and PPC are also key factors in system stability and performance criteria that we should consider as well.

III. System Modeling

The main breaker of the house keeps tripping if the amperage rating exceeds the value labeled on the breaker. The main breaker is further divided into sub-breakers that are used to extend a feed for multiple branch circuits in whole area of house. From there, the sub breaker connects to outlets, lighting and other loads via individual circuit breakers.

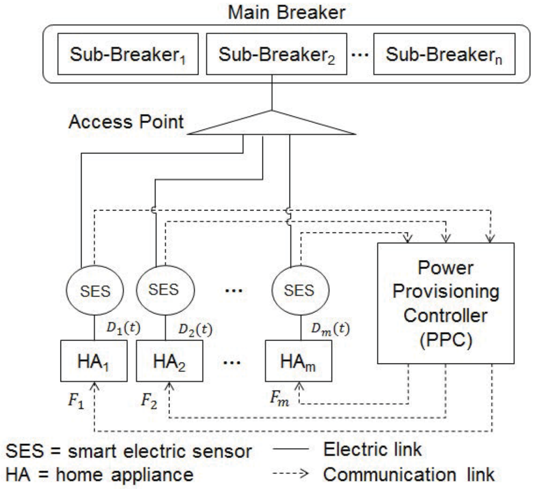

Fig. 2. System overview considered in this paper.

The aim of the proposed system is to implement a control algorithm for maximum power consumption of HAs based on HA priority so that total power consumption does not exceed a certain limit. The proposed system model consists of HAs, SESs and PPC. An example of such a system is illustrated in Fig. 2. We assume that each instantaneous consuming power $D_i(t)$ of HA is modeled by the first order state equation,

$$\dot{D}_i(t) = -a_i \cdot D_i(t) + a_i \cdot F_i \tag{1}$$

where parameter a_i decides the response speed, and F_i decides the steady state response (we call it "final power level"). It is clear that if we assume

$$\dot{D}_i(0) = D_{init_i}, \tag{2}$$

$D_i(t)$ will be given as

$$D_i(t) = (D_{init_i} - F_i) \cdot e^{-a_i \cdot t} + F_i \tag{3}$$

We also assume that the maximum operating power level D_{imax} is specified for each HA.

SESs will help us in measuring the instantaneous consuming power levels of HAs, $D_i(t)$ and send this information to PPC. The functions of PPC are to collect both ON/OFF status from each HA and instantaneous consuming power level $D_i(t)$ from SES. After gathering information, along with HA priority, PPC computes a final power level for each HA, F_i. Upon receiving a message from PPC, each HA behave according to the final power level. We additionally consider that a delay $(\tau)[s]$ is the total time of the sending information from the SES to the PPC, the processing time at PPC, and the sending information from the PPC to the corresponding HA.

IV. SYSTEM CONTROL FOR MAXIMUM CONSUMING POWER

As the proposed system works with message exchanges between HAs, SESs and PPC. For this purpose, we define an interval T_c of consecutive communications between HAs, SESs and PPC. In Figure 3, we define two time variables, one is global time t and other is local time x in each interval.

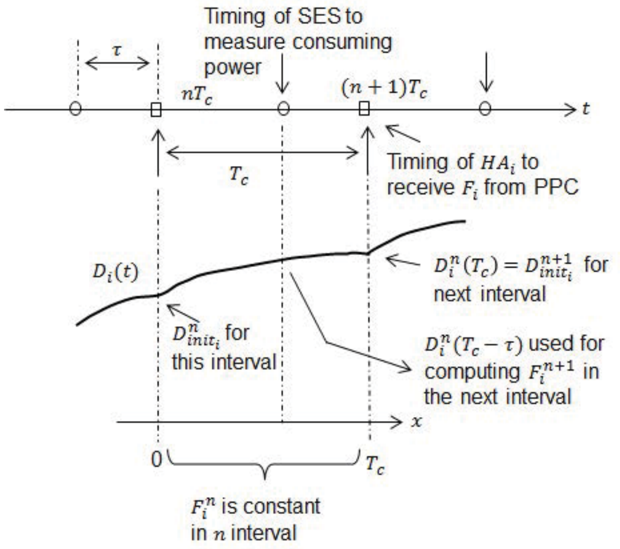

Fig. 3. Time variables considered.

An interval starting at nT_c and ending at $(n+1)T_c$ is called "interval n" and all variables related to interval n are denoted with superscript (n), such as:

$$D_i^{(n)}(x) = \left(D_{init_i}^{(n)} - F_i^{(n)}\right) \cdot e^{-a_i \cdot x} + F_i^{(n)} \tag{4}$$

Note that $D_{init_i}^{(n)}$ is the initial value $D_i^{(n)}(0)$ of the interval n, and is the same with the last value $D_i^{(n-1)}(T_c)$ of the previous interval $n-1$. T_c is a designer's parameter but $\tau \leq T_c$ is more realistic and should be considered because if $\tau > T_c$, PPC needs to compute another information which would overlap with the other information. When the communication interval n starts, each HA receives the information of final power level $F_i^{(n)}$ from PPC, and the last value $D_i^{(n-1)}(T_c)$ is used as $D_{init_i}^{(n)}$ for this interval. Final power level $F_i^{(n)}$ would remain constant during this interval.

A. Ideal Power Level

As PPC assigns final power level $F_i^{(n)}$ for the HAs which can be calculated as:

$$F_i^{(n)} = \begin{cases} D_{imax}, & \text{if } P_{limit} - \sum F_j^{(n)} \geq D_{imax} \\ 0, & \text{if HA is OFF} \\ P_{limit} - \sum F_j^{(n)}, & \text{if } P_{limit} - \sum F_j^{(n)} < D_{imax} \end{cases} \tag{5}$$

The given Eq. (5) work with priority, if the priority of ith HA is higher than the other turned ON HAs, PPC assigns final power level to the ith HA as its maximum consuming power level $(i.e.D_{imax})$. On the contrary, the remaining power is assigned to the lower priority HAs. In our proposed model, the total power available limit for all HAs is P_{limit} and total consuming power at time x in the interval n can be denoted as:

$$\begin{aligned} P^{(n)}(x) &= \sum_{i=1}^{m} D_i^{(n)}(x) \\ &= \sum_{i=1}^{m} \left(D_{init_i}^{(n)} - F_i^{(n)}\right) \cdot e^{-a_i \cdot x} + F_i^{(n)} \end{aligned} \tag{6}$$

$$P^{(n)}(0) = \sum_{i=1}^{m} D_{init_i}^{(n)} \tag{7}$$

$$P^{(n)}(\infty) = \sum_{i=1}^{m} F_i^{(n)} \tag{8}$$

At first, we consider the case when all HAs have same a_i.

$$\begin{aligned} & P^{(n)}(x) \\ &= \sum_{i=1}^{m} \left\{\left(D_{init_i}^{(n)} - F_i^{(n)}\right) \cdot e^{-a \cdot x} + F_i^{(n)}\right\} \\ &= \left\{\left(\sum_{i=1}^{m} D_{init_i}^{(n)} - \sum_{i=1}^{m} F_i^{(n)}\right) \cdot e^{-a \cdot x} + \sum_{i=1}^{m} F_i^{(n)}\right\} \end{aligned} \tag{9}$$

If

$$\sum_{i=1}^{m} D_{init_i}^{(n)} \leq P_{limit} \tag{10}$$

and

$$\sum_{i=1}^{m} F_i^{(n)} \leq P_{limit} \tag{11}$$

then

$$P^{(n)}(x) \leq P_{limit} \tag{12}$$

for $0 \leq x < \infty$.

Fig. 4, shows simulation result in this situation.

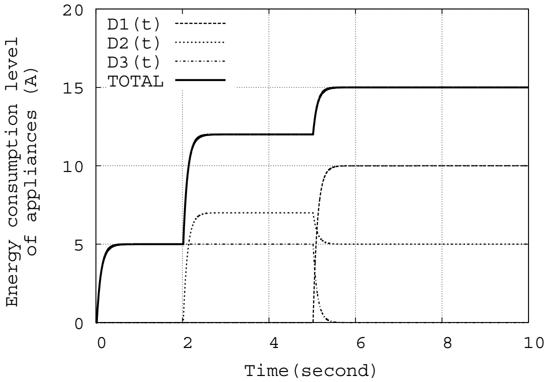

Fig. 4. Power consumption behavior of HAs with $a_i = 10$, turn ON time of HA$_1$ is $t = 5$, turn ON time of HA$_2$ is $t = 2$, and turn ON time of HA$_3$ is $t = 0$.

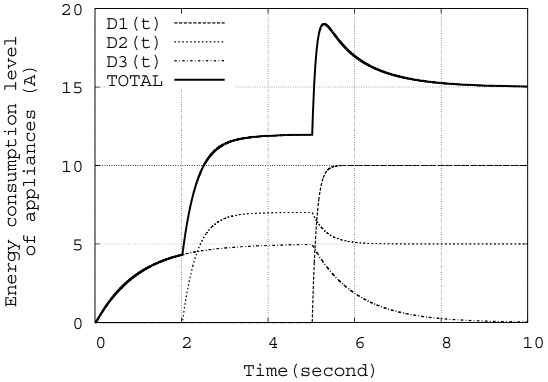

Fig. 5. Power consumption behavior of HAs with $a_1 = 10$, $a_2 = 3$, and $a_3 = 1$, turn ON time of HA_1 is $t = 5$, turn ON time of HA_2 is $t = 2$, and turn ON time of HA_3 is $t = 0$.

For the simulation scenario of our experiment, we consider three SESs attached with three HAs. The maximum consuming power levels of three HAs are $D_{1max} = 10$ (highest priority), $D_{2max} = 7$ (2nd highest priority), and $D_{3max} = 5$ (lowest priority). The total power limit for HAs is $P_{limit} = 15$. We can notice that if the time constant for each HA is same, we can keep the maximum power limit (Fig. 4).

However, if the time constant for each HA is different the proposed scheme for calculating final power level cannot guarantee maximum power limitation (Fig. 5). So, we introduce the concept of reassignment of actual remaining power.

B. Detailed Power Assignment Algorithm

In order to solve the overshoot problem observed with ideal power level algorithm, we propose detailed power assignment algorithm. In this algorithm, the ideal power level defined in the previous section (we will denote it $F^{(n)}_{ideal_i}$) is considered as overall final power level, while the final power level for each interval $F^{(n)}_i$ is computed based on the estimation of the actual remaining power at the beginning of the interval. As PPC only knows the information of $D_i(t-\tau)$ in order to assign $F^{(n)}_i$ for the next interval, PPC has to guess remaining power based on the $D_i(t-\tau)$ and $F^{(n-1)}_i$ and takes the maximum value. By taking the maximum value, we consider the worst case remaining power of the system estimation which reassigns to the HAs based on the HA priority.

$$remain = \sum_{i=1}^{m} max\left\{D_i(t-\tau), F^{(n-1)}_i\right\} \qquad (13)$$

Considering the robustness of the proposed system and ability to maintain the maximum power level, we use the worst case remaining power with this estimation we can guarantee the maximum power consumption between the power limit. The estimated actual remaining power is assigned to each HA. The pseudo code for computing $F^{(n)}_i$ is given as follows:

```
if $\left(\left(F^{(n)}_{ideal_i} - F^{(n-1)}_i \geq 0\right)$
 and $\left(F^{(n)}_{ideal_i} - F^{(n-1)}_i \leq remain\right)\right)$ then
  $F^{(n)}_i = F^{(n)}_{ideal_i}$;
  $remain = remain - \left(F^{(n)}_{ideal_i} - F^{(n-1)}_i\right)$;
else
  if $\left(\left(F^{(n)}_{ideal_i} - F^{(n-1)}_i \geq 0\right)$
   and $\left(F^{(n)}_{ideal_i} - F^{(n-1)}_i > remain\right)\right)$ then
    $F^{(n)} = F^{(n-1)}_i + remain$;
    $remain = 0.0$;
  else
    if $\left(F^{(n)}_{ideal_i} - F^{(n-1)}_i < 0\right)$ then
      $F^{(n)}_i = F^{(n)}_{ideal_i}$;
    end if
  end if
end if
```

V. SIMULATIONS AND DISCUSSIONS

The objective of the simulation is to observe and verify the system behavior and try to show that the power limit is maintained. For simulation scenario of our proposed system, we consider three HAs attached with three SESs. The maximum consuming power levels of three HAs are $D_1max = 10A$, $D_2max = 7A$, and $D_3max = 5A$. The total power available for HAs is $P_{limit} = 15$. The main purpose of this simulation to observe the effect of system parameters, communication delay τ and communication interval T_c, to the total power consumption waveform. As first experiment, we investigate the power consumption behavior of HAs when communication delay is fixed to $\tau = 0.2$ and communication interval changes to $T_c = 0.21$, $T_c = 0.45$, and $T_c = 0.75$, and its result is shown in Fig. 6. As second experiment, we investigate the power consumption behavior of HAs when communication interval is fixed to $T_c = 0.5$ and communication delay changes to $\tau = 0.05$, $\tau = 0.25$, and $\tau = 0.49$, and its result is shown in Fig. 7.

From experiment 1, we observed that the power consumption behavior of the proposed system does not change by changing the system parameter T_c. The detailed waveform of power consumption of HAs is obviously different depending on the value of system parameters but the envelopes of total power consumption waveform is remained same for different T_cs. On the other hand, from experiment 2, we found that the parameter communication delay (τ) affects not only the detailed waveform but also the envelop of power consumption waveform. The larger τ tends to slow down the changing speed of the envelope. We also notice that when a HA reduces its power, the power decreasing speed of HA can be determined by the system parameter a_i. However, when a HA increases its power, the power increasing speed of HA depends on remaining power. If the remaining power is sufficient, HA can achieve its maximum increasing speed which is determined by system parameter a_i, but if the remaining power is not enough, the increasing speed slows down. Therefore, total power consumption limit does not exceed the available power limit.

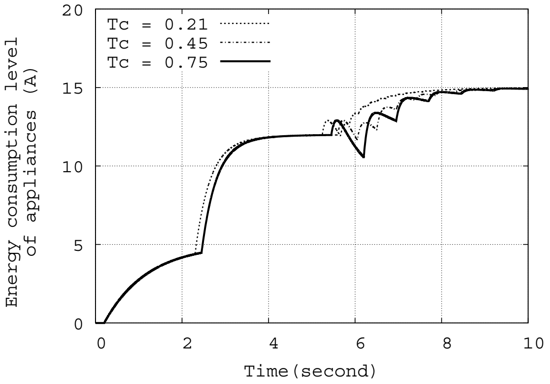

Fig. 6. Total power consumption behaviors with different T_c and fixed $\tau = 0.2$. Three HAs have $a_1 = 10$, $a_2 = 3$, and $a_3 = 1$, respectively, and turn ON time of HA_1 is $t = 5$, turn ON time of HA_2 is $t = 2$, and turn ON time of HA_3 is $t = 0$.

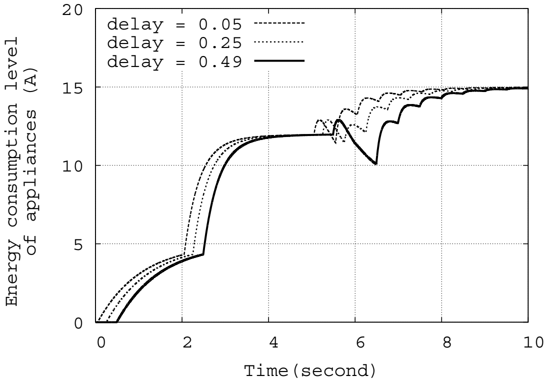

Fig. 7. Total power consumption behaviors with different τ and fixed $T_c = 0.5$. Three HAs have $a_1 = 10$, $a_2 = 3$, and $a_3 = 1$, respectively, and turn ON time of HA_1 is $t = 5$, turn ON time of HA_2 is $t = 2$, and turn ON time of HA_3 is $t = 0$.

VI. CONCLUSION

The main goal of this paper is to prevent the situation when total power consumption of all HAs in smart home exceeds the available power limit. The use of SES helps us in measuring the instantaneous consuming power from the HAs. The functions of PPC are to gather ON/OFF status from each HA, instantaneous consuming power $D_i(t)$ from SESs and calculate the total remaining power for HAs. The remaining power is then reassigned to HAs according to their priority. Considering the robustness of the proposed system and the ability to maintain the maximum power, we use the worst case remaining power. With this estimation, we can guarantee the maximum power consumption between the power limit.

We analyzed our proposed system in simulation environment and verified that the total power limit for HAs is maintained appropriately. From simulation results, we also found that the change of system parameter T_c does not affect the envelope of the detailed consuming power waveform, but the communication delay τ affects the changing speed of the envelope. This shows the robustness of the proposed system against the communication interval but we need to carefully manage the communication delay. For our future work, we will try to consider the important issue of “fail safe” in our proposed system.

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