Formal Verification of Demand Response Based Home Energy Management Systems in Smart Grids

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***Abstract*—Demand Response Management System (DRMS) is used in a smart grid to reduce the gap between power generation and its demand. The knowledge of the demand of the customers is very important because failing to fulfill this demand can lead to serious issues, like system failures and blackouts. Home Energy Management System (HEMS) is a DRMS that is designed specially for residential customers. Traditionally, HEMS is analyzed using simulation-based techniques but such an analysis lacks completeness and exhaustiveness. In order to overcome these issues and to account for the numerous random and unpredictable factors in HEMS, we propose to use probabilistic model checking for its analysis. Our formal model is generic in nature and can be used to model most of the existing HEMS. Important results related to the efficiency and total household power are also presented in this paper.**

I. Introduction

Both the developed and developing countries are facing numerous challenges with the ever-increasing demand of electric power. As per a recently published report on the international energy outlook from U.S. energy information administration, electricity demand is expected to grow tremendously in many Asian countries, which are not member of Organization for Economic Co-operation and Development (OECD) due to rise in the standard of living, demand of heating, cooling, lighting and appliances [1]. Conventional grid is typically used to carry power from central generation units to a huge number of customers [2]. Since it lacks communication between the customer and utility, it is very challenging for the utility to know the requirements of the customer in real-time, which may result in system failures and large-area blackouts [3]. Recently, smart grid [4], also called the *intelligent* or *future* grid, has emerged as a promising concept to solve the energy crisis of this era. It enables two way information and electricity flow between the customer and utility to generate an advanced automated and distributed energy system. Therefore, electric efficiency, safety and reliability can significantly be improved by smart grid [4].

Demand Response (DR) [5] is one of the vital elements in smart grid. Using Demand Response Management System (DRMS), the difference between supply and demand can be reduced, which decreases the overall stress on the grid. There are three main factors that describe DRMS: i) control mechanism, ii) offered motivations and iii) decision variable algorithms [5]. Control based DR mechanism shows the communication between the utility and customers and can be further divided into two types, i.e., centralized and distributed. In centralized algorithms, the utility can communicate directly with all the customers, whereas the customers do not have the privilege to communicate with each other. On the other hand, in distributed DRMS algorithms, the customers can communicate with the utility and one another. The offered motivations can be reduction of prices in peak hours or other incentives, such as payments. The decision variable algorithms are focused on load and energy management, and can be further divided into two types, i.e., task scheduling and energy management. Task scheduling corresponds to the control of activation time of loads, whereas in the energy management technique, the prime focus is on operating the loads with the optimal energy consumption. The customers in DRMS can be divided into three types, residential [6], commercial [7] and industrial [8]. Although simulation based DRMS analysis techniques exist for these customers but they lack completeness and exhaustiveness. Very few DRMS exist for residential customers in comparison with commercial and industrial customers. In this paper, we mainly focus on residential customers using a fully automated DRMS, i.e., Home Energy Management System (HEMS) which monitors and controls home appliances according to the specific requirements.

Traditionally, HEMS has been analyzed using simulations [9]–[11] to obtain insights into the prime decision factors, such as efficiency and user satisfaction. However, such analysis results are incomplete and in-exhaustive for larger and complex HEMS [12]. As these methods involve testing for some specific sets of input vectors, there is always a possibility of missing some corner cases or miscalculating the performance metrics. These limitations may lead to unscheduled power blackouts or an ineffective utilization of power, which is highly undesirable in a smart grid. Formal methods [13] are widely used for complete and rigorous analysis of various complex hardware [14] as well as software [15] systems. Due to their completeness and soundness [16], they can be very suitable for analyzing HEMS as well. In this paper, due to many random factors in HEMS, such as load priority, external temperature, comfort level settings, demand limit and duration, we propose to use probabilistic model checking [17] to formally analyze HEMS functional and performance aspects. For illustrating the usefulness of our analysis framework, we consider a HEMS algorithm proposed by Pipattanasomporn et al. [18] because it is generic in nature and can manage multiple household appliances. We use PRISM [19] to analyze the properties related to the system efficiency and user satisfaction due to its extensive support for a wide range of temporal and probabilistic operators.

II. Preliminaries

A. PRISM Model Checker

PRISM [20] is a probabilistic model checker, i.e., a software tool for the formal modeling and analysis of systems that exhibit random or probabilistic behavior. PRISM can build and analyze several types of probabilistic models, such as discrete-time Markov chains (DTMCs), continuous-time Markov chains (CTMCs), Markov decision processes (MDPs), probabilistic automata (PAs), probabilistic timed automata (PTAs) plus extensions of these models with rewards (or costs), referred to as (discrete- or continuous-time) Markov reward models and priced PTAs.

B. Home Energy Management System (HEMS)

HEMS provides an automated residential DRMS in a smart grid scenario. HEMS is mainly used to implement task scheduling and energy management techniques for the residential customers, where loads are shifted to non-peak hours to reduce the total household power consumption (TP). In this paper, we consider a particular scenario of HEMS [18]. The main focus of this system is to control four power intensive household appliances, i.e., water heater (WH), air conditioner (AC), cloth dryer (CD) and electric vehicle (EV) which are very typical household loads in USA [18], [21] and many other countries around the globe. We have considered the EV here due to the huge impact of this unpredictable load on the grid and distribution transformer [22].

Although renewable resources are an integral part of smart grid, but in the considered HEMS algorithm [18], all the appliances are using electricity from the utility. All the customers who want to participate in a DR program are informed via an external signal from the utility through a smart meter. This signal consists of a demand limit (`DL`) in kilo-Watts and duration (`Dur`) in hours. The overall system ensures that the customer can use the required appliances as long as the total household power consumption does not exceed the demand limit during the specified duration. This system also accepts load priority (LP) and comfort level settings (CLS) from the household owners. In this scenario, some of the loads, such as refrigerators, plug loads and lights are critical and thus need to be served all the times as interruption could be quite inconvenient for the customers. HEMS enabled loads have monitoring and control units whereas the critical loads have a monitoring unit only. The communication between HEMS and all the home appliances is usually done over the bluetooth, wireless or zigbee protocols. With the knowledge of a power profile of a particular appliance, our analysis can be easily extended onto any type of household load within the HEMS context. This makes our example scalable.

Algorithm: The three major steps of the HEMS algorithm [18], depicted in Fig. 1, are described below:

Information Gathering: In this step, the current status, i.e., ON or OFF, of all the appliances is monitored. Accordingly, the total household power consumption (TP) is calculated using the status and rated power of the appliances. Furthermore, the customer defines the load priorities and comfort level settings. According to Pipattanasomporn et al. [18], WH has the highest priority, i.e., 1, and EV has the lowest priority, i.e., 4. Comfort level settings for WH and AC are the required temperature ranges, whereas time of operation is an important factor for EV and CD. The current temperatures of the room and water are measured by sensors. Finally, the demand limit and duration are also acquired from the utility in this step.

Violation Check: In this step, the HEMS algorithm checks comfort level violations, which mainly depend on the type of the appliance and its settings. For the WH and AC, a violation happens if the water temperature or room temperature exceeds or falls below the preset threshold (set by the customer in the previous step). A CD violation occurs if it completes a job after the required completion time. Finally, an EV violation occurs if its charging completes after the charging completion time. Here S_{APP} represents the comfort level violation of a specific appliance.

Actions: If there is a demand limit violation, HEMS turns OFF the appliances according to the customer's priority, starting from the lowest one until `DL` becomes greater than TP. According to Pipattanasomporn et al. [18], TP should remain below DL while customer's comfort should also be kept in mind so the appliances are turned off from the lowest to the highest priority. In case of a comfort level violation, the HEMS algorithm turns ON or OFF the corresponding appliance, as required. While turning an appliance ON, the algorithm goes through a decision-making process to ensure that TP, including the turned ON appliances, does not exceed `DL`. Here LP_{EV}, LP_{CD}, LP_{AC} and LP_{WH} represent the load priority of EV, CD, AC and WH, respectively. LP_{APP} is the load priority of the particular appliance for which comfort level violation has occurred. The status of all the appliances is updated after the comfort level violation is handled, i.e., S_{APP} is turned ON or OFF.

III. Formal Modeling

A. Refinements to the Original Algorithm

The formal modeling of HEMS allowed us to identify various important factors that were missing in the original algorithm [18]. In this section, we present these discrepancies and our proposed improvements.

1) Comfort level violation of WH and AC can occur in two ways, i.e., upper limit violation and lower limit violation. The latter scenario was found to be missing in the flowchart of original algorithm [18]. As shown in Fig. 1, only the ON request is received in the variable S_{APP} in case of a violation. We have used a new variable, `S_app_off`, to cater for this issue, its value is 1 for WH, 2 for AC and so on.
2) If WH, AC and CD are ON and a violation of EV occurs then there may be an error, since EV has the lowest priority and the condition $LP_{EV} < LP_{APP}$ is false. So, to tackle this problem, we have included following inequality in our model, i.e., $LP_{EV} \leq LP_{APP}$.
3) The original algorithm does not describe the isolation between the room temperature and water temperature. Similarly, there is no means to measure the effect of CD or EV operation on the room or water temperature. So in our model, we have considered all these appliances isolated with each other. So WH is not present in the room where AC is operational and a similar relationship also holds for CD and EV as well.
4) The flowchart of the original algorithm [18] does not cater for the violation of demand limit. We solved this problem as shown in Case 3 of Table I and Fig. 2.
5) When the appliances are OFF, the effect of external temperature is not mentioned in the original algorithm. Therefore, we have used the thermal model, proposed by Klauw et al. [21], which takes care of the external temperature, internal temperature and power consumption as well.

B. Modeling the HEMS algorithm in PRISM

We have formally modeled the HEMS algorithm as a DTMC in the PRISM model checker. We incorporated timing in our model because of the varying demand limits for different time intervals. In order to maintain the time sequence, we have used a variable named as `state`. In our formal model of HEMS, the total household power `TP` is calculated using the status of four power intensive appliances, i.e., the rated power consumption is considered only if the appliance is ON. Moreover, the power consumption of the critical loads is always added in `TP` as they have to be considered all the time.

1) Randomness in Model: In order to capture the actual behavior of HEMS and its operating environment, there are various elements of random nature. To model the random environmental factors, we have considered the external temperature `EXT_Temp` as random in our HEMS model. Its value depends upon various components, like geographical location, season weather and time of the day. When the AC and WH are OFF then the change in room and water temperatures directly depends on the external temperature. Similarly, the demand limit `DL` and duration `Dur` are also kept random in our model. The utility can select any value within a specified range of values according to its requirement and generation. Thus, the variable `DL` for a particular value of `Dur` can be different at different durations. The current room `RT_crt` and water `WT_crt` temperatures are also considered to be random during the initialization stage only. Once the algorithm starts executing the steady state operation then it depends upon the status of the AC (`S_AC`) and WH (`S_WH`). Load priority `LP` and comfort level settings `CLS` are also taken as random quantities in our model because a customer can select different `LP` and `CLS` for different durations. In case of multiple users, every user can select different values of `LP` and `CLS`.

2) Timing Model: We have modeled time as a discrete component, where one time step is equal to a specific value. This step value can be selected according to the requirements of the given HEMS. For a particular value of `DL`, timing is incorporated using a variable `counter`. One increment in the `counter` variable is considered to be equal to 20 seconds in our formal model of HEMS. Demand Limit `DL` is specified for a specific duration, `Dur`. As the algorithm repeats itself so there can be two possibilities to move from the end states. First one is to move towards state 1 and the second is to move towards state 2 as shown in Fig. 2. We have modeled it in such a way that if the `counter` value is less than the maximum value `counter_max`, then the algorithm jumps to the state 2 where the same values of `DL` and `Dur` are used. If `counter` is equal or greater than `counter_max` then it goes to the state 1 where a new `DL` and `Dur` is randomly selected. Fig. 2 depicts an abstract form of the complete state machine, presenting the major states only.

3) Temperature Model: The variations in room and water temperatures heavily depend upon the external temperature, current room or water temperature etc. So, we have incorporated these factors by using the thermal model proposed by Klauw et al. [21]:

$$T_{t+1} = aT_t + bx_t + cO_t + d_t, \tag{1}$$

Here a, b, c and d_t are the parameters of the thermal model. T_{t+1} and T_t are the indoor temperatures of next and current time intervals, respectively. O_t and x_t represents the external temperature and the average power consumption by WH and AC. Coefficients of the thermal model are obtained from Pecan Street Inc. dataset [23], which includes data for different houses in Austin, Texas. This dataset is combined with openly accessible weather data from Austin Texas [24].

4) Model of State Transitions: The main behavioral characteristics of our design are depicted in Fig. 2. There are two major functions in our model: The first one maintains `TP` under `DL` and the second is to run appliances in such a way that customer's comfort level settings are not violated. So four different cases can be formulated by this, as shown in Table I.

In Case 1, `TP` is less than `DL` and there is no comfort level violation, so our model only updates the current room and water temperature according to the status of appliances, `counter` and `state` variables. Room and water temperatures are updated according to our temperature model [25].

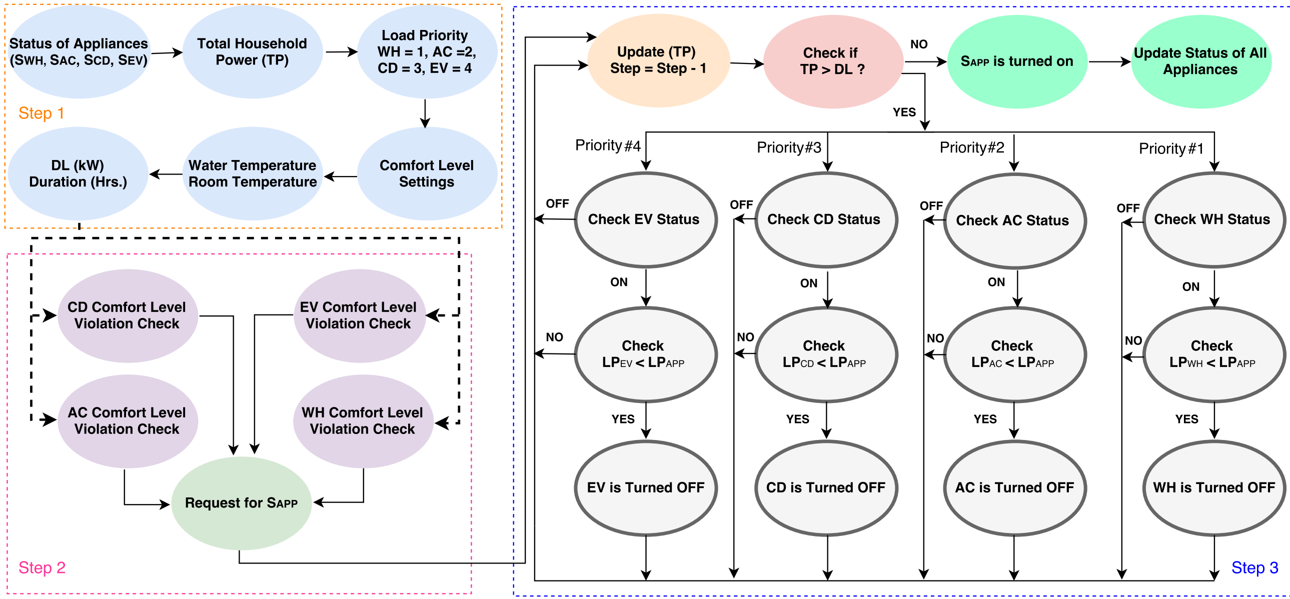


Fig. 1: Flow of HEMS Algorithm [18]

TABLE I: Four Possible Combinations of Comfort Level and Power Violations

No.	TP > DL	CL Violation	Actions
1	No	No	Only update other variables
2	No	Yes	Remove violation by either turning ON or OFF the appliance
3	Yes	No	Turning OFF appliances from lowest to highest priority
4	Yes	Yes	Compare priorities and turn OFF appliances

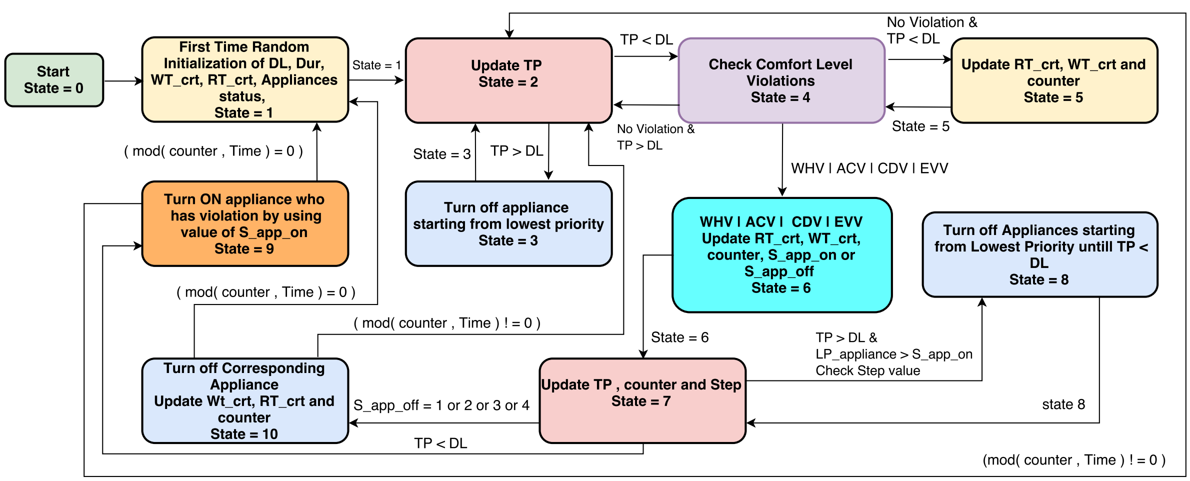


Fig. 2: Abstract form of the proposed model

In Case 2, TP is less than DL but there is a comfort level violation. As we are within the demand limit, so the appliance which have a comfort level violation can be turned ON easily.

In Case 3, TP > DL and there is no violation. So, our model turns OFF appliances starting from the lowest priority [25]. The variable `check` is used to turn OFF appliances in a sequence from the lowest priority to the highest priority. When EV is ON and TP > DL, then EV is turned OFF in the updates. This check is decremented in the next `state` and for CD `check` value becomes 3. In this case, if TP is still greater than DL then CD is also turned OFF and so on until TP < DL.

In Case 4, both comfort level violation and TP > DL are considered. In this case, starting from the lowest priority (EV), if an appliance is ON then the load priority of all appliances is compared with the priority of the appliance having a violation.

If load priority is less, then that particular load is turned OFF and so on until TP $<$ DL. Once TP is less than DL then the appliance with a violation is forced to turn ON in order to remove the violation [25]. A variable named as Step is used to control the loop from the lowest priority to the highest priority. As the load priority of AC (LP_AC) is 2 and suppose S_app_on is 1 then it means that WH has a violation. So, AC is turned OFF here to get TP $<$ DL and ultimately the violation is removed.

Apart from these four cases, there is another possibility for the comfort level violation. As mentioned in Section III-A of refinements, an appliance might be required to be turned OFF to remove the violation. For this purpose, a different variable S_app_off is used, which contains the priority of the load which has the violation. As turning OFF an appliance is beneficial in terms of keeping TP lower than DL, so after checking the violation and storing the value in the variable S_app_off, we directly turn OFF the particular appliance [25]. So according to the value of S_app_off, the appliances are turned OFF. As we are turning OFF appliances, so the result of TP $>$ DL or TP $\leq$ DL does not matter here.

IV. Verification Results

A. Algorithm's Efficiency Property

The efficiency of a HEMS can be examined in terms of total power savings in a fixed duration. If DR is not applied to a home and all appliances are ON, then this can be considered as a worst-case scenario. In this case, the total power consumption TP_Wo_DR at any instant of time is the addition of power of the critical loads (all the loads that needs to be functional all the time are considered as critical loads) and rated power of all appliances.

For usual daily scenario, we selected the AC and CD to be operated for one Dur. This represents a normal operation without DR. In this case, the rated power of AC and CD are used to calculate the total power consumption because the sum of these powers is almost in the middle as compared to the worst-case scenario.

Finally, if we apply HEMS on this house and calculate TP, then a comparison can be done among all three scenarios in terms of total power savings. The power consumption with DR can be computed by adding all the powers of appliances according to their status. So if an appliance is ON then its rated power will be included, otherwise not.

In order to compute the total power consumption, we have used the cumulative reward property of PRISM. So reward for cumulative power with demand response is named as Cum_Power_DR. Based on this, we have formulated the desired property as:

$$R\{\text{“}Cum\_Power\_DR\text{”}\} = ?[Counter{<=}Time]$$

The results of 1 hour duration are shown in Fig. 3a. The curve labeled as TP_Wo_DR represents the total household power consumption without DR. This is the worst-case scenario in which all the appliances are ON. The curve of TP_Avg_Wo_DR is the average case scenario where AC and CD are ON for all the time. The TP_W_DR curve represents the total household power with DR. It is clear from the figure that when demand response is applied on this home then the total household power consumption is significantly reduced compared to the average or worst case scenarios while maintaining the customer's comfort level settings.

B. Analysis of Total Household Power and Demand Limit

The purpose of HEMS is to maintain the total household power consumption below DL, which is random for each Dur. So we propose to analyze the behavior of TP_W_DR, which represents total household power with DR in comparison with DL. As we are observing these two quantities on each instance, so here we have used instantaneous rewards. Based on these rewards, properties for DL and TP_W_DR can be formulated as:

$$R\{\text{“}R\_DL\text{”}\} = ?[I = Steps]$$
$$R\{\text{“}R\_TP\_DR\text{”}\} = ?[I = Steps]$$

Here R_DL represents the reward for DL and R_TP_DR models the reward for total power with DR. Parameter I is used for instantaneous rewards. Due to instantaneous rewards, the expected values of DL and TP_W_DR are used here.

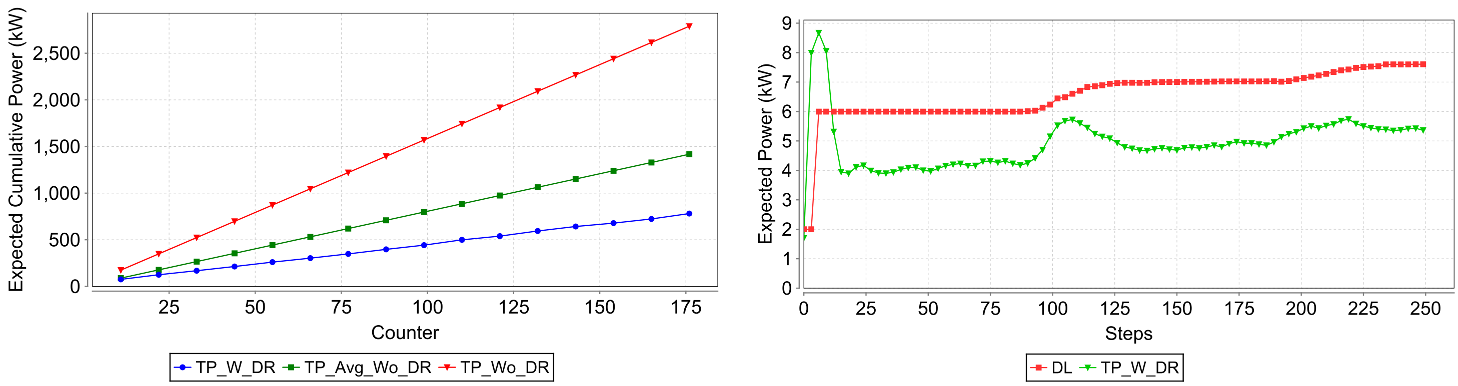
The results are shown in Fig. 3b. As depicted in the figure, HEMS makes sure that the total household power remains under DL by turning OFF the appliances.

Our model has 636764 states and 939325 transitions, which advocate the use of formal methods for a rigorous analysis. The time required to build the model was 30.421 s. The verification time for the analysis of the efficiency property of the algorithm was 7.101 s. Similarly, the verification time for the analysis of the total household power and demand limit was 10.573 s.

The key advantages of this work include a complete and rigorous comparative analysis of the total household power consumption with and without DR, and the inclusion of the external temperature and threshold violations to turn OFF the appliances. Another important benefit is the identification of bugs, such as maintaining TP $<$ DL when there is no violation, which are missing in the simulation-based analysis [18] of the same algorithm. Our PRISM code is available for download [25], and thus can be benefitted by researchers and verification engineers for further developments and analysis of different HEMS algorithms.

V. Conclusion

Due to random factors, like external temperature and demand limits, we propose to use probabilistic model checking for the analysis of HEMS [18] in this paper. There were some corner cases difficult to test using the algorithm proposed in [18]. This was identified during our modeling phase and remained unidentified in the original paper where HEMS was proposed and analyzed using simulations [18]. Comfort level violations are possible for both maximum and minimum ranges, and the original algorithm by Pipattanasomporn et al. [18] focuses only on one range of violation and ignores the other side, which is very important. Similarly, checks in



a) Expected Cumulative Power with and without DR

b) Analysis of TP and DL

Fig. 3: Verification Results

comparing the priorities were found to be inappropriate. The identification of these flaws clearly indicates the usefulness of the proposed methodology for HEMS. The analysis of implementation with or without DR shows that by including DR, the total household power consumption can be reduced while maintaining customer's comfort.

In future, we plan to analyze HEMs with an increased number of customers. In this case, every customer can have a different `DL` and `Dur`. Also, the customers can choose their own different priorities according to their requirements. In this case, the total power savings can be calculated for the whole group of customers. Moreover, comparison of different HEMS algorithms can also be performed based on our proposed properties.

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