Optimal Operation of Home Energy Management Systems in the Presence of the Inverter-based Heating, Ventilation and Air Conditioning System

Mohammad Javadi
INESC TEC
Porto, Portugal
msjavadi@gmail.com

Ali Esmaeel Nezhad
Department of Electrical, Electronic, and Information Engineering, University of Bologna, Bologna, Italy
ali.esameelnezhad@gmail.com

Kimia Firouzi, Farnoosh Besanjideh
Department of Electrical Engineering, Islamic Azad University, Shiraz, Iran
kimkim.firuzi.shz@gmail.com
farbesanjideh95@gmail.com

Matthew Gough
Faculty of Engineering of the University of Porto and INESC TEC
Porto, Portugal
mattgough23@gmail.com

Mohamed Lotfi
Faculty of Engineering of the University of Porto and INESC TEC, Porto, Portugal, and also ERC, Ontario Tech University, Oshawa, ON L1G 8C4, Canada
mohd.f.lotfi@gmail.com

Amjad Anvari-Moghadam
Department of Energy Technology, Aalborg University, 9220 Aalborg, Denmark
aam@et.aau.dk

João P. S. Catalão
Faculty of Engineering of the University of Porto and INESC TEC
Porto, Portugal
catalao@fe.up.pt

***Abstract*—This paper presents the optimal operation strategy for home energy management system (HEMS) in the presence of the inverter-based heating, ventilation and air conditioning (HVAC) system. The main target of this paper is to find the optimal scheduling of the home appliances in line with the optimal operation of the air conditioner system to reduce the daily bills while the end-users discomfort index would be minimized. In this paper, the mathematical formulation is represented in mixed-integer linear programming (MILP) framework to reduce the computational burden and easily be adapted by hardware for implementation. The HEMS is the main responsible for optimal scheduling of controllable and interruptible loads as well as serving the fixed loads. The electricity tariff is based on time-of-use (TOU) mechanism and three different tariffs have been considered during the daily consumptions. The simulation results for the daily operation of a residential home confirms that the proposed model can effectively reduce the electricity bill while the consumer predefined comfort level is appropriately maintained.**

Keywords—Demand Response Program, Discomfort Index, Home Energy Management System, Inverter-based Air Conditioning System, Time of Use Tariff.

I. INTRODUCTION

The emerging development of the home energy management system (HEMS) in recent years from one side and the increasing penetration of the smart home appliances according to the Internet of Things (IoT) protocols in the other side, opens a new window for novel research topics in the field of demand response (DR) [1].

In this area, the current studies have reasonable growing trends to address the permissible incorporation of the IoT at the residential level. One of the new activities in the field of development of HEMS for such purposes is to minimize the consumers' electricity bills while maintaining the end-users' preferences. With the development of various technologies and changes in the way household consumers interact with the distribution network, smart HEMS have emerged as a way to optimize the size and shape of the residential load profile [2]. The HEMS concept has been studied thoroughly in the existing literature.

A Mixed-Integer Nonlinear Programming (MINLP) was developed in [3] to include a penalty for causing the customers inconvenience in the final schedule. The problem took a set of 10 appliances and let the customers decide on their optimal operational schedules and the system was penalized for moving the operation of these appliances outside of the schedules. Results showed a decrease in the customer's energy bill by 25%.

A novel Conditional Value at Risk (CVaR) formulation was used in [4] which included the uncertainty surrounding energy storage systems, PV arrays, price, and load profiles. Incentives were used to raise the participation of customers in such a program and the results show a saving of 18% on the bills should the customers choose to be part of the program. A new optimization algorithm and different tariff regimes were used in [5] to determine the optimal operating schedule of a number of appliances in a residential setting over a period of 24 hours. The optimal operation of the energy management system augmented by model predictive control (MPC) technique has been proposed in [6]. The proposed method has been applied on a grid-connected HEMS to serve the local demands in the presence of energy storage and local generation, as well. The model used the Gaussian process time series model for forecasting the load and PV generation profiles.

A multi-objective mixed-integer linear programming (MILP) model to solve a HEMS model with an integrated battery energy storage system was developed in [7]. The TOU tariff was used to incentivize the customer's participation in the demand side management program. The results indicate that across all of the six different scenarios studied, the HEMS mitigates the customer's bill while reducing the peak demand, benefiting the electric utility [7]. Similar HEMS dispatch models in different working environments and energy pricing schemes have also been developed in [8]–[10] considering economy and user's comfort as objectives.

Another multi-objective model has been proposed for the optimal scheduling of the HEMS using the epsilon-constraint method [11]. The proposed model has been represented as a MILP model according to the standard epsilon-constraint method suggested in [12], [13].

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A stochastic HEMS model is presented in [14] taking into consideration the uncertainties caused by renewable energy production. The results obtained from this research study show a reduction of up to 42% in the monthly electricity bill faced by consumers, although the authors clearly pointed out that the results are highly case-sensitive and dependent upon the relevant information relating to the building and the specific individual. A study by [15] sought to minimise the electricity cost and thermal discomfort of users through a HEMS which also considered heating, ventilation and air conditioner (HVAC) energy demand. This was done through stochastic programming which considered uncertainties associated with electricity price, outdoor temperature, distributed energy resource generation output, load demand, and occupancy state of the home.

This paper investigates on modelling of the inverter-based HVAC system as an interruptible load to control the indoor temperature in the daily self-scheduling problem. Besides, the HEMS has accordingly proposed to manage the daily operation of controllable home appliances and serving the fixed loads in the operating horizon. The main contribution of this paper is to propose a MILP model for both controllable and interruptible appliances using binary decision variables while the preferences of the end-users have been met in the self-scheduling problem.

The rest of the paper is as follows: the main principles of home energy management systems and the definitions of fix, controllable and interruptible loads are provided in Section II. The mathematical formulation of the self-scheduling problem for HEMS systems is provided in Section III. The optimization problem is addressed as a standard MILP problem in this section. Section IV provides the simulation results on different case studies. The concluding remarks are addressed in the last section.

II. HOME ENERGY MANAGEMENT SYSTEM

The increasing emerging smart technologies penetration at residential levels provided in line with the functionality of the smart metering systems brought the interests to develop the HEMS. At the residential level, the consumers may have different home appliances with different functionalities. There are, at least, three types of loads at the residential level. Some parts of the loads are categorized as fixed demand loads, like the refrigerator in which such loads could not be shifted to another time intervals and such appliances must work at all.

However, such appliances have different consumption patterns during the day in terms of compressor functionality, but the consumers haven't any control on shifting such functionalities to another time interval. Therefore, such appliances are categorized as fix demand loads. The second type of home appliances is controllable loads. The controllable loads can be used according to the end-users' preferences, however, when such appliances are plugged in, they have to finish their functionality and they couldn't have any interruptions during the operation time intervals.

Washing machines, spin-dryers, dishwashers are some of the controllable appliances. The end-user has a preference for utilizing such appliances and it can be used in a predefined time window, including the preferred time slots. The last category is interruptible loads.

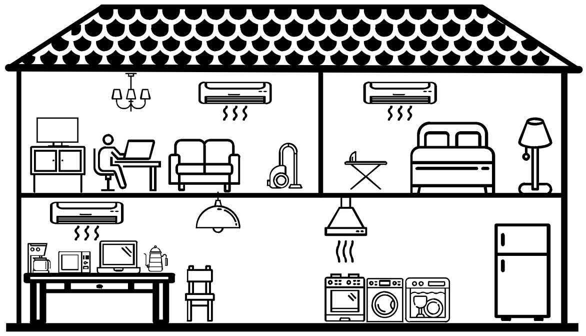

Fig. 1. Conceptual HEMS model in this study.

For the interruptible loads, multiple ON and OFF transitions have been adopted during the operating horizon. For example, the HVAC system is one of the interruptible loads at residential levels. The HVAC system is the main responsible system to provide indoor temperature and air quality for the consumers. The HVAC system can control the indoor temperature with multiple ON and OFF states according to the technology used in the appliance. Some kind of HVAC systems have a thermostat for activating the operation and such HVAC systems couldn't be categorized as interruptible loads. The recent HVAC systems benefit from the inverter technology which empowers the end-user to control the indoor temperature with a diverse range of power consumption as well as the indoor temperature controlling. In this paper, the HEMS benefits from the inverter-based technology and the indoor temperature can be effectively controlled without violating its predefined range.

Fig.1 illustrates the conceptual model of the HEMS in this study including all kinds of abovementioned appliances. In this illustration, the fix, controllable and interruptible loads are shown. The main functionality of HEMS is to find the optimal operation of home appliances to reduce the electricity bills while addressing the consumers' preferences. The HEMS should provide the ON-OFF status of the home appliances for a given horizon and the decision variable of the optimization problem is to determine the status of binary decision variables corresponding to the home appliances ON-OFF actions. In the following section, the mathematical formulation for optimal self-scheduling of home appliances for all kinds of home appliances is addressed.

III. HEMS SELF-SCHEDULING PROBLEM FORMULATION

The mathematical formulation of the HEMS is provided in this section. The self-scheduling problem is formulated as a standard MILP minimization problem. The objective function is to minimize the electricity bills and it is evaluated for a typical day considering all kinds of home appliances, i.e. fix, controllable and interruptible loads. The main objective function is represented as:

$$Min \underbrace{\left(\sum_{t=1}^{NT}\left[\rho_t^{TOU} P_t^{G2H}\ \Delta t\right]\right)}_{Electricty\ Bill} + \omega \underbrace{\left(\sum_{i=1}^{NA}\left[DI_i^{+} + DI_i^{-}\right]\right)}_{Discomfort\ Index} + \underbrace{\left(\sum_{t=1}^{NT}\sum_{i=1}^{NA}\left[ON_{i,t}C_i^{ON} + OFF_{i,t}C_i^{OFF}\ \right] - \sum_{i=1}^{NA}\left[C_i^{ON} + C_i^{OFF}\right]\right.}_{Turn-on\ and\ Turn-off\ Cost} \quad (1)$$

The objective cost function includes three main parts; the first part is corresponding to the electricity bill according to the amount of hourly energy consumption by the consumer. The second part represents the monetizing term regarding the discomfort index for controllable home appliances. The last part deals with the associated costs for multiple ON and OFF actions of controllable home appliances.

It is evident that for each controllable appliance one turn-on and turn-off action is permissible and to avoid multiple ON-OFF stats, the corresponding cost must be considered in the objective function. The ON-OFF cost, C_i^{ON} and C_i^{OFF}, have reasonable values for controllable appliances and zero for the interruptible ones. For the controllable loads, the operator can modify the plugging in time and therefore, the bills can be minimized, accordingly.

The corresponding constraints of HEMS sub-problem are as follows:

$$B_{i,t} = \begin{cases} 0 & t < LB_i \\ 1 & LB_i \le t \le UB_i \\ 0 & t > UB_i \end{cases} \quad B_{i,t} \in \{0,1\} \tag{2}$$

$$S_{i,t} \le \begin{cases} 0 & t < LB_i \\ 1 & LB_i \le t \le UB_i \\ 0 & t > UB_i \end{cases} \quad S_{i,t} \in \{0,1\} \tag{3}$$

$$\sum_{t=1}^{NT} B_{i,t} = T_i \quad \forall i = 1,2,...,NA \tag{4}$$

$$\sum_{t=1}^{NT} S_{i,t} = T_i \quad \forall i = 1,2,...,NA \tag{5}$$

$$\sum_{i=1}^{NA} S_{i,t} P_i = P_t^{D,Shift} \tag{6}$$

$$ON_{i,t} - OFF_{i,t} = S_{i,t} - S_{i,t-1} \quad \forall t > 1 \tag{7}$$

$$DI_i^- \ge \frac{1}{T_i}\left[\sum_{t=1}^{NT} t \times B_{i,t} - \sum_{t=1}^{NT} t \times S_{i,t}\right] \tag{8}$$

$$DI_i^+ \ge \frac{1}{T_i}\left[\sum_{t=1}^{NT} t \times S_{i,t} - \sum_{t=1}^{NT} t \times B_{i,t}\right] \tag{9}$$

$$0 \le P_t^{Ch.} \le I_t^{Ch.} P^{Ch.,\max} \tag{10}$$

$$0 \le P_t^{Disch.} \le I_t^{Disch.} P^{Disch.,\max} \tag{11}$$

$$0 \le I_t^{Ch.} + I_t^{Disch.} \le 1 \tag{12}$$

$$E_t = E_{t-1} + \eta^{Ch.} P_t^{Ch.} - \frac{1}{\eta^{Disch.}} P_t^{Disch.} \tag{13}$$

$$E_1 = E_T \tag{14}$$

$$E^{\min} \le E_t \le E^{\max} \tag{15}$$

$$\theta_t^{in} = \theta_{t-1}^{in} + \mu\left(\theta_t^{out} - \theta_{t-1}^{in}\right) - \psi P_t^{D,HVAC} \Delta t \tag{16}$$

$$\theta^{\min} \le \theta_t^{in} \le \theta^{\max} \tag{17}$$

$$\theta_1^{in} = \theta_{initial}^{in} \tag{18}$$

$$P_t^{D,HVAC} = \left[0.2\delta_t^{(1)} + 0.4\delta_t^{(2)} + 0.6\delta_t^{(3)} + 0.8\delta_t^{(4)} + \delta_t^{(5)}\right] P^{HVAC} \tag{19}$$

$$\delta_t^{(1)} + \delta_t^{(2)} + \delta_t^{(3)} + \delta_t^{(4)} + \delta_t^{(5)} \le 1 \tag{20}$$

$$P_t^{G2H} = P_t^{D,Fix} + P_t^{D,Shitf} + P_t^{D,HVAC} + \left[P_t^{Ch.} - P_t^{Disch.}\right] \tag{21}$$

The optimal scheduling of home appliances at HEMS needs to be managed by the HEMS operator according to the TOU tariff and the preferences of the operator.

The baseline and shifted operating intervals are addressed as binary parameters and binary variables, respectively. For the baseline, the binary string must represent the same interval as the end-user prefers. Therefore binary parameters, $B_{i,t}$ are supposed to be "1" for the predefined intervals and must be "0" for the other time intervals, (2). However, the identical binary variables, $S_{i,t}$, in the case of shiftable loads can be "1" in the acceptable range of operation (3). Equations (4) and (5) are introduced to address the plug-in duration of each shiftable appliance.

It is evident the total number of non-zero binary parameters and binary variables must be equal with the usage duration of the appliances, T_i. Equation (6) deals with the shiftable demand representation considering the total plugged-in status of the shiftable appliances. In order to address the ON and OFF actions, for each shiftable appliance, a simple equality constraint is suggested in (7). By addressing the operation string of the binary variables, the transition states from "0" to "1" and "1" to "0" can provide the turn-on and turn-off actions, respectively.

Equations (8) and (9) represent the shifting the operation duration for the shiftable loads to before and after the baseline intervals, respectively. These equations are provided according to the Euclidian distance index. It is evident that for the baseline operations, the corresponding discomfort index would be zero, while for shifted operations one of the positive variables would be non-zero.

Equations (10)-(15) have been considered for electrical energy storage (EES) devices. The more details of such constraints are available in [16]–[19].

The inverter-based HVAC system constraints are addressed in (16)-(20).

Equation (16) states the dynamic indoor temperature constraints considering the effects of outdoor temperature, θ_t^{out}, the insulation effects, μ, and the thermal coefficient of building, ψ, and the HVAC power consumption [20].

The dead band for convenience temperature is provided by (17), while (18) is addressing the initial indoor temperature at the beginning of the scheduling problem. The exact power consumed by the inverter-based HVAC system is modelled in (19). The inverter-based HVAC can be operated at different levels with respect to the rated power. It is noteworthy that at each time interval the inverter-based HVAC system can only operate at one of the operating range if the HVAC system is in ON mode (20) [21].

Equation (21) is related to the entire power consumed by the end-user at each time interval considering the electricity consumed by fix, controllable and HVAC system as well as the net power consumed by the electrical energy storage system.

The mathematical formulation in this section is provided in the standard MILP optimization problem and it can be easily solved by CPLEX solver. The simulation results are addressed in the next section considering the impacts of inverter-based HVAC system and other home appliances.

IV. Simulation Results

This section provides the materials for HEMS self-scheduling problem for a typical day electricity consumption. The simulation results are obtained for different case studies considering the impacts of electrical energy storage and demand response program (DRP). It is noteworthy that the time slots in this study are supposed to be in 30 minutes. The consequent data are provided based on 30-min time slots.

The fix and controllable load specifics are provided in Fig. 2 and Table I, respectively. The TOU tariff is illustrated in Fig. 3 and the specific features of the inverter-based HVAC system and the EES system are provided in Table II and Table III, respectively. The simulation results are obtained by CPLEX solver formulated by IBM and activated through the General Algebraic Modeling System (GAMS).

In order to validate the HEMS self-scheduling problem, four different scenarios have been introduced in this section. The impacts of DRP and EES have been studied on the self-scheduling problem. The HEMS self-scheduling problem is aiming at minimizing the electricity bills. The simulation results for the case studies are provided in Table IV.

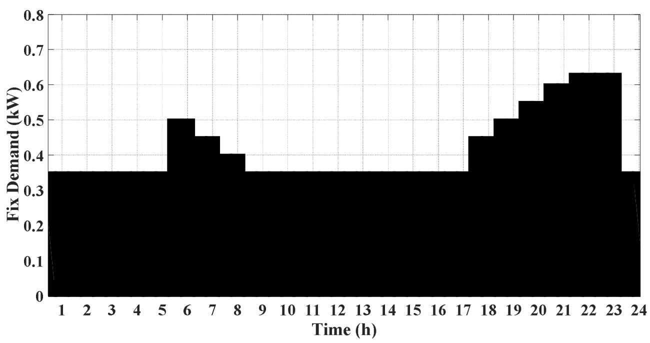

Fig. 2. The daily fix demand of the residential home

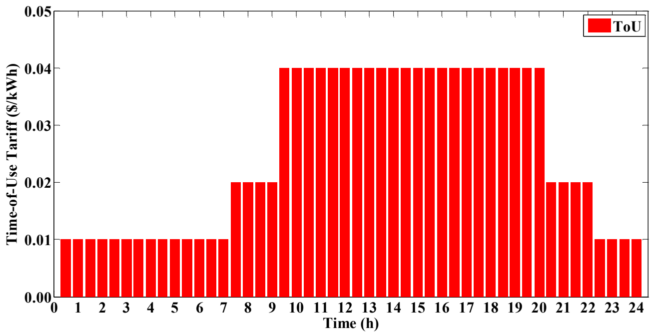

Fig. 3. Typical Time-of-Use tariff in this study [11].

TABLE I. The Specifications of The Controllable Loads

Appliances	P_i(kW)	T_i	LB_b	UB_b	LB_s	UB_s
Dishwasher	2.5	4	19	22	15	33
Washing Machine	3.0	3	19	21	16	23
Spin Dryer	2.5	2	27	28	25	35
Cooker Hub	3.0	1	17	17	16	17
Cooker Oven	5.0	1	37	37	36	37
Microwave	1.7	1	17	17	16	17
Laptop	0.1	4	37	40	33	47
Desktop Computer	0.3	6	37	42	31	47
Vacuum Cleaner	1.2	1	19	19	18	33
Electric Vehicle	3.5	6	37	42	31	47

TABLE II. The Technical Parameters of The EES System

E^{max} (kWh)	E^{min} (kWh)	E^{0} (kWh)	$P^{Ch.,max}$ (kW)	$P^{Disch.,max}$ (kW)	$\eta^{Ch.}$ -	$\eta^{Disch.}$ -
4.0	0.35	2.0	0.5	0.5	0.95	0.90

TABLE III. The Parameters of The HVAC System

θ^{max} (□)	θ^{min} (□)	θ^{0} (□)	μ -	ψ (□/kWh)	P^{HVAC} (kW)
80	65	73	0.9	5.5	2.5

TABLE IV. Daily Bills Assessment for Different Case Studies

Daily Bill	Without EES		With EES	
	Baseline	DRP	Baseline	DRP
HEMS	1.782 $	1.366 $	1.736 $	1.320 $

In the DRP adopted case, the penalty factor regarding the discomfort index, ω, is considered to be zero, while for the baseline, the penalty factor is supposed to be high enough to force the optimization model to set the binary decision variable corresponding to the controllable loads as the baseline plugging in time intervals. In other words, the preferences of the consumer have a high priority rather than bill reduction. The simulation results confirm that the effectiveness of investigation on the DRP results in considerable bill reduction compared with the installation and utilization of the EES system. Moreover, in this study, the operation cost of the EES system and the associated degradation costs of EES are disregarded.

Fig. 4 illustrate the overall power consumption for all case studies, while the indoor temperature control strategy using HVAC utilization is depicted in Fig. 5. The outdoor temperature is depicted in Fig.5, as well.

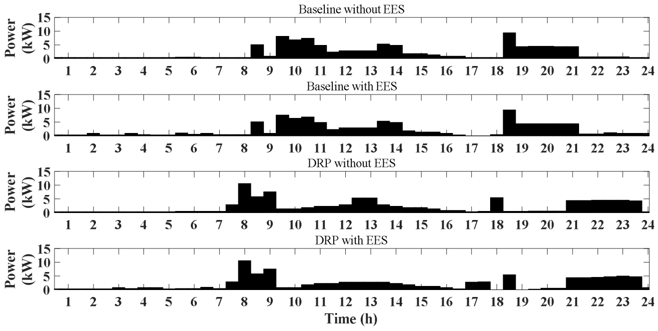

Fig. 4. The daily consumption patterns for different case studies.

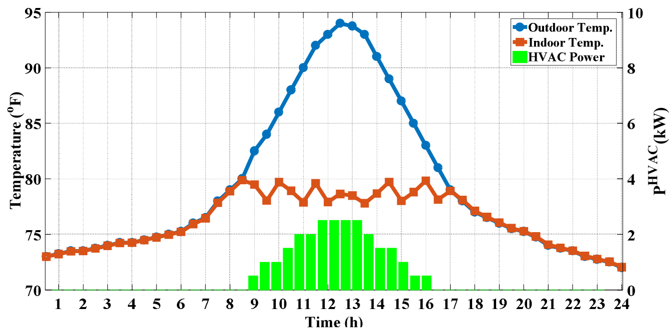

Fig. 5. The daily indoor temperature control by HVAC system.

V. Conclusion Remarks

This paper presents a self-scheduling framework for smart homes considering different types of home appliances. The proposed model is addressed in a standard MILP optimization problem aiming at minimization of the electricity bill while the preferences of the end-users have been definitely met for both controllable and interruptible loads. The inverter-based HVAC system is modelled as an interruptible load and the main functionality of this system is maintaining the indoor temperature in a predefined range. The TOU tariff is applied for the electricity bill assessment and the corresponding impacts of the TOU tariff on electricity bill have been investigated in this paper. In order to reduce the electricity bills, three strategies have been evaluated. In the baseline case study, there is no tendency to shifting the plugging in time and the HEMS hasn't any storage system. In the second case, the effects of the EES system on bill reduction is investigated. In addition, the impacts of EES and DRP are assessed in two different case studies to illustrate the effectiveness of EES and DRP on electricity bill reduction. The simulation results confirm that the TOU tariff can effectively provide considerable insights for the consumers to manage their consumptions to reduce the electricity bills in the presence of HEMS. Besides, the DRP results in a reasonable cost reduction compared with the EES system. It is evident that when both features of the EES and DRP are considered, the electricity bill will be considerably reduced.

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