A Home Energy Management System using an Evolutionary Algorithm

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Abstract— In this research, a home energy management system (HEMS), has been designed where we have first proposed a system model and after that a mathematical formulation for our complete system. We have used GA to optimize the operating time of various home appliances in order to reduce the energy cost and flatten the PAR. In this research, we have used the RTP along with IBR to add flexibility into energy cost. The focus of this research work is to reduce the electricity cost while also considering user comfort. This research model has been tested on three different users having 10, 15 and 20 appliances for simulation purpose. Simulation results show that HEMS model significantly reduces energy cost while also considering user comfort. HEMS controller for the optimum control of home appliances also has designed where a user can be able to monitor the power consumption and energy cost.

Index Terms— Smart grid, energy management system, Demand side management, Genetic Algorithm, real time pricing, inclining block rate, energy management controller.

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1 INTRODUCTION

TODAY'S conventional grid is over 100 years old and based on outdated technologies, when there is no communication infrastructure available. These systems are unable to withstand the growing demand caused by modern development and increased population. This causes a lot of problems like power outages, lack of reliability, technical and non-technical losses, consumer's dissatisfaction, environmental issues etc. as they are operating beyond their lifetime. Higher quality, reliability, and efficiency of energy is the demand of the customers nowadays. To cope with the current demand, the electric power industry needs to be transformed which brings the idea of the smart grid (SG).

A smart grid (SG) integrates modern digital technology with the existing grid system, to optimize energy losses, establish two-way communication, and enhance customer satisfaction by providing them with detailed information on various parameters such as pricing, load consumption, and others. Using this information electricity consumers can change the traditional usage styles and participate in the network operation actively. Relation between Supply and Demand are more precisely represented by dynamic pricing rather than flat pricing schemes. Dynamic pricing comprises of inclined block rate (IBR), time of use (TOU), critical peak pricing (CPP), and real-time pricing (RTP) etc. They encourage and motivate the users to move high load appliances from peak to off peak hours. This shift minimizes the electricity cost and reduces PAR. RTP scheme is more effective as compared to all other pricing schemes mentioned above for electricity market [1]. With the knowledge about flexible pricing schemes, users can now decide how to minimize energy costs and fulfil their preferences for different appliances. This has two-way advantage. The user can reduce his energy bill by using flexible appliances in off peak hours. In addition, this benefits the utilities as demand to generate more power in peak hours is greatly reduced.

To optimize the scheduling and shifting of home appliance according to user needs and comfort automatically, HEMS are used. The process of observing, controlling and conserving electricity usage is termed as energy management or home energy management system. An HEMS solution provides knowledge about energy consumption, pricing information and proposal to shrink energy use [2]. The energy management techniques manage the household loads according to the preset priorities so that the user comfort level is achieved in addition to lowering the electricity cost, eventually reducing peak to average power ratio (PAR). [3].

In past, most HEMS programs focused on the energy scheduling to minimize the total cost and to reduce the peak to average ratio (PAR) and have a very less impact on user comfort [4]. Recent studies about HEMS programs reveals that the interest of users gives more importance in

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reducing their electricity bills without losing user comfort [5]. Flattening PAR graph produces stability between the generation and demand, hence reducing the need for supplementary power plants. These supplementary power plants are mostly based on fossil fuels and hence the HEMS indirectly lower the greenhouse gases in the environment [6]. In [7], the authors schedule the power usage for both interruptible and non-interruptible loads so that the electricity cost is reduced; however, peak power demands may emerge when the electricity price is low. While in [8], Author has suggested that a new parameter that he calls tolerance value can be introduced to minimize the energy cost. This parameter acts a measure of flexibility, a certain user wants to assign to each appliance for its operating time. This way they introduced a system that optimizes the appliance operating time within the set limits to avoid power peaking. This reduces the user comfort and forces them to think about additional factors. This however has a benefit that the user can now assign importance to each appliance. In [9], Author implemented an algorithm to reduce costs, energy consumption and PAR as well, while keeping energy consumption profiles confidential for users. The drawback with this approach is ignorance of user comfort.

In [10] day-ahead pricing scheme is used, where the price of the electricity for the day is determined on the previous day. Authors formulate the problem of appliances scheduling as optimization problem. In this problem cost of total bill that user pay is minimized while ignoring the user preference in terms of ideal start times and ideal operating modes. The focus of authors in [11] is on developing a HEMS for smart homes. A Multi Agent System (MAS) is proposed in this work. It helps to handle the usage of surplus power when supply is greater than demand and vice versa. However, in this work the authors did not consider any scheduling technique for their model. Moreover, the problem of peak formation and user comfort are also neglected. For minimizing cost and energy consumption mixed integer linear programming, mixed integer nonlinear programming and convex programming are used in [12] [13] [14]. However, the techniques discussed have a drawback. They failed to converge data in case of large number of appliances. To take care of this problem certain meta-heuristic optimization techniques can also be employed. For example, in [15] genetic algorithm (GA) have been used to enhance the performance of smart grid.

Bee colony optimization (BCO) has been shown to perform slower in high dimensional problems by authors in [16] and has also shown convergence issues in the mentioned article. The author also concludes that Genetic algorithms performs faster convergence as compared with evolutionary programming (EP), PSO and BCO algorithms. However, the authors did not consider consumers demand in this work. Authors in [17] comparatively evaluate the performance of home energy management controller (EMC) which is designed by using three algorithms named: ant colony optimization (ACO), BPSO and genetic algorithm (GA). In this research work, objective function is formulated by using multiple knapsack problem. The model of EMC has been designed for the energy management of residential system to avoid the formation of peaks. Moreover, according to the consumption pattern and TOU, appliances have been classified into three categories. Later, it is mentioned that this model is designed for three types of users in residential area. This categorization is done based on their energy consumption pattern. The main objectives of this paper include the minimization of PAR, electricity bill, execution time and maximization of user comfort level. In this work, combined model of inclined block rate (IBR) and TOU are used for energy pricing. It has been concluded from the results that the proposed EMC model works more efficiently with GA as compared to the other two heuristic algorithms for the reduction of electricity bill and minimizing PAR while maximizing user comfort level. The execution time of this model using GA is less than the execution time of EMC models using other two algorithms. Based on these reasons genetic algorithm has been chosen as a preferred optimization tool for this research work.

In this research article, we have considered all the major home appliances for cost minimization while taking care of user comfort. The real-time pricing scheme has been considered which is more flexible than other pricing schemes available in the market. If a user schedules most of his home appliances to run in off peak hours then there might be a chance that peaks may occur in these hours which is also not suitable for the system. These peaks are known as Rebound peaks. Therefore, we have combined RTP with IBR. If power consumption is more than that capacity limit than users have pay an extra mobile phones. Load tariff profile can be obtained from utility data center. Smart meter is capable of informing energy consumption pattern of the consumer to the supplier. The scenario is show in Fig. 1. Then we present an approach to schedule the home appliances for the purpose of reducing cost. Appliances will be scheduled in off peak hours so that, we can reduce electricity consumption cost of a residential user. To ensure the consumer satisfaction appliances will be scheduled according to consumer's preferred time. We will further see the reduction in cost with the impact of all the other loads at home.

2 SYSTEM MODEL

In our proposed model, we suppose that every user is equipped with smart meter which is a bridging device between the utility and the consumer and with home energy management system (HEMS). Through HEMS user can able to see the electricity pricing rate and schedule home loads as per his preference and living standard. Scheduling is possible through Energy management controller (EMC) which is a part of HEMS that is installed inside the home. Communication of home appliances with EMC is possible through home area network (HAN) and utility will share their pricing information by using wide area network (WAN) through smart meter. HEMS will optimize the home loads in a best way possible by using the pricing information provided the utility company and the home loads scheduler provided by the user. The basic architecture of HEMS is shown in Fig 1.

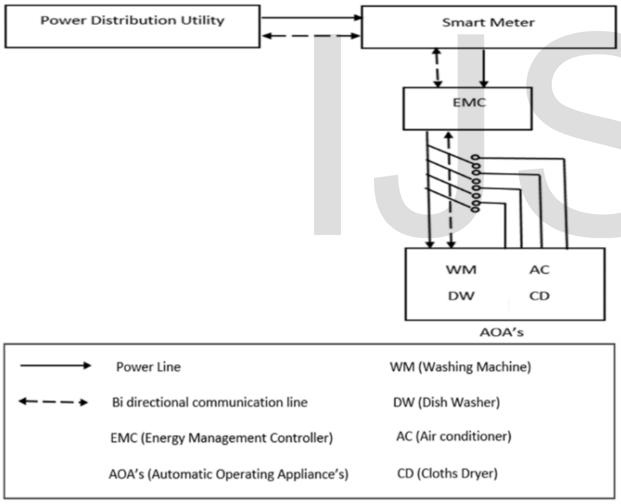


Figure 1: System model of HEMS

MATHEMATICAL FORMULATION

In our research model, user can schedule home appliances in 24 hours scheduling horizon, i.e. single day. Which can be represented as:

$$t \in T = \{1,2,\dots.,24\} \tag{1}$$

1 hour is further divided in to 5 slots of 12 minutes so for 24 hours we have 120 slots in total. This means that user needs to schedule home appliances for at least 12 minutes i.e. 1 slot or multiples of 12 minutes. We can represent the total slots as:

$$g \in G = \{1,2,\dots\dots\dots\dots\dots\dots.,120\} \tag{2}$$

Any appliance in our scenario can be represented as a and we denote the set of all appliances as $\boldsymbol{A}_t$.

$$a \in \boldsymbol{A}_t \tag{3}$$

P_{ca} is the power consumption vector for all 120 slots for all appliances $a \in \boldsymbol{A}_t$ which can be represented as:

$$P_{ca} = \{P_{ca}^{(1)}, P_{ca}^{(2)}, P_{ca}^{(3)}, \dots\dots\dots\dots\dots. P_{ca}^{(120)}\} \tag{4}$$

Where power consumption value of appliance a at g_{th} slot is represented as $P_{ca}^{(g)}$ which is in Kwh. Power consumption for any home appliance a per hour is denoted by y_a. So, the equivalent power consumption in $g^{(th)}$ time slot will be:

$$P_{ca}^{(g)} = \frac{y_a}{5} \tag{5}$$

Total operating time range in which user wants to operate home appliances can be represented as TOT_r. This range consists of two more parameters which are Initial Time represented as I_{ta} and final time represented as F_{ta}. User needs to mention this range for each appliance which needs to be scheduled. Each appliance needs to operate in this range and no appliance can operate beyond this range. So the total operating time range for each appliance can be represented as:

$$\mathrm{TOT} = [I_{ta}, F_{ta}] \tag{6}$$

Also,

$$I_{ta} < F_{ta} \tag{7}$$

User will also need to input total number of slots for which each appliance a will operate which can be represented asTS_a. Starting time of each appliance a isST_a. To start each appliance in its specified time range, two constraints must be followed, which are:

$$ST_a \geq I_{ta} \tag{8}$$

And,

$$ST_a \leq F_{ta} - TS_a + 1 \tag{9}$$

So, total range in which ST_a should start operating can be represented as:

$$ST_a \in [I_{ta}, F_{ta} - TS_a + 1] \tag{10}$$

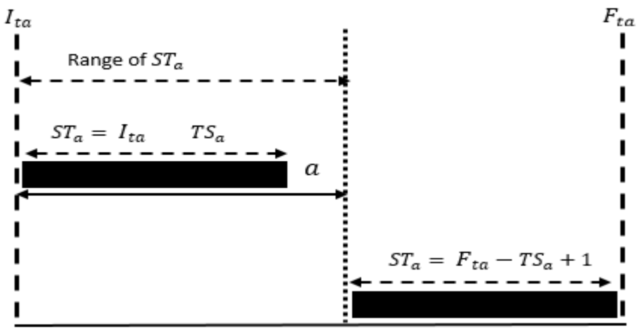


Figure 2: Total operating time range of any appliance a

The graphical representation of total operating time range of each appliance is shown in figure 2. Starting time vector for n appliance can be represented as:

$$[\,ST_1,\ ST_{2,}\ ST_3 \dots\dots\dots\dots\dots\dots\dots ST_n] \tag{11}$$

We can define power consumption vectors for all operated appliances as follow:

$$P_{PWR} = \begin{cases} p \mid p_{ca}^{(g)} = \frac{y_a}{5}, & \forall\, a \in \boldsymbol{A}_t, g \in [ST_a, ST_a + TS_a] \\ p_{ca}^{(g)} = 0, & \forall\, a \in \boldsymbol{A}_t, g \in G \setminus [ST_a, ST_a + TS_a] \end{cases} \tag{12}$$

Here P_{PWR} represents a matrix with rows equal to the number of appliances and each row represents the power schedule of the certain appliance where g represents the column index. The expression $g \in \boldsymbol{G} \setminus [ST_a, ST_a + TS_a]$ means that $g \in G$, but does not include $[ST_a, ST_a + TS_a]$. We can calculate the total power consumption in each time slot as a vector by adding all the values of each column vector represented by $\boldsymbol{P}_{pscd}$.

$$\boldsymbol{P}_{pscd} = \left\{ p_{pscd} \mid p_{pscd}^{(g)} = \sum P_{PWR}{}^{(g)},\ \ \forall\, g \in G \right\} \tag{13}$$

Where $\boldsymbol{P_{PWR}}^{(\boldsymbol{g})}$ represents the $\boldsymbol{g^{th}}$ column of scheduled power consumption vector. For pricing mechanism, we have considered Real time pricing along with Inclining block rate (IBR).
So, we have two pricing constraints which are as follow:

$$prc_g(s_g) = \begin{cases} a_g, if\ 0 \le s_g \le c_g \\ b_g, if\ s_g > c_g \end{cases} \tag{14}$$

Here s_g represents the total power consumption in any g^{th} slot and a_g is the RTP during the g^{th} slot of the given day which will be implemented when the power consumption s_g is lower or equals to the Capacity limit c_g and b_g represents the high pricing rate which will be implemented when the power consumption s_g is greater than capacity limit c_g. So,

$$b_g = \beta * a_g \tag{15}$$

This two-step pricing model has been implemented by British Colombia Hydro [18]. Delay Rate function can be calculated as follow:

$$DTR_a = \frac{ST_a - I_{ta}}{f_{ta} - TS_a - I_{ta} + 1} \tag{16}$$

Delay time rate is the total delay that a user can afford for the operation of its scheduled appliances and user comfort can be defined as how quickly an appliance can operate within a desired time window. So, if a user gives more preference to delay function then there is a chance of increasing electricity bill as our algorithm will start to ignore the cost function and will focus more on minimizing delay rate function to maximize the user comfort. For e.g. if electric kettle(EK) start its operating time from I_{tEK} then it means that DTR_{EK} would be 0 in (18) and user comfort is maximum and if it starts from $f_{tEK} - TS_{EK} + 1$ then the value of DTR_{EK} would be maximum i.e. 1 and user comfort is minimum.
So, it can be represented as:

$$= \begin{cases} 0\ if,\ ST_a = I_{ta} \\ \dfrac{ST_a - I_{ta}}{f_{ta} - TS_a - I_{ta} + 1}\ if\ I_{ta} < ST_a < f_{ta} \\ 1\ if\ ST_a = f_{ta} - TS_a + 1 \end{cases} \tag{17}$$

There is also a delay parameter $\gamma > 1$ which can be expressed as follow:

$$\sum_{a \in \boldsymbol{A}_t} \gamma^{\ DTR_a} \tag{18}$$

Charges of electricity at any slot g can be represented as:

$$prc_g\left(p_{pscd}^{(g)}\right) * p_{pscd}^{(g)} \tag{19}$$

So, for all 120 slots, total electricity charges will be:

$$F_1\left(P_{pscd}\right) = \sum_{g=1}^{120} prc_g\left(p_{pscd}^{(g)}\right) * p_{pscd}^{(g)} \tag{20}$$

Here prc_g represents the electricity price at $g^{(th)}$ slot and $p_{pscd}^{(g)}$ represents the total power consumption at $g^{(th)}$ slot. Delay rate of any appliance a can be represented as D^{DTR_a}
So, for all appliances total delay rate will be:

$$F_2(DTR_a) = \sum_{a \in \boldsymbol{A}_t} \gamma^{DTR_a} \tag{22}$$

Let w_C and w_D are the weights for electricity charges and delay rate function respectively. User will give weightage for both function and then the algorithm will optimize according to user choice. Such that,

$$minimize \quad w_C\ F_1\left(P_{pscd}\right) + w_D\ F_2(DTR_a) \tag{23}$$

$$s.t. \qquad STa \in [I_{ta}, F_{ta} - TS_a + 1]$$

Where sum of $w_C + w_D = 1$
After normalization, our total optimized formula will be:

$$w_C \frac{\sum_{g=1}^{120} prc_g\left(p_{pscd}^{(g)}\right) * p_{pscd}^{(g)}}{\left(\sum_{g=1}^{120} prc_g\left(p_{pscd}^{(g)}\right) * p_{pscd}^{(g)}\right)_{max}} + w_D \frac{\sum_{a \in \boldsymbol{A}_t} \gamma^{DTR_a}}{\left(\sum_{a \in \boldsymbol{A}_t} \gamma^{DTR_a}\right)_{max}} \tag{24}$$

$$\text{s.t.} \qquad STa \in [I_{ta},\ F_{ta} - TS_a + 1]$$

In equation (23) the weights w_C and w_D can be adjusted such that a higher w_C would increase the importance of the cost minimization function and a higher w_D optimizes the fitness function by focusing first on reducing the delay rate function and hence in turn increasing user comfort.

Table 1: List of Appliances

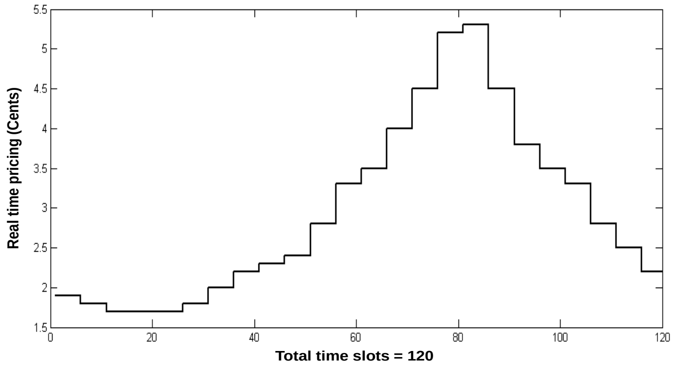
Automatic Operated Appliances	**Operating Time Range (I_{ta} ~ f_{ta})**	**Total Operating slots (TS_a)**	**Power(Kwh)**
Air Conditioner^1	41 ~ 60	5	1
Air Conditioner^2	61 ~ 85	5	1
Air Conditioner^3	86 ~ 120	10	1
Electric Radiator^1	1 ~ 30	5	1.8
Electric Radiator^2	91 ~ 115	10	1.8
Rice Cooker^1	1 ~ 25	2	0.5
Rice Cooker^2	41 ~ 60	2	0.5
Rice Cooker^3	71 ~ 90	2	0.5
Water heater	86 ~ 105	3	1.5
Dishwasher	101 ~ 120	2	0.6
Washing Machine	1 ~ 60	5	0.38
Electric Kettle^1	1 ~ 25	1	1.5
Electric Kettle^2	66 ~ 85	1	1.5
Humidifer^1	1 ~ 30	10	0.05
Humidifer^2	91 ~ 120	10	0.05
Cloth dryer	71 ~ 91	5	0.8

$*^1, *^2, *^3$ means that appliance * operates three times in different operating time range.

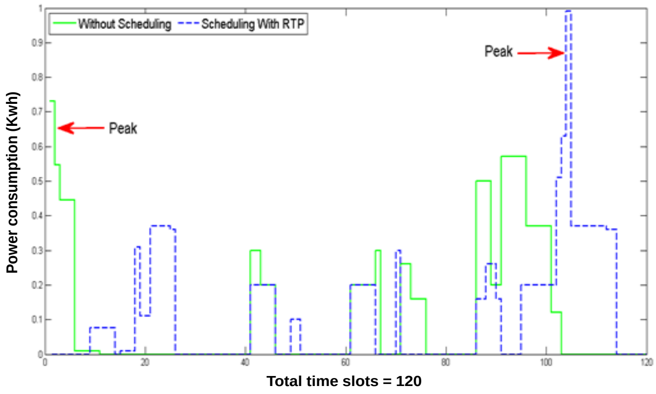
Table 2: GA optimization parameters

Parameters	**Value**
Population Size	100
Selection	Roulette Wheel
Elite Count	2
Mutation	0.20
Cross over	0.80
Stopping Criteria	1000

3 SIMULATION RESULTS



(a)



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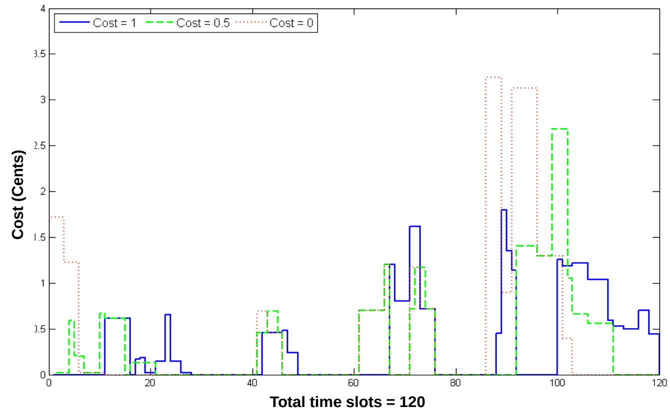

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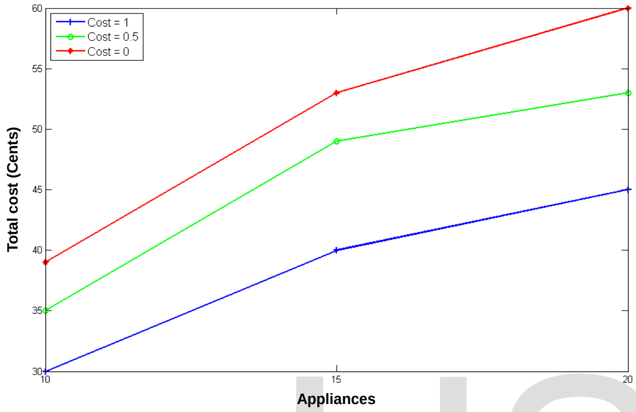
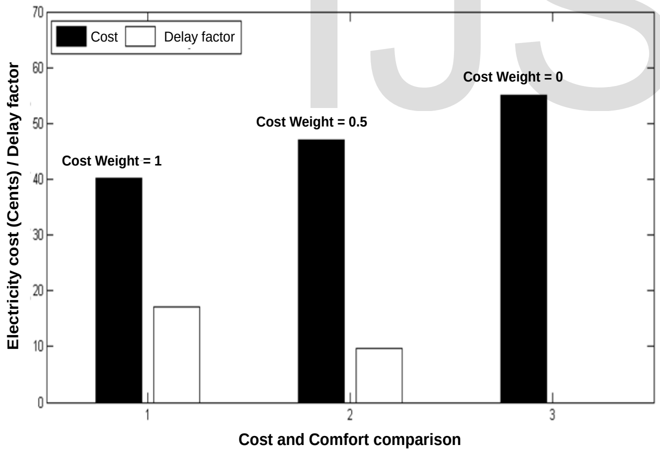


(d)

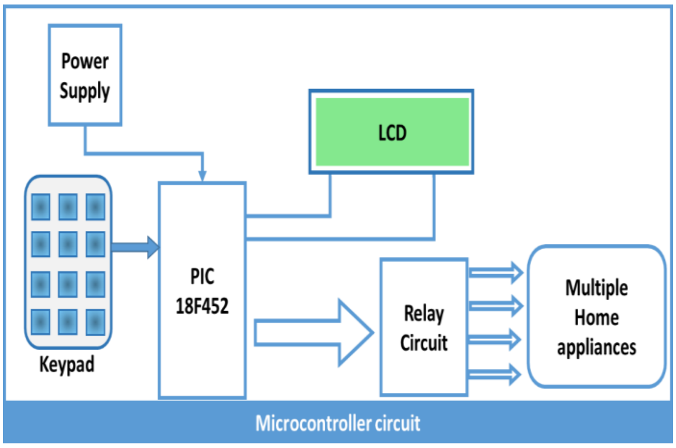


(e)

Fig. 3. (a) Real time pricing (b) Power consumption comparison without IBR (c) Power consumption comparison with IBR by varying cost weightages (d) Total cost by varying appliances. (e) Cost and user comfort comparison. (f) Block diagram of energy management controller. (g) Circuit diagram of energy management controller.

We have taken different home appliances in order to show the superior performance of our proposed system model.

According to the ratio of the two electricity price levels in British Columbia Hydro [18], the value of β in (15) is determined to be 1.4423. Capacity limit value c_g is supposed to be 0.4 and the value of delay parameter γ is 5. List of appliances used for simulation has been shown in Table 1.

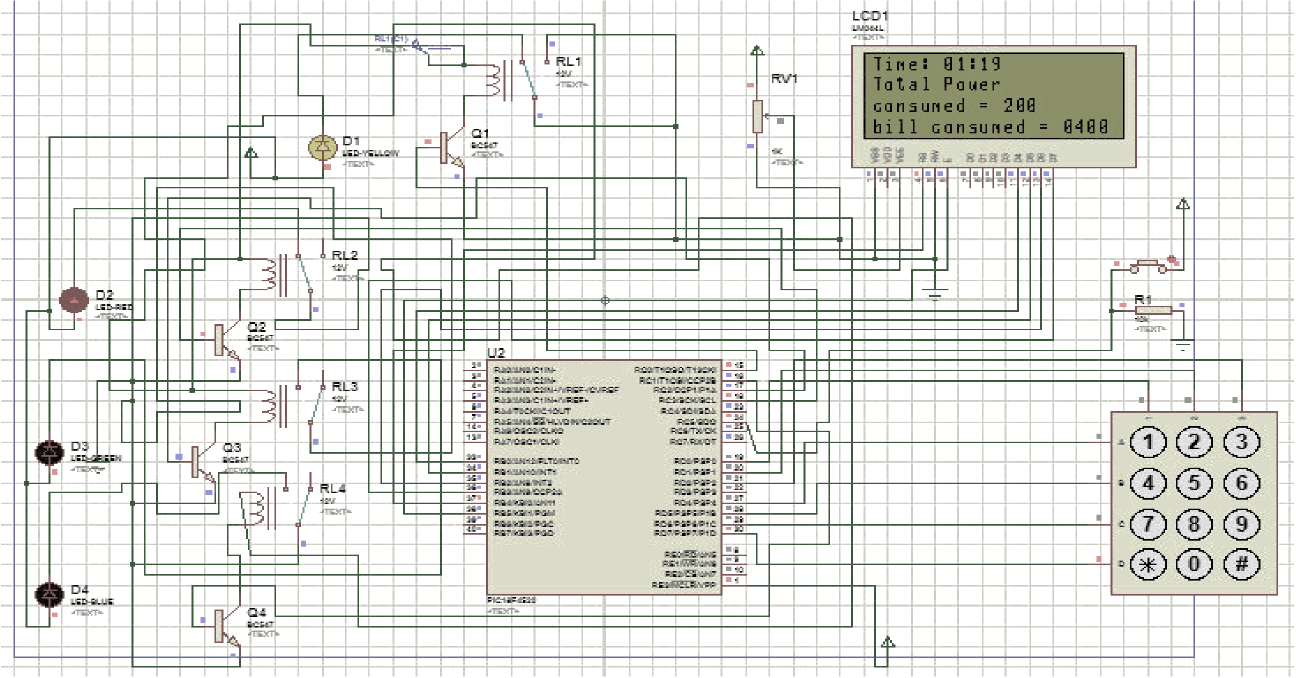


(f)

Parameters used for GA optimization has been shown in Table 2 and MATLAB is used for simulation of the proposed HEMS model. Genetic Algorithm is used to solve optimization problem, Parameters used for optimization are Comparison of power consumption for non-scheduled appliances with scheduled appliances while considering RTP only, has shown in Fig. 3 (b) where large peaks can be seen for both the cases. RTP along with IBR has been implemented in in Fig. 3 (c) in order to reduce the peaks and power consumption that scan be seen by varying cost weightages. Fig. 3 (d) shows the total cost by varying number of appliances and cost weightages for three different users having 10, 15 and 20 appliances. Fig. 3 (e) shows the relation between cost and delay rate function from (25), increasing the cost weightage value will decrease the user comfort as home appliances will take more time to start operating which will eventually increases the delay. If we decrease the cost weightage value then user comfort will start to increase as delay time for appliance operation will decrease.

Based on all the above discussion, an Energy management controller (EMC) has been built that can be seen in a block diagram as shown in fig. 3 (f). PIC 18F452 Microcontroller has been used for controlling and managing home appliances. Coding for PIC 18F452 has been programmed in mikroC programming language. User can input the starting and ending time of each appliance from keypad that has been provided by the MATLAB simulation result after optimization. LCD interface is used for displaying total power consumption and electricity cost consumption.

For appliances security, Relay circuit was used that will operate the desired home appliances. Proteus software is used for making detailed circuit diagram of hardware as shown in Fig. 3 (g)



(g)

4 CONCLUSION

Our main focus in this research work is to reduce electricity bill, discomfort minimization and on minimizing rebound peaks. For this purpose we have used Genetic Algorithm (GA) which is based on a natural evolution process. Through simulation we have presented the usefulness of our model and showed that, if user can shift their load from peak to off peak hours than it can greatly reduce the electricity bill as power consumption in peak hours is quite high as compared to off peak hours.

In order to check the flexibility of our system we have changed the number of appliances and the results are inspiring. At the end we have designed an Energy Management Controller (EMC) and consider all types of loads which are interruptible, non-interruptible and manual loads. Total power consumption of these loads cannot exceed to certain power limit which gives surety of reducing peaks and users will schedule their loads as per their requirement.

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