Demand Side Energy Management using Heuristic Optimization Technique

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Abstract— Electricity demand is increasing and to meet the demand, utilities are increasing the generation capacity. Increase of generation capacity also increases the per unit generation cost. Moreover, in traditional grids consumers are not able to interact dynamically with the grid. To overcome the deficiencies of the traditional power grid the concept of smart grid is proposed. Smart grid is an electricity supply network, integrated with bidirectional communication technology between consumers and utility. Smart grid also offers flexible electricity pricing schemes. Demand side energy management is another one of the most prominent feature of smart grid. In DSM system consumers can control their home loads and operate them during off peak hours, which not only helps the consumers to reduce their electricity bills but also, benefits the utility in terms of reduction of per unit generation cost. In literature, various DSM techniques have been proposed. These techniques mainly focus on reduction in cost by considering only few loads. The impact of manual loads is not included. The main objective of this research work is to develop a DSM model for residential users to reduce the total energy cost by exploiting flexible pricing scheme. The model is based on particle swarm optimization (PSO). In proposed DSM model 16 appliances are categorized into different classes. All classes include different appliances with different operational characteristics. MATLAB is used as a simulation tool to implement this model. Simulation results show that the proposed DSM model minimizes the energy cost by 21.16 percent. Different sets of appliances are used to check the effectiveness of the proposed technique. The reduction in energy cost ranges from 18 to 30 percent.

Index Terms— Demand side management, energy management system, particle swarm optimization, real time pricing, energy management controller

1 INTRODUCTION

THERE have been significant research efforts over the last couple of years to develop efficient DSM/DR strategies in order to achieve the goal of minimizing the consumer's electricity bill. The most important objective of demand side management strategy is to shave the peak loads instead of increasing generation capacity. Peaking power plants generate expensive electricity. Therefore, shifting the demand from peak to off peak hours would reduce electricity bill to be paid by the customers.

Considering the importance of DSM, in [1] the author presents a complete study on DSM/DR and its potential benefits to the utility and the consumers. DSM programs can be classified into two types, individual DSM and cooperative DSM. Cooperative DSM program is applied to a community whereas individual DSM program is applied to the individual user. Author reviewed the advantages and disadvantages of both type of user's interaction. There are some limitation and technical difficulties in implementing the cooperative based optimization and data privacy issues [2]. Home automation is one of the most important aspect of

DSM. Work conducted in [3] presents the application of DSM to reduce the bill of an end user.

The author present DSM mechanism for a building by applying peak clipping method. Peak clipping is a strategy to reduce electricity consumption at the time of peaks. The author suggested the installation of generator set to avoid price penalty from utility which is a costly approach. Residential sector is a major energy consuming entity. Advance metering infrastructure (AMI) is implemented by smart grid in order to predict load in residential areas. In [4] the author presented the DSM model based on AMI. The author mainly discussed the means of communication and data flow between user and utility to manage the loads.

In [5] the author presented a complete comparison of different DSM schemes like optimal residential scheme, game theoretical model and autonomous DSM model. Load scheduling in one of the important feature used in DSM for reduction in consumption cost. For this purpose, loads at home can be categorized into shiftable and nonshiftable. Shiftable loads are the loads which can be shifted anywhere in the time horizon. However, non shiftable loads cannot be shifted [6]. In [7] the author presented an intelligent DSM system which include modern technologies and sensors. In this research work the author improve the traditional DSM technique which considers various factors like environment and load monitoring while optimizing the resources. There are many

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DSM techniques to reduce the energy consumptions, in [8], [9] authors discussed various DSM techniques normally used while implementing DSM programs. These techniques included peak clipping, conservation and load shifting. In [10] the author presented a DSM model that ensures balance in supply and demand. The author presented a program which gives different choices to the user for load management. This model only includes smart appliances. The author further discussed different DSM techniques like peak clipping and valley filling. In [11] the author proposed DSM model using load shifting and load curtailment techniques. In load shifting non-essential appliances can be schedule in off peak hours on the other hand in load curtailment, particular loads are curtailed in order to reduce the peaks. The research work done in [12] also based on load curtailment strategy with smart metering infrastructure (AMI). The author discussed different technologies used for smart meter communication. Further in this strategy loads are curtailed to maintain continuous supply to the customers.

Demand side management (DSM) and demand response (DR) programs have different optimization techniques like mixed integer linear programming, evolutionary algorithms and convex optimization [13]. In [14] author proposed a comparison of different optimization techniques for energy resources in smart home environment. The consumers can minimize their electricity cost by scheduling their intelligent home appliances. Different pricing schemes based and algorithm based home energy management techniques are presented in [15]. In [16] the author proposed a scheduling scheme of home appliances. Appliances are divided into three classes. In each class appliances have different energy consumption and operating time. The focus is on reduction in power consumption and electricity bill, theimpact of manual loads is not included. In [17] the author proposed a discrete time formulation of a home appliances scheduling problem and minimum cut algorithm is used for optimization. Particle swarm optimization (PSO) in one of the robust techniques. In [18] PSO is used to solve DSM problem. The author mainly focused on cost minimization with scheduling, without the involvement of manual loads. In [19] the author designs a controller to manage the domestic loads using combined application of DSM and fuzzy logic. The controller has demand limiter to avoid energy wastage.

Smart grid (SG) provides dynamic pricing schemes for the consumers. In smart grid pricing depends on the time of day. Critical peak pricing (CPP),real time pricing (RTP) and time of use (TOU), and are mostly used. In [20] author used TOU signal for home appliances scheduling problem. Work conducted in [21] proposed home energy management schemes, the focus is on cost reduction, TOU pricing scheme is used. Also in [22], the author discussed various pricing techniques used in home energy management.

Literature review in the previous section is clearly demonstrated that a lot of work has done on DSM and DR. However, the emphasis of the previous research was cost minimization by scheduling only few schedulable appliances. The impact of other loads and randomization of load pattern is not considered. Only scheduling few loads at home cannot minimize the cost significantly. Various optimization techniques have been proposed, but very little work is done on heuristic optimization techniques. The work done in this field and the methodologies used are quite complex.

2 SYSTEM MODEL

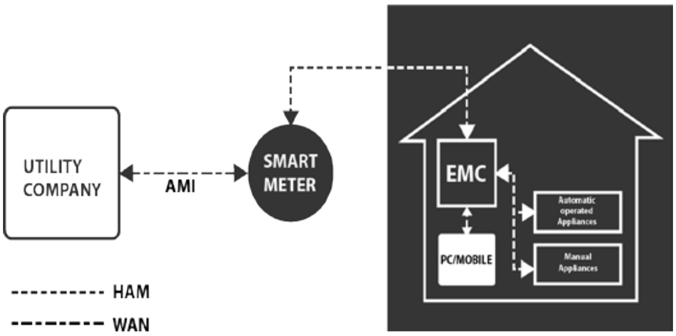


Fig.1 Energy management system in home

Our research work is mainly based on formulating realistic optimization model for DSM. We have considered a scenario of a smart home in which all the house hold appliances are connected through a communication link with an energy management controller (EMC). Communication link can be wired or wireless. EMC sends signal to all appliances via a home area network (HAN).

EMC contains all the data regarding power consumption of each appliance and time of usage. Smart homes are connected with utility through smart meters (AMI). Utility and consumers are connected through a wireless communication link and form a wide area network (WAN). Consumers can see the information like power consumption of house hold appliances, time of use and consumption cost on PCs, tablets or 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.

2.1 LOAD CLASSIFICATION

In our proposed DSM model, electric devices such as home appliances are categorized into four different classes of loads which are given below

Class 1 appliances are the appliances which have low energy consumption but long operating time like lights, fans etc. Class 2 includes those appliances which have high energy consumption and can be operated multiple times like electric stove, televisions etc. In class 3 those appliances are included which operate all day long without interruption like refrigerator, dispenser etc. Finally, in class 4 those appliances are included which have fixed operating time and can be scheduled any time of the day.

The start time and duration of non-schedulable appliances were carefully chosen in such a way that reflects the usage pattern of real life. Appliances are turned on and off randomly during all day. Quantity of some appliances working at a time is randomly chosen e: g in a home at a time one or more fans or one or more lights could be turned on.

There is fixed operational time for appliances of class 4. So, we can schedule these appliances according to the requirement. We are assuming that these appliances are automatic operated appliances which can be scheduled using energy management controller (EMC). To keep the user discomfort with in a limit, appliances are scheduled according to user's preferred time slot window. Some appliances work all day without interruption for example water dispenser, refrigerator etc. These appliances are flexible we can turn them off during peak hours if power consumption of all loads increase from a defined threshold limit value.

2.2MATHEMATICAL FORMULATION

Let **A** denotes the set of appliances of class 1, **B** for class 2, **C** for class 3 and **D** for class 4 [15].

$$A = \{a_1, a_2, a_3 \dots \dots . a_n\} \quad (1)$$
$$B = \{b_1, b_2, b_3 \dots \dots . b_n\} \quad (2)$$
$$C = \{c_1, c_2, c_3 \dots \dots . . c_n\} \quad (3)$$
$$D = \{d_1, d_2, d_3 \dots \dots . d_n\} \quad (4)$$

Where, a $\in A$, $\in B$, $c \in C$ and $d \in D$.

P_A, P_B, P_C, P_D denote the power consuming vectors of appliances of class 1, class 2, class 3 and class 4 respectively.

$$P_A = \{p_{a1}, p_{a2}, p_{a3} \dots \dots p_{an}\} \quad (5)$$
$$P_B = \{p_{b1}, p_{b2}, p_{b3} \dots \dots . p_{bn}\} \quad (6)$$
$$P_C = \{p_{c1}, p_{c4}, p_{c3} \dots \dots . . p_{cn}\} \quad (7)$$
$$P_D = \{p_{d1}, p_{d2}, p_{d3} \dots \dots . p_{dn}\} \quad (8)$$

Where, p_{ai}, p_{bi}, p_{ci} and p_{di} are power consumptions in watts for appliances of each class.

Energy consumption vector for appliances of class 1 can be written as

$$W_{i,n} = \begin{cases} \frac{p_{ai}}{\mu}, & \forall a \in A, n \in N \text{ and } \tau_s \le n \le \tau_e \\ 0, & otherwise \end{cases} \quad (9)$$

Where μ=1000 to convert wattage to kW. Starting time and ending time of class 1 appliances are random. Quantity is also random. At a time,n more than one devices can be turned on.

$$Q_{a,ON}^n \ge 1 \quad \forall n \quad (10)$$

Sum of all the powers of class1 appliances at time slot t_n.

$$\omega_a^n = \sum_{i=1}^{A} (W_{i,n}) \quad \forall n \quad (11)$$

Energy consumption vector in kWh for appliances in class 1 is given by

$$\omega_a^n = \{\omega_{a1}^1, \omega_{a2}^2, \omega_{a3}^3 \dots \dots . \omega_A^N\} \quad (12)$$

Where, ω_{ai}^n energy consumption of appliance ai in n^{th} hour.

For appliances in class 2

$$X_{j,n} = \begin{cases} \frac{p_{bj}}{\mu}, & \forall b \in B, n \in N \text{ and } \tau_s \le n \le \tau_e \\ 0, & otherwise \end{cases} \quad (13)$$

The starting and ending time of the devices in class 2 is also random. The quantity of working appliances can be more than one.

$$Q_{b,ON}^n \ge 1 \quad \forall n \quad (14)$$

Sum of all the powers of class 2 appliances at time slot t_n can be given as

$$\psi_B^n = \sum_{j=1}^{B} (X_{j,n}) \quad \forall n \quad (15)$$

Energy consumption vector in kWh for appliances in class 2 is shown in expression 4.16

$$\psi_b^n = \{\psi_{b1}^1, \psi_{b2}^2, \psi_{b3}^3 \dots \dots . \psi_B^N\} \quad (16)$$

Where, ψ_{bj}^H energy consumption of appliance bj in n^{th} hour.

For appliances in class 3

$$Y_{k,n} = \frac{p_{ck}}{\mu} \quad \forall c \in C, n \in N \quad (17)$$

Appliances in this class remain on all day. But the appliances in this class have flexibility. They can be turned off any time of the day if the overall consumption of power of all the working appliances is greater than a threshold limit.

$$Y_{k,n} = \begin{cases} Y_{k,n}, & \lambda < \delta, \forall c \in C \\ 0, & \lambda > \delta, \forall c \in C \end{cases} \tag{18}$$

Where, λ is sum of all the power of all kind of loads at home

$$\lambda = \sum_{s=1}^{S} (\omega, \psi, \varepsilon, \Delta) \tag{19}$$

Where, S and δ are total number of all kinds of appliances working and threshold value respectively.
Sum of all the powers of class 3 appliances at time slot t_n.

$$\varepsilon_C^n = \sum_{k=1}^{C} (Y_{k,n}) \qquad \forall n \tag{20}$$

Energy consumption vector in kWh is given by

$$\varepsilon_C^n = \{\varepsilon_{c1}^1, \varepsilon_{c2}^2, \varepsilon_{c3}^3 \ldots \ldots \varepsilon_{cn}^N\} \tag{21}$$

Where, ε_{ck}^H energy consumption of appliance ck in n^{th} hour.
For appliances in class 4

$$Z_{l,n} = \begin{cases} \frac{p_{dl}}{\mu}, & \forall d \in D, n \in N[T, T + OT] \\ 0, & \forall d \in D, n \in N \backslash [T, T + OT] \end{cases} \tag{22}$$

Where,

$$T \in [\alpha_s, \alpha_e - OT] \tag{23}$$

α_s , α_e are starting time and ending time given by the user to schedule the appliances and OT is operating time. Sum of all the powers of class 4 appliances at time slot t_n.

$$\Delta_D^n = \sum_{l=1}^{D} (Z_{l,n}) \qquad \forall n \tag{24}$$

Energy consumption vector in kWh is given by

$$\Delta_D^n = \{\Delta_{d1}^1, \Delta_{d2}^2, \Delta_{d3}^3 \ldots \ldots \Delta_{dn}^N\} \tag{25}$$

Where, Δ_{dl}^H energy consumption of appliance dl in n^{th} hour. Let Prc be the per unit cost in the time slot t_n. The aim is to reduce the overall electricity consumption cost of a residential user while considering user's preferred time. To achieve that the optimization problem for DSM is formulated as [39]:

$$min \sum_{n=1}^{N} \left(\sum_{i=1}^{A} (W_{a,n}) Prc(\gamma) + \sum_{i=1}^{B} (X_{b,n}) Prc(\gamma) + \sum_{i=1}^{C} (Y_{c,n}) Prc(\gamma) + \sum_{i=1}^{D} (Z_{d,n}) Prc(\gamma) \right) \tag{26}$$

Where, $W_{a,n} \in (4.9), X_{b,n} \in (4.14), Y_{c,n} \in (4.20)$ and $Z_{d,n} \in (4.24)$. Or,

$$min \sum_{n=1}^{N} (\omega Prc(\gamma) + \psi Prc(\gamma) + \varepsilon Prc(\gamma) + \Delta Prc(\gamma)) \tag{27}$$

Subjected to (18), (23).

3 PARTICLE SWARM OPTIMIZATION

Particle swarm optimization (PSO) stochastic and population based algorithm. It was introduced by Eberhard and Kennedy in 1995. It is inspired from the social behavior and dynamic movement with communication of bird, insects and fish. Each particle in the swarm is represented by a vector in search space.
Particle swarm optimization (PSO) consists of 3 steps

1. Population initialization
2. Fitness function evaluation
3. Updating positions and velocities w.r.t to previous best and global best
4. Terminate on some stopping criteria
5. Go back to step 2

All particles are randomly initialized and distributed in the search space. Each particle is moving in search space with a velocity and altering its position. Using particle fitness values, velocities of all particles are updating at time +1 . The fitness function value of a particle controls the best position of each particle over time, p^i, and also best global value in the current swarm, p_j^g . The velocity update formula uses these two values of particle's best position, p^i and best position of swarm, p_j^g along with the effect of current velocity, v_j^i, to provide the search path, v_{j+1}^i for the next iteration. Equation 3.1 shows the velocity update formula

$$v_{j+1}^i = wv_j^i + c_1 rand(p^i - x_j^i) + c_2 rand(p_j^g - x_j^i) \tag{28}$$

Initial position of the particle is represented by x_k^i, w is the inertial factor ranges from 0.4 to 1.4. c_1 and c_2 are accelerating coefficients range from 1.5 to 2 and 2 to 2.5 respectively.

Position also needs to be updated with each iteration, position update formula is given in equation 3.2.

$$x_{j+1}^{i} = x_{j}^{i} + v_{j+1}^{i} \qquad (29)$$

Velocities, positions are keep on updating with fitness calculations until a preferred stopping criteria is met [18].

4 PARAMETER SETUP

In the proposed model, we are taking 16 household appliances. Appliances are categorized into four classes. Appliances in class 1 have long duty cycle but power consumption is low. We are assuming that each appliance has a starting time and an ending time. Appliance can be turned ON and OFF with no fixed pattern in the given window of starting and ending time. The quantity of operational appliances of this class also vary

TABLE 1
CLASS 1 APPLINACES AND PARAMETERS

Appliance	Power	Start time	Ending time	Quantity
Lights	43	5 -8 PM	10 -12 PM	5
Laptops	45	11AM-3 PM	5 - 9 PM	3
fans	40	6 -9 AM	6 -8 PM	4
Wi-Fi router	6	1:00 AM	12:00AM	1

TABLE 2
CLASS 2 APPLINACES AND PARAMETERS

Appliance	Power	Start time	Ending time	Quantity
Electric Stove	1200	7-8AM & 12AM-1PM & 5-6PM	10AM-11PM & 3-4PM & 9-10PM	1
TV	100	6-9AM& 4-8PM	12-2PM& 8-11PM	3
Air Conditioner	800	2PM	6PM	1

TABLE 3
CLASS 3 APPLINACES AND PARAMETERS

Appliance	Power	Duration of operation
Refrigerator	1200	24 Hrs
Dispenser	80	24 Hrs
Aquarium	70	24 Hrs

TABLE 4
CLASS 4 APPLINACES AND PARAMETERS

Appliance	Power	Starting time	Ending time	Operating Time
Electric radiator	500	12PM	12AM	1 Hr
Washing Machine	380	1AM	6AM	2 Hrs
Clothe dryer	800	6AM	12PM	1 Hr
Dish washer	600	6PM	12AM	1 Hr
Humidifier	50	1AM	11PM	1 Hr
Water pump	1900	1AM	11PM	1 Hr

with respect to user's requirement. Parameters for appliances of this class is shown in Table I.
Appliances in class 2 have smaller duty cycle but large power consumption. The appliances in this category can be turned ON and OFF for more than one times. Operating time and quantity is also random. The parameters of appliances in this category is shown in Table 2.
Appliances in class 3 remain ON all day. But these appliances have flexibility. We can turn them OFF during peak times. In our approach, we are turning these appliances OFF when total power consumption of all the household loads increase a specific threshold limit. Appliances and their parameters are shown in Table 3.
Appliances in class 4 have fixed duration of operation. We can schedule them anytime in the time horizon.

TABLE 5
PARAMETERS USED FOR PSO

Parameter	Value
Swarm size	300
Self-adjustment, c_1	2
Social-adjustment, c_2	2
Inertia range w_{min}, w_{max}	0.4-0.9
Max iteration	100
Threshold limit	3 kWh

In our approach, we are taking user's preferred time. Appliances in this category will remain ON until they complete their operation. Optimizer will find the optimal operating time of these appliances. Appliances and their parameters are shown in Table 4.

5 SIMULATION RESULTS

MATLAB is used for simulation of the proposed DSM model. Particle swarm optimization is used to solve optimization problem, Parameters used for optimization are given in Table 5.
We used 16 home appliances, appliances of class 1 are base loads which consume very less electricity. Appliances of this class turning ON and OFF without any fixed pattern and random in quantity. Similarly, appliances in class 2 are also turning ON and OFF without any fixed pattern. But the appliances in class 3 have flexibility, they can be turn OFF any time during operation. Appliances of class 4 have fixed operating time so they can be scheduled.
For the sake of comparison, we are turning ON the schedulable appliances in a time given range which is not optimized. In our proposed approach cost reduction by

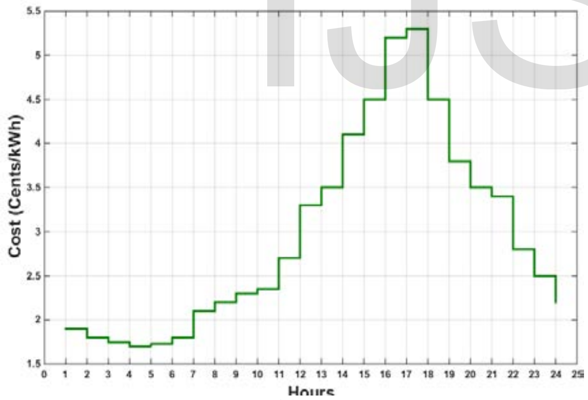
scheduling appliances is 50%. With the impact of all loads at home the overall cost reduction is 21.16%.
The pricing signal we used is shown in

TABLE 6
APPLIANCES AND SHEDULE

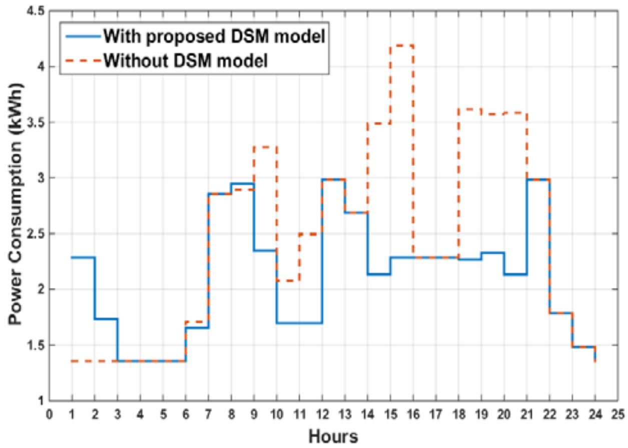
No. of Manual appliances	No. of scheduled appliances	No. of appliances interruptible	Peak without DSM (kW)	Peak with DSM (kW)	Reduction in Cost (%)	TL (kWh)
4	5	3	4.6	2.9	8.61	3
4	6	3	3.8	2.6	12.13	3
4	6	2	4.6	3.1	12.43	3
5	6	3	5.3	2.9	20.32	3

5.1IMPACT OF CHANGE IN THRESHOLD LIMIT

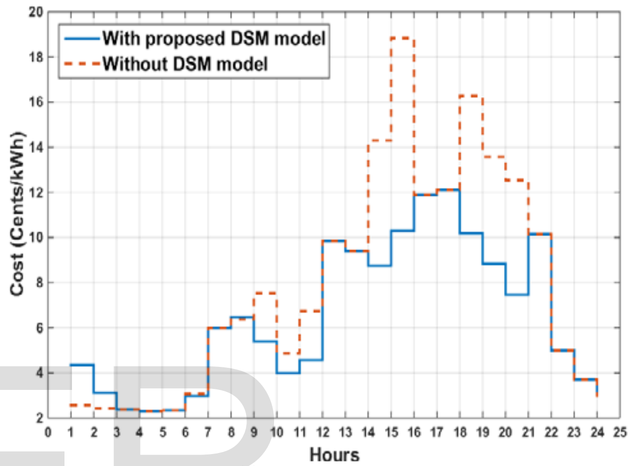
Decrease in threshold limit may increase the load interruptions. There are some loads which cannot be remained off for a long period of time. Therefore, it needs to be set according to power demand.
There are 3 appliances in class 4, aquarium, dispenser, and refrigerator. There is a scenario in which user does not agree to interrupt his/her refrigerator. But user agrees to interrupt his/her air conditioner during peak hours. At the same time user agrees to bring down the threshold limit 3kWh to 2.8kWh. After applying our proposed DSM model, the reduction in cost is 15.72%.



(a)



(b)



(c)

Fig. 2. (a) Real time price profile (b) Power consumption comparison with threshold limit (c) Cost minimization comparison with threshold limit

Fig. 2(a) Energy consumption with proposed DSM model and without DSM proposed model is shown in Fig. 2(b). Total cost reduction is shown in Fig. 2(c).

5.2COST COMPARISON BETWEEN DIFFERENT USERS

We applied our proposed DSM model to different users. Every user has different set of appliances at home. Set of appliances and reduction in cost of different users are shown in table 6.
Load pattern of each user is not fixed so peak demand of the users is also different. Table VI shows that there is significant reduction of peaks after applying proposed DSM technique.
Reduction is peaks also reduces the peak to average ratio. 50.88, 22.00, 34.98 and 49.97 are the percentage reduction of peak to average ratio of user 1, 2, 3 and 4 respectively.
The overall cost reduction comparison of different users is shown in Fig. 3.

TABLE 6
REDUCTION IN COST OF DIFFERENT USERS

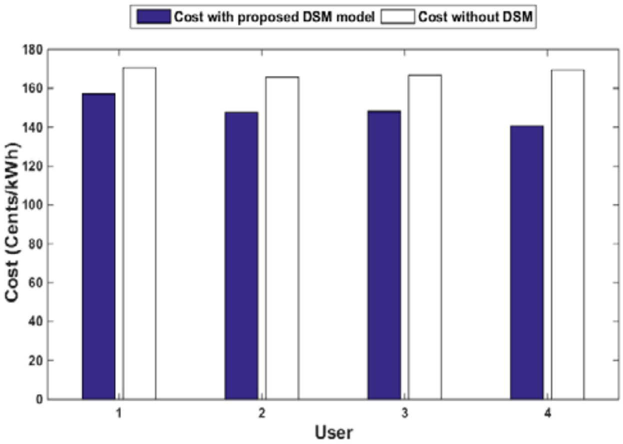


Fig. 3. Cost reduction comparison of different users

6 CONCLUSION

DSM has potential to benefit both utility and consumers. Our aim was to minimize the consumption cost with the impact of all loads working at home. We proposed a particle
swarm optimization (PSO) based DSM model. We introduced a concept of threshold limit for peak clipping i.e. if total consumption crosses that limit a particular load on
which user agrees with utility will be curtailed. Simulation results show the effectiveness of our proposed DSM model. During peak hours, the electricity prices are very high if users schedule their home appliances in off peak hours and set a threshold limit for load curtailment, they can considerably minimize their overall energy expenses.

Finally, we implemented and designed energy management controller (EMC) for experimental demonstration. With the emergence of smart grid and smart home appliances energy management controller (EMC) is being a necessity for every consumer. Consumer can effectively manage and schedule their appliances in off peak hours which will significantly reduce their average power consumption cost.

Our proposed DSM model can be extended in many ways. Model can be modified and redesigned by adding solar panels at home. Solar installation is costly but it can considerably decrease overall consumption cost. New pricing schemes can be used which are offered by smart grid.

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