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Mathematical Modelling Based Demand Response Analysis of Major Household Appliances

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***Abstract:** This paper discusses the power consumption profile and demand response potential of home appliances in India. It includes WH (water heater), HVAC (Heating, ventilation, and air conditioning) system, cloth dryer, washing machine and critical appliances. Mathematical module of these appliances have been developed. Simulation results show that the water heater has highest demand response potential followed by cloth dryer, HVAC, and washing machine. Consumer life style and comfort is affected if DR (Demand Response) is applied in critical appliances. This paper provides an insight that how much DR can be performed for residential consumers.*

***Keywords:** demand response, energy curtailment, water heater, HVAC*

I. INTRODUCTION

In recent years, India has achieved a steady increase in its electric power generation capacity. But the growth in demand increases more sharply than the growth in installed capacity, Which has led to a situation of energy and peak shortages of 6.8% and 8.8% respectively during 2018[1].In order to reduce the gap between the demand and supply of electricity in India, adequate actions or measures should be taken. Balance of electric power at the supply and demand side is important. Supply side management suffers not only from high initial investment but environmental issues and global warming are also serious factor [2]. Therefore Demand side management has taken attention worldwide and many researchers go through demand side management to avail its potential benefits. In India residential sector contributes about 23% of the total energy consumption [1]. Large number of demand response programs and strategies are used by different developed countries to optimize energy consumption in domestic sector[3]–[5]. Most of the work have done to make power system network more reliable and secure, decrease PAR, optimal utilisation of network, minimise energy cost and decrease wastage of energy etc. Many researchers proposed different Demand response strategies and DSM programs[6]–[15]. For example [6] uses a novel prototype for scheduling of home appliances, to minimise the power consumption cost with different pricing for different time interval. In [7] they shows system architecture for autonomous load management in buildings. In [8] Manisa-Pipattanasomporn et al. used an algorithm which keep the total household power consumption below a certain level. They proposed their algorithm for major appliances namely water heater, cooling/heating load, cloth dryer and electric vehicle. In [9], they Scheduled domestic appliances optimally which reduces electricity bill and improves PAR. They combine dynamic pricing with inclination block rate which strengthen the power system network. [10], [11] formulate an optimisation problem where minimum cost is objective function and user comfort as a constraint.[14] Reduces the cost of electricity and minimize the complexity of scheduling program using different algorithm. Some learning based algorithm sets a good relation between capacity of power network and energy consumption of users[16]. It reduces stress on power system network. In most studies, power consumption by each appliances is taken as constant and there in no variation in power consumption pattern with time. Variation in power consumption is internal characteristic of appliances. Domestic appliances are modelled according to their physical characteristics than DR programs are applied on these model. DR programs are applied on varieties of appliances ranging from lower power consumption appliances to several kW appliances. Many authors classify appliances into interruptible, critical appliances and thermal appliances. The appliances whose operation may be interrupted such as cloth washer, cloth dryer, are taken under this category. Critical appliances are those appliances whose interruption may affect the life style of consumer for example light, fan, TV, refrigerator etc., and HVAC and water heater comes under thermal appliances[10], [16]–[19]. DR programs are mainly applied on interruptible appliances and thermal appliances. None of the study finds out the contribution of appliances in DR program and potential of each appliances when DR is applied. Therefore the main contribution of this paper is summarised as:

- Analysis of each appliances based on their physical characteristics.
- Demand response capabilities for each appliances are evaluated individually.
- Comfort level and user convenience are maintain during DR event.

The paper is organised as follows:

DR enabled system modules of water heater, HVAC system, cloth dryer, washing machine and critical appliances are discussed in section 3. Section 4 presents simulation energy consumption pattern of appliances under study. Demand response potential of appliances are discussed and compared in section 5. Finally the paper is concluded in section 6.

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II. DR ENABLED MATHEMATICAL MODEL

DR enabled mathematical models are discussed in this section. Models have developed based on their physical characteristics. These models are implemented according to [8].

A. DR enabled Model of Water heater:

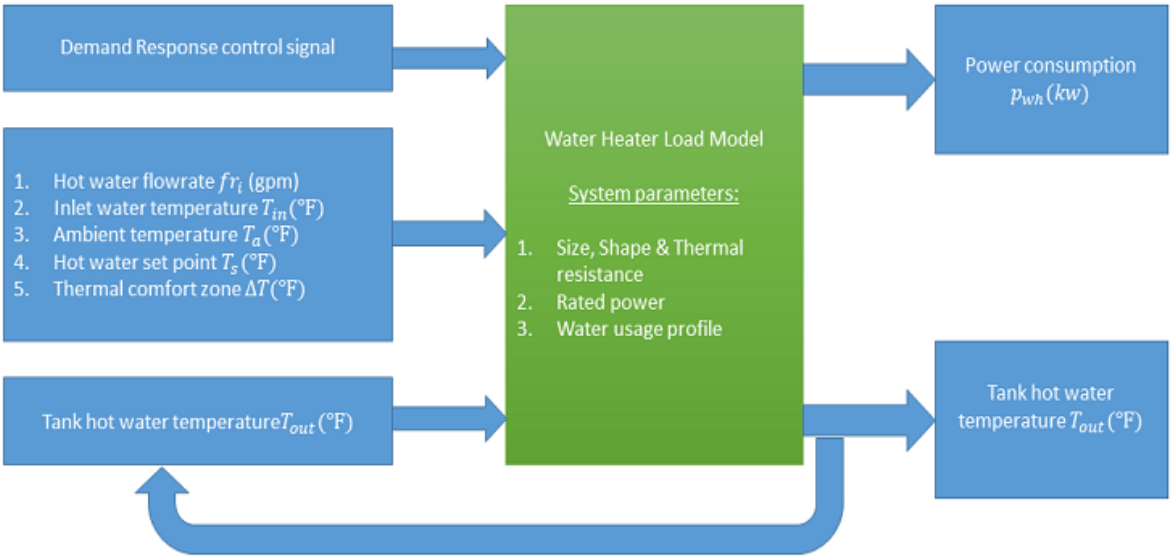

Figure 1: Block diagram of water heater model

For each time instant n the electricity consumption is calculated as:

$$p_{wh(n)} = S_{wh(n)} \,.\, P_{wh} \,.\, D_{wh(n)} \qquad (1)$$

Where:

$p_{wh(n)}$ Electricity consumption in n instant.

P_{wh} Rated power of electric heater (kW)

$S_{wh(n)}$ Status of water heater in time interval n (0=OFF; 1=ON)

$D_{wh(n)}$ Demand response signal for water heater in n instant (0=OFF; 1=ON)

The hot water temperature in the water heater varies as:

$$T_{out(i+1)} = \frac{T_{out(i)}(V_{tank} - fr_i * \Delta t)}{V_{tank}} + \frac{T_{in} * fr_i * \Delta t}{V_{tank}} + \frac{1}{8.34} * \left[p_{WH(i)} * 3412 - \frac{A_{tank} * (T_{out(i)} - T_r)}{R_{tank}}\right] \frac{\Delta t}{60} * \frac{1}{V_{tank}} \qquad (2)$$

Where,

T_{out}: Temperature of water inside water heater (°F)

T_{in}: Temperature of incoming water to water heater (°F)

T_r: Room temperature (°F)

fr_i: Water flow rate in time instant i (gpm)

A_{tank}: Surface area of tank (ft^2)

V_{tank}: Volume of tank (gallons)

Δt: duration of each time slot (minutes)

R_{tank}: thermal resistance of water tank (°F.ft^2.h/Btu)

The modelled water heater is fascinate by smart thermostat with temperature tolerance zone i.e. ΔT. When the temperature of hot water goes below certain level (i.e. $T_{max} - \Delta T$), water heater coils are ON. Due to heating temperature increases and when temperature of water reaches the maximum specified level WH coils goes OFF. When hot water temperature is in tolerance zone the heating coils will remain in their previous state. See (3)

$$S_{wh(n)} = \begin{cases} 0, & T_{wh(n)} > T_{max} \\ 1, & T_{wh(n)} < T_{max} - \Delta T \\ S_{wh(n-1)}, & T_{max} - \Delta T \le T_{wh(n)} \le T_{max} \end{cases} \qquad (3)$$

Where:

T_{max} Maximum hot water set point (°F)

ΔT Temperature tolerance zone (°F)

$T_{wh(n)}$ Temperature of hot water in interval n (°F)

$S_{wh(n)}$ Status of water heater in time interval n (0=OFF; 1=ON)

The electrical power consumption also depends on Demand Response signal which is set by the consumer or utility during DR event.

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This facility is achieve with the help of home energy controller. The DR control signal (D_{wh}) control the operation of water heater. When $D_{wh} = 0$ it will turn OFF water heater and when $D_{wh} = 1$ it will turn ON the water heater.

B. Model development of HVAC system:

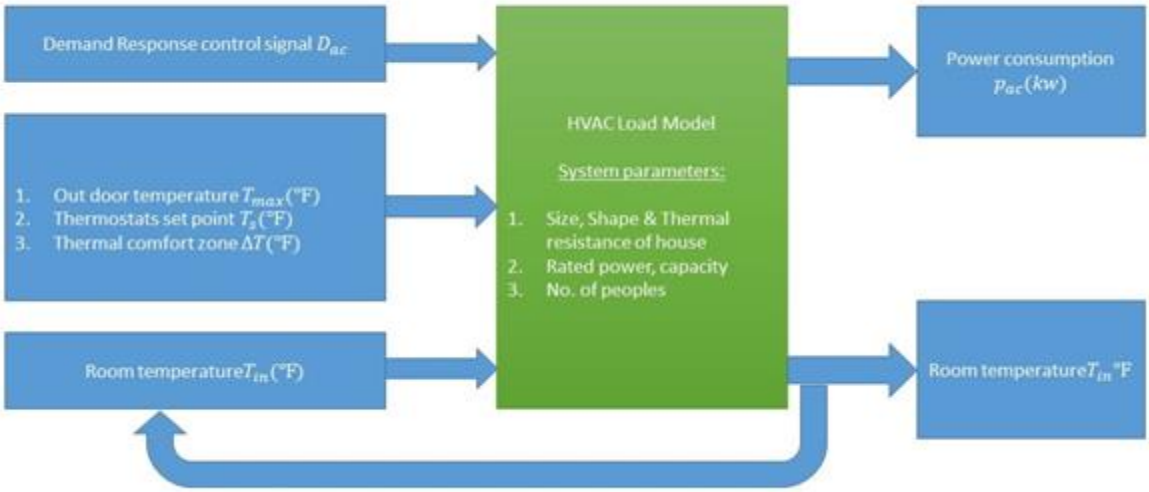

Figure 2. Block diagram of HVAC load model

DR enabled HVAC model block diagram is shown in above figure. DR control signal D_{ac}, outdoor temperature T_{out} , maximum thermostat set temperature T_{max} , comfort zone or allowable temperature range ΔT and room temperature T_{in} are input to the presented model. HVAC electric power consumption series data is output of the system. Room temperature time series data is also output of the system which is feedback to the system for next iteration. Besides these house structure, no of persons and electrical characteristic of HVAC system have also taken into consideration.

The electricity demand of HVAC system for each time instant is calculated as:

$$p_{ac(n)} = P_{ac}.S_{ac(n)}.D_{ac(n)} \quad (4)$$

Where:

$p_{ac(n)}$ Electricity consumption of HVAC in n instant.

P_{ac} Rated power of HVAC (kW)

$S_{ac(n)}$ Status of HVAC in time interval n (0=OFF; 1=ON)

$D_{ac(n)}$ Demand response signal for HVAC in n instant (0=OFF; 1=ON)

For each time instant n the room temperature is calculated as:

$$T_{n+1} = T_n + \Delta t \times \frac{G_n}{\Delta c} + \nabla t \times \frac{C_{HVAC}}{\Delta c} \times S_{ac} \quad (5)$$

Where:

T_n Room temperature (°F) in n instant.

Δt Length of time slot n (hour)

G_n Heat gain rate inside the room, positive values for heating and negative values for cooling.

C_{HVAC} Heating/cooling capacity of HVAC

Δc Energy required to change the temperature of room by 1°F (Btu/°F)

For each time instant n the Heat Gain Rate G_n is calculated as:

$$G_n = \left(\frac{A_{wall}}{R_{wall}} + \frac{A_{ceiling}}{R_{ceiling}} + \frac{A_{window}}{R_{window}} + \frac{11.77\ Btu}{°F \times ft^3} \times n_{ac} \times V_{house}\right) \times \left(T_{out(n)} - T_n\right) + H_p \quad (6)$$

Where A_{wall} , $A_{ceiling}$ and A_{window} represents the area of wall, ceiling and window respectively in ft^2. R_{wall} , $R_{ceiling}$ and R_{window} are thermal resistance of wall, ceiling and window, in °F.$ft^2.h/Btu$.

n_{ac} Rate of air changes in each slot of time.

V_{house} Volume of house of house in ft^3

H_p Heat gain from people (Btu/h)

HVAC is also equipped with smart thermostat, its operation is presented in (7)

$$S_{ac(n)} = \begin{cases} 0, & T_{ac(n)} > T_{max} \\ 1, & T_{ac(n)} < T_{max} - \Delta T \\ S_{ac(n-1)}, & T_{max} - \Delta T \le T_{ac(n)} \le T_{max} \end{cases}$$

Where:

T_{max} Maximum inside room temperature set point (°F)

ΔT Temperature tolerance zone (°F)

$T_{wh(n)}$ Temperature of room in interval n (°F)

$S_{wh(n)}$ Status of HVAC in time interval n (0=OFF; 1=ON)

C. Model Development of washing machine:

In modelling of washing machine we have taken three modes of operations namely normal, permanent press and delicate. Each mode of operation have three cycle of operation wash, rinse and spin. The power consume in every modes are different from each other whereas the consumption of power in wash and spin cycle is approximately same. Rinse cycle is for very short duration of time therefore it is neglected in our study.

Cloth washer is equipped with smart Timer. The timer is set according to types of cloth wash by the consumer. The cloth washer will be ON as long as running time is less than required set time. When running time becomes equal to required time, the dryer will be turn OFF. See (8).

$$S_{wm(n)} = \begin{cases} 0, & T_n \geq T_{max} \\ 1, & T_n < T_{max} \end{cases} \quad (8)$$

Where:

$S_{wm(n)}$ Status of washing machine in time interval n (0=OFF; 1=ON).

T_n Washing machine running time (minutes).

T_{max} Washing machine required running time (minutes).

For each slot of time n the demand of electricity by washing machine, is calculated as:

$$p_{wm(n)} = k \cdot P_{wm} \cdot S_{wm(n)} \cdot D_{wm(n)} \quad (9)$$

Where:

P_{wm} Rated power of washing machine.

k Multiplying factor for different modes.

$S_{wm(n)}$ Status of washing machine in time interval n (0=OFF; 1=ON).

$D_{wm(n)}$ Demand response signal for washing machine in time interval (0=OFF; 1=ON).

Demand response control signal have received by washing machine which decided the operation of washing machine during demand event.

D. Model Development of Cloth dryer:

Cloth dryer consists of heating and motoring parts. Power consumption of heating coils are in kilowatt whereas motor part usually takes several hundred watts. Cloth dryer is equipped with smart Timer. The timer is set according to types of cloth dried by the consumer. The cloth dryer will be ON as long as running time is less than required set time. When running time becomes equal to required time, the dryer will be turn OFF.

$$S_{cd(n)} = \begin{cases} 0, & T_n \geq T_{max} \\ 1, & T_n < T_{max} \end{cases} \quad (10)$$

Where:

$S_{cd(n)}$ Status of cloth dryer in time interval n (0=OFF; 1=ON).

T_n Cloth dryer running time (minutes).

T_{max} Cloth dryer required running time (minutes).

For every time interval n power consumption of dryer unit is calculated as:

$$p_{cd(n)} = k \cdot P_{hcd} \cdot S_{cd(n)} \cdot D_{cd(n)} + P_{mcd} \cdot S_{cd(n)} \quad (11)$$

Where:

P_{hcd} Rated power of heating coil.

k Multiplying factor for different modes.

$D_{cd(n)}$ Demand response signal for cloth dryer in time interval (0=OFF; 1=ON).

The electric power consumption also depends upon Demand response signal during DR event. When DR signal is received from in home controller heating coils are controlled and motor part will not be effected.

E. Modelling of critical loads:

Lighting, fans, refrigerator, dishwasher, TV and mobile charging etc. are taken as critical loads. Controlling of these devices may lead inconvenience or creates consumer dissatisfaction. The power consume by these devices are calculated as:

$$p_{critical} = \sum_1^k P_{ck}$$

Where:

P_{ck} Represents Lighting, Fans, Refrigerator, Dishwasher, TV and Mobile Charging etc. where k varies from 1 to k.

III. DEMAND RESPONSE CASE STUDY

A 2500 square feet home in Mumbai, is taken as a case study. Water heater, HVAC, cloth dryer, washing machine, light, fan, refrigerator and plug-in loads are household appliances under study. System specification and appliances parameter are shown in table 1.

Table 1: parameter of house under study

parameter	value	unit
House size	2000+500 basement	sq ft
A_{floor}, $A_{ceiling}$, A_{wall}, A_{window}	2000,2000,2600,520	sq ft
$R_{ceiling}$, R_{wall}, R_{window}	49,13,2	ft^2*°F/(Btu/h)

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Number of people	3	people
Capacity of AC unit	34,000	BTU
Ac temperature set point	77°F	°F
Ac power consumption	2.3	kW
Ambient temperature	Uniform temperature distribution of 84 °F	°F
Water heater (WH) tank size	200	Liter
WH tank R- value	2	ft^2*°F/(Btu/h)
WH temperature set point	110°F - 120°F	°F
Water consumption	2-3	gallons/minute
Washing machine power consumption	2	kW
Cloth dryer power consumption	3	kW
Critical loads	300-1200	watt

A. Water heater:

Simulation results for 200 L water heater are shown in the figure. Water heater Power consumption along with temperature variations are simulated for 16 hours from 6am to 10pm. A timer turns on the water heater at 6am and turn off it by 10 pm. The heater is equipped with smart thermostat. Maximum temperature water may attain is set to 125°F and temperature comfort zone have taken 10°F. Other parameters which are used in model development is shown in table I.

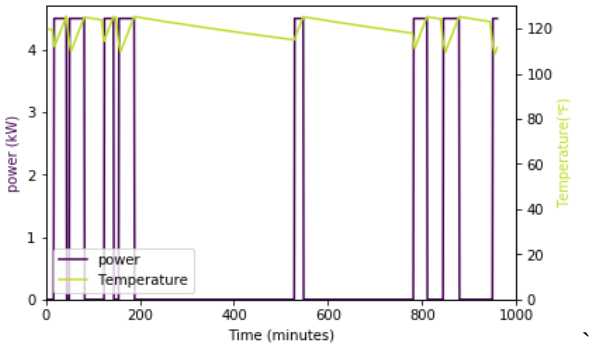


Figure 3.Load profile of water heater

Water heater load profile is shown in fig. 3. Water heater operation is due to water usage in shower, sinking, dish washing and cloth washing etc. WH operation around 6:45am, 8:30 am and 8:30pm for bathing and WH operates at 6:15am, 8:00am and 9:45pm for sinking and dishwashing. At 3:15pm water heater operates without consumption of hot water to retain the temperature of water in comfort zone. The water heater operation for different activities varies from 20 minutes to 30 minutes but to retain the temperature in comfort zone, it is operated for 17 minutes.

B. HVAC:

Simulation result of HVAC system are shown in the fig.4. HVAC Power consumption along with temperature variations are simulated for 24 hours. Fig. 2 shows Zoomed version of centralized HVAC system for three hours. HVAC system is equipped with smart thermostat. The inside temperature of room is set to 77°F and 10°F as temperature comfort zone.

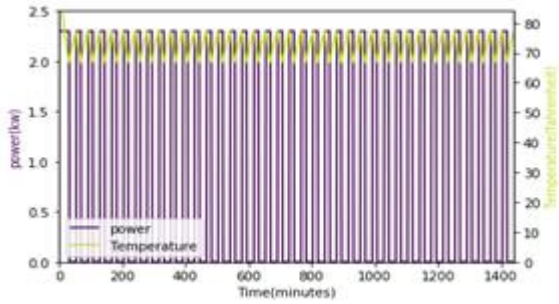


Figure 4 Load Profile of HVAC

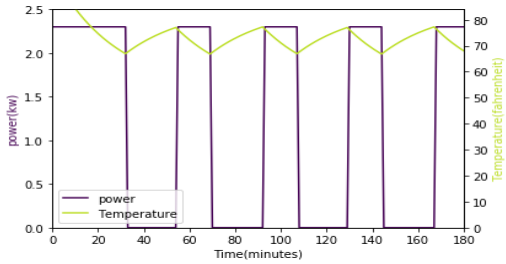
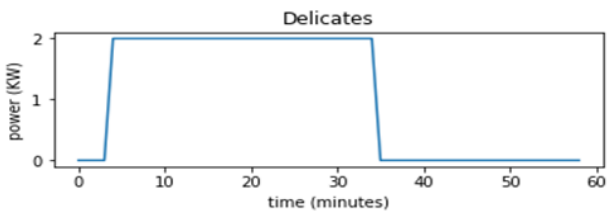


Figure 5. Zoomed load profile of HVAC

HVAC system maintain indoor temperature within comfort zone which is specified above. Other parameters which have used in model development are shown in table I. It is observed from the results that 18-20 minutes HVAC operation have required at an interval of 20 minute.

C. Cloth washer:

Front load type washing machine, energy consumption pattern are shown in above figure 6. The three cycles, normal, permanent press and delicates consumes nearly equal power during its operation. Three modes of operations are taken in each cycle. The washing machine start its cycle by filling the water which generally takes 2-3 minutes. Power consumption during water filling is very low about 3-5 watt. In the above presented model each cycle lasts generally for 30 minutes. The power consumption in each cycle is 2KW. Other system specifications and parameters are shown in table 2.



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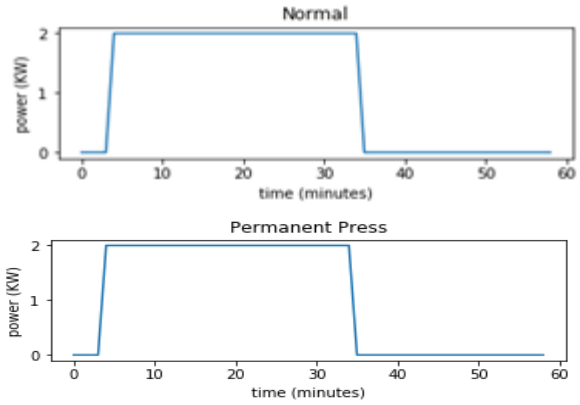

Figure 6. Delicates, Normal and permanent press

D. Cloth dryer:

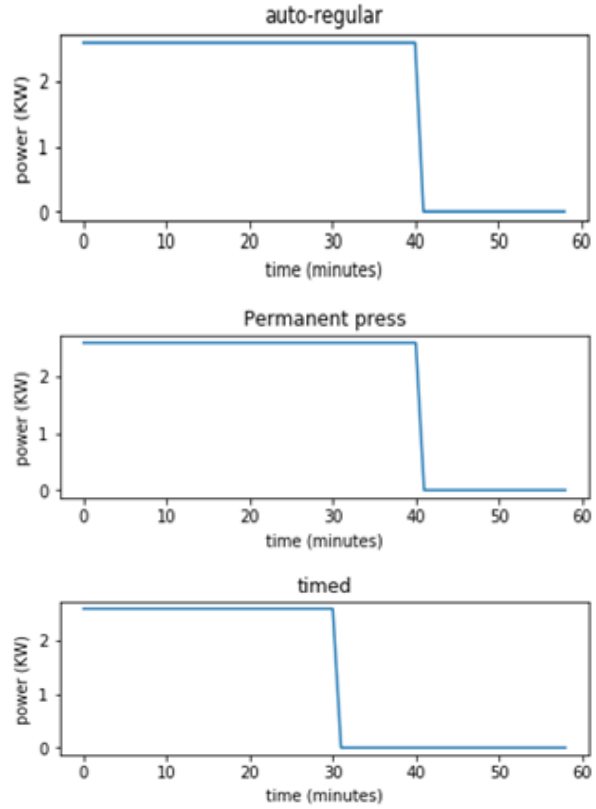

Figure7. Auto-regular, Permanent Press Timed,

Figure 7 represents the load profile of cloth dryer for three modes, namely auto-regular, permanent press and timed. Generally the operation time of these modes varies from manufacturer to manufacturer. In this study it is taken 40, 40, 30 minute for three modes. The power consumption in all three modes is nearly equal to 3KW. The system parameter taken in this study are shown in table 2.

E. Critical loads

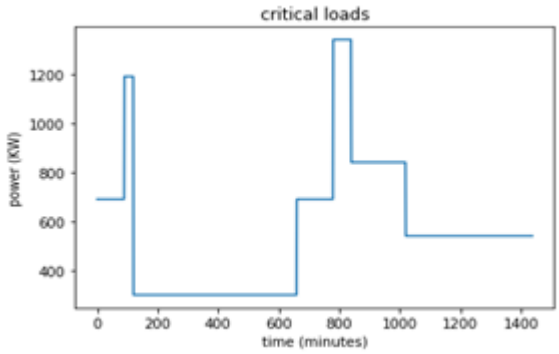

Figure 8 Load profile of critical loads

Figure 12 shows power consumption due to critical appliances in the house. Critical appliances include lights, fans, fridge, oven, television and plug in loads. Interruption of these devices may increase inconvenience to consumer therefore they don't participate in DR event. In the morning load increases due to fan, light and electric oven. Fridge operates throughout the day. In evening hours the load also increases due to same reason as in morning only extra load is television. A constant load is there in night due to fans and fridge.

IV. DISCUSSIONS AND OBSERVATIONS

This section describes operating characteristics of different devices under study along with their demand response potential.

	Average Peak power consumption(watts)	Possible interruptible time(minutes)	Comfort level violation	% curtailment	DR potential rank
Water heater	4500	Vary	Moderate	34.61	1st
HVAC system	2,300	Vary	Moderate	17.69	3rd
Washing machine	2,000	Up to several hours	Least effected	15.38	4th
Cloth dryer	3,000	Up to several hours	Least effected	23.08	2nd
Critical appliances	1,200	None	Highly effected	0.00	None

Table 2 DR comparison of home appliances

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The comparison of power consumption, possible interruptible time, comfort level violation are shown in table 2. DR potential rank is based on the saving of power if DR is performed. DR % curtailment is also shown in table 2. Above table shows water heater has highest DR % curtailment followed by cloth dryer, HVAC system and washing machine. Critical appliances have zero % curtailment. So they do not participate in DR programs. Some observations have taken from different appliances under study are follows:

- The water heater offers highest DR potential. If water heater operation is interrupted, the consumption of electricity is reduced by 4500 watts, which is about 34.61 % curtailment. Interruption of water heater normally does not affect comfort of consumer. At morning and evening if DR is applied it will affect consumer comfort. Therefore comfort level violation is moderate in water heater case.
- HVAC system shows moderate comfort level violation. HVAC has good performance if the interruptible time interval is small. Customer comfort is effected if time interval is large. Usually 30-60 minutes interruptible time interval will least effect consumer comfort. Many DR programs are developed for HVAC and water heating load. Direct load control programs are also used for these appliances.
- The cloth dryer has second highest DR potential. Interruption of cloth dryer reduces the overall electricity consumption by a significant amount in house and also its interruptible time interval may vary up to several hours, even for whole DR event, without comfort level violation. Power consumption by cloth dryer is 3300 watts but heating coils take 3000 watts and only heating coils are disconnect during DR event.
- Washing machine have also DR potential. It may also show good DR potential if washing machine are DR enabled. But most of the washing machine used in homes are not DR enabled models. Thus if consumers replace their existing appliances with DR enabled smart appliances than it will show a significant DR potential.
- Critical appliances have zero DR potential. Interruption of these devices during DR event significantly effects consumer's life style and comfort.

V. CONCLUSION

This paper presents DR enabled load models and their electrical characteristics. Simulation results show major domestic appliances such as water heater, HVAC, washing machine and cloth dryer have good demand response potential. The main contribution of this paper is that to encourage researchers, academicians and industries, to promote Demand response in residential areas.

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