Demand Response from Residential Air Conditioning Load Using a Programmable Communication Thermostat

Saurabh Chanana, Monika Arora

***Abstract*—**Demand response is getting increased attention these days due to the increase in electricity demand and introduction of renewable resources in the existing power grid. Traditionally demand response programs involve large industrial consumers but with technological advancement, demand response is being implemented for small residential and commercial consumers also. In this paper, demand response program aims to reduce the peak demand as well as overall energy consumption of the residential customers. Air conditioners are the major reason of peak load in residential sector in summer, so a dynamic model of air conditioning load with thermostat action has been considered for applying demand response programs. A programmable communicating thermostat (PCT) is a device that uses real time pricing (RTP) signals to control the thermostat setting. A new model incorporating PCT in air conditioning load has been proposed in this paper. Results show that introduction of PCT in air conditioner is useful in reducing the electricity payments of customers as well as reducing the peak demand.

***Keywords*—**Demand response, Home energy management Programmable communicating thermostat, Thermostatically controlled appliances.

I. Introduction

IN today’s world, demand and consumption of electricity is increasing day by day. However, due to insufficient investments in infrastructure side and other constraints, existing power system is not capable of meeting the growing demand. Additionally, lack of effective monitoring and control in distribution system results in slow response during problematic scenarios. These factors may cause instability in power system and situations of black out may arise. Use of fossil fuel based energy has adversely affected the environment and these energy sources are going to vanish in near future. This requires alternate clean energy sources to be introduced to the existing power system. To address these challenges of ageing assets, increasing energy demand, high power losses, power system security, environmental impact and limited control, concept of smart grid has emerged. Research is going on in many countries to realize the concept of Smart grid. Smart grid is basically the existing power grid provided with enhanced capabilities of communication technology and information technology. Key features of smart grid are distributed generation interconnection, energy storage, real-time monitoring, distribution automation, demand response, end to end communication, data management, and power loss reduction. As a result, better monitoring and control of power system is possible which will make the system very efficient, flexible, reliable, and low cost operation.

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With the increase in electricity demand, depletion of fossil fuel resources and introduction of renewable resources, demand response has gained attention in recent years. Demand response (DR) refers to the consumer’s ability to alter its consumption pattern in response to time varying electricity prices. DR programs give opportunity to consumers to manage their consumption economically and impact the market price of electricity. Demand response is an effective tool in mitigating the imbalance between demand and supply of energy. Due to DR, effective use of existing network is possible and investments in networks can be deferred. This ultimately benefits customer. Also it plays an important role in keeping supply market under check. It has been observed that lack of demand response has been a major factor for the energy market crash. For example, California’s Energy crisis at the turn of the millennium could have been avoided if Demand response was in place [1].

The DR system comprises of two parties: the utility and the customers. The utility can send signals to the customers to indicate a need to reduce demand. On receiving the price signal from utility, customer can take an appropriate action based on his preferences and needs. In DR, both the parties try to maximize their own saving while making sure that the other party gains an advantage. Inclusion of DR in ancillary service market is vital for reducing the cost of ancillary services like frequency regulation voltage control and spinning reserves. A variety of DR programs have been explained in [2]. Success of a DR program depends on the pricing model applied. Traditionally, utilities engage only industrial or bulk consumers for DR programs, but with technological advancement, small residential and commercial consumers are also getting involved in DR programs.

In residential load context, individual loads can be categorized into two groups; thermostatically-controlled and manually controlled. Thermostatically-controlled devices such as air-conditioners, heaters, and heat pumps contribute to the large portion of the distribution loads. Thermostatically-controlled devices turned ON for a certain time and then they turn OFF for the remaining time. Manually-controlled loads are switched ON and OFF by the residents of the house as per their requirements [3]. Thermostatically controlled loads are the prime candidates for Demand response in case of residential loads. The ON/OFF cycle of thermostatically controlled appliances (TCAs) can be controlled to manage the energy consumption of consumer and thus results in saving in the electricity bills. The short interruption of these devices may not reduce the comfort level of the customers significantly and may go unnoticed. However, successful implementation of such programs requires approval from customer's side.

The literature includes a wide range of work related to residential demand response. In [4], benefit analysis of DR, problems due to lack of DR and environmental impacts of DR have been discussed. Results indicate that several million tons of coal is saved on incorporating DR. Zhu et al. have also proposed a control scheme for an air conditioner (AC) to reduce peak demand by load shifting and maintaining the temperature inside a comfortable range. In [5], load model of an air conditioner based on stochastic difference equation is used to study the effects of the load parameters and the direct load control actions. In [6], a mechanism for varying thermostat setting with grid frequency/ real-time prices has been proposed. Reference [3] explains set point control strategies for thermostatically controlled appliance in competitive electricity market (taking water heater as an example). In [7], an optimal and automatic residential energy consumption scheduling framework has been simulated which attempts to minimize the electricity payment and the waiting time for the operation of each appliance in household in presence of a Real Time Pricing (RTP) tariff combined with inclining block rates. Similarly, [8] presents a novel appliance commitment algorithm that schedules thermostatically controlled household loads based on price and consumption forecasts minimizing payment or maximizing comfort. Simulation results show a significant reduction in user payments and peak to average ratio. Reference [9], demonstrates the inclusion of smart thermostat into Home Energy Management System for residential DR implementation. Some advantages of temperature set point control over direct load control have also been discussed.

In summer, air-conditioning presents the major portion of peak load. Therefore, it is important to examine the control strategy to reduce the power consumption of air conditioning load during peak hours. This paper discusses thermostat set point control strategy of air conditioner load. Programmable communicating thermostats (PCTs) are used to automatically modify the set point of thermostat when the price of electricity exceeds a pre-specified threshold, thus lowering customer electricity bills. In order to study the effectiveness of this scheme, a computer simulation of air conditioning load has been performed. In the simulation, dynamic model of air conditioner regulating the temperature of a house by a thermostat has been used.

The paper is organized in 5 sections. In Section I, an overview of the Demand response problem and the related literature is presented. Section II describes Residential Demand Response Framework; Section III deals with the modeling of Air Conditioner temperature control for normal thermostat setting and also for PCT setting. Section IV presents the simulation results of temperature, power and energy consumption in case of Normal thermostat setting as well as PCT setting. Reduction in energy consumption due to PCT is obtained when AC is ON for some time and OFF for rest of the simulation time. Section V dedicated to general conclusion followed by references.

II. Residential Demand Response Framework

Demand Response aims at reducing customer energy consumption during peak hours or during emergency conditions. Current DR Schemes are implemented through either incentive-based or time-based rates schemes [2]. In incentive-based DR, customers enroll voluntarily in certain rewarding programs and allow the operators to control directly some of their electric appliances such as air conditioners to shed load during peak or emergency. On the other hand, time-based rates scheme relies on dynamic pricing of electricity to regulate electricity consumption and it can take many different forms, ranging from simple schemes such as scheduled time-of-use pricing (TOUP), to peak-pricing (PP) which sets higher price only during critical peak periods, to real-time pricing (RTP) specified at regular interval based on say the wholesale market rates.

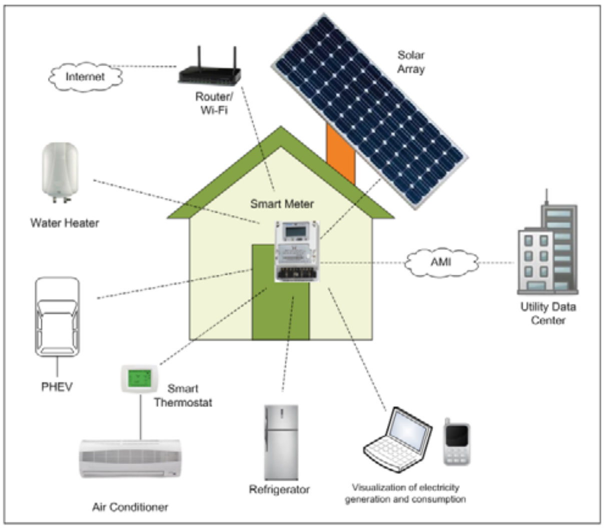


Fig. 1 Smart Home

Implementation of demand response requires huge investments on the part of distribution companies and customers. DR requires open electricity markets and realization of dynamic pricing. In this paper, we are using real time pricing signals to control the energy consumption of air conditioning load. In addition, DR requires advanced metering infrastructure, two way communication and control system to be in place. Smart meters play an important role in DR management and Smart home automation. Smart meter connects distribution and consumption. It provides utility with real-time energy consumption data of customer's premises. In addition, smart meter enables consumers to monitor their electricity consumption and take measures to reduce their usage. We are assuming all the pre-requisite systems (Smart meters, AMI, communication and control) are already in place. The interaction of smart meters with various appliances in home and additionally with the utility is shown in Fig. 1.

Smart meters provide real-time pricing of electricity on hourly basis. Customers can make response according to this real-time price automatically or manually. In this paper, we are using programmable communicating thermostat (smart thermostat) which is able to adjust the set point of thermostat to control the consumer energy. Most of the current PCTs are equipped with capabilities to communicate with a smart meter- a two way communication device. PCTs are the devices which don't require constant programming input by the user. The modeling of PCT to respond to the change in the price of electricity has been explained in the next section.

III. Model of Residential Air Conditioning Load

In literature, various models have been presented to determine the dynamics of the air conditioning load. A discrete-time continuous state stochastic model has been developed in [3]. A Markov chain model which reproduces the steady-state features of stochastic nonlinear difference equation has also been reported. In this paper, we have used a simple model based on differential equations which easy to understand and simulate on computer.

A. With Conventional Thermostat

The dynamic model for the temperature of a house regulated by a thermostatically driven air conditioning load presented in [10], has been used for simulation. The model is as follows:

$$\frac{dT}{dt} = \frac{T_f - T - \omega T_g}{\tau} \quad (1)$$

where:

- τ is the effective thermal constant of the house.
- T is the internal temperature of the house.
- T_g is the temperature gain of the air conditioner.
- ω specifies the state of the thermostat (0-on, 1-off).
- T_f is the ambient temperature in °C

Conventionally, the thermostatically controlled loads operate on following logic. Let T_{st} be the thermostat setting. The upper and lower limit for the internal temperature is $T_{st}+\Delta T$ and $T_{st}-\Delta T$, respectively. Whenever $T > T_{st}+\Delta T$ and thermostat is in OFF state, it would be switched ON; and whenever $T < T_{st}+\Delta T$ and the thermostat is in ON state, it would be switched OFF as illustrated in Fig. 2. We term this control as normal thermostat control.

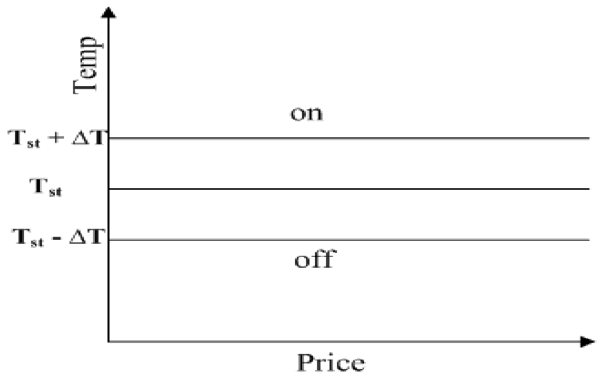
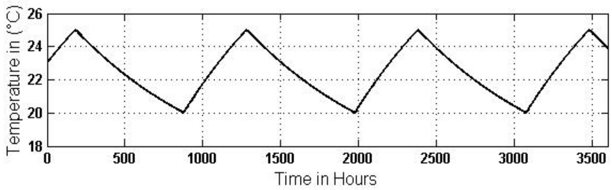
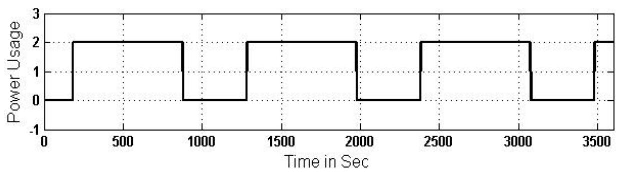


Fig. 2 Thermostat setting in case of Normal Thermostat

The normal working of the thermostat in the air conditioning load with an ambient temperature of 35 °C with a thermal gain T of 20 and the value of τ is taken as 1000 can be understood with the help of Fig. 3 (a). Fig. 3 shows room temperature variation and power consumption of a normal thermostat in air conditioning load. The energy consumed can be analyzed by multiplying the ω signal by the power rating of the air conditioner which is taken as 2 kW in the example. Rising curve in Fig. 3 (a) represent that AC is OFF and falling curve represent AC is in ON state (Cooling).



(a)



(b)

Fig. 3 A typical thermostat operation showing (a) Room Temperature Variation (b) Power Usage

B. With Programmable Communicating Thermostat

A new model for incorporating PCT has been proposed in this paper. The application of PCT states that the thermostat setting varies with the change in the real time price. The thermostat setting changes between the region of minimum RTP λ^{min} and the maximum RTP λ^{max}. The thermostat setting increases from T_{st}^{min} to T_{st}^{max} with the increase in the RTP from λ^{min} to λ^{max} and beyond the region of T_{st}^{min} and T_{st}^{max} the thermostat setting remains constant. The strategy involved here is that the thermostat setting keeps on changing with respect to the change in price. The mathematical formulation of the strategy is

$$T_{st} = m * \lambda + K \quad (2)$$

In a practical situation we can have a Home Energy Management System where a user can feed the values of parameters λ^{min}, λ^{max}, T_{st}^{min}, and T_{st}^{max} based upon his perception of normal and high prices and his comfort level. In this work, we have considered m =1/1000 °C/Rs./Mwh and K is a constant. Value of K is taken as 20. (Rs. Stands for Indian Rupee, whose present value is approx. 0.165 US Dollar)

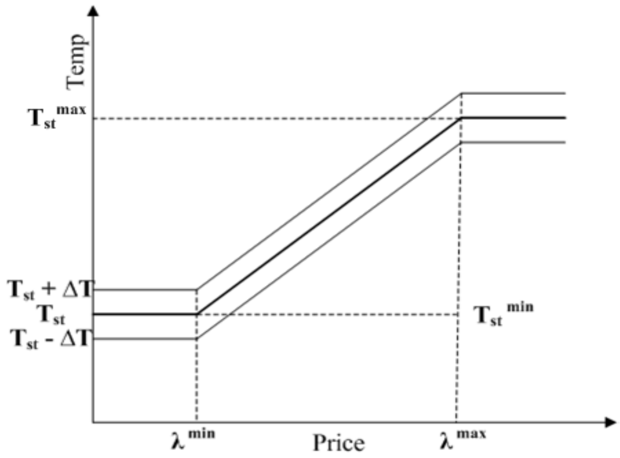


Fig. 4 Thermostat variation with MCP in case of PCT

IV. Results

In this paper, we postulate that use of PCTs can reduce consumer bills as well as their peak demands. In order to confirm our hypothesis we considered a smart home having three air conditioners (ACs) of rating 2kw, 2.5kw, and 2kw. The duty cycle for three air conditioners is shown in Table I ('1' indicates air conditioner is in use and '0' indicates it is not in use). The SIMULINK software has been used for simulating the ACs as governed by (1). Two different cases have been considered, Case 1: ACs with a normal thermostat model, and Case 2: ACs with PCT model.

A. Case1: Residential Air Conditioning Load with Normal Thermostat Control

The air conditioning load comprises of three air conditioners with power rating as 2kw, 2.5kw and 2kw, thermal gain T_g of these ACs is taken as 20, 19 and 21 respectively, the value of thermal constants of the rooms τ is assumed to be as 1000, 1100, and 900 respectively. The SIMULINK model of the entire system is shown in Fig. 5. The functionality of a normal thermostat has been implemented using a Relay block of SIMULINK. The model is run for 24hrs (86400sec). For the normal thermostat operation, the set point T_{st} = 22°C. ΔT= 2°C. Duty Cycle of AC loads are considered as shown in Table I:

Ambient temperature variation and RTP variation for the day under study is shown in Figs. 6 and 7, respectively. This data is based on the day-ahead market price variation at IEX during a typical summer day [11]. The power demand and hourly energy consumption is shown in the Figs. 9 and 10 respectively.

TABLE I
DUTY CYCLE FOR ACS (AC 1- 2KW, AC 2- 2.5KW, AC 3-2KW)

Time (Hour)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
AC 1	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	1	1	1
AC 2	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
AC 3	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	1	1	1

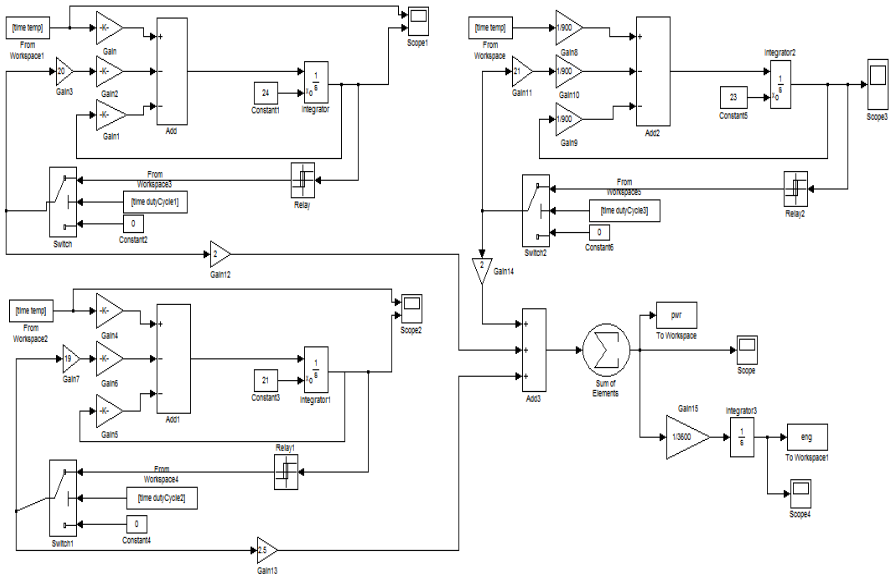


Fig. 5 SIMULINK Model of 3 ACs with Normal thermostat setting considering duty cycle

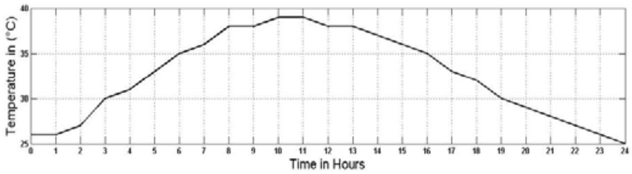


Fig. 6 Variation of Ambient Temperature with time

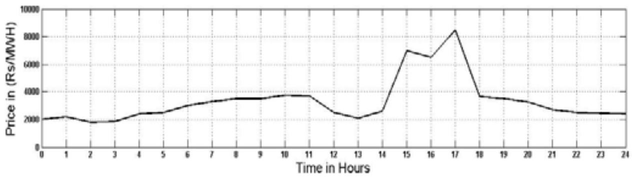


Fig. 7 Variation of RTP with time

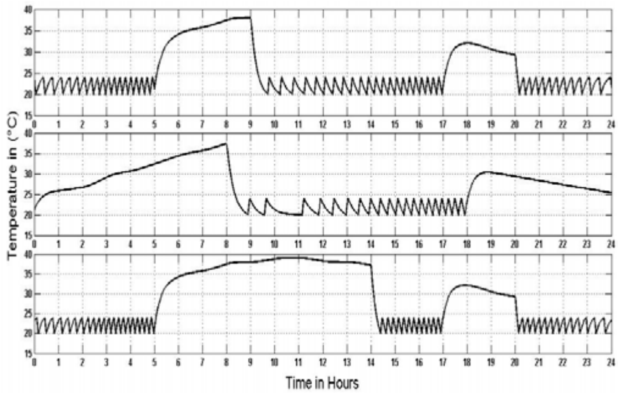


Fig. 8 Variation of Room Temperature with time in case of Normal thermostat setting (AC 1- 2kw, AC 2- 2.5kw, AC 3-2kw)

As per duty cycle of ACs, room temperature remains in the limit 20-24°C when the AC is in use. When AC is not in use, room temperature rises as per the ambient temperature.

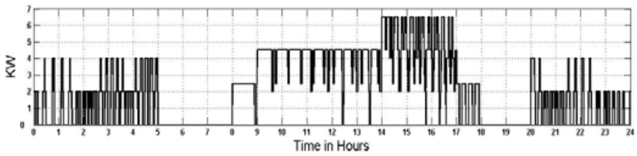


Fig. 9 Power consumption during 24 hrs in Case 1

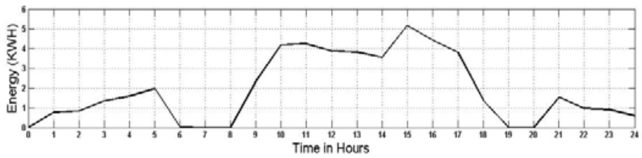


Fig. 10 Hourly Energy consumption during 24 hrs in Case 1

The overall energy consumption by ACs during 24 hours in case of normal thermostat setting considering duty cycle of ACs, comes out to be 47.2442 kWh.

B. Case2: Residential Air Conditioning Load with PCT

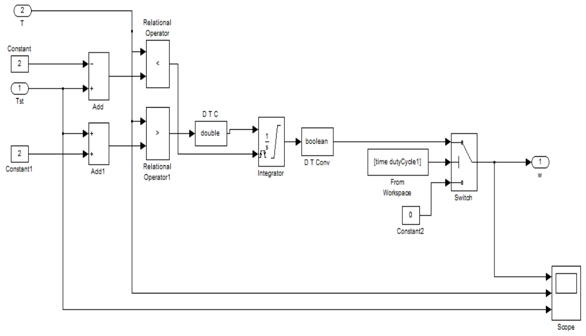


Fig. 11 SIMULINK Model for a PCT

Since the Relay block of SIMULINK is incapable of varying the Thermostat setting T_{st}, a separate logic has been employed for implementing PCT functionality as shown in Fig. 11. In this model, thermostat setting is varied as a function of electricity price and PCT is switched ON or OFF to maintain the temperature within the limits around the thermostat setting at that time. When electricity price increases during peak hours, thermostat setting also increases. Thus, energy consumed by AC to maintain the room temperature near the thermostat setting is reduced. In this, the group of air conditioning load comprising three air conditioners of the same specification as mentioned above has been taken for simulation. Duty cycle of AC loads is taken same as mentioned in the case with normal thermostat setting. The power demand and hourly energy consumption in case of PCT is shown in Figs. 13 and 14 respectively. The hourly variation of the MCP changes the thermostat setting and thus changing the internal room temperature and result in low energy consumption than the group of air conditioners working on normal thermostat principle. The total amount of energy comes out to be 39.7866 kWh.

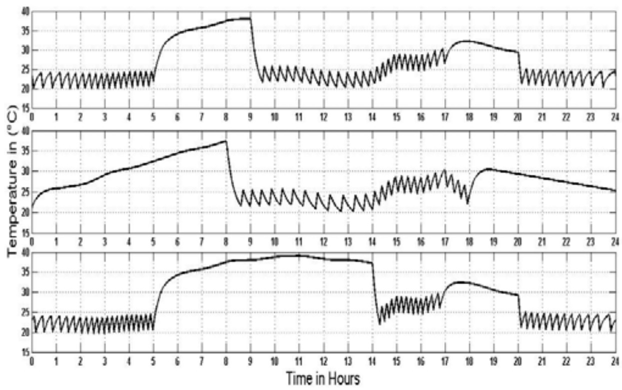


Fig. 12 Variation of Room Temperature with time in case of PCT setting (AC 1- 2 kW, AC 2- 2.5kW, AC 3-2kW)

When AC is in use, thermostat setting varies as per RTP of electricity. Thus room temperature also varies with in the new limits set by the PCT thermostat setting as shown in Fig. 12. When AC is not in use, room temperature varies as per the outside temperature.

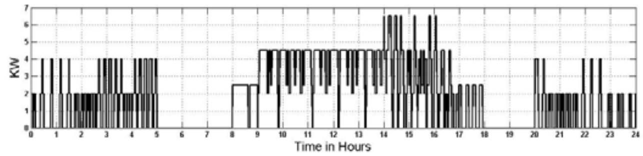


Fig. 13 Power consumption during 24 hrs in Case 2

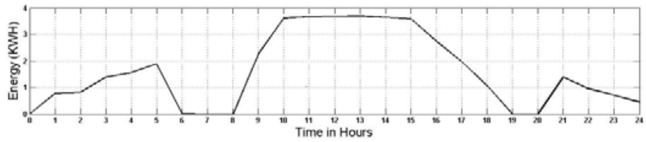


Fig. 14 Hourly Energy consumption during 24 hrs in Case 2

This shows that energy consumption is reduced when PCT is employed. Hourly consumption of energy in both Normal thermostat setting and PCT setting considering duty cycle of ACs is shown in the Table II.

TABLE II
HOURLY MEASURE OF ELECTRICITY CONSUMPTION WITH NORMAL THERMOSTAT SETTING AND PCT USING THE DUTY CYCLE CONSIDERED

Time (in hour)	Hourly energy consumption (in kWh)		Change in Hourly energy consumption (in kWh)	Real Time Price (in Rs./ kWh)	Saving in Electricity Bill (in Rs.)
	Case1	Case2			
1	0.775	0.7694	0.0056	2.37	0.01
2	0.8256	0.8134	0.0122	2.50	0.03
3	1.345	1.3811	-0.0361	2.29	-0.08
4	1.5955	1.5564	0.0391	2.19	0.09
5	1.9833	1.8847	0.0986	2.50	0.25
6	0.0005	0.0005	0	2.50	0.00
7	0	0	0	2.50	0.00
8	0	0	0	3.00	0.00
9	2.3068	2.2551	0.0517	3.50	0.18
10	4.1801	3.6055	0.5746	3.30	1.90
11	4.2366	3.6587	0.5779	3.81	2.20
12	3.8553	3.683	0.1723	3.50	0.60
13	3.8092	3.6885	0.1207	2.98	0.36
14	3.5482	3.639	-0.0908	2.50	-0.23
15	5.168	3.573	1.595	2.70	4.30
16	4.4252	2.7438	1.6814	4.00	6.72
17	3.7916	1.9785	1.8131	4.25	7.70
18	1.3713	1.06	0.3113	4.19	1.30
19	0	0	0	3.75	0.00
20	0	0	0	2.99	0.00
21	1.5387	1.3815	0.1572	2.50	0.39
22	0.9822	0.9481	0.0341	2.50	0.09
23	0.9161	0.7153	0.2008	2.50	0.50
24	0.59	0.4511	0.1389	2.39	0.33
Total	47.2442	39.7866	7.4576		26.66

From the Table II, it can be observed that when PCT is employed, energy consumed during 24 hours is reduced by

7.4576 kWh and the saving in cost of energy consumption is obtained as Rs. 26.66.

V. Conclusion

This study proposes a real-time price based DR program for reducing the peak energy consumption of customer. The DR program uses MCP data as a control signal for controlling the thermostat setting of air conditioner. A group of three air conditioners with normal thermostat and PCT have been simulated. Energy consumption in case of normal thermostat and PCT has been observed. The results of simulation show that the application of PCT in place of normal thermostat results in reduction in energy consumption during the peak prices. Thus this strategy results in the considerable saving in customer's electricity bill. This type of proposed model can be applicable to the Indian market and also to the other markets.

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