A Real Time Price based Optimal Scheduling Mechanism for Centralized Air Conditioning Load

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Abstract—This paper proposes a real time price based optimal scheduling mechanism for centralized air conditioning load. In residential context, air conditioners are the main reason for peak load in summers. The proposed mechanism aims to determine optimal operation of air conditioner such that it results in reduction in consumer’s electricity bills. Mixed Integer Programming technique is used for obtaining optimal schedule. The results obtained are compared with a previously established Linear Sequential Algorithm for evaluating the effectiveness of the scheme. The results show that Mixed Integer Programming technique provides higher reduction in electricity bill as compared to Linear Sequential technique.

Keywords—Air conditioner; demand response; home energy management system; real time price; thermostatically controlled appliance

I. INTRODUCTION

Increasing energy demand has been the prime concern for the utilities these days. One solution is to set up new generating plants to supply the increasing demand. This will put an extra burden on the fossil fuel resources that are depleting day by day. Existing power system (PS) is also facing issues in integration of renewable energy resources with the power grid. To handle these problems, PS needs to undergo some fundamental changes in its architecture. The new PS should be more reliable, intelligent and environment friendly. This has led to the evolution of future power grid that is known as Smart Grid. With the advanced capabilities of communication, monitoring and control, smart grid will be able to effectively resolve the existing PS problem.

Demand response (DR), a key technology in smart grid area, has received considerable attention in recent years. DR can be defined as the changes in electricity usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time [1]. It has the potential of shifting peak demand and reducing energy consumption cost. With the introduction of dynamic pricing schemes in the market, consumers have been encouraged to shift the electricity demand from peak hours to off-peak hours. Selection of suitable pricing scheme is responsible for the success of DR program. There are a number of time-varying pricing models available in the market e.g. time of use pricing, critical-peak pricing and real time pricing (RTP). RTP scheme is considered to be the most suitable among other pricing schemes [1].

After the successful implementation of DR programs in commercial and industrial area, effort is being made to evolve efficient energy scheduling programs for residential use. In residential context, air conditioner (AC) consumes large amount of energy as compared to other home appliances. ACs are the main reason for peak load in summer. AC is a thermostatically controlled appliance (TCA) in which thermostat operation control the energy consumed by the appliance.

A variety of work has been done in the area of residential DR. In [2], a control scheme for an AC to reduce peak demand by load shifting is proposed. In [3], load model of an AC based on stochastic difference equation is used to study the effects of the load parameters and the direct load control actions. Various set point control strategies have been explained in [4] by Nu and Katipamula for TCAs (water heater taken as an example). Reference [5], demonstrates the inclusion of smart thermostat into home energy management (HEM) system for residential DR implementation. Some advantages of temperature set point control over direct load control have also been discussed. In [6], a mechanism for varying thermostat setting with grid frequency/ real-time prices has been proposed.

In this paper, problem of optimally scheduling of AC load is considered. Within AC model, two different thermostat settings, Fixed Thermostat and Variable Thermostat, are considered. The program uses RTP model for energy management and DR. A comparative study of operation of AC with two scheduling techniques has been performed. Firstly, a Linear Sequential algorithm (LSA) [7] has been implemented for AC load. The algorithm is indeed simple and fast. Secondly, a scheduling mechanism using mixed integer programming (MIP) technique is applied to obtain the optimal results for AC. The results obtained from both the techniques are then compared.

The paper is organized in V sections. Section I represents the overview of DR. Section II describes the modeling of AC and AC thermostat settings. Section III presents implementation of LSA and proposed scheduling mechanism for AC load. Section IV displays a comparison of the results.
of these techniques. Section V contains the conclusion followed by references.

II. SYSTEM MODEL

Smart grid provides two-way communication infrastructure that enables bi-directional flow of information between utilities and consumers. Smart meter is an important component in this regard. It receives RTP signal provided by utility and sends residential energy consumption details back to the utility. It also enables consumers to monitor the price of electricity throughout the day. Consumer may take necessary action on the basis of electricity price. However awareness as well as active participation of consumer is required for successful implementation of DR program. Therefore fully automatic DR programs with reduced user intervention are getting preference over manual control. These fully automated programs are implemented by installing HEM systems in the houses. Interaction of HEM system with smart meter and home appliances has been shown in Fig. 1. Price information from smart meter and energy consumption of home appliances can be displayed on the display unit. User can specify their comfort settings through the user interface (UI) provided by HEM system. Consumers have the authority of overriding the scheduling decisions of HEM systems, through UI of HEM system. In this study, we are focusing on obtaining optimal scheduling mechanism for centralized AC. Rest of the home appliances are not considered in this study.

Suitable modeling of AC is required for its effective scheduling. AC model along with thermostat settings has been explained as follows:

A. Air conditioner Model

Various models of AC have been presented in the past [2], [3], [8] and [9]. In this work, discrete time model of AC explained in [10] is used. Model relates the inside temperature of the house with outside temperature and ON/OFF state of AC thermostat. The model is as follows:

\[ T_{in}(t) = T_{in}(t-1) + \tau(E(T_{out}(t) - T_{in}(t)) - \phi S_{AC}(t)) \]  

where

- \( T_{in}(t) \) – Inside temperature of a house during time slot \( t \)
- \( T_{out}(t) \) – Forecasted outdoor temperature during time slot \( t \)
- \( S_{AC}(t) \) – Status of AC thermostat during time slot \( t \)
- \( E \) – Warming effect of difference in outside and inside temperature on inside temperature
- \( \phi \) – Cooling effect of ON state of AC on inside temperature
- \( \tau \) – Time interval duration

B. Thermostat Setting of Air conditioner

AC contains a thermostat to maintain the room temperature near the desired set point. We will use two different thermostat control strategies as discussed below:

1) Fixed thermostat control

In Fixed Thermostat setting, set point is maintained at a fixed temperature. The inside temperature of the house is allowed to vary within a dead band around set point. Let \( T_{st} \) be the fixed set point temperature and the dead band is \( \Delta T \). If inside temperature exceeds above \( T_{st} + \Delta T \), thermostat is switched ON. If house temperature is less than \( T_{st} - \Delta T \), thermostat is switched OFF.

2) Variable Thermostat Control

In Variable thermostat setting, set point is varied in response to RTP of electricity as described in (2). Let the variable set point is taken as \( T_{st}(t) \), and dead band for upper temperature limit as \( \Delta T \). Upper limit of temperature varies as \( T_{st}(t) + \Delta T \). However lower temperature limit is considered as fixed. Inside temperature has to be maintained with upper and lower temperature limit. Advantage of this control is that during high price period, thermostat set point is raised. Thus energy required to maintain the temperature near the set point is reduced.

\[ T_{st}(t) = a\lambda(t) + b; \]

where

- \( T_{st}(t) \) – Thermostat set point during time slot \( t \)
- \( \lambda(t) \) – RTP of electricity during time slot \( t \)
- \( a, b \) are constants.

III. SCHEDULING APPROACH

Two scheduling approaches have been presented in this section. They are as follows:
A. Linear Sequential Algorithm

The Sequential algorithm adopted for optimal scheduling of AC is as follows:

Step 1: Hourly Real-time price information of the next day is obtained.

Step 2: Time for which AC needs to be ON is estimated keeping in view the temperature constraints. AC model is run for 24 hours specifying the initial conditions.

Step 3: Threshold price \( \lambda_c \) is obtained from the ascending price curve corresponding to \( T_{ON} \) time.

Control logic for AC is as follows:

\[
S_{AC} = \begin{cases} 1, & \lambda(t) \leq \lambda_c; \\ 0, & \lambda(t) > \lambda_c; \end{cases}
\]

where

\( S_{AC} \) – ON/OFF status of AC thermostat.

Step 4: Obtain the solution of the problem with the status specified in (3). In case of constraint violation, status of AC is changed so as to obtain the solution without sacrificing the user comfort. Calculate total electricity payment for the whole day.

B. Optimization Technique

A MIP optimization problem is formulated to efficiently manage the state of AC thermostat such that the energy consumption cost is minimized. Optimization technique tries to maximize the electricity usage during low cost period. During this process, temperature needs to be maintained within comfortable range. Hence the objective function is specified as follows:

\[
\min C = \sum_t P_{AC} S_{AC}(t) \lambda(t)
\]

For all \( t \in [1,2,\ldots,N] \);

where

\( t \) - Time slot

\( N \) - Total no of time slots

\( C \) - Cost of electricity over the entire time period

\( P_{AC} \) - Rated power of AC

\( S_{AC}(t) \) - Status of AC thermostat during time slot \( t \)

\( \lambda(t) \) - RTP of electricity during time slot \( t \)

subject to

1) Equality Constraint:
   a) Thermal dynamics of centralized AC

Temperature maintained by centralized AC inside the house is governed by (1). Inside temperature at time slot \( t \) depends on the inside temperature at previous time slot \( i.e. t - 1 \) and other factors like ON/OFF state of AC thermostat and difference of inside and outside temperature during time slot \( t \). Energy required by AC to maintain comfortable temperature inside a house depends on status \( S_{AC}(t) \).

   b) Thermostat Setting

Thermostat set point for Fixed and Variable setting is defined as follows:

For Fixed thermostat control

\[
T_{st} = \text{Const}. \quad (5)
\]

For Variable thermostat control

\[
T_{st}(t) = a\lambda(t) + b; \quad (6)
\]

c) Temperature Limits

Upper and lower limits of temperature specified by thermostat set point and temperature dead band are presented below:

For Fixed thermostat control

\[
T_L(t) = T_{st}(t) - \Delta T; \quad (7)
\]
\[
T_U(t) = T_{st}(t) + \Delta T; \quad (8)
\]

where

\( T_L(t) \) – Lower limit for inside temperature

\( T_U(t) \) – Upper limit for inside temperature

For Variable thermostat control

Lower limit is kept fixed in this case as shown in (9).

\[
T_L(t) = \text{Const}. \quad (9)
\]

However, representation of upper limit is same as in (8).

2) Inequality Constraint:
   a) State of thermostat

State of thermostat can be ON or OFF. Thus \( S_{AC}(t) \) is considered as binary variable in the problem. \( S_{AC}(t) = '1' \) represents thermostat is ON, ‘0' represents thermostat is OFF.

\[
0 \leq S_{AC}(t) \leq 1; \quad (10)
\]

b) Inside Temperature constraints

For maintaining a comfortable temperature inside a house, temperature needs to be confined within upper and lower limit.
\[
\begin{align*}
T_L(t) & \leq T_m(t) \\
T_m(t) & \leq T_U(t)
\end{align*}
\] (11) (12)

IV. RESULTS

In this section, we present the results of scheduling of centralized AC obtained from the implementation of LSA and MIP technique. Both the techniques aim to achieve an optimal operation schedule resulting in the reduction of consumer’s electricity bill. AC with both the thermostat settings (Fixed and Variable) are considered while comparing the results of the scheduling techniques. GAMS and MATLAB software are used for implementing the approach.

Smart home is installed with centralized AC of 11.5 kilowatts. Input data required for executing the program are outdoor temperature and RTP of electricity. Outdoor temperature for a typical summer day has been shown in Fig. 2. RTP data is based on day-ahead price variation at Indian Energy exchange [11]. RTP in Rs\(^2\) per kilowatt hour has been shown in Fig. 3. The program is run for a day i.e. 24 hours. Each day is divided into 96 time slots of 15 minute each.

Parameters \(E\) and \(\phi\) for 15 minute interval are taken as 0.0408 and 2.64 respectively.

A. Fixed Thermostat

Fixed thermostat set point of AC in this case is taken as 22 °C. Lower and upper temperature limit has been taken as 20 °C and 24 °C respectively.

As step 1 of LSA, ON time of AC is obtained as 2.5 hours. For obtaining threshold price, RTP price curve arranged in ascending order is shown in Fig. 4. Price threshold comes out to be 2.049 Rs per kilowatt hour corresponding to ON time of AC. Electricity payment in this case, comes out to be Rs 620.58.

On the application of MIP technique, the electricity cost obtained is Rs 557.07. Temperature remains with comfortable range in cases of both the techniques. A comparison of resulting temperature profile is shown in Fig. 5. Average temperature of the house comes out to be little lower in case of MIP technique.

B. Variable Thermostat

Upper temperature limit is varied according to (8). Value \(a\) and \(b\) in (2) are taken as 0.89 and 22 respectively. Lower temperature limit has been taken as 20 °C. \(\Delta T\) is taken as 2 °C.

Application of LSA in case of Variable Thermostat setting results in electricity payment of Rs 463.78. On solving the problem using MIP technique, cost comes out to be Rs 449.54. A comparison of inside temperature of house as a result of application of both the techniques is shown in Fig. 6.

From Fig. 6, we can observe during peak hours, inside

\(^1\)Rs stands for Indian Rupees. Conversion rate: 1 Indian Rupee = 0.016 US Dollar
temperature rises up to 27.85 °C in LSA. However in MIP technique, temperature profile is maintained 0.5°C lower than in case of LSA. Maximum temperature rises up to 27.3 °C in MIP technique. During off-peak price period inside temperature remains within a comfortable range in case of both the techniques. From the above scenarios, we can observe that MIP technique gives improved results.

A comparison of electricity cost via LSA and MIP technique has been shown in Table 1.

TABLE I. ELECTRICITY COST OF AC IN CASE OF LSA AND MIP TECHNIQUES

<table>
<thead>
<tr>
<th>Cost</th>
<th>AC with Fixed Thermostat</th>
<th>AC with Variable Thermostat</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSA</td>
<td>620.58</td>
<td>463.78</td>
</tr>
<tr>
<td>MIP Technique</td>
<td>557.07</td>
<td>449.54</td>
</tr>
</tbody>
</table>

It can be observed that MIP technique gives lesser cost and better temperature profile as compared to the results obtained from LSA technique.

V. CONCLUSION

This study performs a comparative analysis of proposed scheduling technique with LSA. Results show that scheduling technique gives 10% lesser cost than LSA in case of AC with Fixed thermostat setting. In case of Variable thermostat, scheduling technique results in 3% cost reduction as compared to LSA. In Fixed thermostat setting, indoor temperature obtained from both the techniques remains within the specified temperature range. However in case of variable thermostat setting, indoor temperature obtained from solving the problem using scheduling technique comes out to be 0.5 °C below during peak hours than that obtained from LSA technique. Thus adoption of MIP technique will result in reduction in electricity bills of residential consumers and more comfortable temperature inside the house during peak hours.

REFERENCES