Peak Load Scheduling in Smart Grid Communication Environment

M. A. Khan\textsuperscript{1}, N. Javaid\textsuperscript{1}, M. Arif\textsuperscript{1}, S. Saud\textsuperscript{1}, U. Qasim\textsuperscript{2}, Z. A. Khan\textsuperscript{3}

\textsuperscript{1}COMSATS Institute of Information Technology, Islamabad, Pakistan
\textsuperscript{2}University of Alberta, Alberta, Canada
\textsuperscript{3}Internetworking Program, FE, Dalhousie University, Halifax, Canada

Abstract—In this paper, we consider an Energy Consumption Scheduler (ECS) unit inside a smart meter. The function of ECS is to flatten the peaks in the load curve of residential type users. The ECS dually communicates with the user as well as power utility in smart grid real time communication environment. Each user has a specific power capacity limit for their appliances operation. The ECS keeps check and balance condition whenever a user exceeds its power capacity limit. Also the most urgent appliance operations are given priority based on their internal preemption state. By adopting ECS unit, the total peaks in the load curve are reduced up to 33.3\%. Also the user’s payment to the power utility becomes less due to efficiently managing their appliance operations. Additionally, the cost of per unit energy generation is also reduced by avoiding the peak power plants. Matlab/Simulink is used as a simulation tool for the realization of this model.

Index Terms—Smart grid, demand side management, load scheduling.

I. INTRODUCTION

The smart management subsystem includes management and control services. Whereas, smart protection subsystem consists of failure protection, security, reliability and privacy [1]. In USA special attributes used for smart grid. For example, it is self-healing for power disturbance events, provides power quality as needed in 21\textsuperscript{st} century, accommodates the option of Distributed Generation (DG) and storage, active participation by consumers in Demand Response (DR) and protects itself both from physical and cyber-attacks. Additionally, optimization of asset utilization, and more space for new technologies and economic improvements. According to European Commission (EC) report the smart grid must be reliable, economical, accessible and flexible. Nonprofit Joint US-China Cooperation on clean energy defines the smart grid as, a power transmission and distribution system that integrates the elements of conventional and modern power engineering, communication, information and monitoring technology. It also uses sophisticated sensing for better performance and advanced services to customers [2]. The gradual replacement of traditional meters by IC card prepayment meters is also an important aspects of smart grid. Also, standards are developed for security techniques (for example, Q/GDW365 in China). The extensive analysis of Q/GDW365 is presented in [24].

Energy efficiency is one of the most critical issues for existing as well future smart grid. With the advent of new types of loads such as Plug-in Hybrid Electric Vehicles (PHEVs), and the involvement of DG has badly affected the energy efficiency. Different types of techniques are used to improve energy efficiency, i.e., economic dispatch, unit commitment, reducing power transmission & distribution losses, reactive power plant management, load forecasting and proficient attempts to distribute the generated power [18]. In smart grid, Demand side management (DSM) is one of the most attractive areas having a significant impact on energy efficiency [19]. DSM is the planning, implementation and monitoring of those utility activities designed to influence the customer use of electricity in ways that will produce desired changes in the utilities load shape, i.e., changes in the time pattern and magnitude of a utility’s load [3], [4]. The need for DSM was first realized in 1970s [5]. The first attempt towards DSM is the Direct Load Control (DLC). However, in smart grid, smart pricing is an alternate to DLC [6], [7].

II. RELATED WORK AND MOTIVATION

A three layered autonomous DSM model is presented in [7]. This model consists of Admission Controller (AC), Load Balancer (LB), and Demand Response (DR) with Load Forecaster (LF) modules. Loads are categorized based upon their operational characteristics and user requirements. Whenever a user starts an appliance operation, the request is generated by appliance interface for AC to process it further. The AC checks the available capacity. If the capacity is available and also off-peak hours are running, then AC accepts an appliance request and initiates an appliance operation. In case, when an appliance operation exceeds an available capacity, then the request is rejected and forwarded to LB. The LB then solves an optimization problem and assigns a future time slot for that specific appliance to start later. DR and LF is the upper layer and communicates with the smart grid interface for real time information. However, DR and LF
modules are not considered. Also, when the number of appliances request exceeds from a certain level, then the proposed three layered autonomous DSM model cannot maintain the available capacity limit. The results obtained are satisfying. The flaws identified are the motivation of our work.

A game-theoretic approach is used by Mohsenian-Rad A., et al. [8], for residential energy consumption scheduling. The pricing mechanism introduced is based on convex and increasing cost function. The Authors presented a distributed algorithm for optimization problem. This work is considered as a reference for DSM techniques. An alternative mechanism known as Vickrey-Clarke-Grove (VCG) mechanism is proposed in [9]. The aim of this mechanism is to achieve efficiency, nonnegative transfer (i.e., payments from power utility to user) and truthfulness among users. The proposed VCG mechanism encourage users to shift their load from peak hours to off-peak hours. Besides from obtaining social welfare, the utility also gets benefit by getting a reduced average load shape curve. To achieve effective DSM model, pricing scheme also plays an important role. Weighted average filter based price prediction and combining inclining block rates with real time pricing are discussed in [10]. Price predictor and energy scheduler are considered within a smart meter. Overall results of this work is satisfying, however the problem of fairness is not explored. Whereas in [11], a heuristic optimization based DSM is adopted. This model is based on Evolutionary Algorithm (EA). Also a new pricing scheme known as day-ahead load shifting pricing scheme is used. The model is simulated for all types of end user including: residential, commercial, and industrial type. In this model, the authors show that the waiting time of appliances is inversely proportional to the delay of scheduling algorithm. Simulation results are efficient in terms of PAR reduction and total energy cost minimization. However, the fairness issue among users is not addressed in their proposed work.

The above discussed DSM techniques have considered users with a fixed load curve. However, load uncertainty is a big challenge especially in modeling a pricing mechanism. This important issue is considered in [12]. The adopted DSM model forecasts the load curve of the user from the previous knowledge of their energy usage. Real Time Pricing (RTP) and Inclining Block Rates (IBR) are combined for effective pricing mechanism. The mechanism proposed in this model is multi-stage, i.e., information related with appliances revealed after time. The model presented is performing optimization based scheduling. Simulation results show efficiency by reducing total PAR, total energy cost and also fairness. However, the issue of reducing waiting time of appliances is not addressed. Two most effective and related ideas, i.e., fairness and optimality are addressed in [13]. The authors presents an alternative pricing scheme by combing RTP with hour by hour billing mechanism. Analytical case study is evaluated, which shows that the proposed scheme is 73% more efficient in fairness and is inversely related to optimality. Backtracking algorithm, based on artificial intelligence technique for ECS in DSM is proposed [14]. In this technique, RTP billing mechanism is adopted for residential type users. The issues, PAR reduction and execution time of algorithm are achieved effectively. However, all other issues regarding fairness, coverage area and waiting time of appliances are not considered. An alternatively, incentives are provided for users to encourage them to efficiently schedule their load [15]. Comparison of different type of DSM techniques is performed in [20]-[24]. This is practically true if the utility companies provide information about price some hours ahead of usage time. For the communication of smart appliances with ECS, special consideration has been taken in [17]. Zigbee based communication is proposed for remote power controlling at home and at transmission side. In this paper, the authors discussed the effective role of Zigbee in DLC for residential users.

III. SYSTEM MODEL

In this section, the detailed description of load categorization on residential level as well as smart appliances modelling are presented. Moreover, we assume that each residential user is equipped with a smart meter consisting of ECS unit.

A. Load Categorization

In the power sector, users are divided into three main categories: residential, industrial and commercial type. In this paper, we focus only on residential type users (i.e., homes, offices, etc.) due to their high energy consumption profile. Residential users may have different types of loads (e.g., Air Conditioner (AC), refrigerator/ fridge, water heater and washing machine). For simplification, we further divide residential type load into three subcategories based on their internal characteristics. This subcategorization is flexible to prioritize the user’s choice. The users are capable to make changes in their ECS unit through a user interface, according to their own choice. This subcategorization is given below.

1. Must-Run Load (MRL) (e.g., lighting, television, laptop charger, etc.): This type of load consists of users prime appliances. The operation of such appliances cannot be delayed. Moreover, these appliances are not considered by the ECS for efficient energy consumption scheduling.

2. Shiftable Load (SHL) (e.g., dishwasher, washing machine, Plug-in Hybrid Electric Vehicles (PHEVs), etc.): SHL includes all those appliances which have a
specific time period for their operation (i.e., deadline). Their operation can be delayed based on the remaining time for their operation. However, if the remaining time is equal to or less than their deadline, then the operation of SHLs cannot be interrupted any more.

3. Steady load (SL) (e.g. refrigerator, water heater, house heating, etc.): In this sub category, the loads are running steadily, according to their internal temperature control system. Upper and lower temperature limits are defined by thermostat for their operation. Appliance running at these limits is said to be in a comfort zone. As shown in fig. 1, in comfort zone the appliance goes to complete state (5) and then immediately to initiate state (2) and so consumes no power. Additionally, from the complete state (5), the user also changes the state of appliance to off (1) or sleep state (6).

Seven different types of electric appliances are considered for the detailed simulation study of this model. These appliances include water heater, house heating, refrigerator, electric iron, microwave oven, washing machine, and baseline load. The operation of the first four appliances (i.e., SLs) is controlled by thermostat, while microwave oven and washing machine are SHLs having fixed deadline. The MRL is the users prime appliances acting as a constant load, which directly communicates with smart meter, i.e., bypassing the ECS.

B. Modelling of Smart Appliances

In this work, each appliance is considered as a Finite State Machine (FSM) having six different states (as shown in fig. 1): off state (1), initiate state (2), run state (3), interrupt state (4), complete state (5), and sleep state (6).

More specifically, the status of a smart appliance varies among:

- OFF state (1): Appliance is not yet started, and hence consumes no power.
- INITIATE state (2): SWITCH_ON command received, appliance is ready to run. Power consumption is minimum.
- RUN state (3): The START command received from user or from thermostat, and so rated power consumption.
- INTERRUPT state (4): User wants to interrupt appliance during operation, so HALT command asserted and the appliance absorbs minimum power (e.g., thermostat).
- COMPLETE state (5): Appliance operation completed, jump to initiate (2), sleep (6) or off (1) state.
- SLEEP state (6): An auxiliary status for power saving option.

IV. SIMULATION STUDIES

In this section, we discuss the setup of simulation as well as simulation results.

A. Simulation Setup

For simulation purpose, all seven types of appliances are modeled using Matlab/Simulink with Stateflow toolbox. The power consumption for each appliance is assumed to be 20 watts. The lower and upper limits of temperature for the water heater is 20°C and 60°C respectively. Similarly, for house heating and refrigerator the temperature ranges are 22°C - 24°C and 2°C - 5°C respectively. However, the accuracy, power consumption, and constraints of a practical model of these appliances may be different.

The time span for simulation is set to 30 minutes. The water heater, house heating, and refrigerator are modeled using the combination of one dimensional Fourier’s law in its integral form for homogeneous material (1) and 1-D specific heat equation (2) given in [16].

\[
\frac{\partial Q_{exch}}{\partial t} = -K \oint_{s} \nabla T.dA \quad (1)
\]

\[
Q_{total} = mc\Delta T \quad (2)
\]

where,

\[
\Delta T = T_{external} - T_{room} \quad (3)
\]

\[
Q_{total} = Q_{exch} + \eta_{h}P_{h} \quad (4)
\]

\(T_{external}\) is the external temperature, \(P_{h}\) is the heater power, \(\eta_{h}\) is the heating system thermal efficiency, \(K\) is room global thermal conductivity, \(Q\) is the heat transferred and \(m, c\) are the mass and specific heat capacity of air respectively.

The electric iron is modeled upon the principles of thermostat. Upper and lower threshold limits of temperature are defined for their operation. The burst loads, microwave oven and washing machine have a fixed deadline. They can be interrupted during their operational time if they have enough time remaining to complete their operation and hence a preemptive state of zero. However, when their preemption state becomes one (i.e., active), then burst loads cannot be delayed anymore due to their internal characteristic.

B. Simulation Results

Fig. 2, shows the refrigerator FSM implementation in Stateflow toolbox. Only three status of refrigerator is considered for the simulation: initiate state (2), run state (3) and complete state (5). The characteristic curves of refrigerator and house heating are presented among SLs in fig. 3. The x-axis shows time in minutes and the y-axis represents status, preemption, absorption and
Fig. 1. FSM for smart appliances modeling.

TABLE I

LIST OF TYPICAL HOUSEHOLD APPLIANCES AND THEIR CHARACTERISTICS

<table>
<thead>
<tr>
<th>Appliance</th>
<th>Power (W)</th>
<th>Temp. Range (°C)</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Heater</td>
<td>1380-2300</td>
<td>20-60</td>
<td>Status, Preemption, Absorption, Temperature</td>
</tr>
<tr>
<td>Refrigerator</td>
<td>3100-6400</td>
<td>2-5</td>
<td>Status, Preemption, Absorption, Temperature</td>
</tr>
<tr>
<td>House Heating</td>
<td>1000-5000</td>
<td>22-24</td>
<td>Status, Preemption, Absorption, Temperature</td>
</tr>
<tr>
<td>Microwave Oven</td>
<td>600-1500</td>
<td>25-10</td>
<td>Status, Preemption, Absorption, Temperature</td>
</tr>
<tr>
<td>Washing Machine</td>
<td>300-500</td>
<td>——</td>
<td>Energy and water consumption, Spin-drying ef-</td>
</tr>
<tr>
<td>Clothes Iron</td>
<td>1000-1800</td>
<td>90-230</td>
<td>Status, Preemption, Absorption, Temperature</td>
</tr>
<tr>
<td>Baseline Load</td>
<td>Variable</td>
<td>——</td>
<td>Lighting, Entertainment, Office work</td>
</tr>
</tbody>
</table>

Fig. 2. Implementation of refrigerator FSM in Stateflow toolbox.
Fig. 3. Characteristic curves of house heating.

Fig. 4. Characteristic curves of refrigerator.

Fig. 5. Combination of overall loads in Simulink.
temperature values respectively. In case of refrigerator, the status shifts between initiate (2) and run state (3). The preemption value shows that a task of an appliance can be interrupted or not. The power consumption of appliances is represented by an absorption curve. The maximum power consumption that an appliance is used for its operation is assumed 20 watts. The lowermost curve shows the temperature of refrigerator in degree centigrade. The comfort zone for refrigerator is $2^\circ C$ - $5^\circ C$. In case of house heating shown in fig. 4, the status is varying between initiate (2) and run state (3). However, at 21 minute of simulation, the status jumps to complete state (5) because the comfort zone (i.e., $22^\circ C$ - $24^\circ C$) has been reached.

The combination of overall loads in Simulink is given in fig. 5. Fig. 6 shows the overall load curve and the individual curve of each appliance. The highest peak load is observed during the fifth minute of simulation, reaching up to 120 watts. In this simulation, no scheduler is used to manage the load. Requests coming from all types of appliances are accepted and turned on without checking any condition. As a result, the peak is generated in the overall load curve, which is undesirable. The simulation results shown in fig. 7, demonstrate the behavior of the scheduler by maintaining the peaks in the load curve within certain limits. The same set of appliances are considered again. In this simulation, the scheduler is set to limit the total load curve within 80 watts power limit.
As shown in fig. 6, the limit of 80 watts is only exceeded between 3 to 10 minutes of simulation. So, the scheduler is working on these time limits only to manage the peaks of the overall load curve. In this paper, the peak load is reduced up to 33.3%. So, the users payment to the utility is also reduced by the same amount.

V. CONCLUSION

The work presented in this paper is based upon online power scheduling in smart grid communication environment. The ECS installed inside the smart meter, is responsible for efficient power scheduling of residential type users. The users equipped with ECS, have a power consumption limit depending upon their load requirement. Whenever an appliance starts an operation, it initially sends an admission request to ECS. The ECS concern the power utility through smart grid interface for the power capacity limit of that specific user. If there is enough power capacity limit, the appliance is allowed to operate. Otherwise, the appliance operation request is deferred. Also, the ECS checks the preemption value of each appliance. If an appliance has a preemption value of 1, it is given priority. The less urgent appliance operation having a preemption value of 0, is replaced by the more urgent appliance operation having a preemption value of 1. By applying the proposed ECS mechanism, simulation results show that the peak load is reduced by 33.3%.

REFERENCES