A New Scheme for Demand Side Management in Future Smart Grid Networks

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Abstract

This paper presents a new energy consumption scheduling scheme to enable Demand Side Management (DSM) in future Smart Grid Networks (SGNs). Electrical grid has been facing important challenges regarding quality and quantity to meet the increasing requirements of consumers. Environment friendly and economical generation along with efficient consumption through effective DSM in future SGNs will help in addressing most of these challenges because of integration of advanced information and communication technologies. In this work, we propose an autonomous energy scheduling scheme for household appliances in real-time to achieve minimum consumption cost and reduction in peak load. We assume that every user is equipped with smart meter which has an Energy Consumption Controlling (ECC) unit. Every ECC unit is connected with its neighbours through local area network to share power consumption information. ECC units run a distributed algorithm to minimize the peak load by transferring the shiftable loads from peak hours to off-peak hours. This ultimately minimizes the total energy consumption cost. Simulation results confirm that our proposed algorithm significantly reduces the peak load and energy consumption cost.

Keywords: Smart grid; Demand side management; Optimal energy consumption; Appliance scheduling; Peak load reduction.

1. Introduction

Energy efficiency, reliability, economic constraints and integration of renewable energy resources are important issues to enhance the stability of power system infrastructure. Increasing population and energy demand have worn out the traditional grid which has been serving the humanity since decades. Inclusion of a large number of electric appliances brings instability to the existing grid¹. Demand curve of traditional grid is characterized with a steep peak which is caused by accumulation of heavy loads during peak hours. This situation leads utilities to rely on the expensive peaker plants in order to fulfil the peak demand. Usually peaker plants are thermal power plants and their

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excessive use results in high emissions of Green House Gases (GHGs). Increasing energy demand and its dependency upon fossil fuels have raised serious environmental concerns.

Integration of bidirectional communication, networking and advanced control technologies for monitoring and supervision of power systems will formulate smart grid. This integration will bring more automation, reliability of electrical services, safety of electrical equipments and ultimately boost the consumers’ comfort level. Smart grid automates the energy management upon the basis of information gathered from energy suppliers and consumers. This results in improved load management and energy efficiency. Smart grid can integrate distributed power resources efficiently. This locally generated power can be sold to the grid by feed in tariff after fulfilling the local requirements. Efficient electricity consumption has been proven beneficial economically and socially.

Introduction of new and versatile electrical loads like Plug-in Hybrid Electric Vehicles (PHEVs) etc. has raised the demand exponentially. Peak load management becomes more significant in context of this increased load. Smart grid implements AMI for load prediction in residential areas and improves energy efficiency. It will help in reducing the wide use of thermal power plants to meet the peak demands. This reduction in CO₂ and GHGs emission is necessary to address the serious environmental issues.

Smart grid enhances the customers’ satisfaction because of the bidirectional communication which enables the effective DSM programs. DSM consists of the activities designed for influencing the behaviour of customers regarding their electricity consumption. It also includes different other schemes like installation of load limiters, Direct Load Control (DLC) etc. Early DSM schemes were introduced in late 1970s. A major portion of the global power consumption is reported in buildings which is approximately 40%.

Various dynamic and effective schemes for autonomous DSM in smart grids have been found in literature. Authors in discussed a scheduling model in which a layered structure consisting of three modules for admission control, load balancing and demand response management is used to control the peak load demand. Run-time scheduling is used to control the appliances in order to meet the power capacity limit. In , backtracking based scheme is used to schedule the home appliances for local and global peak load reduction. This scheduling model consists of actuation time, operation length, dead line and consumption profile. Scheduler copies the profile entry of different appliances one by one according to task profile in allocation table. In , a game-theoretic model based optimization technique is discussed to schedule the energy consumption of appliances. Game theory is implemented to minimize the peak load and reduce the energy consumption cost. In this scheme, users are players and their daily use of appliances are strategies. Optimal performance in terms of energy cost minimization is achieved at Nash equilibrium of energy scheduling game. Presented model considers a common scenario where a single utility company serves different users. This model systematically manages the appliances schedule and shifts them in order to reduce energy cost. has explained an incentive based energy consumption scheme to reduce the peak load demand and energy cost. In , an automatic and optimal energy consumption scheduling scheme is proposed to minimize the PAR and reduce the waiting time of each household appliance operation. For optimal scheduling of appliances, residential load controller requires the capability to predict the prices in real time. Vickrey-Clarke-Groves (VCG) mechanism is proposed in to maximize the social welfare i.e. the difference between aggregate utility function of all users and total energy cost to the provider.

Present work focuses on an energy consumption scheduling scheme to meet the peak load demand and reduce the monetary cost. Pricing strategies are also involved in scheduling the appliances in real time. In our proposed scheme, a central processing unit is the decision making centre and we call it as Energy Consumption Controlling (ECC) unit. ECC units are used for scheduling the household appliances. We consider that smart meter of every subscriber is equipped with an ECC unit. These ECC units are also connected with neighbouring units through Local Area Network (LAN) to share information about power usage and interact with each other in real time for feasible energy consumption scheduling. By running a distributed algorithm in each ECC unit, all users automatically interact and overall system’s performance is improved. By scheduling the appliances, heavy loads are shifted from peak-hours to off-peak hours according to their energy consumption profile. Peak demand is reduced by controlling the appliances in different ways and consequently the energy cost is reduced significantly.

Remaining sections are sequenced as: section 2 is reserved for power system modeling, section 3 elaborates the proposed algorithm and section 4 describes the simulation results. Conclusions are drawn in section 5.
2. Power System Modeling

The power system model given below is based on the work of 9. This model considers a set of consumers, in the assumed smart grid scenario, who obtain electricity from a single power supplying company as elaborated in Fig. 1. In the power system model, consumer requests are taken as input which are then used to generate an optimum scheduling of the home appliances as output in order to minimize peak demand and total energy cost. Appliances operating in off-peak hours cost less as compared to peak hours because of the Time of Use (TOU) pricing which is easily implementable in smart grid.

Consider all users \( n \in \mathbb{N} \); in this set, each user have set of appliances denoted by \( A_n \). Every one has 10 appliances.

For each appliance \( a \in A_n \), we specify an energy consumption scheduling vector as presented in 9:

\[
\mathbf{Z}_{n,a} \triangleq [z_{n,a,1}, \ldots, z_{n,a,H}]
\]

(1)

Where

\( z_{n,a,h} \): Energy consumption of appliance “a” scheduled for 1 hour from user n.

We also define:

\[
E_{n,a} = \sum_{h=1}^{H} z_{n,a,h}
\]

(2)

Each user “n” specify his total daily energy consumption of appliance “a”, denoted by \( E_{n,a} \), defined by user according to consumption profile, e.g. \( E_{n,a} = 16 \text{KWh} \) for a Plug-In Hybrid Electric Vehicle (PHEV) for a daily driving range of 40 mile. An objective function for daily predetermined energy consumption of user “n” is also defined. Each appliance is scheduled according to its daily predetermined energy consumption that is:

\[
\sum_{h=\beta_{n,a}}^{\gamma_{n,a}} z_{n,a,h} = E_{n,a}
\]

(3)

Where, \( E_{n,a} \): Predetermined daily energy consumption of appliance “a”.

\( \beta_{n,a} \): Interval starting time that appliance consumption can be scheduled.

\( \gamma_{n,a} \): Interval end time that appliance can be scheduled.

Fig. 1: Smart grid power architecture.
To find the optimal solution, we divide the time span of 24 hours into equal time slots. Let \( h \in H \) be the hour of the day, then total load at each hour “\( h \)” is:

\[
L_h \triangleq \sum_{n \in N} p_{n}^{h}
\]  

(4)

We propose a cost function \( C_h(E_h) \) that shows cost of energy in each hour “\( h \)” provided by the utility company. Energy consumption cost is different in peak hours and off-peak hours because per unit cost is different.

Consumers’ energy demand increase during peak hours. Utility companies run peaker power plants to meet this peak demand during peak hours. Peaker plants charge higher prices per kilowatt hour. So per unit cost increases in peak-hours. We consider peak hours between 6:00 PM to 10:00 PM (18 to 22). Electricity price per unit in peak hours is greater than the per unit price in off-peak hours.

\[
U_{hp} > U_{ho}
\]  

(5)

Where

\[
1 \leq h_o \leq 17, \quad 23 \leq h_o \leq 24, \quad 18 \leq h_p \leq 22
\]

Per unit electricity prices are:

Electricity price per unit (\( U_{ho} \)) in off-peak hours = Rs. 8.2/KWh
Electricity price per unit (\( U_{hp} \)) in peak hours = Rs. 13.6/KWh

The cost function of off-peak hours and peak hours is given as:

\[
C_h(E_h) = \begin{cases} 
\sum_{a=1}^{A} \sum_{h=1}^{h_o} E_{n,a}^h U_{ho} & \text{if off peak hrs} \\
\sum_{a=1}^{A} \sum_{h=18}^{h_p} E_{n,a}^h U_{hp} & \text{if peak hrs}
\end{cases}
\]  

(6)

The cost function of 24 hours will be the sum of peak hours and off peak hours and given as:

\[
C_h = C_{ho} + C_{hp}
\]  

(7)

The loads have been divided into two types, shiftable loads and non-shiftable loads. The shiftable loads are the appliances whose operation can be shifted to off-peak hours with minimum comfortability loss to the consumer e.g. washer, dryer, PHEV etc. On the other hand the operation of non-shiftable loads cannot be delayed e.g. refrigerator, lighting etc. Appliance minimum standby power level is defined by \( \alpha_{n,a}^{min} \) and maximum power level \( \alpha_{n,a}^{max} \). To minimize the peak load in peak hours, optimal scheduling of appliances can be achieved by solving the following optimization problem:

\[
\text{minimize} \sum_{h=1}^{H} C_h \left( \sum_{n=1}^{N} \sum_{a=1}^{A} (z_{h,n,a}^{h}) \right) 
\]  

(8)

s.t.

\[
E_{n,a} = \sum_{h=1}^{H} z_{n,a}^{h} \quad \forall a \in A_n, n \in N, \\
z_{n,a}^{h} = 0 \quad \forall h \in H \setminus H_{n,a}, \\
U_{hp} > U_{ho} \quad \forall h \in H.
\]

The above problem minimize the peak load in peak hours and reduce the energy consumption cost.
3. Proposed Algorithm

In this section, we propose an energy consumption scheduling algorithm to enable DSM in future smart grid. ECC units are used for optimal scheduling of appliances. We consider that each user is equipped with smart energy meter. ECC units are embedded in smart meters for interaction among users and bidirectional communication through LAN. The aim of this scheme is to decrease the electricity bill of the consumer by shifting the appliances operation from peak to off-peak hours. The consumer may turn on any appliance at any moment irrespective of the peak hours concern and ECC unit suggests a convenient start time to the consumer. ECC unit provide feasible schedule to all household appliances. The proposed algorithm is shown in Fig. 2 and steps are defined as:

**Step-1:** In our proposed algorithm, the nth user turns on his ith appliance randomly. The request of nth user for ith appliance is generated randomly. The appliance is not switched ON immediately, in fact the request is sent to ECC unit.

**Step-2:** When ECC receives the request, it confirms the peak hours condition. If the condition is not satisfied, appliance “i” is switched ON immediately. Otherwise the algorithm moves to next step. ECC communicates with smart meter to know about the time of use (ToU) prices. The ToU prices scheme informs the ECC unit about the corresponding energy consumption prices at that particular moment.

**Step-3:** During peak hours, ECC unit checks all the standby appliances in home and turns off all, irrespective of their requests to be switched ON, as it has been reported that a significant amount of energy has been wasting in standby state of appliances.

**Step-4:** In peak hours, ECC inquires about nature of the appliance to be switched ON. The appliance may be a shiftable load e.g. a washer or a non-shiftable load e.g. refrigerator. If the received request belongs to a non-shiftable load, the appliance is switched ON immediately. Otherwise the load is scheduled to be operated with some delay according to delay condition. Ultimately the appliance operation is shifted from peak to off-peak hours.

**Step-5:** In case of a shiftable load in peak hours, ECC reads the power ratings of the corresponding appliance and compares it with preset threshold value $P_{max}$. For all $P_i \leq P_{max}$, the appliance is directed to start immediately otherwise the algorithm moves to the next step. If the power ratings of the ith appliance is less then the fixed threshold value $P_{max}$, the appliance is switched ON immediately without any delay. Otherwise the algorithm moves forward to the next step.

**Step-6:** If peak hours condition is satisfied, shiftable appliance having rating greater than the threshold value, the operation of appliance is shifted from peak to off-peak hours. A delay factor is introduced for the operation of each appliance cycle. As the appliance operational cycle has been delayed, and it is shifted from peak to off-peak hours, a delay $d_i$ is introduced which is equal to the difference of the scheduled time suggested by ECC unit and the request.

Fig. 2: Flow chart of proposed scheme.
start time. This delay is inversely proportional with comfortability level of consumer. They are never satisfied with large delays so we have introduced a threshold value of delay called $D_{\text{max}}$. If $d_i$ is greater than $D_{\text{max}}$ the appliance is directed to start immediately otherwise the operation cycle of $i_{th}$ appliance is shifted. This load shifting will help in reducing the peak demand and hence minimize the electricity bill of the consumer.  

**Step-7:** After each request, ECC schedules the appliances and sends a control message to other users. According to this scheduling message, other users schedule their appliances.  

**Step-8:** If a control message is received from any other user then user should update its local memory.  

### 4. Simulation Results  

We consider the scenario of smart grid system where N=10 users; all users are equipped with ECC units. Each user has 10 major appliances with shiftable and non-shiftable operation. We include 4 shiftable appliances and 6 non-shiftable appliances. Appliances with shiftable operation i.e., with scheduling constraints of soft energy consumption are called shiftable appliances. We consider 4 shiftable appliances in our scenario i.e., washer (daily usage: 3.4 kWh), dryer (daily usage: 2.5 kWh), dishwasher (daily usage: 7.1 kWh) and PHEV (daily usage: 9.9 kWh). Non-shiftable appliances are those with non-shiftable operation i.e., with strict energy consumption scheduling conditions. We consider 6 non-shiftable appliances i.e., Electric stove (daily usage: 4 kWh), entertainment (daily usage: 3 kWh), refrigerator (daily usage: 2.3 kWh), lighting (daily usage: 2 kWh), air conditioner (daily usage: 1 kWh), fan (daily usage: 0.04 kWh).

In our scheme, we schedule the appliances from 12:00 AM to next day 12:00 AM. We consider peak hours between 6:00 PM to 10:00 PM. We apply Time of Use (ToU) pricing scheme in our model. Per unit electricity price is different in peak hours and off-peak hours. Electricity price per unit ($U_{\text{hp}}$) in peak hours = Rs. 13.6/KWh and electricity price per unit ($U_{\text{op}}$) in peak hours = Rs. 8.2/KWh. All users ON their appliances randomly.

The simulation results of our proposed energy consumption scheduling scheme is quite efficient in terms of reducing peak load demand, electricity consumption charges with an increase in comfortability level of consumers. Our proposed technique shifts the household appliances from peak to off-peak hours and peak demand is reduced with a different design approach. Our scheme has referred to the well known problem of peak load reduction for grid stability and energy cost saving. Optimal scheduling manages the appliances in such a way that operation of heavy loads is shifted to off-peak hours. For optimal scheduling, our scheduling scheme tackles this problem by introducing a threshold value of energy consumption in the peak hours and off-peak hours. If an appliance ratings are higher than the threshold value; its operation cycle is shifted to off peak hours. As in the future smart grid both power companies and users can take advantage from economical and environmental aspects of smart pricing models\(^1\). Electricity prices increased during peak hours and low during off-peak hours. Therefore consumers avoid high price peak hours and shift their heavy loads to off-peak hours.

Our scheme has referred to the problem of minimizing energy wastage by standby devices in home. Standby power of an appliance is the power consumed by the appliance when it is not functioning or when switched off. Standby appliances are consuming 10% of electricity\(^1\). Standby devices have been reported to contribute to electricity wastage and hence it was necessary to tackle the wastage due to standby appliances during the scheduling of household appliances to enable DSM. Furthermore our proposed scheduling scheme contributes more to comfortability level of the consumer by putting a limit on the delay factor of an appliance. If the appliance cycle is shifted to off peak hours and the delay goes beyond the limit the cycle is retained and the appliance is switched ON immediately.

#### 4.1. Peak Load Reduction  

Fig. 3 shows the energy consumption of users with scheduling and without scheduling in 24 hours. In peak hours, load increases to 33kWh. When we schedule the appliances according to our proposed scheme, load evenly distribute over the entire day. Energy consumption reduces to 24%. Fig. 4 shows the percentage load of each user in peak hours with scheduling and without scheduling of household appliances. Simulation results show that when ECC units are not implemented in smart meters (without scheduling of household appliances), the percentage load is high. In our scheme, ECC unit schedules the energy consumption more efficiently reduces the peak load to 24%.
4.2. Monetary Cost Minimization

We also minimize the monetary cost by applying our efficient energy consumption scheduling scheme for load management. Energy consumption cost without scheduling and with scheduling of appliances shown in fig. 5. When users equipped with ECC units in smart meters and all subscribers utilize the energy consumption in efficient way; consequently energy cost reduces by 21%. By scheduling of energy consumption, monthly bill of each user also reduces. Monthly bill reduction of each user is shown in Fig. 6 which shows that with scheduling of appliances each user pays less to the utility. Ultimately the subscribers might be willing to engage in the intended DSM scheme.
5. Conclusion

In this paper, we proposed an autonomous and distributed energy consumption optimal scheduling scheme in order to minimize the peak demand and total energy cost. This scheme has evenly distributed consumers’ load over entire day and balanced the residential load in scenario where different users are connected to a single power supply company. We also focus on the interaction among users for energy consumption information exchange. Simulation results confirm that our proposed autonomous demand side load management strategy efficiently reduce the peak demand and energy cost. In the future work, our scheme can be extended for integration of renewable energy resources available at users’ premises and inclusion of feed in tariff. Second, it is interesting that our model can be modified for optimality of user comfortability.

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