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Autonomous Demand Side Management using Demand Response in Residential Sector - A case study in Sanothimi, Nepal

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Abstract

The electricity sector is facing a major challenge of energy deficit as well as energy surplus problem in different period of the day. Power deficit in evening and morning time and surplus in the midnight and day is the general trend of the residential energy consumption. To cope with this challenges, Demand side management plays the vital role. This study discuss the autonomous demand side management in Real time pricing environment incorporating game theoretic energy consumption scheduling, focused on reducing the daily billing cost of electricity. The solution of the problem is by finding the optimal peak to average demand ratio of the system by scheduling the different appliances of consumers. In this research a household survey is done to know the demand profile over different seasons of the 220 voltage single phase distribution feeder from a typical residential area of Kathmandu valley, Sanothimi, consisting 122 consumers, each having 13 numbers of appliances considered for the study and the appliances are categorized as shift-able and non-shift-able appliances. Shift able appliances are re-scheduled so as to reduce the peak. In this study, the autonomous scheduling is considered to avoid the manual switching inconvenience and this function is done by Energy consumption scheduler(ECS). The ECS minimizes the peak to average ratio of system demand, rescheduling the shift able appliances. To change the consumer behaviour the pricing of electricity is made based on the demand of the system. The result shows that if the demand of the system is less, then the electricity cost also be less and vice versa. The simulation result confirms the reduction of peak in all seasons of the year. In the average load curve, the system peak clipped from 72.805kW to 52.105kW and filling of the valleys of the load curve thereby improving the load factor of the system from 27.4% to 38.8%.

Keywords

Demand Side Management, Energy Consumption Scheduler, Peak to Average ratio, Demand Response, Dynamic Pricing, Load Factor

1. Nomenclature

DR	Demand Response
RTP	Real Time Pricing
ECS	Energy Consumption Scheduler
N	The set of users
PAR	Peak to average ratio
l_n^h	Total load at hour, $h \in H = 1,2,\ldots,H$
A_n	Set of household appliances, $a \in A_n$
$X_{n,a}$	The corresponding half-hour energy consumption that is scheduled for appliance 'a' by user 'n'
$\alpha_{n,a}$	Starting time
$ß_{n,a}$	Ending time
E_n	Total energy consumed by all appliances

2. Introduction

A power system is stable and reliable up to when the power supply and power demand are equal. Balancing the supply and demand would be a major challenge necessitating larger amount of operating reserve from energy storage, demand reduction etc [1]. The electricity consumption pattern is not uniform throughout the day. Variations in demand during a day are mainly due to changes in the level of electricity-driven activities at different times [2]. The concentrated activities in morning and evening causes the peaking in power demand, while mid day and mid night may face a significant fall in power demand in residential sector which cause the power deficit to mitigate the demand in peak load time and on the other hand, increase in transformer and line loading thereby increasing the power loss as well as the voltage drop up to the service main. Traditionally, smart pricing like Time of use pricing, critical-peak pricing has been adopted to decrease the peak to average ratio of electricity consumption. But this method required a centralized control, which was ineffective because of many reasons like those techniques merely shifted the peak from one hour to next hour. Further, users don't entertain when there were some aggregators controlling their pattern of electricity use.

Demand side management (DSM) refers to incentives that utility offer to its clients so that the users optimize their energy use. This paper introduces a concept of DSM for the appliances scheduling optimization and proposes an incentive-based energy scheduling scheme. For the optimization, the objective function is the minimization of the energy charge paid by the consumer, keeping the total energy before and after RTP must be same and the energy charge be the function of the Real time demand of the system. In the optimization model, Appliances of each users are categorized as shift able and non-shift able loads. Shift able loads can be shifted in scheduling optimization while the optimization problem can not reschedule the non-shift able load.

The vital part of the this DSM scheme is ECS, which is a smart instrument whose function is to schedule the energy consuming devices. It receives the signal from system and sends its energy consumption information to system as well. The ECS is nothing but a smart switches which can discriminate the shift able and non-shift able load of the house hold and gives an optimized schedule.

A binary programming is proposed for solving the problem in order to achieve the best result as the objective of the study is to give an energy consumption schedules of the appliances for each users. Therefore, the binary variable 0 or 1 would represent on or off state of the appliances. For that CVX, a MATLAB-based modelling system is used. CVX supports a number of standard problem types, including linear and quadratic programs, second-order cone programs (SOCPs), and SDPs [3]. CVX turns MATLAB into a modelling language, allowing constraints and objectives to be specified using standard MATLAB expression syntax [4]. The optimal load scheduling program can be determined using an optimization model which gives the cost effective energy consumption scheduling vector for each user controlled autonomously by an ECS. ECS, is a smart instrument whose function is to schedule the energy consuming devices. It receives the signal from system and sends its energy consumption information to system as well and it is nothing but smart switches which can discriminate the shift able and non-shift able load of the house hold and gives an optimized schedule [5].

In Nepal, 93.83% of electricity consumers are covered by residential sector [6]. Nepal managing its peak demand by importing electricity from neighbouring country India. Out of total 19288 MWh demand, only 8410MWh is covered with domestic Generation [7]. To reduce the dependency and the trade deficit, it seems the clear necessity of immediate peak reduction. The proposed model is adopted to find the optimal appliances scheduling for single phase residential users in a typical residential area placed in Sanothimi, Bhaktapur Nepal, under a 100kVA secondary distribution transformer.

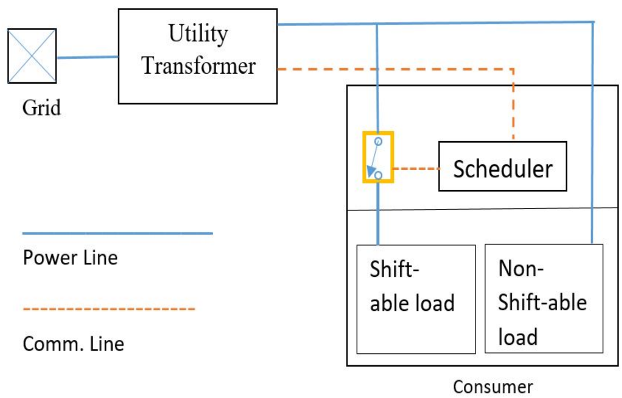

Figure 1: ECS Basic Architecture

3. System Model

Consider a smart power system with distribution lines connected with a appropriate means of communication.

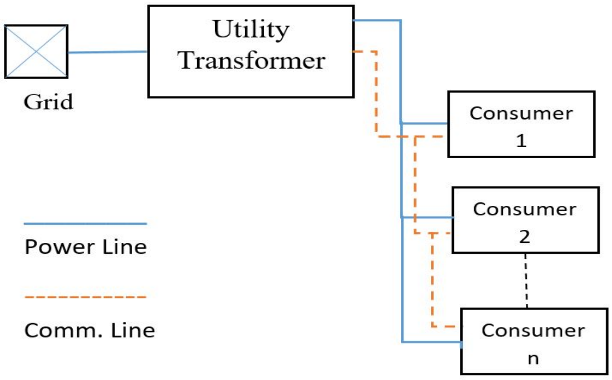

Figure 2: Distribution network

Without loss of generality, the granularity of time is taken as one-half hour. The total load across all users at each half-hour of the day $h \in$ H an be calculated as,

$$L_h \equiv \sum_{n \in H}^{n} l_n^h \tag{1}$$

The daily peak and average demand of the system are calculated as,

$$L_{peak} = max(L_h) for h \in H and \tag{2}$$

$$Ł_{avg} = \frac{(\sum_{n \in H} L_h)}{H} \tag{3}$$

$\therefore$ the PAR of the system is,

$$\text{PAR} = \frac{L_{peak}}{L_{avg}} \tag{4}$$

3.1 Cost Model

It is assumed that the cost of electricity is varying for the varying system demand. As the system demand increases the cost of electricity also increases and decreases for the reduced system demand.

The cost considered for the optimization is the day long cost of the total consumer n. Per unit cost at hour h is being given by a linear function of system demand,

$$PUC = a * L_h + b \tag{5}$$

Total cost in hour given by:

$$C_h = a * L_h^2 + b * L_h \tag{6}$$

where $a > 0$ and $b, c_h \geq 0$

3.2 Residential Load control

The time interval for which appliance a can be scheduled equals to its predetermined daily consumption schedule. That means the model can not decrease the total operating time of the the appliances.

$$\sum_{h \in \alpha_{n,a}} x_{n,a}^h = E_{n,a} \tag{7}$$

And,

$$x_{n,a}^h = 0 \qquad \forall h \in H \backslash H_{n,a} \tag{8}$$

where, $H_{n,a} \equiv \{\alpha_{n,a}, \ldots, \beta_{n,a}\}$

Then Energy balance equation is,

$$\sum L_h = \sum_{n \in H} \sum_{a \in A_n} E_{n,a} \tag{9}$$

The model can not reschedule the appliances beyond the limit given. For the simplicity of the notation, is formed by stacking up energy consumption schedule vectors X_n for all appliances $a \in A_n$. The problem now boils down as:

$$X_n = \{x_n \| \sum_{\alpha_{n,a}}^{\beta_{n,a}} = x_{n,a}^h = E_{n,a}, x_{n,a}^h = 0,$$
$$\forall h \in H \backslash H_{n,a}, \gamma_{n,a}^{min} \leq x_{n,a}^h \leq \gamma_{n,a}^{max} \forall h \in H \backslash H_{n,a}\} \tag{10}$$

3.3 Optimization Problem

The objective of the proposed system is to minimize the peak to average ratio. Therefore PAR minimization is formulated as below,

$$\textbf{minimize} \left(\frac{L_{peak}}{L_{avg}} \right)$$

4. Data Collection

In this study, a part of typical residential area of Kathmandu valley, Sanothimi is considered. The reason is, it is purely a residential area. There are no commercial and industrial load connected to this secondary distribution feeder, therefore the whole load can be studied as a residential load.Sanothimi is the western part of the Bhaktapur district in State 3 of Nepal and laying on the boarder of the capital city of

Nepal, Kathmandu. A central area of Sanothimi town is selected so as to avoid the effect of other commercial and industrial loads, where 122 consumers are connected to the 100kVA secondary distribution transformer.

Figure 3: Study area in map [source: Google Map Imagery, 2019]

To determine the existing load characteristics of consumers, a load survey is done for the consumer. The algorithm of data collection and processing are as followings.

1. Questionnaire design
2. Identify the appliances and their usage pattern for the users
3. Calculate the daily and monthly and seasonal electricity consumption of consumer n as per the answer received from Consumers
4. Find the 12 months energy consumption of consumer n from utility
5. Determine the deviation of surveyed energy consumption(3) and actual energy consumption got from 4.
6. If deviation is under limit, i,e., (Deviation $\geq$ 10%), Discard the sample, otherwise go to 7.
7. Select the sample.
8. Count the number of sample(n_0)
9. Calculate the sample size of the total population for 95% confidence interval
10. Check n_0, if (n_0 $\geq$sample size), go to 11 otherwise go to 2.
11. Finalize the sample n for the research.

With this approach, out of 122 consumers, each of them were provided the questionnaire to achieve the demand profile of each appliances of all four seasons of the year(spring,summer,autumn and winter) and the energy consumption of each user is compared to the utility data and all of them falls under 10% deviation limit. The 100 samples out of 122 total population, the sample size holds the 95% confidence level with 4.2% margin of error as per determined by the Slovin's formula [8].

$$n_0 = \frac{N}{1+Ne^2}$$

where, N= Total population size. e= Margin of error.

5. Model setup

100 residential users served by a utility company is considered for the simulation setup. Each user consists of 13 numbers of appliances, which are categorized as shift able and non-shift able appliances.

Table 1: Non-shift able Appliances and their general consumption pattern(in hours)

Appliances	Morning shift	Evening shift	Duration
Lighting	5 to 7	6 to 12	4 to 9
Space heater	Random	Random	2 to 8
Fan/cooler	Random	Random	2 to 8
Refrigerator	-	-	24
Routers/Modems	-	-	24
Television	Random	Random	2 to 8
Phones charging	5 to 8	18 to 24	2 to 4
Computer	Random	Random	2 to 6

Table 2: Shift able Appliances and their general consumption pattern(in hours)

Appliances	Morning shift	Evening	Duration
Induction Heater	7 to 9	6 to 8	1 to 3
Hotplate	7 to 9	6 to 8	1 to 3
Oven	7 to 9	6 to 8	0.5 to 2
Induction motor	Random	Random	0.5 to 1
Washing Machine	Random	Random	0.5 to 1
Laptop	Random	Random	2 to 4

A model is developed consisting of 100 users with 13 numbers of appliances. Each consumers operate their appliances as their intended time throughout the day. Then Energy consumption schedule is tabulated in Spreadsheet for each user over a 48 time slot in a day. The spreadsheet file is then imported to MATLAB in order to process the data. With the MATLAB, the load duration curve of each user and system is extracted.

A CVX, convex programming approach is used to solve the QP problem which is formulated in previous section. It is assumed that the ECS can control the power consumption of every shift able devices autonomously. For the optimization, the appliances switching on and off time are the variables. Therefore the problem is a scheduling optimization, objective function of the problem being peak to average ratio minimization.

5.1 Dynamic Pricing

In order to change the consumer behaviour of switching their appliances for the sake of the system health, consumers are to be subsidized to increase the load usage in off peak time and charge more than usual in peak time in order to discourage adding more devices in operation. Therefore, a real time pricing is considered for the study, in which the electricity charge is dependent to the System load. For the model development,the Simplified cost function considered for the optimization problem is as below, which is selected so that the total cost of the system do not exceed the cost before optimization as because the consumers are to be benefited by participating in the DSM program than that of without participating in DSM program.

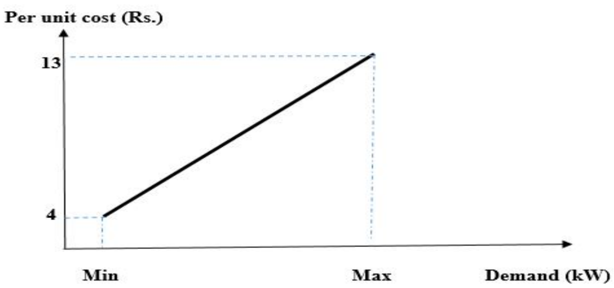

Figure 4: Per unit cost function

The existing electricity pricing is a block rate tariff. The Nepal Electricity Authority charges the energy cost with different rates for numbers of energy blocks. To make the consumer to participate in the DSM, the block rate tariff has been modified by a dynamic price based on system demand. The proposed tariff system charges the electricity use at different rates at different time of the day depending upon the system demand. To modified the block rate tariff to dynamic pricing tariff. A linear demand function has been proposed for the cost. The existing NEA tariff charges Rs. 4 to Rs. 13 for different blocks of energy consumption for residential consumers [6]. Based on these price gap, a price has been set from Rs. 4 to Rs. 13 for minimum and maximum demand respectively over a day representing a linear function.

The cost function is selected so as to hold benefit for both utility and consumers. In order to achieve this condition, the consumers are benefited by lesser cost of electricity while utility will be benefited by increased load factor and decreased loss. The cost function is chosen in such a way that the cost of electricity throughout the day is just equal to that of the existing system.The adjusted simplified cost function of the proposed system is,

Per unit cost(PUC)

$$PUC = 0.1948L_h + 2.8563 \tag{11}$$

Total cost in hour given by:

$$C_h = 0.1948L_h^2 + 2.8563L_h \tag{12}$$

5.2 Problem Formulation

1. Variable: Appliances(13), Total hours(48), Number of consumers(100)
   (a) All assigned as a binary variables.
2. Objective Function: Minimization of PAR
3. Constraints:
   (a) Total operating hours of each appliances of each users should be same as that of as usual scenario.
   (b) The optimization cannot reschedule the non-shift able appliances.
   (c) The shift able appliances can be shifted only to the permissible time slot (shifting preference)
   (d) The cost of electricity should be less or equal to the existing cost of electricity

6. Result and Discussion

The program is simulated in MATLAB,CVX to solve the research problem. In the simulation, the secondary distribution grid is considered consisting of 100 real residential users serviced by a utility company. Shift-able appliances are the load like Refrigerator, Lighting etc. while Load like Water pump, Washing Machine are categorized as shiftable load. For non-shiftable load, It is assumed that the refrigerator runs throughout the day. While other non shiftable load should operate exactly what the consumer operates even before subscribing the ECS service.

It is assumed that some flexibility to operate the cooking devices, that is Induction heater, hot plate and oven could be rescheduled the appliances by half an hour delay or prior than the consumer wants in traditional tariff system. On the other hand the water pump and washing machine were rescheduled to optimize the energy use with flexibility of shifting anytime except in mid night 10:00PM to 4:00AM to avoid switching inconvenience.

6.1 Analysis of Existing Demand Pattern

The load profile of the existing system has been observed so uneven. There appeared peak for two times in a day. On the other time the demand was so less. This can be clearly seen in the figure 1. This load profile results higher peak value with lower average value of Power demand.The system peaks reaching 72.80 kW at 6:30PM-7:00PM. The system is loaded 5.87 kW during mid night from (1AM to 4AM).

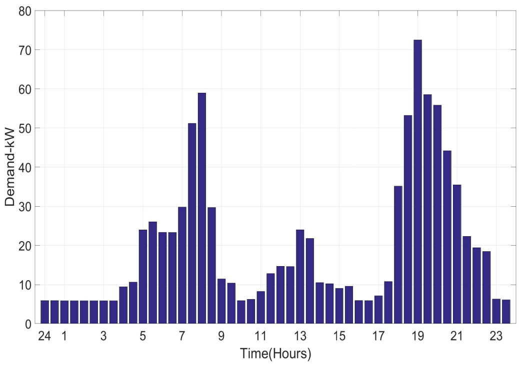

Figure 5: Demand pattern before DSM

6.2 Analysis of New Demand Pattern after DSM

The load has been drastically re-scheduled so as to formation of more smooth load curve. The peak and valley are filled by significant amount. The peak load is reduced from 72.80kW to 52.06 kW, which is 28.15% reduction. The valleys were occupied by small amount of power are not filled by larger amount of power. That is the loads are shifted effectively with the average demand 20.03kW.

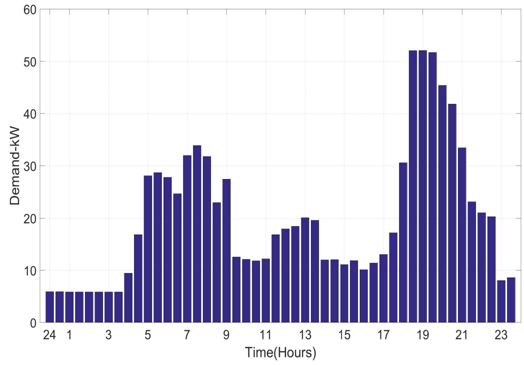

Figure 6: Demand pattern after DSM

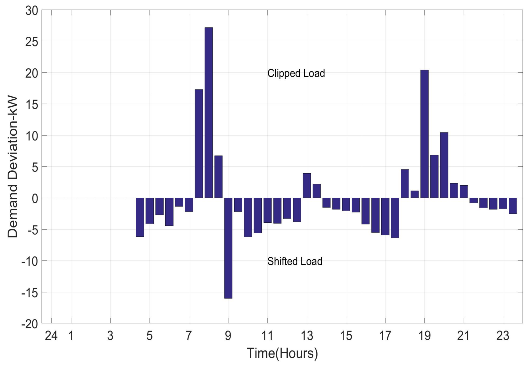

Figure 7: Demand Deviation

The demand deviation graph in figure 6 is achieved by subtracting the Demand after DSM from Demand before DSM over different time of the day. The negative values represent the load has increased. Here, the day time, from 10AM to 6PM, the load has being shifted from other time except 1:00 PM to 2:00PM, which effectively helped fulfilling the objective of DSM.

The positive kW is also the indicator of the scale of clipped load. A major clipping can be seen in morning and evening as in the figure 3. The reason behind it is 95% of the households use Induction motor, and 10% of the household operates Washing Machine and their existing operation hour is random but concentrated in morning and evening time. The simulation model allows their operation to shift any time in the day except in the mid night (10 PM to 4 AM).

6.3 Analysis of Electricity Cost

The cost of electricity considered for the traditional tariff is taken from the Utility's annual average electricity cost for their Domestic consumer which was calculated NRs. 9.72. And is charged per kWh of energy consumption. The cost of Electricity is calculated for the simplicity of the calculation by averaging the monthly electricity bill and total energy consumed.

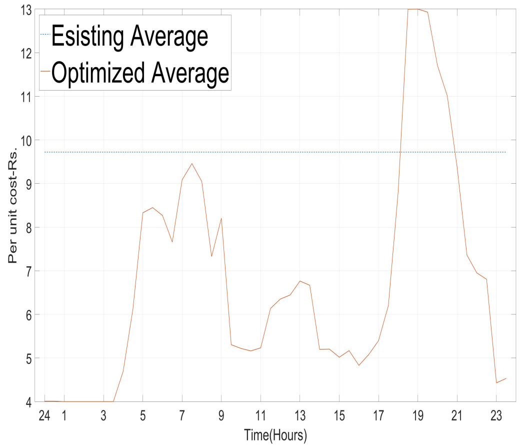

Figure 8: Per unit cost comparison

In the proposed system, the cost of electricity was made dynamic, that was the price was depending on the system demand. Therefore the price was varying with time as the demand changes.

That was there should be the lesser price for less system demand and higher price for higher demand given by cost being the quadratic function of system demand. The per kWh cost of the system is as shown in the (figure:3). The minimum price achieved from the simulation was NRs. 4 at off peak load in midnight and maximum of NRs.13 at peak load in the evening. Most of the time in the day, the optimized price is less than that of traditional tariff with an average cost of NRs. 9.72 per kWh of energy.

6.4 Analysis of PAR and Load Factor

As the main objective of Demand side management is to minimize the PAR. As the appliances were rescheduled so as to reduce the peak demand of the system, the peak to average ratio should have been reduced as long as the total operating hours was not cut for any appliances thereby maintaining the average value by the same figure to that of the existing system, Therefore the PAR value should have decreased with decreasing the peak load. The significant fall of PAR is achieved after the optimization was run. The PAR reduction achieved by the reduction of 28.76% than the existing system.Although the PAR of each user is significantly high, the system PAR is found to be comparatively lower as because of the diversity of the consumer load pattern. The PAR value of the each consumer has been decreased by a significant figure as in figure 10 after the proposed DSM.

SN	Parameters	Before DSM	After DSM
1	PAR	3.6519	2.58
2	Load Factor	27.38 %	38.8%

Table 3: PAR and Load Factor comparison

The load factor being the reciprocal of PAR, which reflect the cost of the service provided by the utility obtained with the major improvement of 38.36 % from 27.38%. The increase of load factor is a direct benefit to the utility as the peak reduced as well as the valley is filled .The shut down and starting up cost of the generators are reduced and the installation of new plant is also avoided with the increment of this indicator.

7. Conclusion

In this paper, appliances scheduling optimization model was formed for the Demand side management. A 100 residential users energy consumption data are adopted in the model. Simulation results show that the proposed DSM strategy can reduce the peak average demand of the evening from 72.80 kW to 52.06 kW by giving the benefit of reduced energy cost from NRs. 9.72 to the variable price of range NRs.(4 to 13) with an average value NRs. 6.94. The load factor has been significantly improved from 27.38% to 38.8% . This leads that the electricity utilization rate and the efficiency of electrical energy usage has been significantly stepped up. The scale of benefit to both consumers and utility can be adjusted by changing the cost function of the system. Therefore, The proper DSM measures like Demand response appliances scheduling can be an effective option to protect the system and achieve the economic and stable operation of power system.

8. Future Enhancements

This research is done taking a time slot of 30 min, which can be reduced further more in order to get more accurate and precise result. Further, this model can be adopted to the distribution feeder and primary substation, so that the demand side management opportunities can be determined for the city and big areas. This model can be adopted to other types of consumers like, industrial and commercial sectors. Further the appliances shifting inconvenience can also be considered in optimization so that the shifting can be minimized along with cost and peak to average ratio.

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