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Demand Side Management Using Battery Energy Storage System for a Sample Residential Load of Pakistan

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Abstract- **This research contributes to sustainable energy development by mitigating the electrical energy crisis through demand-side management using the battery energy storage system. It proposes an algorithm for optimal energy usage through peak shaving in the residential areas of developing countries like Pakistan. It uses the original load data of 42 houses in Lahore, Pakistan, for 2018-2019, named the Pakistan Residential Electricity Consumption data set. The load profiles for the individual households and their groups are used and analyzed. Daily, monthly, and annual load factors are calculated for the groups of houses based on original data. The daily load factors are improved through DSM techniques such as peak shaving at the individual and municipal levels. The loads are categorized into baseload, peak load, and mid-range load from the given load profiles. The economic advantage related to battery type is also considered. This research proves that the presented algorithm is valid for peak shaving, load factor improvement, load profile improvement, and the possibility of providing optimal and reliable energy at reasonable energy prices.**

Index Terms-- **Residential load profile, load factor, battery energy storage system, peak shaving, valley filling, demand-side management**

I. INTRODUCTION

The history of load shedding in various world regions expands over the same era as electricity generation. Because of load shedding due to the change in demand and supply equilibrium, every demand sector is affected. According to a survey conducted in 2019 [1], Pakistan faced a supply-demand gap of 7GW during the last decade. In Bangladesh, the average annual growth rate of electricity production is 7.98%, and electricity consumption is 8.47% [2]. A study determined the required increase in kW per person in Nigeria to fill the demand-supply gap. It suggested an increase of 430% in kW per person representing a high supply-demand gap in Nigeria [3]. The residential sector consumes 40-45% of the world's electricity. The residential sector makes up around 47% of the electrical energy consumption in Pakistan [4]. Load shedding is the only solution to avoid overloading. The losses in the industrial and commercial sector and deterioration of the equipment of generation, transmission, and distribution systems further reduce the efficiency of the overall power system [5]. The grid's burden is the random peak load demand pattern, and it is difficult to schedule the generation for the demand with this diversity. The electricity unit price has almost doubled within the last two years in Pakistan. The statistics suggest the need for an increase in electricity production in Pakistan at the rate of 9% annually [6]. A strategic arrangement is required to cope with the increasing electricity demand due to continuous population growth and urbanization in various regions of Pakistan till the accomplishment of this goal.

One of the modern solutions to deal with overloading, load shedding, and demand diversity is Demand Side Management (DSM) [7]. Demand Side Management provides ways of managing electricity generation and consumption to reduce the generation-demand gaps in real-time. There are multiple ways of Demand Side Management. It is possible to apply DSM with the cooperation of both utility and the customer, or by one of them, independently [8]. Most of the time, the demand side is meant for peak shaving/valley filling. One of the methods associated with demand response is the implication of the Time-Of-Use Rates strategy. Different world countries employ this strategy. In KSA, a time of use tariff was designed for the commercial sector with 0.76SR unit price during peak hours 1 pm-5 pm and 0.19SR unit price during off-peak hours [9]. Some regions of Pakistan also apply Demand Response (DR) technique. According to the Islamabad Electric Supply Company (IESCO) tariff guide, a fixed rate of Rs. 20.70 is charged to the residential electricity consumers during peak hours that are 6 pm-10 pm [10]. This strategy sometimes results in a rebound effect of peak shaving. This effect occurs when most people use less electrical energy during peak time, but as soon as that duration ends, many customers at once switch on the appliances/loads. This effect results in even higher peaks in the residential demand profiles. For this reason, there is a need to find alternatives. The most approachable, widely acceptable, and affordable method for peak shaving of the residential load sector is through the use of battery energy storage systems (BESS). The scheduling of BESS will be such that it may help improve the grid-seen residential load profile and share the burden of the grid. The battery usage will make consumption relatively uniformly distributed over time, as customers don't have to change their electricity usage patterns. They only have to shift their peak loads to the BESS and charge the batteries during off-peak hours, and the load profile appearing to the utility would be rather less-peakier than before.

Various methods have been devised and proposed aiming at residential load management. Residential loads include both households and high-rise residential buildings. Yu Wang, Luyao Liu, Ronald Wennersten, and Qie Sun proposed an algorithm for the demand side management in the high-rise residential buildings with Energy Management (EMS) and the results showed the significant peak shaving and valley filling potential of EMS that contributed to 3.75% and 7.32% peak-to-valley ratio reduction in demand and net demand profiles, respectively [11]. Their work is remarkably beneficial, but they have used a Photovoltaic (PV) storage system. In this research work, batteries are charged directly from the grid without the need to install a separate solar panel-based system that demands high capital costs. Moreover, in developing countries like Pakistan, there is a need to manage the household level at the priority as it will, in turn, manage around 50% of the total electricity sector.

Kangping Li *et al.* worked on a strategy for the estimation of the baseline load for a residential customer in a residential area so that the generation could be scheduled accordingly [12]. Their method is valid to estimate the valleys of the load under study, but it does not provide the peak load estimation. The algorithm proposed in this work can be used to estimate both the peaks and the valleys of the load under study. Various real-time residential load data sets are developed to work on improving the efficiency and reliability of the electrical power systems of the respective countries. A review of similar data sets is done by Mohamed *et al*. in their paper where they have developed a Moroccan residential demand data set [13]. The Moroccan data set contains purely residential data of 12 households, while the secondary data set used in this research is composed of per-minute loads of 42 households from the residential sector of Pakistan.

This research uses novel data set of Pakistan to test the developed algorithm of peak shaving through DSM to look into the behavior of DSM techniques in a local scenario. This is the real-time data set gathered under the umbrella of the Electrical Engineering department of Lahore University of Management Sciences (LUMS) [14]. This data set is named the Pakistan Residential Electricity Consumption data set (PRECON). PRECON is the original dataset of 42 homes in Lahore fed by different feeders. The data of 42 houses are collected at a per-minute basis using smart meters from mid-July 2018 to the end of May 2019. The total electricity usage of the given house is in the units of kW, and the usage of the installed devices in different rooms is also separately mentioned.

The algorithm proposed in this paper is a general algorithm that performs the tasks of analyzing the original load profiles of the residential data to find the peaks and valleys in the demand profiles, and the charging and discharging hours for the recommended BESS. It also suggests the method of charging and discharging the battery in such a way that the peak hours only get the battery discharged and the valley hours only get the battery charged. The results of this research work show that this algorithm can improve the daily load factors (LF) of 76% of the households up to 29%, which is not proposed previously for the residential sector of Pakistan.

The remaining portions of this paper cover the PRECON data set description, and modeling of the residential system, the simulations performed for the algorithm developed for the determination of the optimal time slots for the charging and discharging of the recommended BESS, the results of the simulation, the relevant discussion, the conclusions, and future work.

II. DATA AND MODELING

A. DATA DESCRIPTION

This research uses novel data set named Pakistan Residential Electricity Consumption data set (PRECON), which is developed for the 42 houses of Lahore which is the capital of Punjab, Pakistan [14]. Smart meters were specifically installed in each of these houses for the sake of per minute load measurement throughout the year from June 2018 to May 2019. This data set is representative of the electricity consumption pattern of not only households with different demographics in Pakistan but also the electricity consumption pattern of the similar category of developing countries in the world.

B. MODELING

The network of 42 households was modeled in MATLAB .m file. Missing data were interpolated for house numbers 1, 6, 30, 35, and 38; the variance in the timeline was made similar for each house for the exact determination of the total load demand of the 42 houses at the given minute/day/month of the year.

On analyzing the household load data, it was noticed that for some houses (for example house numbers 6 and 14, the load data was equal to or very close to zero. This can be an indication of the absence of the residents of the respective houses for that period. This data was kept as it is, as the purpose of this work is to design an algorithm to tackle every possible circumstance that can occur in real-life practice and that can have an impact on the electricity consumption patterns. The data was modeled in such a way that it was possible to evaluate the hourly load profile of any house for any given day of the year. The day selected for this research work is 1 June 2019. This day can be regarded as one of the peak hot summer days and high peaks are expected to be seen in the demand profiles of most of the houses due to high usage of air conditioners and water pumps. The system model allows to increase or decrease the number of houses to be analyzed to reasonable values till the algorithm remains valid. Up till now, the validity of this algorithm is proven for the 42 houses precisely given in the PRECON data set.

III. SIMULATION

The simulations for the proposed algorithm were done in MATLAB. The flowchart of the algorithm is shown in Fig. 1. This pathway was followed for both categories: individual household loads and municipal level load. The load curves of each household were plotted. The baseload and peak load of the households included in the dataset were determined. Each hour at which the load ranged from minimum to 140% of the minimum load was recorded in an array as the valley hour and each hour at which the load ranged from 80% of maximum load to maximum load was recorded in another array as the peak hour. These percentages were determined based on the consumption patterns of consumers. The valley hours were selected for discharging and the peak hours were selected for charging the battery.

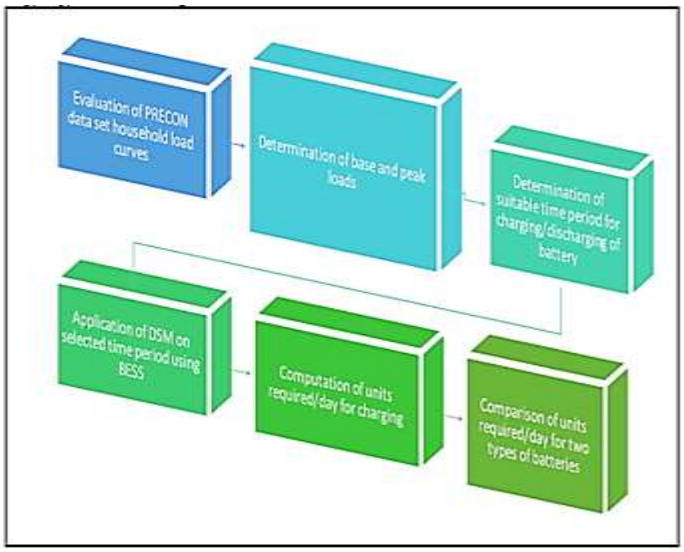

FIGURE 1: Flow chart for the proposed DSM algorithm, summarizing each step followed.

To find the optimal time durations for charging/discharging of batteries, the time durations with base loads and peak loads were considered. The time duration of 1 hour for any load falling under the category of the valley, was recorded and selected as the suitable charging slot for each house/combined load. The time duration of 1 hour for any load falling under the category of the peak was selected and recorded as the optimal battery discharging slot for each house/combined load. The charging and discharging hours for each house and combined load were recorded. One approach for the charging and discharging of the BESS was to charge or discharge it during the selected hours. The other method was iterative whose results showed that it is better to charge around 20% of the battery during the deepest valley of the day and charge the remaining battery during other valleys of the day. For discharging, firstly, 20% of the battery was discharged during the highest peak hour of the given day and the remaining 80% of the battery was discharged during other peaks of the day. Secondly, it was proposed to discharge around 20% of the battery during the highest peak hours of the given day, like the previous approach, and discharge the remaining 80% of the battery during peak time which is consecutive 4 hours from 5 pm-11 pm in Pakistan, depending upon the usage month. The minimum units required to charge the battery were selected by combining a percentage of peak load for all the peak hours. For practical purposes, the units required for the two types of most commonly used batteries i.e., lithium-ion battery and lead-acid battery were also calculated.

IV. RESULTS

A. CHARGING/DISCHARGING SLOTS

Table I includes the values of optimal hours of charging and discharging of batteries for 14 out of 42 houses. The reason for selecting these households is the major improvement in their load factors after DSM. The optimal charging and discharging durations for the selected houses were selected using the algorithm explained in the simulation section. It can be seen in Table 1 that some time slots are in the form of the duration of hours, while others only give the hour number.

TABLE I
SUITABLE HOURS FOR BATTERY CHARGING/DISCHARGING

House No.	CHARGING HOURS	Discharging Hours
2	9-10	14-15
4	11-12, 13-14	1-3, 19-20, 22-24
5	17-18	1-2, 5-6
8	6-9, 22-23	2-3, 18-19
11	10-11	1-3
13	13-14	1-2, 4-5, 6-8, 14-16, 23-24
16	14-15	1-2, 13-14, 20-21
18	13-14	11-12, 16-20
19	12-13, 21-22	2-3, 15-18
31	19-24	1-3
33	13-16	2-3, 18-20
36	11-12, 16-17, 23-24	1-2, 9-10, 14-15, 20-21, 22-23
38	14-15	6-12
40	14-18	2-7, 11-12
Combined	11-14, 16-17	1-3, 5-7

B. LOAD FACTORS

The load factors of the households were calculated using (1), (2), and (3). P(t) represents the power usage at the given time, E(t) represents the energy usage by the household, t represents the hour of the day and T represents the total hours in a day. Table 2 includes the values of load factors of the 14 out of 42 houses just to give an idea about the overall gain of the algorithm. Using the first approach of discharging, around 60% of the houses had 20% better load factors than before. Using the second approach of discharging, around 76% of the houses had 2.5-29% better load factors than their previous load factors. At the municipal level, the load factor after the implementation of the suggested DSM strategy was around 20.6% better (0.82) than the previous load factor (0.68). The load factor is improved for most of the houses as the major portion of the battery is discharged during the peak hours i.e., 6 pm to 10 pm. Along with this, any peak load beyond this duration is also handled by the remaining 20% charge of BESS. The charging takes place during the lowest demand (valley) hours thus improving the mean demand for the given day.

$$E(t) = P(t) \times t \tag{1}$$

$$Mean\ kW = \frac{\sum_{t=1}^{24} E(t)}{T} \quad (2)$$

$$LF = \frac{Mean\ kW}{Max\ (E(t))} \quad (3)$$

The percentage improvement in the load factors was calculated using (4). Some major improvements can be seen in Table II. For house 2, the new load factor of 0.61 is 25% better than the old load factor of 0.48. For house 5, the new load factor of 0.55 is 15% better than the old load factor of 0.48. For house 13, the new load factor of 0.68 is 8% better than the old load factor of 0.63. For house 19, the new load factor of 0.56 is almost similar to the old load factor of 0.57.

$$\Delta = \frac{Old\ lF - New\ lf}{Old\ lf} \times 100 \quad (4)$$

TABLE II
LOAD FACTORS OF HOUSES BEFORE AND AFTER DSM

House Number	Old Load Factor	New Load Factor
2	0.49	0.61
4	0.67	0.68
5	0.48	0.55
8	0.51	0.61
11	0.54	0.65
13	0.63	0.68
16	0.52	0.54
19	0.56	0.57
31	0.56	0.65
33	0.56	0.63
38	0.60	0.61
40	0.56	0.59
Combined	0.68	0.82

C. LOAD CURVES

Figure 2 shows the load curves of the 14 selected houses before DSM application and Fig. 3 shows the load curves of those selected houses after DSM application. It can be seen in most of these profiles that peak shaving comes with simultaneous valley filling at some point of the demand profile.

For combined load, the load factor before the application of DSM was calculated to be 0.67 and it was improved to a value of 0.82. This can be seen in the load curves of Fig. 4 that represent the load curves before and after DSM application for the combined load.

D. BATTERY RATINGS

Figure 5 and 6 show the battery ratings required for combined and individual households. The sum of battery ratings for individual households is almost double (200kWh) the battery capacity for the municipal level (105kWh). It corresponds to double the operational cost for the batteries for the sum of the individual household. Each household requires a battery of 5kWh capacity, on average, for a given day.

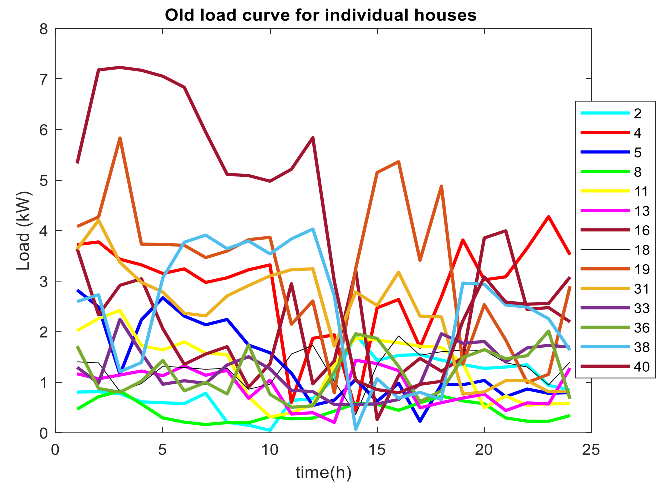

FIGURE 2: Load curves of individual households before DSM

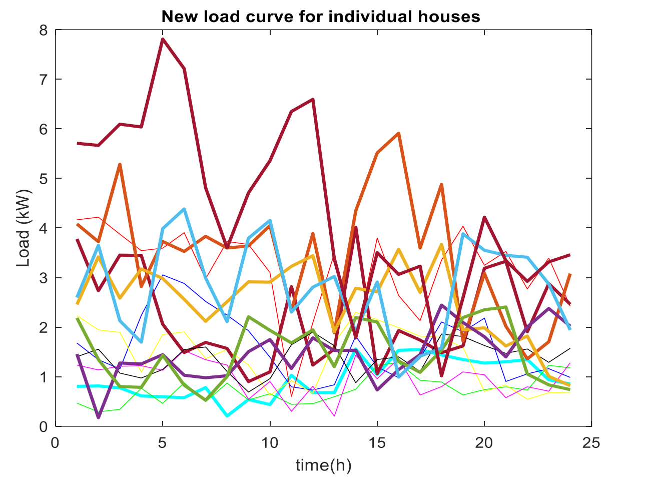

FIGURE 3: Load curves of individual households after DSM

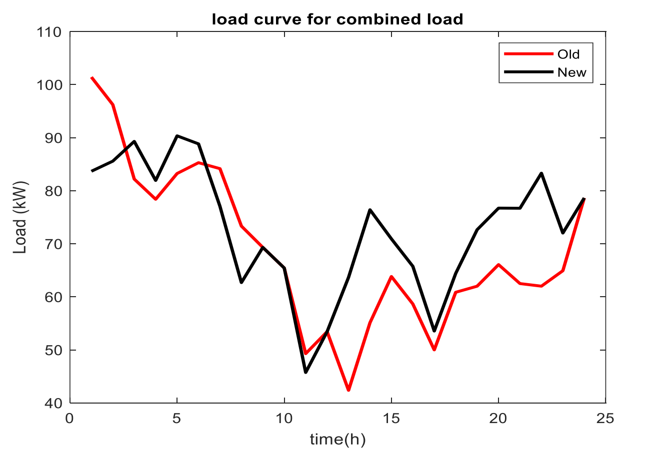

FIGURE 4: Load curves of combined households before and after DSM

Practically, a lithium-ion battery of 6kWh and a lead-acid battery of 10kWh are required for each household. Some variation can be seen in the battery ratings for individual houses when some houses have ‘no battery required’ status. This can occur because of the reasons mentioned in the data section. The same analysis can be done for another day of one’s choice with no data corresponding to zero electricity usage.

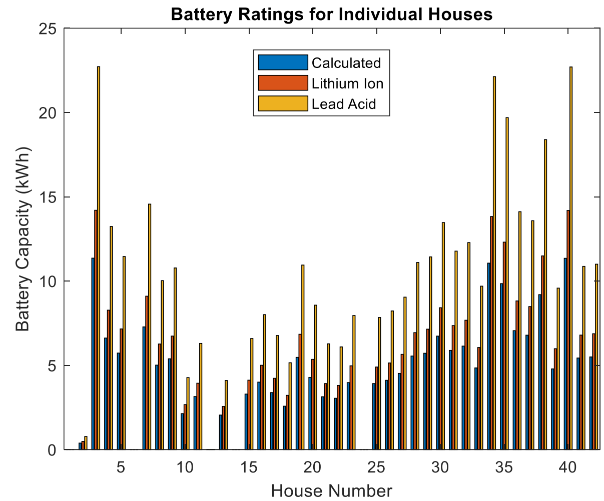

FIGURE 5: Battery ratings for individual household loads

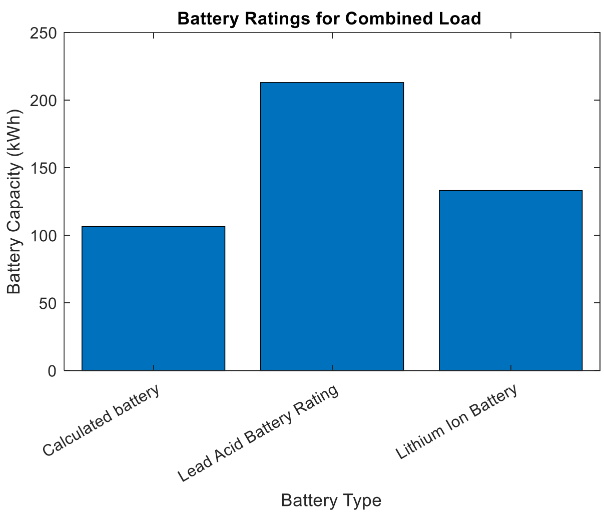

FIGURE 6: Battery ratings for combined load

V. CONCLUSION

The algorithm proposed in this paper proved to be reliable for improving load factors of households at both the individual and municipal levels. It proved that a better approach is to charge 20% of the battery during the lowest off-peak hours and charge 80% of it uniformly throughout the day whenever the load is below baseload, excluding the duration of the highest peak hours. It proposes to discharge around 20% of the battery during maximum-demand hours of the given day and discharge the remaining battery during the peak-rate time. The case study shows that for the individual houses, 76% had 2.5% to 29% better load factors than before. At the municipal level, the load factor after implementing the suggested DSM strategy was 20.6% better (0.82) than the previous load factor (0.68).

It is economically advantageous to use BESS for a group of houses/municipal level than individual houses. Among the lead-acid and lithium-ion batteries, lithium-ion batteries take 37.5% lesser energy units in daily operation. If capital and installation cost is not an issue, lithium-ion batteries are a better option regarding operational cost and efficiency at the municipal level. The algorithm proposed in this paper is a unique approach for demand-side management, but it has the limitation that it was tested for residential load profiles only. It can be tested and improved for other types of loads as future work.

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