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Optimal operation of BESS for peak shaving of distribution network using fuzzy logic controller

Moh Moh Win Shwe[a], Wunna Swe[a] and Shouji USUDA[b]

[a] Department of Electrical Power Engineering, Mandalay Technological University, Myanmar

[b] Hosei University Graduate School, Institute of Climate Change Energy Policy

Abstract

Responding to the increase in the production of electric energy from renewable resources has become a new development theme for the energy supply network. Today's power systems need to maintain a stable supply-demand balance at all times, manage the supply grid more flexibly, and ensure optimal levels of energy efficiency. Battery Energy Storage System (BESS) have received significant observation over the last decade because of their role in grid modernization. Currently, energy storage plays an important part in grid modernization to provide a number of services, such as peak shaving. In this research, BESS for peak shaving of utility grid MWh storage applications, Chauk township distribution system (located in Magway division of central Myanmar) is studied. A novel Fuzzy Logic Control (FLC) algorithm is developed based on the load characteristic of the grid and takes into account the usable energy from the batteries during the operation of the BESS based on their State-of-Charge (SOC) and determined the amount of power delivered to the grid. Experiments have been carried out to evaluate the performance of the Fuzzy Logic Control (FLC) algorithm.

Keywords: Battery Energy Storage System (BESS), Fuzzy-logic control (FLC) algorithm, Peak Shaving, SOC

1. Introduction

The implementation of distributed energy storage system will play a vital role in the Smart Grid of the future. With an ever increasing energy demand and the introduction of more and more power demanding devices, the electricity grid is facing supply challenges. Especially a high power demand causes a stress on the grid, as it is dimensioned with regards to the peak power it needs to deliver [1]. One solution would be to expand the existing grid, resulting in substantial investment costs. Another promising solution could be to implement a peak demand charge, encouraging end users to shift or reduce their power demand [1]. Overall, different energy storage technologies are classified into two major categories. The first group is best suited for power applications and the other group is desirable for large energy applications [2]. Mitigation of transient power quality disturbances requires high power output, usually for relatively short period of time from seconds to minutes.

The energy storage systems like SMES, capacitors and flywheel energy storage are the choices for power applications since they have the capacity to store fairly modest amounts of energy per rated MW output power, but have only relatively short period of discharge time. On the contrary, energy applications require relatively large amount of energy, often for discharge durations of many minutes to hours [2]. Therefore, the storage systems like CAES, pumped hydro, thermal energy storage as well as most of batteries are usually the right devices for these applications due to the fact that they have fairly long discharge times [3]. Batteries currently have the widest range of applications as compared to other energy storage technologies.

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Corresponding author. Tel.: +959-943058320; *E-mail address*: moh2winshwe@gmail.com.
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The type and the number of battery storage applications are constantly expanding mainly in electric utility energy storage [4]. They are also used for a variety of applications such as: power quality assurance, transmission and distribution (T&D) facility deferral, voltage regulation, spinning reserve, load leveling, peak shaving, and integration with renewable energy generation plants [4]. Amount all, the most commercially and economically viable for LV and MV storage application is based on battery. This is because the cost of the battery has a declining trend in the past decade [5].

Among various energy storage technologies, electrochemical technology based BESS is mostly used for peak load shaving. Lithium-ion batteries can be used for peak shaving and improve power quality of grid. In such cases the benefit of peak shaving is double; by reducing both the power fee and the cost of energy [6]. Peak shaving can also be used by utilities or plants of renewable energy to increase the capacity of the existing grid infrastructure. T&D upgrades can be deferred into the future providing a more cost efficient upgrade path for the power system [6].

By optimal management of the stored energy, the peak power that is demanded from the generator/power supply is minimized. However, this approach was found computationally expensive, puts unnecessary stress to the battery and it is strongly depended on historical data. If the actual data deviate from the historical then inaccurate charge/discharge commands will lead to increase the peaks rather than shaving them [3].

Different methods have been proposed for finding optimal amounts of charging and discharging and their corresponding time intervals in order to eliminate the peaks and valleys from the load profile [7]. A fuzzy-based control algorithm is developed based on the load characteristic and takes into account the usable energy from the batteries during the operation of the ESS based on their state-of-charge (SOC)[8]. Experiments are carried out to evaluate the performance of the fuzzy-based control algorithms.

The Fuzzy system has been applied to various control systems such as crystal growth of semiconductors, robot and rocket control technology. We have newly introduced the concept of the Fuzzy system in the development of a cooperative system of renewable energy (secondary battery) and electric power system, which has been researched so far. In this study targets peak shaving as a service provided by Lithium-ion battery storage located in the distribution grid, with the purpose of achieving increased flexibility that may prevent grid under-utilization and delay the need for grid reinforcements.

In this study, peak shaving is mainly analyzed in 11kV Chauk Feeder line in Chauk Substation, Chauk in Magway Division as case study because the Chauk area is situated in Magway region (dry zone area) and then it has more interruption than others feeder line according to the collected data. The seasonal variation in energy consumption is addressed by using the annual consumption average as reference, with various use of buffer capacity to provide energy in times of high load [9]. The concept of peak shaving is to control the load profile to achieve a stable energy consumption from the power grid over a given time period [10]. This is achieved by shifting the peak energy consumption to periods of low consumption. The battery capacity strategy is validated by a simulation model. The model that is built is an idealized model that calculates the mean energy consumption over a 24-hour period.

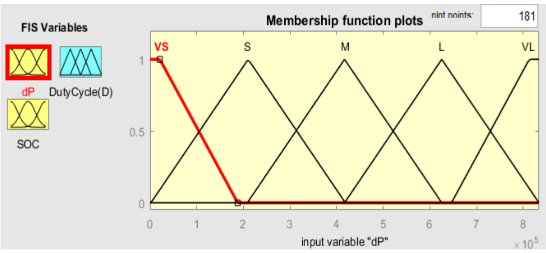
2. Fuzzy Logic Controller for Peak Shaving

Fuzzy logic describes plants in terms of a combination of numeric and linguistics. This has advantages over pure mathematical approaches or pure symbolic approaches because the system knowledge is usually available in such a combination [8]. The fuzzy-based control algorithm developed for peak reduction takes into account the SOC and dP to determine the amount of power to be delivered to the grid during the peak shaving process. The input variables for the fuzzy-based controller are the SOC of the batteries and dP while the output variable is the duty cycle (D) of the buck and boost DC/DC converters.

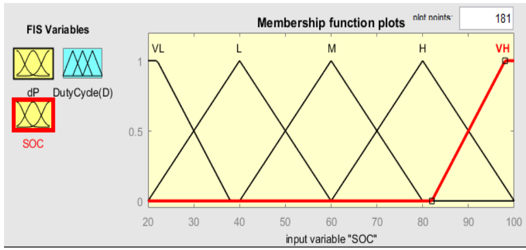
The crisp inputs and output are fuzzificated into fuzzy sets that can be characterized by membership functions. Instead of denoting the inputs and output with values, the fuzzy sets express the inputs and output with a vague description [8]. Table1 shows the definition of the fuzzy sets of the SOC and dP in linguistic terms. There are five membership functions for both the SOC and dP. For output duty cycle, five memberships functions are also assigned.

Table 1. Definition of the fuzzy sets of the SOC and dp in linguistic variables

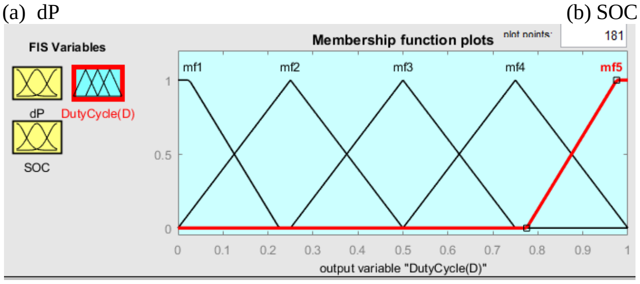
SOC	Power difference(dP)	Duty cycle(D)
VL - Very Low	VS -Very Small	VS -Very Small
L - Low	S - Small	S - Small
M - Medium	M - Medium	M - Medium
H – High	L - Large	L - Large
VH -Very High	VL - Very Large	VL - Very Large



(a) dP



(b) SOC



(c) Duty Cycle

Fig. 1. Membership function of (a) dP (b) SOC (c) Duty Cycle

The fuzzy inference system is developed using the Fuzzy System Designer Toolbox in LabVIEW^{TM}. There are two basic fuzzy system inference method, namely Mamdani and Takagi-Sugeno inference method.

In this study, a Mamdani's fuzzy inference method is adopted because it is the most commonly used fuzzy methodology in control systems. The SOC is set in the range of 20 % to 100 % while dP is the difference between the load power and average power. The duty cycle is range from zero to one. The membership functions of the SOC, dP and Duty cycle are illustrated in Fig. 1. Table 2 shows the values of the fuzzificated SOC and dP of the fuzzy controller.

Table 2. The fuzzificated SOC and dP of fuzzy controller

SOC / dP	VS	S	M	L	VL
VL	VS	VS	S	S	M
L	VS	VS	S	M	L
M	S	S	M	L	L
H	S	M	L	VL	VL
VH	m	L	L	VL	VL

(a)Discharge

SOC / dP	VS	S	M	L	VL
VL	M	L	L	VL	VL
L	S	M	L	VL	VL
M	S	S	M	L	L
H	VS	VS	S	M	L
VH	VS	VS	S	S	M

(b) Charge

The fuzzy inference rules are keyed into the Fuzzy System Designer Toolbox as shown in Fig.2. The defuzzification method chosen for this study is the center of area (COA). The AND antecedent with minimum consequent implication is chosen.

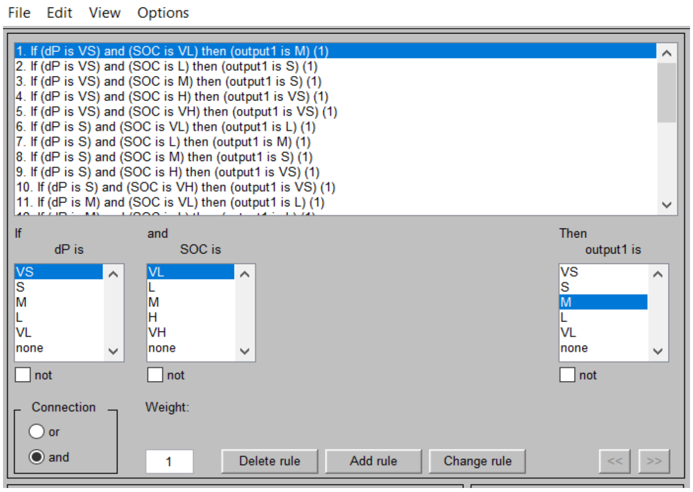


Fig. 2. Fuzzy inference rules in Fuzzy System Designer Toolbox

A surface chart as shown in Fig 3 shows a three-dimensional surface of the SOC, dP and Duty Cycle plotted from the surface viewer in the Fuzzy System Designer toolbox. The surface chart indicates the optimal Duty Cycle to be delivered by the energy storage system based on SOC and dP.

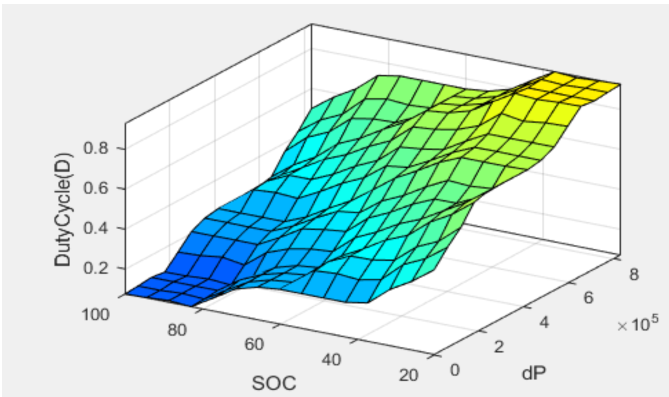


Fig. 3. Surface chart of the SOC, dP and Duty Cycle plotted using LabVIEW Fuzzy System Designer Toolbox

3. Modeling of System

For the modeling of the system Matlab 2016a software is used. The system mainly consists of the utility grid, the load and battery charging/discharging systems. In this system, the battery charging with buck converter and battery discharging with boost converter are assigned with different blocks so that the charging and discharging circuit breaker can operate separately.

When the load is larger than the average power, the battery discharging circuit with inverter is operate. In the other hand, if the load demand is less than average power, the charging circuit is operate with rectifier. According to cost optimization results, the battery energy storage system consists of ten numbers of 1 MWh batteries. Fig. 4 shows system block diagram for peak shaving with BESS system.

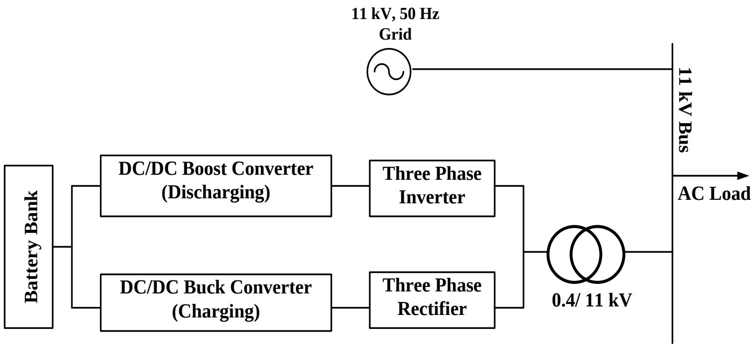


Fig. 4. System block diagram for peak shaving with BESS system

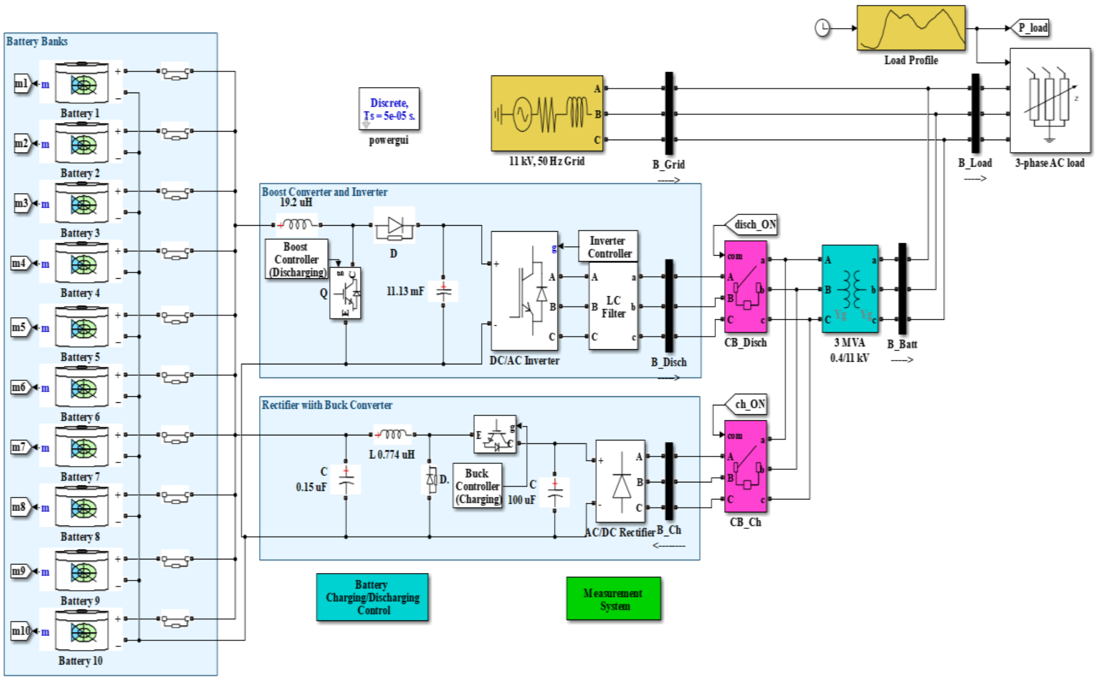


Fig. 5. Simulink model for peak shaving of BESS system

Fig.5 shows Simulink model for peak shaving of Battery Energy Storage System. The simulation model is developed based on system block diagram shown in Fig 4. The variable load is used in the model so that the actual load variation within a day can be represented. The inverter controller is used to control inverter output voltage at 400 V nominal value. The PI controller is used for inverter control. The boost controller and buck controllers are used to transform DC to DC voltage level as well as to control charging/discharging rate so that peak shaving function can be performed. For this purpose, two Fuzzy Logic Controllers are used for buck/boost controller.

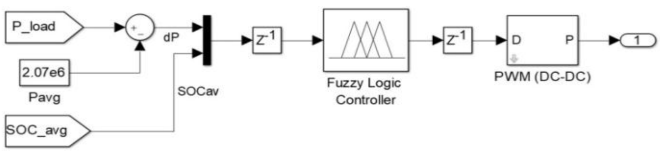


Fig. 6. Boost controller (discharging)

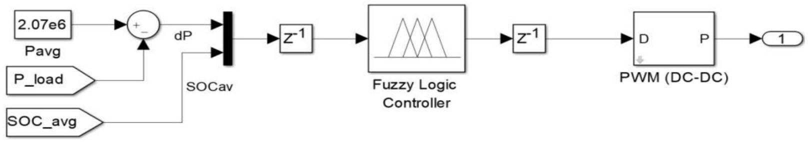


Fig. 7. Buck controller (charging)

Fig.6 and Fig.7 show the models of boost controller and buck controller respectively. As mentioned before, the inputs of FLC are dP (power difference) and SOC (average state of charge of the battery). The output is D (duty cycle) which is fed to PWM generator.

In case of boost controller, the average power is subtracted from load demand power and the reverse process is done for buck controller. The membership functions, ranges and rules for FLC are described in previous section.

4. Simulation Results and Analysis

In the simulations of the model, four conditions are carried out as (i) average load condition, (ii) Winter season load condition, (iii) Summer season load condition and (iv) Rainy season load condition. For each simulation, the powers and voltages/currents are measured.

Fig.8 through Fig.11 shows the simulation results for average load condition. Fig 8 and Fig.9 show RMS voltage and current at Battery Bus and Grid Bus respectively. According to inverter control, the bus voltages are maintained at 11 kV throughout the simulations. The RMS current of battery bus is negative for charging periods and positive for discharging periods. The minimum and maximum RMS current at grid bus is 99.8 A and 122.5 A respectively.

In current display, the increase and decrease of current are somewhat stepwise due to switching of charging/discharging if circuit breakers of batteries.

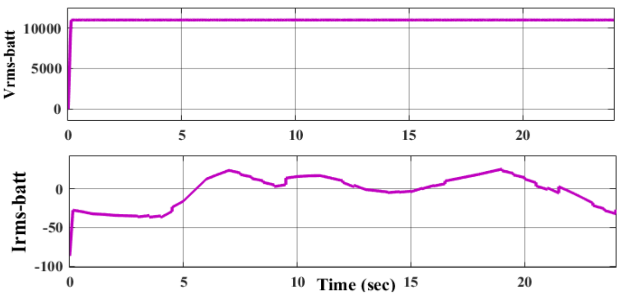


Fig. 8. RMS voltage and current at battery bus

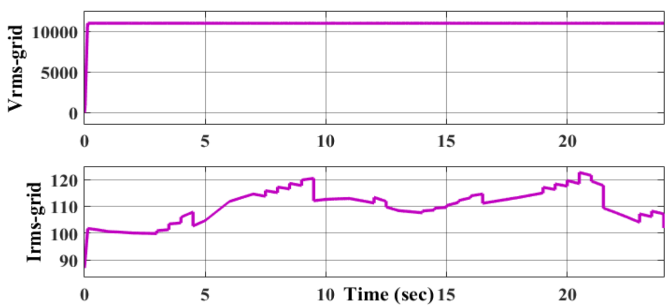


Fig. 9. RMS voltage and current at grid bus

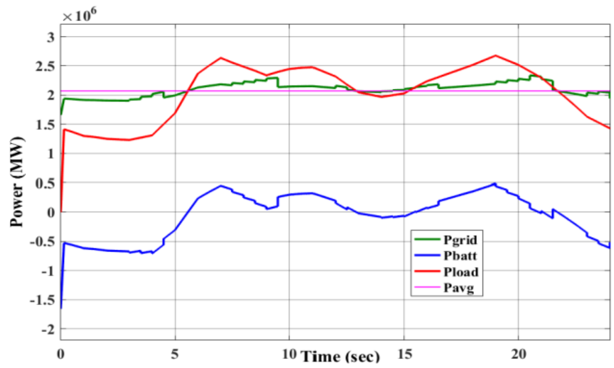


Fig. 10. Comparison of powers for average condition

Fig.10 shows comparison of powers for average condition. In this case average power is 2.07 MW as shown in this Fig. When the load demand is larger than average power, the battery discharge its power and reduced power taken from the grid. When the demand power is smaller than the average power, the battery charged and its SOC are increased.

In this way, the grid power is quite flatten compared to the load demand power and peaks are shaved. The stepwise nature in battery and grid powers are due to charging/discharging of additional battery. Positive battery power represents discharging and negative power represents charging power to the battery.

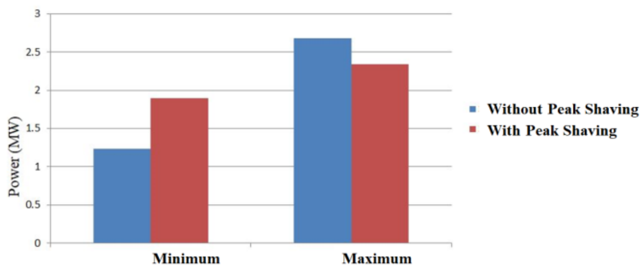


Fig. 11. Comparison between without peak shaving and with peak shaving for average condition

Fig.11 shows without peak shaving, the grid power is ranging between 1.23 MW and 2.68 MW. With peak shaving by BESS, the power variation range is between 1.902 MW and 2.338 MW.

Thus, the application of BESS for peak shaving can significantly reduce the peak powers.

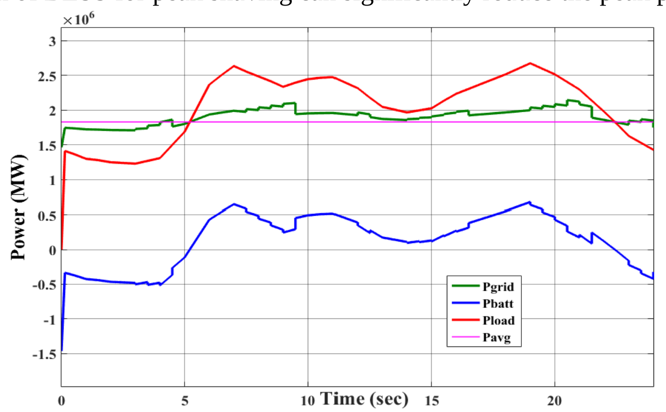


Fig. 12. Comparison of powers for winter season

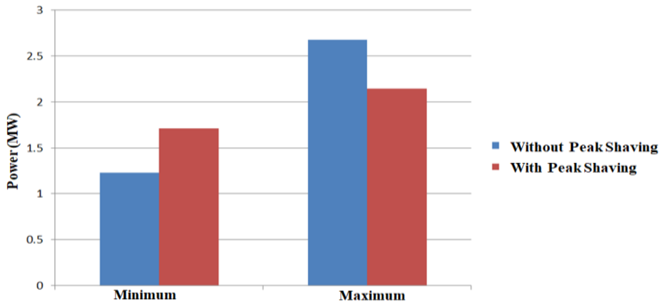


Fig. 13. Comparison between without peak shaving and with peak shaving for winter season

Fig.12 shows comparison of powers for winter and Fig.13 shows comparison between with and without peak shaving for winter season. In this case, average power is about 1.83 MW. The load power demand is ranging between 1.227 MW and 2.679 MW. But, the power taken from the grid is ranges between 1.71 MW and 2.146 MW.

Thus the power taken from the grid is rather smooth compared to load demand power and the peak powers are reduced.

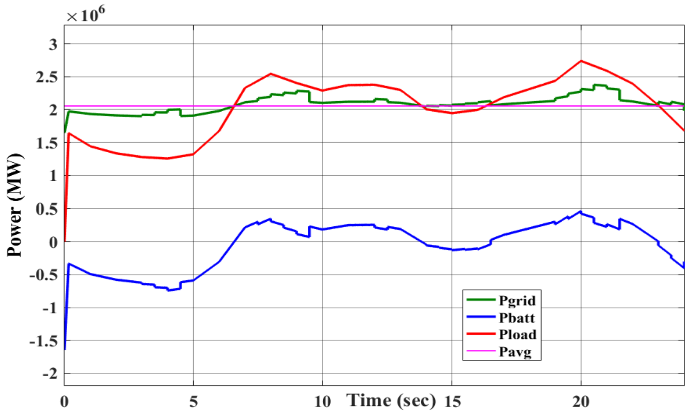


Fig. 14. Comparison of powers for summer season

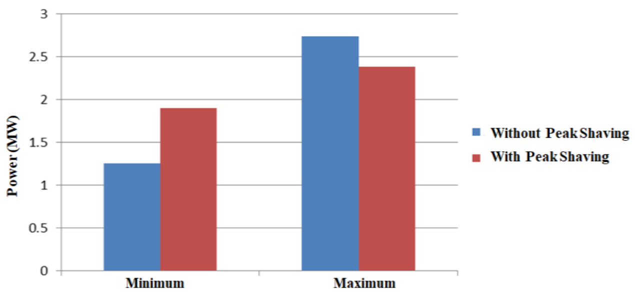


Fig. 15. Comparison between without peak shaving and with peak shaving for summer season

Comparison of powers for summer is shown in Fig.14 and Fig.15 shows comparison between with and without peak shaving for summer season. The average power for summer is 2.056 MW. In this season, load demand power is 2.74 MW maximum and 1.25 MW minimum. But, the power taken from the grid is 2.38 MW maximum and 1.90 MW minimum.

As shown in these Figs, the peak shaving by BESS system is noticeable and power taken from the grid is within a narrow range.

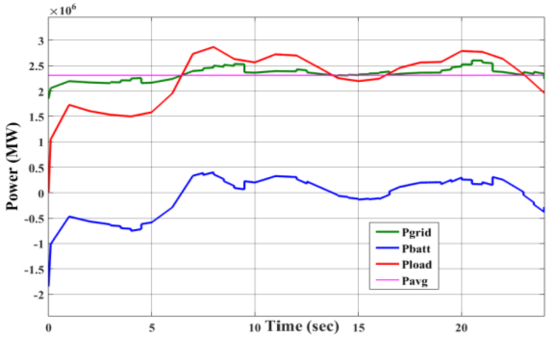


Fig. 16. Comparison of powers for rainy season

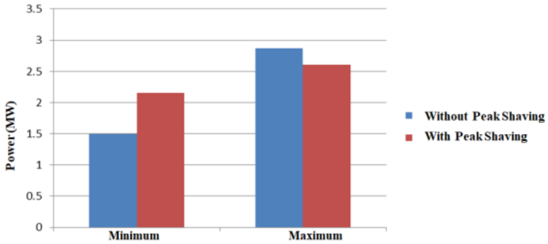


Fig. 17. Comparison between without peak shaving and with peak shaving for rainy season

The average power for the rainy season is about 2.31 MW. It is the largest average value among three seasons. Fig.16 shows comparison of powers for rainy season. The power taken from the grid is ranging between 2.154 MW and 2.604 MW while the load power is ranging between 1.495 MW and 2.871 MW. The power taken from the grid is near average value and peak powers are reduced. Fig.17 shows comparison between with and without peak shaving for rainy season.

Table 3. Comparison for power ranges of three seasons

Seasons	Avg (MW)	Load demand (MW)			Power taken from grid (MW)		
		Max	Min	Range	Max	Min	Range
Summer	2.056	2.74	1.25	1.490	2.38	1.9	0.480
Rainy	2.31	2.871	1.495	1.376	2.604	2.154	0.450
Winter	1.83	2.679	1.227	1.452	2.146	1.71	0.436

Table 3 shows comparison for power ranges of three seasons. Without power shaving the power taken from the grid will be the same as load demand data. It is largest in summer and smallest in rainy season. With peak shaving with BESS, the power ranges are significantly reduced and less than 0.5 MW.

Therefore, the application of BESS can reduced the peak demand from the grid.

5. Conclusion

In this study, we collected the data with an hourly resolution and over the period of one year. There are three seasons in Myanmar-Summer season (February, March, April and May), Rainy season (June, July, August and September) and Winter season (October, November, December and January).

Recent improvements in battery energy technologies and the decline in the cost of the battery can imply that the energy storage is a financially viable solution for peak reduction one day. Peak shaving of distribution networks by using BESS was presented in this study. It has also been proposed that peak shaving of distribution networks using BESS is very important for countries such as Myanmar, which have two seasons.

Fuzzy logic controllers were used to control the charging/ discharging rate of buck/boost converter. The peak shaving performance was studied for all three seasons. According to the simulation results, the battery energy storage system with the FLC scheme could significantly reduce the peak power of distribution network.

In further study, the application of bidirectional converter should be carried out for peak shaving with battery energy storage system.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

The corresponding author developed the model, analyzed the data and wrote the paper. Prof. Dr. Wunna Swe supervised the research, analyzed the data, and revise the final paper. Prof. Dr. Shouji USUDA further analysed the results and revised the manuscript. All authors had approved the final version.

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