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Peak Load Shaving in Isolated Microgrid by Using Hybrid PV-BESS System

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ABSTRACT

Photovoltaic (PV) and Battery Energy Storage System (BESS) are becoming more popular in global energy landscape. Some excellent characteristics such as versatility, expansion performance, fleet response time and modularity, make BESS more effective device.By considering Isolated Microgrid (IMG) system, PV-BESS hybrid system can be used for peak load shaving application. Here, charge-discharge operation of BESS and optimal usage of PV is the most important requirement. Previously few techniques have been proposed for shaving the peak load and they controlled the charge-discharge operation of battery. However, the techniques contain some limitations. It cannot ensure the optimal usage of PV and the charge-discharge controlling techniques are not well fitted for IMG system. In this work, we have proposed a Modified Decision Tree Algorithm to achieve peak load shaving service. The proposed algorithm can control the charge-discharge operation of BESS and ensure the optimal usage of PV generation unit. The proposed method has been applied on the load profile of UniversitiTeknologi PETRONAS (UTP). The results demonstrate that, the proposed algorithm can minimize the demand of UTP. A comparative analysis has been done between the proposed algorithm and the latest peak shaving decision tree algorithm. The comparative analysis reflects that the proposed algorithm can ensure the optimal usage of PV unit and can minimize the demand by few hours more than the latest algorithm. The proposed algorithm has also considered the optimal generation dispatch which can save more energy, reduce fuel consumption, and carbon emission. This method is more environment friendly and economically benefited.

Key words: BatteryEnergy Storage System (BESS), Photovoltaic (PV), Scheduling Technique, Peak Load Shaving.

1. INTRODUCTION

The increasing use of electricity is a new concern for power system. Due to the environmental issues, the power generation is highly moving towards the renewable energy generation sources i.e. PV, wind generation system, hydro-electric generation system, geo-thermal system etc. The highly penetration of PV can create numerous problems such asvoltage drop, reverse power flowing, supply-demand imbalance and etc. [1]. To ensure the smooth and reliable use of electricity, it must need to control the electrical power supply. For PV generation system, a proper power converter can ensure the reliable operation. A suitable power converter design for modern power system can be found in [2].

A power system has peak and base load according to its capacity and area. Peak load is a sensitive factor which can increase the cost of electrical power generation because, tosupply the peak demand, a peaking generator is required. Most of the time, during peak periods, the peaking generator operates at very low efficiency. For this reason, the cost of fuel consumption, cost of transmission and distribution, operation and maintenance cost and so on will be introduced [3]. During peak hours, frequency variation, supply-demand imbalance, generator overloaded problem, voltage drop, and so on can take place which can decrease the power quality [4]–[5].

In small scale IMG system, the difference between peak load and average load may have reduces the power reliability. During peak hours, the generators generally not operatingat its optimum capacity which can decrease the fuel efficiency. During optimum operating period, the generators consume optimum fuel. Generally, at the peak load, the system loss increases because more current required to supply the load[6]–[8].

Peak demand should be mitigated for the optimal power flow. Peak load shaving is the peak smoothing process of the daily load curve by shifting the load from peak period to off-peak period or to meet the peak demand by handy devices i.e. battery, PV, super-capacitor and so on. There are mainly three effective ways to shave the peak load which are: implementing Energy Storage System (ESS), integrating Electric Vehicle (EV) to the power system and Demand Side Management (DSM). A brief explanation of different peak demand reduction methods and their pros & cons can be found in [8].

Previously, few strategies have been proposed for controlling the charge-discharge operation of BESS in PV connected power system to shave the peak demand. M. J. E. Alam has proposed Constant Charging-discharging technique to control the charge-discharge operation of battery to achieve the peak load shaving application [9]. Hence, for sudden change of PVgeneration, this technique cannot charge the battery properly. Later, he proposed a Dynamic Charging-discharging Rate Adjustment Method [10]. This time, the method can detect thesudden change of PV generation and it can fix the charging rate to charge the battery. During evening time BESS will be discharged to meet the demand but this method did not consider the power loss minimization and other existing power issues. For this reason, this method causes more power losses which is not beneficial for the IMG system. After that, Menglian Zheng has proposed a Storage Dispatch Strategy which can shave the peak demand and can ensure optimal smaller storage devices for peak shaving service [11]. Hence, this technique is only valid for the load profiles of U.S. household, not for other load profiles. For time varying load profile, some technologies of this strategy cannot bring any benefit. Ehsan Reihani proposed a Non-linear Programming technique to reduce the fluctuation of power and to minimize the demand by shifting the loads from peak period to off-peak period [12]. Hence, the inaccurate forecast of loads is responsible for unsuitable charge-discharge operation of BESS.Weather factor and seasonal effect did not consider here. For this reason, it shows very poor reliance of load data.

Yang Zhang has proposed a Multi-objective Genetic Algorithm for peak load shaving application [13]. This method can shave peak load and can maximize the self-sufficiency and self-consumption. Here, three strategies have been considered but optimal size of BESS did not consider here which can increase the installation cost of BESS and can make the system bulky. Among the three strategies, conventional operation strategy cannot bring any economic benefit. R.A. Thokar has proposed a Nested Multi-objective Optimizing strategy for reducing evening peak [14]. This method controlled the charge-discharge operation of BESS and shaved evening peak. It can prevent the reverse current flow and minimize the power losses. Hence, this method cannot deal with more than one PV-BESS hybrid system. M R Jannesar has proposed a Genetic Algorithm with Linear Programing method for same purpose [15]. This technique can deal with more than one PV-BESS hybrid system,butit cannot ensure the optimal usage of PV unit. After charging the battery fully, PV will remain on standby mode.

This work presents a Modified Decision Tree Algorithm for controlling the charge-discharge operation of BESS and ensuring the optimal usage of PV for achieving the peak load shaving application. This algorithm also considers the optimal generation dispatch which can overcome the limitations of the existing works. This algorithm has been applied on UTP load profile which exhibited positive results and shows the potentiality. PV has been used here as the main device for peak demand shaving, not for charging the battery only. When PV generation is not available with the system or PV generation is not enough to fulfill the demand, that time BESS will operate to supply the power to the demand. The proposed algorithm will work both on PV connected IMG system and without PV connected IMG system. This paper is organized as:

- Working procedure of the proposed algorithm can be found (Section 2).
- The outcomes of the algorithm, discussion of this work and a comparative analysis has been exhibited (Section 3).
- Finally, the conclusion and the direction for future improvement of this work can be found (Section 4).

2. METHODOLOGY

The proposed algorithm has been tested on UTP campus which is an ideal IMG system. UTP has its own generation system consists of two Gas Turbine Generators (GTG) and both generators have 4.2MW rated capacity and 3.8MW optimum generation capacity. UTP maintains 11KV generation system and it distributes 415V around the whole campus including academic buildings, student hostels, administrative buildings and so on. The load profile of UTP is depends on the availability of the students. During weekend, semester break, public holiday and working day, the variation of students can change the load profile of UTP. In working day, the demand isthe highest and opposite is true for public holiday. In semester break and weekend, the load profile of UTP looks almost similar.

In this work, we consider 400KW (900KWh) BESS units and 2MW photovoltaic generation unit. The maximum demand of UTP is around 5.8MW (expect working). So, we consider 2MW PV generation because during daytime PV generation may have enough to meet the demand and second generator can be turned off. On the other hand, during morning and evening time the demand varies from 3.8MW to 4.2MW. So, we consider 400KW because this time BESS will discharge to meet the demand and the operation period of BESS is around 2 hours &15minutes. The details of UTP Microgrid can be found in [16]. In Figure 1, the load profile of UTP has been demonstrated.

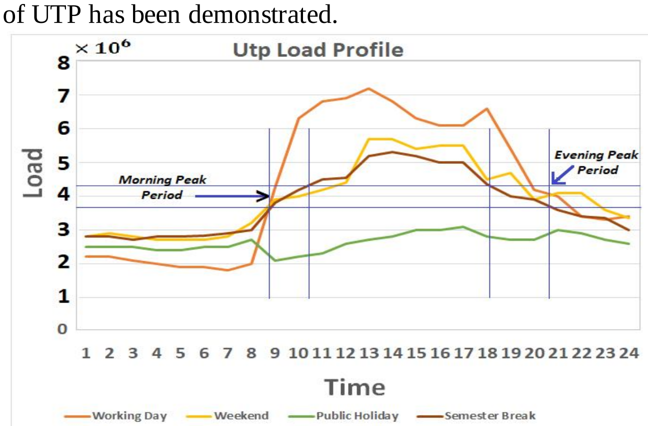
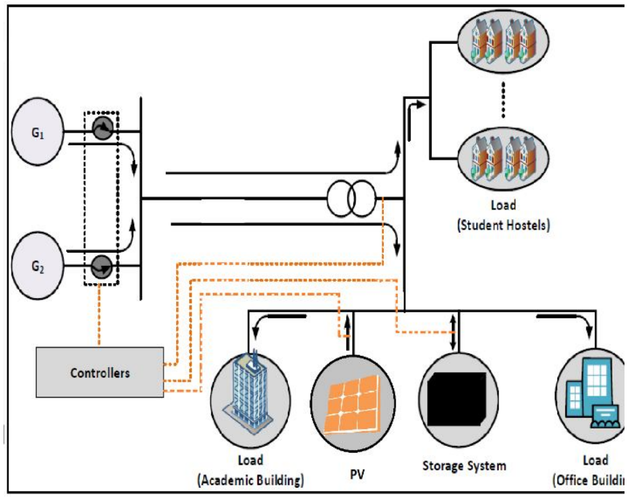


Figure 1:UTP load profile under different scenario (weekend, semester break, public holiday, working day)



1)

Figure 2: Simplified configuration of the proposed UTP Microgrid

A simplified configuration of the proposed UTP Microgrid including the time varying load profile, two GTGs, PV generation unit and BESS unit has been exhibited in Figure 2. The control unit has also been shown there which can control the operation of the connected resources.

The generation of PV has been shown in Figure 3. Here PV generates the power based on real time data of temperature and solar irradiation which is collected from PV generating station of UTP. The solar irradiation value of UTP is very poor.Here, we consider 2MW PV generation system, but under the poor solar irradiation, the maximum power generation of the PV is around 1250KW. The generation of PV has been shown in the following figure.

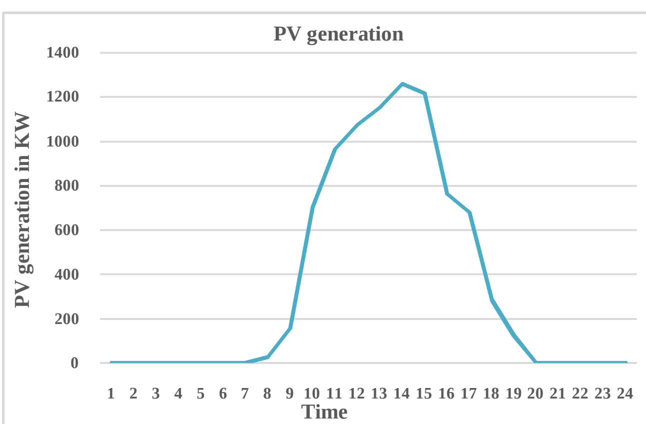


Figure 3: Power generation of PV based on real time data of solar irradiation and temperature

The proposed peak load shaving algorithm that can control the charge-discharge operation of BESS and ensure the proper usage of PV is shown in Figure 4 (simplified form) & Figure 5 (detailed form of Loop-B).

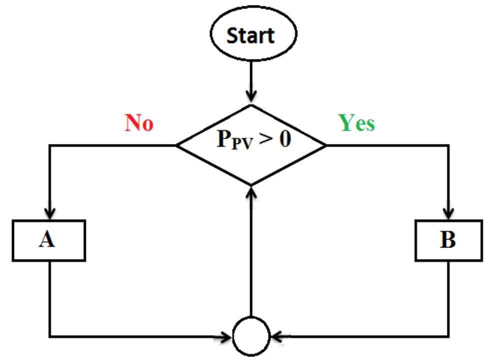


Figure 4: Simplified form of the proposed peak load shaving algorithm

The algorithm has two loops (Loop-A & Loop-B) and both loops have four different operational modes. Loop-A will work when PV is not available with the system and Loop-B will work when PV generation is available. The working procedure of the proposed method will start from comparing of the PV generation (P_{PV}) with zero. If P_{PV} is greater than zero, it means PV generation is available with the system and if P_{PV} is less than or equal to zero, it means PV generation is not available.

A. Operational Loop-A

Operational loop-A has indicated that PV is not available with the system and only BESS will operate to meet the demand. This loop contains four different operational modes and the operation process of Loop-A can be found in[17].

B. Operational Loop-B

Mode-1: At first, the system will compare the demand (P_D) with total optimum generation of the generators (μP_T). If P_D is higher than μP_T then Generator(s) (G_n) will turn on and next it will compare the P_D with P_{PV} and μP_T. If the demand is higher than the summation of P_{PV} and μP_T, it means the generation is not enough to meet the demand (equation 2). Then, if the State of Charge (SOC) of battery is also higher than the Minimum State of Charge (SOC_{min}), then the battery (P_B) will be discharged to supply the power for the end users. But, if the demand is lowerthan the summation of P_{PV} and μP_T, it means the generation is enough to meet the demand (equation 1). The extra power will be supplied by the PV generation. The power balance equations will be-

If P_{PV} is enough to meet the demand

$$\mu P_T = P_D - P_{PV} \quad (1)$$

If P_{PV} is not enough to meet the demand

$$\mu P_T = P_D - P_{PV} - P_B \quad (2)$$

Mode-2: If P_D is lower than μP_T but higher than ($\mu P_K + P_B$) then operational mode-2 happens and it will again compare the demand with ($\mu P_K + P_{PV}$). If demand is lower than ($\mu P_K + P_{PV}$) then G_n will turn off and power will be supplied by PV (equation 3).

Hence, if demand is higher than ($\mu P_K + P_{PV}$) then G_n will still turn on and power will be supplied by both PV and generators (equation 4). This time, if SOC of battery is lower than Maximum State of Charge (SOC_{max}), then battery will be charged otherwise the system will follow the power balance equation. The power balance equations will be-

If P_{PV} is enough to meet the demand and $SOC \geq SOC_{max}$

$$\mu P_K = P_D - P_{PV} \quad (3)$$

If P_{PV} is enough to meet the demand and $SOC < SOC_{max}$

$$\mu P_T + P_{PV} + P_B = P_D \quad (4)$$

$$here, P_K \text{ is } G_{n-1}$$

Mode-3: If P_D is lower than ($\mu P_K + P_B$) but higher than μP_K, then G_n will turn off and next it will compare P_D with the summation of P_{PV} and μP_K. If the demand is higher than the summation P_{PV} and μP_K and the SOC of battery is also higher than the SOC_{min}, then the P_B will be discharged to meet the demand (equation 6). But if the demand is lower than the summation of P_{PV} and μP_K, it means the generation is enough for the demand (equation 5).

The loads will be fulfilled by the PV generation and it will follow the power balance equation. The power balance equations will be-

If P_{PV} is enough to meet the demand

$$\mu P_K = P_D - P_{PV} \quad (5)$$

If P_{PV} is not enough to meet the demand

$$\mu P_K = P_D - P_{PV} - P_B \quad (6)$$

$$here, P_K \text{ is } G_{n-1}$$

Mode-4: If P_D is lower than μP_K and ($P_B + P_D$), then G_n will turn off. If SOC of battery is less than SOC_{max}, then the battery will be charged (equation 8), otherwise the demand will be equal to summation P_{PV} and μP_K(equation 7). The power balance equations will be-

If $SOC \geq SOC_{max}$

$$\mu P_K = P_D - P_{PV} \quad (7)$$

If $SOC < SOC_{max}$

$$\mu P_K + P_{PV} + P_B = P_D \quad (8)$$

$$here, P_K \text{ is } G_{n-1}$$

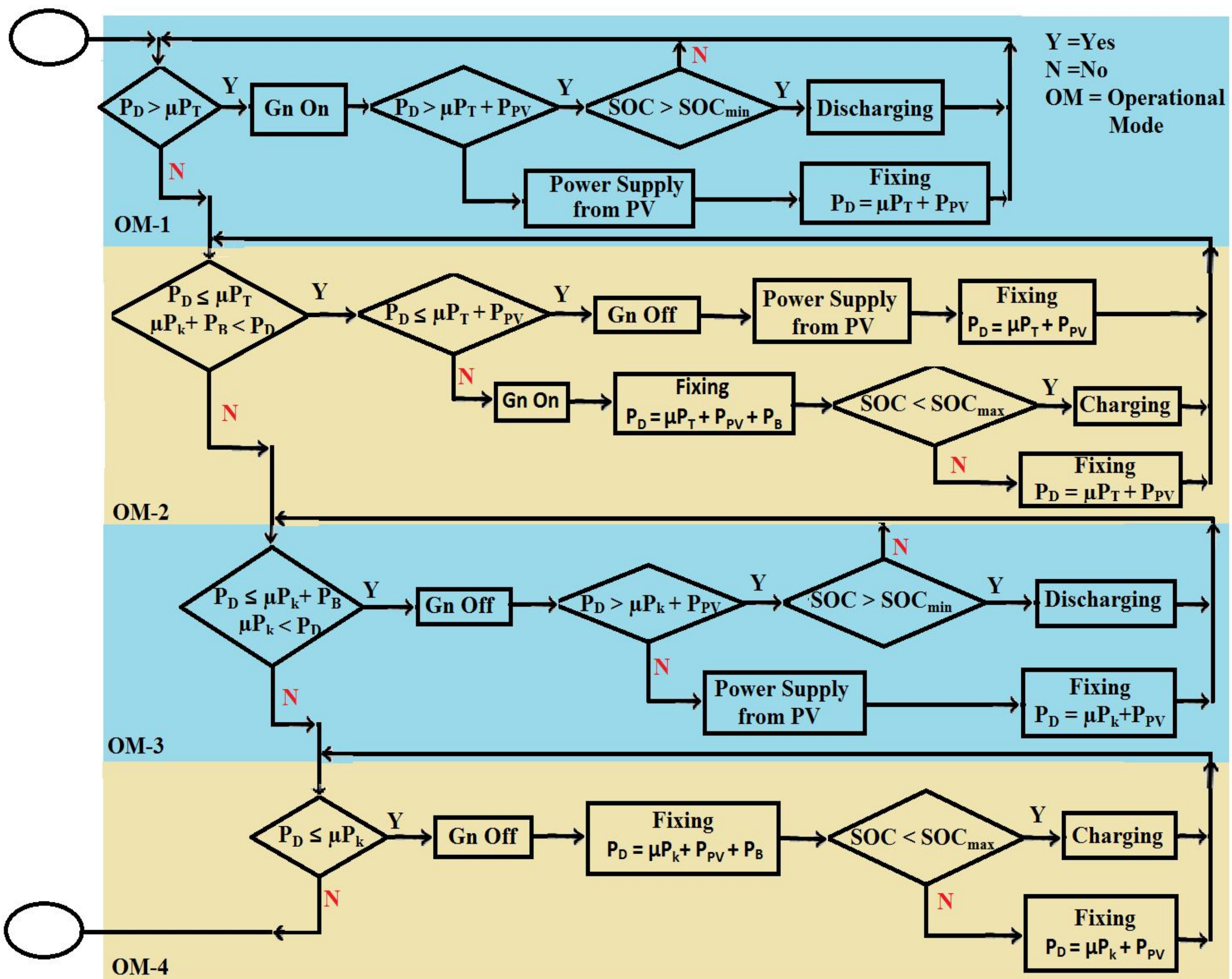


Figure 5: Flowchart of the Operational Loop-B of the Proposed Peak Load Shaving Algorithm

The working principle of the four different operational modes of the operational loop B has been shown separately as a graphical view in the following Figure 6.

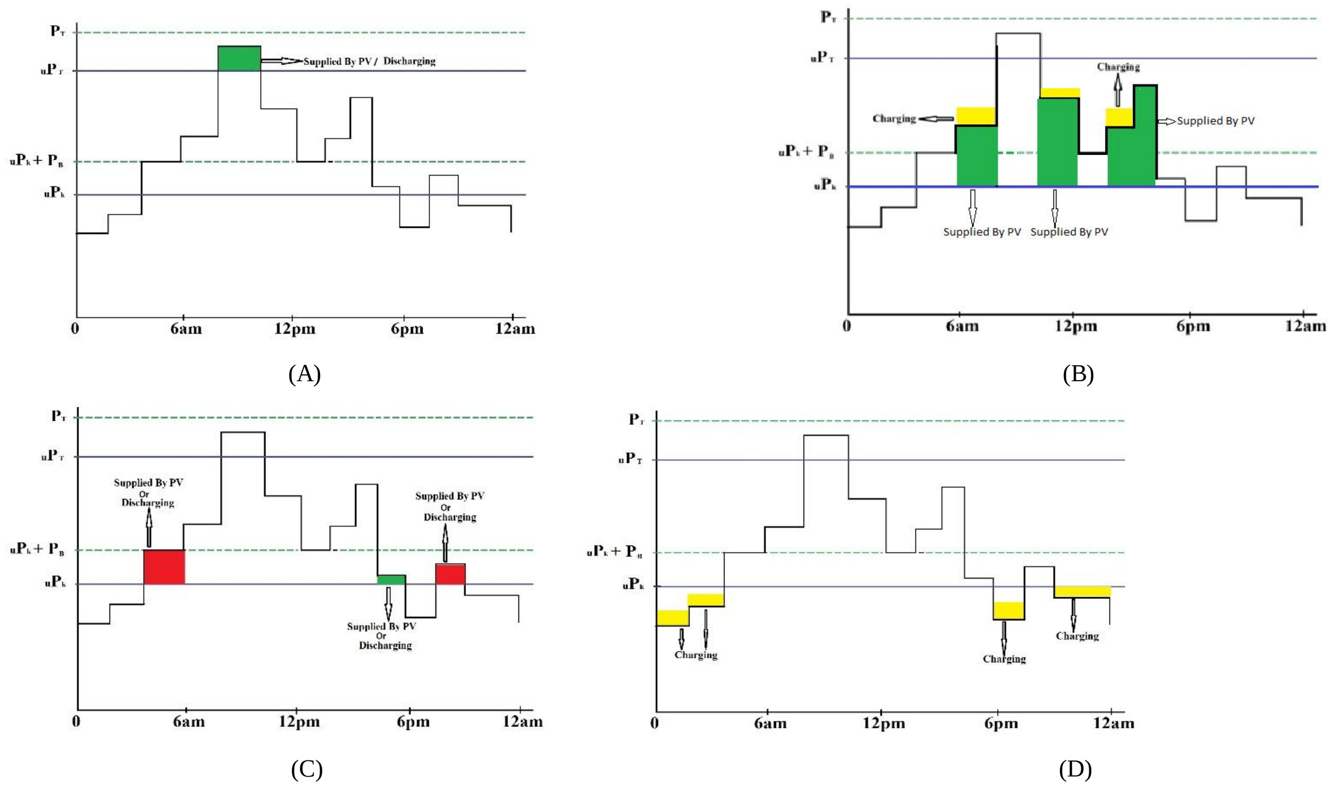


Figure 6: Working Principle of Operational Loop-B; (A) Operational Mode-1, (B) Operational Mode-2, (C) Operational Mode-3, (D) Operational Mode-4

3. RESULTS AND DISCUSSION

Different case studies have been presented in this section. Weekend, semester break, public holiday and working day load profiles are some possible scenario of the UTP. The comparison between the proposed algorithm and the latest peak shaving Decision Tree Algorithm also has been presented in this section. The advantages and the disadvantages of the proposed algorithm have been presented shortly here. The demand of UTP is higher during daytime (from around 8am to 6pm the demand is higher) than night-time. The generation of PV starts from around 8am and it reaches to zero around 8pm.

Weekend: In weekends the highest demand of UTP is approximately 5.8MW. The generation of PV starts from 8am and reaches to zero around after 8pm. From 8am to around 10am the load varies from 3.8MW to 4.2MW and operational mode-3 performed. The Proposed algorithm ensurePV and BESS both to operate to meet the demandfrom 8am to 9am because this time only PV generation is not enough to meet the demand. Again from 9am to 11.30am, the load is between 4.2MW to 7.6MW and operational mode-2 happened. In this period, PV contributes to meet the demand and it can turn off the second generator. Again from 6:35pm to 9pm, operational mode-3 performs and this time also PV and BESS both operate to fulfill the demand. On the other hand, from 11amto 5amand 11:30am to 3pm, the Proposed Algorithm allows the battery to charge. For the latest Decision Tree Algorithm, only BESS operates to supply power for the demand. From 8am to around 10am and from 6:35pm to 8pm for operational mode 3, the battery discharged to meet the demand. From 10am to 2pm and from 11pm to 4am, the battery is charged from the generators. The comparative results have been exhibited in Figure 7 and a short summary has been shown in tabular form in Table 1. It is transparentthat the proposed algorithm can minimize the demand around 3.5 hours more than the latest work which is economically beneficial for the system.

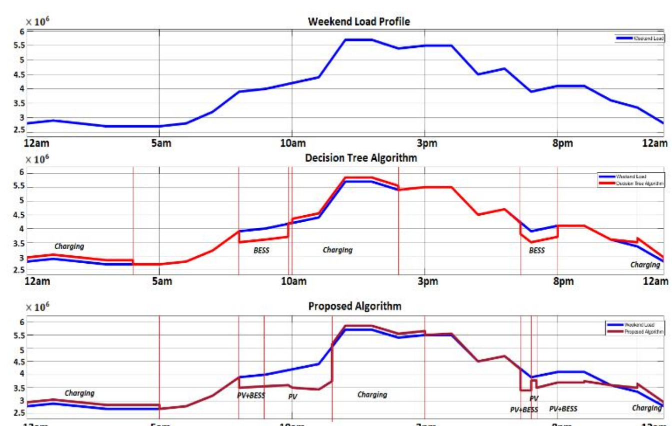


Figure 7: Performance comparison between the Proposed Algorithm and the Decision Tree Algorithm on UTP weekend load profile

Table 1: Short summary of the comparison between the Proposed Algorithm and the Decision Tree Algorithmon UTP weekend load profile

Categories	The Proposed Algorithm	Decision Tree Algorithm
Morning Peak shaving	Around 2 hours	Around 2 hours
Daytime Peak Shaving	Around 1hour 30 minutes	Failure
Evening Peak Shaving	Around 2 hours 30 minutes	Around 1hour 30 minutes
Operation of 2nd GTG	Around 1.5 hours less than the latest work	During whole daytime

Semester Break: In semester break, the maximum demand is approximately 5.3MW. For Proposed Algorithm, from 8:15am to 9am operational mode-3 happens, it means the demand varies from 3.8MW to 4.2MW. This time from 8:15am to 8:30am, only PV supplies the power to meet the demand. Again from 8:30am to 9am, both PV and BESS operate to fulfill the loads. After that, from 10am to 11:30am, from 3pm to 3:30pm and from 4:30pm to 7:45pm, only PV has supplied power and all these timeperiods, second generator can be turned off. The charging operation has been allowed from 12am to 4am and 9am to 10am.

On the other hand, for the latest peak shaving algorithm, from 8:15am to 9am and from 5:45pm to 7pm, the BESS operatesto meet the demand. The charging operation has been allowed from 9am to 11am and 9pm to 4am. The comparative resultshave been shown in Figure 8 and a short summary has been demonstrates in Table 2. It can observe that the proposed algorithm can ensure the optimal use of PV and BESS. It can minimize the load profile around 3.5 hours to 4 hours more than the latest work.

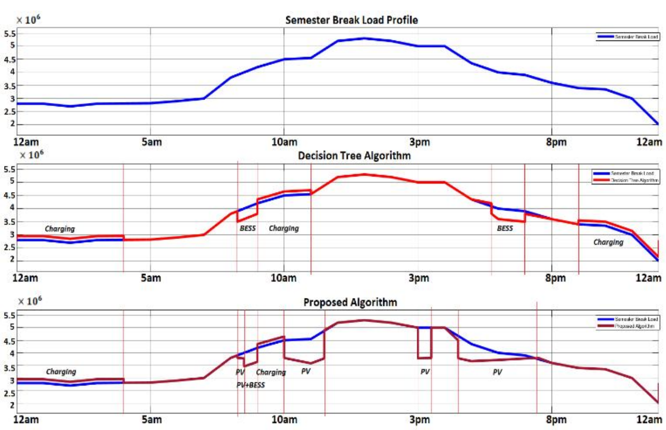


Figure 8: Performance comparison between the Proposed Algorithm and the Decision Tree Algorithm on UTP semester break load profile

Table 2: Short summary of the comparison between the Proposed Algorithm and the Decision Tree Algorithmon UTP semester break load profile

Categories	The Proposed Algorithm	Decision Tree Algorithm
Morning Peak shaving	Around 45 minutes	Around 45 minutes
Daytime Peak Shaving	Around 3 hours 45 minutes	Failure
Evening Peak Shaving	Around 1 hour 45 minutes	Around 1 hour 15 minutes
Operation of 2nd GTG	Around 3.75 hours less than the latest work	During whole daytime

Public holiday: In public holiday, the maximum demand of UTP is around 3.1MW and the load varies from 2MW to 3.1MW in whole day. The demand is always lower than the generation of single generator. So, the operational mode-4 operates in the whole day. The peak shaving operation does not need to perform there. For the Proposed Algorithm, PV generates power accordingly and the conventional gas turbine generation needs to generate lower power to fulfill the demand. For generating less energy from the GTG, it saves more energy and brings economic benefit. It reduces the fuel consumption and carbon & other greenhouse gasses emission. For charging the battery, the charging operation has been performed from 12am to 4am.

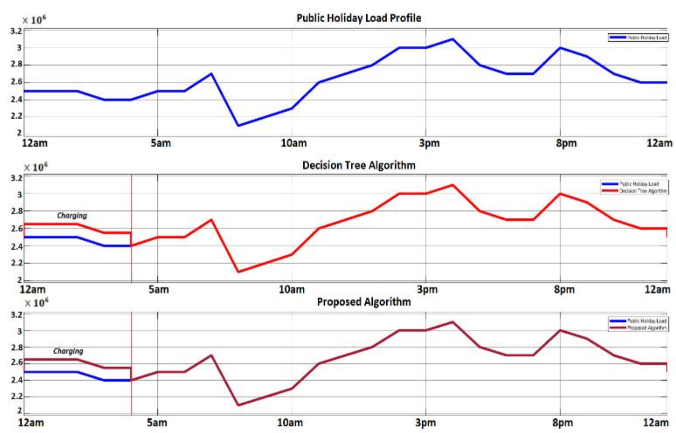


Figure 9: Performance comparison between the Proposed Algorithm and the Decision Tree Algorithm on UTP public holiday load profile

On the other hand, for the latest work, one generator generates power to fulfill the demand whole day. This time, the generation of single generator is exactly equal to the demand. The charging operation of BESS has been performed from 12am to 4am. The comparative result has been demonstrated in Figure 9 and a short summary has been shown in Table 3. Itcan observe that the Proposed Algorithm allows the GTG to generate lower energy that the latest algorithm which ensure more economic benefit and ensure an environment friendly system.

Table 3: Short summary of the comparison between the Proposed Algorithm and the Decision Tree Algorithmon UTP public holiday load profile

Categories	The Proposed Algorithm	Decision Tree Algorithm
Morning Peak shaving	No need to minimize	No need to minimize
Daytime Peak Shaving	No need to minimize	No need to minimize
Evening Peak Shaving	No need to minimize	No need to minimize
Operation of 2nd GTG	No need to operate	No need to operate

Working day: In working day, the maximum demand of UTP is around 7.2MW. The demand of UTP in working days is higher than the other possible scenario. This day both GTG needs to turn on to supply the power to the demand. For the Proposed Algorithm, from 7:45am to 8am and 7pm to 8:30pm operational mode-3 happens and these times both PV and BESS contribute to meet the demand. During daytime generators and PV both generate energy where the second generator need to turn on for few time periods but generates lower energy which can reduce the fuel consumption of GTG. More energy saving and economic benefit is the visible outcome here. The charging operation can be done from 9pm to 4am and 8am to 9am.

On the contrary, for the latest Decision Tree Algorithm, from 7:45am to 8am and 7pm to 8:30pm operational mode-3 operates and these times only BESS operates to supply the power for the demand. During daytime both generators generates power and the power generation is exactly equal to the demand. The charging operation can be done similarly from 9pm to 4am and 8am to 9am. The comparative results have been demonstrated in Figure 10 and a short summary has been shown in Table 4. More economic benefit and environmental friendliness system is the possible outcomes here than the latest works.

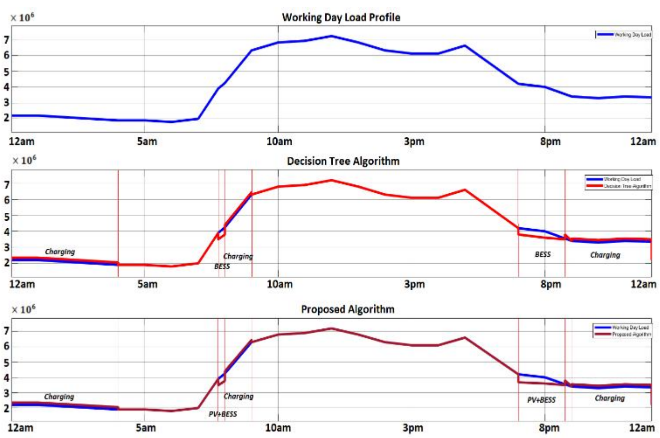


Figure 10: Performance comparison between the Proposed Algorithm and the Decision Tree Algorithm on UTP working day load profile

Table 4: Short summary of the comparison between the Proposed Algorithm and the Decision Tree Algorithmon UTP working day load profile

Categories	The Proposed Algorithm	Decision Tree Algorithm
Morning Peak shaving	Around 15 minutes	Around 15 minutes
Daytime Peak Shaving	P_{PV} was not enough, failure to shave	Failure
Evening Peak Shaving	Around 1 hour 45 minutes	Around 1 hour 45 minutes
Operation of 2nd GTG	During whole daytime but performs huge energy saving	During whole daytime

By analyzing the results, it can be found that when PV-BESS hybrid system is used for peak load shaving application,it will bring more economic benefit than that of only PV or only BESS system. During daytime, second generator need to turn on for few time periods because here PV power is supplied directly to meet the demand, not only for charging the battery. The proposed Algorithm can ensure the optimal use of hybrid PV-BESS system and minimize the demand more than the latest works undoubtedly. Besides it, the proposed algorithm is a modified decision tree algorithm which is a complex algorithm though it is easier to understand. The model has been designed in MATLAB/ Simulink for UTP Microgrid under the proposed algorithm is very complex process though it gives the satisfactory outcomes. Small changes of the proposed algorithm require large modification on the model.

4. CONCLUSION AND FUTURE DIRECTIONS

A Modified Decision Tree Algorithm has been proposed in this work for achieving peak load shaving service in IMG system. This algorithm can control the charge-discharge operation of BESS and can ensure the optimal usage of PV for achieving the goal. This algorithm has been tested on UTP load profile which is an ideal Isolated Microgrid consist of two conventional generators, PV generation unit, BESS, and dynamic load profile. Daytime peak load shaving and generation dispatch problem has been considered in this work. This algorithm compares the demands with the generation and can minimize the demand based on some dynamic decisions. Hybrid PV-BESS has used here for peak shaving directly and this algorithm can minimize both the daytime and evening or night-time peak effectively. The limitations of the existing techniques for peak load shaving have overcome a lot by this method. The comparative study between the latest algorithm and the proposed algorithm has been shown that the proposed method can bring more economic benefits and it is more environment friendly.

The proposed method does not consider the improvement of the lifetime of PV-BESS hybrid system. For better performance, the lifetime improvement of PV-BESS hybrid system can be analyzed further deeply. Here, a large-scale PVarray has been considered hence, a large battery bank also can be considered for peak shaving application in the future.

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