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# Fuzzy Control Algorithm for Battery Storage and Demand Side Power Management for Economic Operation of the Smart Grid System at Naresuan University, Thailand

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**ABSTRACT** This paper presents a fuzzy logic-based algorithm developed for battery storage power management (BSPM) and demand side power management (DSPM) for the School of Renewable Energy Technology (SERT)-Smart Grid (SSG) at Naresuan University in Phitsanulok, Thailand. This algorithm enables lower cost operation of the SSG by utilizing the time of use electricity-pricing concept and thus is called the Fuzzy Low-cost Operation (FLO) algorithm. After applying the FLO algorithm to the SSG, the BSPM can strategically handle fluctuating PV production by intelligently alternating between absorbing power during high solar irradiation periods and discharging power to the load during peak consumption times. The FLO algorithm also empowers the SSG's DSPM to decrease the peak load by using SERT's building energy management system to disconnect noncritical load as desired, for example lighting, air conditioners, and dummy heater load (used for research testing purposes). Research results show that the FLO algorithm successfully decreased SERT's annual electricity bill by 17.58%, equivalent to a grand total of $ 9148 in annual savings. Of 17.58% in savings, 5.78% came from modifications to the BSPM and 11.81% came from modifications to the DSPM. The average monthly savings correspond to $762 ($250 from BSPM and $512 from the DSPM), significant savings that without the FLO algorithm would not be available.

**INDEX TERMS** Fuzzy logic control, smart grid system, battery power management, demand response, demand side management, TOU electricity price.

## I. INTRODUCTION

Today increasing air pollution, global warming concerns, looming exhaustion of fossil fuels and their increasing cost have made it imperative to look to renewable energy Sources as a future energy solution [1]–[4]. Solar energy in particular has high potential in Thailand. Increased renewable energy systems connected to low voltage distribution system have some negative impacts such as decreased power quality (voltage variations, frequency variations, harmonics distortion, etc.) [5]–[13]. The ideal solution to these problems is to use a smart grid system in order to support the expansion of electricity generation from renewable energy systems [14]–[16]. Smart Grid Technology can reduce transmission losses and lead to large reductions in GHG emissions. Thailand's Smart Grid Master Plan (for 2015-2036) was developed under the Energy Policy and Planning Office (EPPO) of the Ministry of Energy [17]. Pilot smart grid projects, both hardware and software, are being planned to develop and demonstrate feasibility. The School of Renewable Energy Technology (SERT) at Naresuan University knows that in the near future a smart grid will be vital for Thailand and so has developed the SERT-Smart Grid (SSG) to advance this research and to facilitate the soon to arrive smart grid in Thailand. Demand side power management (DSPM) has been one of the main focuses for studying and developing the SSG. The concept of demand response was implemented throughout all the buildings of SERT. Load, lighting and air-conditioning can be controlled by the building energy management system (BEMS).

The term of demand response (DR) refers to a change in load usage by the user from their normal load consumption pattern in response to changes in incentive payments, the price of electricity or available power quality in the distribution system [18]–[21]. Within DR, price based programs are a set of tools used intentionally modify electricity prices in response to various situations. Current examples are time of use pricing (TOU), critical peak pricing (CPP), dynamic real time pricing (RTP), and day-ahead pricing (DAP) [22]–[24]. When the price of electricity is high, these price base programs can be used to encourage the end user to reduce their electricity consumption [25], [26]. Incentive based programs are another type tool within the DR concept, which allows utility administrators to switch noncritical load on and off when demand is too high and could compromise system power quality and system reliability [18]–[21].

Battery Storage Systems (BSS) are an essential part of any Smart Grid because BSS support grid network stability by establish and maintain a balance between fluctuating power generated from the RE system and load demand that is using that power. BSS benefits the grid operator by assisting in grid network operations such as peak shaving, load shifting, load levelling, frequency regulation and voltage stability control [27], [28]. BSS also benefits the customer by enabling them to manage their own energy demand; with BSS customers can store electricity at their own site, either electricity from the grid, or electricity from their own on-site RE generation system and then discharge it later when needed. This can increase the use of demand-site generated electricity and thereby reduce the amount of additional electricity needed from the grid [29], [30].

The purpose of this research is to develop an algorithm for controlling battery storage and demand side power management in the SERT-Smart Grid (SSG) and in this way save electricity cost. This control algorithm has been developed by applying fuzzy logic to BSPM and DSPM, providing more economical operation of the SSG by using time of use pricing. This Fuzzy Logic Operation (FLO) Algorithm has already been tested and is currently deployed in actual operation throughout the SSG, smoothly and efficiently managing both BSPM and DSPM. The FLO Algorithm is a boon for both grid users and administrators, not only reducing electricity costs but also increasing stability and reliability of the whole grid network, because electricity demand on the grid during peak time is reduced providing the balance between supply and demand.

## II. SERT-SMART GRID

The School of Renewable Energy Technology (SERT) at Naresuan University established a 120 kW Microgrid system in 2005. This system was built for school consumption, demonstration and research purposes. As SERT expanded, additional RE components were installed: a battery energy storage system and a monitoring & control system. These transformed SERT's Microgrid into the SERT Smart Grid (SSG). SSG's infrastructure, shown in Figure 1, comprises 350 kW of ground mounted PV arrays, 50 kW PV of rooftop systems, 500 kWh of battery storage capacity in 3 units and 600 kW capacity of grid inverters in 22 units, all managed through a SCADA system. The newly installed BEMS manages energy efficiently in all the buildings of SERT. The SSG system functions seamlessly in both grid connected and island modes to ensure uninterrupted power supply to the campus. Demand and supply balancing is carried out using a SCADA system and BEMS.

The control and monitoring system of SSG consists of two parts; the first is the SCADA system, which controls the grid inverter and the battery inverter. Among its many functions, SCADA manages alternation between grid connected mode and island mode. SCADA not only controls the electric power but also continually monitors and records numerous electrical parameters concerning system performance, power quality, load power and meteorology, delivered in one minute intervals. The second control and monitoring component of SSG is BEMS, which can manage lighting and air conditioning loads remotely from any internet connected device. Time scheduling can be set for certain loads to turn them on or off. These sorts of modernizing components and automated operations can significantly improve performance, reduce losses and reduce the cost of operating the SERT Smart Grid.

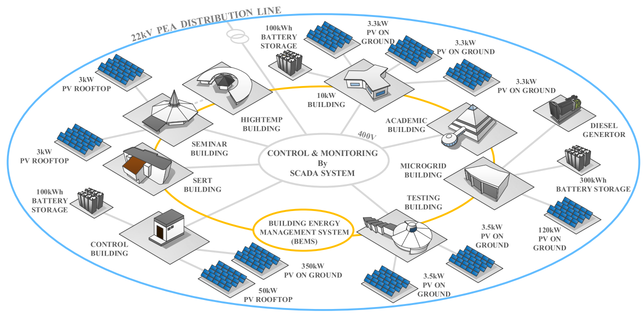


FIGURE 1. The SERT smart grid (SSG).

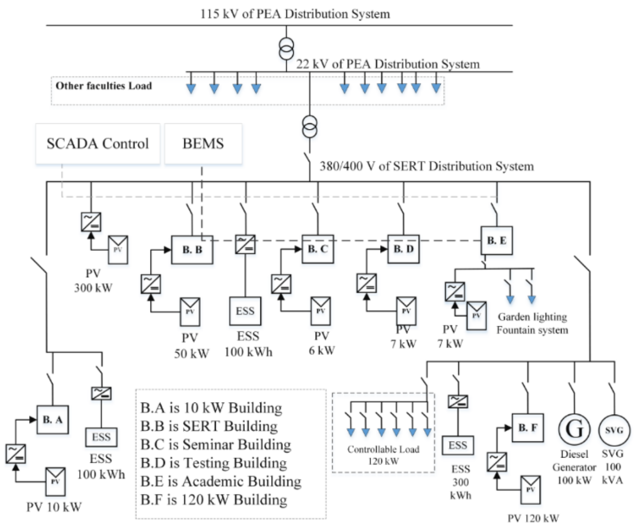


FIGURE 2. Schematic diagram of the SERT smart grid (SSG).

## III. DEVELOPMENT OF THE FLO ALGORITHM

After collecting extensive data on the SSG, and analyzing both the advantages and disadvantages of the original system, an algorithm operating with fuzzy logic (FL), the FLO Algorithm, was developed to greatly increase control of the BSS and load for maximum economic operation. Fuzzy logic method (FLm), a flexible and powerful tool with much potential for electrical power systems, is similar to human beings' feelings and a decision-making processes. Fuzzy logic control is a range to point or range-to-range control. The output of FLm is derived from Fuzzifications of both input and output using the associated membership functions [31]–[33]. A crisp input will be converted to a membership function based on its value. In this way, the output of FLm is based on the various membership functions, each of which can be thought of as a range of inputs. FL techniques have been widely applied throughout many aspects of modern life. Implementing fuzzy logic in a real application involves three essential steps: 1. Fuzzification, to convert crisp values to fuzzy data using membership functions (MF), 2. Inferance process, to process MF within sets of rules or laws to develop the fuzzy output and 3. Defuzzification, to determine the correct output. Fuzzy logic controller of the FLO Algorithm is shown in Figure 3. The FLO Algorithm consists of BSPM and DSPM, which were developed by fuzzy logic, It performed well in electrical power application like SSG. The advantages of the FLO Algorithm was achieved; maximum of RE energy source, load leveling, load balancing and cost efficient.

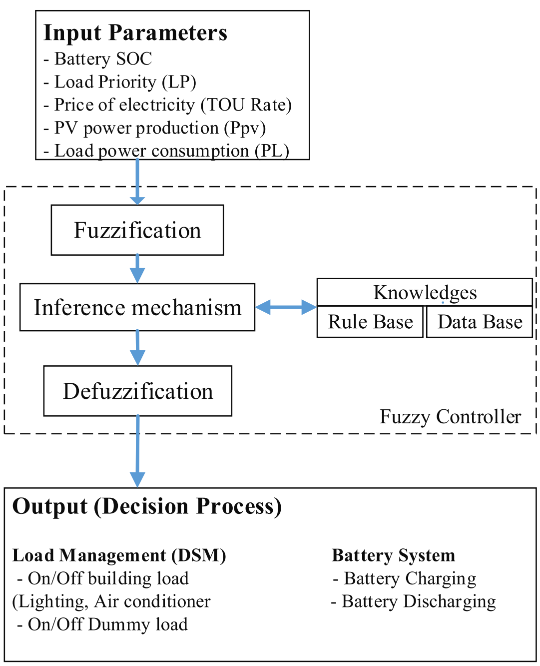


**FIGURE 3.** Fuzzy logic controller of the FLO algorithm.

The input and output parameters of fuzzy logic controller are showed in Figure 3. The FLO Algorithm, which was developed for SSG is illustrated in Figure 4.

The purpose of the FLO Algorithm is for economic operation of the SSG, reducing the price of electricity consumption by using variable TOU pricing. It means that the pricing is according to peak and off peak time. In Thailand, the electricity price is \$0.122 per kWh during peak times and \$0.079 per kWh during the off peak times. The control strategies empowers to manage a DSPM and BSPM following the peak and off peak times.

During peak times, if PV production is higher than PL and the state of charge (SOC) of the battery is lower than 0.98. The SSG system designed to charge the battery by using FLm (Charging mode). Inputs parameters concerning the charging mode are, SOC of the Battery, PV power production (Ppv) and load power (PL). If Ppv is still higher than PL plus Pb (Power of battery) then SSG system will look for load filling (Turn on load for using electricity from PV system) by FLm. The parameters of this process consist of Ppv-PL and load priority (LP) that is a capacity of load which is able to turn on in percentage. After this process, if Ppv is still higher than PL + Pb then SSG order to inject electrical power to grid (PVtG). The advantage of the FLO Algorithm during the peak time when Ppv higher than PL is to maximize the use of electricity from the PV system.

During the peak times, if Ppv $<$ PL and the SOC $>$ SOCmin (0.35) then the SSG designed to discharge the battery system by using FLm to decrease the peak load and to decrease energy demand during the peak period. Input parameters in this process consist of Ppv-PL and the SOC of the batteries. The battery will discharge until SOC is equal to 0.35 then the process will stop. On the other hand, if the SOC $\leq$ SOCmin (0.35) then the process is directed to decrease the load power by using the load crippling process. Describable, input parameters in this process consist of load priority (LP) which is the capacity of load power that can be turned them off for decreasing the peak load. The advantage of this process is to decrease the peak load and energy demand during peak time by BSPM and DSPM.

During off peak time, PV-P $>$ 0 and SOC $<$ 0.98 then SSG will operate as the charging mode by FLm. Input parameters in this process consist of Ppv-PL and SOC of the battery. If PV-PL-Pbatt $>$ 0 then the SSG will look for a load filling process. The load filling was designed by using FLm. Then if PV-PL-Pbatt $>$ 0 the electricity will be fed to the grid (PVtG). The advantage of this process is to maximize the use of electricity from the PV system.

During off peak time, PV-PL $<$ 0 and SOC $<$ 0.98 then SSG will operate as the charging mode by FL method. Input parameters in this process consist of Ppv-PL and SOC of battery. This process will fully charge battery (SOC = 1 by theory). The electricity in charging process comes from the main grid (GtB) because during off-peak period, electricity cost is cheaper than peak time. The advantage of this algorithm is the battery will permanently be full capacity waiting for the next coming peak time.

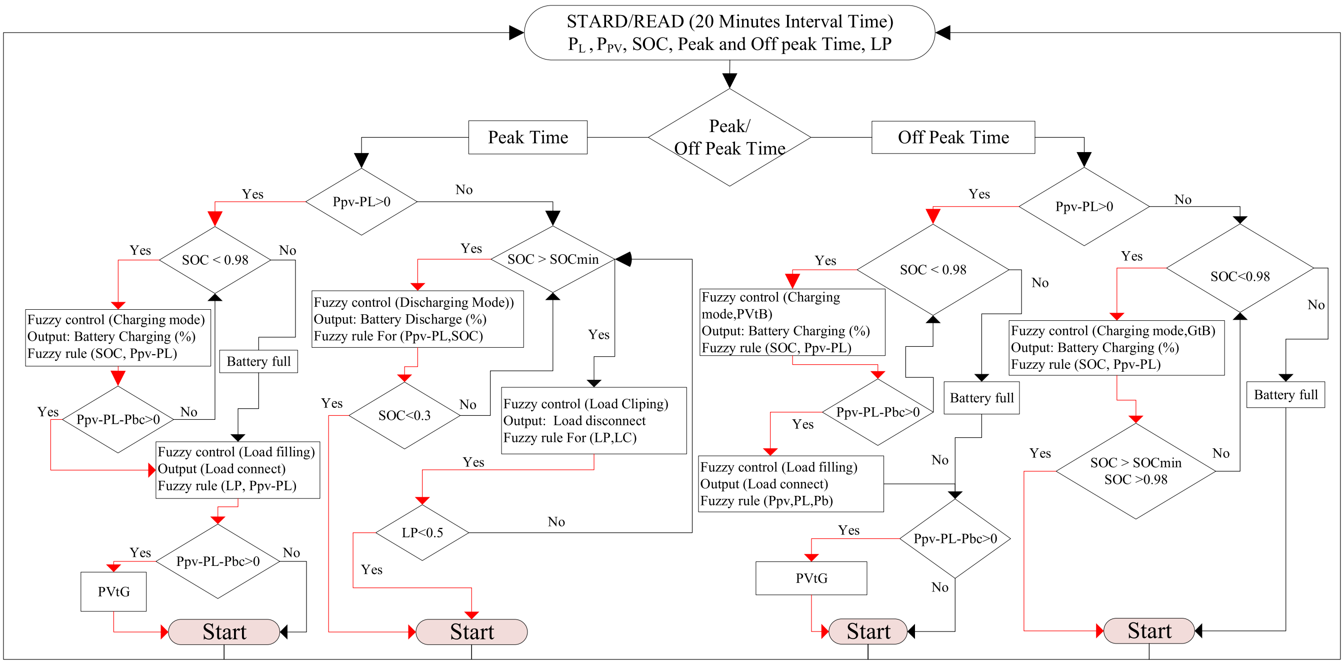


**FIGURE 4.** **Fuzzy logic operation algorithm (Flo Algorithm).**

### *A. MODEL OF CONCERNED PARAMETERS*

This research mainly focuses on battery and load management. The model of both parameters can be described as follows.

#### 1) BATTERY

The battery state of charge (SOC) is very important for battery management during charging mode or discharging mode. SOC is estimated based on the amount of power charge or power discharge that has been extracted from the battery [34], [35]. The SOC value can be simply calculated as follows.

$$SOC = \alpha SOC_c + (1 - \alpha) SOC_v \tag{1}$$

Where, SOC$c$ is the Coulomb-counting based on SOC and SOC$v$ which is the voltage-based SOC. Term $\alpha (\in [0, 1])$ is the weight factor. SOC$c$ is calculated based on the amount of charge and discharge. SOC$c$ can be estimated as follows.

$$SOC_c(t) = SOC_c(0) - \frac{1}{Q}\int_0^t I(t)\,dt \tag{2}$$

Where, $Q$ is a constant that relates to the current with charges ($I$). SOC $v$ is an estimation based on the open-circuit voltage (OCV) of the battery. It is defined as the voltage between the anode and cathode of the battery when there is no external load connected and no external current between the terminals. The relationship between OCV and SOC is given as below.

$$OCV(t) = \alpha SOC(t) + b \tag{3}$$

Where is a slope of SOC decreasing and increasing during charge and discharge modes. b is a constant determined by the test measurement.

#### 2) LOAD MANAGEMENT

In the SSG, the energy storage system (ESS) can work as a load during charging mode. On the other hand, ESS can work as a generator during discharging mode. Therefore, it is able to perform a peak shifting to reduce the peak load consumption during the peak time. It results in improving the economic operation of the SSG by load shave management. Load shave management refers to the reduction of large fluctuations in energy demand. During the peak time, total power production ability of RE system ($DG_{RES}$) in SSG is $P_{DG,peak}$ [36]

$$P_{DG,peak} = \sum\nolimits_{i \epsilon M_{peak}} P_{DGi} \tag{4}$$

When, $Mpeak$ is the set of all $DG_s$ that operate during the peak period. The desired load level ($P_{level}$) is designed as economic load shave management for ESS in SSG operation during peak and off peak times. The energy consumption during the peak time for the next day is required as follows.

$$E_{peak} = \int_{Ta,peak}^{Tb,peak} (P_D(t) - P_{level})dt \tag{5}$$

The total energy demand for ESS during peak time is the load shaved by by $P_{level}$.

$$(SOC_{res} - SOC_{min}) \times E_{rq} = E_{peak} \tag{6}$$

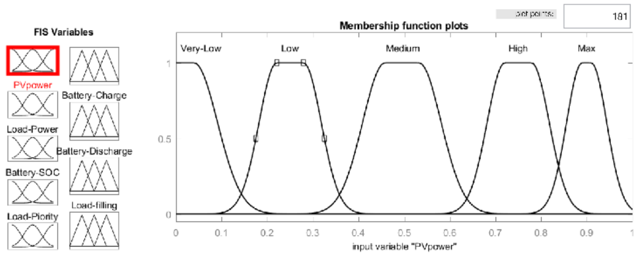


**FIGURE 5.** Membership functions of PV power production.

All parameters were converted into membership functions by Fuzzification process and then go for others process of fuzzy logic method as describe below.

### B. FUZZIFICATION

Fuzzification is the process to convert crisp values to fuzzy data using membership functions (MF). Input parameters concerned economics operation of SSG consists of Vgrid, SOC, Ppv, PL, and LP as showed in Figure 3. All parameters were converted in to the membership function as listed below.

Figure 5 illustrates the membership functions (MF) of PV power production (Ppv) which was classified into ranges of MF; very low, low, medium, high and max based on power production in percentage of capacity at any instance of time.

**TABLE 1.** Ranges of membership functions of Ppv.

| MF (Ppv) | Vary-Low | Low | Medium | High | Max |
|---|---|---|---|---|---|
| Ranges | 0-0.2 | 0.1-0.4 | 0.3-0.7 | 0.6-0.9 | 0.8-1 |
| Ppv(kW) | 0-24 | 12-48 | 36-84 | 72-108 | 96-120 |

The range of Ppv's MF was in between 0 to 1, 1 is mean 100 % of PV power production (120 kW).

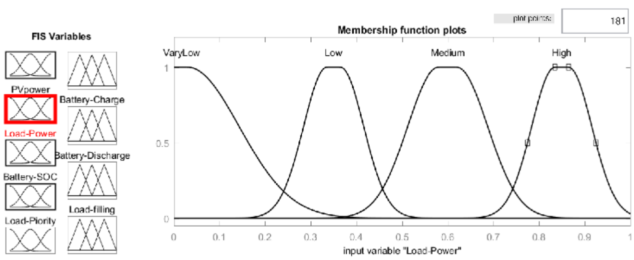


**FIGURE 6.** Membership functions of load power consumption.

Figure 6 shown the load power demand (PL) consumption which was divided into ranges of MF; very lower, low, high and very high base on load demand in percent of capacity at any instance of time. The maximum power demand in this research was 240 kW.

The range of PL's MF was in between 0 to 1, 1 is mean 100 % of load power demand (240 kW).

Figure 7 shows the battery state of charge (SOC). It is divided into ranges of MF; very low, low, medium, high and full that based on the available charge capacity in percentage at any instance of time.

The range of SOC's MF was in between 0 to 1, 1 is mean 100 % of battery full capacity (SOC equal 1).

**TABLE 2.** Ranges of membership functions of PL.

| *MF (PL)* | *Vary-Low* | *Low* | *Medium* | *High* |
|---|---|---|---|---|
| Range | 0-0.3 | 0.2-0.5 | 0.4-0.8 | 0.7-1.0 |
| Load (kW) | 0-72 | 48-110 | 96-192 | 168-240 |

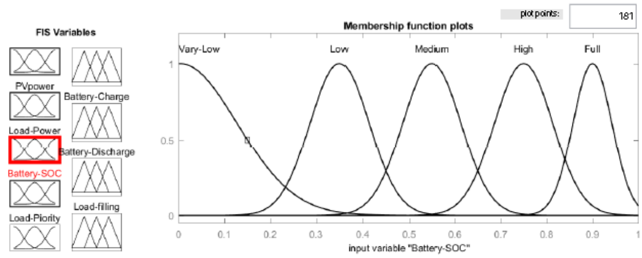


**FIGURE 7.** Membership functions of battery SOC.

**TABLE 3.** Ranges of membership functions of SOC.

| *MF (SOC)* | *Vary-Low* | *Low* | *Medium* | *High* | *Full* |
|---|---|---|---|---|---|
| Range | 0-0.3 | 0.2-0.5 | 0.4-0.7 | 0.6-0.9 | 0.8-1 |
| SOC | 0-0.3 | 0.2-0.5 | 0.4-0.7 | 0.6-0.9 | 0.8-1 |

**TABLE 4.** Ranges of membership functions of LP.

| *MF (LP)* | *Vary-Low* | *Low available* | *Medium available* | *Critical* |
|---|---|---|---|---|
| Range | 0-0.2 | 0.1-0.4 | 0.3-0.55 | 0.5-1.0 |
| Load Power (kW) | 0-32 | 24-96 | 72-132 | 120-240 |

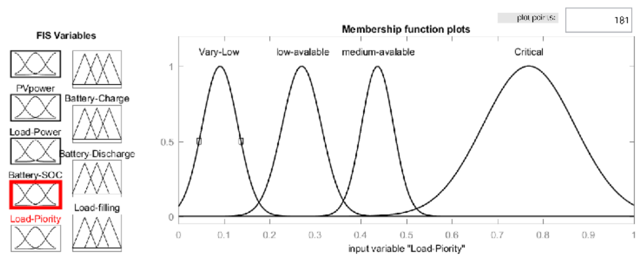


**FIGURE 8.** Membership functions of load priority (LP).

Figure 8 illustrates the load priority, it is the capacity of load, which is able to disconnect in emergency cases or as an economic operation. LP was classified into ranges of MF; very low, low available, medium available, Critical. The critical loads is the load demand, which was unable to disconnect because this load was the base loads about 50 % of SSG total load.

The range of LP's MF was in between 0 to 1, 0.5-1 is unable to disconnect.

TOU electricity prices in this research was referenced from Provincial Electricity Authority (PEA), Thailand. Electricity

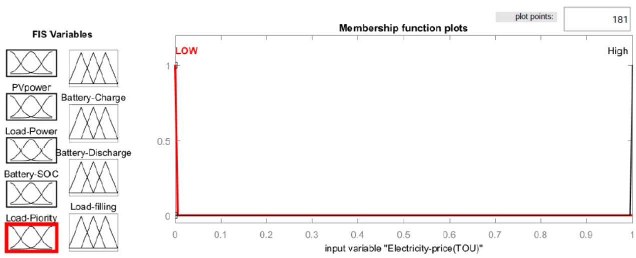


**FIGURE 9.** Membership functions of electricity prices.

**TABLE 5.** Electricity price at TOU rate.

| Distribution Voltage | Electricity Price (USD) | |
|---|---|---|
| | Peak Time (high) | Off Peak Time (Low) |
| 22 kV | $0.122 | $0.079 |
| The peak time is at 9.00 A.m. – 22.00 P.m<br>The off peak time is on Saturday ,Sunday and others official holidays<br>1 USD (U.S. Dollar) = 33 THB (Thai Baht) | | |

prices were divided into two rates, high value during peak time and low value during off peak time as show in the Table 5 [37].

### C. FUZZY INFERENCE

The Fuzzy Inference Process is the combination of membership functions with the knowledge, rule base and control rules to refine the fuzzy output. The fuzzy control rule is considered as the knowledge of experienced persons in any field of application. A fuzzy IF-THEN rule membership described linguistic variants and fuzzy sets to investigate a fuzzy output or conclusion. Fuzzy inference of the FLO Algorithm consisted of battery charging and discharging modes and load filling and clipping modes during peak/off peak time as show in Figure 4. An example of Fuzzy inference of the FLO Algorithm is battery-discharging process as show in Table 6.

**TABLE 6.** Fuzzy inference of discharging process.

| Inputs/Outputs Parameters | MFs | Rule base No. | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 |
| Input parameters PL-Ppv | Vary Low | ■ | ■ | ■ | ■ | ■ | | | | | | | | | | | | | | | | | | | | |
| | Low | | | | | | ■ | ■ | ■ | ■ | ■ | | | | | | | | | | | | | | | |
| | Medium | | | | | | | | | | | ■ | ■ | ■ | ■ | ■ | | | | | | | | | | |
| | High | | | | | | | | | | | | | | | | ■ | ■ | ■ | ■ | ■ | | | | | |
| | Max | | | | | | | | | | | | | | | | | | | | | ■ | ■ | ■ | ■ | ■ |
| Input parameter Battery SOC | Vary Low | ■ | | | | | ■ | | | | | ■ | | | | | ■ | | | | | ■ | | | | |
| | Low | | ■ | | | | | ■ | | | | | ■ | | | | | ■ | | | | | ■ | | | |
| | Medium | | | ■ | | | | | ■ | | | | | ■ | | | | | ■ | | | | | ■ | | |
| | High | | | | ■ | | | | | ■ | | | | | ■ | | | | | ■ | | | | | ■ | |
| | Full | | | | | ■ | | | | | ■ | | | | | ■ | | | | | ■ | | | | | ■ |
| Output Battery Discharging | Vary Low | ■ | ■ | ■ | ■ | ■ | ■ | | | | | ■ | | | | | ■ | | | | | | | | | |
| | Low | | | | | | | ■ | ■ | ■ | ■ | | ■ | | | | | ■ | | | | | ■ | | | |
| | Medium | | | | | | | | | | | | | ■ | ■ | ■ | | | ■ | | | | | ■ | | |
| | High | | | | | | | | | | | | | | | | | | | ■ | ■ | | | | ■ | |
| | Max | | | | | | | | | | | | | | | | | | | | | | | | | ■ |

### D. DEFUZZIFICATION

The defuzzification process converses the fuzzy output to a crisp output, number or digital output to the control objective of any related field of application. After the inference process, the output is still has linguistic variants, it needs to be converted to the crisp variable outputs, which is easy to understand for controlling the equipment. This research used the centroid method as show in equation 7.

$$D_{output}^{crisp} = \frac{\int \mu_p(x).xdx}{\int \mu_p(x)dx} \tag{7}$$

When, $D_{output}^{crisp}$ is the decision output of BSPM and DSPM and $\mu_p(x)$ is the degree of output membership function.

The outputs by Defuzzification of the FLO Algorithm for the SSG were simulated with the academic version of MATLAB. The outputs of the FLO Algorithm can be separated into two parts, first is BSPM, which consisted of battery charging and discharging mode and second is DSPM, which consisted of load filling (load connect) and load clipping(load disconnect). The examples of outputs of the FLO Algorithm were followed, Figure 10 is a battery discharging mode, Figure 11 is a battery charging mode and Figure 12 is a load filling mode.

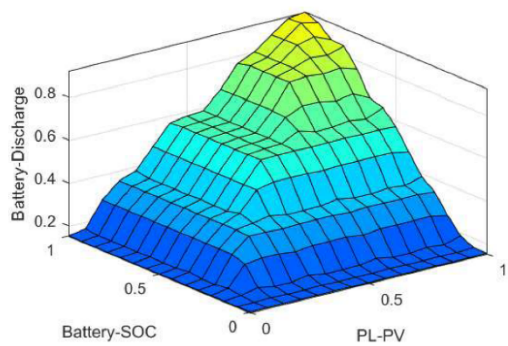


**FIGURE 10.** Output of the FLO Algorithm for battery discharging mode.

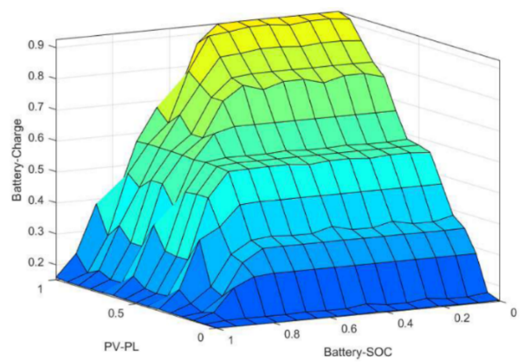


**FIGURE 11.** Output of the FLO Algorithm for battery charging mode.

## IV. RESEARCH RESULTS AND DISCUSSION

As previously mentioned, the prime mission of the FLO Algorithm is to decrease power purchase from the main grid during peak times and also to maximize use of electricity that can be sourced from PV systems (as opposed to electricity purchased from the main grid). Tests of the FLO

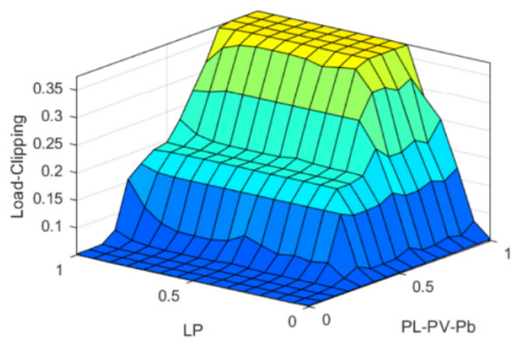


**FIGURE 12. Output of the FLO Algorithm for load clipping.**

Algorithm went well, and its performance and output were successful. The results of the experiment illustrate how load shaving, peak load clipping and load filling are controlled and managed in a balance between two main entities in the SSG. The first entity is the BSPM, which discharges electrical power during peak times in order to decrease the amount of electricity that must be purchased at the high price. Conversely, electricity is charging the batteries during off peak times when the price is low. Power is also sent to charge the battery when PV power production is in excess of what is being used. The second entity is the DSPM, which disconnects noncritical loads (for example certain lighting, air conditioning and heating) during peak time. The operation results of the SSG equipped with the FLO Algorithm are shown in Figure 13.

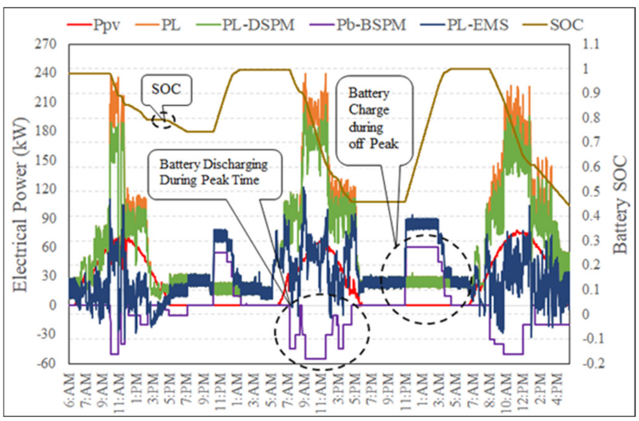


**FIGURE 13. Operation of the SSG when equipped with the FLO Algorithm (PL-DSPM is load power that is managed by DSPM, Pb-BSPM is battery power that is managed by BSPM and PL-EMS is load power is fully managed by the FLO algorithm).**

Figure 13 shows that during peak times, load (i.e. power consumption) is decreased by the DSPM. This process decreased the load by 11.81 %. This was calculated from the difference between PL and PL-DSPM. During battery discharge, energy demand can be decreased by about 18.98 %. During peak time, 30.79 % of electrical energy demand was decreased by the DSPM and the BSPM. During off peak time, the FLO Algorithm directs the SSG to charge the battery when the battery SOC is lower than 0.98. This is when the batteries are charged from the main grid, because the price of electricity is lower than during peak time. The battery always needs to be charged to full capacity prior to the next coming day. In Figure 13, when the BSPM line (purple) dips below zero (on the left vertical axis), that means the battery is discharging, and when the BSPM line is above zero, the battery is charging. During this process, the normal and unavoidable energy loss was 6.82 % from the charging and discharging processes, these losses depend on the efficiency of power conversion units in the system.

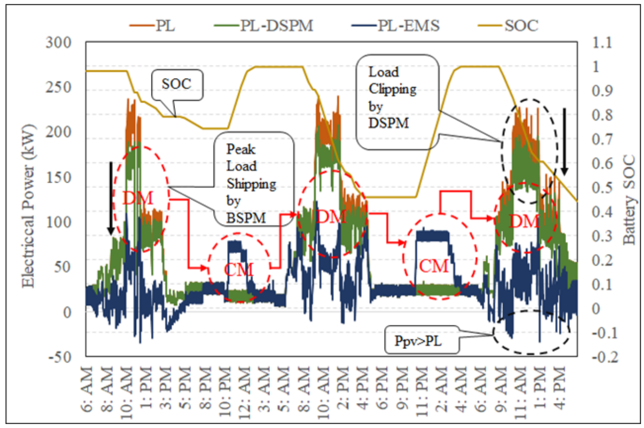


**FIGURE 14. SSG's response to the BSPM and DSPM to decrease the load demand at peak time. (DM = discharge mode, CM = charge mode).**

Figure 14, shows that the SSG responded correctly according to the vision of the applied the FLO algorithm, changing the load profile as planned. The load demand decreases during the peak time in response to the DSPM and BSPM (P-ESM = PL – Ppv – PL-EMS). The SOC of battery storage (seen in Figure 14) decreases during discharge mode (DM) and increases during charging mode (CM). During off peak time, electricity prices are lower than during peak time, so if the SOC is not full (SOC > 0.98), the FLO Algorithm directs it to charge until SOC reaches full capacity.

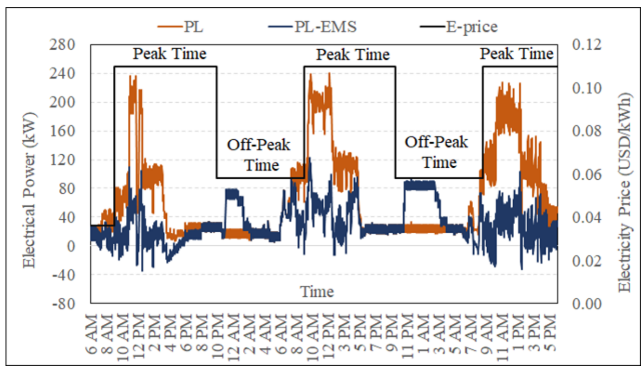


**FIGURE 15. SSG's load profile before (orange) and after (blue) application of the FLO algorithm. (E-price is electricity prices).**

Figure 15, shows how the power load without energy management (orange, PL) is high during peak time,

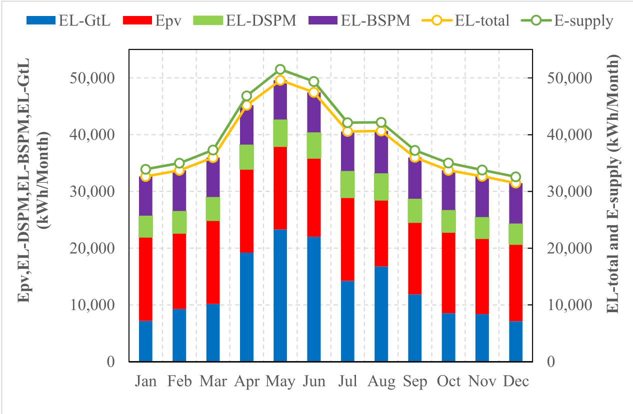


**FIGURE 16.** Percentage for energy consumption in the SSG (EL-GtL is load demand that is supplied from main grid, EL-total is the total energy consumption, E-supply is total energy supply to the load include loss from battery charging/discharging processes).

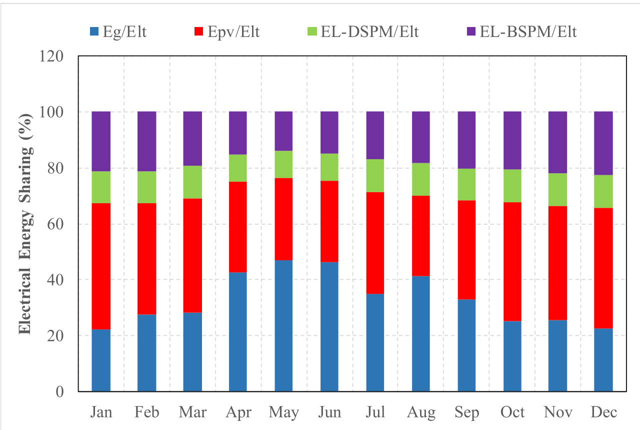


**FIGURE 17.** Electricity costs saved by the DSPM and BSPM with the FLO Algorithm (Eg/Elt is the percentage of electricity from main grid per total energy consumption, Epv/Elt is the percentage of electricity from PV system per total energy consumption, EL-DSPM/Elt is the energy demand that is managed by DSPM per total energy consumption, EL-BSPM/Elt is the energy demand that is managed by BSPM per total energy consumption).

corresponding to the University's normal pattern of electricity use. The staff and students have classes and other activities from 8.00 a.m. – 16.30 p.m. The BSPM following the FLO Algorithm (blue PL-EMS) applies load shifting so that the battery discharged electricity to load demand during peak times for decreased electricity purchase from main grid. During this period, if PV output is higher than load consumption, electricity is charged to battery system, i.e. during the off peak periods. The set start time of the charging mode is 11:00 PM, because very few people are working at that time, corresponding to very low load demand. In contrast, during peak times the battery was discharging in response to energy demand.

The annual operation results of the SSG with the FLO Algorithm found that, average total energy consumption (EL-total) of the SSG was 38,295 kWh/month, this among of electricity consumption was supplied from PV system about 13,866 kWh/month. The electricity demand during peak time was significantly decreased by DSPM and BSPM about 4,191 kWh/month and 7,071 kWh/month, respectively. The BSPM manages the SSG to charge the battery during off peak time when battery state of charge is not full on the other hand battery is discharge to electricity demand during peak time for decreased electricity purchase from main grid. The electrical energy sharing in percentage compare to the total electricity consumption, which was supplied about 36.98 %, 11.06 % and 18.90 % by 120 kW PV system, DSPM and BSPM, respectively.

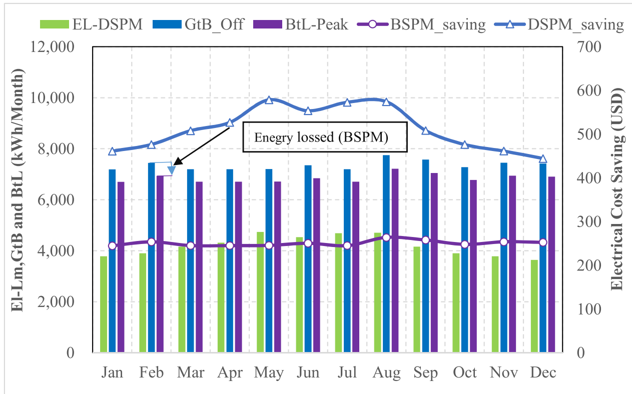


**FIGURE 18.** Electrical energy and cost saving by applied the FLO Algorithm (GtB_off is electricity is charged to battery from main grid during off peak time, BtL-peak is electricity is discharged from battery to load demand during peak time, BSPM_saving is total amount of money saving by BSPM, DSPM_saving is total amount of money saving by DSPM).

Figure 18 indicated that during the off peak time, especially at nighttime, the FLO Algorithm commands to charge the battery permanently full capacity by purchasing electricity from the main grid. Charge and discharge electricity processes of battery storage system to minimize purchased electricity from main grid, the electrical energy loss was 6.82 %. This energy loss be influenced by the efficiency of power conversion system (PCS) which was installed in SSG. Although, during this process energy loss was occurred but it is worth to follow this process because the process significantly enable to save money. Forasmuch, the TOU electricity prices is so different about 34.74 %, it is calculated by prices of electricity during peak time ($0.122/kWh) and off peak time ($0.079/kWh). Thus, the SSG with the FLO Algorithm designed to charges the batteries during off peak times at a lower price of electricity on the others hand discharged electricity from battery to load demand during peak times for decreasing purchased electricity from the main grid.

This process, BSPM pretty save money about $3006/year or 5.78 % when compared to total electricity bill (52,021/year). 5.78 % of saving is rather small amount but this value is direct proportion to the capacity of battery storage and load. During BSPM process enables to save money about 29.94 % (Analyzed by charge battery with low price during off-peak time on the other hand discharge electricity with high price during peak time). DSPM reduced the electrical energy demand by disconnected noncritical load (certain lighting, air conditioning and heating) during peak time. This process (DSPM) can significantly save money about $6,144 per year or 11.81 % when compared to total electricity bill. Figure 19 indicated that after applied the FLO Algorithm into the SSG, the monthly electricity cost was significantly decreased. The total annual electricity cost was saved $9,148 or 17.58 % when compared to total annual electricity bill.

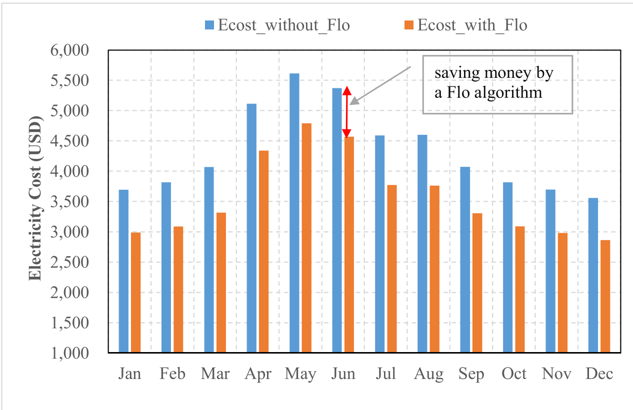


**FIGURE 19.** Monthly electricity cost compared between with and without the FLO Algorithm applied to the SSG (Ecost_without_Flo is electricity cost of the SSG without the FLO algorithm, Ecost_with_Flo is electricity cost of the SSG with the FLO algorithm).

## V. CONCLUSION

The School of Renewable Energy Technology (SERT) anticipates the importance of a national Smart Grid in Thailand and so developed the SERT Smart Grid (SSG) as a research vehicle to prepare for the future. The FLO Algorithm skillfully manages power load and battery storage systems to optimize operations in response to peak and off peak electricity prices for the most economical outcome. A smart and advance algorithm enables to decrease the negative impacts of power fluctuation from RE systems and allows them to make quick and correct decisions. An importance of applying the FLO Algorithm in SSG significantly reduced cost of electricity by two entities, demand side power management (DSPM) and battery storage power management (BSPM) following Time of Use (TOU) pricing. DSPM can monthly reduce cost of electricity about 11.81 % and BSPM, charge and discharge strategy of battery storage system can pointedly reduce 5.78 % compared to total electricity bill and 29.94 % during BSPM process. For the process of BSPM, unavoidable energy loss during charging and discharging processes was 6.68 %. In conclusion, the FLO Algorithm, encompassing both the BSPM and DSPM, can significantly reduce the SSG's electricity costs, about 17.58 % or $9,148 per year. The amount of money saved is directly proportional to the difference between the peak rate and off-peak rate (which the FLO Algorithm strategically leverages by intelligently managing the BSPM and DSPM) as well as the battery storage capacity and load volume. Today as avenues are sought to decrease consumption of fossil fuels, A Smart Grid empowered with an innovative, intelligent algorithm is a robust solution for the near future.

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