Augmentation of Battery Management Systems in Smart-Grid operation using Fuzzy Logic

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Abstract— **This paper proposes an idea of optimizing battery management system using fuzzy logic for a smart grid system. The involvement of a fuzzy logic controller makes the existing control mechanisms for the battery management system more intelligent hence allowing the system to prioritize between the loads and multiple batteries in the battery storage system (BSS) which enables the utilization of the harnessed solar energy with greater service continuity. This design involves a much more effective algorithm of a load and battery management system using fuzzy sets which allows to optimize solar power utilization and maintaining smooth battery health conditions. Finally, a comparative study is illustrated showing the differences between a system working with a greater number of membership functions (64 rules) and the one working with only two membership functions(8 rules).**

Keywords— Fuzzy Logic Controller, Rule base, Battery management systems, Smart-grid, Super-capacitor batteries.

I. INTRODUCTION

Near 17% of people on the earth do not have the availability of using electricity i.e. 635 million people and 235 million people who lived in Africa and India [1]. Statically 2.7 billion people in the world are dependent on traditional energy sources [2]. Most importantly around 95% of people who lived in rural areas are facing a lack of electricity and to fulfill their energy demand they are bound to be dependent on the traditional energy source which caused deforestation and greenhouse emissions [1, 2]. To get rid of this kind of environmental effect reliable, affordable additional energy is needed. Though a sustainable development of energy provides a reliable, affordable energy system, it is harmful to industries as there are some issues regarding environmental effects [3]. To overcome these environmental effects, the utilization of renewable energy sources can play a vital role for human beings to survive. In many developing countries like India, they have planned to maximize the use of renewable energy by increasing the framework of the capacity of renewable sources from 32GW in 2014 to 175GW in 2022 [4]. Nowadays usage of renewable energy assimilated with the distribution network has become more popular day by day. Smart grid is an option that consists of one or more distribution unit which can be operated with greater intelligence on a small scale or a large scale independently or connected by the utility like in cities, communities, campuses. As solar energy is a clean and environment-friendly source so the connection of the grid in the distribution side of the power system makes it eco-friendly also perception approach of the energy storage system will make the system more efficient. There are multiple reasons for choosing a smart grid system firstly they use a substitute of energy resources which is environment friendly so few technical skill required to run the system, secondly, it will be the only option if a new transmission and distribution technique can't be developed timely in a cost-efficient way [5]. In this paper, a relation in grid with fuzzy members like solar irradiance, load current, battery charge condition has been established and also optimized the energy to the battery with fuzzy controller, by integrating all the fuzzy members a smart grid system has been proposed which is based on advanced communication and information system.

II. BATTERY CAPACITY AND PERFORMANCE

Battery performance & capacity can be described by their long life, charging capacity like fast charge, quick charge, duty cycle, etc. These performances can also be determined by monitoring the state of charge and state of battery health [6]. To access the maximum efficiency of energy storage, each battery needs to be connected in such a way that their charging and discharging operation can operate with priority-based circumstances rather than having equally charged or discharge patterns. There are different kinds of energy storage systems with different characteristics. In table 1, none of them are good enough for both low and high-frequency applications [7]. By taking all the factors into account supercapacitor-battery has been excogitated for energy storage systems because of their availability, reliability, low cost, and most importantly they supplement their constraints very adequately. In this paper, the supercapacitor energy storage system is using the fuzzy logic algorithm so that the energy storage system could be prioritized with the given condition for solar power in the grid system so that batteries can work as a substitute for PV panel when the grid is needed.

Table I. Different aspects of Energy Storage System [7]

Energy Storage System	Energy Density	Power Density	Life Cycle	Response Time	Cost
Chemical Battery	High	Low	Short	Medium	Low
Sodium Sulphur (NaS-Battery)	Medium	Low	Short	Low	Medium
Flywheel	Low	High	Long	Fast	High
Supercapacitor	Low	High	Long	Fast	Medium
Superconducting Magnetic Storage System	Medium	High	Long	Fast	High

The fuzzy logic algorithm will provide an efficient way of charging the battery with the help of a rule-based optimized value. In this paper, four supercapacitor batteries having different sizes and voltage were connected to the bus bar. According to the input parameters like irradiance from the solar cell, load current, and battery charge condition, supercapacitor-batteries will respond just as power demand. For each input parameter, there were different membership functions and for the performance of the battery, there were five membership functions like very low (VL), low (L), medium (M), high (H), very high (H). These membership functions will prioritize the batteries in such a way that they could provide energy to the battery only when they satisfy the optimal condition. As the output of the battery performance was controlled with the fuzzy logic controller so there were some priority-based rules which will allow the energy to the particular battery only when it was needed but in the conventional controller, there was no freedom of prioritizing according to the input parameter. To some extent, if the energy demand might be high, in that case, the fuzzy controller can be used to accomplish the energy demand by finding out which battery should be charged first to fulfill the demand, and then the next battery on the priority list is energized and so on but in the conventional controller it was not possible to prioritize the charging-face of each battery, they will charge all the batteries simultaneously so the maximum efficiency of battery performance might not be achieved. Following some researches, battery performance with fuzzy and without fuzzy logic can be demonstrated in various way that is given below.

Table II. Battery performance comparison [5, 7]

With Fuzzy	**Without Fuzzy**
Deals with variable membership function.	Deals with only two variable
Batteries can be prioritized	Batteries can't be prioritized
All the batteries will be charged according to the demand of the load.	All the batteries will be charged simultaneously.
More flexible, logical algorithm.	Deterministic based rule
Deals with real-time data.	Doesn't deal with real-time data.

The supercapacitor batteries are about to pay up the desired energy demand when the necessity of power is occurred due to the input parameter performance. For adjusting the power to the grid an inverter is required that can provide a quick response with power grid condition. The quasi-Z-Source inverter is a worthy choice as it has numerous enticing advantages having a low cost, good capability of handling power. To change the amplitude of the input voltage just as the dc-dc converter, a buck-boost converter can be used, on the other hand, quasi-Z-Source topology provides an efficient way of drawing constant current from the solar panel, and also they are suitable for dealing with a large number of the input voltage range[8].

III. Smart Grid Requirements

Smart grid requires both way communication and recent statistic shows it is cost-effective and it can increase the overall utilization of the system [9,10]. The smart grid system is an advanced network design that includes monitoring, controlling all the parameters of the individual equipment efficiently with a fast dynamic response. That means an algorithm is required to be chosen that will continuously monitor the real-time data on both sides and that can be developed by using the fuzzy logic algorithm. And so renewable sources are integrated with the fuzzy logic algorithm that deals with all the real-time data and can also achieve fast dynamic response as they will deal with all the intermediary value that can exist wherein conventional algorithm there will be no intermediate value.

In this paper, the main focus was on the battery management system. With the fuzzy logic controller, the output batteries were prioritized so that for the given input the output energy to the battery could be used efficiently as per load demand. Loads are also classified into three terms like peak load, intermediary load, and base-load. For each type of load, a specific group of batteries is designated to feed power when required. Only if all the batteries are charged fully like 100%, they will delicately distribute the energy so that energy can't be dissipated. As the batteries are fully charged they will fulfill the baseload demand with greater urgencies and the rest of the energy will be distributed to the intermediary load and peak-loads. On a large scale, several PV solar modules are cascaded according to the power demand with this fuzzy-based control system economizing between source, load, and storage. In a conventional controller, it is not possible to maintain the priority of energy to the battery and load as they don't deal with intermediary value so it will be way more difficult to detect which load should be treated with seniority and which one should be given lesser preference. Moreover, they provide us an automated selection of the group of batteries to be charged first instead of charging all at once. Thus this application of the fuzzy logic algorithm is a sophisticated way for a smart grid system to control and monitor the whole power system network.

IV. Fuzzy Logic Controller Design for Battery Management

Fuzzy logic refers to a special kind of logic which can be operated on different levels to express different situation. Fuzzy logic can give any value from 0 to 1 while in Boolean logic this result can be either 0 or 1. Thus fuzzy logic is more appropriate than Boolean logic and is often recalled as a specialized version of Boolean logic. [11]. In this paper, the analysis was mostly done in MATLAB. The MATLAB has its built-in library called 'Fuzzy Logic Designer". In that block, the parameters can be customized by the will of the user. The number of inputs and outputs was first decided. In each input and output parameter, suitable membership functions are selected and assigned with a particular range of values. Three inputs and 1 output variable were taken in this analysis.

Each input and output is enriched by four levels and five levels of membership functions respectively. Input 1 is taken as irradiance level whereas input 2 is taken to be the amount of connected load and input 3 is taken as the state of battery charge. Similarly, output 1 is taken to be the degree of energy transfer to the batteries. The membership functions and their ranges are selected and added to the fuzzy controller block. [11] The segments of the FLC design is illustrated next.

A. Fuzzification

Fuzzification is the process that converts the crisp value to a fuzzy value that will execute information and function identified with the user. These fuzzy sets have different membership functions such as Gaussian, triangular, trapezoidal. In this paper, trapezoidal membership functions were used. The three inputs were denoted by X1, X2, X3, where X1 goes for input 1(irradiance) and X2 for input 2(connected loads), and X3 for input 3(State of charge). And the membership functions for input 1 are Ux1 which is subdivided into four functions like NS= not satisfactory; S=Satisfactory; G=Good; VG=Very Good. Again, the membership functions for input 2 and 3 are Ux2 and Ux2 respectively which is also subdivided into four functions, L=Low; M=Medium, H=High; VH=Very High. Similar approaches were undertaken for output membership functions. The membership functions used for enriching the outputs levels were VL=Very Low; L=Low; M=Medium, H=High; VH=Very High.

B. Inference Engine and Rule base

The target of the fuzzy inference system is to give the fuzzy output set according to the set of rules. At first, it will decide which rules are appropriate for the current situation then the inference system incorporates the guidelines of all rules to draw a final decision, and then the action was taken for each membership function. The Rule base is made on a trial and error basis in accordance with the optimization of solar energy consumption. For example: - if there is not enough solar irradiance the energy flow is minimal to both the loads and batteries. On the other hand, if the irradiance level is high enough and the amount of connected load is too high, and the battery is almost fully charged, strong energy discharge is observed for the loads and less energy discharge for the batteries. Similarly, for high solar irradiance and low connected load with the battery SOC too low, maximum discharge is allocated for the batteries where the loads receive less or as required. The table below shows the suitable rule base on which the fuzzy logic controller works. For 4 membership functions for each input, 64 rules were set for 3 sets of inputs. Table 3 shows some of the rules used for this fuzzy inference engine.

Table III. 64 Rule Base

Rule#	Irradiance	Load Connected	State of Charge	Energy TO Battery
1	NS	L	L	VL
16	NS	VH	VH	VL
17	S	L	L	H
20	S	L	VH	VL
21	S	M	L	M
24	S	M	VH	VL
25	S	H	L	L
28	S	H	VH	VL
30	S	VH	M	VL
32	S	VH	VH	VL
35	G	L	H	VH
36	G	L	VH	VL
37	G	M	L	H
39	G	M	H	H
40	G	M	VH	VL
43	G	H	H	M
44	G	H	VH	VL
47	G	VH	H	L
48	G	VH	VH	VL
49	VG	L	L	VH
51	VG	L	H	VH
52	VG	L	VH	VL
56	VG	M	VH	VL
59	VG	H	H	H
60	VG	H	VH	VL
61	VG	VH	L	M
63	VG	VH	H	M
64	VG	VH	VH	VL

C. Defuzzification

It is the final step in the fuzzy inference system that generates the crisp output value from the fuzzy output set. For each rule, the center of gravity or centroid method is used for the conversion of fuzzified output to crisp output. The centroid defuzzification method is one of the most effective defuzzification methods that is used nowadays. Unlike other techniques like maximal defuzzification, they don't tend to cluster around the centers of the membership functions. For the maximal defuzzification method, any points having a certain level of minimal value are not considered to the final result, hence a slight change in output composition has no impact on the final output value. On the contrary, the centroid method accounts for every piece of values from the output composition to calculate the final defuzzified value.[11]

V. Results and Discussion

This paper proposes an efficient procedure of harnessing PV solar panels and charging the battery simultaneously by increasing the level of intelligence of the controller by fuzzy logic. Normalized values were used instead of actual values to denote all the input and output parameters for simplicity, better understanding, and convenient analysis.

Graphical representation of 3D Surface view:- Fig 1 shows surface re-presentation of the variation of energy supplied to the batteries w.r.t 2 input parameters like irradiance and connected loads.

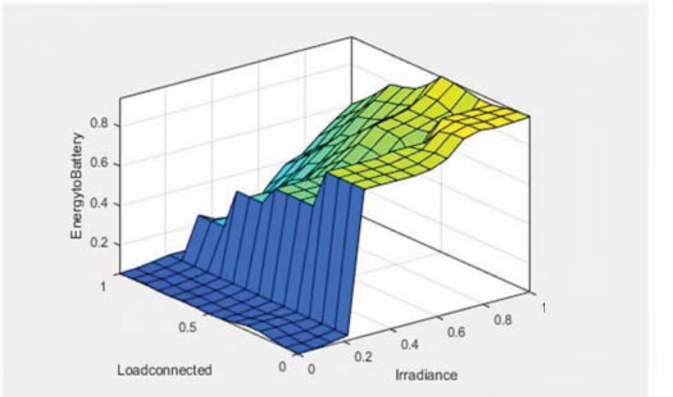

Fig. 1. Variation of Energy allocation to the batteries w.r.t the variation of Irradiance and Connected loads for a moderate level (50%) of battery charge condition.

The surface view of the variation of Energy supplied to the batteries w.r.t the changes in Irradiance and battery charge condition, for a moderate level (50%) of connected load is represented in figure 2. The variation of energy allocation for the batteries w.r.t the changes in the connected load and the battery charge condition with a moderate level of solar irradiance are presented in fig 3.

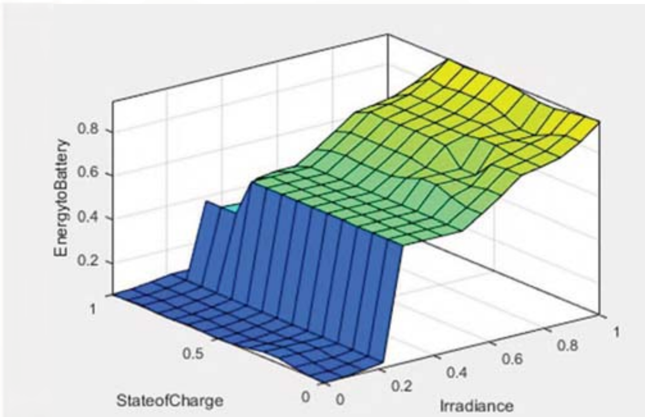

Fig. 2. Variation of Energy allocation to the batteries w.r.t the variation of Irradiance and battery charge condition for a moderate level (50%) of connected loads.

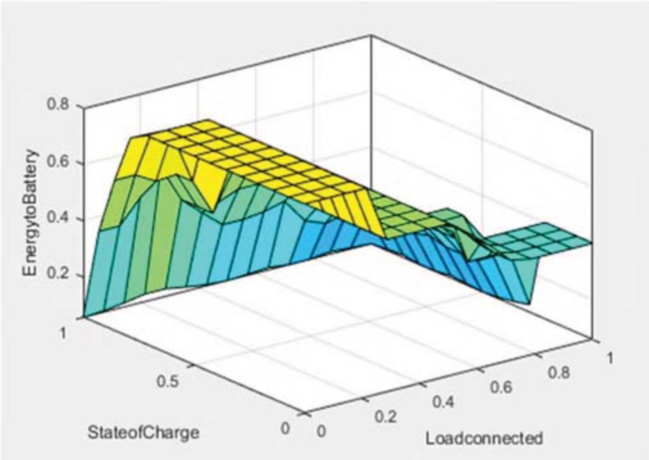

Fig. 3. Variation of Energy allocation to the batteries w.r.t the variation of connected loads and battery charge condition for a moderate level (50%) of Irradiance.

The advantages of using this fuzzy interference system can be illustrated by drawing a difference between a system designed with a fuzzy controller whose inputs and outputs are enriched with 4 and 5 membership functions respectively, and a system working with two membership functions only which can be modeled as if they are using Boolean logic (0s and 1s) to make decisions. The system designed with a greater number (4 MFs) of membership functions outweighs the lesser one (2 MFs) since they decide by considering more variables with more details hence provides the result with greater resolution. Their comparison is illustrated in the next section.

Graphical representations and analysis using 2D surface plot:-In this section, a separate analysis was performed based on 2D plots. From the 2D plots, several conclusions can be drawn. The observations are illustrated below using suitable figures.

Observation 1:- Energy to batteries vs. Irradiance curve with a low level of loads connected (10%) and a poor battery state of charge (10%) is displayed in figure 4

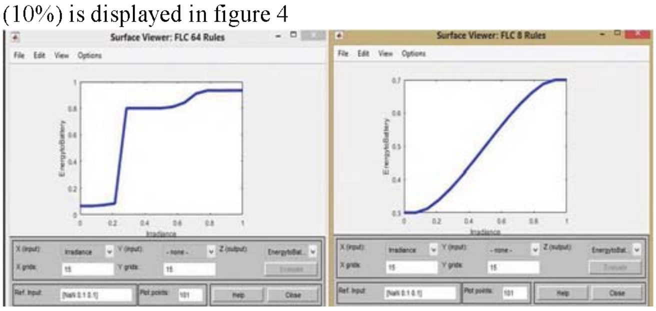

Fig. 4. Energy to batteries vs. Irradiance curve with a low level of loads (10%) connected and a poor battery state of charge(10%)

From the diagram above it can be observed that as the irradiance level increases more and more energy is allowed to be feed to the batteries for both 64 rules and 8 rules FLC controller. But the maximum allowable discharge for 64 rules FLC controller is about 95% whereas for 8 rules fuzzy controller it is only 70%. This provides compelling evidence about the fact that the 64 rules FLC controller allows faster charging of the batteries with 25% extra utilization of energy from the PV panel. It can also be concluded that at the poor value of Irradiance the 8 rules FLC controller allows 30% energy discharge which might jeopardize the energy allocation for our critical loads which are always given high priority. However with 64 rules FLC controller it is only 5% or less.

Observation 2:- Energy to batteries vs. Irradiance curve with a high level of loads connected (90%) and a poor battery state of charge (10%) is displayed in figure 5

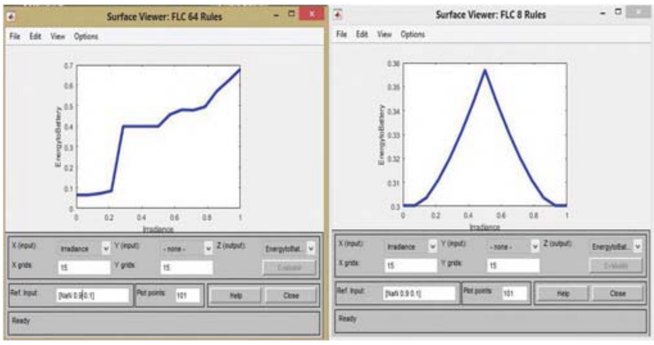

Fig. 5. Energy to batteries vs. Irradiance curve with a high level of loads connected (90%) and a poor battery State of Charge (10%)

From the diagram above it can be observed that at a poor level of irradiance the 64 rule FLC allows less than 10% discharge whereas the 8 rules FLC allows around 30% even if the load connected is high. If irradiance is not satisfactory there is no point in charging the batteries with our critical loads staying unsatisfied. On the other hand, as the level of irradiance increases the batteries should be feed with more energy since their state of charge is too low. The 64 rules FLC shows a discharge of a maximum of 70% at a high level of irradiance whereas for 8 rules FLC they are almost 30%. Besides 8 rules FLC the graph shows an abnormal behavior since the energy discharge to batteries falls after the level of irradiance reaches 50% which is completely not desirable and inconclusive. Doubtlessly, the controller design with more membership functions improves the intelligence of our energy dispatch controller.

Observation 3:- Energy to batteries vs. Load connected with a high level of Irradiance (90%) and a poor battery State of Charge (10%) is displayed in figure 6

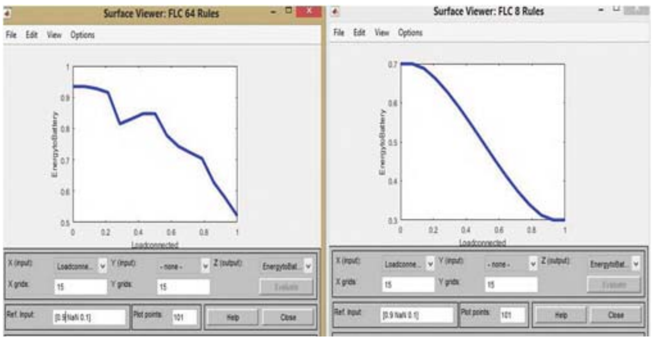

Fig. 6. Energy to batteries vs. Load connected with a high level of Irradiance (90%) and a poor battery state of charge (10%)

From these graphs, it can be observed that when the connected loads are too low but the level of irradiance is around 90% with a poor battery charge condition, the 64 rule FLC allows an energy transfer to the battery by 95%. But for the 8 rules FLC, it is just 70%. With a lower value of load connected it is reasonable to charge up the battery with maximum possible capacity, and this act is performed judiciously by 64 rules FLC with 25% more energy allocation for the batteries. On the other hand when the amount of connected load increases and reaches maximum the battery still receives 50% energy from the PV panel compared to the 30% in 8 rules FLC. Most importantly this comprehension doesn't violate the energy conservation rule since it is assumed that the amount of irradiance is high enough to satisfy high connected loads and still economizes 50% energy for charging the batteries. If the area under both graphs is estimated the 64 rules FLC harnesses more energy for the battery which lowers the risks of over-drainage of battery charge increasing their lifetime.

Observation 4: - Energy to batteries vs. Battery State of Charge with a high level of Irradiance (90%) and low connected load (10%) is displayed in figure 7

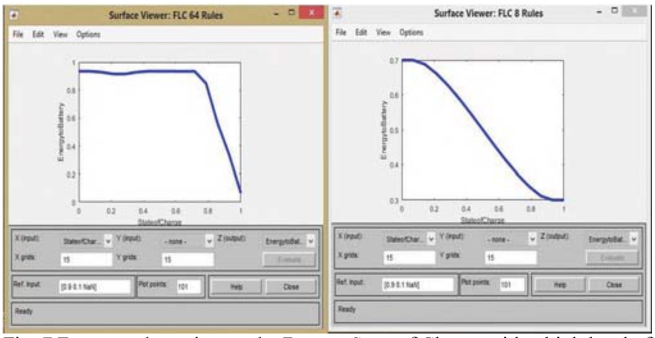

Fig. 7 Energy to batteries vs. the Battery State of Charge with a high level of Irradiance (90%) and low connected load (10%)

From the graphs above it can be observed that the energy allocation to the batteries for 64 rules, FLC remains steady at around 95% until the battery charge condition increases to 75% of its maximum charge. Generally, the charging rate decreases exponentially but here it remains steady for a considerable amount of time until it falls rapidly to 10% after 75% battery is fully charged, ensuring faster charging. Assuming that the level of irradiance is high enough and with a low connected load, the batteries should be charged as fast as possible for future backup purposes. At the low state of charge condition, the energy allocation is 95% and for the high state of charge, the allocation decreases to below 10% eventually minimizing the risk of over-charging of the battery which might be unsuitable in some cases. On the other hand the 8 rule FLC shows a variable rate of discharge throughout the time hence the net charging time becomes longer and unsatisfactory. The battery health is dependent upon several parameters among which a steady flow of power is one of the crucial ones. The 8 rules FLC also shows other disadvantages like, not sufficient energy allocation (70%) at low SOC and high state of charge unnecessarily more energy (30%) is allocated which increases the risk of the battery overcharging and overheating. [14]

Observation 5: - Energy to battery vs. battery state of charge for a moderate level of irradiance (50%) and low connected loads (10%) is displayed in figure 8. For 64 rules FLC when there is a moderate level of irradiance (50%) and the amount of connected load is pretty low (10%), the energy discharge remains steady at 80% until the battery capacity reaches 80% of maximum, whereas for 8 rules FLC it is just 50% and this value is maintained for only until the battery reaches 60% of the full charge. From this observation, it can be concluded that the 64 rules set FLC system provides a faster charging capacity than the 8 rule base system. From their area under the graph, it can be assessed that more energy is allocated when a 64 rule base system is used. Moreover when the battery state of charge is high, the 64 rule FLC acts more intelligently by minimizing its energy allocation to below 10% in comparison to the 8 rules FLC, hence reducing the waste of energy and minimizing the risk of over-charging. Another analysis can be run in a similar situation where the number of connected loads is high (90%) with a moderate level of irradiance. As the battery SOC increases the energy discharge to the battery decreases. For the 64 rule FLC the allocation starts with 40% of the full capacity and changes periodically hence reaching a minimum level of 10% when the battery SOC is high. Whereas for 8 rules FLC the discharge is almost constant despite the situation of SOC which is proven to have less intelligence level for controlling and desolates energy.

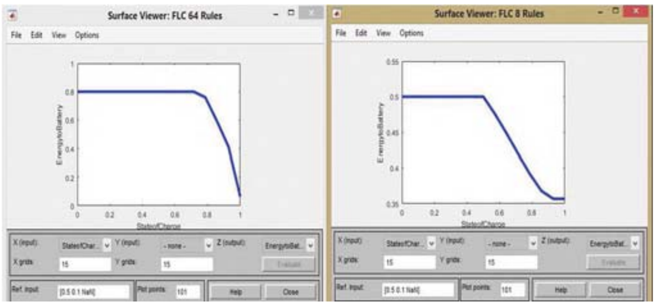

Fig. 8. Energy to battery vs. battery state of charge for a moderate level of irradiance (50%) and low connected loads (10%)

VI. CONCLUSION

The electricity demand is increasing day by day so it has become more difficult to cope up with the existing resources where environmental pollution is also a considerable fact to avoid. To accomplish the energy demand it is required to shift on renewable energy sources and utilization of renewable energy sources is the only option for the human to survive and solar power is to become the most advantageous solution for countries having a higher value of solar irradiance. In this paper, the smart grid system with photovoltaic solar energy and energy storage system coordinated by a fuzzy-based control system was mentioned. The battery management is upgraded using fuzzy sets and it was observed that as the number of membership functions increases the level of intelligence also increases which provides us with better battery and load management for smart grid operation. The results can be made more satisfying and percipient by optimizing the membership functions with several optimization algorithms.

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