Fuzzy Logic Based Hybrid Energy Storage System

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Abstract

The manuscript proposes the implementation of parallel full active topology of a Hybrid Energy Storage System (HESS). It includes combination of a lead-acid battery and super-capacitor on microgrid. An active topology has been simulated using four direct current/direct current (DC/DC) converters with switches controlled by Fuzzy Logic Controller. The proposed model is implemented to provide the additional power for the requirement of the load. The proposed model also minimizes the power fluctuation between the load and supply and maintain the power demand from the grid within limit. The Energy Management System (EMS) is designed with help of Fuzzy Logic Controller (FLC). The simulated EMS provides a dependable and continuous power supply to local loads while ensuring a stable supply condition.

Keywords. Energy Management System (EMS), Energy Storage Systems (ESSs), Fuzzy Logic Controller (FLC), Lead-Acid battery (LA Battery), Super-capacitor (SC).

1. INTRODUCTION

A microgrid is a distributed small-sized grid. It is often denoted as systems that are connected to the Distributed Generations units and usually consists of various renewable energy resources, power generators, Supercapacitors, Battery Energy Storage Systems (BESSs) and Load Demand (LD). This is normally capable of functioning in either stand-alone mode or grid-connected mode.

In a period for 24 hours, a grid faces various fluctuations like change in demands, change in power supply, electrical malfunctions, short circuits, etc. All these issues combined cause an increase in stress on the grid along with its EMS. An effective way to solve this is addition of localized energy storage systems, which can reduce the mismatch between consumption and power generation, ensuring system power balance [1]. Energy Storage Systems are classified based on various characteristics like energy density, power density, ramp rates, etc. Unfortunately, there is no single Energy Storage System, that fulfills all requirements [2]. Considering this fact, Hybrid Energy Storage Systems, which uses the benefits of all ESS emerge to be an effectual solution for solving economic and performance issues.

In recent times, research is being carried out in the field of Energy Management Systems including Hybrid Energy Storage Systems. In [3], a decoupled controlling strategy has been proposed for supercapacitors and batteries which is based on nonlinear PI controller (NPIC) and k - Type compensators respectively. In [4], the existing LPF has been replaced with single rate limiter, for ensuring proper battery discharge rate. This has resulted in solving challenges like non-systematic selection of cut-off frequency at much ease. In [5], a new approach to energy management has been proposed. A two-level energy management strategy has been used, in order to optimize the operation cost and manage uncertainties. In [6], a novel power management strategy has been approached to solve the demand generation gap and maintain DC bus voltage, in addition to minimizing stress levels in the battery. In [7]-[8] a Fuzzy Logic based controlling is used in the functioning of a grid-tied MG and standalone MG. FLC controller for voltage and/or frequency control using flywheel ESS operation also presented in [9]. FLC for evening the variation in stand-alone wind power generation with BESS is given in [10].

The main intent of this work is to develop a controlling strategy for a HESS consisting of Lead-Acid battery and Super-capacitor to improve stability and efficacy of the microgrid while constantly considering SoC of both SC and LA battery at an acceptable limit. The SoC is being considered in order to prevent the damages of ESS due to excess charging and discharging of ESS. An FLC-based controlling algorithm has been proposed for energy management and distribution. The model is designed on MATLAB/Simulink platform.

The rest of the paper is organized as given: Section 2 provides a general overview and system configurations, Section 3 gives the proposed energy management system, Section 4 demonstrates the simulations and results obtained and the paper has been concluded with Section 5.

2. GENERAL OVERVIEW AND SYSTEM CONFIGURATION

The microgrid system considered in this simulation is shown in Figure 1. It shows configuration of microgrid with proposed energy management system. The model consists of seven parts: Lead-Acid battery, Super-capacitor, DC-DC boost converter, DC-DC buck converter, FLCs, DC supply, and DC Load. Lead-Acid battery and Super-capacitor (that constitutes the Hybrid Energy Storage System) have been connected in parallel to DC bus with the DC-DC converter. Two separate fuzzy logic controlling systems are being used for switching between charging and discharging modes for ESSs.

The main objective of proposed energy management system has been provided as to:

i) Decompose systems power demand into lower and higher frequency components.

ii) Power distribution among HESS for realizing power-sharing based on ESs' characteristics.

iii) Scheduling dynamic charging and discharging of the HESS with FLCs.

iv) Maintain a constant power drawn from the grid irrespective of the load.

Let P_{Total} be the active power flowing in the microgrid. P_{HESS} denotes the power output/input from/to the HESS, the power that is shortage/surplus is injected/absorbed by the HESS. P_{Supply} denotes the power supplied by the utility to the grid and P_{Load} refers to the power demand. The main objective is to reduce the fluctuation of power balance. The power balance equation can be given by:

$$P_{Total} = P_{Supply} + P_{Batt} + P_{SC} - P_{Load} = P_{Supply} + P_{HESS} - P_{Load} \tag{1}$$

$$P_{Total} = \begin{cases} P_{Total} < 0 if P_{load} > P_{HESS} + P_{Supply} \\ P_{Total} = 0 if P_{load} = P_{HESS} + P_{Supply} \\ P_{Total} > 0 if P_{load} < P_{HESS} + P_{Supply} \end{cases} \quad (2)$$

SoC is given by [16]:

$$SoC_{ess}(n) = (E_{ess}(n) / E_{ess,max}) \quad (3)$$

$SoC_{ess}(n)$ denotes current capacity of ESS, $E_{ess,max}$ denotes the maximum capacity and $E_{ess(n)}$ is current capacity of the ESS.

The state-of-charge of the HESS SOC_{HESS} is connected to the SOC of Lead-Acid battery and Super-Capacitor, which is given as [11]:

$$SOC_{HESS} = ((Q_{bat} \times SOC_{bat} + Q_{sc} \times SOC_{sc}) / (Q_{bat} + Q_{sc})) \quad (4)$$

Where Q_{bat} and Q_{sc} respectively denotes the rated-capacity of battery and supercapacitor. SOC_{HESS} tells the remaining capacity of the HESS.

A Low Pass Filter (LPF) has been used to divide power into high and low frequency components. P_{net} denotes difference between P_{load} and P_{supply} [1]

$$P_{low}(t) = (1/(1+T_s)) * P_{net}(t) \quad (5)$$

Here low-frequency component is denoted by P_{low}. T indicates reciprocal of the cut-off frequency. High-frequency component P_{high} is calculated by removing low-frequency component from the P_{net}. It is given as follows [1]:

$$P_{high}(t) = P_{net}(t) - P_{low}(t) = (T_s/(1+T_s)) * P_{net}(t) \quad (6)$$

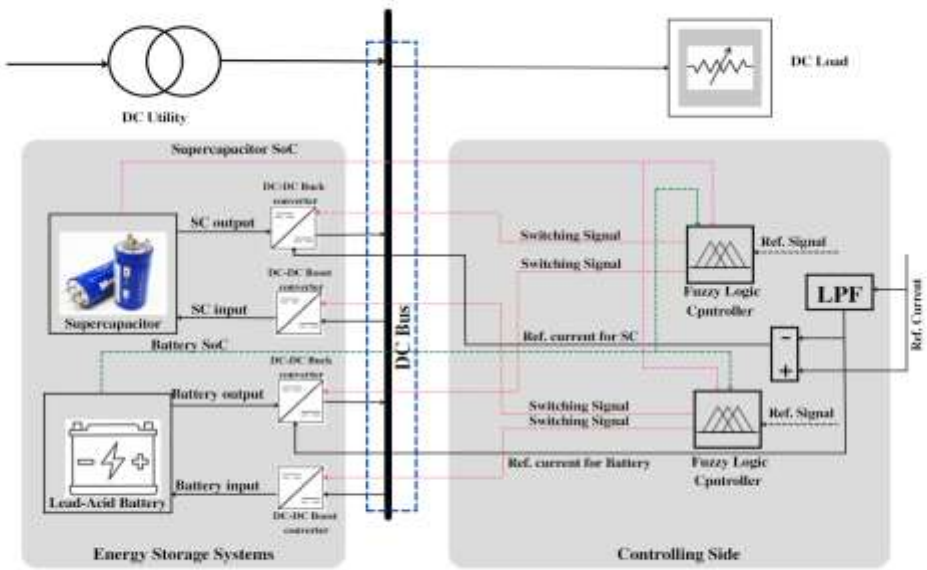


Figure 1. Configuration of the microgrid with proposed EMS

3. PROPOSED ENERGY MANAGEMENT SYSTEM

3.1 Fuzzy Logic Controlling:

By simulation of unreliable judgment and rational thinking, FLC has been used to manage with optimization problem that is strenuous to solve with old control methods [11].

A normal FLC consists of:

- *Fuzzification*: In this step, crisp inputs are converted into fuzzy values using membership functions.
- *Rule base*: This block stores the defining commands for the operation of FLC.
- *Fuzzy Interference Engine*: It is a process of simulation of human decisions which is built on fuzzy concepts. It is depicting from a given input(s) to an output(s) [12].
- *Defuzzification*: This process will evaluate a crisp output which is developed based on the output of inference. Mamdani − type FIS is used in this paper. A block diagram is exhibited in Fig 2

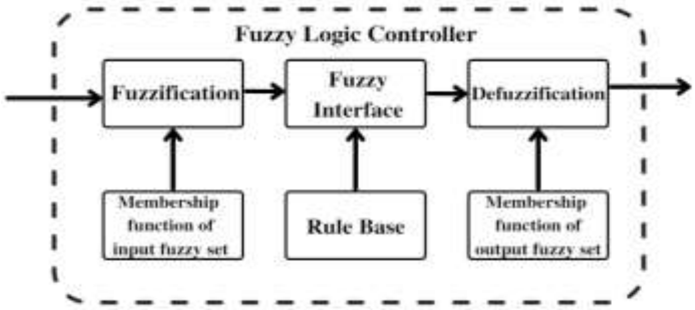


Figure 2. Mamdani type FLC

The EMS that has been proposed consists of Low Pass Filter (LPF) and two Fuzzy Logic Control (FLC). Two FLC have been used for scheduling of charging and discharging of HESS.

Fuzzy Logic Control-1 (FLC-1) is used to control the recharging of HESS. There are three inputs to the FLC: Battery State-of-Charge (*SoC_B*), Super-capacitor State-of-Charge (*SoC_SC*) and the difference between reference Supply Power and Load (*Value*). The *SoC_SC* and *SoC_B* are divided into three levels: High (H) Medium (M) and Low (L). The other component, *Value* is divided into two components, Neg (N) and Pos (P). The output of the FLC-1 gives two outputs that control two switches (*SW_Batt_Conv and SW_SC_Conv*). Separate switches are used for Battery and Super-capacitor to increase the system reliability. The input/output membership functions are given at figure 3(a) and 3(b) respectively.

Possible values of SOC states of Lead-Acid Battery = $\left\{ \begin{array}{c} High\ if\ 90 \le SOC_B \le 100 \\ Medium\ if\ 30 \le SOC_B \le 90 \\ Low\ if\ 30 \le SOC_B \le 0 \end{array} \right\}$ (7)

Possible values of SOC states of Super-Capacitors = $\left\{\begin{matrix} High\ if\ 90 \le SOC_{SC} \le 100 \\ Medium\ if\ 20 \le SOC_{SC} \le 90 \\ Low\ if\ 20 \le SOC_{SC} \le 0 \end{matrix}\right\}$ (8)

Fuzzy Logic Control-2 (FLC-2) is used to control discharging of the HESS into grid. There are three inputs to the FLC: difference between reference Supply Power and Load (*Difference*), Battery State-of-Charge (*SoC_Battery*) and Supercapacitor State-of-Charge (*SoC_SC*). *SoC_SC* and *SoC_Battery* are divided into two levels: High (H) and Low (L) both. The other component, *Difference* is divided into two components, Neg (N) and Pos (P). The output of the FLC-2 controls two switches (*Switch_B* and *Switch_SC*) which control the discharge of HESS into the grid according to the rule. Separate switches are used for Super-capacitor and Battery to increase the system reliability. The input/output membership functions are given in figure 3(c) and 3(d) respectively.

SOC states of Lead-Acid Battery = $\left\{\begin{matrix} High\ if\ 30 \le SOC_{Battery} \le 100 \\ Low\ if\ 0 \le SOC_{Battery} \le 30 \end{matrix}\right\}$ (9)

SOC states of Super-Capacitors = $\left\{\begin{matrix} High\ if\ 20 \le SOC_{SC} \le 100 \\ Low\ if\ 0 \le SOC_{SC} \le 20 \end{matrix}\right\}$ (10)

Charging and discha

rging scenarios of HESS = $\left\{\begin{matrix} Discharge\ if\ P_{Total} \ge 0 \\ Charge\ if\ P_{Total} < 0 \end{matrix}\right\}$ (11)

3.2 Membership functions:

Membership functions engages in an important position in controlling operation of FLC. These MFs are defined with linguistic terms having specified boundaries [13]. The input membership functions are being used as transitions among different operating modes [14]. In the proposed EMS, Trapezoidal MFs are being used. Various membership functions that are used in this energy management are shown in figure 3(a), 3(b), 3(c) and 3(d).

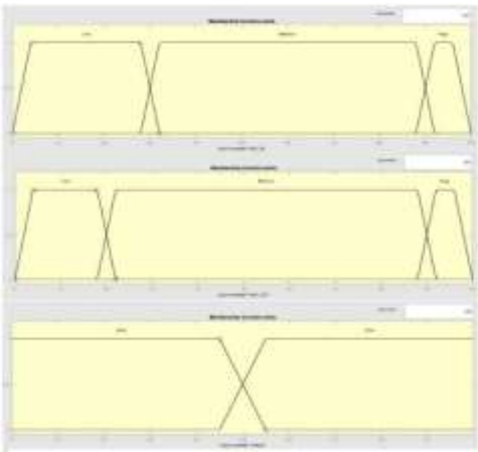


Figure 3(a): Input MFs for FLC-1

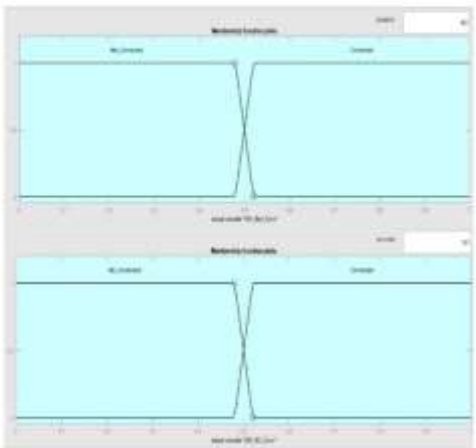
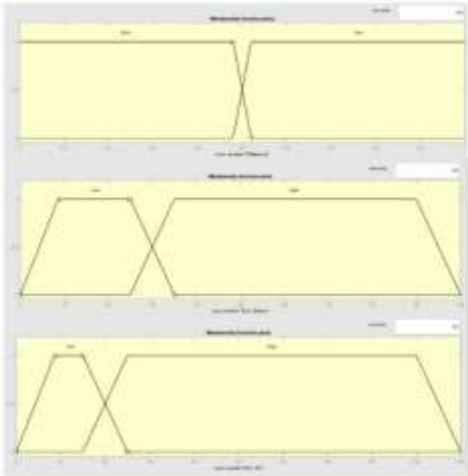


Figure 3(b): Output MFs for FLC-1



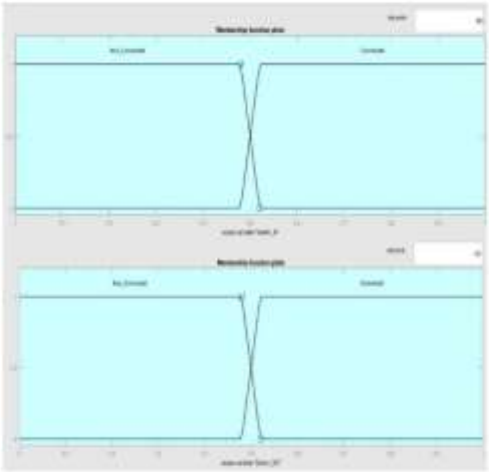


Figure 3(c): Input MFs for FLC-2 Figure 3(d): Output MFs for FLC-2

Overall system Specifications

Table 1: Overall system specification

System Specifications	
System Parameters	**Rating**
Capacity of the Microgrid	4KW
DC Bus voltage	72 V
Supercapacitor rating	29F
Lead-Acid Battery rating	250Ah
DC-DC buck converter input/output	100V/72V
DC-DC boost converter input/output	72V/100V
Number of Residential Houses considered	3 Nos
Number of FLCs considered	2 Nos
Simulation duration considered	24 Hours

3.3 Power allocation strategy:

The power allocation strategy used is this energy management system is achieved with the help of LPF. The LPF separates the High and low frequency components from the difference between supply and demand. The separated value then acts as an input to the PWM generators, which generated a specific pulse for the DC-DC converters accordingly. Figure 4 gives a schematic for the power allocation strategy used.

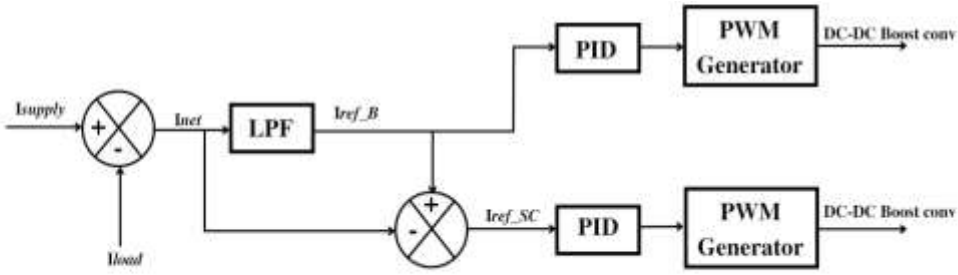


Figure 4. Controlling structure for power allocation strategy

3.4 Functioning of the EMS:

The value of the P_{Total} can be calculated by the formula given in eqn. 1. It reflects the power shortage or power surplus in the grid. The term P_{Load} refers to the load power demand at a specific time and is measured in KW. The value P_{Load} is compared to a predefined threshold value P_{Ref} (4000KW). Based on the comparison, three modes are possible:

(i) *Positive Value*: This result is observed when reference power demand is more than load power demand, which demonstrates that the supply is in excess and excess energy is used to charge the Energy Storage Elements.

(ii) *Negative Value*: This result is observed when reference power demand is less than load power demand, which shows that there is an outage of power and additional sources of energy is required to fulfill the requirements.

(iii) *Ideal*: This situation is seen when the power load demand and reference supply are equal, thus resulting in an ideal stage.

$$\text{Possible outputs of the comparison} = \begin{Bmatrix} Positive\ if\ P_{Ref} > P_{Load} \\ Negative\ if\ P_{Ref} < P_{Load} \\ Ideal\ if\ P_{Ref} = P_{Load} \end{Bmatrix} \quad (12)$$

The proposed Energy Management System has been designed to operate in four states to manage the flow of energy in system which depends on power drawn by load [15] and SoCs. The states are briefly discussed in the paragraphs following:

- State 1: This state is operated when load power demand is more than the reference power and the SOC of ESS i.e., Lead-Acid Battery / Supercapacitor is in between 30% and 100% / 20% and 100% respectively. In this mode, the ESS is connected to the microgrid to fulfill the shortage of supply.
- State 2: This state is switched on when the load power demand is more than the reference power and the SOC of the Energy Storage Systems are not within the limits i.e., less than 30% for Lead-Acid Battery and less than 20% for Supercapacitor. In this situation, due to the non-availability of the ESSs, the DC supply is directly connected to the load without ESS.

- State 3: This state is switched on when load power demand is less than reference power denoting that the supply is excess than the demand and the SOC of both the Energy Storage Systems is below 90%. In this mode, the ESSs are connected to microgrid with the help of a DC-DC boost converter, and ESSs are charged till the SOC of both the Energy Storage Systems reaches 90%.
- State 4: This state is switched on when load power demand is less than the reference power denoting that supply is excess then the demand and the SOC of both the ESSs i.e., Lead-Acid Battery and Supercapacitor is 90% or above. In this mode, the ESSs are not connected to the microgrid and are kept in the same ideal state.

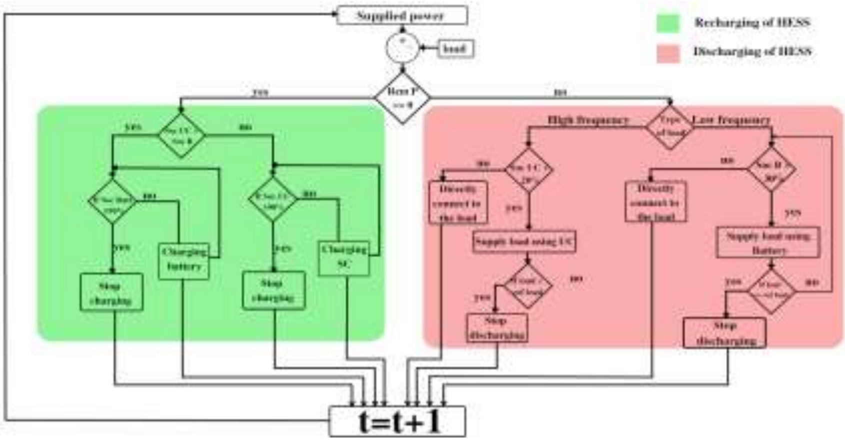


Figure 5. Various operation stages in proposed energy management system

4. SIMULATION RESULTS AND DISCUSSION

This simulation has been executed out in the MATLAB/Simulink software. A source-controlled Voltage source has been used as a supply from the microgrid. A uniform voltage of 72 V has been maintained for the DC bus utilizing a DC source. SoC of the ESSs have also been maintained in the limits.

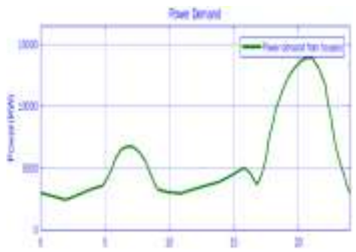


Figure 6(a). Load demand for 24 Hours

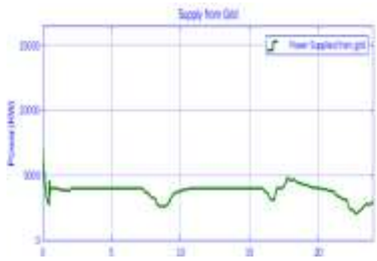


Figure 6(b). Power supplied from grid to load

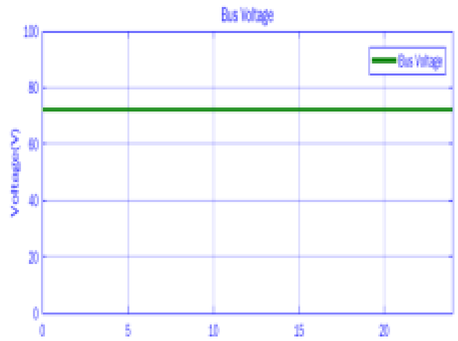


Figure 6(c). DC Bus voltage

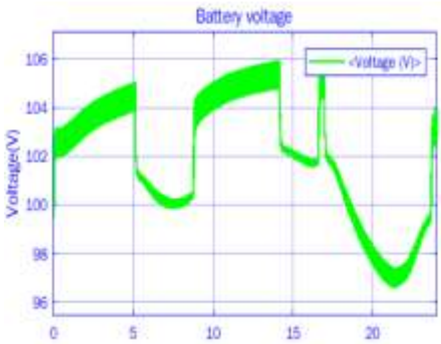


Figure 6(d). Battery Voltage levels

Figure 6(e). SoC levels of battery

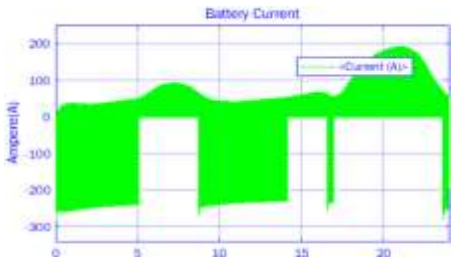


Figure 6(f). Battery current levels

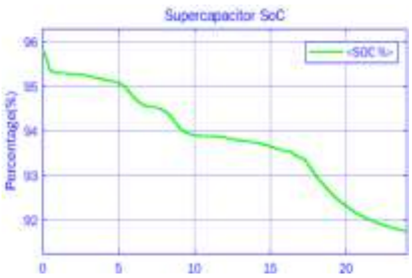


Figure 6(g). SoC level of SC

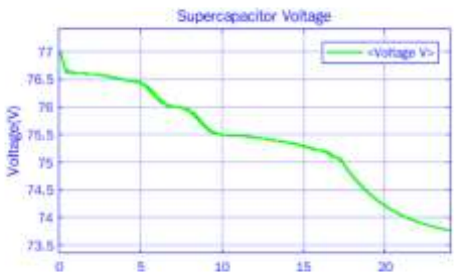


Figure 6(h). Voltage level of SC

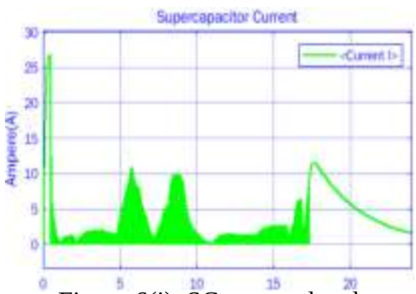


Figure 6(i). SC current levels

Three resistive loads have been considered, for three houses for a period of 24 hours. In the presented simulation, a grid has been designed to supply a power of 4KW. The purpose of the proposed EMS is to connect ESSs to the grid, whenever the load exceeds the capacity limit of the grid, it feeds the excess load demand and the other purpose of EMS is to recharge the ESS to the predefined values when there is excess power in grid. The microgrid system presented in this simulation has been tested for 24 hours. Overall parameters of the model have been mentioned in Table 1.

A LPF has been used to distribute demand according to the frequency at τ = 0.3 sec. The initial SoC of the Battery and SC was considered 50% and 95.8%. Fig 7(e) and Fig 7(f) show SoC capacity of ESSs in the simulation. Figure 7(a) represents the load demand from three houses for 24 hours. The graph shows us two peaks around 7:00 hrs and 21.00 hrs.

From the demand graph (Fig. 7(a)), it can be observed that the presented grid is insufficient to supply the load and needs more energy. At t= 5 to t=8.55; t=14.15to t=16.66; t=17to t=23.65, it is noticed that the load demand is exceeding the capacity of the grid which resulted in the activation of the EMS and connecting ESS to the system. The graph response that is being shown in Fig 7(b) gives us the data about how much power is being taken from the grid. It shows us that there has been stability in the power taken from the grid, irrespective of the load being increased in 24 hours. The additional demand is being stabilized to a limit of around 4KW with the help of the proposed EMS.

The controller is mainly responsible for balancing the power taken from the grid by using energy being stored in the ESSs. The proposed Energy Management System Successfully reduces the demand on the grid within the predicted range (4KW) as shown in Fig. 7(b), reducing the load on the grid, reducing the prices, and prolonging the lifespan of the critical devices in the grid.

A fall in the SoC levels of LA-Battery and SC has also been noticed, proving the fact that the ESS power is being utilized. For the period, when the load demand is less than the grid capacity, the EMS directs the additional power to recharge the ESS. In the Lead-Acid Battery, for a duration of t=0.00 to t=5.10; t=8.75 to t=14.15; t=16.58 to t=16.96 and t=23.65 to t=0.00 a rise in SoC level has been noticed confirming the recharge of the battery. Whereas, in the case of SC, no rise in SoC has been observed as the ESSs are recharged only if the SoC is below 90%.

The graphs show a remarkable improvement in grid system after the implementation of localized ESSs. The use of Fuzzy Logic Systems has made the system more reliable and functional.

5. CONCLUSION

In this paper, a new Fuzzy Logic based Energy Management has been developed and proposed for a HESS connected microgrid. It is exhibited that the presented EMS is dependable and ensures continuous power supply without increasing power draw from the grid irrespective of the load demand. Stable DC bus voltage, maintained SoCs of the ESS, smooth transition between charging and discharging modes and fast response are a few other pros of the proposed EMS that have been observed. Simulation of the model has been carried out in MATLAB/Simulink. Results with varying values of loads and smooth transition between modes prove the effectiveness of the proposed EMS.

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Biographies

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