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Fuzzy Logic based Energy Management System Design for AC and DC Microgrid

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***Abstract*—This paper deals with fuzzy logic control based energy management system for dc and ac microgrids. AC microgrid includes renewable energy sources connected to ac load and storage facility. Main intention of the design is to decrease the grid power profile deviations while preserving battery state of charge within the acceptable boundary. As a replacement for forecasting method we uses energy rate of change concept also a comparison with other method is introduced at simulation level. In addition to the above fuel cell is present in case of dc microgrid. Main target is to enhance the characteristics of battery, fuzzy logic control supervises the preferred state of charge. Modeling, analysis and control are done in matlab simulink platform.**

***Index Terms*— Energy management system (EMS), fuzzy control, microgrid.**

I. INTRODUCTION

The population among the world continues to increase nowadays and there by demand of electricity is also increasing day by day. In this scenario we have to think about our Renewable Energy Sources (RES) and properly use them for an environment friendly operation. In this paper we are mainly dealing with renewable energy sources such as solar panel and wind turbine. Today, the technologies are developing, which makes the difference between grid and smart grid [1]. We can say the key building block of smart grids are microgrids [2],[3]. A microgrid is small scale power grids that can be operate either in islanded mode or grid interconnected mode. In a microgrid, the renewable sources and load connected are random in nature, so in order to enhance system performance and steadiness we have to include energy storage elements (battery, ultra capacitors etc) and Energy Management Systems (EMS). The main purpose of providing EMS is to control the power fluctuations in the grid and also to reduce the operating cost of microgrid. During the design of EMS we should account for microgrid power architecture and also power management capabilities of elements in microgrid.

In this paper we are dealing with DC and AC microgrid separately. Considering AC microgrid our aim is to diminish the power variations while caring the battery state of charge within the allowable restrictions. We are in agreement with rate of change method instead of other forecasting methods. Considering dc grid, we have to optimize energy allocation. Also set up the battery SOC within the allowable limits and maintains a constant value.

In AC microgrid, for designing EMS fuzzy logic control is applied and is designed for selling additional electricity generated and maintains the battery State Of Charge (SOC) within the allowable boundaries.ie above 50% to extend battery life. Also it should be designed with the purpose to flat power exchanged with grid. It spotlights on residential grid connected microgrid with solar panel and wind as generation units and a residential load [4] , [9]. First we are dealing with simple moving average technique to flat the grid power profile. In this we use the approach is a Low Pass Filter (LPF) to split the high and low frequency elements of the power existing in microgrid. Also we can do it using a FLC with 100 rules and controller complexity was increased. A familiar weakness to above is they do not operate properly when the RES generation produces a large difference from one time interval to another. So with the aim of improving power profile fluctuations as well as reducing FLC complexity this paper presents a new FLC based EMS system with only 25 rules, two inputs and one output. The main factor in this design is microgrid Energy Rate of Change (ERoC) as an input [6]. EMS is also having predefined objectives such as minimizing the operating cost of microgrid [7],[8].

DC microgrid consists of solar panel, wind turbine, Li-ion battery, fuel cell and a dc load [11]. If power failure occurs in dc grid, battery will first discharged to deliver power for small period and if failure last longer, fuel cell will start to deliver power. Fuel cells provide only the base power in case of any power failure. The proposed fuzzy controller is used to optimize the energy allocation and sustain the SOC parameters.

II. AC MICROGRID

The microgrid contains a photovoltaic array of 4kW, a wind turbine of 5 kW , lead acid battery and ac load with rated power of 5 kW is shown in figure 1.

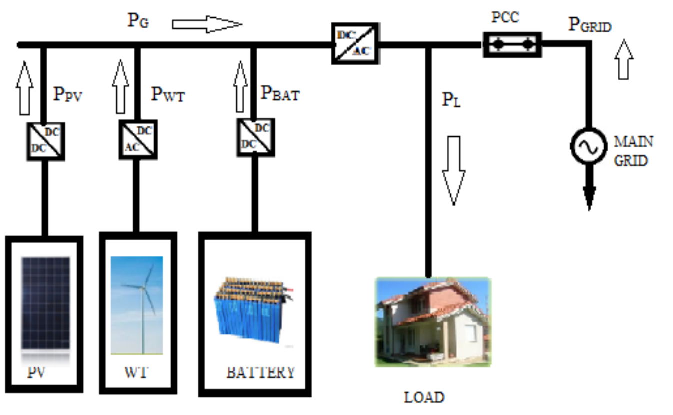

Figure 1: microgrid

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Referring to figure1, the power fluxes are considered positive as per the direction flows. The net power P_{LG} and the grid power P_{GRID} are:

$$P_{LG} = P_L - P_G \quad (1)$$

$$P_G = P_{PV} + P_{WT} \quad (2)$$

$$P_{GRID} = P_{LG} - P_{BAT} \quad (3)$$

Where, P_G is renewable power generation, P_{PV} is photovoltaic power, P_{WT} is wind power, P_L is load power, P_{BAT} is the battery power and D is Depth of discharge.

$$SOC_{MIN} \leq SOC\ (k) \leq SOC_{MAX} \quad (4)$$

Where

$$SOC_{MIN} = (1\text{-}D)\ SOC_{MAX} \quad (5)$$

We know battery power will directly depend on battery SOC and which should be kept between SOC minimum SOC_{MIN} and SOC maximum SOC_{MAX} limits. In this we considers a maximum of Depth Of Discharge (DOD) of 60%, because the life time of battery drastically reduced when operates at high DOD levels [12].

EMS should disconnect the power delivered / absorbed by the battery in order to avoid discharging/ overcharging the battery out of safe limits. Battery energy estimator is used to estimate the current battery SOC is shown in figure 2.

. It can be written as:

$$SOC(k) = SOC(k\text{-}1) - \Delta SOC(k) \quad (6)$$

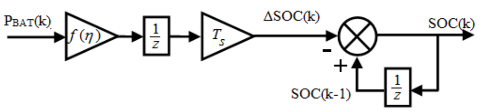

Figure 2: Battery energy estimator block diagram

ΔSOC(k) can be expressd as

$$\Delta SOC(k) = \int f(\eta)\ P_{BAT}(t)dt \quad (7)$$

$$\Delta E\ (t) = \int_{t}^{t+\Delta t} P(t)dt \quad (8)$$

ΔSOC(k) symbolizes the battery energy deviation during the sampling period T_s and it can be determined using general definition of energy ΔE of a power variable P_i during a period ΔT. Where $f(\eta)$ is the battery efficiency. For charging and discharging process we have to consider different efficiencies.ie,

$$f(\eta) = \begin{cases} 1/\eta & \text{for all } P_{BAT} > 0 \\ \eta & \text{for all } P_{BAT} < 0 \end{cases} \quad (9)$$

In this case under study we have to assume that the modules are extracting the maximum renewable power and ac load power utilization is not controllable. The key intention of EMS design is to control the power inverter rectifier in order to smooth the power profile while keeping the SOC within the secure limits. In order to numerically evaluate the degree of grid power profile smoothness achieved by an EMS design, we have to consider grid power profile quality criteria and for better EMS performance the criteria values should be lower.

A. Positive and Negative Grid power peaks

The positive grid power peak $P_{G,MAX}$ is defined as the maximum value of power delivered by the grid and negative peak $P_{G,MIN}$ is maximum value of power fed into the grid.

III. SIMPLE MOVING AVERAGE TECHNIQUE

Simple Moving Average (SMA) technique is a previous EMS strategy, which is used to flat the grid power characteristics. In this strategy we use an average filter to separate the low and high frequency elements of the microgrid net power. Thus, the low frequency element is swapped with the grid (injected to grid if $P_{GRID} < 0$, or delivered by the grid if $P_{GRID} > 0$) whereas the high frequency component is replaced with battery (if $P_{BAT} > 0$, delivered by the battery and if $P_{BAT} < 0$ injected into the battery)

$$P_{AVG}\ (k) = \frac{1}{M} \sum_{n=k-M}^{k-1} P_{LG}\ (n) \quad (10)$$

$$P_{BAT}\ (k) = P_{LG}(k) - P_{AVG}\ (k) \quad (11)$$

$$P_{GRID}\ (k) = P_{AVG}\ (k) \quad (12)$$

Where P_{AVG} is the low frequency element of P_{LG} and M is number of samples. The block diagram of SMA technique is shown in figure 3.

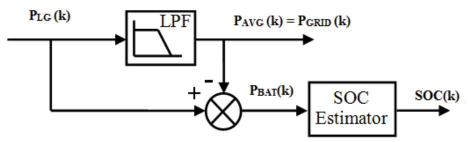

Figure 3: Block diagram of SMA technique

In SMA technology LPF is used to attain the low frequency components of P_{LG} and a SOC estimator as shown in figure 3. Figure 4 shows the simulation results of grid power profile of SMA strategy.

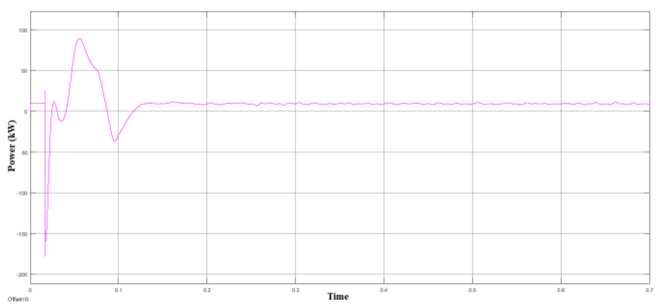

Figure 4: simulation result for SMA strategy

It can be concluded from the figure that the grid power profile has large oscillations as long as this strategy leads the battery to extend secure limits during several time intervals.

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IV. FUZZY EMS DESIGN BASED ON MG ENERGY RATE OF CHANGE (EROC)

Main target of enhanced FLC based energy management system design is to reduce the power peaks and grid power profile variations while keeping the battery SOC within a certain boundary as well as to reduce the FLC difficulty. In this method, SOC of battery SOC(n), as an input to make sure that its value at any time in order to fit the constraints forced by the maximum DOD of battery and conserve its life. Also, P'_{GRID} (n) is an another input to FLC , gives the details of the magnitude of the microgrid energy change of two successive samples. In this manner, a negative slope corresponds to a microgrid renewable power generation increase or load utilization reduces. On the other hand, a positive slope means reduction of renewable power generation or raise load consumption in the microgrid.

EMS design suggests that grid power as the sum of average value of the microgrid net power P_{GRID} (n) and an additional component P_{FLC} (n).

$$P_{GRID,T}(n) = P_{GRID}(n) + P_{FLC}(n) \qquad (13)$$

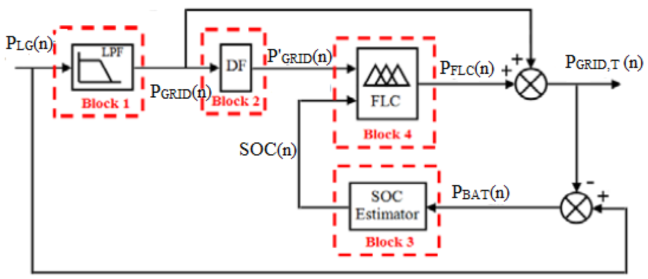

Figure 5: fuzzy EMS design based on microgrid EROC block diagram

P'_{GRID} (n) can be understood as the local prediction of battery SOC future behavior if grid power is not changed. So from the information of SOC (n) and P'_{GRID} (n) the FLC tries to modify P_{FLC} (n) to decrease, increase or maintain the power delivered / absorbed by the mains to satisfy the SOC within acceptable limits and load power demand. The block diagram is shown in figure 5. P_{LG}(n) is passes through a LPF, split the low frequency elements we get P_{GRID} (n) . A digital filter inhibits the high frequency gain and noise associated with the derivative term[4]. Block diagram also comprises of SOC estimator shown in figure 2.

Regarding fuzzy control design which assumes mamdani based inference and defuzzyfication with two input and one output. In this five triangular membership functions are used for each input variable. The subsets are noted as NB, NS, ZE, PB, PS. Where N represents negative, P for positive, B for Big, S for Small, ZE for Zero. Similarly for the output P_{FLC} (n), nine triangular membership functions are used. The MFs are associated with nine fuzzy subsets noted as NB, NM, NS, NSS, ZE, PSS, PS, PM and PB. Labels P,N,B,S and ZE are same as previously defined. M represents medium, SS represents smallest FLC optimized rule base is given in table 1.

Table 1 : FLC control rules

P_{FLC}		P'_{GRID} (n)				
		NB	NS	ZE	PS	PB
SOC(n)	NB	ZE	PSS	PS	PM	PB
	NS	NSS	ZE	PSS	PSS	PM
	ZE	NS	NSS	ZE	PSS	PS
	PS	NSS	NS	NSS	ZE	PSS
	PB	NB	NM	NS	NSS	ZE

If there is a big energy rate of change (P'_{GRID} (n) is PB) and amount energy stored in the battery is low (SOC(n) is NB) then it requires increasing the power injection from the mains to recharge the battery, ie to increase the P_{FLC}. This leads to control rule

If P'_{GRID} is PB and SOC is NB then P_{FLC} is PB

On the contrary, if the battery is near to full charge state, then the grid power should be reduced or cancelled. This leads to

If P'_{GRID} is PB and SOC is PB then P_{FLC} is ZE

Extending this reasoning to other cases leads to the definition of rule base shown in table1.

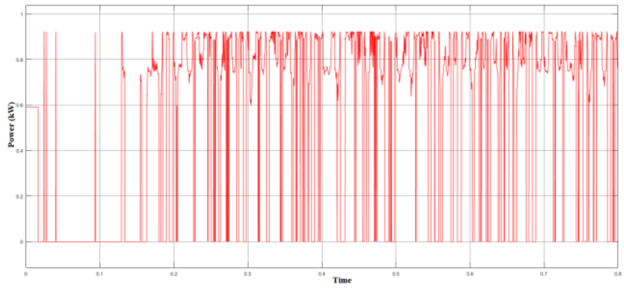

Figure 6: Grid power profile variation

figure6 shows the simulation result of grid power profile variation using microgrid energy rate of change concept. From this figure we can clear that the power variation is reduced compared Simple moving average technique. Also grid power profile quality criteria such as $P_{G,MAX}$ and $P_{G,MIN}$ are also reduced by using this technique.

V. DC MICROGRID

In the previous sections we discussed with AC microgrid, now we are dealing with DC. For the resourceful use of renewable energy sources, load should be directly supplied by dc electricity. Figure7 shows the dc distribution system with grid connected.

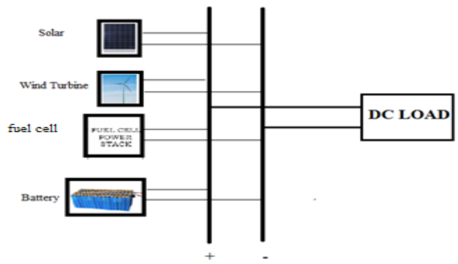

Figure 7: configuration of dc microgrid

DC microgrid in this system composed of 1.5 kW wind turbine model, 4kW solar panel, a Li-ion battery, fuel cell and 6.5 kW load. Fuel cells provide only the base power in case of any power failure. Maximum power point tracker is coupled to PV panel and wind turbine to collect maximum power, which is fed in to dc grid. DC load is directly connected to grid. If the generated power fails to supply, battery will first

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discharged to deliver power for a short time period and if the failure continues the fuel cell will start delivering power. That is based on the availability of power in the grid; the battery can charge or discharge. The suggested fuzzy control is to optimize energy circulation and setup the battery SOC factors.

VI. FUZZY EMS DESIGN

Fuzzy control is applied in EMS for the dc microgrid system to realize the optimization of system. Maximum power point tracker is used in both solar panel and wind turbine in order to achieve maximum power, which is supplied to grid. In this design the difference between load power and total generated power is taken into account for the battery charging and discharging modes. The life cycle of battery is directly proportional to battery SOC. For better life of Li-ion battery , we can control and sustain the battery SOC within the acceptable boundary by using fuzzy control. To get the preferred SOC value, fuzzy controller is considered to be in charging mode or discharging mode for the microgrid system. The input variables to fuzzy controllers are ΔP and ΔSOC, the output variable is ΔI.

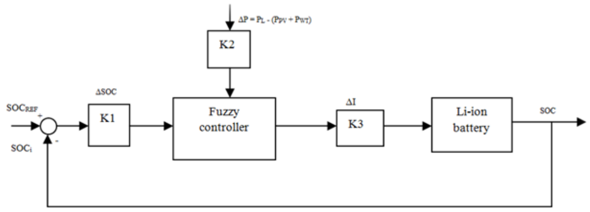

Figure 8: Block diagram of fuzzy control

$$\Delta P = P_L - (P_{PV} + P_{WT}) \qquad (14)$$
$$\Delta SOC = SOC_{ref} - SOC_i \qquad (15)$$

Fuel cell is not regarded as power source; offer base power for the loads when system fails. So that fuel power not included in equation (14). Coming to fuzzy controller, input and output membership function of fuzzy controller include five subsets: NB, NS, ZO, PS, PB. Labels N, P, B, S, ZO are same as previously defined. K1 and K2 are input scaling factors, we can find out the degree of membership and substitute into fuzzy control rules to attain output current for charge and discharge variance ΔI of Li-ion battery. K3 is also a factor which relates current I and SOC of the battery. The battery should function in discharging mode; if ΔSOC is positive, which indicates that state of charge of the battery is smaller than state of charge demand. If ΔP is positive, it shows that renewable source supply sufficient energy to the load. Therefore battery must activate in charging mode. Table 2 shows the fuzzy rules of the system. If the input variable ΔSOC is NS (better than the SOC $_{ref}$ and membership degree is small) and ΔP is NB (amount of electricity to sell is large) then output variable ΔI is PB (scale of discharging current is large). Fuzzy control rules are placed to preserve the battery state of charge above 50% to extend the life of batteries. In fuzzy control rules the battery is compelled to discharge as the control policy when load power require was greater than generated power.

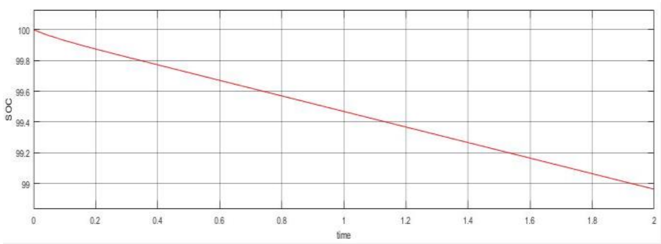

Figure 9: SOC of battery

Table 2 : Fuzzy control rules

ΔI		ΔP				
		NB	NS	ZO	PS	PB
ΔSOC	NB	PB	PB	PB	PB	PB
	NS	PB	PB	PS	PS	PB
	ZO	ZO	ZO	ZO	PS	PB
	PS	NS	NS	NS	NS	PB
	PB	NB	NB	NB	NB	PB

Figure 9 shows the simulation result with an initial battery SOC at 100%. This proves the precision of the system with fuzzy controller that can sustain the state of charge of the battery at a certain level whether initial value of state of charge is high or low.

VII. CONCLUSION

This paper has presented energy management system design for both ac and dc microgrids. Energy management system supposes that neither renewable energy sources nor loads are controllable. Considering ac microgrid, fuzzy logic control supported energy management system for smoothing the grid power fluctuations. This design allows the EMS to react fast against microgrid energy changes in order to set the battery SOC at 80% of rated capacity. Also an evaluation with other method searching for same goal has been carried out at simulation level. Current work is focused for extension of energy rate of change approach for controllable loads also. From the simulation results of dc microgrid, system attains stability and battery state of charge preserves the desired value for extension of battery life. The proposed system maintained state of charge of battery at a particular stage even if initial value of state of charge is low or high.

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