FuzzyControl Based Design and Implementationof Energy Management for DC Microgrid Systems

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Abstract-***Most of the electricity in India comes from fossil-fuels like coal, oil and natural gas. Today the demand of Electricity in India is increasing and is already more than the production of Electricity whereas the reserves of fossil-fuel are depleting every day. There is strong need to shift for other sources and the best option is renewable energy sources. In this paper, a DC micro gird system is proposed in order to decrease the transmission charges and increase the efficiency of the system. This system consists of a fuzzy controller to improve the performance of the energy management system (EMS). The fuzzy logic controller has two input signals, and one output signal.***

Keywords: Energy management system (EMS), fuzzy control, microgrid.

1. INTRODUCTION

There is an increased awareness of the running down of customary energy sources and environmental damage caused by increased carbon dioxide discharges from coal-fired power generation, the use of renewable energy has become the goal for energy development. Current green energy used in power generation includes: solar, wind, geothermal, biomass, and tidal [1]. Many countries have fixed a goal of increasing the usage of renewable energy above 20% of their total power consumption by the year 2020. In addition, distributed power systems are subject to the effects of environmental factors and constraints of nature. In general power system uses battery energy storage to avoid a power outage or power surges caused due to various natural environmental factors. The recent trend of renewable energy development is to combine the distributed power sources and energy storage subsystems to form a small microgrid [2],[3] that reduces the loss of energy which usually occur during power transmission over long distances. Renewable energy is converted into dc and buffered with energy storage elements, and then it is inverted to ac and fed into the utility grid. This approach can readily adapt to contemporary electrical facilities and accelerate use of renewable energy. However, existing high efficiency and compactappliances andequipment are powered by dc, which is converted by rectifying an AC source with power factor correction. To use renewable energy more efficiently, DC electricity should be directly suppliedto these loads. Such a supply scheme is far different from that of the conventional AC distribution and supply system.

In this system there will be a reduction of power loss by around 7%, area which is used for the production is saved by 33%, charges for the installation are reduced by about 15% and the reliability of the system increased by about 200%[1], [5]. Low voltage applications especially for lightening can easily be developed. This proposed system includes renewable energy i.e. green power generation, energy storage element, energy management system(EMS) with a fuzzy controller. This fuzzy controller helps to optimize energy distribution of microgrid system.

The system configuration consists of four major blocks: power generator, energy storage equipment, DC load and EMS. In this power generation includes PV panels, wind turbines and fuel cells. The fuel cells provide base power during a power failure for the emergency loads. The PV panels and the wind turbines are associated with maximum power point tracking, which are later fed into the DC grid. If there is power failure, the Li-ion battery will be firstdischarged to supply power for a short-time interval and if thefailure lasts longer (e.g., 2 min), the fuel cell will start supplyingpower.If there is power shortage, the bidirectional inverter will take power from the ac grid.The battery discharger will be also responsible for dc-grid voltage regulation if the bidirectional inverter is not in operation. If the bidirectional inverter is in operation, the battery can be charged.

The proposed fuzzycontrol is to optimize energy distributionand to set up battery state of charge (SOC) parameters.This fuzzy controller consists of a fuzzy logic controller. The fuzzy logic controller has two input signals, and one output signal.The designnotion of this study helps to increase the useful life of lithiumbatteries and to include charge and overdischarge protectionmechanisms.

2. MODELING OF GREEN ENERGY COMPONENTS

The modeling of dc microgrid distributed energy and an energy storage component is built by MATLAB simulink mathematical modules, based on equivalent circuits of the components. The following describes the model of each subsystem in detail.

2.1Modeling of Solar Cell

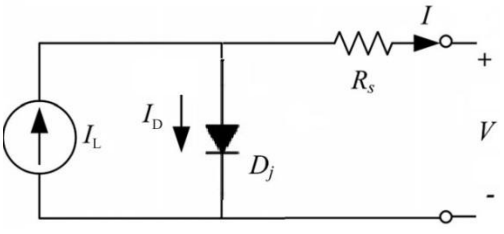


Fig.1 A four parameter model of solar cell equivalent circuit

$$I=I_L-I_D \quad (1)$$

Where I_L refers to the light current and I_D is the diode current. Using Shockley equation, the diode current can be expressed as

$$I_D = I_0\left[\exp\left(\frac{q(V+IR_s)}{\gamma k T_C}\right)-1\right] \quad (2)$$

Where

$$\gamma=A.NCS.NS,(3)$$

$$I_L = \left(\frac{G}{G_R}\right)\left(I_{LR}+\mu_{ISC}\left(T_C-T_{CR}\right)\right),(4)$$

And

$$I_0 = I_{0R}\left(\frac{T_C}{T_{CR}}\right)^3 \exp\left[\left(\frac{qEg}{kA}\right)\left(\frac{1}{T_{CR}}-\frac{1}{T_C}\right)\right](5)$$

In this equations above, I_{LR} refers to the light current at reference condition, I_0,I_{0R} the reverse saturation current, actual and reference condition respectively, T_C,T_{CR} the cell temperature, actual and at reference condition respectively, G, G_R irradianceactual and at reference condition respectively,'q' the electron charge, 'R_S' series resistance, 'γ' the shape factor, 'k' the Boltzmann constant, 'A' the completion factor, 'NCS' the number of cells connected in series per module, 'NS' the number of modules connected in series of the entire array, 'μ_{ISC}' the manufacturer supplied temperature coefficient of short-circuit current and 'Eg' the material bandgap energy.

In this case Sharp NUS0E3E solar modules are used, each with a power rating of 180 W, as the photovoltaic device of the microgrid system. The total capacity of solar power is 5 kW, generated by two photovoltaic arrays in parallel, where each array was built with 14 solar panels in series. The simulated output power versus output voltage of the solar cell is shown in Fig. 2. This study used constant illumination intensity 1 kW/$m^2$and constant temperature with varying V forsimulation verification.

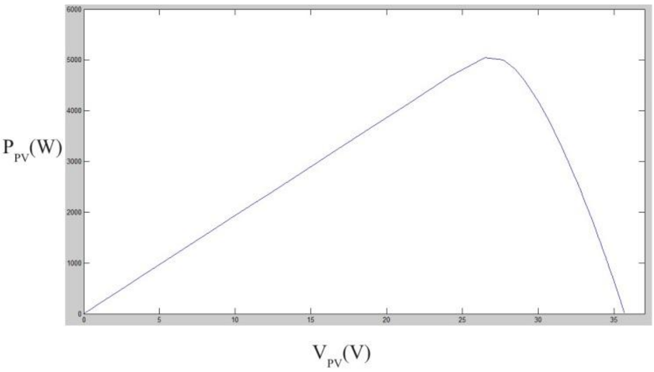


Fig.2: Simulated output power P_{PV} versus output voltage V_{PV} of the solar cell with constant illumination intensity 1 kW/m^2

2.2 Wind Turbine Modeling

The power generated by wind turbine is expressed as

$$P_W= 0.5\rho AV^3C_P\,(\lambda, \theta)(6)$$

Where$P_W$is power generated by the wind turbine W, ρisdensity of gas in the atmosphere (kg/m), Ais cross-sectionalarea of a wind turbine blade m^2, Vis wind velocity (m/sec), and$C_P$is the wind turbine energy conversion coefficient.

The density of gas ρand energy conversion coefficient $C_P$in is expressed by (7) and (8), respectively

$$\rho = \left(\frac{353.05}{T}\right)\exp^{-0.034\left(\frac{Z}{T}\right)} \quad (7)$$

$$Cp(\lambda,\theta) = \left(\frac{116}{\lambda i}-0.4*\theta-5\right).0.5\exp^{-\frac{16.5}{\lambda i}}(8)$$

Where Zis the altitude, Tis the atmospheric temperature, λiisthe tip speed ratio, and θis the blade tilt angle.

Equation (9) gives the expression of the tip speed ratio λiin (8) and (10) is the expression of the initial tip speed ratio λin (9)

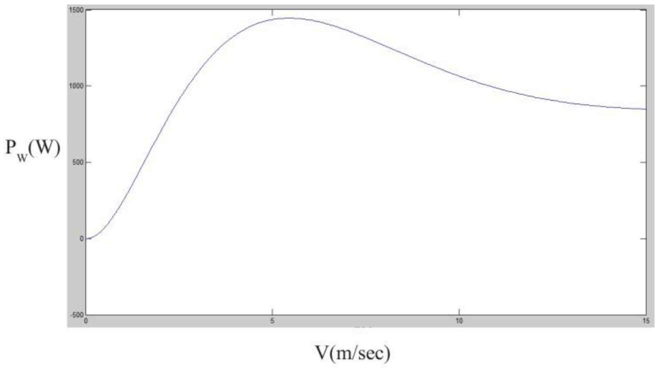


Fig.3:Simulated output power $P_W$with various wind speeds V.

$$\lambda i = \frac{1}{1/(\lambda + 0.089\theta) - 0.035/(\theta^3 + 1)} \quad (9)$$

$$\lambda = r\frac{\omega}{V} \quad (10)$$

The wind turbine used in this studyisAWV-1500 of GallantPrecision Machining Company, Ltd. Wind speed is the mostcritical factor in wind power generation. This simulated outputpower $P_W$of the wind turbine with various wind speeds Visshown in Fig. 3.

2.3 Lithium-Ion Battery Modeling

Eq. (11) is the discharge equation and (12) the charge equation of the lithium-ion battery

$$f_1(it\ i^*\ i) = E_0 - K \cdot \frac{Q}{Q - it} \cdot i^* - K \cdot \frac{Q}{Q - it} \cdot it + A \cdot \exp(-B . it)$$
(11)

$$f_2(it\ i^*\ i) = E_0 - K \cdot \frac{Q}{0.1Q + it} \cdot i^* - K \cdot \frac{Q}{Q - it} \cdot it + A . \exp(-B \cdot it)$$
(12)

Where$E_0$is initial voltage (V), Kis polarization resistance (Ω), $i^*$is low-frequency dynamic current (A), iis battery current (A),it is the battery extraction capacity (Ah), Qis maximum battery capacity (Ah), Ais exponential voltage (V), Bis exponential capacity $(Ah)^{-1}$.

SOC of the battery is an important factor, which is calculated by

$$SOC = 100\left(1 - \frac{\int_0^t idt}{Q}\right) \quad (13)$$

Knowing the amount of energy left in a battery compared with the energy it had when it was full gives the user an indication of how much longer a battery will continue to perform before it needs recharging. The SOC is defined as the available capacity expressed as a percentage of some reference, sometimes its rated capacity but more likely its current (i.e. at the latest charge-discharge cycle) capacity but this ambiguity can lead to confusion and errors. It is not usually an absolute measure in Coulombs, kWh or Ah of the energy left in the battery which would be less confusing.The battery voltage is easy to measure and implement in the circuit. There exists nonlinearity between voltage and SOC. Therefore, the SOC parameter of batteries has been selected as the design factor instead of battery voltage in this paper.

2.4 Fuel Cell Modeling

Fuel cells provide a high efficiency clean alternative to today'spower generation technologies. The polymer electrolyte membrane(PEM) fuel cell has gained some acceptance in mediumpower commercial applications such as creating backup power,grid tied distributed generation, and electric vehicles. Theoutput voltage *E* of the PEM fuel cell is represented as

$$E = E_n - (-V_{act} + V_{ohm} + V_{con}) \quad (14)$$

Where$E_n$is Nernst voltage, $V_{act}$is the activation over potential,$V_{ohm}$is ohmic over potential, and $V_{con}$is concentrationover potential.

$$V_{act} = -[\xi_1 + \xi_2 \cdot T + \xi_3 \cdot T \cdot \ln(C_{O2}) + \xi_4 \cdot T \cdot \ln(i_f)] \quad (15)$$

$$V_{ohm} = i_f \cdot R_M \quad (16)$$

$$R_M = \frac{181.6\left[1 + 0.03\left(\frac{i_f}{A_f}\right) + 0.062\left(\frac{T}{303}\right)^2\left(\frac{i_f}{A_f}\right)2.5\right]}{\left[\lambda 1 - 0.634 - 3\left(\frac{i_f}{A_f}\right)\right]\exp\left[4.18\left(\frac{T-303}{T}\right)\right]} \cdot \frac{l1}{A_f}$$

$$V_{con} = -B_o \cdot \ln\left(1 - \frac{J}{J_{max}}\right) \quad (18)$$

where Tis operating absolute temperature, $C_{O2}$is concentrationof oxygen, i_f is output current of the fuel cell, $\xi_{1,2,3,4}$ arereference coefficients, l1is effective thickness of membrane, λ1is adjustable coefficient, $A_f$is effective area, $B_0$is operatingconstant, Jis current density, and $J_{max}$is maximum currentdensity.

3. INTELLIGENT ENERGY MANAGEMENT SYSTEM

The system configuration of the proposeddc microgrid system includes four major blocks. To design anaccurate controller of the proposed microsystem, the dynamicmathematical models of the power sources (PV, wind turbine,and fuel cell), dc/dc converters (buck-boost, buck, and phaseshiftedfull-bridge converters), bidirectional converter (symmetricalfull-bridge converter), and bidirectional inverter (full bridgeinverter) of the integrated micro-system are necessary.However, the modeling, analysis, and design of the proposed integrateddc microsystem are not simple. To maintain the batterySOC with EMS, the fuzzy controller is needed to meet designspecifications, because the control for EMS is a low responsecomponent and the models of dc/dc converters, dc/ac convertersof the micro-DC microgrid system are unnecessary.

Fuzzy control theory is designed and implemented in EMSfor the dc microgrid system to achieve the optimization of thesystem. The design criterion requires that both the photovoltaicdevice and the wind turbine are supplied by a maximum powerpoint tracker to maintain the maximum operating point. Thedifference between actual load and total generated power istaken into account for Li-ion battery in charge and dischargemodes. The life cycle and SOC of the battery are in directproportion. To improve the life of the Li-ion battery, we cancontrol and maintain the SOC of battery with fuzzy control.Fig4 shows the Block diagram of fuzzy control to maintain the desired SOC of thebattery.

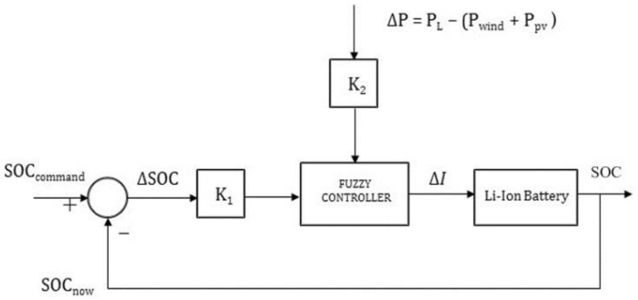


Fig.4:Block diagram of fuzzy control to maintain the desired SOC of the battery.

3.1 Fuzzy Control

Lotfi. A. Zadeh,an American scholar of automatic control, suggestedFuzzy theory first in 1965, as a tool of computableexpression for concepts that could not be clearly defined.A fuzzy control system is based on fuzzy-logic thinking in thedesign of how a controller works. The so-called fuzzy logicis to establish a buffer zone between the traditional zero andone, with logic segments of none-zero and none-one possible.It allows a wider and more flexible space in logic deductionfor the expression of conceptual ideas and experience. A fuzzycontroller differs from a traditional controller in that it employsa set of qualitative rules defined by semantic descriptions.

The fuzzy controller is applied in the proposed microgridpower supply system, as shown in Fig. 4. To obtain the desiredSOC value, the fuzzy controller is designed to be in chargingmode or discharging mode for the proposed microgrid system.The input variables of the fuzzy control are ΔSOC(%) and ΔP(W)and output variable is ΔI. The definition of input and outputvariables are listed as follows:

$$\Delta SOC = SOC_{command} - SOC_{now} \qquad (19)$$

$$\Delta P = P_L - (P_{wind} + P_{pv}). \qquad (20)$$

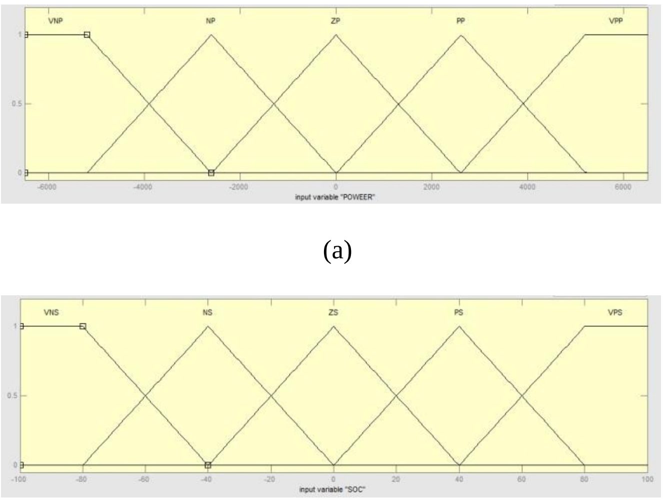
The power difference ΔPis between required power for loadand the total generated power of the microgrid. The fuel cellsonly provide base power for the emergency loads when thesystem fails. Therefore, the fuel cell is not considered as powersource in (20). The generated power comes from solar powerP_{pv}, wind turbine $P_{wind}$and power load $P_L$for the proposedsystem. The input and output membership functions of fuzzycontrol contain five grades: VN (Very negative), N (negative), Z (zero), P (positive), and VP(Very positive), ‘S’ for state of charge, ‘P’ for power and ‘D’ for chargeas shown in Figs. 5 and 6. By input scaling factors $K_1$and K_2,we can determine the membership grade and substitute it intothe fuzzy control rules to obtain the output current for chargeand discharge variance ΔIof the Li-ion battery. If the ΔPisnegative, it means that the renewable energy does not provideenough energy to the load. Thus, the battery must operate incharging mode; if the ΔSOC is negative, it means that the SOCof the battery is greater than the demand SOC. Thus, the batterymust operate in discharge mode.

The control rules of this study prioritize selling additional electricity generated by the renewable energy in response to the present control strategy of microgrid development for selling electricity and increasing the life of Li-ion batteries. Table I shows the fuzzy rules of the proposed system. For example, the output variable ΔIis VP (the degree of discharging current is large) when the input variable ΔPis VNP (the amount of electricity to sell is large) and input variable ΔSOC is NS (greater than the SOC command and the membership degree is small). However, the output variable ΔIis ND (the degree of charging current is small) when the input variable ΔPis

TABLE I
FUZZY CONTROL RULES

ΔSOC ΔP	VNS	NS	ZS	PS	VPS
VNP	VPD	VPD	ZD	ND	VND
NP	VPD	VPD	ZD	ND	VND
ZP	VPD	PD	ZD	ND	VND
PP	VPD	PD	PD	ND	VND
VPP	VPD	VPD	VPD	VPD	VPD

VNP (the amount of electricity to sell is large) and input variable ΔSOC is PS (smaller than the SOC command and the membership degree is small). The output variable is ND instead of VND when the system is operated in the above conditions because selling electricity is the first priority in this case. Thus, the fuzzy control table of the proposed dc microgrid system is not symmetrical. To extend the life of storage batteries in the design of fuzzy control, the fuzzy control rules are set to maintain battery SOC above 50%. Moreover, in the fuzzy control rules the Li-ion battery is forcedto discharge as the control strategy when power demand at load was greater than the power generated by the renewable energy.



(a)

(b)

Fig.5. Input membership functions of variables: (a)P and (b)SOC

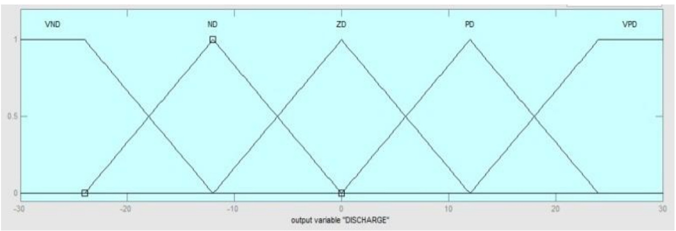


Fig.6: Output membership function of variable ΔI

In many previous studies, the fuzzy controller has been applied to improve control performance andhas shown better control performance than conventional linear controllers.

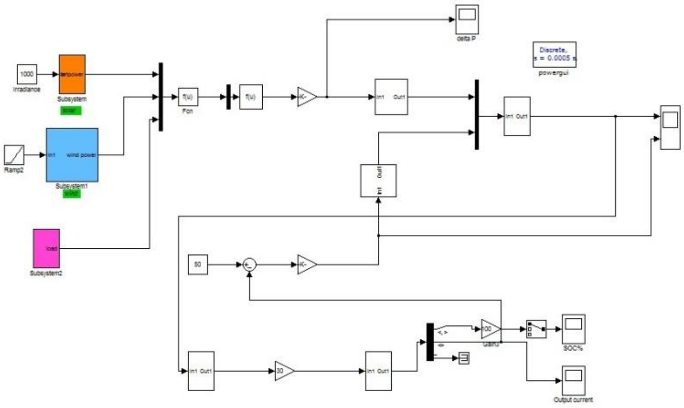


Fig.7: Dynamic model of the microgrid system using MATLAB simulink

In this, a fuzzy controller with double input is proposed to improve the control performance of the EMS, as presented in Figure 4. This fuzzy controller consists of a fuzzy logic controller with the above described rule base. The input variables of the fuzzy control are ΔSOC and ΔPand output variable is ΔIof the fuzzy logiccontroller.Theoutput signal from theconventional fuzzy controller, called the control signal (*Δ*I), is used for stabilizing the battery performance.

3.2 Illustration

The dynamic model of the proposed dc microgrid systemusingMATLAB simulink is shown in Fig. 7, where the systemconsists of a 5 kW solar module, a 1.5 kW wind turbine module,a 1.5 kW Li-ion battery module, and a 6.5 kW load.

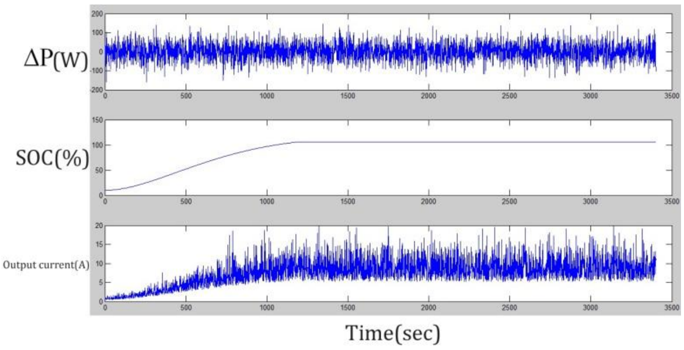


Fig.8: Simulation results with initial battery SOC at 10%.

This example verifies the accuracy of the proposed systemwith fuzzy controller that can maintain the SOC of the batteryat a certain level whether initial value of the SOC is low or high.As shown in Fig. 8, the fuzzy controller Li-ion battery SOC ismaintained at 50% with an initial value of 10%. As shown inFig. 9, the fuzzy controller Li-ion battery SOC is maintainedat 50% with an initial value of 100%.To control strategy of this study is to sell electricity as apriority and to maintain battery SOC.

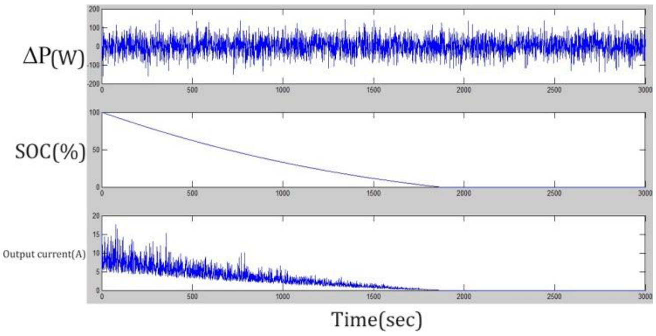


Fig.9: Simulation result with initial battery SOC at 100%.

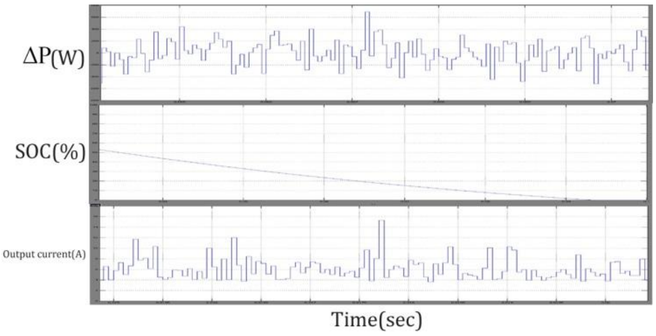


Fig.10: Simulation results when the bidirectional Inverter rating is over the power rating.

Fig. 10 shows that thefuzzy controller forced the Li-ion battery to discharge whenΔPis greater than 5 kW to keep the system in power equilibrium without going over the power rating of the bidirectional invertersubsystem. However, the SOC of the battery is not the firstpriority to achieve the safety when the inverter is over the powerrating.

4. CONCLUSION

In this paper the modeling, analysis, and design offuzzycontrol is done to achieve optimization of an energy management for a dc microgrid system. From the simulationresults, it can be concluded that the system achieves power equilibrium, and the batterySOC maintains the desired value for extension of battery lifeby using the control rules for a dc microgrid. Thus the fuzzy controller for EMS provides better performance than any other controller. The management system takes advantage of the design to control the SOC of the Li-Ion battery and increasing its life and achieves optimal control of the DC microgrid.

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