A Fuzzy Logic based Battery Management System for a Microgrid

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***Abstract*-- This paper proposes an approach for the hybrid solar photovoltaic and wind power system in Battery management for stand-alone applications. Battery charging process is non-linear, time-varying with a considerable time delay so it is difficult to achieve the best energy management performance by using traditional control approaches. A fuzzy control strategy for battery charging or discharging used in a renewable power generation system is analyzed in the paper. To improve the life cycle of the battery, fuzzy control manages the desired state of charge (SOC). A fuzzy logic-based controller to be used for the Battery SOC control of the designed hybrid system is proposed. The entire designed system is modeled and simulated using MATLAB/Simulink environment.**

Index Terms- Distributed Energy Resources(DER's), Energy Storage System(ESS), Point of Common Coupling(PCC), SOC(State of Charge).

I. INTRODUCTION

With the increased use of renewable energy resources, substantial efforts have been invested in the installation of distributed energy resources (DERs) for establishing a green and smart distribution system. Generally, DERs include diverse technologies, such as diesel generator, fuel cell, micro turbine, and energy storage system (ESS) belonging to controllable energy resources, as well as wind energy and photovoltaic as non-controllable renewable energy resources. According to the US Department of Energy, relying on the advanced communication tools and power electronic control devices, the utilization of DERs is potentially in favour of increasing the energy utilization efficiency, mitigating the power flow congestion in distribution system, improving the system stability and reliability, providing more benefits in both economic and sustainability reasons, and strengthening the centralized control for grid operation.

Even if DERs have many advantages, they also bring problems to the power network. A single and small DER is treated as a non-regulated energy resource compared to the large power grid. The integration of DERs into power grid causes voltage fluctuations and affects power quality. Moreover, DERs need to be disconnected instantly if severe faults occur in the main grid. It may limit the performance of DERs to a large extent. To obtain a better and stable use of DERs and release the conflicts between a single DER and large power network, a new concept called "Microgrid" has been developed in recent years.

Microgrid is an important and necessary part of the development of smart grid. A microgrid is a low-voltage and small network connected to a distribution grid through the point of common coupling (PCC), and contains both distributed generations and loads. Several types of distributed energy resources (DERs) are used in a microgrid, such as microturbine (MT), fuel cell (FC) and energy storage system (ESS) as controllable units.

Due to uncertainties of the renewable energy availability, battery storage is adopted. So the electricity energy will be saved to the battery when the excessive electricity is generated and the stored energy will supply electricity to the load. Many Countries count on coal, oil and power being generated. As we know, frequent charging and discharging will shorten the life time of a battery.

With such a system, the problem is how to determine when the battery should be charged to provide the best energy efficiency and to prolong the life time. The proposed fuzzy control is to optimize energy distribution and to set up battery state of charge (SOC) parameters. A control strategy based on fuzzy control theory has been proposed to achieve the optimal results of the battery charging and discharging performance, and compared with a classical PI controller for performance validation.

II. SYSTEM DESCRIPTION

The Hybrid System is made up of solar PV array, wind turbine generator, Li-ion battery with the combination of storage batteries, etc. as shown in Figure-1.

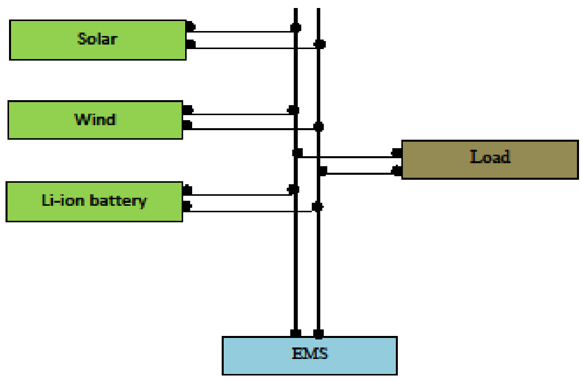


Fig.1 Configuration of the hybrid system

Rectifier is used in wind turbine to convert AC into DC. DC-DC converter is used in Solar PV to convert variable DC into constant DC. The AC Bus is connected to batteries through charge controller. Here battery will ensure reliability of the power system for all climatic conditions. Batteries will charge when the power generation from wind and solar PV system is in excess and it will discharge when the power generation from wind and solar PV is not enough to meet the load demand. As shown in Fig. 1, the system configuration includes three major blocks: power generator, energy storage equipment, utility load. The power generator typically includes PV panels, wind turbines. In the system, the output electrical power is provided to the loads with the highest priority. If the output electrical power is excessive for the demands of the loads, the surplus is used to charge the battery. Provided that the loads can't use up the whole output power, and the battery is fully charged, the superfluous power is then sent to the local distribution network if it exists. The battery works in three cases: disconnected from the system, charged by the system or discharge the supply power to the loads.

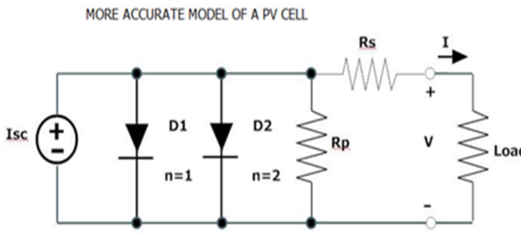
III. SYSTEM MODEL

To verify the accuracy of the designed controller, a dynamic model of the proposed system is necessary. It is basically done by distributed energy and energy storage components were mainly built in MATLAB/SIMULINK mathematical modules, based on equivalent circuits of the components. The model of each subsystem is explained in detailed manner below.

A. Modeling of solar cell

The equivalent circuit of solar cell, composed of photo-generated current source, internal series resistance and parallel resistance, is shown in Figure-2.

Fig.2 Equivalent circuit of a PV cell



The PV circuit in figure 2 can be equivalent to a constant current source in parallel with a diode and a shunt resistor. The output current I equals to the solar generated current I_{ph} subtracted by the current I_d through the diode and the current I_{sh} through the shunt resistor. The modeling is done on the basis of the following equations.

- Output current from the PV cell

$$I = I_{sc} - I_d \quad (1)$$

$$I_d = I_0^*(e^{q*V_d/(k*T)} - 1) \quad (2)$$

$$I = I_{sc} - I_0^*(e^{q*V/(k*T)} - 1) \quad (3)$$

where, I_{sc} is the generated current by absorbing solar energy, I_d is the current through the diode 1, I is the current through the load, I_0 is the current through the diode 2, q is the electron charge equal to 1.6e-19, V is the open circuit voltage, k is the Boltzmann constant equal to 1.38e-23, T is the temperature. Taking into account the R_s, R_p and recombination's, the equation becomes

$$I = I_{sc} - I_0^*(e^{q*V+I*R_s/(n*k*T)} - 1) - (V + I^*R_s)/R_p \quad (4)$$

where, R_s is the series resistance R_p is the shunt resistance.

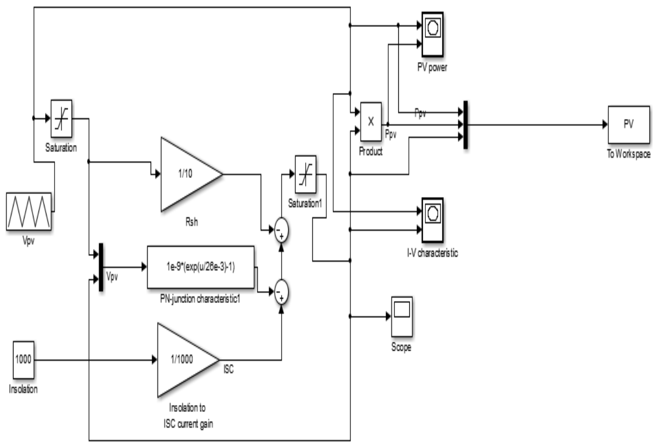


Fig.3 Modeling of a PV cell in MATLAB

Based on the modeling we obtain the IV and PV characteristics of the PV panel as shown in figures 4 & 5.

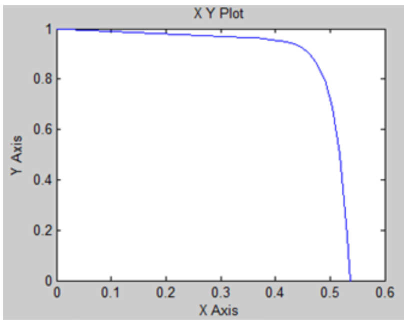


Fig.4 IV characteristics of PV cell

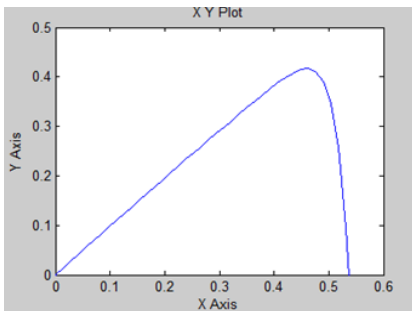


Fig.5 PV characteristics of PV cell

B. Modeling of wind turbine

The wind turbine model, consisting of the aerodynamic, drive train and electrical generator model. The wind turbine blades extract the kinetic energy in the wind and transform it into mechanical energy. According to aerodynamics principle, output power characteristic of wind turbine is described by equation (5) considering the main components of a wind turbine for modeling purposes consist of the turbine rotor, a shaft and gearbox unit, an electric generator, and a control system.

$$P_w = \frac{1}{2}.\rho A C_p v^3 \quad (5)$$

where P_W is the power generated by the wind turbine ρ is the density of gas in the atmosphere (kg/m), A is the cross-sectional area of a wind turbine blade m^2 , v is the wind velocity (m/sec), and Cp is the wind turbine energy conversion coefficient.

The wind turbine is normally characterized by its Cp-TSR characteristic, where TSR is the tip speed ratio(λ) and is given by equation (6),

$$\lambda = \frac{\omega_m R}{v} \quad (6)$$

where R and ω_m are the turbine radius and mechanical angular speed respectively.

The mechanical power of the wind turbine is converted into electric power by a synchronous machine which is most widely used in the wind power industry and so a PMSG was selected for this work. The set of equations of the asynchronous generator model is usually converted into a model related to an arbitrarily set reference frame: the machine is converted into the so-called dq$_0$ reference frame model.

The wind turbine based on PMSG is used for Simulink model as shown in Figure 6.

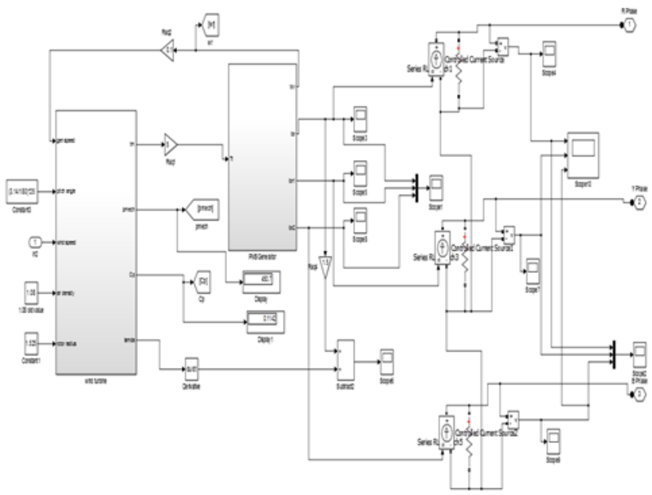


Fig.6 Simulink model of Wind Turbine

Wind speed is the most critical factor in wind speed generation. The simulated outputs are as shown in figure 7.

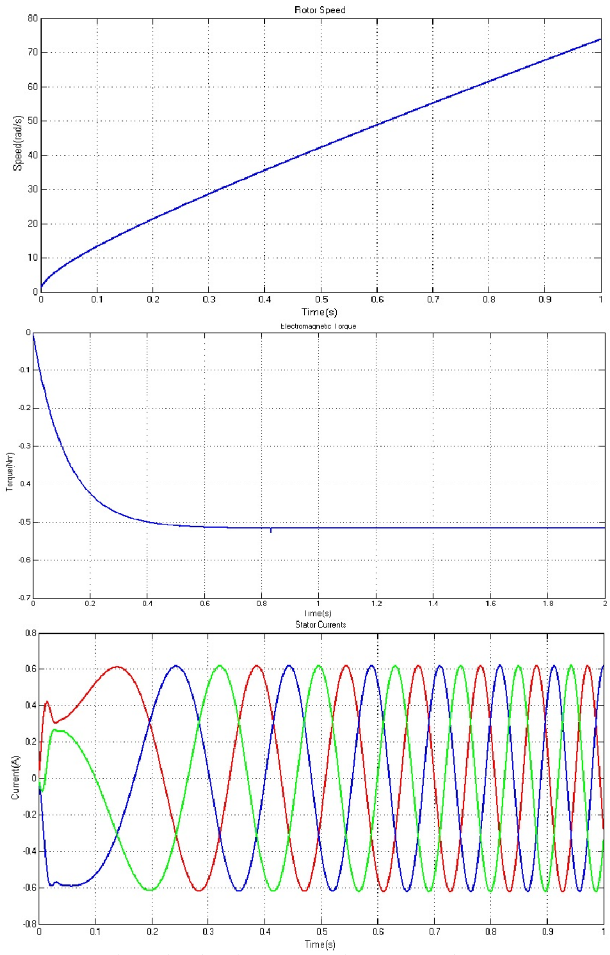


Fig.7 Simulated Rotor speed, Torque and Stator currents

C. Modeling of Lithium-ion battery

Among different battery technologies, Li–ion batteries represent a suitable option for hybrid energy storage systems due to their high energy density and efficiency, light weight, and good life cycle .The generic Li–ion battery model is used. The battery state of charge (SOC) is an indication of the energy reserve and is expressed by equation (7).

$$SOC = 100(1 - \frac{\int_0^t idt}{Q}) \quad (7)$$

where, i is the battery current (A) and Q is the battery capacity (Ah).

The discharge equation and the charge equation of the lithium-ion battery is given in equation (8) and (9).

$$f_1(iti*i) = E_0 - \left(K + \left(\frac{Q}{Q-it}\right) + it\right) + it + A + \exp(-B+it) \quad \rightarrow (8)$$

$$f_2(iti*i) = E_0 - \left(K + \left(\frac{Q}{Q+0.iQ}\right) + it\right) + it + A + \exp(-B+it) \quad \rightarrow (9)$$

where E_0 is initial voltage (V), K is polarization resistance (Ω), i* is low-frequency dynamic current (A), it is the battery extraction capacity (Ah), A is exponential voltage (V), B is exponential capacity $(Ah)^{-1}$.

Battery is simulated with constant discharge of 5 A for validation and observation of SOC variation. The results are shown in Figure 8. The battery voltage is easy to measure and implement in the circuit. From the simulated results, we can see the nonlinearity between voltage and SOC of the Li-ion battery. Therefore, the SOC parameter of batteries has been selected as the design factor instead of battery voltage in here.

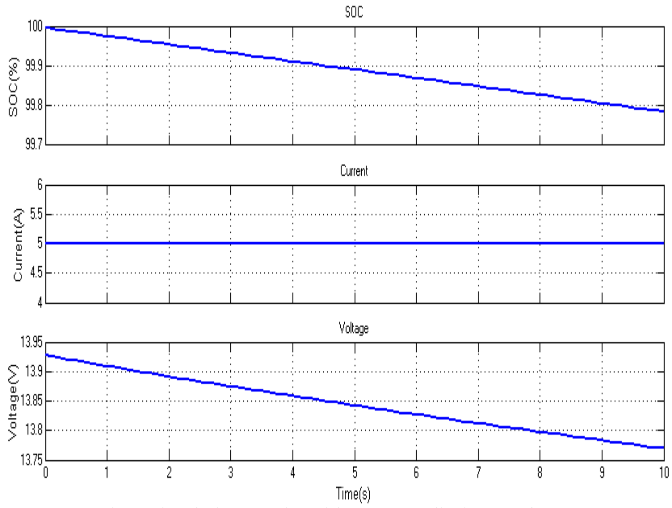


Fig.8 Simulation results with constant discharge of 5 A

IV. INTELLIGENT BATTERY MANAGEMENT SYSTEM

In general, to charge and discharge the battery frequently will shorten its life time, and it also should be avoided to Overcharge or insufficiently charge the battery. The wind Speed is always unstable naturally. With such a renewable energy generation system, the problem is when and how the battery should be charged to provide the best energy efficiency and to prolong the life time. If the output electrical power is excessive for the consumption of the loads, the surplus is provided to charge the battery. It is extremely difficult to determine whether the battery should be charged or to prevent it from being over or insufficiently charged based on certain traditional mathematical model, so systems based on empirical rules may be more effective. We employ fuzzy control strategy to solve this problem that will be discussed in detail in the following sections.

A. Fuzzy control

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

Fuzzy control theory is designed for the hybrid system to achieve the optimization of the system. The design criterion requires that both the photovoltaic device and the wind turbine are supplied by a maximum power point tracker to maintain the maximum operating point. The difference between actual load and total generated power is taken into account for Li-ion battery in charge and discharge modes. The life cycle and SOC of the battery are in direct proportion. To improve the life of the Li-ion battery, we can control and maintain the SOC of battery with fuzzy control. The fuzzy controller is applied in the proposed hybrid power supply system, as shown in Figure 9.

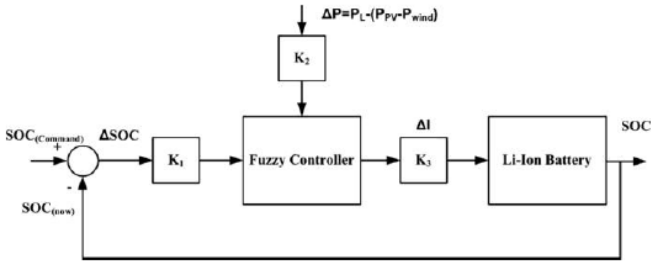


Fig.9 Block diagram of fuzzy control to maintain desired SOC of the battery

To obtain the desired SOC value, the fuzzy controller is designed to be in charging mode or discharging mode for the proposed hybrid system. The input variables of the fuzzy control are SOC and *P* and output variable is *I*.

B. Design of fuzzy controller

The definition of input and output variables are listed as follows:

$$\Delta SOC = SOC_{command} - SOC_{now} \quad (10)$$

$$\Delta P = P_L - (P_{wind} + P_{pv}) \quad (11)$$

The power difference *P* is between required power and the total generated power of the hybrid system. The generated power comes from solar power P_{pv}, wind turbine P_{wind} and power load *PL* for the proposed system. The input and output membership functions of fuzzy control contain five grades: NB (negative big), NS (negative small), ZO (zero), PS (positive small), and PB (positive big), as shown in Figs. 10 and 11. By input scaling factors K1 and K2 ,we can determine the membership grade and substitute it into the fuzzy control rules to obtain the output current for charge and discharge variance *I* of the Li-ion battery. If the *P* is negative, it means that the renewable energy does not provide enough energy to the load. Thus, the battery must operate in charging mode; if the SOC is negative, it means that the SOC of the battery is greater than the demand SOC. Thus, the battery must operate in discharge mode.

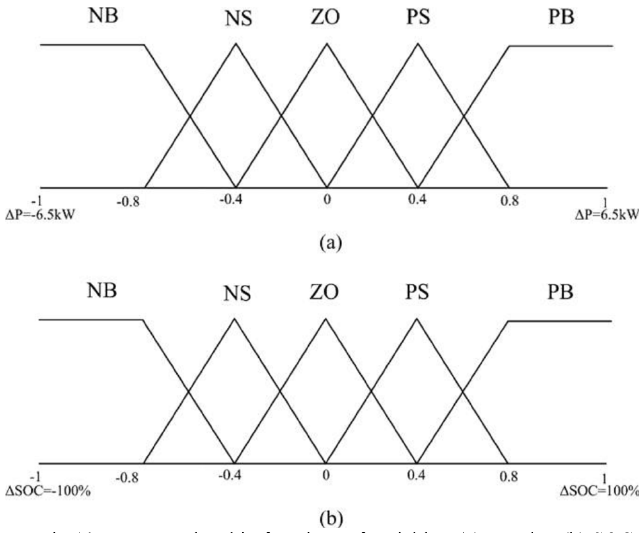


Fig.10 Input membership functions of variables: (a) P and (b) SOC

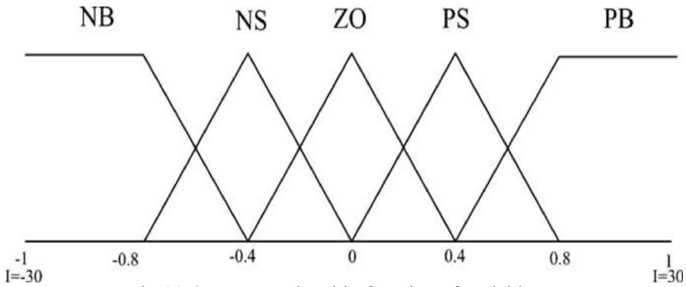


Fig.11 Output membership function of variable I

There are several methods to design a fuzzy controller. The design of fuzzy controller involves formation of membership function and rule base. Here, we have taken the rule base proposed by Mamdani for the simulation of the Fuzzy controller. These rules are shown in Table-1.

Table-1. 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

If variable *P* is NB and input variable SOC is NS (greater than the SOC command and the membership degree is small). However, the output variable *I* is NS (the degree of charging current is small) when the input variable *P* is NB (the amount of electricity to sell is large) and input variable SOC is PS (smaller than the SOC command and the membership degree is small).

V. DISCUSSIONS AND RESULT ANALYSIS

The dynamic model of the proposed hybrid system using MATLAB simulink is shown in Figure 12. Where the system consists of a solar module of 850 W, a wind turbine module of 5.8 kW, a Li-ion battery module, and a 6.5 kW load.

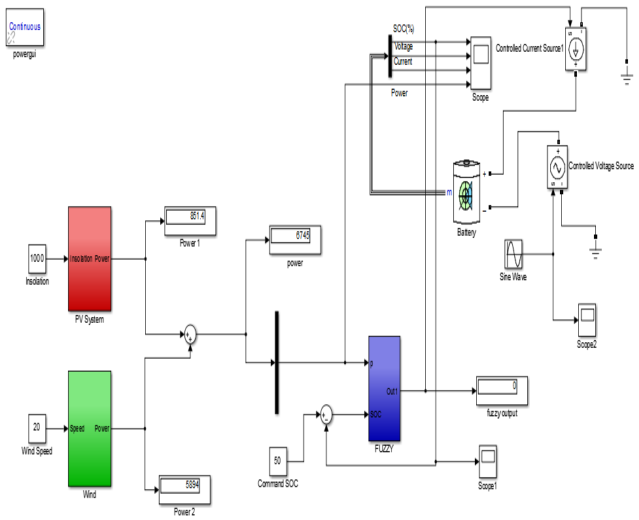


Fig.12 Dynamic model of the hybrid system using MATLAB Simulink

A. Fuzzy controller

This example verifies the accuracy of the proposed system with fuzzy controller that can maintain the SOC of the battery at a certain level whether initial value of the SOC is low or high. The Simulink model of Fuzzy Controller is shown in Figure 13.

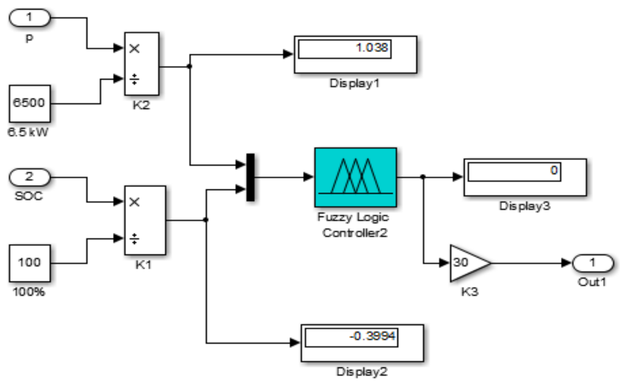


Fig.13 Simulink model of fuzzy controller

As shown in Figure 14, the fuzzy controller Li-ion battery SOC is maintained at 50% with an initial value of 10%. As shown in Figure 15, the fuzzy controller Li-ion battery SOC is maintained at 50% with an initial value of 90%.

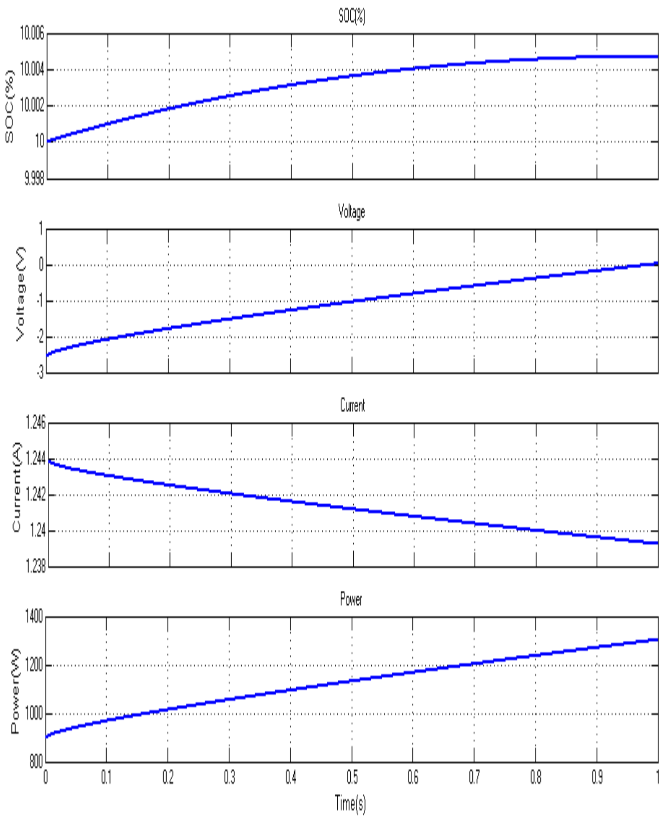


Fig.14 Simulation results with initial battery SOC at 10%

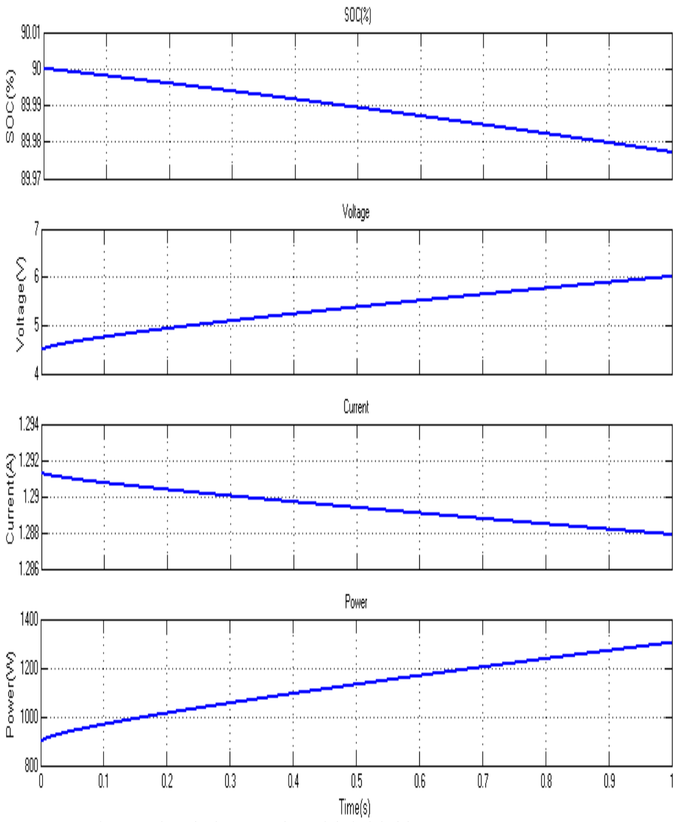


Fig.15 Simulation results with initial battery SOC at 90%.

VI. CONCLUSION

This paper presents the modeling, analysis, and design of fuzzy control to achieve optimization of a Battery management system for a Wind/ Solar hybrid system. According to the variation of the wind speed, solar isolation and the load demand, the fuzzy logic controller used to work effectively by turning on and off the batteries. Simulation results were obtained by developing a detailed dynamic hybrid system model. From the simulation results, the system achieves power equilibrium, and the battery SOC maintains the desired value for extension of battery life. The control process of the battery charging and discharging is non-linear, time-varying with time delays. It is a multiple variable control problem with unexpected external disturbances. Many parameters such as the charging rate, the permitted maximum charging current, the internal resistor, the port voltage, the temperature and moisture, *etc.* keep changing during the charging and discharging process can't be directly obtained, so it is difficult to achieve the optimal operation performance by using traditional control methods. A fuzzy control unit for battery charging and discharging used in a renewable energy generation system is developed. Simulation results based on fuzzy strategies show that the control unit has satisfied performance.

VII. REFERENCES

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