Journal of Multidisciplinary Engineering Science and Technology (JMEST)
ISSN: 3159-0040
Vol. 3 Issue 2, February - 2016

Fuzzy Logic Energy Management for a Renewable Hybrid Energy System

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***Abstract*— This paper presents power management for a PV-Wind hybrid energy system with battery storage. The hybrid system is modelled using Matlab/Simulink environment. A management system using Fuzzy logic Control has been developed to control the energy flow between solar array, wind turbine generator and battery bank. The main aim is to provide reliable power from the renewable resources and battery storage to meet the load demand. The controller ensures the load is met and protects the batteries from overcharge and deep discharge states. The effectiveness of the proposed controller is confirmed by the simulation results.**

Keywords*— *Fuzzy Logic Control, Solar, Wind, Battery (key words)

I. INTRODUCTION

Electricity plays a crucial role in the social and economic development of society. Despite the importance of electricity in today's life, a significant part of the world's population still lacks access to electricity. Most of these non-electrified regions are found in developing countries. These areas can be electrified by extending the grid or by use of alternative energy sources. Since grid cannot be extended to all the regions because of the huge costs involved, there is huge potential for solar and wind resources to provide sustainable and reliable power to these areas. The abundant energy available can be harnessed and converted to clean electricity to provide sustainable and low-cost power for electrification of villages, schools, hospitals, police stations and base stations in off-grid and remote areas.

Renewable energy sources are abundant in almost every region on the earth. This is the main reason why many countries are now putting more emphasis on the development of these forms of energy. Harnessing of renewable energy resources will help meet growing electricity demand, improve access to electricity and enhance energy security [1]. The main advantage of renewable resources is that they are sustainable and environmentally friendly. They are sustainable in the sense that they can meet our present power needs without compromising the ability of future generations to meet their own power needs with little or no adverse effect on the environment.

Hybrid Energy Systems integrate renewable energy sources such as wind, Solar PV, mini/Pico-hydro, fuel cells, biomass and diesel generators to provide electrical power. Combining renewable energy resources improves efficiency, ensures power reliability and is cost effective as the different resources complement one another. These systems can be connected to the grid or operated independently in remote areas. Hybrid systems also offer the opportunity to expand the system in future to cater for increasing electricity demand [2]. Different combinations of renewable sources have been tested and used in different parts of the world for electrification of remote areas [3].

However, a major problem common to solar and wind generation is their intermittent nature which is dependent on weather and climatic changes. The variations of their output may not match the time distribution of the load demand resulting in reduced system's energy performance[4]. Significant improvements of the performance of hybrid systems can be achieved through use of proper energy management techniques.

Conventional control methods require a mathematical model for the dynamic system to be controlled. The mathematical model is then used to construct a controller. However, in many practical situations it is not always feasible to obtain an accurate mathematical model of the controlled system. On the other hand, Artificial intelligent (AI) control offers a way of dealing with modeling problems by implementing control laws expressed in non-formal linguistic terms derived from expert knowledge [5,6]. Fuzzy logic control is ideal for applications where a mathematical model is either known or not known especially with problems of varied parameters and nonlinear models [7].

The main aim of this paper is to develop an intelligent controller that responds to the variations in the renewable resources as well as the load demand. A Fuzzy Logic Controller (FLC) to manage the energy in the hybrid system is developed in this paper. The purpose of the fuzzy logic controller is to guarantee load power under different prevailing conditions or operating modes while maintaining the State of charge(SOC) of the battery in the desirable range to avoid damage.

In the following sections, the structure of the hybrid system is described and energy management for the hybrid energy system are discussed. The proposed control strategies are then verified by simulation.

II. SYSTEM DESCRIPTION

The system under study consists of a solar array, a wind generator and a battery bank as shown in Fig.1. The solar and wind generator are the primary sources of power and the surplus is stored in batteries to provide power during periods of no output from the renewable sources.

There are various methods for integrating hybrid energy systems such as DC-coupled, AC-coupled and mixed-coupled systems. In the DC-coupled systems, the different electrical resources are connected to the DC bus through appropriate power electronic circuits. In the AC-coupled system, the different energy resources are coupled to the AC bus whereas the mixed-coupled system incorporates both the DC and AC bus. This means the different energy resources can be connected to the DC bus or AC bus. The mixed-coupled topology offers a higher energy efficiency and reduced cost and has been selected for this study.

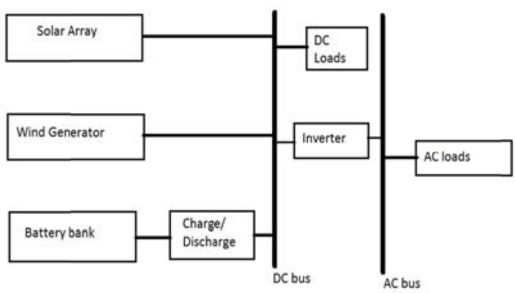

Fig.1 Block diagram of the hybrid system

III. MODELLING OF HYBRID SYSTEM COMPONENTS

The dynamic models describing the behavior of each of the hybrid system components are described in the following subsections. The models have been developed in the Matlab\Simulink environment. The hybrid energy system consists of a PV array, wind turbine and a Lead-acid battery bank.

A. *PV Model*

The model of the PV array is designed based on the mathematical model developed by Villalva et al [8]. The basic equation that mathematically describes the I-V characteristic of the ideal photovoltaic cell is;

$$I = I_{PV,Cell} - I_{0,Cell}\left[exp\left(\frac{qV}{akT}\right) - 1\right] \quad (1)$$

Where $I_{PV,Cell}$ is the current generated by the incident light, I_d is the Shockley diode equation, $I_{0,Cell}$ is the reverse saturation or leakage current of the diode, q is the electron charge, k is the Boltzmann constant, T is the temperature of the *p-n* junction, and a is the diode ideality constant. Fig. 2 shows the equivalent circuit of the ideal photovoltaic cell.

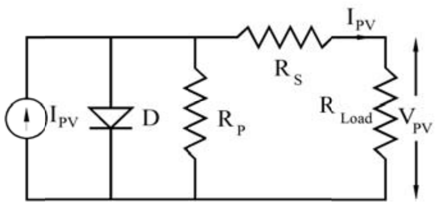

Fig.2 Equivalent circuit of a PV cell

The equation representing the basic PV cell does not represent the *I–V* characteristic of a practical PV array. In practice arrays are made of several connected PV cells and the characteristics at the terminals of the PV array requires the inclusion of additional parameters to the basic equation.

$$I = I_{PV} - I_0\left[exp\left(\frac{V+R_S I}{V_t a}\right) - 1\right] - \frac{V+R_S I}{R_P} \quad (2)$$

Where I_{PV} and I_0 are the photovoltaic (PV) and saturation currents respectively of the array and V_t is the thermal voltage of the array with N_S cells connected in series. R_S is the equivalent series resistance of the array and R_P is the equivalent parallel resistance.

B. *Wind generator model*

The power output of a wind turbine can be estimated based on the manufacturer's power curve [9]. Power curves specify the performance of a wind turbine and give the relationship between the wind speed at the hub height and the average output power during an average time interval. The power extracted from the wind usually has a mean value during a specific time interval with variations about the mean due to changing wind speeds. Wind speeds are normally measured at a height of 10m using anemometers. To calculate the power output, the speeds have to be corrected to the hub height of the selected turbine. The power law profile has been used to adjust the wind speed from the anemometer height to hub height.

The power law profile assumes that the ratio of wind speeds at different heights is given by the following equation[10]:

$$\frac{V(Z_{hub})}{V(Z_{anem})} = \left(\frac{Z_{hub}}{Z_{anem}}\right)^{\alpha} \quad (3)$$

Where $V(Z_{hub})$ is wind speed at the hub height of the wind turbine [m/s], $V(Z_{anem})$ is the wind speed at anemometer height [m/s] , Z_{hub} is the hub height of the wind turbine [m], Z_{anem} the anemometer height [m] and α is the power law exponent. The power law exponent is a parameter that characterizes the roughness of the surrounding terrain.

The power output of the wind turbine is then calculated by performing an air density correction to the power calculated at standard temperature and pressure as indicated by the manufacturer's power curve as;

$$P_{WTG} = \left({}^{\rho}/_{\rho_0}\right) * P_{WTG,STP} \quad (4)$$

Where P_{WTG} is the wind turbine power output [Watts], $P_{WTG,STP}$ is the wind turbine power output at standard temperature and pressure [Watts], ρ is the actual air density calculated based on altitude of site [kg/m3], ρ_0 is the air density at standard temperature and pressure (1.225 kg/m3). Fig. 3 below shows power curves for selected wind turbines.

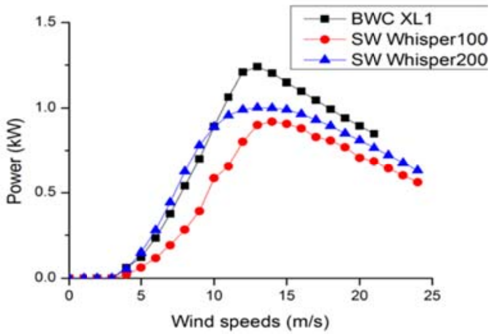

Fig. 3 Selected wind turbine power curves

C. Battery model

In this section, the mathematical modeling of the Lead acid battery bank used in the simulation program is introduced. The battery capacity at any instant is related to the previous state of charge and the net energy into or out of the battery depending on whether the battery is being charged or discharged [11].

During charging:

$$C_{bat}(t) = C_{bat}(t-1) * (1-\sigma) + \left(E_{PV}(t) + E_{WTG}(t) - \frac{E_L(t)}{\eta_{inv}}\right)\eta_{batt} \quad (5)$$

During discharge:

$$C_{bat}(t) = C_{bat}(t-1) * (1-\sigma) + \left(\frac{E_L(t)}{\eta_{inv}} - E_{PV}(t) + E_{WTG}(t)\right)\eta_{batt} \quad (6)$$

Where $C_{bat}(t)$ and $C_{bat}(t–1)$ are the available battery bank capacity at time *(t)* and *(t–1)* respectively, σ is self-discharge rate of the battery bank, $E_{PV}(t)$ and $E_{WTG}(t)$ are the energy generated by the solar and wind generators respectively while $E_L(t)$ is the load demand at time *t*, η_{inv} and η_{batt} are inverter and battery efficiency respectively. Since the simulation times are short in terms of seconds, the battery self-discharge is assumed to be zero while the efficiencies are taken as unity.

IV. FUZZY LOGIC CONTROL

The Fuzzy Logic graphical user interface (GUI) toolbox implemented by MATLAB/Simulink has been used in this study. It provides graphical tools, Matlab functions and a Simulink block for analyzing, designing and simulating systems based on fuzzy logic. The fuzzy logic toolbox lets you model complex system behaviors using logic rules and then implement these rules in a fuzzy inference system.

Fuzzy logic(FL) is synonymous with the theory of fuzzy sets that relates to classes of objects with uncertain boundaries in which membership is a matter of degree. The basic concept underlying FL is that of a linguistic variable, that is, a variable whose values are words rather than numbers. In effect, much of FL may be viewed as a methodology for computing with words rather than numbers. Although words are inherently less precise than numbers, their use is closer to human intuition. Furthermore, computing with words exploits the tolerance for imprecision and thereby lowers the cost of solution in terms of computational time and memory required[12].

The main strength of fuzzy logic is mapping an input space to an output space. The primary mechanism for achieving this is a list of IF-THEN statements called rules. The fuzzy inference system is a method that interprets the values in the input vector and assigns values to the output vector. It includes five parts: fuzzification of the input variables, application of the fuzzy operator (AND or OR) in the antecedent, implication from the antecedent to the consequent, aggregation of the consequents across the rules and lastly defuzzification

A. Fuzzy logic controller design

The Fuzzy Logic Controller model is constructed using a Mamdani fuzzy inference system with two inputs and three outputs. The inputs are the batteries state of charge(SOC) and the net power(Pnet) which is the difference between the generated power and the load demand. The outputs are three signals to either charge or discharge the batteries or to dump excess power to a dummy load. The net power has six membership functions where the linguistic terms for the membership functions are high deficit(HD), medium deficit(MD), small deficit(SD), small surplus(SS), medium surplus(MS) and high surplus(HS.) The batteries SOC has three membership functions representing a low(L), medium(M) or high(H) SOC. The outputs for charging and discharging both have two membership functions which are STOP or CHARGE(C) for battery input(BI) and STOP or DISCHARGE(D) for battery output(BO). The dump power(DP) has two membership functions; either ON or OFF.

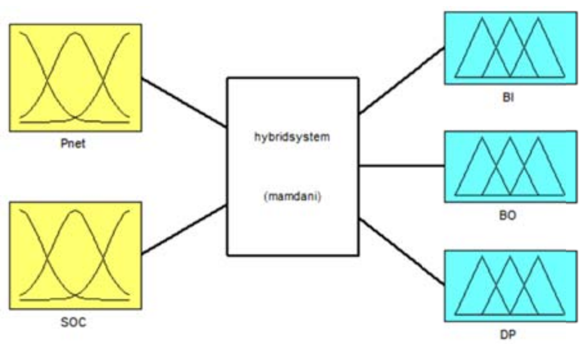

Fig.4 Block diagram of the Fuzzy logic controller

The FLC relates the outputs to the inputs using a list of if-then statements called rules. The if-part of the rules describes the fuzzy sets of the input variables while the then part describes the fuzzy sets of the outputs. Eighteen rules have been written that closely describe various operational conditions of the hybrid system. The fuzzy rules are;

1-3: IF Pnet is HD and SOC is L\M\H THEN BI is STOP and BO is STOP\D\D and DP is OFF

4-6: IF Pnet is MD and SOC is L\M\H THEN BI is STOP and BO is STOP\D\D and DP is OFF

7-9: IF Pnet is SD and SOC is L\M\H THEN BI is STOP and BO is STOP\D\D and DP is OFF

10-12: IF Pnet is SS and SOC is L\M\H THEN BI is C\C\STOP and BO is STOP and DP is OFF\OFF\ON

13-15: IF Pnet is MS and SOC is L\M\H THEN BI is C\C\STOP and BO is STOP and DP is OFF\OFF\ON

16-18: IF Pnet is HS and SOC is L\M\H THEN BI is C\C\STOP and BO is STOP and DP is OFF\OFF\ON

The rules are evaluated at random and the ones that satisfy the prevailing condition are fired. The output of the FLC depends on which rules are fired at any instant any time. The following figures show the surface view for the outputs.

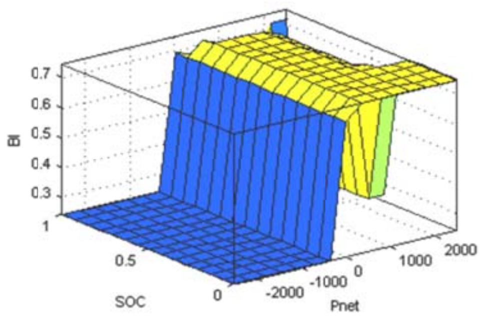

Fig.5 FLC surface for battery input

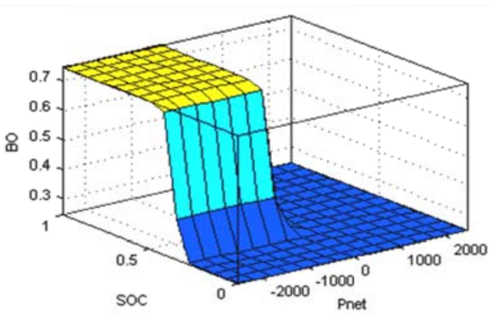

Fig.6 FLC surface for battery output

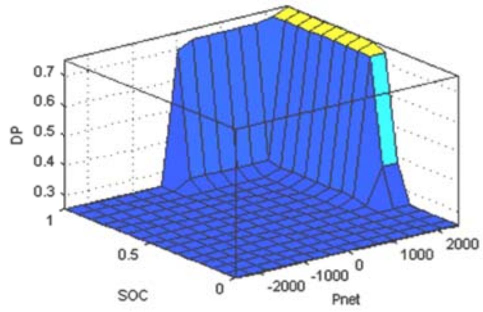

Fig.7 FLC surface for dump power

V. SIMULATION RESULTS AND DISCUSSION

The Fuzzy Logic Controller (FLC) manages the energy in the hybrid system by continuously monitoring the net power and the batteries SOC. The purpose of the fuzzy logic controller is to guarantee load power under different prevailing conditions or operating modes and at the same time protect the batteries from deep discharge states and overcharging.

Mode 1: This case deals with an excess of generated power from the renewable resources. The battery is assumed fully charged at the beginning. Results of the simulation are shown in Fig. 8.

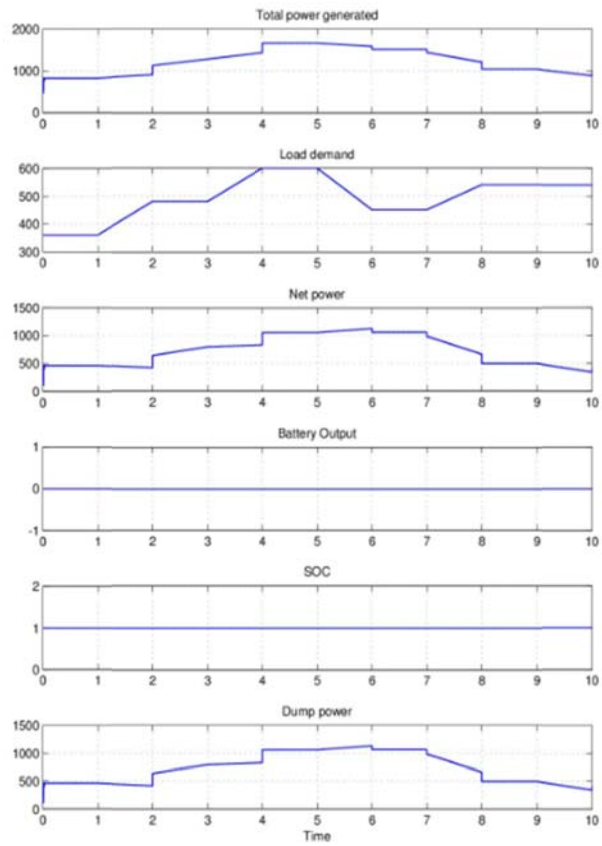

Fig.8 Simulation results for mode 1

From the simulation, the power generated at all times is greater than the load demand. This means the system has excess power generated. Batteries are not employed in this mode as can be seen from the battery output curve and the SOC remains 1 throughout. All the excess power is therefore delivered to a dump load

Mode 2: This case deals with excess and shortage of power generated by the renewable resources. The battery is assumed fully charged at the beginning. Results of the simulation are shown in Fig. 9.

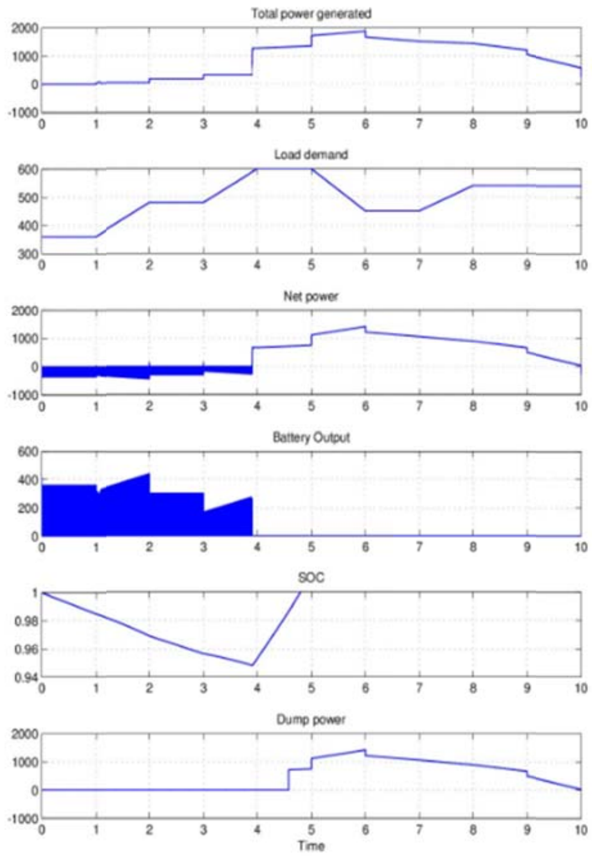

Fig.9 Simulation results for mode 2

(0-2s): At this point there is no generation from the renewable sources such that the net power is negative and the batteries supply the load. As the battery is discharging, the SOC of the battery falls to about 0.97.

(2-4s): There is little generation from the renewable resources but not enough to cover the load. The batteries SOC falls further as the batteries is still employed to cover the difference between the generated power and the load demand.

(4-6s): The power generated increases and is enough to completely supply the load demand. The generated power exceeds the load demand and the excess power is now used to charge the batteries. As the batteries near full capacity the excess power is the supplied to the dump load.

(6-10s):} The generated power remains high and continues to supply the load demand while the excess power is delivered to the dump load. The batteries remain fully charged as they are not employed to cover the load demand.

Mode 3: This case deals with no power generated by the renewable resources. The battery is assumed fully charged at the beginning. Results of the simulation are shown in Figure 8.

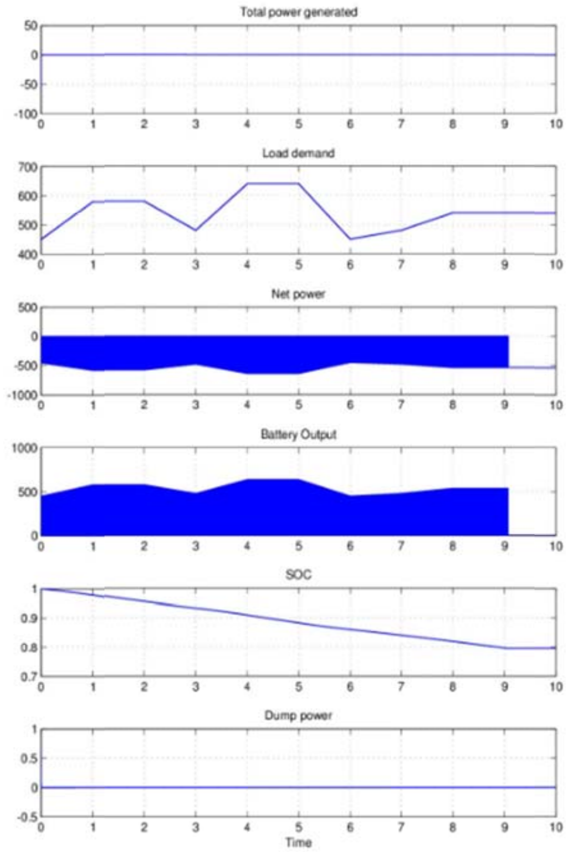

Fig.10 Simulation results for mode 3

From the simulation, there is no power generated by the renewable resources. This means there is a deficit of power and batteries are employed to deliver power to the load. In this mode as can be seen from the battery output curve and the SOC, the batteries supply the load until the SOC falls below 0.8 at which point the batteries are disconnected. The depth of discharge for this study was taken to be 20% and this shows the controller is able to protect the batteries from deep discharge states.

VI. CONCLUSION

A Fuzzy Logic controller has been proposed for the power management of a renewable hybrid energy system consisting of a PV array , wind turbine generator and battery bank. The controller continuously monitors the load demand, net power and the batteries SOC to ensure the load demand is met under different operating modes. The proposed controller has been implemented in Matlab/Simulink environment to check the effectiveness of the proposed controller under different operating conditions. Results indicate that the FL controller provides uninterrupted power to the load from either the renewable generators or the batteries, excess power is also delivered to a dump load in case excess power is generated. It was concluded that the controller effectively manages the power in the renewable hybrid energy system.

ACKNOWLEDGMENT

The authors would like to thank the National Commission for Science, Technology and Innovation (NACoSTi) of Kenya for their support towards this project.

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