Energy management system for a remote renewable fuel cell system

Doudou N. Luta, and Atanda K. Raji

Abstract— This study proposes an energy management algorithm for a renewable fuel cell system aiming to maintain the balance between the supply and the demand of a remote community load. In most cases, such communities receive power from off-grid systems due to their location as opposed to main electric utilities. For years diesel generators have been the favourite power source for these places, however, the trend is now on the use of renewable off-grid systems. Different renewable off-grid systems can be considered depending upon the available renewable resources. However, all of them required energy storage facilities to deal with the unpredictable nature of their outputs power. This paper focuses on a system including a PV array, an electrolyser, a hydrogen tank and a Proton exchange membrane (PEM) fuel cell. The objective is to develop an energy management system to reduce power losses and to maintain the balance between the supply and the demand depending on the availability of power. Matlab/Simulink software is used to model and simulate the system. The scenario presented in this study shows that the proposed energy management algorithm permits to balance the share of energy between the PV array and the fuel cell to the load.

Index terms— **Energy management, Hydrogen & Fuel cell, Microgrid, PV system, Renewable energy.**

1 INTRODUCTION

Power utilities in several countries are established around large centralised power plants using either fossil fuels or nuclear reactants as the principal source of energy. These units are generally situated far from cities and involve transmission and distribution systems to convey power to the consumers. Alternative solutions need to be proposed to allow energy access to remote areas. In Africa for instance, such areas are usually subjected to severe poverty and little development activities [1].

Islanded or off-grid systems are the most cost-effective solutions as opposed to the grid extension. These systems can provide power for different applications in these areas including houses, community services, water pumping and purification systems, telecommunications, etc.

In a typical islanded power system, the electricity can be provided either from a single or multiple source which can be renewable for instance wind turbine, photovoltaic panels, and micro hydro, fuel cell, etc. or non-renewable. In some countries, diesel generators are the favourite types for remote areas power supply. However, these technologies can impose economic and social problems on the local population. Furthermore, diesel engines in general, are the major contributors of greenhouse gas emissions [2]. As a result, the trend is now on the use of renewable islanded systems for remote areas power supply.

Furthermore, these technologies can provide benefits for remote areas ranging from energy access and security, and socioeconomic development, on top of creating opportunities for jobs creation, and contributing in reducing poverty.

Renewable islanded power systems are classified in three topologies based on the energy technology. These are topologies are:

- single energy technology power system,
- hybrid power system,
- single technology power system with energy storage system

Of the three topologies, renewable single energy technology power system is the less reliable system due to the intermittent nature of renewable generators. Deploying renewable hybrid configuration can enhance the system flexibility as the power supply is based on two or more sources. Adding an energy storage technology to the system can further increases the reliability of the system [3]. Different hybrid energy systems can be considered depending upon the available renewable resources.

This paper focuses on a system including a PV array, an electrolyser, a hydrogen tank and a Proton exchange membrane (PEM) fuel cell.

Generally, in such configuration, the PV unit operates as the primary source to supply power to the load and any excess is used to produce hydrogen via the electrolyser. This hydrogen is then stored into a tank and used to generate power through the PEM fuel cell whenever the PV array generate less or zero power to meet the load demand. The challenging side when integrating different energy sources is how to control each of them. This is achieved through an energy management strategy. The most common strategies use rule, filtration and fuzzy logic approaches. Reported energy management algorithms focus on aspects such as preventing the battery from deep discharge, reducing the peak power demand, charging/discharging cycle and dynamic stress level of battery, minimizing operational cost of a system, maintaining stable DC voltage, frequency regulation, reducing the loss of power supply possibility, reducing the operation and maintenance cost and improving the system efficiency.

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In this study, the focus is on maintaining the balance between the supply and the demand of a remote renewable fuel cell system. Matlab/Simulink software is used to model and simulate the system.

The rest of the paper is structured as follows, the next section focuses on the system description and modelling, section three presents and discusses the results and the last section concludes the investigation

2 SYSTEM DESCRIPTION AND MODELLING

2.1 System description

A layout of a renewable fuel cell system is shown in Fig 1; the system includes components such as photovoltaic array, a fuel cell stack and an electrolyser, a hydrogen tank and power conditioning and management unit. The role of power management unit is to enable the coordination between the different energy sources involved.

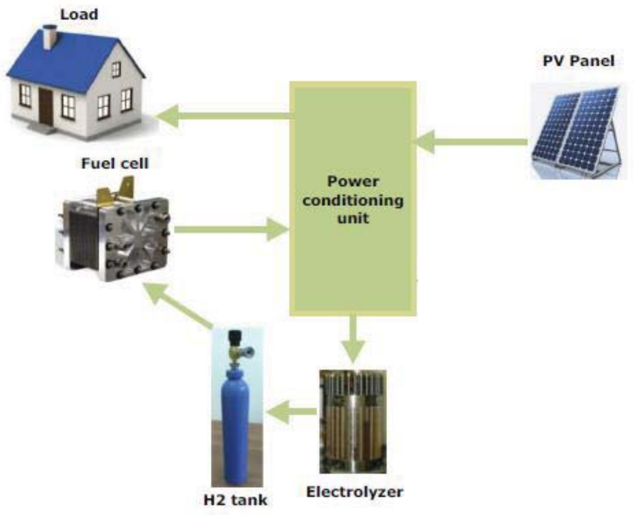

Fig. 1. Renewable fuel cell layout [4]

The system operates such that depending on the available solar resources, the PV generate power to meet the load and produce hydrogen through the electrolyser. The produced hydrogen is then stored into a tank and used whenever needed. The load considered in this study is of a community building situated in a remote area. The parameters of components used in this investigation are given in Table I.

TABLE I. COMPONENT CHARACTERISTICS

PV generator	
Maximum power	4.5 kW
Maximum voltage	220 V
Electrolyser	
Nominal voltage	110 V
Rated capacity	3 kW
H2 Tank	
Volume	5 m^3
Fuel cell	
Nominal voltage	24 V
Rated capacity	1.26 kW
Load	9.6 Ω

The PV system is designed to meet the 1.056 kW load demand of the community facility (9.6 Ω suppled at 110 V), as well as provides 3 kW for hydrogen production.

2.2 System modelling

2.2.1 *Photovoltaic system*

Photovoltaic system is built around photovoltaic cells, the most used cell model is based on a one diode model depicted in the equivalent circuit in Fig. 1. This circuit consists of a photon represented by a current source and a p-n junction represented by an anti-parallel diode in parallel with a shunt and series internal resistances R_S and R_P. The parameters in the equivalent circuit are defined as follows: Series resistance R_S express the losses caused by the electrical contact and the resistivity of the cell materiel, the shunt resistance R_p is related to the losses generated by the p-n junction, Diode current I_D is the current in the diode when it is directly polarised, photovoltaic current I_{Ph} is the current generated by the solar cell due to the sunlight incidence into it., Output current I is the existing current at the terminals of the solar cell.

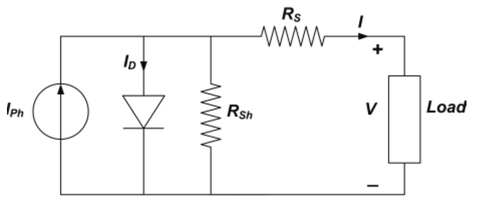

Fig. 2 Photovoltaic cell model

Based on the circuit in Fig. 2, the output characteristics of a photovoltaic cell is described as:

$$I = I_{Ph} - I_S\left\{exp\left(\frac{V+IR_S}{A}\right) - 1\right\} - \frac{V+IR_S}{R_{Sh}} \qquad (1)$$

Where, A is the thermal voltage in V, m is the ideality factor, k is the Boltzmann's constant in J/K, T_c is the cell temperature in K, q is the electric charge and V is the voltage.

2.2.2 *Fuel cell*

The type of fuel cell selected in this study is a PEMFC (proton exchange membrane fuel cell) which is the most used and most available fuel cell in the market [5]. The model adopted in this study is an electrical model including both the dynamic and the steady state behaviour of a PEMFC.

Assuming that the fuel cell is supplied with pure hydrogen and oxygen gases, the temperature of the stack is controlled and unchanged at steady state, the system obeys the Nernst equation, the water by-product from the fuel cell stack is liquid, the gases used are ideal and obey the ideal gas law and a shocked orifice is assumed at the exhaust, the output voltage of the fuel cell stack is as follows:

$$V_{FC} = N\left(E_{Nernst} - E_{Drop}\right) \qquad (2)$$

Under load condition, the fuel cell voltage drops to a value lower the Nernst voltage thanks to the activation voltage drop V_{act} caused by the slow nature of the reaction happening in the surface of the electrodes, ohmic drop voltage V_r caused by the resistance in the electrolyte, electrodes and all the interconnections, and the concentration voltage drop V_c due to the diminution of reactant gases in the electrodes while the reaction is continuing.

The voltage loss in a fuel cell is expressed in Equation 3 as:

$$E_{Drop} = V_{act} + V_r + V_c \tag{3}$$

Nernst voltage expressed as a function of the stack temperature and partial pressions is given by Equation 4 as:

$$E_{Nersnt} = E^0 + \frac{RT}{2F} ln\left(\frac{P_{H_2}(P_{O_2})^{\frac{1}{2}}}{P_{H_2O}}\right) \tag{4}$$

Where E^0 is the Electromotive force (EMF) at 298°K and 1 atm which are the standard conditions, P_{H_2}, P_{O_2} and P_{H_2O} are the partial pressions of hydrogen, oxygen and water respectively, and R, T and F are the universal gas constant, stack temperature and Faraday constant respectively.

By assuming that the partial pression of water is 1 atm, Equation 5 will be expressed as:

$$E_{Nersnt} = E^0 + \frac{RT}{2F} ln\left(P_{H_2}(P_{O_2})^{\frac{1}{2}}\right) \tag{5}$$

2.2.3 *Electrolyser*

Hydrogen can be produced in different ways, some of the methods used involve removal of hydrogen from hydrocarbons and the production from the steam reforming of natural gas. Hydrogen can also be produced through electrolysis of water. In such a case, the electrolyser is the machine used for the conversion.

The model of electrolyser used in this study is defined by its steady-state electrochemical operation. In this case, it is considered that the operations of both electrolyser and fuel cell are opposed.

The voltage in an electrolyser cell is expressed by Equation 6 as [6]:

$$elV = V_{rev} + \frac{r_1 + r_2 T}{A} I_{el} + slog\left(\frac{t_1 + \frac{t_2}{T} + \frac{t_3}{T^2}}{A} I_{el} + 1\right) \tag{6}$$

Where V_{rev} = 1.2297 V is the reversible ideal potential, T the operating temperature in °K, I_{el} is the current of the cell in A, r_1= 8,05 x 10-5 Ω is an ohmic parameter, r_2=-2,5 x 10-7 (Ω m^2)/ °C is also an ohmic parameter, t_1=-0.1002 m^2 /The coefficient of over-voltage, t_2=8,424 (m^2 °C)/A is another coefficient of over-voltage, t_3=247,3 (m^2 °C^2)/A is the third coefficient of over-voltage, and s=0.185 V is the coefficient of the electrode over-voltage

In an electrolyser, the production if hydrogen follows the Faraday's law hence it is directly proportional to the current. The equation that describes the Hydrogen production is given by:

$$\overset{\circ}{m}_{H_2} = 2\overset{\circ}{m}_{O_2} = \overset{\circ}{m}_{H_{20}} = \eta_F \frac{N_s.I_{el}}{n.F} \tag{7}$$

Where N_s is the number of cells in series, I_{fc} is the current in the electrolyser cell in A, n is the number of electrons per mole, F=96485.309 C/mol is the Faraday's Constant and η_F is the Faraday's efficiency.

2.2.4 *Hydrogen storage tank*

Hydrogen can be stored using different methods, the most common storage approaches of storing hydrogen include compressed hydrogen storage, liquid hydrogen storage, and metal hybrid storage.

In this study, the Hydrogen stored in the tank is assumed to be in a compressed form and follows the Ideal Gas Law equation given by [7]:

$$P.V = nRT \tag{8}$$

Where P is the hydrogen pressure in Pa, V is the tank volume in m^3, T is the temperature in °K, n is the stored number of moles in mol, R=8.31451 J/ (K mol) is the Universal Gas Constant.

3 RESULTS AND DISCUSSION

The model of the investigated shown in Fig. 4 was simulated using Matlab/Simulink environment based on the energy management algorithm depicted in Fig. 3. This algorithm is such that the PV array operates as the primary source to meet the load demand. The fuel cell system intervenes only if the PV array does not generate or generate less power than the load demand. In the event that both the PV array and the fuel cell generate no or less power than the load demand, the system will be shutdown. The system is simulated for a duration of 150 seconds and the results for the considered scenarios are displayed in Fig. 5, Fig. 6 and Fig. 7. The scenarios considered is that of the PV array supplying power to the load for the first 80 seconds while producing hydrogen and the fuel cell being switch-off. For the remaining 70 seconds, the PV array is not generating power; the load is fully met by the fuel cell.

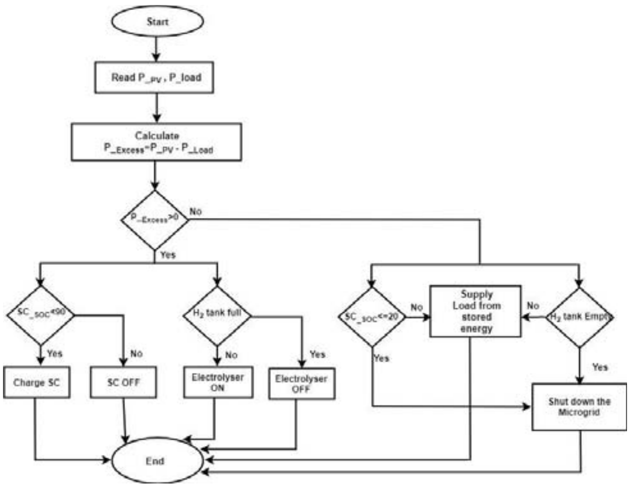

Fig. 3. Energy management algorithm

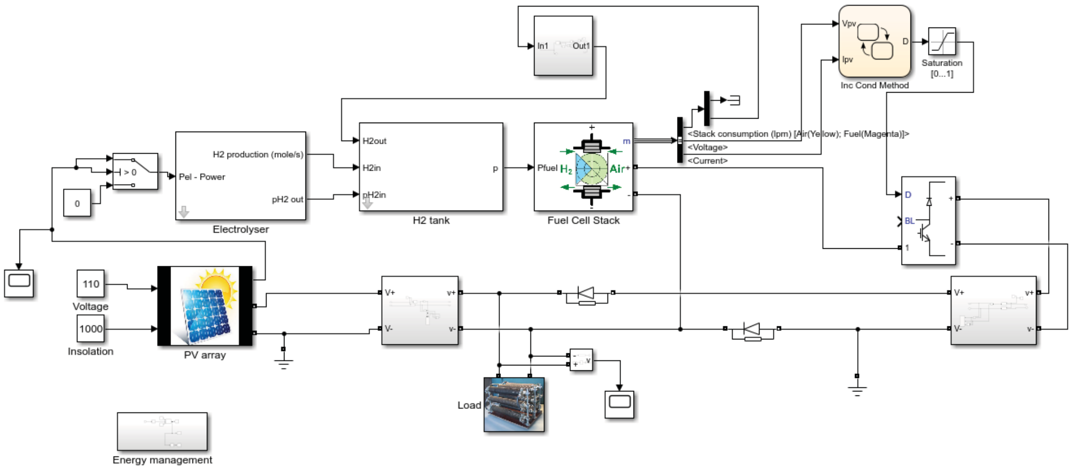

Fig. 4. System model

In this study, it was assumed that the hydrogen tank is half-full at the beginning of the simulation. While the PV array is supplying power to the load, the hydrogen produced in the electrolyser and that consumed in the fuel are shown in Fig. 5. No hydrogen is fed into the fuel cell at that stage (see Fig. 5a), as the load is receiving its power from the PV array (see Fig. 5). On the other hand, the electrolyser produces hydrogen depending on the excess energy generated from the PV array (see Fig. 5a). At time t=80 seconds the energy from the photovoltaic system becomes unavailable (see Fig. 6), causing the fuel cell to take over the supply to order the meet the load demand. The fuel cell is connected to the load through a boost converter as the load voltage is 110 V and that of the fuel cell is 24 V.

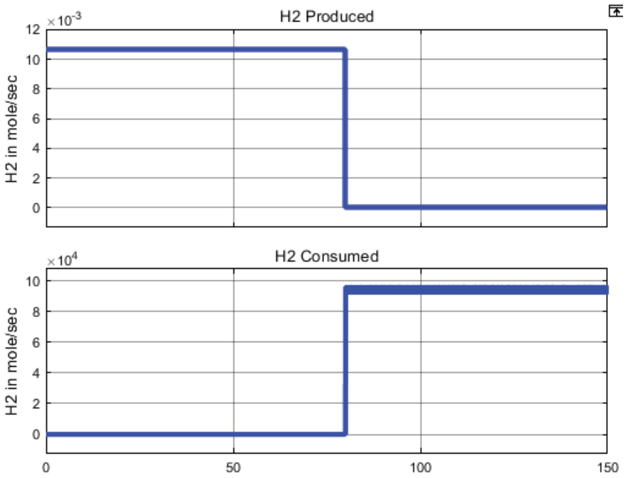

Fig.5 Hydrogen produced and consumed

The PV array voltage, current and power are depicted in Fig. 6. The output voltage at the PV array terminal is 110 V as shown in Fig. 6a, this voltage drops to zero at time t=80 seconds as at that time the load is supplying the fuel cell using hydrogen stored into the tank.

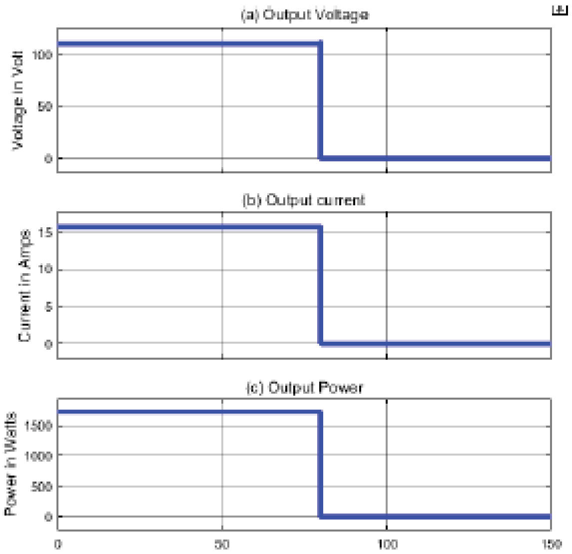

Fig. 6 PV array output characteristics

The current to feed the load is about 11.45 amperes (see Fig 6b), thus the power required to feed the load is 1259.5 watts (see Fig. 6c). The voltage at the load terminal is depicted in Fig. 7, this voltage remains 110 V from time t=0 to t= 80 seconds. The undershoot observed in the voltage curve (see Fig 7) results from the switching of power supply from the PV array to the fuel cell. From time = 80 seconds to t=150 seconds, the load is met from the fuel cell using the stored hydrogen.

The output voltage of the fuel cell is boosted from 24 V to 110 V to adapt the voltage at the fuel cell terminal with that of the load, this voltage is equal to 40 V while the fuel cell is not operating due to the fuel cell initial conditions (see Fig. 8a). From time t=80 seconds to t=150 seconds, the voltage increases to 115 V as the fuel cell is operating to fully meet the load demand. Similarly, the current generated in the fuel cell to feed the load is about 15 amperes (see Fig 8b), thus the power to feed the load is 1725 watts (see Fig. 8c).

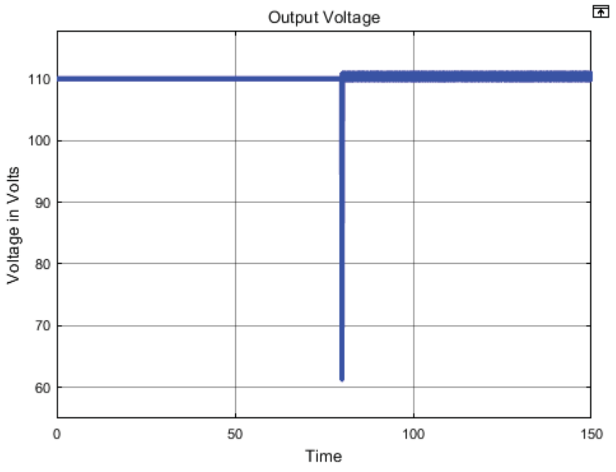

Fig. 7 Voltage at the load terminal

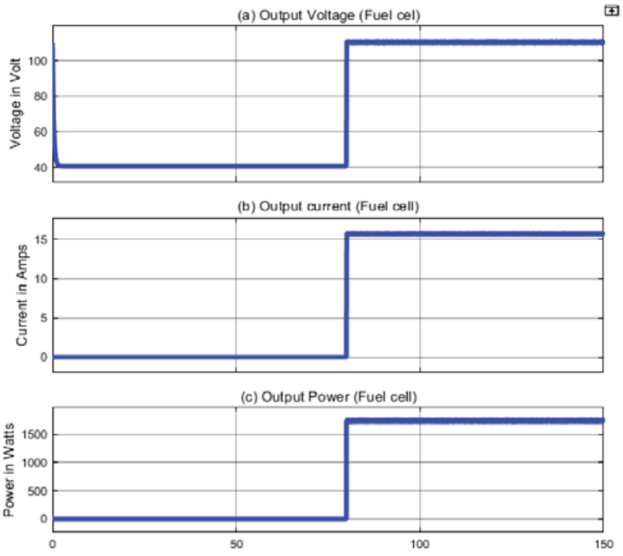

Fig. 8. Fuel cell voltage, current and power characteristics

4 CONCLUSION

Renewable generators based on solar and wind are generally characterised by intermittent power outputs. In the context of islanded microgrids, these generators caused unbalance and inefficient system operation. In such a case, ab backup power source is often used to overcome these issues. This study proposed an energy management strategy for an energy system composed of a PV array and fuel cell system to meet the load demand of a community building located in a remote area. The objective was to develop a control strategy to maintain the balance between the supply and the demand. The scenario presented in this study shows that the proposed energy management algorithm permits to balance the share of energy between the PV array and the fuel cell to the load. Further research will focus on increasing the system complexity and using intelligent methods for energy management algorithm development.

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