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Dynamic modelling and simulation of a solar-PV hybrid battery and hydrogen energy storage system

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ABSTRACT

This paper develops mathematical models for dynamic simulation and predicting of the future performance of a solar-PV hybrid battery and hydrogen energy storage system that is capable of satisfying residential electrical loads in the example at Port Harcourt in Nigeria. The models from experimentally determined works were taken from various published sources in order to develop a detailed, validated and generalised model for the proposed integrated system that is hitherto lacking. Thus, the hybrid energy storage system is implemented using ideal electronic switches that ensure solar-PV power is directly utilised for battery charging, and any excess generated PV power can be converted into hydrogen fuel for domestic applications including fuel cell power generation systems. The results indicate that conversion efficiency of the solar-PV module is about 34% at this location, and battery power can satisfy low power loads for relatively longer operating period compared to fuel cell power that can satisfy higher power loads but for a shorter operating time. Apparently, the fuel cell dynamic response was limited due to reactants flow conditions near the electrodes which increase internal resistances. The inverter output waveform however, can be maintained at the standard magnitude and frequency that is required by the load.

1. Introduction

Photovoltaic and battery technology have been practically inseparable combining quite well to convert energy and store it to meet power needs. However, for the battery-specific solar-PV technology the requirements for larger battery banks could be expensive especially when the solar irradiation intensity is at its highest, and relatively cost-effective small battery banks could have limited charge and discharge capacity [1] constraints although depending on the overall rated capacity and the need to be constantly cycled in order to avoid being degraded over a certain time or become less efficient. On the other hand, hydrogen fuel cell system has the potential to be optimised and operate without interruption since there are no charge or discharge limits only depending on relative size of the hydrogen energy storage, and as long as the fuel cell is continuously being supplied with both fuel and oxidant reactants. This also means that during peak power production times or upon fully charging a battery bank, any excess electricity produced from the PV panels can be converted into hydrogen fuel and stored for future use which is limited only by the amount of hydrogen storage available and thereby taking advantages of a hybrid energy storage system that might be needed to support grid independent solar-PV power systems.

In Nigeria (located in sub-Saharan Western Africa), socio-economic lifestyle of people in the urban areas reflect a typical residential electricity demand profile that is affected due to factors such as weather changes, work, school, leisure and religious activities which usually result into relatively high electricity demand during both day and night times. Although with a population of about 138, 283, 240 (based on 2008 estimate [2]), the National grid electricity supply is erratic varying between 27% to 60% of about 4000 MW net available electricity generation capacity [3], which could be caused mainly due to inefficiency, poor maintenance, vandalism and sabotage of about 8 major centralised power generating stations [4] in the country, in addition to transmission and distribution losses which accounts for about 28% of the electricity that is generated [5,6]. In spite of this, only about 40% of households in Nigeria are connected to the National electricity grid [5]. Consequently, it has become imperative to investigate other decentralised methods of alternative power generation that can also support the existing grid electricity supply particularly at the level of residential/domestic applications.

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Nomenclature for Eqs. (1)–(8)

A_{pv} effective area of the PV cell/module (m^2)
A_f ideal factor dependent on the PV technology
C_{PV} overall heat capacity per unit area of the PV cell/module ($J\,^{\circ}C^{-1}\,m^{-2}$)
e_{gap} band gap of the material (1.17 eV for Si materials)
I load current (A)
I_L light current (A)
I_0 saturation current (A)
$I_{L,ref}$ light current at the reference condition ($1000\,W\,m^{-2}$ and $25\,^{\circ}C$)
$I_{0,ref}$ saturation current at the reference condition (A)
$I_{sc,ref}$ short circuit current at the reference condition (A)
$I_{mp,ref}$ maximum power point current at the reference condition (A)
k Boltzmann's constant ($1.38 \times 10^{-23}\,J\,K^{-1}$)
$k_{in,PV}$ transmittance-absorption product of PV cells
k_{loss} overall heat loss coefficient ($W\,^{\circ}C^{-1}\,m^{-2}$)
N_s number of cells in a series of a PV module
q charge of an electron ($1.60217733 \times 10^{-19}\,C$)
R_s series resistance (Ω)
T_a ambient temperature ($^{\circ}C$)
T_c PV cell temperature ($^{\circ}C$)
T_{ref} reference temperature ($25\,^{\circ}C$ is used in this study)
U output voltage (V)
$U_{oc,ref}$ cells open circuit voltage at the reference condition (V)
$U_{mp,ref}$ maximum power point voltage at the reference condition (V)

Greek letters
α thermal voltage timing completion factor (V)
α_{ref} value of α at the reference condition
ϕ irradiance ($W\,m^{-2}$)
ϕ_{ref} reference irradiance ($1000\,W\,m^{-2}$ is used in this study)
$\mu_{1,SC}$ reference coefficient of the short-circuit current ($A\,^{\circ}C^{-1}$)

Subscript
a ambient
c PV cell
L Light
mp maximum power point
oc open circuit
pv photovoltaic
ref reference
s series
sc short-circuit

Amongst all the available renewable and clean energy sources, the solar-PV technology meets these requirements.

Port Harcourt in Rivers state (located at the southern region) of Nigeria is on a latitude of 4° 47′ N and longitude of 6° 59′ E with a mean global solar radiation of about 4.37 kWh $m^{-2}\,day^{-1}$ [7]. Although this is relatively weak mean global solar radiation intensity (according to the solar irradiation map of Nigeria [7–9]), the sunshine lasts for about 4–6 h during the day times which might be reasonable opportunity for implementing energy storage with the conventional solar-PV technology.

In many of the already reported experimental works [1,10,11] involved with combining battery and hydrogen fuel cell hybrid energy storage systems, lead-acid battery bank in particular has been used as an energy storage/buffer device due to its cost advantages and also to support a domestic scale fuel cell (FC) system. For instance as reported in Ref. [11], an integrated system based on hybrid power sources with the lead-acid battery banks and a bench-scale PEM electrolyser and fuel cell energy storage system was investigated experimentally for effective and reliable power control management in order to efficiently satisfy the electrical load demand. However, as the mathematical models for each subsystem were not fully described accurately it might be difficult to use the equations from that report to predict future performance of similar systems, except for replicating only the experimental procedures described in the report; and this is also as observed from other similar works reported in the literature [12–17]. Therefore, the original contribution in this paper is that it provides a more detailed, reliable and accurate mathematical models for dynamic simulation, and for predicting the future performance of a proposed solar-PV hybrid battery and hydrogen energy storage system that can be capable for both short and long-terms of energy storage applications. The proposed models can be considered validated as they are based from an already published experimentally determined works.

2. Electric load profile

The advantages of a hybrid battery/FC system can be easily understood by analysing a typical residential load profile as shown in Fig. 1.

The residential electric load profile of a typical single household in Nigeria gives an average power demand of about 1.1 kWe, but a peak power demand slightly greater than 2 kWe. This profile is assumed constant throughout the year, as thermal demand is ignored. With FC prices currently between \$ 2130 kWe^{-1} and \$ 7099 kWe^{-1} [10], FC stacks remain far more expensive than battery systems (\$99 kWe^{-1}–\$426 kWe^{-1}); hence it would make economic sense to use a FC with rating capable to supply approximately the average power demand in order to allow a relatively high running time of the FC [10,18–20]. The additional power can be provided by back-up system (e.g. batteries) that is capable to also provide for the peak power demand at a relatively short-running time.

3. Dynamic component models

The major component models for the proposed integrated system consist of a solar-PV module, battery, electrolyser, fuel cell stack, and power converter and controller units. Therefore standard classical methods of representing the various component models by sets of algebraic, differential equations and PID controllers using transfer functions are presented.

3.1. Solar energy resource potential and solar-PV model

Considering the solar radiation in Port Harcourt (4° 47′ North, 6° 59′ East) which varies between 3.5 and 4.9 kWh $m^{-2}\,day^{-1}$ [21], a 500 W solar-PV module that consists of about 126 cells connected in series as manufactured by Viridian Solar UK (PV 30/500) [22] is modelled based on a simplified four parameter model that is expressed in Eqs. (1)–(8) [23] (the parameters in Eqs. (1)–(8) are described only in the Nomenclature Section):

$$I = I_L - I_D = I_L - I_0\left[exp\left(\frac{U + (I \times R_s)}{\alpha}\right) - 1\right] \quad (1)$$

$$I_L = \phi/\phi_{ref}\left[I_{L,ref} + \mu_{1,SC}(T_c - T_{ref})\right] \quad (2)$$