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Design and Control of photovoltaic-fuel cell Hybrid system for electric power generation

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ABSTRACT: This paper focuses on the design, modelling, and control of Photovoltaic-Fuel Cell (PVFC) hybrid system for the generation of maximum power output using the method of incremental conductance technique via buck and boost converter. A maximum power of 8232W was obtained from an initial power of 6000W.The obtained results are presented and show the feasibility of a solar-fuel cell energy production for use with an inverter on standalone application such as office and residential applications. The results also show that the overall power management strategy is effective and the power flows between the two energy sources and the load demand was balanced successfully.

KEYWORDS: Photovoltaic-fuel cell (PVFC), Proton Exchange Membrane fuel cell (PEMFC), incremental conductance (inc.) technique.

1. INTRODUCTION

Hybrid power systems (HPS) combine two or more sources ofrenewable energy into one or more conventional energy sources[1]. The renewable energy sources such as photovoltaicand wind or fuel cell do not deliver a constant power, but due to their harmonizing action, their combination provides morecontinuous electrical output. The purpose of ahybrid power system is to produce as much energy fromrenewable energy sources. Inaddition to sources of energy, a hybrid system may alsoinclude a DC or AC distribution system, a storage system,converters, filters and a control system for load management.All these components can be connected in different architectures.The renewable energy sources can be connected tothe DC bus depending on the size of the system. The powerdelivered by an HPS can vary from a few watts for domesticapplications up to a few megawatts for systems used in theelectrification of small villages.

Fossil fuel reserves are not sufficient to meet the growing national energy demand, and the negative impact of this type of fuel is already a matter of national concern[2]. In order to cope with both the increasing energy demand and the climatic change, there is a need for efficient and carbon-free energy sources. In this imminentdevelopment, hydrogen fuel cells and photovoltaic energy are being considered a key component.

From an operational point of view, a Photovoltaic (PV) power generation experiences large variations in its output power due to intermittent weather conditions. One method to overcome this problem is to integrate the photovoltaic plant with other power sources such as diesel, wind, fuel cell (FC), or battery back-up. The fuel cell back-up power supply is a very attractive option to be used with an intermittent power generation source like PV power because the fuel cell power system is characterized with many attractive features such as efficiency, fast load-response, modular production and fuel flexibility.The potential for PEMFC to produce zero emissions creates a great prospect for clean energy in the transport industry.

Due to the fast responding capability of the fuel cell power system, a photovoltaic-fuel cell (PVFC) hybrid system may be able to solve the photovoltaic inherent problem of intermittent power generation. The fuel cell power can also produce electricity for unlimited time to support the PV power generator. Therefore, a continuous supply of high quality power generated from the PVFC hybrid system is possible day and night.The fuel cell power system has a great potential for

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being coordinated with the PV generator to smooth out the photovoltaic power fluctuations.

This paper presents the designof a Photovoltaic-fuel cell (PVFC)hybrid system using an incremental conductance algorithm to control current, voltage and power output of the system for use with an inverter on standalone applications.

II. LITERATURE REVIEW

Proton-exchange membrane fuel cell (PEMFC) is regarded as one of the cleanest alternative energy conversions which is promising to replace traditional power generation technologies[3]. Due to its properties of low operation temperature and fast start-up compared with other types of fuel cells, it has drawn wide attention in the fields of power station systems and vehicle systems.

[4]in their paper presented improved energy management for grid-inverter of a hybrid photovoltaic (PV)/fuel cell(FC) energy system with unbalanced sensitive loads. In the system, unbalanced loads draw unbalancedcurrents at each phase and consume power from energy units at different levels. This condition makesthe grid unbalanced, which cannot be compensated by a conventional energy management controllerused in grid inverters.

[5]practically modelled a fuel cell kit and simulated a stand-alone renewable power system which maximized the use of a renewable energy source. HOMER, the micro power optimization model, was employed to simulate the PV-Battery system and PVFC-Battery hybrid systems. In the process of simulation, the total electrical load of Chittagong University of Engineering and Technology (CUET), Chittagong, Bangladesh was considered to meet its energy demand and to get optimal cost of energy, cost effectiveness and efficient power of PV-Battery and PVFC-Battery systems.

On the other hand, most control strategies mainly depend on a reliable mathematical model while more accurate models with multiple dimensions can introduce mathematical complexities. Due to those complexities, many control design methodologies cannot be applied. Thus, it is significant to develop a control-oriented model to eliminate the unknown disturbance and enhance the controller performance.However, designing a proper control strategy with consideration of unknown dynamics remains as an open and interesting problem for PVFC system.

III. SYSTEMDESCRIPTION

A schematic diagram of the studied system is illustrated in Figure1.The role of a hybrid system is the production of electricity without interruption. It consists generally of a photovoltaic generator (PV), and a proton exchange membrane fuel cell (PEMFC). Energy is produced by a PV generator to supply a user load. Whenever there is enough solar radiation, the user load can be powered totally by the PV energy. The PEMFC supply the user load demand when the PV generator energy is deficient and works as an auxiliary or back-up generator. A PEMFC is used to keep the system reliability at the same level as for the conventional system while decreasing the environmental impact of the whole system.

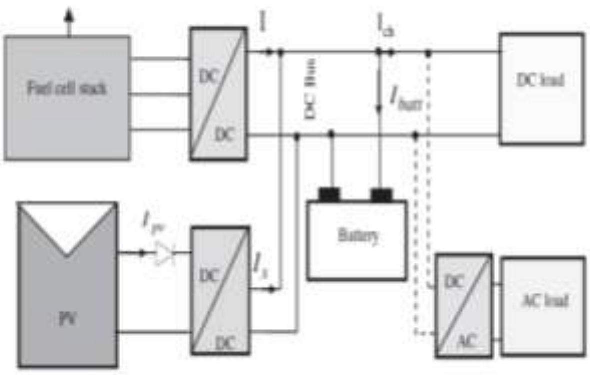

Figure 1: Description of a hybrid photovoltaic-fuel cell (PVFC) system[6]

IV. PHOTOVOLTAIC (PV) CELL MODELLING

The ideal photovoltaic cell consists of a single diode connected in parallel with a light generated current source (I_{ph}). The current generated in the solar cell by the current source (I_{ph}) is proportional to the amount of light falling on it. When there is no load connected to the output, almost all of the generated current flows through diode D. The series resistor R_S and shunt resistor R_{SH} represent small losses due to the connections and leakage respectively. There is very

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little change in open circuit voltage V_{OC} for most instances of load current. However, if a load is connected to the output, then the load current draws current away from the diode D. As the load current increases, more and more current is diverted away from the diode D. So, as the output load varies, so too does the output current, while the output voltage V_{OC} remains largely constant. That is, until so much current is being drawn by the load that diode D becomes insufficiently biased and the voltage across it diminishes with increase in load. The equivalent circuit of a PV cell is shown in Figure2.

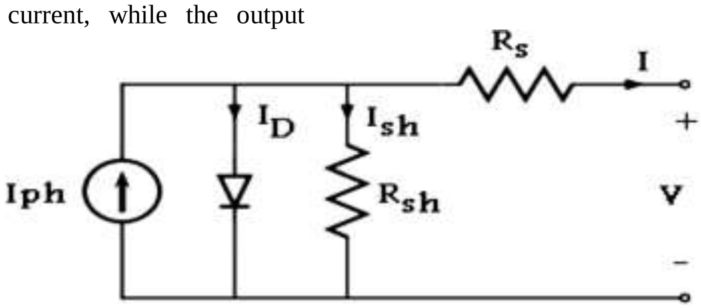

Figure2: PV cell equivalent circuit [7]

The current source Iph represents the cell photocurrent while Rsh and Rs are the intrinsic shunt and series resistances of the cell, respectively. Usually the value of Rsh is very large and that of Rs is very small, hence they may be neglected to simplify the analysis.
The conversion of solar radiation into electricity by the photovoltaic process is one of the exploitation means of solar potential. A photovoltaic panel is mathematically modelled as follows:
The photo generated current of photovoltaic cell is given by Kirchhoff's current law as:

$$I_{ph} = I_D + I_{sh} + I \tag{1}$$

where I_{ph} is the photo-generated current,
I_{sh} is the shunt current,
I_D is the diode current,
I is the output current,
From equation (3.1), the output current is given by:

$$I = I_{ph} - I_D - I_{sh} \tag{2}$$

The diode current is expressed as:

$$I_D = I_o(e^{\frac{V}{nV_t}}) - 1 \tag{3}$$

Where I_O is module saturation current,
V is module voltage (V),
n is an ideality factor of the diode,
V_t is diode thermal voltage (V)
The shunt current on the other hand is given by

$$I_{sh} = (\frac{V + I R_s}{R_p}) \tag{4}$$

where V is PV module voltage (V),
R_s is series resistor (Ω),
I is PV module current (A),
R_p is parallel resistor (Ω),

Substituting I_D and I_{sh} in equation (2), the output current is:

$$I = N_p I_{ph} - N_p I_o(e^{\frac{V}{nV_t}}) - 1 \tag{5}$$

The thermal voltage of the diode is given by:

$$V_t = \frac{N_s KT}{q} \tag{6}$$

Where N_P is the number of modules connected in parallel,
N_s is the number of cells connected in series,
K is Boltzmann constant,
T is operating temperature (K),
q is electron charge
The equation (5) becomes;

$$I = N_p I_{ph} - N_p I_o(e^{\frac{qV}{nKTNs}}) - 1 \tag{7}$$

The photo-generated current is given by:

$$I_{ph} = (I_{sc} + Ki(T - T_r))\frac{G}{Gr} \tag{8}$$

Where I_{SC} is short-circuit current (A),
T_r is Reference temperature (K),
T is operating temperature (K),
G is actual solar irradiation (W/m^2),
G_r is Reference solar irradiation (W/m^2).
The module saturation current varies with the cell temperature and is given by:

$$I_o = I_{on}((\frac{T}{T_r})^3 * e(\frac{qE_g}{nK}) * ((\frac{1}{T_r}) - (\frac{1}{T}))) \tag{9}$$

where T_r is Reference temperature,
T is operating cell temperature in Kelvin
E_g is Band gap energy for silicon.
I_{on} is modules reverse saturation current

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The modules reverse saturation current I_{on} is given by:

$$I_{on} = \frac{I_{SC}}{e^{\frac{qV_{OC}}{nKTNs}} - 1} \quad (10)$$

Where q is electron charge

I_{SC} is short circuit current (A),

V_{oc} is Open-circuit voltage (V),

Ns is number of cells connected in series,
n is an ideality factor of the diode,
K is Boltzmann constant,
T is operating cell temperature (K).

PV parameter specifications

The parameter specifications of PV module and array are listed in table1.

Table1: Electrical characteristics data of Bosch solar Energy 300Wp 10 series modules 2 parallel strings

Parameters	PV module	PV array
Maximum power (P_{max})	300W	6000W
Open circuit voltage V_{oc} (V)	46V	460V
Short circuit current I_{sc} (A)	8.44A	16.88A
Voltage at P_{max}	37.5V	375V
Current at P_{max} (I_{mp})	8A	16A
Cells per module (Ncell)	72	1440

V. PEMFC ELECTROCHEMICAL MODEL

PEM Fuel Cellis represented by anElectrical model as shown in figure3.

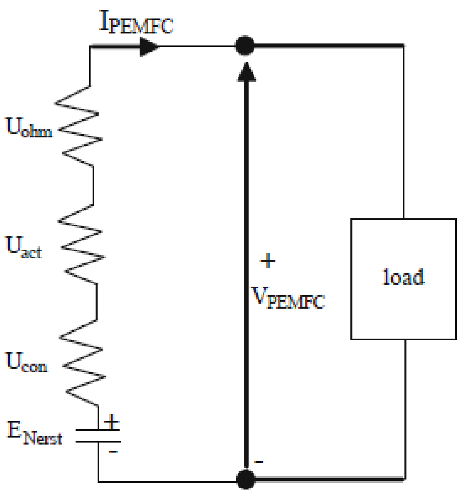

Figure3: Electrical model of a fuel cell[6]

The output of PEMFC is a function of open circuit voltage, activation loss, Ohmic loss and concentration loss.

This loss develops significant at higher currents when the fuel and oxidant are used at higher rates and the attention in the gas channel is at a minimum [8].

The electrochemical model can be used to predict the dynamic behaviour of PEMFC stacks. This mathematical model uses a group of parameters whose definition is essential for the best simulation results. The output voltage of a single cell can be defined as follows [9]:

$$V_{FC} = E_{Nersnt} - V_{act} - V_{ohmic} - V_{con} \quad (11)$$

The fuel cell voltage V_{FC} is lower than the theoretical voltage E_{Nernst}due to various irreversible loss mechanisms. These losses, which are often called polarization or over-voltage losses, originate primarily from three sources: activation overvoltage Vact; concentration or diffusion over-voltage V_{conc} and resistive or ohmic over-voltage V_{ohm}.E_{Nersnt} is the thermodynamic potential of each unit cell and represents its reversible voltage; V_{act} is the voltage drop associated with the activation of the anode and of the cathode; V_{ohmic} is the ohmic voltage drop (a measure of the voltage drop associated with the conduction of protons and electrons); V_{con} represents the voltage drop resulting from the decrease in the concentration of

oxygen and hydrogen. The first term of eqn.(11) represents the FC open-circuit voltage, while the last three terms represent reduction in this voltage. The resulting voltageV_{FC} , is the FC useful voltage for a certain operating condition. In addition to the three terms representing voltage drops, there is another term involving the PEMFC operation. This additional voltage drop results from the circulation of electronic currents through the electrolyte or, similarly, from the fuel crossover through the electrolyte. This voltage drop is modelled considering a permanent FC current density that is added to the main FC current density, even when the FC is operated without any load.
For cells connected in series and forming a stack, the voltage can be calculated by:

$$V_n = nV_{FC} \tag{12}$$

Each individual term of (11) is defined by:

$$E_{Nernst} = 1.229 - 0.85x10^{-3}.(T - 298.15) + 4.31x10^{-5}.T.[In(PH_2) + \frac{1}{2}In(Po_2)] \tag{13}$$

$$V_{act} = -[\xi 1 + \xi 2xT + \xi 3xTxIn(Co_2) + \xi 4xTxIn(ifc)] \tag{14}$$

$$V_{ohmic} = ifc(R_M + R_C) \tag{15}$$

$$V_{con} = -B.In(1 - \frac{J}{J_{max}}) \tag{16}$$

$$Co_2 = \frac{Po_2}{5.08x10^6 e^{-(\frac{418}{T})}} \tag{17}$$

where P_{H2}andP_{O2} are the partial pressures (atm) of hydrogen and oxygen, respectively, T is the cell absolute temperature(K), ifc is the cell operating current(A), and Co_2 is the concentration of oxygen in the catalytic interface of the cathode . The ξ (i=1…4) represent the parametric coefficients for each cell model. R_M is the equivalent membrane resistance to proton conduction. R_C is the equivalent contact resistance to electron conduction. J_{max} is the maximum current density. B (V) is a constant dependent on the cell type and its operation state. And J is the actual cell current density (A/cm2) including the permanent current density J_n. The equivalent membrane resistance R_M can be calculated by:

$$R_M = \frac{\rho M.\ell}{A} \tag{18}$$

where R_M is the membrane specific resistivity obtained by:

$$\rho M = \frac{181.6x[1 + 0.03x(\frac{ipc}{A}) + 0.062(\frac{T}{303})^2 x(\frac{ipc}{A})^{2.5}]}{[\psi - 0.634 - 3(\frac{ipc}{A})] \text{x} \exp[4.18x(\frac{T-313}{T})]} \tag{19}$$

An analysis of the influence of these operating conditions is interesting, so a thermo dynamical model should be used in this case.

Equations (11) – (19) represent the FC stack static electrochemical behaviour. An electrical circuit can be used to model the FC dynamical behaviour as represented in Figure3. The dynamical behaviour of a PEMFC stack is modelled as an equivalent electrical circuit. The effects of parameter variation on the equivalent resistances can be evaluated, taking into account that the resistance values actually change with the modelling parameters.

Fuel cell parameter specifications

The parameter specifications of fuel cell stack are listed in table2.

Table2: Electrical characteristics data of Proton Exchange Membrane Fuel Cell (PEMFC)

Stack power	5998.5W
Voltage at 0A	65V
Voltage at 1A	63V
Nominal operating current (I_{nom}(A))	133.3A
Nominal operating voltage (V_{nom}(V))	45V
Maximum operating voltage (V_{max})	37V
Maximum operating current (I_{max})	225A

VI. CONTROLLER DESIGN

This research aims to maintain the photovoltaic fuel cell output current, voltage and power to a predefined desired value as per load requirements. Whenever any load fluctuation occurs, the power demand or the operating point changes proportionally to the chemical reaction process of the fuel cell by controlling the critical variables. Hence positive control over these process and variables is required to regulate the output current, voltage and power of fuel cell and photovoltaic system. In this study, incremental conductance controller is used to control current, voltage and power output of the PVFC system.

Incremental conductance (inc) algorithm

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The theory of the incremental conductance method is to determine the variation direction of the terminal voltage for the system by measuring and comparing the incremental conductance and instantaneous conductance. The principle of the algorithm is that, the derivative of the power with respect to the voltage or current becomes zero at the maximum power point (MPP).The power increases with the voltage in the left side of the MPP and the power decreases with the voltage in the right side of the MPP. This description can be written in the following simple equations [10]:

$\frac{dp}{dv} = 0$ at the MPP (20)

$\frac{dp}{dv} > 0$ to the left of the MPP (21)

$\frac{dp}{dv} < 0$ to the right of the MPP (22)

Where

$\frac{dp}{dv} = \frac{d(iv)}{dv} = i + V\frac{di}{dv}$ (23)

$\frac{i}{v}\frac{dp}{dv} = \frac{i}{v} + \frac{di}{dv}$ (24)

The InC algorithm can track the MPP in the case of rapidly changing operating conditions easily, because this algorithm uses the differential of the operating point, dp/dv. Basically, the algorithm can move the operating point towards the MPP under varying operating conditions. If the value of incremental conductance is equal to that of instantaneous conductance, it represents that the maximum power point is found.

VII. SYSTEM EXPERIMENTATION

To validate the operating characterisics of the system, different values of load resistors were used to generate data in both the PV and fuel cell to plot I-V/P-V andV-I/ P-I curves respectively. The setup are illustrated in figure 4 and figure5 respectively.

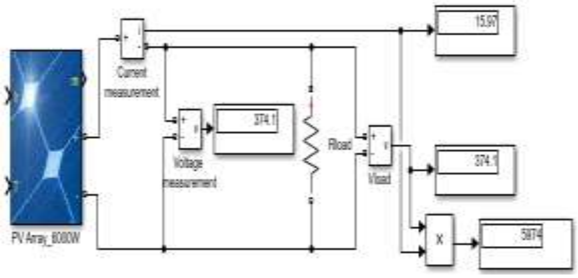

Figure4: PV array experimentation

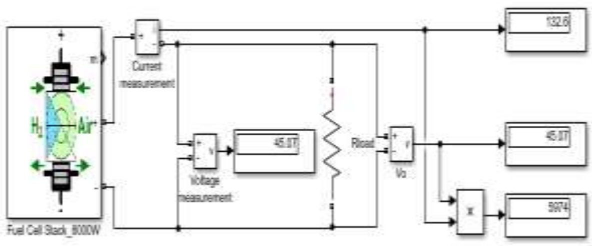

Figure5: Fuel cell stack instrumentation

VIII. HYBRID PVFC SIMULINK MODEL

The hybrid system simulink model is as presented in figure6 using inc algorithm via buck and boost converter as interface.

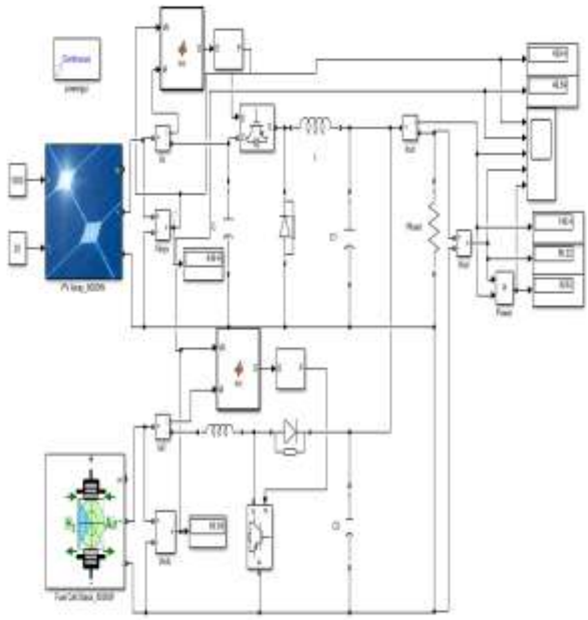

Figure6: Controlled PVFC Hybrid system using Incremental conductance algorithmby buck and boost converter

IX. RESULTS AND DISCUSSIONS

The solar array is modelled, experimented and simulated using Matlab/Simulink software. The experimentation and simulation was based on the Bosch solar Energy 300Wp photovoltaic array. The parameters of this solar array are given in Table1.The module is made of 72 solar cells connected 10 in series and 2 in parallel to give a maximum power output of 6000W.The plotted current–voltage (I–V) and power-voltage (P–V) characteristic of the PV array based on data generated is shown in Figure7 and figure8. The characteristic is obtained at a varying level of load and maintaining a constant irradiance and cell temperature.

Similarly, the fuel cell stack is modelled and simulated using Matlab/Simulink software. The simulation was based on PEMFC-6KW-45Vdc stack. The parameters of this fuel cell stack are given in Table2.The stack is made of 65 fuel cells to give a maximum power output of 6000W. The plotted voltage-current (V-I) and power-current (P–I) characteristic of the stack based on data generated is shown in Figure9 and figure10.

Figure11 shows the controlled output current, voltage and power delivered by the PVFC hybrid system using Incremental conductance algorithm via buck and boost converter as an interface to the PVFC hybrid system.

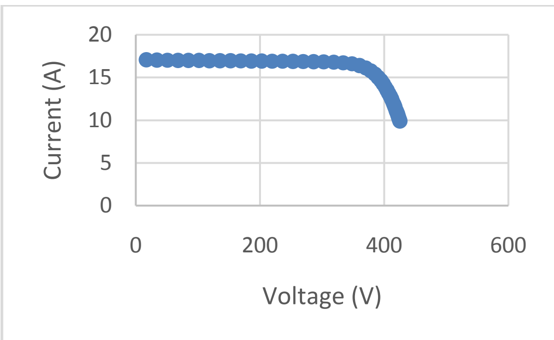

Figure7: Experimental I-V characteristic of a 6000W PEMFC stack

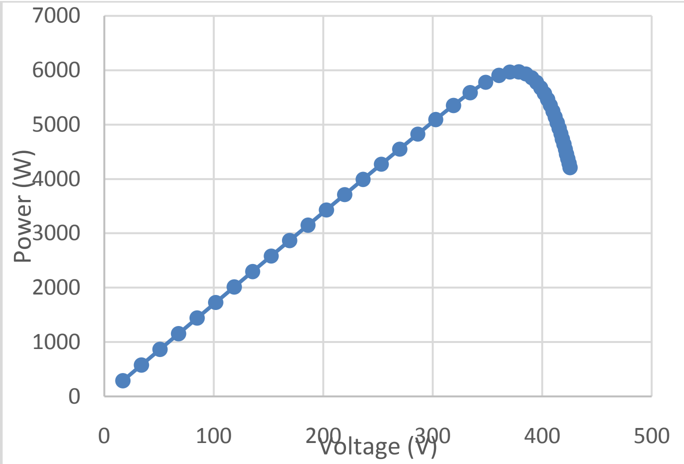

Figure8: Experimental P-V characteristic of a 6000W PEMFC stack

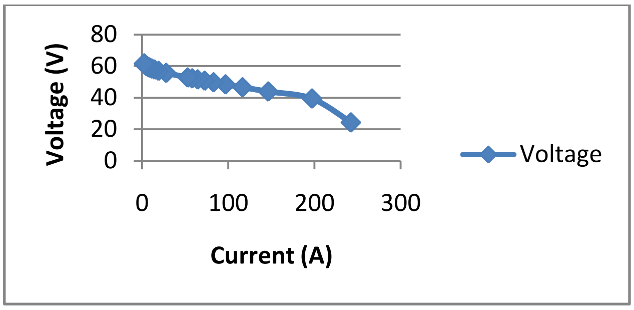

Figure9:Experimental V-I characteristic of a 6000W PEMFC stack

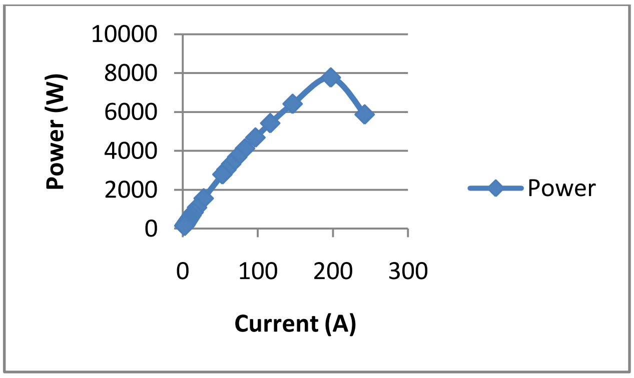

Figure10:Experimental P-I characteristic of a 6000W PEMFC stack

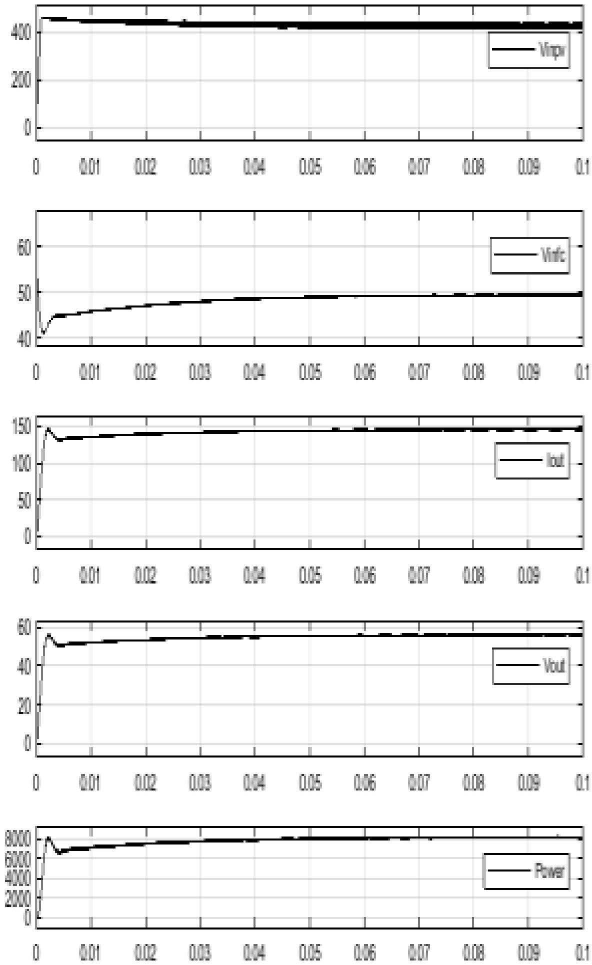

Figure11: Controlled output current, voltage and power delivered by the PVFC hybrid system using Incremental conductance algorithm.

X. CONCLUSION

In this paper, the experimental and simulated model of the hybrid system wasdeveloped and presented using matlab/Simulink. The incremental conductance algorithm applied via buck and boost converter increased the power level from 6000W to 8232W. The obtained results show the feasibility of a solar-fuel cell energy production for stand-alone applicationsuch as office and residential applications.The results also shows that the overall power management strategy is effective and the power flow between the two energy sources and the load demand is balanced successfully. The results show that the proposed method works well.

Further work

To further enhance the performance of the system, other renewable sources such as wind turbine can still be added to the system. A wind energy conversion willreduce the required PV array area, and reduce the hydrogen storage tank.

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