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Grid Independent Photovoltaic Fuel-Cell Hybrid System: Design and Control Strategy

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Abstract - In this paper, a hybrid photovoltaic fuel-cell generation system employing an electrolyzer for hydrogen generation and battery for storage purpose is designed and simulated. The system is applicable for remote areas or isolated DC loads. Control strategy has been considered to achieve permanent power supply to the load via the photovoltaic/battery or the fuel cell based on the power available from the sun. MATLAB and SIMULINK have been used for the simulation work. A sensitivity analysis is conducted for various load level based on availability of solar radiation.

Keywords: Hybrid system, modelling, control strategy

1. Introduction

Renewable energy sources (solar, wind, fuel cell etc) are considered as alternative energy sources to conventional fossil fuel energy sources due to environmental pollution and global warming problems. However, control problems arise due to large variances of output under different insolation or wind speed levels. To overcome this problem, photovoltaic system can integrate with other power generators or storage systems such as battery bank and fuel cells. The feasibility of photovoltaic fuel-cell systems has been successfully demonstrated for both grid-connected and stand alone applications [1].

In this research work, design and control strategy of an autonomous photovoltaic fuel-cell energy system has been developed and simulations have been performed in order to supply electricity to a DC-load without being connected to the electric grid. The photovoltaic module produces electricity to meet the requirements of a load. When there is enough solar radiation available, the external load can be powered totally by the photovoltaic electricity. For continuous supply of power to the load, a battery bank is used with the photovoltaic module. During the period of low insolation, auxiliary electricity is required. A fuel-cell system formed by a water electrolyzer, a hydrogen storage system, and a fuel-cell stack works as a back-up system. Excess electricity generated in the photovoltaic module is sent to an electrolyzer to produce hydrogen, which is stored for a period of time. When required, it is converted back into electricity using the fuel cell. The fuel cell can be considered as a back-up generator to meet the load requirement. The system behaviour is simulated with a time resolution in the minute-range. All the developed models are based on physical and chemical principles, as well as empirical parameters. The system control is designed to optimize the input and output currents for the different components of the overall system during a period of one year. The research work as a whole includes modelling and optimization of the components and the determination of an appropriate control strategy.

2. Design Options

For this research work, the photovoltaic module has been used as the main source of power generation. A battery bank is employed to store energy. A fuel-cell stack is used as back-up source of power. The photovoltaic module with the battery, the load and the electrolyzer are connected directly. During operation, the fuel cell is also connected directly to the load. The idea behind this kind of system is to operate the load with photovoltaic electricity by storing it in battery bank during high insolation periods.

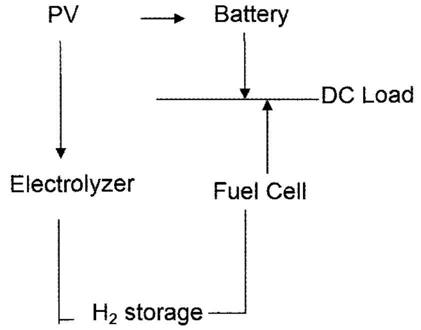

Fig. 1 Schematic diagram of the photovoltaic fuel-cell hybrid system

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The electrolyzer produces H_2 using excess photovoltaic energy; which is stored for the time being and the fuel cell converts H_2 back to electricity during the months of low insolation. The battery storage system is used for short-term storage of electricity and to supply power to load. A schematic diagram of the system is shown in Fig.1.

3. Control Strategy

The system control is designed to optimize the input and output currents for the different components of the overall system during a period of one year. Three different sets of conditions have been considered for the system control. These are:

a) The current from the photovoltaic module is high enough to power the load, and there is no excess current to be used in other components of the system.
b) There is enough photovoltaic current to operate the electrolyzer as well as to power the load. Excess current from the photovoltaic module is sent to the electrolyzer. If the depth of discharge (DOD) limit of the battery is reached, the photovoltaic current is sent to the battery first.
c) There is no photovoltaic current, so the electricity must be obtained from the fuel cell.

To implement these strategies, three parameters have been defined as follows:

$$PV\_state = \begin{cases} on & if\ PV \quad power \geq P_{STC} * x_1 \\ off & else \end{cases} \tag{1}$$

$$Battery\_state = \begin{cases} on & if\ SOC > SOC\_critical \\ off & else \end{cases} \tag{2}$$

$$FC\_state = \begin{cases} on & if\ SOC \leq SOC\_critical \\ & and\ PV \quad power < P_{STC} * x_1 \\ & \\ off & else \end{cases} \tag{3}$$

Where x_1 is a fraction, SOC_critical is a critical value of state of charge (SOC) of the battery and on/off indicates whether the system is in operation or not.

The idea of this kind of system is to use the battery in periods of high insolation and the fuel cell in periods of low or no insolation and or when the discharge limit of the battery is reached.

4. Modeling

4.1 Photovoltaic Module

For a photovoltaic system that operates in the clamped voltage mode, the output voltage of the module is fixed at the system's operating voltage, which is usually equal to the battery voltage.

It is assumed that module temperature is linearly depending on ambient temperature and power [2]. Hence,

$$T_{cell} = T_{amb} + K.G \tag{4}$$

With,

T_{cell} : Cell temperature
T_{amb}: Ambient temperature
G: Irradiance, W/m^2
K: Equivalent thermal resistance

The module power is calculated with the parametric equation (5) given below: [3]

$$P_{\mathrm{mod}} = P_{stc} \cdot \frac{G_{rel} + L}{G_{rel} + O} . N . G_{rel} \tag{5}$$

With,

$G_{rel}=G/G_{ref}$
$G_{ref}=1000\ W/m^2$
$L=0.001267789$
$O=0.025403774$
$N=(1+O)/(1+L)$

MPP Power corrected by temperature coefficient is given in equation (6):

$$P_{mpp,corrected} = P_{\mathrm{mod}} . (1 + ci.dT)(1 + cv.dT) \tag{6}$$

With,

dT: difference of T_{cell} and T_{stc}
ci: current temperature coefficient (1/deg.C) $=6e\text{-}3/P_{stc}*V_{mpp}$
cv: voltage temperature coefficient (1/deg.C) $= -73e\text{-}3/V_{mpp}$

The value of K has been determined as 0.021 [4] from 5 sec average value of irradiance over a year measured in a photovoltaic research project at K.U. Leuven, Belgium.

The calculation has been carried out for a standard photovoltaic module with the parameters shown in Table I below:

4.2 Battery

The battery model describing the relationship between the voltage, current and the state of charge (SOC) can be found in [5-7]. Battery terminal voltage, V_B can be expressed as:

$$V_B = E_{oc} + I_b.R_b \tag{7}$$

With,

E_{oc}: battery open circuit voltage (V)
I_b: battery current (A)
R_b: internal resistance of battery (ohms)

E_{oc} and SOC can be calculated from the following equations:

$$E_{oc} = V_F + b.\log(SOC) \tag{8}$$

$$SOC = SOC_0 + (\Delta Q/C_x) \tag{9}$$

With,

V_F: voltage in fully charged condition (V)
b: an empirical constant
SOC_0: initial state of charge
C_x: battery capacity (C)
ΔQ: amount of exchanged charge (= $\int_0^t I_b dt$)

Finally, an equation for battery terminal voltage can be constructed that brings together all the necessary parameters as:

$$V_B = V_F + b\log(SOC) + I_b\left[r_1 + r_2(SOC) + \frac{1}{r_3 - r_4(SOC)}\right] \tag{10}$$

Where r_1, r_2, r_3 and r_4 are empirical constants and can be determined by conducting charging and discharging operation of the battery [8]. The values of various empirical parameters for the battery have been taken from [9].

4.3 Fuel Cells

Fuel cells are electrochemical devices that convert the chemical energy of a reaction directly into electrical energy. The ideal standard potential (E) of an H_2/O_2 fuel cell is 1.22 volts with liquid water product. The actual cell potential is lower than its equilibrium potential because of irreversible losses. Several sources contribute to irreversible losses in a practical fuel cell. The losses originate primarily from the activation polarization, ohmic polarization and concentration polarization. These losses result in a cell voltage (V) for a fuel cell that is less than its ideal potential, E (V = E - Losses). The combined effect of thermodynamics, mass transport, kinetics, and ohmic resistance determines the output voltage of the cell as defined by [10,11],

$$V = E - (j + j_n)r - A\ln\left(\frac{j + j_n}{j_0}\right) + B\ln\left(1 - \frac{j + j_n}{j_l}\right) \tag{11}$$

valid for $j_0 < j+j_n < j_l$.

With,

j: current density
j_n: internal and fuel crossover equivalent current density
j_0: exchange current density
j_l: limiting current density
r: specific resistance
A: slope of Tafel line
B: a constant that depends on the fuel cell and its operating state

The values of various constants have been taken from [11] for low temperature proton exchange membrane fuel cell (PEMFC).

5. Simulations and Results

The mathematical models of the system described in the previous chapter have been simulated in Simulink version 5 and MATLAB 6.5. The Simulink simulation model consists of four parts i.e. photovoltaic module, battery, fuel-cell system and control mechanism. Meteorological data and a given load characteristics are used as input for the simulations. The system voltage is chosen as 12V. The photovoltaic module stops supplying battery (i.e. 100Ah) when the battery is full or when the photovoltaic power is less than 10% of P_{stc}. Rather it supplies current to the electrolyzer. Battery stops supplying load when its voltage goes below the critical level (i.e. 10V), which triggers the fuel cell in operational mode. The critical state of charge (SOC_critical) of the battery is chosen as 40% of SOC. The load level has been varied in the steps of 15W, 20W, 30W and 40W. Five-second average value of irradiance measured over the year 2002 at K.U. Leuven, Belgium has been used as input for the simulation. The simulation results are shown in Figs.2, 3, 4, 5, 6 and 7.

Fig.2 shows the variation of the ambient and the photovoltaic module temperature of a summer day in the year 2002. Percentage of photovoltaic power available in the whole year can be determined from Fig.3 and that can be used to choose load level for the system.

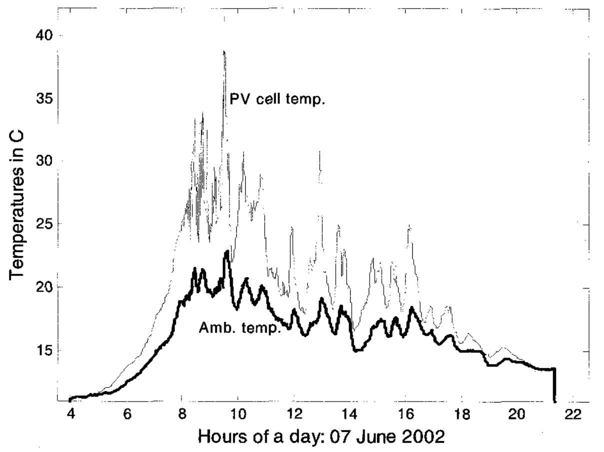

Fig. 2 Ambient and photovoltaic cell temperature for a summer day

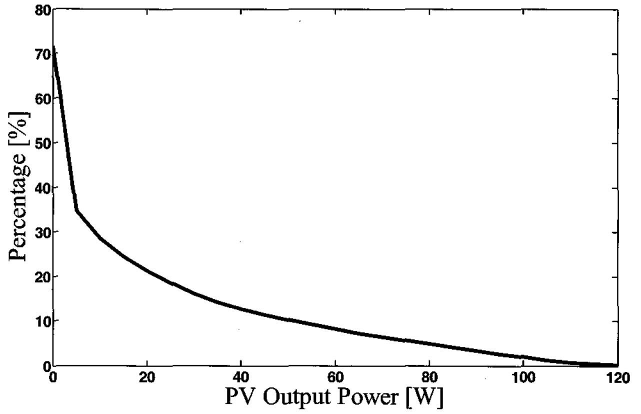

Fig. 3 Power exceedence curve at 30° tilt angle for the year 2002

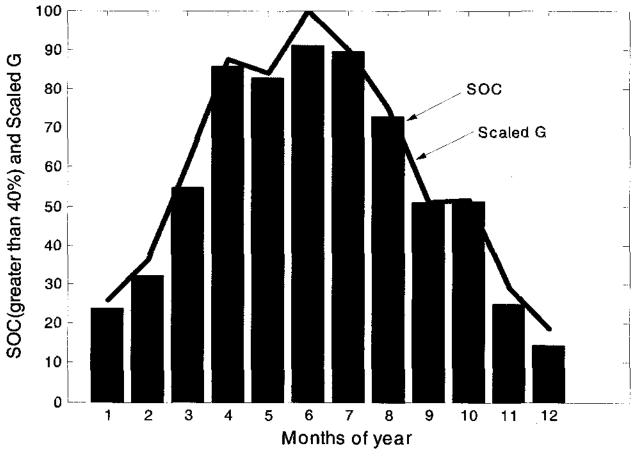

Fig. 4 Monthly average SOC and normalized radiation distribution for the year 2002; load level is 20W

In Fig.4, the percentage of the time during which SOC is higher than 40% and the scaled G are plotted against months of the year for 20W load. Scaled G is the defined as,

$$ScaledG = \frac{G_{avg,monthly}}{G_{\max.,avg}}.100 \qquad (12)$$

Where $G_{avg,monthly}$ is the monthly average irradiance and $G_{max.,avg}$ is the maximum average irradiance, which occurs in June and is equal to 209 W/m^2. The average availability of the battery is much higher in the summer months than that of the winter months due to the similar trend of irradiance over the year.

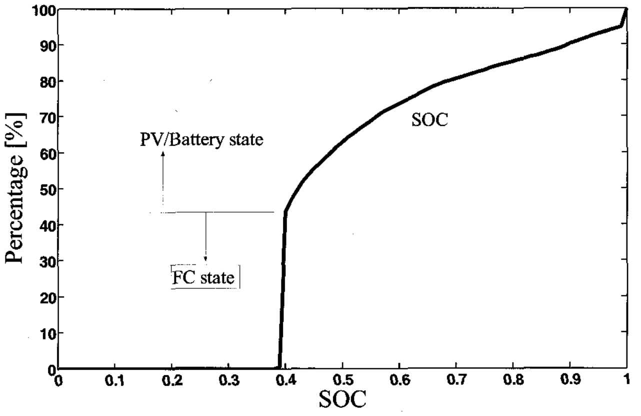

Fig. 5 Availability of the battery and state of the system components for one year at 20W

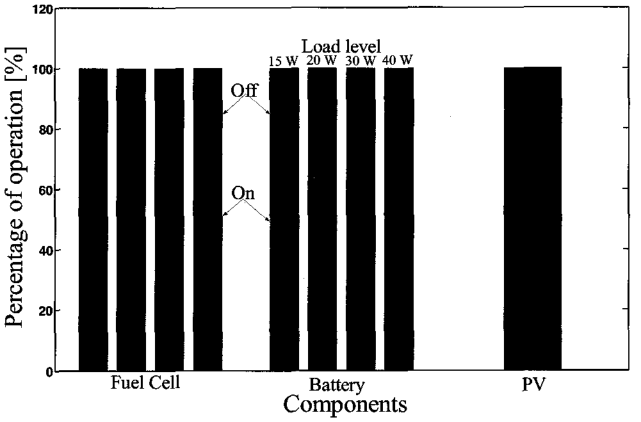

Fig. 6 Operational status of the system components for the year 2002; load levels are 15W, 20W, 30W and 40W

Fig.5 shows that the state of charge of the battery is above its critical level for 58% time of the year at 20W load. Hence, the photovoltaic/battery part of the system will supply load this period and the fuel cell will power the load for the rest of the time. Fig.6 shows the operational status of the different system components at varying load conditions. Higher load means shorter period of battery and longer period of fuel cell in operation and vise versa.

Operation of photovoltaic is independent of load variation; rather operational status depends only on the availability of irradiance. Total 27% time of the year photovoltaic module will be in operation. Fig.7 shows the availability of battery in each month of the year 2002 at three different load levels.

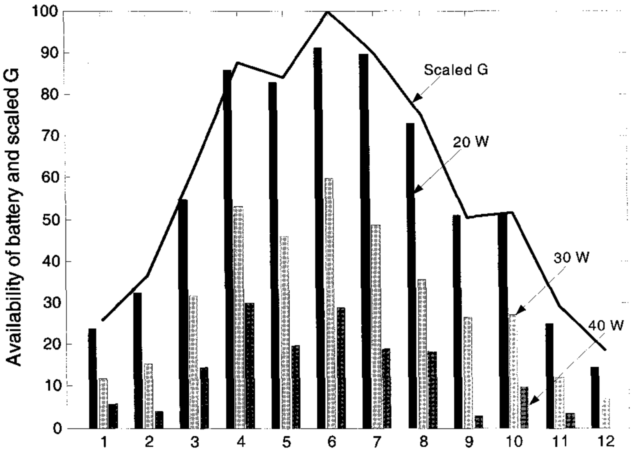

Fig. 7 Availability of the battery over the year 2002 at different load level and normalized radiation distribution

6. Simulations and Results

Results show that a photovoltaic fuel-cell hybrid system can perform well to meet the external load using energy produced by the system.

The system has been designed and optimized and control strategy has been considered for DC load only. In order to supply AC load, which are more frequently used, the system requires inverters to convert DC power to AC. However, the choice of the components in any case should rather be determined by economic consideration.

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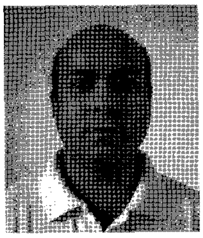

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He received M.Sc degree in Renewable Energy from the University of Oldenburg, Germany, in 2001.

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