Simulation of Solar Regenerative Fuel Cell Power System for High Altitude Airship Engineering

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Abstract - A solar regenerative fuel cell system as a power supply system for high altitude airship application was modeled using MATLAB/SIMULINK. The power supply system consisted of a polymer electrolyte membrane fuel cell, electrolyzer, photovoltaic array, storage tanks, compressors, heat exchanger, power control unit and piping and valves. During day time the photovoltaic array produced required power to the airship station and supply power to the electrolyzer to generate hydrogen and oxygen which are stored in tanks. During dark hours the fuel cell generates electricity using the stored hydrogen and oxygen. Each component was modeling using basic integral transient equations for mass and energy. Each components response was first studied to check validity physical correct outputs and then all components were integrated as power supply system. The integrated system response was studied for 24 hour period where day light correspond to 12 hour period with sinusoidal intensity and results of power distribution among the electrolyzer and fuel cell are presented.

Keywords-Solar regenerative fuel cell system, simulation model, MATLAB/SIMULINK, high altitude airship.

1 INTRODUCTION

The Regenerative Fuel Cell (RFC) is a power system that can operate in a closed loop and could serve as the basis of a hydrogen economy operating on renewable energy. Fuel cells generating electricity, heat, and water from hydrogen and oxygen would be used throughout the economy, powering factories, vehicles, and houses. The hydrogen would be generated from the electrolysis of water, splitting it into its constituent components of hydrogen and oxygen, using renewable energy sources such as wind, solar, or geothermal. Such a system would not require any specific type of fuel cell, but would need an infrastructure to deliver hydrogen to the many fuel cells in use. Little to no new technology is required to implement a renewable-based system.

Energy storage is necessary when solar energy is used in applications that require power 24 hours a day. In terrestrial applications, this is usually accomplished with banks of batteries. Unfortunately, deep cycling of batteries on a daily basis has a negative impact on their life. Batteries are also heavy. Because of the negative effects of durability and mass on the overall system design, the use of existing battery technology for energy storage in aerospace applications is limited. Regenerative H2/O2 fuel cells have the potential of achieving much higher specific energy densities than any of the advanced battery systems. These regenerative fuel cell systems may be used in applications, where relatively large amounts of energy must be stored (Mitlitsky,1994, 1999). These applications include energy storage for remote off-grid power sources, emergency or back-up power generation, zero emission vehicles, hybrid energy storage propulsion systems for spacecraft, and high altitude long endurance solar rechargeable aircraft. Barbir et al. (2005) state that the theoretical specific energy of hydrogen and oxygen combined in an electrochemical reaction is 3.6 kWh/kg. However, when the mass of hydrogen and oxygen storage tanks, as well as the mass of the regenerative fuel cell itself are taken into account, the overall specific energy density is reduced from 0.4 to 1.0 kWh/kg—still several times higher than that of any battery.

The present study is on a solar powered RFC (SRFC) system which comprises of several components which are individually modeled and then interfaced with one another, using the simulation tool, MATLAB/SIMULINK. The core components include Proton Exchange Membrane (PEM) fuel cell stack, PEM electrolyzer, photovoltaic array, power control bus, multi-stage compressors, storage tanks and a heat exchanger which are effectively modeled in SIMULINK. It is a closed-loop system, implying it is self sustained once supplied by a renewable energy source for instance solar energy.

The hydrogen and oxygen produced from the electrolysis of water are stored and supplied to the fuel cell which produces electrical power, heat and water. This electrical power is connected to a power control bus and is utilized to power the High Altitude Airship (HAA), while the water is re-used in the electrolysis process and the heat is balanced by the heat exchanger system. The HAA serves the purpose of remote visualization, weather monitoring, etc. that flies above 65,000 ft and is geostationary.

2 SOLAR RFC SYSTEM DESCRIPTION

Figure 1, shows the schematic layout of the system. During the day, the solar energy is converted into electrical energy by the photovoltaic arrays, and is sent to the power control bus. The electrical energy powers the electrolyzer, to produce water into hydrogen and oxygen which are stored in storage tanks to later fuel the fuel cell during the dark hours.

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Each component is individually modeled in SIMULINK based on their principle governing equations and each model is tested for various conditions before interfacing them together. Individual SIMULINK models and the results obtained when the entire system is run for 24 hours, are presented in this work.

Fig. 1 Schematic representation of the closed-loop solar RFC system

3 PEM FUEL CELL MODEL

PEM fuel cells operate at relatively low temperatures when compared to other types of fuel cells (about 80°C), have high power density, and can vary their output quickly to meet shifts in power demand (Larminie, 2003). They are the primary candidates for replacements of rechargeable batteries in aerospace or underwater submarines. The fuel cell can be broken down into three sections— anode, cathode and membrane. Hydrogen is fed through the anode channel, and oxygen through the cathode channel. The membrane is made of a specially designed solid polymer that allows protons (hydrogen ions) to pass through it without letting the two gases come in direct contact. The membrane is coated on both sides with highly dispersed metal alloy particles (mostly platinum) that are active catalysts. As the protons cross from the anode to the cathode, they combine with oxygen atoms to create water. The electrons, which cannot pass through the membrane, travel from the anode to the cathode as electricity when a circuit is completed.

\[
\text{Anode: } \text{H}_2 (g) \rightarrow 2\text{H}^+ (aq) + 2e^- \\
\text{Cathode: } \frac{1}{2}\text{O}_2 (g) + 2\text{H}^+ (aq) + 2e^- \rightarrow \text{H}_2\text{O} (l) \\
\text{Overall: } \text{H}_2 (g) + \frac{1}{2}\text{O}_2 (g) \rightarrow \text{H}_2\text{O} (l)
\]

The polymer membrane must be kept hydrated by humidifying the two gases before they enter the fuel cell, in order to allow the protons to pass through it. The number of protons crossing the membrane is different at each point along the channel, with more protons crossing near the inlet, where the hydrogen concentration and membrane humidity are highest. The amount of power produced is greatly dependent on current density, temperature, and the humidity of the membrane. If the membrane gets too dry, it will no longer transmit protons. If it is too wet, the pores in the membrane become blocked, and protons cannot pass through (Larminie, 2003).

A PEM fuel cell for the regenerative power generation system is modeled based on physical laws (Springer, 1991, Xue, 2004). In order to simplify the process of modeling, the properties of the three control volumes, or sections, of the fuel cell— anode, cathode and membrane are considered to be uniform. In other words the model will not describe what happens at an exact point along the membrane, but will attempt to analyze the average values. In addition, several assumptions are made that will greatly simplify the calculations without degrading the accuracy of the model: (i) All gases are assumed to be ideal, (ii) kinetic and potential energy of the gases are insignificant and will be ignored and (iii) heat transfer by radiation is much smaller than by convection and can be neglected.

The present model is an improvement on a fuel cell model by Xu et al (2004). The Xu et al model does not allow for variation in the humidity of the reactants or monitor water flow and uses air for the cathode supply.
The present model considers oxygen at the cathode rather than air and the variation in the humidity of the reactants is taken into account.

The fundamental governing equations for a control volume are the continuity equation, based on the conservation of mass, the energy equation and the momentum equation. Because this study considers the overall effects, the momentum equations are omitted. The continuity and energy equations are shown below in integral form as equations (1) and (2), respectively.

\[
\frac{\partial}{\partial t} \iiint_{CV} \rho dV + \iint_{CS} \rho (\vec{V} \cdot \vec{n}) dA = 0
\]  
\[
\frac{\partial}{\partial t} \iiint_{CV} \rho e dV + \iint_{CS} \rho (\vec{V} \cdot \vec{n}) dA = \frac{dQ}{dt} + \frac{dW}{dt}
\]

These two basic governing equations can be applied to the three control volumes of the fuel cell, but they are very abstract and generic.

The mass flow in the anode and cathode consists of mass entering at the inlet, mass exiting at the outlet and mass crossing the membrane. The inlet and outlet mass flow can be simplified using the nozzle flow rate equation,

\[
\iiint_{inlet} \rho h(\vec{V} \cdot \vec{n}) dA = k_{flow}(\Delta p)
\]

where \(k_{flow}\) is a flow coefficient and \(\Delta p\) is the pressure difference across the inlet or outlet. The mass flow across the membrane is made up of hydrogen splitting into a proton and an electron, the proton passing through the membrane while the electron travels through the electrode, oxygen combining with protons to become water, and water passing through the membrane by diffusion and also by electro-osmotic drag. Electro-osmotic drag occurs when a proton pulls one or two water molecules with it as it crosses the membrane. Both diffusion and electro-osmotic drag are functions of the water content of the membrane (Larminie, 2003., Springer, 1991). The consumption of hydrogen and oxygen is directly related to the electrical current, as shown in equation (4)

\[
\iiint_{electrode} \rho h(\vec{V} \cdot \vec{n}) dA = N \frac{i}{zF} M
\]

where, \(z\) is the number of electrons transferred for each mole of the reactant. The energy balance in the anode and cathode channels consists of the energies of the masses entering and leaving the control volume, and the heat transfer between the anode or cathode and the fuel cell body. These phenomena are modeled by equations (5) and (6).

\[
\frac{\partial}{\partial t} \iiint_{CV} \rho e dV = \sum_{i} \left( \frac{dm}{dt} C_i T_i \right)
\]

\[
\frac{dQ}{dt} = h_{conv} A (T_{an} - T_{st})
\]

When determining heat transfer in the cathode, the subscripts \(an\) and \(H_2\) would be replaced by \(ca\) and \(O_2\) respectively. The current model calculates separate temperatures for the anode channel, cathode channel, and cell body.

The mass of the cell body does not change, so the general continuity equation (1) can be ignored. The energy equation relates the heat transferred by convection to the anode, cathode and environment, the heat generated during the chemical reaction and the electrical power generated. This can be characterized as

\[
\frac{dQ}{dt} + \frac{dW}{dt} = h_{an} A (T_{an} - T_{body}) + h_{ca} A (T_{ca} - T_{body}) + h_{amb} A (T_{amb} - T_{body}) + \Delta H_{R,T} - Vi
\]

where, \(h\) represents the corresponding convective heat transfer coefficient and \(\Delta H_{R,T}\) is the lower heating value of hydrogen gas.

The PEM fuel cell was model with MATLAB/SIMULINK (Figure 1). The current MATLAB/SIMULINK model is broken down into four subsystems- the anode channel, the cathode channel, stack temperature, and...
stack voltage. The model was set to study different dynamic parameters of the fuel cell, including anode pressure, reactant flow, temperatures and voltage. Figures 3 and 4 demonstrate the results of a test of length five thousand seconds.

**Fig. 2** PEM fuel cell SIMULINK model

**Fig. 3** Current load on fuel cell and corresponding cell voltage

**Fig. 4** Anode, cathode and stack temperatures
4 PEM ELECTROLYZER MODEL

Electrolysis is the process of splitting water into hydrogen and oxygen. It is essentially a fuel cell running in reverse. In fact, as mentioned earlier, some fuel cells are capable of also running as an electrolyzer. Just as with fuel cells, there are multiple methods of splitting the water, including using alkaline cells or polymer electrolyte membranes.

A PEM electrolyzer is physically set up just like the PEM fuel cell, with an anode channel and a cathode channel, separated by a polymer membrane (Görgün, 2006). Electricity applied across the anode and cathode splits the water at the anode side into oxygen and protons (hydrogen ions). The protons travel through the membrane and combine with electrons from the supplied current to become hydrogen, while the oxygen remains at the anode. The last several years have seen a dramatically increased interest in hydrogen as a source of clean renewable energy. This has led to constant improvement in technology in both electrolyzers and fuel cells (Ulleberg, 2003).

In developing a dynamic electrolyzer model, several reasonable assumptions have been made in order to simplify calculations: (i) all gases are assumed to be ideal; (ii) kinetic and potential energies are assumed to be negligible and were not included; (iii) water entering the anode is considered to be 100% pure. The model was somewhat empirical, which made it difficult to adapt for use in other applications. The mathematical model described below is based on a PEM electrolyzer modeling and should prove much more suitable for a generalized regenerative fuel cell system (Görgün, 2006).

The mathematical model for a PEM electrolyzer is based on the same general equations that applied to the fuel cell, namely the continuity equation (1) and the energy equation (2). Because the electrolyzer is essentially a PEM fuel cell running in the opposite direction, it can also be broken down into three control volumes—the anode, the cathode, and the membrane. The electrolyzer is modeled in SIMULINK as shown in Figure 5. The MATLAB/SIMULINK model is broken down into four subsystems—the anode, the cathode, the membrane and voltage analysis.

![Diagram of PEM Fuel Cell Electrolyzer SIMULINK Model](image)

Figures 6 and 7 demonstrate the required voltage and gas production for a varying supply of power.
Fig. 6 Required voltage to the electrolyzer due to a variable supply of power

Fig. 7 Gas production by electrolyzer

5 PHOTOVOLTAIC SYSTEM

The solar cell is the basic unit of the photovoltaic generator. The solar cell is the device that transforms the sun’s rays or photons directly into electricity. There are various models of solar cells made with different technologies available in the market today. These models have varying electrical and physical characteristics depending on the manufacturer. The element most commonly used in the fabrication of solar cells is silicon.

Cells are normally grouped into “modules”, which are encapsulated with various materials to protect the cells and the electrical connectors from the environment. The photovoltaic array is nothing but modules connected in series and parallel. The PV array for the SRFCS consists of several modules which in turn consist of solar cells. The solar cells used in designing the present PV array are crystalline Si solar cells. The solar irradiation or the flux for any given day is like a positive sine curve. The photovoltaic array is model using a model by Hansen et al (2000). The SIMULINK model is shown in Figure 8. For the MATLAB/SIMULINK model, the flux is the input and the output is the power produced by an array. This power can be altered by just changing the number or cells or modules that are connected in series or parallel.

The model is designed so that it calculates the operating cell temperature as a function of solar flux as

\[ T^e = T_o + C_e \times G_o \]  

where,
\[ C_2 = \frac{T_{\text{ref}}^C - T_{a,\text{ref}}}{G_{a,\text{ref}}} \]  

(9)

If \( T_{\text{ref}}^C \) - reference cell temperature is not known, it is reasonable to approximate \( C_2 = 0.03 \text{Csq.m/W} \).

The operating cell open circuit voltage depends exclusively on the operating cell temperature

\[ V_{OC}^C = V_{OC,0}^C + C_3(T_c - T_0^C) \]  

(10)

where, \( C_3 = -2.3 \text{mV/C} \)

The operating short circuit current

\[ I_{SC}^C = C_1 G_a \]  

(12)

where,

\[ C_1 = \frac{I_{SC,0}^C}{G_{a,0}} \]  

(13)

Fig. 8 Photovoltaic System SIMULINK Model

In Figure 9 shows the solar flux and the corresponding short circuit current. In Figure 10, the efficiency of a solar cell and the power produced by the solar array for day.

Fig. 9 Solar flux for a day and (b) corresponding photovoltaic cell short circuit current
6 COMPRESSOR AND TANK

The purpose of the compressors in the regenerative fuel cell system is to be able to fill the reactant tanks to a high pressure in order to increase storage capacity. The current model of the closed-loop power system includes centrifugal compressors. This is because a centrifugal compressor is compact, versatile and does not risk contaminating the flow with lubricant. A multistage compressor with intercooling is capable of producing large pressure increases at high flow volume. Should a high-pressure electrolyzer be selected for use in the final system, a smaller compressor with fewer stages would be required.

For modeling centrifugal compressors there are two principal methods - adiabatic and polytropic (Ulleberg, 1960., Lapina, 1982., Walker, 1972). An adiabatic process is one in which there is not heat transferred in or out of the control volume. A polytropic process allows for heat transfer, and is a more realistic approximation of what occurs. A polytropic process is one for which \( P_1 v_1^n = P_2 v_2^n \) for all states.

The principle concern when modeling the compressors is to determine the electrical power required to generate the necessary pressure difference to fill the tanks. Rather than separately model an electrical motor to provide mechanical power to the compressors, the electrical motor will simply be represented as an additional inefficiency. The power required as a function of pressure difference, mass flow, and inlet temperature for the compressor is given as (Lapina, 1982),

\[
P_{\text{wr}} = \frac{m_{\text{dot}}}{\eta} Z R T n \left( \frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \tag{14}
\]

where, \( Z \) is the compressibility factor and is assumed to be one in the current model. The exit temperature can also be found using another formula (Lapina, 1982) as

\[
T_2 = \left( \frac{P_2}{P_1} \right)^{\frac{n-1}{n}} T_1 \tag{15}
\]

The tank model simply monitors the amount of gas entering and uses a compressible gas equation to calculate the pressure. It is assumed that the flow of the gas is sufficiently slow to allow the gas to reach the temperature of the tank before entering. While there are several equations used to calculate tank pressure, the current model uses the Beattie-Bridgeman equation (Van Wylen, 1976),

\[
P = \frac{R T}{v^c} \left( 1 - \frac{c}{v T} \right) \left( 1 + B_1 \left( 1 - \frac{b}{v} \right) - \frac{A v}{v^c} \left( 1 - \frac{a}{v} \right) \right) \tag{16}
\]

where a, b, c, A, and B are empirical constants that depend on the gas being compressed. The current SIMULINK compressor model is only a single stage compressor without intercooling. The SIMULINK models for compressor and tank are shown in Figures 11 and 12.
OTHER SYSTEM COMPONENTS

The other systems components include control system and the heat exchanger system. The dynamic/transient SRFC system model is designed to control reactant gases and the electrical load. The reactant gas control needs control on the flow rate, temperature, pressure and relative humidity.

For the present system, the fuel cell component is ~ 50% efficient, electrolyzer is ~85% efficient, and compressors are ~ 80% efficient. To keep the fuel cell system a closed loop system, the heat ejected from the various mentioned components is managed by a heat exchanger. The heat exchanger for this system, removes the heat i.e. the inefficiencies from all the components. The SIMULINK models were developed for the control system and the heat exchanger system. Figures 13 and 14 show respectively the control system and the heat exchanger system.
Fig. 13 The SIMULINK model for RFC Control System

Fig. 14 The SIMULINK model for the SRFC heat exchanger

8 INTEGRATED SRFC SYSTEM AND RESULTS

The solar regenerative fuel cell system is designed to provide a continuous power supply for an external load. During much of the day, that power can be supplied by the solar panels with the excess going to the electrolyzer and auxiliary components, but there will be times when the solar panels do not produce sufficient energy to meet the required load. At these times the fuel cell will be activated to provide additional power for the external load and for the auxiliary components that the fuel cell requires. The complete SRFC model is shown in Figure 15. The power required by the auxiliary components was assumed to be roughly 15% of the power sent to the electrolyzer or drawn from the fuel cell.

Simulations were carried out with the complete model. In Figure 16, the results of the simulation for power in terms of solar power, external load and the power required by the auxiliary system such as compressor and control system are shown. The external power is the net power produced from the SRFC system. In Figure 17, the power drawn from fuel cell is shown. The fuel cell is active during the dark hours when the solar power is low or not available. In Figure 18, the power sent to electrolyzer is shown which shows the active hours for the electrolyzer that match the solar power available.
Fig. 15 The integrated model for solar regenerative fuel cell system

Fig. 16 Integrated SRFC system simulation results: system power distribution
Fig. 17 Integrated SRFC system simulation results: power drawn from fuel cell

Fig. 18 Integrated SRFC system simulation results: power sent to electrolyzer

9 CONCLUSIONS

The various components for a detailed solar regenerative fuel cell (SRFC) system are identified. These components included fuel cell, electrolyzer, photovoltaic solar array, power bus, humidifiers, compressor/motor assembly, expander, pumps, phase separators, storage tanks for hydrogen, oxygen and water, control valves and piping. A proton exchange membrane (PEM) fuel cell was modeled in detail that included the mass momentum, energy, chemical reaction rates at cathode and anode. The cell voltage was modeled accounting cell activation and ohmic polarizations. A PEM electrolyzer (which is a reversible PEM fuel cell) was modeled in detail which includes the mass momentum, energy, chemical reaction rates at cathode and anode.

A MATLAB/SIMULINK model for the proton exchange membrane (PEM) fuel cell, electrolyzer, PV system and auxiliary system such as tank, compressors were developed. The performance for each of them was studied. The physical models for each components of SRFC were developed. The physical models were based on the physics, electrochemistry and standard correlations. The principle of operation for each component were defined and based on the governing equations the SIMULINK models for each component were developed. Each component performance were examined and the dynamic response of the integrated SRFC system model was studied.
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