2012 International Conference on Applied Physics and Industrial Engineering

Performance Analysis of Hybrid Solar-Hydrogen Energy System

Jinsheng Xiao, Xuehua Guan

School of Automotive Engineering, Wuhan University of Technology, Wuhan, China

Abstract

The system of solar thermoelectric-photovoltaic hybrid generation for hydrogen production is designed in this paper. The mathematical model of the hybrid system using MATLAB/SIMULINK software is carried out. And the logic control system is designed. The current of the various sub-systems and the energy of the hydrogen storage tank are simulated and analyzed, this paper proves the solar hybrid system can be reliable and effective.

© 2011 Published by Elsevier Ltd. Selection and/or peer-review under responsibility of [name organizer]

Keywords: solar energy; hybrid system; hydrogen production; thermoelectric; photovoltaic

1. Introduction

The demand of the global energy tends to exceed the supply. This situation requires that we must find new energy; it’s an extreme trend to research on a new energy technology to improve the current energy crisis and environmental pollution. In recent years, the use of the hybrid power systems (solar photovoltaic (PV)-thermoelectric (TE), battery, electrolyzer (EL), fuel cells (FC), storage tanks) is becoming a hot point in the field of energy [1]. Therefore, the paper research on a solar hydrogen hybrid system, the system is a combination of different technologies, as a whole, they have a ability of converting solar energy, storing it as chemical energy (in the form of hydrogen) and turning it back into electrical energy when needed. This paper builds a dynamic model, which can predict the dynamic performance of the system, can be used to study the control system, simulation and analysis of power dynamic performance.

For such complex dynamic systems which compose multiple power sources, the mathematical model and simulation model are necessary foundation for design and development of control strategy. Based on some preliminary studies and experimental data, this paper focus on the hybrid vehicle power system, discussing the mathematical and simulation modeling deeply.
2. Hybrid system modeling

Solar hybrid systems are composed of solar, electrolyzer, fuel cells, battery, hydrogen storage systems and the necessary converters\(^\text{[2]}\). Solar hybrid systems can charge the battery through the DC/DC converter; can supply the load through the DC/AC converter. The electricity energy produced by fuel cell can charge the battery through the DC/DC converter; can also supply the load through the DC/AC converter. The electrolyzer can be used to store excess energy of the system, if neither the solar hybrid system nor the battery can provide sufficient electricity; the fuel cell will utilize H\(_2\) to produce electricity for the load. Otherwise, the solar hybrid system can provide sufficient electricity both for load and the battery, the electrolyzer can convert the excess electricity energy into chemical energy and storage inside the hydrogen storage system. The solar hydrogen subsystem that is shown by Fig. 1

![Solar hybrid system principle](image)

**Fig 1 Solar hybrid system principle**

2.1. Solar photovoltaic-thermoelectric system

The PV cells are solid-state devices that convert the solar energy directly into electricity by using the electronic properties of semiconductor materials\(^\text{[3]}\). The work of solar cells can be described as follows\(^\text{[4-5]}\).

Using Kerchief’s current law the terminal current through the PV cell can be expressed as:

\[
I = I_{\text{ph}} - I_d - I_{sh}
\]

where \(I_{\text{ph}}\) is the photocurrent, \(I_d\) is the diode loss current, and \(I_{sh} = \left( V + IR_s \right) / R_{sh} \) is shunt current, respectively.

\[
I_{\text{ph}} = \left[ I_{\text{SCR}} + K_t (T - 298) \right] \frac{\lambda}{1000}
\]

where \(I_{\text{SCR}}\) is the short-circuit current of the photovoltaic on the standard test conditions (A); \(\lambda\) is the solar radiation intensity; \(K_t\) is the temperature coefficient of the short-circuit current.

\[
I_d = I_{os} \left\{ \exp \left[ \frac{q(V + IR_s)}{AKT} \right] - 1 \right\}
\]

where \(I_{os}\) is the dark saturation current of photovoltaic cells; \(q\) is the electron charge; \(K\) is the Bolt Mann constant; \(T\) is absolute temperature; \(A\) is ideal factor of the PN junction; \(R_{sh}\) is the parallel resistance of photovoltaic cell; \(R_s\) is the series resistance of the photovoltaic cell.
\[ I_{on} = I_{on} \left[ \frac{T}{T_r} \right]^3 \exp \left[ \frac{qE_{GO}}{Bk} \left( \frac{1}{T_r} - \frac{1}{T} \right) \right] \] (4)

where \( T_r \) is the reference temperature (301.18 K); \( I_{on} \) is the dark saturation under the current \( T_r \) (A); \( E_{GO} \) is the band gap of the semiconductor materials (J); \( B \) is ideal factor of the PN junction \(^6\).

Solar thermoelectric generator can transform thermal energy directly into electricity by Seebeck effect. It mainly consists of solar collector and thermoelectric PN junction. Focused sunray radiates on the collector makes it to be hot- side, and the temperature of the cold side is controlled by cooling water.

The Heat energy entering the hot side of thermoelectric PN junction consists of Paltier heat, Joule heat and conduction heat. The heat balance equation can be expressed as follows,

\[ Q_h = \alpha I_{TE} T_r - I_{TE}^2 R / 2 + K(T_1 - T_2) \] (5)

where \( Q_h \) is the heat entering into the thermoelectric device is the Seebeck coefficient; \( T_1, T_2 \) is the temperature of hot and cold side; \( R \) is the resistance of thermoelectric device; \( K \) is the total conduction coefficient of the PN junction. The expression of current is as follows,

\[ I_{TE} = \frac{(S_p - S_n)(T_1 - T_2)}{R + R_L} \] (6)

where \( S_p \) is Seebeck coefficient of P-type material, \( S_n \) is Seebeck coefficient of N-type material, \( R_L \) is load resistance.

The total current of solar hybrid system is as follows,

\[ I_{tot} = I_{pv} + I_{TE} \] (7)

2.2. Electrolyzer and fuel cells

The EL and FC share several analogies in their mathematical modeling due to their inherent similarities. The FC provides energy to the system through the process of chemical reaction of hydrogen and oxygen generating into water, while EL converts the electrical energy received from the photovoltaic field to chemical energy splitting water into oxygen and hydrogen store excess energy. This is the PEM fuel cell, the model of the system is as follows \(^7\),

\[
\begin{align*}
P_{bus} &= \eta_{be} P_{fc} = \eta_{be} U_{fc} I_{fc} \\
U_{fc} &= U_{fc,0} + C_{1,fc} T_{fc} + C_{2,fc} \ln \left( \frac{I_{fc}}{I_{fc,0}} \right) + \frac{R_{fc} I_{fc}}{T_{fc}}
\end{align*}
\] (8)

where \( V_{fc,0}, C_{1,fc}, C_{2,fc}, I_{fc,0}, R_{fc} \) are parameters of the fuel cell which determined by experiments. \( T_{fc} \) is the operating temperature of the FC system, we set to 70°C. Saluting the two equations above, we can get \( I_{fc} \), and then we can get the rate of hydrogen consumption by FC. The formula is as follows,
where $\eta_{F, fc}$ is the Faraday efficiency (90%), $N_{fc}$ is the number of the battery cell, $Z$ is the number of electron in the water. Electrolyzer is similar to the fuel cell:

$$V_{el} = V_{el,0} + C_{1,el} T_{el} + C_{2,el} \ln \left( \frac{I_{el}}{I_{el,0}} \right) + \frac{R_{el} I_{el}}{T_{el}}$$ (10)

where $V_{el,0}$, $C_{1,el}$, $C_{2,el}$, $I_{el,0}$, $R_{el}$ are all constants of the electrolyzer, determined by experiments.

$$\dot{V}_{el} = \eta_{F,el} \frac{N_{cells} I_{el}}{zF}$$ (11)

where $\eta_{F, el}$ is the Faraday efficiency (90%), $N_{fc}$ is the number of the battery cell, $Z$ is the number of electron in the water.

2.3. Battery

This sub-system is used with the main purpose of assuring quality of distribution of electrical power to all the connected sub-systems. It acts as control components of EL and FC[8], and improves the dynamic performance of the system. We can calculate the voltage according to the current.

$$U_B(t) = (1 + \alpha t) U_{B,0} + R_I I_B(t) + K_i Q_R(t)$$ (12)

where $\alpha$ is the rate of self-charging, $U_{B,0}$ is the open circuit voltage at time 0, $R_i$ is resistance, $K_i$ is the polarization factor, $Q_R$ is the cumulative charge coefficient. The expression of total storage energy inside the battery $E(t)$ is as follows,

$$E(t) = E_{in} + \int_0^t U_B(\tau) I_B(\tau) d\tau$$ (13)

where $E_{in}$ is the initial battery energy, the battery state of charge defined here as SOC:

$$SOC = \frac{E(t)}{E_{max}}$$ (14)

where $E_{max}$ is the total storage capacity of the battery, SOC is a percentage, will be used as a logic control input.

2.4. Hydrogen storage

Adsorption hydrogen is used in this paper[9]. The remaining amount of hydrogen (the difference between the produced and consumed hydrogen) is sent to the storage tanks.

$$n_a + n_b = n_{tot}$$ (15)
where \( n_a \) is the number of moles adsorbed by activated carbon in hydrogen storage tank. \( n_g \) is the number of gas in hydrogen storage tanks.

This paper will use D-A (Dubinin-Astakhov) adsorption model which can be well expressed by the experimental data.

\[
n_a = n_{\text{max}} \exp \left[ -\frac{RT}{\varepsilon} \ln \left( \frac{P_0}{P} \right) \right]
\]

(16)

where \( n_{\text{max}} \) is the limit adsorption capacity of hydrogen is characterized adsorption energy, \( P_0 \) is the limit pressure.

2.5. Control logic

To coordinate the work of the entire system, the paper introduce the logic control system basing on the operating conditions of the various subsystems \([10\text{-}11]\), according to Kerchief’s current law (KCL):

\[
I_{\text{tot}} - I_{\text{el}} - I_{\text{comp}} + I_{\text{fc}} - I_{\text{load}} \pm I_{\text{bat}} = 0
\]

(17)

If \( I_{\text{tot}} < I_{\text{load}} \), solar hybrid system does not convert enough power to supply the load and the battery releases a positive \( I_{\text{bat}} \). If SOC reaches the minimum set at 25%, the control logic switches off the battery and activates the FC. If \( I_{\text{tot}} > I_{\text{load}} \) the FC is disconnected and the battery is charged. If the battery reaches the maximum SOC set at 85%, it is disconnected and EL switches on. The flow chart is show in Fig. 2.

3. Simulation

MATLAB/SIMULINK is an interactive simulation tool used to design and simulate the control system. This paper establishes a mathematical model using simulation system. The temperature of the fuel cells is assumed to be 70°C, collecting solar radiation intensity from 8:00 to 20:00 one day as an input \([12]\).
The inputs of the system are current of solar hybrid system and load, as shown in Fig. 3.

![Fig. 3 Current of solar hybrid system and load](image)

**4. Simulation Results**

When the system begins to work, the initial pressure of hydrogen is 4 Mpa which can be shown in Fig 4.

![Fig. 4 Pressure and mole number of stored hydrogen](image)

The current which is growing in the form of parabolic produced by the solar hybrid system is less than the required current of the load at 8 am in Fig 4. While the battery compensates for the remaining current of the load, so the value of SOC decreases. It can be seen that the curve begins to decline in Fig 5 at 2400s.
When SOC is getting to 0.25 at 5200s, the control system will disconnect the battery, and start the FC system, while the battery begins to charge, and the FC system begins to supply load and the battery. The currents of FC and EL are shown in Fig 6.

The current provided by the solar hybrid system increases with the increasing of solar intensity, the energy of hybrid system can not only supply the load but also have a redundant energy which can be used to charge the battery. The SOC curve rises as shown in Fig 5 at 8000s. But the SOC is still between 0.25 and 0.85, so the FC system and the EL system do not work. Therefore, we can find that the value of the curve is 0 in Fig 6 between 7200s and 19600s, when the SOC is getting 0.85 at 19600s, the current generated by the solar hybrid system is more than load current, the EL system will be start, and the excess energy will be changed into the energy of compressed hydrogen through the EL system in Fig 6 at 19600s, the EL system produces electricity, and the value of SOC decreases in Fig 5 at 19600s, we can find that the energy curve is rising in Fig 4 at 19600s because the hydrogen begins to be stored.
5. Conclusions

This paper establishes a dynamic model of solar hybrid system, and develops several subsystem models that can accurately predict the dynamic characteristics of the hybrid system. The model can be used for studying dynamic characteristics, designing the control systems as well.

- Solar hybrid system can produce current and supply the load, battery and electrolyzer which can convert the electrical energy to chemical energy in the form of hydrogen supplying FC.
- The system can be control by the logic control system. Each subsystem can work effectively and harmony.
- The hydrogen supplied FC comes from EL by splitting the water.
- The battery plays the role of an energy buffer to handle current spikes and for short-term energy storage. It can also control the system; guarantee the solar hybrid system more reliable and effective.

References

[1] Shijun Hai, Xin-Jian Zhu, Sui Health, Zhongzhi Dan. Modeling and Simulation of Fuel Cells - Photovoltaic Hybrid Power System. Power Sources (In Chinese)

[2] S. Kelouwani, K. Agbossou, R. Chahine, Model for an energy conversion in renewable energy system with hydrogen storage, J. Power Sources 140 (2) (2005) 392–399.

[3] Yun Hai-Tao, Zhao Yulan, Wang Jizhong. modeling and simulation of Fuel cell hybrid vehicle. System Simulation (In Chinese)

[4] J.P. Dunlop, Batteries and charge control in stand-alone photovoltaic systems fundamentals and application, Cocoa, Sandia National Laboratories, 1997.

[5] Gabriele Zini,Riccardo Marazzi,Simone Pedrazzi,Paolo Tartarini. A solar hydrogen hybrid system with activated carbon storage. International journal of Hydrogen Energy,2009,1-9

[6] DuHui,Research on the Control Systerm of Solar Energe Potovotic Generation. Dissertation(2008) 7-15 (In Chinese)

[7] M. Uzunoglu , O.C. Onar, M.S. Alam, Modeling, control and simulation of a PV/FC/UC based hybrid power generation system for stand-alone applications. Renewable Energy 34 (2009) 509–520

[8] S. Pedrazzi, G. Zini , P. Tartarini, Complete modeling and software implementation of a virtual solar hydrogen hybrid system, Energy Conversion and Management 51 (2010) 122–129

[9] Valenciage F, Pulestun P F, Battaiotto P E. Power control of a photovoltaic array in a hybrid electric generation system using sliding mode techniques. IEE Proceedings: Control Theory and Applications, 2001,148 (6): 448-455.

[10] S.R. Vosen, J.O. Keller, Hybrid energy storage systems for stand-alone electric power systems: optimization of system performance and cost through control strategies, International Journal of Hydrogen Energy 24 (1999) 1139-1156

[11] Maclay JD, Brouwer J, Samuelsen GS. Dynamic modeling of hybrid energy storage systems coupled to photovoltaic generation in residential applications Power Sources 2007;163:916-25.

[12] A. Bilodeau, K. Agbossou, Control analysis of renewable energy system with hydrogen storage for residential applications. Journal of Power Sources 162 (2006) 757–764