Maximum Efficiency Point Tracking Control for Hydrogen-Production Load Based on Optimal Gradient Algorithm

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Abstract. Renewable energy sources are limited to connect to the grid because of the fluctuating and intermittent output power, and a large-scale power curtailment phenomenon thus appears recently. Many energy storage technologies can realize peak-shaving and valley-filling function, but there is no suitable method that can be widely used because of the cost, geographical position, capacity, materials and so on. Hydrogen production load (HPU) can effectively absorb the electrical power and the produced hydrogen gas can be used as a high-energy fuel. But the energy conversion efficiency of HPU is an important factor that directly determines whether it can be widely used. The energy conversion efficiency curve from electric energy to chemical energy is deduced, and the result shows that it increases first and then decreases with the increase of the input current. Then the optimal gradient algorithm is used to track the maximum efficiency point in order to improve the efficiency of the whole system. Besides, a compromise control strategy considering the efficiency and power consumption capacity is given to absorb much more renewable energy. Finally, the control strategies are verified with experimental results.

Introduction

The distributed generators can extract the power energy from the renewable energy sources, such as solar energy, wind energy and hydro energy, which can alleviate the energy crisis problem to a large extent [1]. However, the intermittence and fluctuation of the renewable energy sources fail to realize the accurate scheduling and reliable grid-connection operation, which has caused large power curtailment phenomenon [2]. According to the report, it has abandoned 54.3 billion kWh hydrogen energy, 41.9 billion kWh wind energy and 7.3 billion kWh solar energy in China last year. Since the local loads only consume a small part of the renewable energy power, it is significant to find effective energy storage methods or transfer techniques from electrical energy to other kinds of energies.

Energy storage methods are mainly divided into mechanical energy storage, electrical energy storage, electrochemical energy storage, thermal energy storage and chemical energy storage. Mechanical energy storage includes pumped energy storage, compressed air energy storage and flywheel energy storage [3]. The pumped energy storage method can absorb a great deal of energy, but the location of pumped storage is very limited, the investment cycle is large, and the water evaporation loss should also be considered. Similarly, electrical energy storage includes supercapacitor energy storage and superconducting energy storage [4]. The supercapacitor has the low energy density and bulky volume. The electrochemical energy storage includes lead-acid battery energy storage and lithium-ion battery energy storage [5]. Lead-acid owns the disadvantages of low energy density, short lifespan and gradually decreasing available capacity. The thermal energy storage means that the phase-change materials filled in the buildings can transfer electrical energy into thermal energy, which can replace the air conditioners to maintain the temperature of the room stable. But the application is very limited [6]. In summary, there are many energy storage methods trying to
absorb the renewable energy source, but they cannot be widely applied due to the cost, geographical location, capacity or materials and so on.

HPU belongs to one of the chemical energy storage methods, which can achieve large-capacity and long-term absorption of the renewable energy sources [7]. Besides, the product hydrogen is stored as clean high-energy fuel or can feed back to the main grid through fuel cell power generation. Although the energy conversion efficiency of the alkaline electrolyzer method is slightly lower, it has been widely applied because of the easy working conditions. Based on experimental parameters, the effects of temperature and cathode plate area on the voltage of alkaline electrolyzer were analyzed, and the empirical equations based on thermodynamics, heat transfer theory and electrochemical theory were established [8]. According to the abovementioned electrochemical model, the system model maintaining photovoltaic generation, HPU, fuel cell and supercapacitor is constructed to realize coordinated control strategy, which can provide a junction between the electricity energy and chemical energy and promote the development of integrated energy internet [9].

As mentioned above, scholars have studied the hydrogen energy for years, but they don’t focus on the energy conversion efficiency of hydrogen product unit, which is an important factor that can determine its wide application. In this paper, we first analyze the relationship between the voltage and current based on the alkaline electrolyzer. Second, the energy conversion efficiency from electrical energy to hydrogen energy is derived and the result shows that it increases first and decreases gradually with the increase of input power. Third, the optimal gradient algorithm is applied in the control strategy, which can guarantee the economy of the hydrogen product unit. Fourth, in order to increase the capacity of hydrogen production load, a compromise control strategy between efficiency and capacity is proposed. Finally, the experimental results are presented to show the control effectiveness of the proposed control strategy.

### Analysis of the Hydrogen Production Load Characteristics

The hydrogen product unit (HPU) contains many cell monomers. Based on the electrical energy and extra thermal source, the hydrogen product unit can electrolyze water and produce hydrogen and oxygen. There are reversible and irreversible reactions in each cell monomer, and the irreversible reaction includes ohmic polarization reaction and concentration polarization reaction. The output voltage of hydrogen production load can be expressed as

\[
\begin{align*}
V_o &= V_{rev} + V_{ohm} + V_{con} \\
V_{rev} &= NV_{re}
\end{align*}
\]

where \(V_{re}\) is the terminal voltage of the single electrolyzer unit, \(V_{rev}\) is the reversible voltage, \(V_{ohm}\) is the overvoltage caused by the ohmic polarization, \(V_{con}\) is the overvoltage caused by concentration polarization, \(N\) is the number of the electrolyzer, \(V_o\) is the terminal voltage of HPU.

The reversible voltage, ohmic polarization voltage and the concentration polarization voltage are obtained as [8]

\[
\begin{align*}
V_{rev} &= 1.253 - 2.4516e^{-T} \\
V_{ohm} &= \alpha + \beta T + \gamma T^2
\end{align*}
\]

(2)

| variable | value | variable | value | variable | value | variable | value |
|----------|-------|----------|-------|----------|-------|----------|-------|
| \(r_1\) | 2.3e-32m\(^2\) | \(t_2\) | -1.3029e-2 m\(^8\)C\(^{-4}\) | \(F\) | 96485 Cmol\(^{-1}\) | \(R_0\) | 284.7 kJmol\(^{-1}\) |
| \(r_2\) | -1.107e-72m\(^8\)C\(^{-4}\) | \(t_3\) | 2.513e-3 m\(^3\)C\(^{-1}\) | \(a\) | 2 | \(S\) | 90 Jmol\(^{-1}\)K\(^{-1}\) |
| \(s_1\) | 1.286e-1V | \(a\) | 3 m\(^2\) | \(K\) | 1300 | \(\lambda\) | 0.3 |
| \(s_2\) | 2.378e-3 V\(^\circ\)C | \(A\) | 0.25 m\(^2\) | \(T\) | 25\(^\circ\)C | \(\beta\) | 2.98e-3 |
| \(s_3\) | -0.606e-5 V\(^\circ\)C\(^2\) | \(N\) | 100 | | | | |
| \(t_1\) | 3.559e-2 m\(^2\)A\(^{-1}\) | | | | | | |

Table 1. Parameters of the equation (2) and (8).
where $T$ is the working temperature, $I$ is the operating current, $A_{ele}$ is the cathode plate area, $r_1$, $r_2$, $s_1$, $s_2$, $s_3$, $t_1$, $t_2$, $t_3$, $\alpha$ are the correlation coefficients.

According to the equation (2) and the parameters in Table 1, the relationship among the terminal voltage, working current and temperature is shown in Figure 1. It can be found that the terminal voltage is greatly affected by the working current and increases rapidly when the current is very small. Besides, the terminal voltage increases slowly when the working current locates at a relatively large value. Similarly, the influence of the working temperature on the terminal voltage is concluded that the terminal voltage decreases gradually with the increase of the working temperature. It is because the concentration polarization voltage decreases at the high temperature.

According to Faraday’s law of electrolysis, the molar flow rate of the produced hydrogen can be calculated according to the rate of the input charge as

$$v_h = \frac{dn}{dt} = K \frac{NI}{\sigma F}$$

(3)

where $v_h$ is the hydrogen production rate, $n$ is the Mole number, $K$ is electrochemical equivalent coefficient, $F$ is the Faraday coefficient, $\sigma$ is the chemical valence variation of the reactant.

According to the calorific value coefficient of hydrogen, the chemical heat energy of the produced hydrogen in unit time can be calculated as

$$Q_c = K \frac{NI}{\sigma F} R_h$$

(4)

where $R_h$ is the calorific value coefficient of hydrogen.

The input energy consists the input electric energy $Q_{power}$ and the heat energy $Q_{heat}$ from the extra heat source. According to equation (1), the input power can be obtained as

$$Q_{power} = V_I = N(V_{em} + V_{ohm} + V_{con})I$$

(5)

The ohmic polarization process and concentration polarization process of HPU will generate extra heat energy $Q_{extra}$, which can be calculated as

$$Q_{extra} = N(V_{ohm} + V_{con})I$$

(6)

To maintain the temperature of the reaction process, the external heat source is necessary to compensate the lost heat for HPU, and it can be written as

$$Q_{heat} = TS - \lambda Q_{extra} = (TS - \lambda N(V_{ohm} + V_{con})I)$$

(7)

where $S$ is the entropy at the temperature $T$, and $\lambda$ is the thermal dissipation coefficient.

Based on the equations (1)~(7) and the specified parameters in Table 1, the energy conversion efficiency is calculated as

$$\eta\% = \frac{Q_{c} \cdot (1 - \beta T)}{Q_{con} + Q_{power}} \times 100\% = \frac{KR_h(1 - \beta T)}{2FV_{em} + 2F(1 - \lambda)\frac{L_T + r_2 T}{\lambda \alpha} I + (s_1 + s_2 T + s_3 T^2) \log(\frac{t_1 + s_1 T + s_2 T^2}{\lambda \alpha} I + 1)} + \frac{2FTS}{NT} \times 100\%$$

(8)

Figure 1. Relationship between voltage and current as well as temperature of hydrogen production load.

Figure 2. Relationship between efficiency and current as well as temperature of hydrogen production load.
According to the equation (8) and the parameters in Table 2, the relationship among the efficiency, the input current and the temperature of HPU can be drawn in Figure 2. It can be seen that the energy conversion efficiency increases first and then decreases with the increase of the input current. The reasons are presented as follows. The additional heat energy needs to be added to maintain the temperature in the reaction process. Hence, the power consumption of HPU will be limited when the input current is very small, thus the efficiency of the system is very low in this situation. With the increase of the input current, the absorbed power is increased, and the compensated thermal energy is relatively small, therefore the efficiency of the system gets improved. When the input current increases to a certain value, the concentration polarization and ohmic polarization will consume lots of electric energy. This part of energy cannot be transformed into chemical energy, which will reduce the efficiency of the system. The concentration polarization and ohmic polarization process will produce much heat, which can compensate some of the heat provided by the external thermal source. Hence, the efficiency will decrease slowly.

**Control Strategy of the Hydrogen Production Load**

The hydrogen production load can be equivalent to a controlled voltage source according to equation (2), and the specific circuit is shown in Figure 3(a). Since the terminal voltage of hydrogen production load is determined by its working current, the working current is sampled to be the control signal in the control strategy. Considering the bus voltage is much larger than the terminal voltage of hydrogen production load, the Buck converter is used. The reference current value can be obtained by the control strategy in Figure 3(b) or Figure 3(c). Figure 3(b) shows the maximum efficiency point tracking mode. Figure 3(c) shows the setting efficiency point tracking mode. The optimal gradient algorithm is used to accelerate the tracking speed which can be expressed as

\[ i_{H2}(n+1) = i_{H2}(n) + kg(i_{H2}) \]

where \( i_{H2}(n) \) is the sampling current of the \( n \)th cycle, \( i_{H2}(n+1) \) is the sampling current of the \( (n+1) \)th cycle, \( k \) is a non-negative constant, and \( g(i_{H2}) \) is the gradient value of efficiency to current and can be expressed as

\[ g(i_{H2}) = \frac{d\eta(i_{H2})}{di_{H2}} = \frac{\eta(n+1) - \eta(n)}{i_{H2}(n+1) - i_{H2}(n)} = \frac{\Delta \eta}{\Delta i_{H2}} \]

If \( g(i_{H2}) > 0 \), it indicates that the working point is on the left side of the maximum efficiency point. If the gradient value is large, it means that the working point is far from the maximum efficiency point. Then a large step size is adopted as shown in region \( S_1 \) in Figure 3. If the gradient value is small, it means that the working point is near the maximum efficiency point. Then a small step size is adopted as shown in region \( S_2 \) in Figure 3. If \( g(i_{H2}) < 0 \), it indicates that the working point is on the right side of the maximum efficiency point. If the gradient value is large, it means that the working point is far from the maximum efficiency point. Then a large step size is adopted as shown in region \( S_3 \) in Figure 3.

![Diagram](image-url)
3. If the gradient value is small, it means that the working point is near the maximum efficiency point. Then a small step size is adopted as shown in region $S_3$ in Figure 3. Therefore, the optimal gradient iteration algorithm can vary the step size to effectively achieve the rapidity of climbing and the stability in the maximum efficiency point.

**Experimental Results**

The control strategy is verified on the RTLAB experimental platform as shown in Figure 4. The analogy signal generated by RTLAB is output into the controller DSP28335. The controller executes the control algorithm and then inputs the PWM pulse signal into the driving circuit module of RTLAB. The parasitic parameters and other factors are considered in the circuit model to make it run in the same way as in the actual environment, thus ensuring the feasibility of the control strategy. The results based on RTLAB experimental platform are shown in Figure 5. Figure 5 (a) shows the control result based on maximum efficiency point tracking mode. The operating temperature in stage I and stage III is $T=75^\circ C$, and that in stage II is $T=80^\circ C$. Figure 5 (b) shows the control result based on the setting efficiency point, in which the operating temperature in stage I and stage III is $T=75^\circ C$, and that in stage II is $T=80^\circ C$. Figure 5 (c) shows the switching control effectiveness between the two abovementioned control modes. Stage I and III are based on the maximum efficiency point, and Stage II is based on the set efficiency point. As can be seen from Figure 6, the hydrogen production load can be switched rapidly between the maximum efficiency point tracking mode and the setting efficiency point tracking mode, thus achieving the absorption of renewable energy.

![Figure 4. Experimental platform.](image1)

![Figure 5. Experimental results.](image2)

**Conclusion**

Hydrogen production load can realize large-scale and long-term power consumption by converting electrical energy into chemical energy, which may be able to solve the power curtailment of the renewable energy sources because of the disadvantages of fluctuation and intermittence. But the energy conversion efficiency is particularly important, which can determine its wide application. Firstly, the energy conversion efficiency of the hydrogen production load is derived and the result shows that the energy conversion efficiency increases first and then decreases slowly with the increase of the input current. Secondly, the maximum efficiency point tracking mode and setting efficiency point tracking mode are designed. The experimental results show that the switching of the control strategy can guarantee that the hydrogen production load works at the maximum efficiency point tracking mode when the renewable energy is limited, and at the setting efficiency point tracking mode when renewable energy is sufficient.
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