Design and Simulation of LLC Resonant Converter for Hydrogen Production Based on Proton Exchange Membrane Electrolysis

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Abstract—This paper studies the relationship between the parameters in LLC resonant circuit based on the fundamental wave analysis method, analyzes the gain curve and the soft-switching conditions of the power tube, gives the selection method of the parameters k and Q and calculates the resonant component parameters. In this paper, a closed-loop frequency modulation control method is used to control the DC output voltage of the resonant converter. At the same time, mathematical modeling and analysis are carried out for the electrochemical model and thermal model of the proton exchange membrane (PEM) hydrogen production electrolyzer, and the Simulink simulation tool is used to complete the joint simulation of the PEM electrolysis model and the LLC resonant converter. The simulation results fully reflect the actual control process.

1. INTRODUCTION

With the launch of the national "dual carbon" plan, hydrogen as clean energy has been gradually valued by society [1-2]. At present, the main method of producing hydrogen is the electrolysis of water to produce hydrogen [3-5]. The hydrogen production power supply generally uses traditional thyristor rectification, which is bulky and low in efficiency. With power electronic devices, new topologies, and new control strategies, the introduction of hydrogen production power converters has made considerable progress. To pursue higher power density and smaller conversion volume, the switching frequency of hydrogen production power converters has become higher and higher. However, with the increase of switching frequency, switching loss has become one of the bottlenecks in the development of high power density converters [6]. For this reason, domestic and foreign scholars have proposed many new converter topologies and key control technologies to solve this practical problem. Among them, the LLC resonant DC-DC converter suitable for wide voltage or wide load range has natural soft switching characteristics, which can achieve high power density and high conversion efficiency at the same time, and is highly valued by industry and academia [7]. The LLC resonant circuit, as a kind of high-efficiency DC/DC converter, achieves the purpose of reducing switching loss through the opening and closing of the resonant cavity voltage and current. This paper takes the full-bridge LLC resonant converter as the research object, designs the resonance parameters [8-11], and realizes closed-loop control by collecting the output voltage signal feedback [12-15]. With the help of MATLAB software, the control simulation...
of the LLC resonant converter was completed and combined with the mathematical modeling and analysis of the PEM electrolytic cell[16-18], the joint simulation between the LLC resonant converter and the PEM electrolytic cell was realized. The main factors affecting the PEM electrolyzer are given, which has a good guiding significance for practical applications.

2. THE WORKING PRINCIPLE OF LLC RESONANT FULL-BRIDGE CONVERTER

Figure 1 shows the LLC DC converter and electrolytic cell topology. The primary is an H-bridge structure, and the resonant inductance $L_r$, the resonant capacitor $C_r$ and the magnetizing inductance $L_m$ form a resonant circuit. The secondary is composed of rectifier diodes VD1, VD2, and output filter capacitor $C_o$.

![Fig 1. LLC DC converter and electrolytic cell topology](image)

The converter has two resonance points, the resonance frequencies of $L_r$ and $C_r$ are:

$$f_r = \frac{1}{(2\pi\sqrt{L_rC_r})}$$  \hspace{1cm} (1)

The resonant network is composed of $L_m$, $L_r$, and $C_r$, and its resonant frequency is:

$$f_m = \frac{1}{(2\pi\sqrt{(L_r + L_m)C_r})}$$  \hspace{1cm} (2)

This circuit adopts frequency conversion control. When $f_m < f_r < f_f$, the converter has many advantages. At this time, the main operating waveform of the circuit is shown in Figure 2. One switching cycle can be divided into 8 switching modes for analysis. The working principle of the converter in half a switching cycle is shown in Figure 2.

![Fig 2. The current and voltage waveforms of each switch tube](image)

(1) Mode 1: $t_0-t_1$

At time $t_0$, the switch VS2 and VS3 are off, and the secondary current $i_{VD}=0$. Since $L_m$ is relatively large, it can be considered that the excitation current $i_{Lm}$ remains unchanged. In this interval, $i_{Lm}$ charges...
the output capacitors of VS2 and VS3, and the drain-source voltages $u_{ds}$ (VS2) and $u_{ds}$ (VS3) of VS2 and VS3 rise linearly. At time $t_1$, $u_{ds}$ (VS2) and $u_{ds}$ (VS3) rise to be equal to $E_{in}$.

(2) Mode 2: $t_1-t_2$

Starting from $t_1$, the primary current $i_{Lr}$ changes the flow path, that is, the parasitic body diode flowing through VS1 and VS4, which creates conditions for VS1 and VS4 to achieve ZVS. The resonance of $i_{Lr}$ rises, and the secondary diode VD1 turns on. The voltage across the primary and secondary windings of the transformer is clamped, and $i_{Lm}$ rises linearly.

(3) Mode 3: $t_2-t_3$

At time $t_2$, VS1 and VS4 are triggered to turn on, and $i_{Lr}$ crosses from negative to zero. $L_r$ and $C_r$ form a resonance network. $i_{Lm}$ continues to rise linearly.

(4) Mode 4: $t_4-t_5$

As $i_{Lr}$ decreases and $i_{Lm}$ increases, at $t_3$, $i_{Lr}=i_{Lm}$, and $i_{VD}$ drops to zero. Therefore, the secondary diode can realize ZCS, and the reverse voltage it bears is clamped to the output voltage, eliminating parasitic oscillation. At $t_4$, VS2 and VS3 are triggered to conduct. The working process of the other half cycle is the same as the first half cycle.

3. CHARACTERISTIC ANALYSIS AND CONTROL SIGNAL DESIGN OF LLC RESONANT CONVERTER

Because of its frequency-selective characteristics, the resonant cavity is most sensitive to the fundamental wave components near the resonant frequency and has a good filtering effect on the higher harmonic components that deviate from the resonant frequency. It can be considered that only the fundamental wave component can transmit power, so it can be analyzed by the fundamental wave equivalent method. The equivalent circuit diagram is shown in Figure 3.

![Fig 3. Equivalent circuit diagram](image)

The output voltage of the resonant cavity is $E_{os}$, and the input voltage of the resonant cavity is $E_{in}$. The gain of the resonant cavity is defined as the ratio of the two. The normalized direct current gain formula of the resonant cavity can be obtained:

$$
|G(f)| = \frac{Kf_n^2}{\sqrt{(1+K)f_n^2 - 1}^2 + QKf_n(f_n^2 - 1)^2}
$$

In the formula: $k = \frac{L_m}{L_r}$, $f_n = \frac{f_s}{f_r}$, $Q = \frac{2\pi f_L}{R_{eq}}$, $R_{eq}$ is the equivalent load resistance, $f_s$ is the switching frequency.

3.1 Operating characteristics of LLC under no-load condition

At no load, the operating characteristics of the LLC resonant converter are shown in Figure 4. As the frequency increases, the gain gradually becomes a constant, and the DC output becomes non-adjustable, which causes the ZVS to be not satisfied at light load, and there is a The empty ratio is lost. In the no-load state, it is equivalent to the load impedance approaching infinity, the quality factor $Q$ in formula (3) can be regarded as zero, and the voltage gain can be simply expressed as:
\[ \text{Gain} = \frac{1}{1 + \frac{1}{k} \left( \frac{1}{f_n} - 1 \right)} \] (4)

\[ I_{\text{min}} = 4C_{\text{oss}} \frac{E_{\text{in}}}{I_{\text{dead}}} + 2C_j \frac{E_o}{I_{\text{dead}}} \] (5)

\[ I_{pk} \geq \frac{2E_{\text{in}}C_j}{I_{\text{dead}}} \] (6)

\[ L_m \leq \frac{T \cdot I_{\text{dead}}}{C_j} \] (7)

3.2 DC gain analysis of LLC resonant converter

The relationship between the normalized frequency and gain is shown in Figure 5. Given the value of \( k \) unchanged, the value of \( Q \) is used as a variable. It can be seen from the figure that as the frequency fluctuates within the switching frequency range, the converter gain decreases. When the LLC resonant converter works at the resonant frequency, the gain is not affected by the load parameter settings.
Fig 5. Only change the resonant network characteristic curve of $Q$

As shown in Figure 6 at the resonance point ($f_n > 1$) in the area on the right, $Q$ value does not change, change the magnitude of the inductance ratio $k$, the gain of LLC resonant converter will drop very slowly, showing very hard characteristics. Considering the application of an LLC resonant converter, to achieve the ideal gain, this feature can be used in the region below the resonance point ($f_n < 1$). When the frequency is in this region, it can be seen that the gain of the LLC resonant converter increases as the value of $k$ decreases. Therefore, when designing the parameters of the resonant converter, the values of $Q$ and $k$ are selected as far as possible to satisfy the region below the resonance point, and the adjustable gain range becomes wider at this time.

Fig 6. Only change the resonant network characteristic curve of $k$

LLC resonant converter has the characteristic of natural soft-switching ZVS, and the turn-on loss occupies the main part in the actual process. The parameter selection of inductance and capacitance energy storage components affects the resonant frequency, which is closely related to it. When $f_r$ is constant, the resonant inductance $L_r$ is determined, and the value of $k$ will affect the value of the magnetizing inductance. For the inductor voltage value, the larger the inductance, the smaller the current flowing through the inductor. The inductor loss is proportional to the inductance value and the square of the inductor current value. Within a given frequency range, the greater the difference between the switching frequency and the resonance frequency, the greater the gain of the LLC resonant converter.
Therefore, broadening the gain range of the LLC resonant converter can be achieved by changing the frequency range.

3.3 Design of Driving Signal of LLC Resonant Converter

The pulse control signal module is shown in Figure 7. The full-bridge LLC resonant converter is used as the research object. The difference between the given voltage signal and the DC output voltage signal collected by the load is used as input. After closed-loop PI calculation, the voltage-controlled oscillator is used. After adjustment, the switching frequency corresponding to the voltage value is obtained. The trigger signal is generated through the delay module and the dead time is set in the driving signal at the same time to prevent the two switching tubes of the same bridge arm from being turned on at the same time. In this link, proportional integral control can make the dynamic process of the system get a quick response. This process uses a voltage-controlled oscillator to adjust the PI parameters of the error signal, converts the voltage signal into a drive signal with a corresponding response frequency, and uses the output voltage signal feedback to achieve closed-loop control, and the control structure is simplified.

![Fig 7. Drive signal generation module](image)

4. MODELING AND ANALYSIS OF ELECTROLYZER

Analyzing the working process of the electrolytic cell, it can be found that in the process of electrolyzing water, there are mainly two parts of work. One part is the electrochemical reaction, which mainly reflects the changes in the voltage of the electrolytic cell during the hydrogen production process, and the other part is the heat exchange. Reflect on the heat transfer and heat exchange between the system and the internal and external environment during work.

4.1 Electrochemical submodel

The electrochemical sub-model defines the working voltage $U_{cell}$, which reflects the working status of the entire system. Its value is equal to the open-circuit voltage $U_{ocv}$, the activation overvoltage $U_{act}$, the ohmic overvoltage $U_{ohm}$ and the concentration overvoltage $U_{con}$.

$$U_{cell} = U_{ocv} + U_{act} + U_{ohm} + U_{con}$$  (8)

4.2 Thermal submodel

To better study the heat transfer and heat exchange between the internal and external environments of the entire electrolytic cell during the working period, a control volume $C$ is defined, and the expression of $C$ is as follows

$$C \frac{dT}{dt} = W_1 - W_2 - Q_{cool} - Q_{loss} - Q_n$$  (9)

In the formula: $W_1$ is the sum of heat and electric energy input during the electrolysis of water; $W_2$ is work input by the water pump due to hydraulic, mechanical, and total heat dissipation; $Q_{cool}$ is the heat discharged by the system in the heat exchange; $Q_{loss}$ is the heat loss of the system to the environment;
\( Q_n \) is the sum of the enthalpy leaving the control volume \( C \) and the enthalpy of oxygen and hydrogen.

5. ANALYSIS OF SIMULATION VERIFICATION RESULTS

In this paper, MATLAB/Simulink software is used to conduct system joint simulation of LLC resonant converter and electrolyzer under PID control of closed-loop frequency conversion. During the simulation, the resonance frequency of the LLC resonant converter is set to 20kHz, and the rated input works at the resonance frequency. According to the above analysis, other parameter settings are shown in Table 1.

The parameters of the LLC converter simulation model are shown in the table below.

| Parameters            | Values       |
|-----------------------|--------------|
| Input voltage         | 750V         |
| Input voltage         | 200V         |
| Power                 | 7.5kW        |
| Inductance ratio      | 6            |
| Resonant frequency    | 20kHz        |
| Resonance inductance  | 0.3*10^{-3}H |
| Resonant capacitor    | 2*10^{-7}H   |
| Magnetizing inductance| 1.8*10^{-3}H |
| Transformer ratio     | 4            |

Figure 8 is a joint simulation diagram of LLC resonant converter and electrolysis hydrogen production. The output voltage of the LLC resonance circuit will link the two simulations into a system simulation. The LLC resonance circuit includes a main circuit module, a resonance circuit module, and a drive signal generation module. The electrolyzer model mainly includes an anode module, cathode module, hydrogen storage module, and output voltage module.

![Diagram of LLC resonant converter and electrolyzer simulation](image)

**Fig 8. System joint simulation diagram**

Figure 9 shows the waveform of the output voltage. It can be seen from the figure that the waveform of the output voltage is relatively smooth and can be well stabilized at 200V, meeting the design goal of ripple less than 1%.
Figure 10 shows the waveforms of $u_{ds}(VS_1)$ and $i_{VS1}$. It can be seen from the figure that when $i_{VS1}$ is high, $S_1$ turns on and $u_{ds}(VS_1)$ drops to 0; when $i_{VS1}$ is low, $S_1$ turns off, and $u_{ds}(VS_1)$ bears a 750V DC voltage. When $i_{S1}$ is still low, $u_{ds}(VS_1)$ quickly drop from 750 to 0, which shows that the charge of $C$ is released to 0 during this period, and then $D_1$ is naturally turned on. After a while, $i_{VS1}$ rises to high. In other words, $u_{ds}(VS_1)$ drop to 0 first before $S_1$ is opened, that is, $S_1$ realizes ZVS. $S_2$-$S_4$ achieves similar ZVS waveforms, so I won’t repeat them here.

Figure 11 shows the waveforms of $i_{VD1}$ and $U_{VD1}$. When the rectifier diode is disconnected, the voltage at both ends should be high, and the current flowing through the diode has dropped to 0 at this time, and a zero-current shutdown is reached in this process.

As shown in Figure 12, it is the voltage waveform of the resonant capacitor voltage in the steady-state. It can be seen that the working process of the circuit is stable, and the output waveform is a sine wave.
Fig 12. The resonant capacitor voltage waveform

Figure 13 is a static simulation experiment diagram of the system. Figure 13 depicts the stack polarization curve under the conditions of the working pressure of the electrolytic cell stack at 0.3MPa and the stack temperature from 320K to 390K. The curve shows that the stack voltage decreases as the operating temperature of the stack increases. Figure 14 describes the relationship between the voltage of the electrolytic cell and the output pressure under different current densities. The curve shows that when the pressure is constant, the greater the current density, the higher the voltage.
Figure 15 is a dynamic simulation experiment diagram of the system. An oxidation reaction occurs at the anode of the electrolytic cell, and electrons are lost. After electrons enter the cathode, a reduction reaction occurs. To carry out the dynamic response experiment of the electrolytic cell stack, the following structure and operating parameters are given. The electrolyzer is composed of 50 single cells in series, each cell has an activation area of 50cm². Assume that the working temperature is 353K and the working pressure is 100KPa. Figure 15(a)-(f) are the current, voltage, hydrogen flow, storage tank pressure, anode pressure, and cathode pressure of the electrolytic cell stack, respectively.

The simulation results are described as follows:

(1) When t=1s, t=2s, and t=4s, the current of the electrolyzer increases step by step, and the voltage, anode pressure, and cathode pressure all increase rapidly. This is because the purpose of the electrolyzer is to electrolyze water to produce hydrogen and oxygen. The amount of hydrogen and oxygen produced is directly proportional to the current density. The higher the current, the faster the hydrogen and oxygen produced, and the corresponding pressure increases. Similarly, at t=3s, the current decreases, and the voltage, anode pressure, and cathode pressure all decrease accordingly. The relationship between current and voltage conforms to the polarization characteristics of the electrolytic cell battery.

(2) The hydrogen flow rate and the pressure change of the hydrogen storage tank are caused by the current change. When t=1s, t=2s, and t=4s, the current of the electrolytic cell suddenly increases, and the hydrogen flow rate and the pressure of the storage tank also suddenly increase. This is because the increase in current accelerates the production rate of hydrogen. Since the volume of the storage tube remains unchanged, according to the ideal gas law, the gas flow increases, and the pressure in the storage tank increases, which is in line with the actual situation. The flow rate of hydrogen and the pressure of the hydrogen storage tank are changed due to the current change. At t=1s, t=2s, and t=4s, the current of the electrolytic cell suddenly increases, and the flow rate of hydrogen and the pressure of the storage tank also suddenly increase. This is because the increase in current accelerates the production rate of hydrogen. Since the volume of the storage tube remains unchanged, according to the ideal gas law, the gas flow increases, and the pressure in the storage tank increases, which is in line with the actual situation. When t=3s, the current of the electrolytic cell suddenly decreases, and the pressure of the storage tank does not decrease suddenly but slowly increases. This is because the gas in the storage tank does not flow out of the storage tank. Although the current decreases, the electrolyzer electrolyzes the water. The process is still going on, so the gas in the tank continues to increase, but the rate of increase is relatively slow. It is also in line with actual working conditions. However, since the PEM electrolytic cell is composed of proton exchange membranes, catalysts, etc., if the input current changes frequently, the working pressure of the electrolytic cell changes, which also has a great impact on the life of the
electrolytic cell. Therefore, buffer energy storage devices and certain energy management amplification should be used to maintain the stability of the input power of the electrolytic cell. Because the supercapacitor is directly connected to the DC bus, it can quickly output or absorb the energy needed due to power or load fluctuations, alleviate frequent changes in the pressure of the electrolytic cell, and extend the working life.

6. CONCLUSION
By studying the working principle of the LLC resonant circuit, the fundamental wave analysis method is used to perform equivalent analysis on the circuit, and the relationship between the various resonant parameters is given. Because it is difficult to select the resonant parameter $k$ value and $Q$ value, this paper analyzes the DC gain curve and the conditions for realizing the switch tube ZVS, obtains the selection method of $k$ value and $Q$ value, and calculates the parameters of the corresponding resonant components. For hydrogen production by electrolysis, this article analyzes the various voltage modules in the electrochemical reaction, the energy modules in the heat exchange process, and models them. For hydrogen production by electrolysis, this article analyzes the various voltage modules in the electrochemical reaction, the energy modules in the heat exchange process, and models them. Finally, MATLAB simulation software was used to carry out the system joint simulation: The LLC resonant circuit realizes output voltage stabilization through closed-loop control of the DC converter output voltage signal feedback, which simplifies the design of the control loop, the output response is fast and stable, and the switching tube realizes zero When the voltage is turned on, the rectifier diode completes zero-current turn-off; the electrolysis hydrogen production system builds a Simulink model of electrolysis hydrogen production, and gives the models of each sub-module. In the static experiment, the simulation adjusts the temperature, air pressure, and current density. Then analyze the value of each output module, and explore the factors that have a greater impact on the working state of electrolysis hydrogen production, mainly current density and temperature. When the temperature rises, the value of each voltage module will drop, and the rate of hydrogen and oxygen produced will be slower. In the dynamic experiment, when the electrolyzer current step increases, the hydrogen and oxygen production rate increases accordingly, and the corresponding storage tank pressure increases. When the current of the electrolytic cell decreases step by step, the production rate of hydrogen and oxygen decreases, and the pressure of the storage tank increases slowly, which is in line with the actual situation.

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