Design of Power Converter for Aluminum Air Battery

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Abstract. In order to improve the output voltage performance of the aluminum air battery and improve the conversion efficiency, according to the output voltage characteristics of the aluminum air battery pack, we propose an LLC resonant converter based on integral separation PID control and voltage feedforward control. Then the main parameters of the converter were designed and finally simulated by MATLAB/Simulink. The experiment proves that the control method adopted by the aluminum air battery converter effectively improves the dynamic performance index of the system compared with the conventional PID control.

1. Introduction

Aluminum air battery is a new type of high-energy chemical power source. It uses aluminum alloy as the negative electrode, air electrode as the positive electrode, neutral or alkaline aqueous solution as the electrolyte. During the operation of the battery, energy is output by consuming aluminium alloy negative electrode and oxygen in the air [1]. For this battery has the advantages of high energy density, light weight, abundant material sources, non-pollution, high reliability, long life and safe use, so it is called "green energy facing the 21st century" [2-3]. It can be widely used in reserve power supply, portable power supply, electric vehicle power supply, underwater power supply and other fields [4], in recent years, high-power aluminum air battery in the communication base station as a backup power supply has also been successfully applied.

However, the output voltage of the aluminum air battery pack has poor dynamic characteristics and exhibits large fluctuations. In the case of high requirements, in order to obtain a stable, high-precision output voltage, aluminum air batteries are generally used in conjunction with DC/DC converters. Therefore, a unidirectional DC/DC converter with wide voltage gain range, high power density and high conversion efficiency is studied to realize efficient use of new energy, which has high practical value [5].

Compared with other converter topologies, LLC resonant converter has good soft-switching advantages. It can realize zero-voltage switching in full load range, and high-frequency and magnetic integration technology can effectively reduce the volume of converter, easily realize the requirements of high efficiency and high power density of converter, which makes it widely used in many fields such as battery charging, communication power supply and so on [6]. In control aspect, as the earliest practical control algorithm, PID control is widely used. However, in conventional PID control links, there are mutual constraints among overshoot, regulation time and steady-state precision indexes. Generally, the compromise value of multiple control indexes is taken as the optimal control parameter. In special cases, when one performance index needs to be emphasized, it is at the expense of other
indexes [7]. Therefore, in different applications, different methods will be used to improve. There are two main aspects to improve the PID control, one is the advanced technology of parameter tuning, the other is the research of control structure. The advanced technology of parameter tuning is mainly realized by the technology of fuzzy, neural network, adaptive control, etc. The improvement of control structure includes integral separation, anti-integral saturation, incomplete differential, differential advance, feedforward compensation, dead zone, etc [8]. In this paper, according to the characteristics of aluminum-air battery, the principle and working characteristics of LLC resonant converter are analysed. Integral separated PID control with voltage feed-forward is adopted. Finally, through the simulation of MATLAB, we compare with the traditional PID control effect.

2. Discharge Characteristics of Aluminum Air Batteries

First, the discharge characteristics of the aluminum air battery were analyzed experimentally. A plurality of single-unit aluminum air batteries are connected in series to form a high-power aluminum air battery pack, as shown in Fig. 1. In a 6 mol/L KOH solution, three aluminum air battery packs are respectively discharged under a certain load. Test, set the interval time 30s, get the curve of aluminum air battery voltage with time, as shown in Figure 2.

According to the discharge characteristic curve of the aluminum air battery, the output voltage range of the battery pack is 65 ~ 100V. Aluminum air battery output voltage changes frequently, some periods fluctuate greatly, and some periods are relatively stable. Therefore, the converter of aluminium air battery needs a wide input range of voltage and a fast response speed.

3. Design of Aluminum Air Battery Power Converter

3.1. Converter topology and working principle

For the standby power supply of the base station, the main circuit chooses LLC resonant full bridge topology, which combines the power and efficiency factors, as shown in Figure 3.

The main circuit of LLC resonant full bridge topology consists of three parts: inverting network, resonant network and secondary rectifying network. Among them, Q1-Q4 is four MOS transistors, which are diagonally complementary and conducting, D1-D4, C1-C4. They constitute four MOS transistors' body diodes and parasitic capacitors. The resonant network consists of resonant capacitor Cr, resonant inductance Lr and excitation inductance Lm. The secondary side of transformer is full bridge rectifier circuit, which consists of diodes Dr1~Dr4, Cf is output capacitor and R is load.

3.2. Converter DC characteristics analysis

There are two resonant inductances Lr, Lm and a resonant capacitor Cr in the resonant network of LLC resonant full bridge converter, and two resonant frequencies [9] are formed in the resonant network. When the secondary diode is working, the magnetizing inductance Lm is clamped by the output voltage. Only the resonant capacitor Cr and the resonant inductance Lr participate in the resonance. The excitation inductance Lm does not participate in the resonance. At this time, the resonant frequency is:

\[ f_r = \frac{1}{2\pi \sqrt{L_r C_r}} \]
When the secondary rectifier diode is not working, the excitation inductance \( L_m \) is not clamped by the output voltage. The resonant capacitor \( C_r \), the resonant inductance \( L_r \) and the excitation inductance \( L_m \) all participate in the resonance. The resonant frequency is:

\[
f_m = \frac{1}{2\pi \sqrt{(L_m + L_r)C_r}}
\]  

(2)

The gain characteristics of LLC resonant converter are obtained by fundamental wave analysis FHA (First Harmonic Approximation):

\[
M = \frac{1}{\left[(1+K-R f_n^2)^2+Q^2(f_n^2-1)^2\right]^{1/2}}
\]  

(3)

\( f_n = f/f_r \) is the normalized frequency and \( Q \) is the quality factor. Taking \( K = 3 \), the voltage gain curve of LLC resonant full bridge converter is obtained as shown in Figure 4.

\[\text{Figure 3. LLC Resonant Full Bridge Converter.}\]

\[\text{Figure 4. Voltage gain curve}\]

3.3. Converter parameter design

According to the discharge experiment of the battery, the output voltage range of the aluminum air battery is 65 ~ 100V. In order to leave some margin for the converter, the input voltage range is set to be 60 ~ 110V. For standby power supply of base station, output voltage 48V, output power: \( P_0 = 1000W \). Resonant frequency \( f_r = 100KHz \), diode conduction voltage drop: \( V_d = 0.7V \), parasitic capacitance of power transistor: \( C_z = 2 \times C_s + C_o + C_r \).

3.3.1. Calculation of Transformer Ratio

Transformer Ratio \( n = \frac{V_{in\_normal}}{V_{out\_normal}} = \frac{80}{48} = 1.67 \), Take the value of transformer ratio \( n \) as 2.

3.3.2. Determining maximum gain \( M_{\text{max}} \) and the Minimum Gain \( M_{\text{min}} \)

\[M_{\text{min}} = \frac{n \times (V_{out\_normal} + V_d)}{V_{in\_max}} = \frac{2 \times (48 + 0.7)}{110} = 0.89\]  

(4)

\[M_{\text{max}} = \frac{n \times (V_{out\_normal} + V_d)}{V_{in\_min}} = \frac{2 \times (48 + 0.7)}{60} = 1.62\]  

(5)

3.3.3. Equivalent load resistance and reflective resistance under rated load

\[R_L = \frac{V_d^2}{P_o} = \frac{48^2}{1000} = 2.3\Omega\]  

(6)

\[R_{eq} = \frac{8 \times n^2}{\pi^2} \times \frac{V_{out\_max}}{I_{out\_max}} = \frac{8 \times 4}{\pi^2} \times \frac{48}{20} = 7.79\Omega\]  

(7)

3.3.4. Calculate \( Q_{\text{max}}, f_{\text{max}}, f_{\text{min}}, L_r, L_m, C_r \)

First, \( K \) value is selected. \( K = L_m/L_r \), the smaller the \( K \) value, the same gain, the narrower the frequency range, the larger the \( K \) value, the same gain and the wider the frequency range. The larger the \( K \) value, the lower the conduction loss and switching loss of MOSFET near \( f_r \). Therefore, the \( K \)
value should not be too large or too small[10]. K is generally in the range of 2.5-6 and K = 3 in the calculation, thus:

\[ f_{\text{max}} = \frac{f_r}{[1+k\times(1-M_{\text{min}})]^{1/2}} = \frac{100}{[1+3\times(1-\frac{1}{0.89})]^{1/2}} = 127 \text{KHz} \]  
\[ f_{\text{min}} = \frac{f_r}{[1+k\times(1-M_{\text{max}}^2)]^{1/2}} = \frac{100}{[1+3\times(1-\frac{1}{1.62^2})]^{1/2}} = 59 \text{KHz} \]  

(8)

(9)

Maximum Quality Factor:

\[ Q_{\text{max}} = \frac{1}{k\times M_{\text{max}}} \times \sqrt{k + \frac{M_{\text{max}}^2}{M_{\text{max}}^2-1}} = \frac{1}{3\times1.62} \times \sqrt{3 + \frac{1.62^2}{1.62^2-1}} = 0.44 \]  

(10)

Resonant inductor:

\[ L_r = \frac{R_{\text{eq}} \times Q_{\text{max}}}{2\pi f_r} = \frac{7.79 \times 0.44}{2\pi \times 100} = 6 \mu \text{H} \]  

(11)

Resonant capacitor:

\[ C_r = \frac{1}{2\pi f_r L_{\text{eq}} Q} = \frac{1}{2\pi \times 100 \times 0.44 \times 7.79} = 460 \text{nF} \]  

(13)

Excitation current:

\[ I_m = \frac{V_{\text{inMax}}}{4f_{\text{max}} \times (L_r + L_m)} = \frac{110}{4 \times 127 \times (6+18)} = 9 A \]  

(14)

Resonant current:

\[ I_r = \left(2C_{\text{oss}} + C_{\text{stray}}\right) \frac{V_{\text{inMax}}}{T_d} \]  

\[ = 500 \times 10^{-12} \times \frac{110}{200 \times 10^{-9}} = 0.275 A \]  

(15)

Because \( I_m > I_r \), ZVS can be implemented.

3.4. Converter Control

Discharge process of aluminium air battery is a non-linear process. If conventional PID control is adopted, it is difficult to adapt to this complex and high precision system. According to the discharge characteristics of aluminium air battery, integral separation PID control is adopted. Integral separated PID control can not only give full play to the simplicity and flexibility of classical control technology, but also give full play to the advantages of PD control for fast tuning of non-linear systems. The integral separation control algorithm is expressed as:

\[ u(k) = K_p[e(k) + \beta \frac{T}{T_i} \sum_{i=0}^{k} e(i) + T_d \frac{e(k)-e(k-1)}{T}] \]  

(16)

\[ \beta = \begin{cases} 1 & |e(k)| \leq \varepsilon \\ 0 & |e(k)| > \varepsilon \end{cases} \]  

(17)

According to the actual situation of the system, it is determined that if the value of \( \varepsilon \) is too large, the purpose of integral separation will not be achieved. If the value is too small and the integration area is not reached, the system will have a residual error. In order to further reduce the influence of the
input voltage of the converter on the output voltage, improve the response speed of the system, add the input voltage feedforward in the output voltage feedback, and provide a corresponding modulation factor by adding voltage feedforward to realize the dynamic adjustment of the system. The aluminum air battery converter can quickly respond to voltage fluctuations at the input.

Using the combination of input voltage feedforward and output voltage feedback, the sampled value U\text{out} of the output voltage is compared with the reference value U\text{ref} to obtain a deviation value e, and the deviation value e is processed by the integral separation PID algorithm; before the input voltage is used The feed loop detects the DC input voltage U\text{in} in real time, and corrects the return value after the integral separation PID program processing according to the ratio of the detected DC input voltage U\text{in} and the set input voltage U\text{set}, thereby eliminating the voltage fluctuation of the aluminum air battery by this method. The influence of the output voltage of the converter increases the dynamic response speed of the converter.

4. Simulation results and analysis

According to the above parameters, the control performance of LLC resonant full bridge is simulated in MATLAB-2017b. The main parameters of LLC resonant full-bridge converter are as follows: input voltage is 60V~110 V, output voltage is 48V, output power is 1 KW, resonant frequency is 100 kHz, switching frequency is 59~127 kHz, Lm=18 uH, Lr=6 uH, Cr=460 nf. The simulation model is built in MATLAB/Simulink software, and the parameters are adjusted by trial and error method. The model is shown in Figure. 5.

![Simulation model of LLC resonant full bridge converter](image)

Figure 5. Simulink.

Take the threshold of integral separation \( \varepsilon =0.3 \), Through the simulation of MATLAB, the control performance of conventional PID control and integral separated PID control with voltage feedforward are compared. The comparison chart is shown as follows:

![Conventional PID control](image)  ![Integral Separation PID Control with Voltage Feedforward](image)

Figure 6. Conventional PID control  Figure 7. Integral Separation PID Control with Voltage Feedforward

By comparison, the regulation time of conventional PID control is 2 ms, and that of integral separated PID control with voltage feedforward is 0.5 ms. Compared with conventional PID control, integral separated PID control can shorten the regulation time of converter, and the overshoot is relatively smaller. Aluminum air battery converter adopts integral separation PID control algorithm with voltage feedforward, and its control performance is obviously better than that of conventional PID control.
5. Conclusion
Based on the analysis of the characteristics of LLC resonant circuit and the output voltage characteristics of Al-air battery, the specific design method of Al-air battery converter is given, and the related design is completed. The simulation experiment in MATLAB software shows that the integrated separated PID control with voltage feed-forward is adopted in the converter of aluminum air battery, which has strong ability to suppress overshoot and good steady-state performance. The output terminal of the converter can respond quickly to the voltage fluctuation of the input terminal, and the control effect is ideal.

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References
[1] WANG Z W.LI Q F.GAO B L.QIU Z X (2002) Adances in Development and Application of Aluminum-air Batteries. NON-FERROUS MINING AND METALLURGY, 18(1): 38–41.
[2] FANG Z Q.LIU W X.CHEN Y R (2003) Development of aluminium/air fuel cell. ORDNANCE MATERIAL SCIENCE AND ENGINEERING, 26(2): 67–72.
[3] XIONG Y Q.LIU C Q.ZHOU M J (2014) Research progress in aluminium-air battery. BATTERY BIMONTHLY, 44(2): 116–118.
[4] HUANG R X.ZHU X G (2009) Application and design of the Al-air battery.
[5] Chinese Battery Industry, 14(1): 60–64
[6] ZHANG L.ZHU L Z.CHEN N.ZHAO D W. QU L N (2015) Review on Generic Model for Renewable Energy Generation. Automation of Electric Power Systems, 39(24): 129–137
[7] ZHONG S.XU J P. ZHAO S. et al. (2016) Bi-frequency control for LLC resonant converter with fast transient response[J]. Institution of Engineering and Technology, 52(20): 1710–1712.
[8] JIA B Z.CAO H.MA J L.REN G (2012) Fuzzy PD and PI switched way-point tracking algorithm. Journal of Harbin Engineering University, 33(5): 562–566.
[9] LI X Y.CHEN J H.LI S L.CHENG Z G (2004) Application of Integral Separated PID Control in Anti-aircraft Missile. Armament Automation, 23(4): 12–13
[10] IVENSKY G.BRONShteIN S.ABRAMovITZ A. (2011) Approximate analysis of resonant LLC DC-DC converter[J]. IEEE Transactions on Power Electronics, 26(11): 3274–3284.
[11] YU R.HO G K Y. PONG B M H. et al. (2012) Computer-aided design and optimization of high efficiency LLC series resonant converter[J]. IEEE Transactions on Power Electronics, 27(7): 3243–3256.