Research on Performance Speed Regulation System of Direct Conversion AC-DC Power Conversion Device

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Abstract. With the continuous development of social economy, the application market of electric motors has become more and more broad. Based on the principle of modular design, this paper designs the hardware circuit system of the matrix converter, and completes the parameter calculation of the input LC filter. The modulation algorithm needs to determine the sector and position angle of the input three-phase voltage. The DC speed regulation system powered by the conversion AC-DC power conversion technology is compared with the Buck circuit power supply system. Practice shows that the system has good static and dynamic indicators and load robustness.

Keywords: Switch Linear Composite, Buck Circuit, Ripple, Power Conversion Device

1. Introduction

With the continuous development of social economy, the application market of electric motors has become more and more broad [1-3]. In small-capacity mobile systems or precision systems powered by independent DC power sources (such as batteries), DC motors still have a certain market due to their excellent performance. Load transmission pulse width can be adjusted to average DC voltage, so as to realize power transmission [4-8]. With the development of power electronic device manufacturing technology, the capacity level of a single device has become larger and larger. Simpler circuits can be used to meet the requirements of stable DC power supply for small-capacity irreversible systems, and achieve power supply effects that are close to DC generators. The single-switch Buck converter is a typical circuit that realizes this simple power supply method. It is analyzed, and on this basis, in order to further improve the static and dynamic indicators of the power supply, a voltage follower is connected behind the Buck circuit. Switch-Linearity Hybrid (Switch-Linearity Hybrid) converter power supply mode [9-10].

According to the modular design principle, this paper designs the hardware circuit system of the matrix converter, and proposes a DC speed regulation system based on the direct conversion AC-DC power conversion technology, and tries to compare it with the Buck circuit power supply system.

2. Design of input filter of matrix converter
The matrix converter modulation algorithm is complex, the switching devices are numerous, the switching frequency is high, and the high-frequency harmonics generated by the switching action will inevitably produce high-frequency harmonic pollution on the input side of the power supply. The measures taken for the commutation of various devices have further increased. To avoid the generation of high-frequency harmonics, it is necessary to filter out as many high-frequency harmonic components as possible, reduce the harmonic pollution on the grid side, improve the input power factor, and reduce the interference to the signal acquisition circuit.

2.1. Design principles of matrix converter input filter

There are many related literatures on the design of matrix converter input filter, here do not do too much research on which form the input filter adopts, comprehensive cost and effect, first-order passive LC filter is a more reasonable choice. The design of the input filter of the matrix converter needs to meet the following principles:

1) The cut-off frequency of the input filter should be lower than the sampling frequency of the matrix converter and higher than the power frequency of the power supply voltage;

2) Due to the limitation of the modulation algorithm, the voltage transfer ratio of the matrix converter is limited. In order to improve the voltage utilization, the voltage drop on the filter inductor should be as small as possible;

3) Due to the existence of the filter capacitor, it is necessary to minimize the phase shift of the fundamental frequency of the input current;

4) Comprehensive consideration of the size, weight and cost of the filter.

2.2. Parameter calculation of the input filter of the matrix converter

According to the requirements of the matrix converter for the design of the input filter, the cutoff frequency of the filter should be selected between the grid voltage base frequency (50Hz) and the sampling frequency (switching frequency, 10KHz), usually the cutoff frequency is selected as 1/6 of the sampling frequency -1/3, here is 1/4 of the sampling frequency. Let fs be the sampling frequency and f0 be the cut-off frequency, then:

$$f_0 = \frac{1}{4} \cdot f_s = 2.5Kz$$

(1)

The filter inductance and capacitance satisfy the formula:

$$LC = \frac{1}{\omega_0^2}$$

(2)

$\omega_0$ is the cutoff angular frequency, $\omega_0 = 2\pi f_0$.

Taking into account the requirements of the input filter size, weight and rental cost in the design principle, the actual inductance coil is wound and measured. The filter inductance value $L=1.1mH$ is selected, and the enameled wire with a diameter of 0.8mm is used. Due to the magnetic ring and winding The individual difference of the method, the inductance values of the three inductors are 1.1mH, 1.101mH, 1.08mH respectively.

According to formula (2), the capacitance value is calculated:

$$C = \frac{1}{\omega_0^2} L = \frac{1}{(2\pi f_0)^2} L = 4.06 \mu F$$

(3)

The inductance withstand voltage value is calculated as follows:

$$\frac{1}{2}LI_n^2 = \frac{1}{2}CU^2$$

(4)

$$U = \sqrt{\frac{L}{C}I_n} = 82.3V$$

(5)
Wherein is the rated input phase current, which is taken as 5A, and U is the minimum withstand voltage value of the capacitor. Considering the current overload, short circuit, overvoltage and the standard of the capacitor on the market, the filter capacitor is selected as 5μF/450V.

Voltage drop across the inductor.

\[
\frac{\Delta U}{U_N} = 1 - \sqrt{1 - (\omega t L)^2} \left( \frac{I_N}{U_N} \right)^2 = 0.012\% \tag{6}
\]

UN is the rated input phase voltage, and \(\omega t\) is the fundamental frequency of the grid voltage. It can be seen from the calculation result of the above formula that the voltage drop on the inductance of the designed filter is very small and will not affect the voltage utilization rate of the matrix converter.

The calculation of the phase shift of the fundamental frequency of the input current needs to be equivalent to the input filter, now the calculation is as follows:

\[
\Delta \theta = -\arctan \frac{\omega t C I_N}{U_N} + \arctan \frac{\omega t C U_N}{I_N(1 - \omega t LC)} = 7.88^\circ \tag{7}
\]

The fundamental frequency offset of the input current at this angle is acceptable, so the designed matrix converter LC filter can meet the requirements.

Research shows that the harmonics generated by the matrix switch mainly include sampling frequency and high-frequency harmonics that are multiples of the sampling frequency. There are few low-frequency harmonics above the fundamental frequency and below the sampling frequency. Parallel damping resistors at both ends of the inductor can effectively attenuate high frequencies. The amplitude of the current component, taking into account the voltage drop across the inductor, the resistance value of the damping resistor is selected here as \(R_d=100\Omega\). From a practical point of view, the influence of the damping resistor on the filter voltage drop, the offset of the input current fundamental frequency and the magnitude of the high-frequency current component will not be studied too much.

3. Design of sampling circuit and power supply

The signal conditioning circuit mainly completes the voltage sampling and conversion of the 220V AC three-phase input phase voltage, and converts the 220V AC voltage into a DSP AD analog-to-digital conversion. The voltage range is a unipolar signal with a voltage range of 0–3V, thereby completing the AD analog-to-digital Convert, detect the magnitude of the three-phase input voltage, and then judge the input voltage sector.

3.1. Power supply design of sampling circuit

The sampling circuit power supply part provides -5V, 0V, +3V and +5V direct current for the voltage sampling conversion circuit. The power supply circuit design is as follows: the input side is a 20V switching DC power supply, and a 3-terminal positive voltage regulator circuit 7805 and a resistor and a voltage regulator tube are connected in series to generate the required voltage. R and 5.1V zener tube are connected in series to divide the voltage, the anode of zener tube DZ1 is -5V, the input end of 7805 meets the requirements of input voltage, and the output end also uses resistor R3 and zener tube DZ3 to divide voltage in series to generate +5V and +3V direct current, LED indicates whether the power supply part of the signal conditioning circuit is working normally, the input terminal and output terminal of 7805 are connected in parallel with the capacitor for voltage stabilization and filtering. The designed power supply circuit is simple to implement, has a certain drive power, meets the requirements, and has a small cost.

Power circuit test conditions and results:

20V DC adopts MEAN WELL 24V/1.5/A35W switching power supply, and the no-load test voltage can be adjusted from 21.01V to 26.95V.
The output voltage of the switching power supply is adjusted according to the voltage at the end of the Zener tube DZ1-5V and 7805 output +5V. In order to ensure the stable operation of the circuit, DZ uses a voltage regulator tube rated at 5.1V/2W. When the DZ1 terminal voltage is -5.02V and the 7805 output terminal voltage is 5.04V, the switching power supply voltage is adjusted to 20.57V, and the 7805 input terminal voltage is 15.55V.

As long as it does not exceed the rated power of the voltage regulator tube, the greater the working current, the better the voltage regulation effect, so the heart resistance value is 270Ω.

3.2. Design and working principle of sampling circuit

Due to the particularity of the matrix converter and DSP for the control signal requirements, the design of the sampling circuit has the following requirements:

1) The output signal of the sampling circuit is adjustable, that is, when the input signal that changes within a certain range is sampled, the output sampling signal can be adjusted to the maximum value read by AD to ensure the accuracy of A/D sampling. The modulation algorithm is effective for switching devices. The control of the switching time will also be more precise.

2) The input AC voltage signal sampled by the voltage transformer is a positive and negative symmetrical bipolar signal, and the voltage signal needs to be biased and reversed, so as to meet the DSP's A/D requirement for the input signal level range of 0~3V.

3) The high-order harmonics generated by the on-off of the matrix converter's high-frequency switching devices may be coupled into the input side, so it is necessary to low-pass filter the sampled input AC signal.

According to the design requirements of the matrix converter sampling circuit, the designed three-phase input voltage sampling circuit A phase, B and C phase sampling circuits are the same.

To collect the three-phase input phase voltage, three samples are required. Take the UA phase as an example. The rated voltage of the primary side of the voltage transformer is 400V, the rated output voltage is 7.37V, and the 220V AC input voltage is transformed into a secondary side AC output signal of 3.8885V by the voltage transformer. The maximum amplitude is 5.4992V. R4 and R5 form a low-pass filter. RL1 and RL2 are potentiometers, and the bias voltage is -5V. The operational amplifier LM324N adds a bias voltage through a negative feedback circuit to output 3.8885V on the secondary side of the voltage transformer. The sine AC signal is converted into a sine AC signal of 0~3V. The op amp is composed of a negative feedback circuit. It is necessary to reversely connect Vout+ and Vout- on the output side of the voltage transformer to obtain the required 0~3V sinusoidal AC signal, that is, Vout+ is connected to the negative terminal of the op amp, and Vout- is connected to the positive side of the op amp.

Assuming that the output signal of the voltage transformer is Vi, the output voltage V0=(5/RL1+Vi/(R4+R5))*RL2 through the negative feedback circuit of the op amp. When the voltage transformer has no input signal, the negative feedback circuit of the op amp needs to be adjusted. For a suitable operating point, take half of the maximum output voltage amplitude of 3V as the bias output, then 5/RL1*RL2=1.5V, and the maximum amplitude of the secondary side output of the voltage transformer is 5.5V then 5.5/( R5+R5)*RL2=1.5V, so that RL1 is 13.73KΩ, RL2 is 4.12KΩ, and the next operational amplifier is a voltage follower. Adjusting RL1 can adjust the bias voltage, and adjusting RL2 can adjust the amplification of the negative feedback circuit. Multiplier, the principle of adjustment is to try to adjust the output signal of the op amp to a sinusoidal AC signal with a peak-to-peak range of 0~3V, so as to meet the requirements of the A/D of the DSP for the input signal. The collected UA phase signal is sent to the AD of the DSP The input channel ADN1AO, the UB phase signal is sent to ADNINA1, the & phase signal is sent to ADNRMA21, so that the signal acquisition of the three-phase input voltage is completed.

4. Circuit topology and analysis

4.1. Buck power supply circuit
The DC drive system powered by the direct conversion AC-DC power converter is shown in Figure 1, and the load is a permanent magnet DC motor. By adjusting the given voltage \( V_{gd} \) in Figure 1, the single tube stable voltage power supply and speed adjustment can be realized. Compared with the duty cycle controlled H-bridge circuit plus smoothing reactor power supply mode, the ripple voltage is much less, which reduces the heat of the motor and the aging degree of the armature winding insulation caused by the switching spike, but in high-precision applications Under the circumstances, its application is subject to certain restrictions. Further analysis of the Buck power supply circuit, in the continuous conduction mode, the ripple coefficient is:

\[
\frac{\Delta V_0}{V_0} = \frac{\pi^2}{2} (1 - D) \left( \frac{f_c}{f_s} \right)^2 = \frac{T_s^2 (1 - D)}{8LC}
\]

\( (8) \)

![Schematic diagram of Buck circuit power supply scheme](image)

Figure 1. Schematic diagram of Buck circuit power supply scheme

Among them: \( V_0 \) is the output voltage, \( \Delta V_0 \) is the peak-to-peak ripple voltage; \( D \) is the duty cycle; \( T_s \) is the switching period. It can be seen from the formula that the ripple coefficient has nothing to do with the load. When \( LC \) is fixed, it is a function of \( T \) and \( D \). With the increase of \( T_s \) (decrease of \( f_s \)), the ripple coefficient increases, and the output voltage ripple content increases. Therefore, in order to reduce the ripple, a higher switching frequency must be used.

\[
n = \frac{V_0}{K_e \Phi} - IR
\]

From the DC motor speed equation, it can be seen that when the step-down speed regulation reaches the low-speed stage, the duty cycle \( D \downarrow \), and the switching frequency \( f_s \) is not high, the output voltage ripple of the Buck circuit \( \Delta V_0 \uparrow \), the resulting \( \Delta n \uparrow \). It may cause slight rotation speed oscillation, which will reduce the life of the bearing during long-term operation. In precision systems, the switching frequency can be made very high, but its EMI problems have adverse effects on the surrounding equipment and human body.

4.2. Direct conversion AC-DC power conversion power supply circuit

The DC drive system powered by the direct conversion AC-DC power converter is shown in Figure 2. A voltage follower is connected behind the Buck converter to form a switch linear composite power supply mode. Because the switch linear composite power conversion technology has low-impedance output characteristics, the system can obtain better static and dynamic indicators and maintain good low-speed performance.
The basic working principle of the direct conversion AC-DC power converter is: the voltage follower's gate level VG is obtained by DC amplification of a given voltage value Vgd, and the amplitude is the same as the peak voltage of the Buck circuit output voltage ripple. The value is close. In this way, the output voltage V0 of the voltage follower completely tracks the given voltage Vgd in proportion, and the accuracy of Vgd also determines the accuracy of V0, and is not affected by the output voltage ripple of the Buck circuit. In other words, the output voltage of the Buck circuit is only used as the power supply voltage of the back-stage linear circuit, and all the peak-to-peak ripple voltages fall on the VT2 tube.

The VT2 tube works in a linear state close to the critical saturation, and its tube consumption is not high. It can be balanced by the switching dynamic loss reduced by the switching tube VT1 frequency reduction operation. Even if it cannot be fully balanced and a little efficiency is sacrificed, due to the high-impedance input and low-impedance output characteristics of the voltage follower, it must have various excellent performances similar to traditional linear power amplifiers, as well as good load adaptability and robustness. It can make the low-speed performance of the DC motor speed control system show obvious advantages, which is exactly what the precision drive system expects.

At present, the saturation voltage drop of IGBT devices is higher than that of MOSFETs in the low-voltage range. Considering from the efficiency and linearity, in the low-voltage system, MOSFET should be selected as VT1 and VT2. However, because the excellent performance of SLH depends on the high-impedance input and low-impedance output characteristics of the downstream power tube, the voltage follower is equivalent to a power-level buffer to isolate the Buck circuit from the load, so that the influence of both parameters is minimized. The output resistance is approximately the reciprocal of the transconductance of the final stage tube. Since the transconductance of the IGBT is many times larger than that of the MOSFET, the output resistance is also many times lower. From this perspective, choosing IGBT as a voltage follower has better performance. In practical applications, IGBT or MOSFET can be used according to the emphasis on efficiency and performance of specific occasions.
But the choice of power tube is common, that is, no matter which kind of device, a tube with a low turn-on voltage should be used. A voltage-controlled device with a 2V turn-on voltage is now available.

5. Analysis of experiment and simulation results
From the theoretical analysis, it can be known that because the direct conversion AC-DC power converter has a post-voltage follower, the output impedance is small, the terminal voltage drop is small, and the output characteristics are harder than the Buck converter, which is consistent with the experimental results.

Since the direct-conversion AC-DC power conversion post-stage voltage follower is actually a deep negative feedback circuit with a gain close to 1, when the load increases and causes the voltage drop, the gate potential VG of VT2 is controlled by the reference voltage. Keep it constant (due to the high input impedance between the gate and ground, the DC voltage amplifier unit almost does not absorb current), then VGS=VG-V0 increases immediately, and V0 quickly returns to the voltage value of tracking VG (one lower than VG is turned on) Voltage threshold.

Simulation waveform diagram of output voltage V0 of Buck converter and direct conversion AC-DC power converter (not adjusted according to the optimal parameters) [10]. Since the output stage of the direct conversion AC-DC power conversion is a voltage follower, the speed of its V0 tracking the given signal is almost no delay compared with the system parameters, and the PI regulator only adjusts the ripple voltage of the power supply to make it fluctuate VT2 has a certain range of conduction voltage to withstand its fluctuations, but the loss increases during the transition process. Buck converters do not have this advantage.

6. Conclusion
The direct conversion AC-DC power conversion is the product of the Buck circuit composite voltage follower. It achieves better static and dynamic indicators due to its low resistance output characteristics. It is suitable for occasions with high precision requirements. If the speed is closed loop, it will be better effect. At the same time, the high-impedance input and low-impedance output characteristics of the direct conversion AC-DC power converter determine that it has good load adaptability and robustness similar to traditional linear power amplifiers.

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