New Energy Buffer for Highly Integrated T-joint Module Drive in Cooperative Robots

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Abstract

Highly integrated T-joint modules are used in cooperative robots. The miniaturized module driver is built in the joint, and the bus capacitance is small. Emergency braking of one joint makes the bus voltage fluctuate, which affects the operation of other joint modules of common DC bus. Therefore, this paper solves the problem from the perspective of pure hardware, and proposes a new energy buffer for highly integrated T-joint module drive in cooperative robots. The new energy buffer is characterized in that the voltage of the capacitor in the buffer is designed in the form of large ripples, which allows most of the fluctuating energy to be stored in the energy buffer, reducing the voltage fluctuation of DC bus. The new proposed energy buffer can reduce the voltage fluctuation of DC bus with low cost and low space occupation, which is conducive to the popularization of miniaturization of highly integrated T-joint modules.

Keywords

T-joint Modules; Miniaturized Module Driver; Energy Buffer; Voltage Fluctuation.

1. Introduction

With the increasing demand for miniaturization and lightweight of cooperative robots, highly integrated T-joint module are commonly used in cooperative robots [1]. The module driver is built in the joint, which needs to make the driver extremely small. Traditional large capacitor can only be replaced by the small. However, emergency braking of one joint makes the bus voltage fluctuate, and each joint shares common DC bus power, which will have adverse effects on the operation of itself and other joints [2]. To solve this problem, a bleeding resistor is usually added to the bus power to absorb the feedback energy when one joint is emergency braked, so as to further stabilize the DC bus voltage. However, this method has a delay in voltage stabilization, and the bleeder resistor takes up extra space. For this reason, some scholars have proposed the bus voltage control strategy from the aspect of software. Reference [3] has proposed a DC bus voltage closed-loop control strategy for d-axis current generator, which can effectively reduce the fluctuation amplitude of bus voltage. In reference [4], an active damping control algorithm for DC bus voltage stability is proposed, which improves the bus voltage stability by directly controlling the inverter output voltage. However, this kind of software control method also have some defects, such as large motor side power fluctuation, large motor torque ripple, which can not be applied to high-end occasions such as cooperative robots.

Accordingly, this paper solves the problem from the perspective of pure hardware, and proposes a new energy buffer for highly integrated T-joint module drive in cooperative robots, which can reduce the voltage fluctuation of DC bus with low cost and low space occupation.

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2. Design of New Energy Buffer Circuit

Figure 1 is the new energy buffer circuit proposed in this paper. The buffer consists of an inductor L, two capacitors C_1, C_2, three diodes D_1, D_2, D_3 and two power devices S_1, S_2. S_1 and S_2 work in coordination to control the absorption and release of energy from C_1 and effectively reduce bus voltage fluctuations. U_{dc_in} is the DC bus input and U_{dc_out} is the DC bus output.

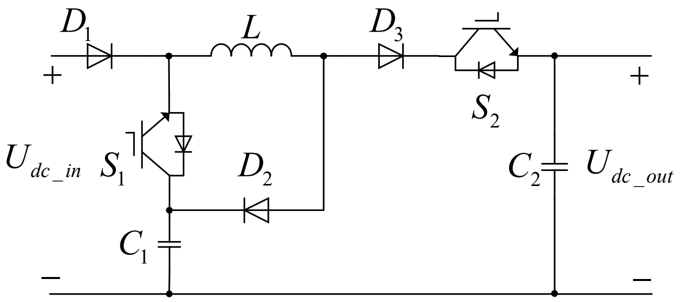


Figure 1. Circuit of new energy buffer

3. Working Principle of New Energy Buffer

Figure 2 shows the energy flow diagram of joint module drive. When the input energy P_{in} of the bus is greater than the energy P_0 required by the module, the energy buffer absorbs the extra energy. When the input energy P_{in} of the bus is less than the energy P_0 required by the module, the energy stored in the energy buffer is released, and the bus together provides energy for the module.

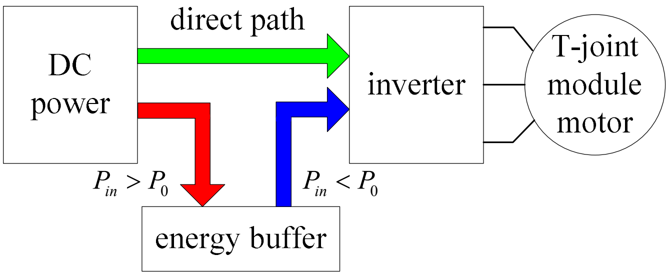


Figure 2. Energy flow diagram of joint module drive

The energy buffer has two capacitors, and the maximum energy it can store is

$$\Delta P = 0.5C_1\left(U_{C1\max}^2 - U_{C1\min}^2\right) + 0.5C_2\left(U_{C2\max}^2 - U_{C2\min}^2\right) \tag{1}$$

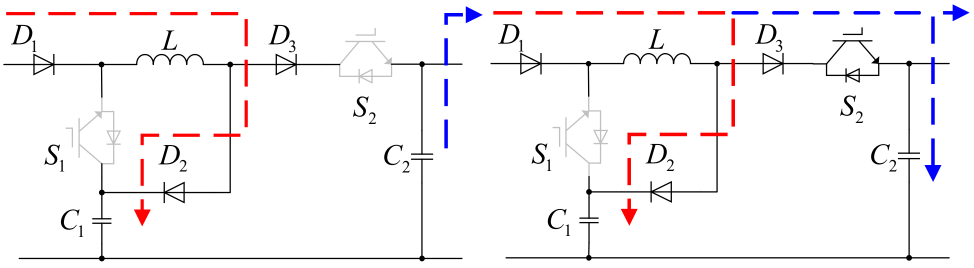
In (1), $U_{C1\max}$ and $U_{C1\min}$ are the highest and lowest working voltage of C_1, respectively, and $U_{C2\max}$ and $U_{C2\min}$ are the highest and lowest working voltage of C_2 (i.e., the highest and lowest working voltage of DC bus output). When ΔP and the capacitance of C_1, C_2 are constant, the voltage of C_1 is designed to have a large ripple, that is, $U_{C1\max}$ and $U_{C1\min}$ are determined. According to (1), the voltage of C_2 can be determined. In other words, by controlling the DC bus output voltage, most of the pulsating energy in the buffer is transferred to C_1, then C_2 has only a small part of pulsating energy.

According to the analysis above, suppressing bus voltage output fluctuation can be divided into the following three working modes: When the voltage U_{C2} of C_2 is greater than $U_{C2\max}$, S_1 and S_2 are turned off, the bus input energy is stored in C_1, and C_2 provides energy to the module through the inverter. When U_{C2} is between $U_{C2\min}$ and $U_{C2\max}$, S_1 is turned off and S_2 is turned on. The bus input and L jointly provide energy to C_1 and the module. When U_{C2} is less than $U_{C2\min}$, S_1 and S_2 are turned on, and the bus input and C_1 jointly provide energy to the module and C_2. The working modes are shown in Table 1 below.

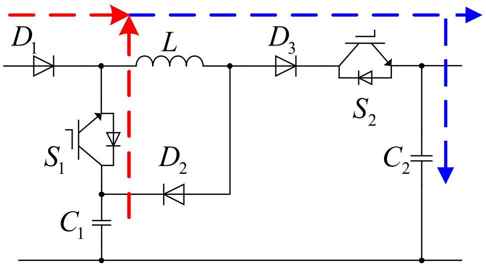
Table 1. Working modes of the energy buffer

DC bus output voltage (U_{C2})	S_1 state	S_2 state	C_1 voltage change (U_{C1})
$U_{C2\max} < U_{C2}$	turned off	turned off	rise
$U_{C2\min} < U_{C2} < U_{C2\max}$	turned off	turned on	basically unchanged
$U_{C2} < U_{C2\min}$	turned on	turned on	drop

Figure 3 shows the equivalent circuit of each mode. The following is a detailed analysis of each mode.



working modeI working mode II



working mode III

Figure 3. Equivalent circuit of each working mode

Working mode I: S_1 and S_2 are turned off, the bus input and L are connected in series to transmit energy to C_1, U_{C1} rises rapidly, C_2 provides energy to the module through the inverter, then U_{C2} drops.

Working mode II: S_1 is turned off, and S_2 is turned on, the bus input and L are connected in series to transmit energy to C_2 and the module, then U_{C2} rises rapidly. In the state of working mode I, U_{C1} rises to a higher value and the potential is higher. Only a small part of the energy flows into C_1, so U_{C1} is basically unchanged.

Working mode III: S_1 and S_2 are turned on, C_1 and the bus input are connected in series to provide energy to the module and C_2, then U_{C1} drops rapidly. Based on the analysis of working mode I and II, a large ripple voltage is formed on C_1. Therefore, more pulsating energy can be stored in C_1.

4. Experiment Results

Performance of the new energy buffer is evaluated in the laboratory with a 450W highly integrated T-joint module, and the experiment platform is shown in Figure 4. The module is controlled by a motion controller, and it communicates with the driver through EtherCAT. The joint module is highly integrated with 48V, 11.6A, 8-poles PMSM, harmonic drive, double encoder (absolute type at low speed end and incremental at high speed end), brake and driver. The control algorithm is implemented through a dual core digital processor, TMS320F28377. The new buffer is integrated on the power board of the driver, and the C_1 on the buffer is a 100V, 100uF small electrolytic capacitor, and the C_2 is composed of three same capacitors of this type in parallel.

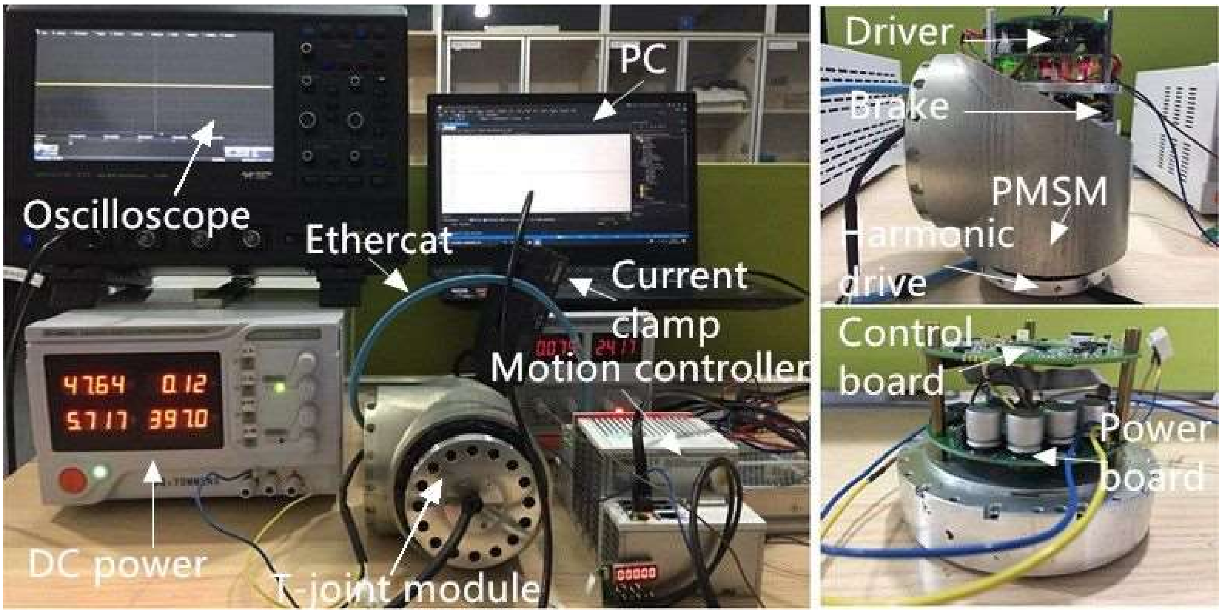


Figure 4. High integration T-joint module drive experiment platform

Figure 5 shows the DC bus input / output voltage comparison through energy buffer. In order to simulate the voltage fluctuation of DC bus input, based on the 48V DC power, a sinusoidal AC voltage with 12V amplitude and 50Hz frequency is added into the DC voltage through the AC voltage regulator, so that the DC bus voltage input becomes the 48V DC voltage with sinusoidal fluctuation. It can be seen from Fig. 5 that through the energy buffer, the output voltage fluctuation of DC bus is greatly droped compared with that of the input, from 12V to 2V ($\Delta U_{dc\_in} = 12V$, $\Delta U_{dc\_out} = 2V$), which verifies that the new energy buffer can effectively reduce the voltage fluctuation of DC bus.

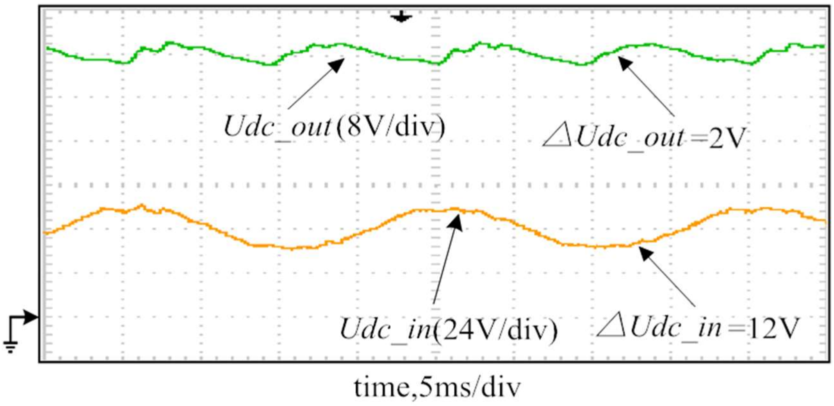
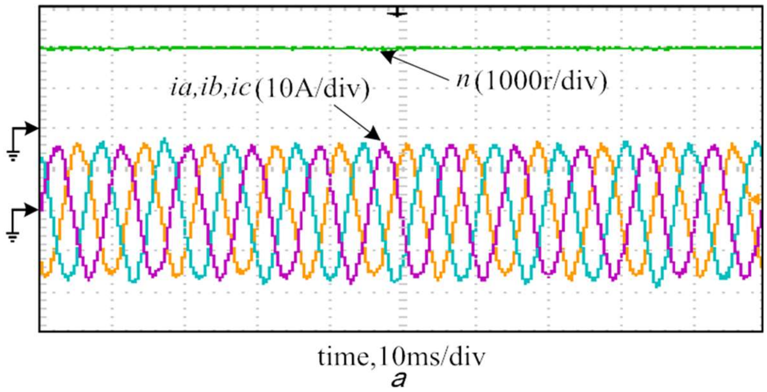
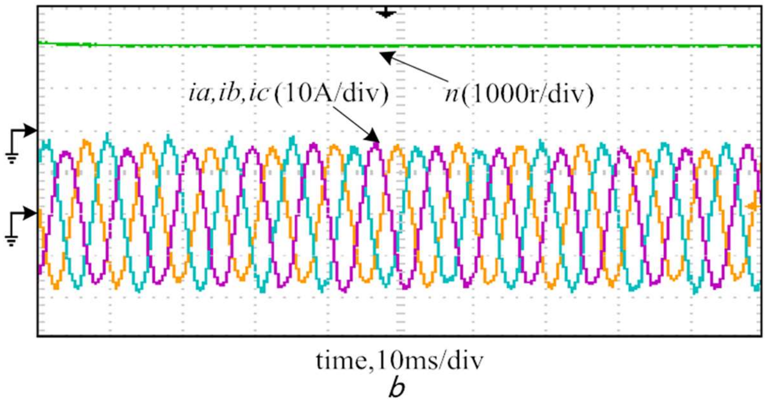


Figure 5. DC bus input / output voltage comparison

Figure 6 shows the comparison of module motor speed and three-phase current under steady-state and sinusoidal fluctuation for a given DC bus voltage input under rated load and 2000r/min operating condition, where Figure 6a shows the waveform under the given DC bus voltage input of steady state and Figure 6b shows the waveform under the given DC bus voltage input with sinusoidal fluctuation. According to Figure 6, after the driver adds the energy buffer, the driving performance of the joint module under the sinusoidal fluctuation voltage input is not weaker than the performance under the steady state voltage input. In order to further verify the effectiveness of the new energy buffer, at the same time, the rated load of the joint module and 600r/min operating condition are given, as shown in Figure 7. It can be seen from Figure 7 that the joint module at low speed still has good operating performance.



a



b

Figure 6. Comparison of module motor speed and current under steady / sinusoidal fluctuation of DC bus input (2000r/min)

a DC bus voltage input is steady

b DC bus voltage input is sinusoidal

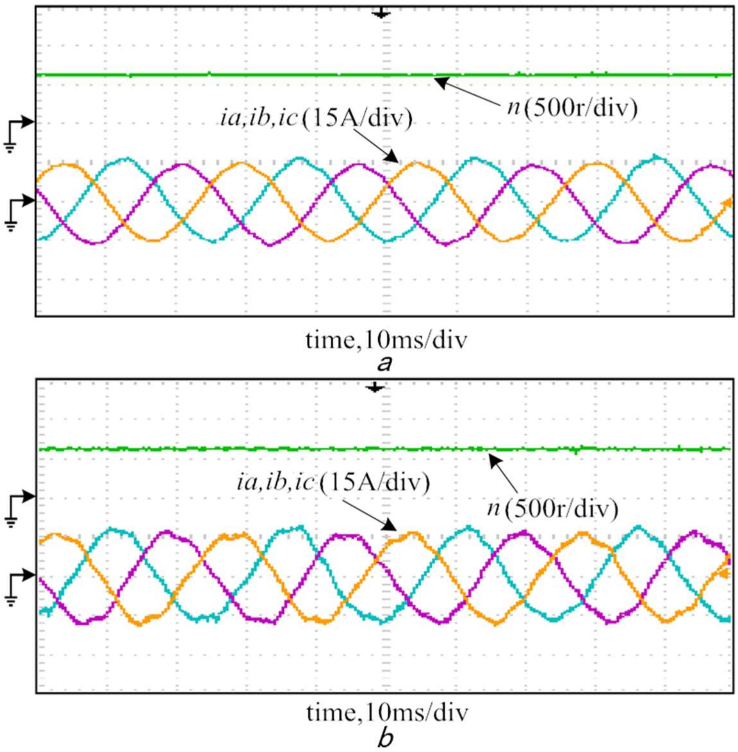


Figure 7. Comparison of module motor speed and current under steady / sinusoidal fluctuation of DC bus input (600r/min)

a DC bus voltage input is steady

b DC bus voltage input is sinusoidal

5. Conclusion

This paper proposes a new energy buffer for highly integrated T-joint module drive in cooperative robots from the perspective of pure hardware. The new buffer can reduce the DC bus voltage fluctuation and ensure the normal operation of the joint module, and it requires fewer components, low cost and takes up small space, which is conducive to the popularization of miniaturization of highly integrated T-joint modules. Experiment results verify the feasibility and effectiveness of the new buffer.

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