A Medium-Voltage High-Power Cascaded Motor Drive System with Low Voltage Fluctuation in the DC Bus

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***Abstract*—To reduce the low-frequency voltage fluctuation in the DC bus of conventional medium-voltage high-power cascaded H-bridge motor drive systems, this paper proposes a topology solution using quad-active-bridge DC/DC converters. The proposed system eliminates the instantaneous fluctuating power from three converter cells through a high frequency link. This removes the need for large filter capacitors in the DC bus and the reliability is improved. Meanwhile, the multi-winding (zig-zag) transformer in the conventional cascaded H-bridge motor drive system can also be removed because of the high frequency transformer included in the quad-active-bridge DC/DC converter. The proposed topology has advantages such as higher reliability by removing the low-frequency filter capacitors, and higher power density by removing the multi-winding transformer. Simulation and experimental prototypes have been built and validated the feasibility of the proposed medium-voltage high-power motor drive system.**

***Index Terms*—Medium voltage, Motor drives, Cascaded H-bridge, Voltage fluctuation, Low-frequency power cancellation, Quad-active-bridge DC/DC converter.**

I. Introduction

With the continuous industrial development, multilevel converters are playing an increasingly important role in medium-voltage high-power motor drive systems. In multilevel converters, the power device bears a low voltage, the output voltage is closer to sinusoidal waveform, and the output current waveform distortion is small [1].

Generally, the neutral-point clamped (NPC) three-level converter is widely used in medium-voltage high-power motor drive systems [2]. Compared with the conventional low-voltage two-level motor drive system, the NPC motor drive system has a low harmonic content of output voltage, and the motor-side voltage can cover 1140V, 3.3kV or 4.16kV voltage levels. Therefore, the NPC motor drive system has high output voltage levels, good harmonic performance. However, as the number of output levels of the NPC converter increases, the control is more complicated and the reliability decreases, making it difficult to increase the number of output levels, which restricts the development power and voltage level.

Among various multilevel converters, the cascaded H-bridge (CHB) multilevel converter can increase continuously the voltage level by increasing the number of cascaded stages. Moreover, the CHB multilevel converter has a modular structure [3-5]. In higher voltage motor drive systems, e.g., >6kV, it has become a mainstream choice, e.g., Siemens Robicon perfect harmony and Delta Electronics MVD 2000 series. Fig.1 shows the conventional CHB motor drive system [3]. The motor is connected to the CHB inverter which is composed of a number of single-phase H-bridge units. The motor voltage can be as high as 10kV, and each H-bridge unit is connected to the grid through a three-phase converter and a multi-winding (zig-zag) grid-frequency (50Hz/60Hz) transformer.

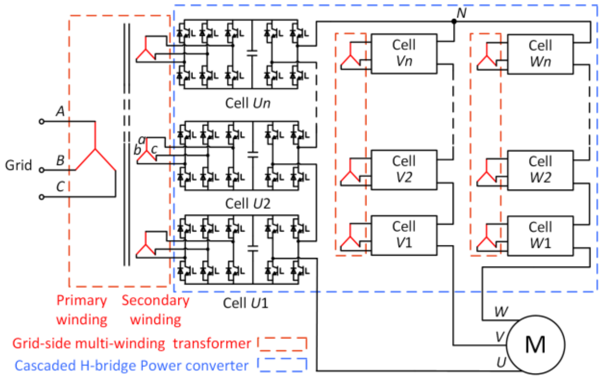

Fig. 1. The conventional cascaded H-bridge motor drive system.

However, there is a large low-frequency (double of the motor stator frequency) fluctuating power in each H-bridge unit thereby causing a large DC bus voltage fluctuation. Hence, large capacitor banks are needed to absorb the fluctuating power in the DC bus of H-bridge units. Due to the low reliability of filter electrolytic capacitors (generally used), the reliability of the DC bus is reduced [6].

To mitigate the issue mentioned above, a number of methods such as the wave utilization method [7] and the active power decoupling method [8] have been proposed to reduce the DC bus voltage fluctuation. But these methods can not eliminate the low-frequency fluctuating power in essence, the low-frequency fluctuating power still remain inside the system. With the fact that the low-

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frequency fluctuating power is symmetrical and can cancel out each other in the three-phase system, methods of instantaneous power aggregation and elimination in the multi-winding (zig-zag) transformer are used to remove the low- frequency fluctuating power [9-10]. By these methods, the low-frequency fluctuating power can be eliminated, thereby the voltage fluctuation of the DC bus and the required filter capacitors are greatly reduced. However, these methods can also cause negative effects on the grid-side converter like additional low-frequency harmonic currents [9] or larger the grid-side converter power loss [10].

At present, with the development of SiC power devices and new magnetic materials, high-frequency isolated power electronic transformers (PET) develop rapidly [11-13]. Capacity of it is constantly increasing, and cost of it is constantly decreasing, which has the potential to solve the DC bus voltage fluctuation issue in medium-voltage high-power CHB motor drive systems. In the CHB motor drive system with high-frequency transformers, the high-frequency transformer can be used to transfer low-frequency fluctuating power, which can be aggregated and eliminated, so that the fluctuation in the DC bus can be greatly reduced, thus reducing the required filter capacitors. Fig. 2 shows a medium-voltage high-power CHB motor drive system with dual-active-bridge (DAB) DC/DC converters. As seen, the motor-side converter is still a CHB inverter, and a DAB DC/DC converter is connected to the DC side of each H-bridge unit. The DAB DC/DC converter output adopts a parallel structure. By using the DAB DC/DC converter, the low-frequency fluctuation power can be aggregated and eliminated in the output parallel side, and hence the voltage fluctuation in the DC bus can also be reduced. However, this method requires too many power devices and DAB DC/DC converters. Because the whole DAB DC/DC converter is greatly affected by the low-frequency fluctuating power in the working process, the power loss in the power transfer is relatively large.

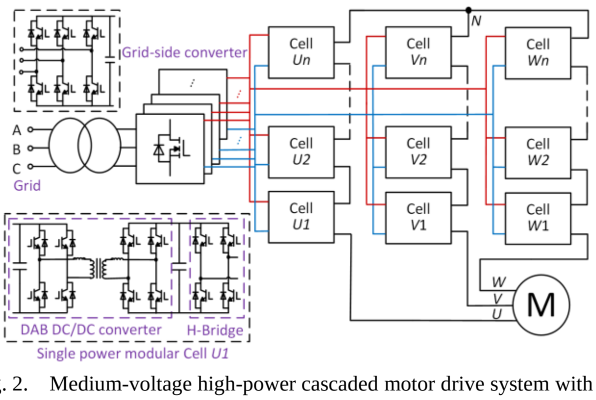


Fig. 2. Medium-voltage high-power cascaded motor drive system with DAB DC/DC converters.

To reduce the voltage fluctuation of the DC bus and improve the reliability in the DC bus, this paper proposes a medium-voltage high-power cascaded motor drive system with high-frequency quad-active-bridge (QAB) DC/DC converters. The QAB DC/DC converter provides a low-frequency fluctuating power aggregation path to realize instantaneous low-frequency fluctuating power aggregation and elimination. Hence, the low-frequency voltage fluctuation in the DC bus is greatly reduced, and then there is no longer need large filter electrolytic capacitors. Meanwhile, the multi-winding (zig-zag) transformer can also be removed because of the use of high-frequency isolated transformer in the QAB DC/DC converter. Compared with the conventional system in Fig.1, the proposed motor drive system has advantages of higher reliability, higher power density and higher efficiency.

The paper is organized as follows. The proposed system structure and parameter comparison with conventional systems are discussed in Section II. Section III explains the low-frequency power aggregation and elimination strategy and simulation results are given and analyzed. Experimental results obtained from one stage prototype with a grid-side converter, a QAB DC-DC converter and a motor-side H-bridge inverter driving an induction motor are shown and discussed in Section IV. In Section V, the conclusion is given.

II. System Configuration

A. System Structure

In this paper, the medium-voltage high-power cascaded motor drive system with QAB DC/DC converters overall structure and the configuration of a single power module are shown in Fig. 3(a) and (b), respectively. In Fig. 3(a), the overall structure adopts a standard modular structure, *n* stages are cascaded in the motor-side and connected in parallel in the grid-side to form the whole system.

Generally, a stage consists of three link. In the first link, the grid-side converter is a three-phase two-level converter, the grid-side converter is connected with single power module in the DC bus. The grid-side converter can obtain electrical energy from the grid by the dual-winding transformer and send it to the power module.

In Fig. 3(b), a single power module consists of the middle link QAB DC/DC converter and the third link motor-side three single-phase H-bridge inverter. Among, in the middle link QAB DC/DC converter, there are four H-bridge units consisting of SiC MOSFET power devices and a four-winding high-frequency isolating transformer, the high-frequency transformer adopts a single input, three output structure, the coil ratio *n* of the four windings is1:1:1:1. Fig. 4 shows the QAB DC/DC converter equivalent circuit. As seen, the transformer can transfer grid energy to the motor-side converter, but also can provide an aggregation path for the low-frequency power of the motor-side converter, so as to eliminate the low-frequency fluctuation in the DC bus. The detailed working principle is described in section III.

The motor-side converter is three single-phase H-bridge inverter which connect A, B and C phase respectively. H-bridge units are composed of low-voltage power devices which is the same as the conventional CHB converter. The motor can be directly connected through cascaded *n* units in each phase. Therefore, the topology can improve motor voltage as high as 10kV.

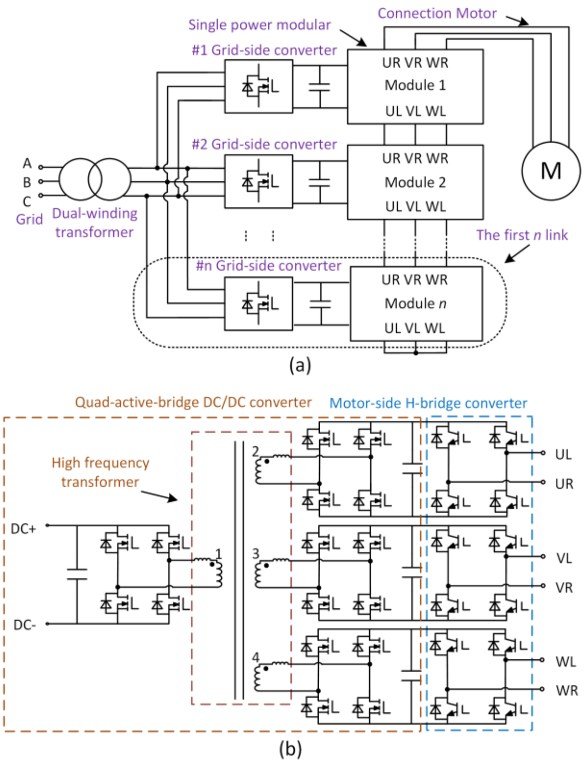


Fig. 3. Medium-voltage high-power cascaded motor drive system with quad-active-bridge DC/DC converters:(a) System overall structure and (b) single power modular internal structure.

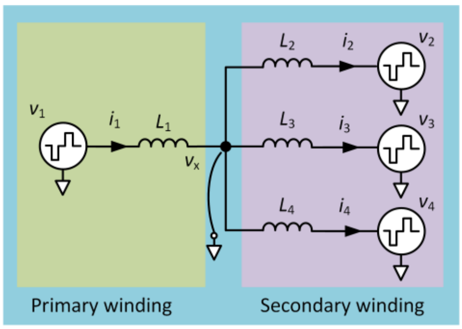


Fig. 4. The quad-active-bridge DC/DC converter equivalent circuit.

B. Systems Parameter Comparison

Systems parameter comparison between the proposed cascaded motor drive system with QAB DC/DC converters, the conventional CHB system and the cascaded system with DAB DC/DC converters are shown in Table I.

As can be seen from Table I, with the addition of the middle link, the number of power devices and capacitors of the proposed motor drive system is more than that of conventional CHB system, and the proposed system also needs to add a high-frequency transformer in every stage. However, due to the volume of the high-frequency transformer is much smaller than that of the multi-winding (zig-zag) low-frequency transformer, and the DC bus capacitor is much smaller than that of the conventional CHB system, so the overall power density is higher than the conventional CHB system. Meanwhile, due to the cascaded motor drive system with DAB DC/DC converters needs more power devices and capacitors than that of the proposed system, so the power density of the cascaded system with DAB DC/DC converters is also lower than that of the proposed motor drive system.

The efficiency of the conventional CHB motor drive is about 96%~97%. Due to the proposed topology adds a high-frequency isolating DC/DC power conversion link, the overall efficiency of the proposed system will be reduced. While, the proposed motor drive system can eliminate the H-bridge unit DC bus voltage fluctuation after realizing low-frequency power elimination, which helps to reduce the switching loss of H-bridge units, and the loss of capacitors can also be reduced after removing the large low-frequency filter capacitor. With the development of SiC devices and high-frequency magnetic materials technology, the overall efficiency of the proposed motor drive system is expected to reach the level of the conventional CHB system. At the same time, because of the low- frequency fluctuation in the system passes through the whole DAB DC/DC converter, the switching loss of the DAB DC/DC converter will increase, so the power loss of the cascaded system with DAB DC/DC converters is the largest.

TABLE I
SYSTEM PARAMETER COMPARISON

	Conventional CHB motor drive system	CHB with DAB motor drive system	CHB with QAB motor drive system
The number of power devices	30n	38n	34n
The number of DC bus capacitors	3n	6n	4n
Capacitance	heavy	small	small
four-winding high-frequency transformer	0	0	n
dual-winding high-frequency transformer	0	3n	0
multi-winding transformer	1	0	0
Power density	Conventional CHB motor drive system <CHB with DAB motor drive system < CHB with QAB motor drive system		
Power loss	CHB with DAB motor drive system < CHB with QAB motor drive system< Conventional CHB motor drive system		

III. Low-Frequency Power Aggregation and Elimination

In this paper, the proposed system increases the QAB DC/DC converter in every stage, and provides a low-frequency power aggregation path. The low-frequency power aggregation and elimination strategy is proposed in this section.

A. Three-Phase Low-Frequency Power

In Fig.1, according to the instantaneous power theory, motor-side H-bridge units not only generate stable DC power, but also generate AC power with a frequency twice that of the motor stator. The instantaneous power of three-phase H-bridge units at each stage of the motor-side CHB converter can be expressed as:

$$\begin{cases} P_u(t) = \dfrac{U_m I_m}{2}\cos\varphi + \dfrac{U_m I_m}{2}\cos(2\omega t - \varphi) \\ P_v(t) = \dfrac{U_m I_m}{2}\cos\varphi + \dfrac{U_m I_m}{2}\cos(2\omega t - \varphi - \dfrac{4\pi}{3}) \\ P_w(t) = \dfrac{U_m I_m}{2}\cos\varphi + \dfrac{U_m I_m}{2}\cos(2\omega t - \varphi + \dfrac{4\pi}{3}) \end{cases} \quad (1)$$

Where, U_m and I_m are the amplitude of AC voltage and current, ω is the frequency of the motor stator, φ is the power factor angle of the motor. It can be seen that the output power of each phase H-bridge unit fluctuates sinusoidal regularly, which can be decomposed into constant power component with amplitude of $(U_m \times I_m)/2$, and the amplitude of the fluctuating power is same as that of the constant power component. Generally, the filter capacitor (usually electrolytic capacitor) is used in industry to absorb the above low-frequency fluctuation power, when the DC voltage fluctuation range is ΔU, the required filter capacitor capacity value C is:

$$C \geq \frac{U_m I_m}{2\omega \times \Delta U \times U_{DC}} \quad (2)$$

As seen, the second term of every equation in (1) represents the low-frequency fluctuating power, which causes voltage fluctuation of the DC bus. Three-phase fluctuating power has a same amplitude, and which phase is 4π/3 different from each other. If three-phase low-frequency power can be aggregated, the fluctuating powers can be eliminated and three-phase voltage fluctuation of the DC bus will be reduced significantly.

B. Low-Frequency Power Aggregation and Elimination

In this paper, the QAB DC/DC converter is connected to the motor-side inverter in every stage to provide an aggregation path for the three-phase low-frequency fluctuating power, thereby the fluctuating power can be eliminated in the four-winding high-frequency transformer of the QAB DC/DC converter. Fig.5 shows the process of instantaneous power transmission elimination. As seen, according to the change of phase-shift angle, the process of the power aggregation in a fundamental frequency period can be divided into six cases. In every case, the primary side can receive the power from the grid-side converter and distribute it equally to three secondary sides. Meanwhile, due to secondary sides are connected to the H-bridge units in the same stage, the motor-side three-phase low-frequency fluctuating power can be aggregated and eliminated into the four-winding transformer and the primary side of the QAB DC/DC converter is not affected.

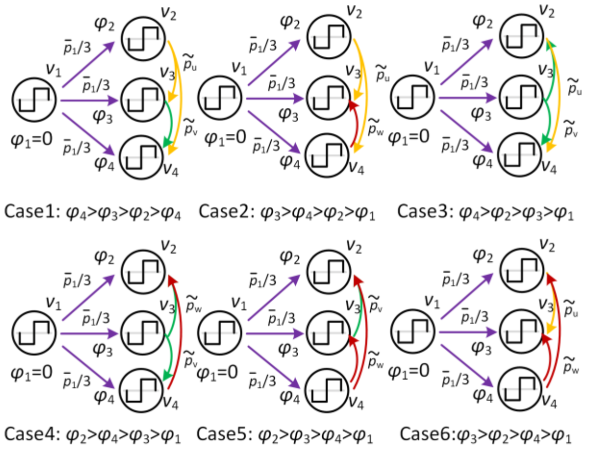


Fig. 5. The quad-active-bridge DC/DC converter instantaneous low-frequency power flow process.

In order to better eliminate the low-frequency fluctuating power, in this paper, the proportional integral resonance (PIR) regulator which is high gain at the resonant frequency is adopted to realize instantaneous power aggregation transmission [10]. The form of the quasi-resonant controller is shown in (3), which has a relatively large gain (Ki) at the resonant frequency of ω, which is set to be twice of the motor stator frequency $2\omega_0$ in this case. ω_b is an additional variable for adjusting the bandwidth of the resonant controller.

$$G(s) = \frac{2K_i\omega_b s + \omega_b^{\ 2}}{s^2 + \omega_b s + (\omega_b^{\ 2} + \omega^2)} \quad (3)$$

Generally, the transfer function shown in (4) in the continuous (s) domain must be discretized into the z-domain to execute control algorithms through a digital signal processor (DSP).

$$H(z) = \frac{1 - e^{-\omega_b T}\cos(\omega T)z^{-1}}{1 - 2e^{-\omega_b T}\cos(\omega T)z^{-1} + e^{-2\omega_b T}\cos(\omega T)z^{-2}} \quad (4)$$

Where T is the sampling period.

Compared with the used proportional integral (PI) regulator commonly, the PIR regulator has better dynamic performance and can realize the dynamic variation of low-frequency pulsating power without static error control.

In summary, based on low-frequency power aggregation and elimination strategy, the proposed motor drive system DC bus voltage fluctuation is low, the proposed system no longer requires low-frequency electrolytic capacitors, but only needs high-frequency filter capacitors. Under the same voltage fluctuation range, the required DC filter capacitance can be reduced by 50-100 times.

C. Simulation Validation

In order to validate the proposed topology feasibility, a 10kV/30MW medium-voltage high-power cascaded motor drive simulation system has been built in MATLAB/Simulink. The overall system consists of 5 stage with each DC bus voltage of 1800 V, and the DC bus capacitance is 100uF (About 1/80 of what the conventional CHB system uses).

Fig.6 shows simulation results at the rated state. Fig.6(a) shows the motor-side CHB converter output phase to phase voltage, which has 11 levels. Fig.6(b) shows the motor-side CHB converter output current, which is kept as sinusoidal and balanced. The effective value of the phase current is 1732A. Fig.6(c) shows the QAB converter secondary side DC voltage. The simulation result shows that the DC bus voltage can be stabilized at 1800V, and compared with PI control, the voltage fluctuation in the DC bus is smaller when the converter adopts PIR control. Fig.6d) shows the four-winding transformer input current, three-phase instantaneous low-frequency power can be aggregated and eliminated inside the transformer, and the primary side current is not affected. Fig.6(e) shows the QAB converter primary side DC voltage, which can also be stabilized at 1800V. Above results prove that the low-frequency power aggregation and elimination does not affected the grid-side converter. Fig.6(f) shows the single-stage grid-side converter input current, which is kept as sinusoidal and balance. The effective value of the phase current is 2829A. Fig.6(g) shows the grid-side converter voltage, which is 658V (phase to phase). Fig.6(h) shows the grid output power, the grid transmits 30MW power to the overall proposed system.

Simulation results can prove that the proposed cascaded motor drive system with QAB DC/DC converters has good performance in eliminating DC bus voltage fluctuation and can realize stable operation in medium-voltage high-power motor drive system.

IV. Performance Evaluation Of The Cascaded Motor Drive System With A QAB DC/DC Converter

In order to verify the practical performance of the proposed system, a low power cascaded motor drive system with a QAB DC/DC converter experiment prototype, as shown in Fig.7. Experimental parameters are given in Table II.

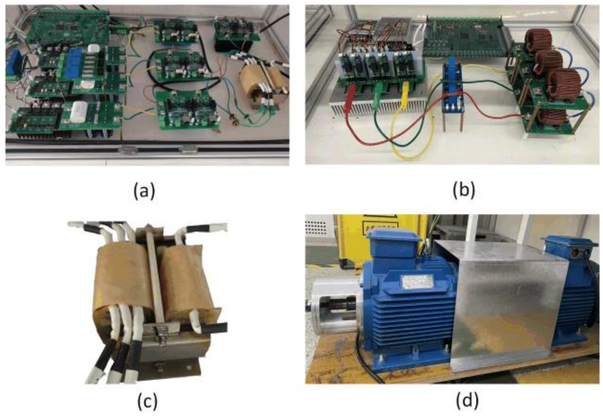


Fig. 7. Experiment prototype: (a) motor-side single power modular, (b) grid-side converter, (c)four-winding high-frequency transformer and (d) induction motor.

TABLE II
EXPERIMENT PLATFORM PARAMETERS

Parameters	values
Rated power	2kW
Input voltage frequency	50Hz
DC bus voltage	200V
Grid-side filter inductance	4mH
DC/DC switching frequency	50kHz
Transformer leakage inductance	100uH

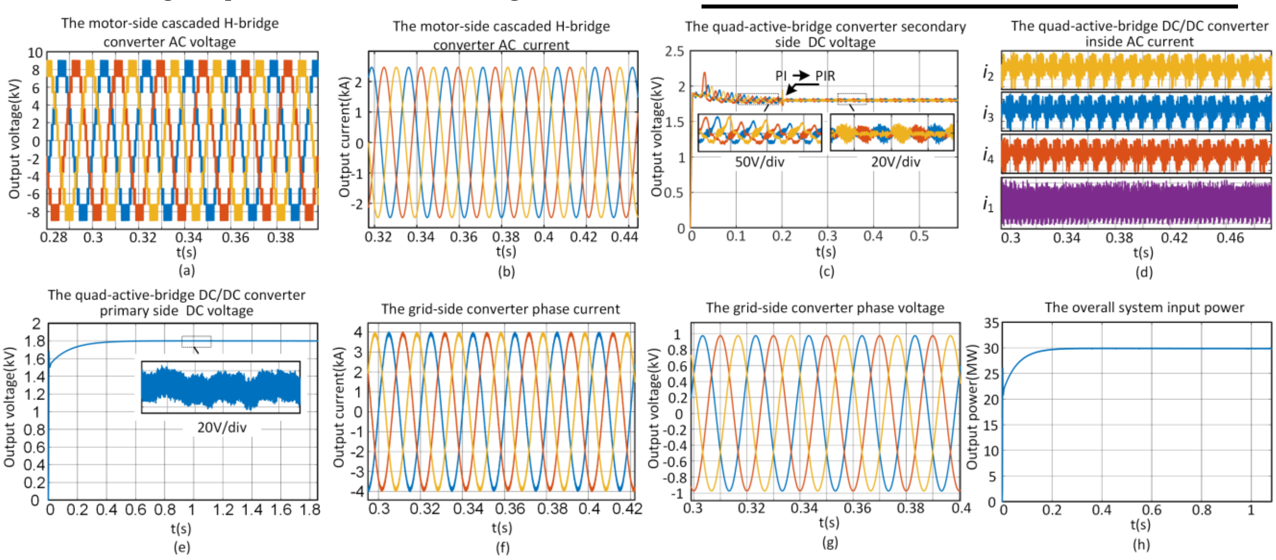


Fig. 6. Simulation results of the medium-voltage high-power cascaded motor drive system with low voltage ripple in DC bus at the rated steady state with 10kV/30MW.

In experimental, the number of cascaded stage is one. The motor-side converter adopts the 1200V/50A IGBT power module PM50RL1A120 from Mitsubishi Corporation. Power devices for the QAB DC/DC converter and the grid-side converter are all 1200V/30A SiC MOSFET C2M0080120D form Wolfspeed.

Fig. 8 shows steady state results of the motor-side H-bridge inverter output three phase-phase voltage waveforms. It can be seen that output voltages of the motor-side converter are stable three-level waveforms. Fig.9 shows waveforms of converter output currents at the motor side. It can be seen that three-phase currents of the motor-side H-bridge inverter are symmetric sinusoidal waveforms. As seen, the motor-side H-bridge inverter can work well at the rated operating point.

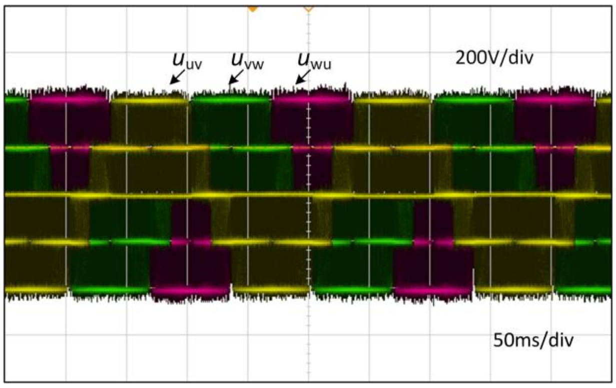


Fig. 8. Experiment results of motor-side H-bridge inverter phase-phase voltage waveforms.

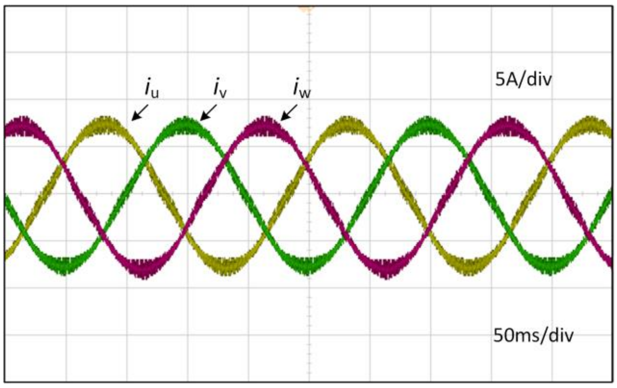


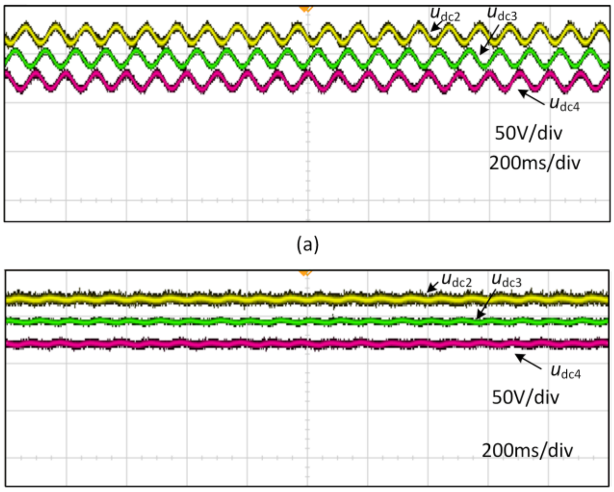
Fig. 9. Experiment results of motor-side H-bridge inverter three-phase current waveforms.

Fig. 10 shows experimental results of DC voltages of the motor- side H-bridge inverter at different control strategies. When the conventional PI control is adopted, the DC voltage of each H-bridge unit has obvious low-frequency fluctuation, and the fluctuation frequency is 100Hz (double motor stator frequency). After switching to PIR control strategy, the DC bus voltage fluctuation can be almost completely eliminated. Above experimental results show that the proposed motor drive system and control method can completely eliminate the low-frequency fluctuation in the DC bus of the motor-side H-bridge inverter.

Fig. 11 shows current waveforms of the four-winding high-frequency transformer. It can be seen that three-phase currents peak value of the secondary side have low-frequency fluctuation. The power flowing into the transformer consists of three-phase low-frequency power. The low-frequency fluctuation power is aggregated and eliminated in the four-winding high-frequency transformer, and the current amplitude of the primary side of the four-winding high-frequency transformer is basically unchanged. The primary side of the QAB DC/DC converter is basically unaffected by fluctuating power.

Fig.12 shows waveforms of grid-side converter output voltages. As seen, the grid-side converter can work well at the rated operating point. Fig. 13 shows the steady state result of grid-side current waveforms. It can be seen that three-phase currents of the grid-side converter are symmetric sinusoidal waveforms, and the grid-side converter is not affected by the low-frequency fluctuation.

Above experiment results can prove that the cascaded motor drive system with QAB DC/DC converters proposed in this paper can work well at the rated operating point. The three-phase low-frequency power can be aggregated and eliminated in the QAB DC/DC converter, and the low-frequency voltage fluctuation in the DC bus is small.



(b)

Fig. 10. Experiment results of motor-side H-bridge inverter DC bus voltage waveforms under different control strategies: (a) PI control strategy and (b) PIR control strategy.

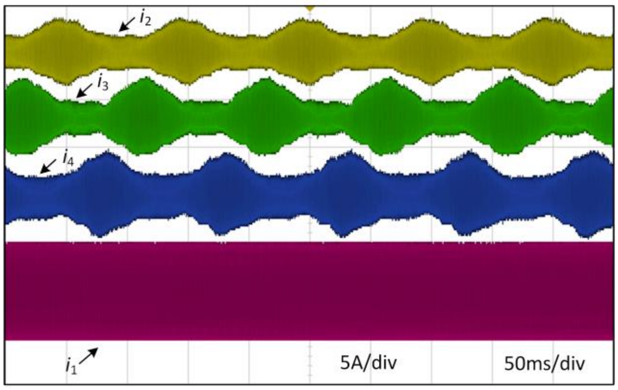


Fig. 11. Experiment results of quad-active-bridge DC/DC converter current waveforms.

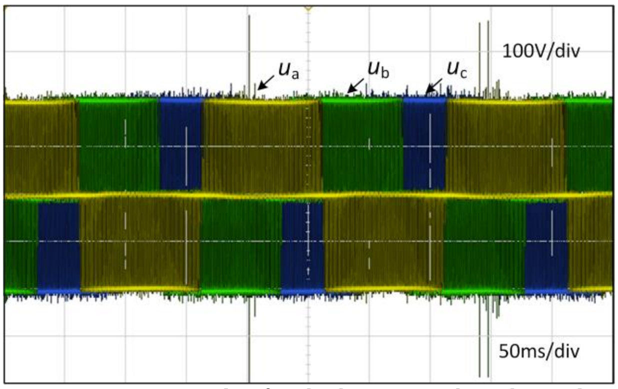


Fig. 12. Experiment results of grid-side converter three-phase voltage waveforms.

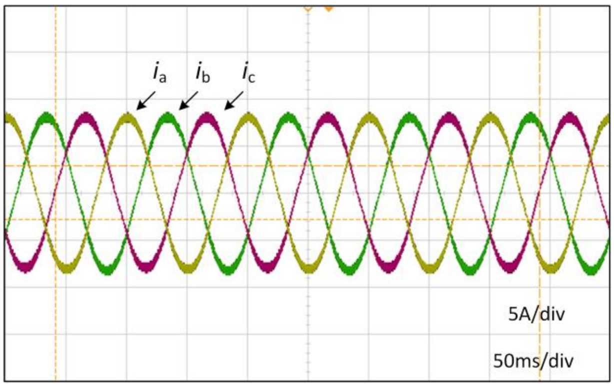


Fig. 13. Experiment results of grid-side converter three-phase current waveforms.

V. Conclusions

In this paper, the proposed medium-voltage high-power cascaded motor drive system can achieve low-frequency fluctuating power aggregation and elimination by using high-frequency QAB DC/DC converters, and then the problem of voltage fluctuation in the DC bus is solved. Hence, compared with the conventional CHB motor drive system, the required DC filter capacitance can be reduced by 50-100 times, the reliability of the DC bus can also be improved. Meanwhile, the power density of the proposed system is also improved because that the multi-winding transformer is removed. Both the simulation and experimental results prove the correctness of the proposed motor drive system with QAB DC/DC converter and the low-frequency power aggregation elimination theory. In the future, how to realize the adaptive of the PIR regulator under the condition of motor stator-frequency change is the focus of future work.

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