Common-mode Noise Reduction with Impedance Balancing in DC-fed Motor Drives

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Abstract— **Unlike conventional passive or active filters, an impedance balancing circuit reduces the common-mode (CM) electromagnetic interference (EMI) noise by establishing an impedance balancing bridge. The EMI noise can be significantly reduced when the impedance bridge is designed to be well balanced. This paper investigates impedance balancing circuits in Dc-fed motor drive systems where both DC input and AC output need to meet EMI standards and thus EMI filters are needed for both sides. An impedance balancing circuit is proposed to reduce both DC and AC side CM noise. Two auxiliary branches are added to the conventional passive filters to establish an impedance bridge and reduce CM noise. The design criteria are presented, and the impact of the proposed impedance balancing circuit on both sides CM noise are investigated. It shows that the proposed impedance balancing circuit can reduce DC side and AC side CM noise based on different mechanisms. The CM noise reduction performance of the proposed method does not depend on the motor and cable models. Experiment results are presented to demonstrate the feasibility and effectiveness of the proposed method.**

Keywords—DC-fed motor drives; Common-mode noise; EMI filter; Impedance balancing.

I. INTRODUCTION

Electromagnetic interference (EMI) noise emissions from the power converters need to be limited to comply with certain electromagnetic compatibility (EMC) standards. To reduce EMI noise and EMI filter weight in motor drive systems, much research work has been conducted. Generally, two EMI noise reduction methods are developed. One is "filtering" and the other is "cancelling". Filtering method usually refers to the use of passive filters. LC type filters are inserted to the converter system to block or bypass EMI noise. The DC input side and AC motor side passive filter design and optimization are illustrated in [1] - [5]. Cancelling method usually refers to the use of active filters. Active filters use sensing components or active devices together with control circuits to generate a current/voltage that cancels with EMI noise current/voltage. Active or hybrid common-mode (CM) filter techniques for motor drive system are proposed in [6] - [10]. Comparing the two methods, passive filters are easier to design but usually bulky and heavy. Active filters, on the other hand, are small and light and can achieve good attenuation performance in low EMI frequency range. However, the high frequency attenuation performance of active filters is limited due to the bandwidth limitation of the control circuit. The reliability of active filter is also a concern, especially in high-power motor drive systems.

Another "cancelling" method is the impedance balancing circuit. It relies on the passive filters but can significantly reduce the required passive filter weight or volume. By adding several passive components to the conventional filter system, a Wheatstone impedance bridge can be established. If the impedance bridge is well balanced, CM noise could be theoretically eliminated. The impedance balancing concept has been applied to dc-dc converters [11] and boost power factor correction (PFC) converters [12] for CM noise reduction. This method is first introduced to DC-fed motor drive system by Xing *et al.* to reduce DC input side CM noise [13]. As presented in [13], a CM inductor is added from the inverter output terminals to the DC input to establish the impedance bridge to reduce CM noise. However, this approach cannot reduce AC motor side CM noise. Also, the DC side CM noise attenuation performance is dependent on the motor and cable models. Good attenuation can be achieved in the frequency range where motor and cable CM impedance can be modeled as a fixed value capacitor.

In some applications, the EMI standard is only enforced at the DC source side to ensure the source is not polluted by the switching action of the power electronics. In many aircraft and electric vehicle applications, the power electronic converter is connected to the motor load through long power cables. The cables behave like an antenna and will generate noise which may influence the operation of other electronics in the system. Therefore, EMI standards are also enforced at the AC output side. For example, in aircraft applications, DO-160 standard has defined EMI noise current limits for both the AC and DC sides, and EMI filters are needed for both sides. In addition to pass EMI standards, AC side EMI filters will also benefit motor operation by reducing motor-end leakage current, potential overvoltage, and so on.

Fig. 1 shows the DC-fed three phase motor drive system with both input and output EMI filters. EMI noise is usually divided into differential-mode (DM) noise and common-mode noise based on the noise propagation path. DM noise conducts between phases. CM noise conducts in the same direction of each phase and flows to ground through parasitic capacitance.

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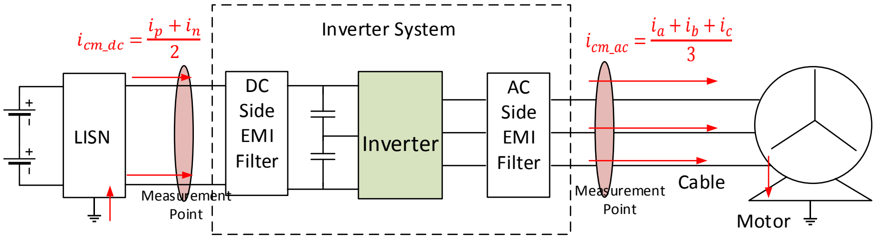


Fig. 1. DC-fed motor drive system with input and output EMI filters.

CM noise current flows to ground through motor parasitic capacitance and the AC side EMI filter and then flows back to the noise source through line impedance stabilization networks (LISNs) and the DC side EMI filter. As shown in Fig. 1, CM noise current is measured at both input and output of the inverter system. The DC side CM noise current is defined as $i_{cm\_dc} = (i_p + i_n)/2$ and the AC output motor side CM noise current is defined as $i_{cm\_ac} = (i_a + i_b + i_c)/3$. Both the DC and AC sides EMI noise current need to meet EMI standards.

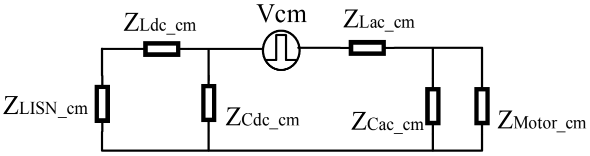


Fig. 2. CM equivalent circuit.

The DC side and AC side CM noise share the same propagation path and are coupled with each other, which makes the CM noise reduction more complex. Fig. 2 shows the CM equivalent circuit when one stage LC filter is applied to both the DC and AC sides. The CM impedance of the LISNs is represented as Z_{LISN_cm}, motor and cable CM impedance is represented as Z_{Motor_cm}. EMI noise current flowing through AC side motor and DC side LISNs can be reduced by increasing the conventional CM filter inductance or capacitance. However, increasing CM capacitance in one side will decrease CM current noise in this side but increase CM current noise in the other side. For example, when AC side CM capacitance increases, CM noise current flowing to the motor decreases. But the entire loop CM impedance decreases, and CM current flowing to the DC side LISNs increases. Also, the total capacitance that can be applied to the system is limited by leakage current requirement. Increasing CM inductance increases the entire loop CM impedance and thus reduces both DC and AC side CM noise. However, unlike capacitors which only conduct high frequency harmonics, the inductors are in the power current conduction path and are usually bulky since large core and winding should be used to deal with the power current produced leakage flux density and power loss. Increasing the inductance may significantly degrade system efficiency and power density, especially in high power converters. Therefore, it is desired that the impedance balancing circuit can reduce both the DC and AC sides CM noise current, so the required inductances of the conventional CM inductors can be reduced.

This paper proposes an impedance balancing circuit for DC-fed motor drive where both the DC and AC sides need to pass EMI standards and thus EMI filters are needed for both sides. Two auxiliary branches are added to the conventional CM filters to establish an impedance bridge and reduce both DC and AC sides CM noise. The added impedance balancing circuit only conducts the CM current, and will not bring much weight and loss penalty to the inverter system. The design criteria of the proposed circuit are presented. The impact of the proposed impedance balancing circuit on CM noise of both the DC and AC sides are illustrated. Experimental results are presented to demonstrate the feasibility and effectiveness of the proposed approach.

II. PROPOSED IMPEDANCE BLANCING CIRCUIT FOR CM NOISE REDUCTION

The proposed impedance balancing circuit is shown in Fig. 3. Two auxiliary branches are added to the conventional CM filter: one branch is an inductor L_r connecting the AC side and the ground (C_r is used to block the fundamental and low frequency components and R_r is used to damp the LC resonance); another branch is a capacitor C_{return} which connects the AC and DC sides through the AC DM capacitors and DC-link cap mid-point.

First, an investigation of the influence of the proposed impedance balancing circuit on the AC motor side CM noise current is given. Fig. 4(a) shows the CM equivalent circuit of the converter system. In the EMI frequency range (150 *kHz* ~ 30 *MHz*), the impedance relationship satisfies

$$\begin{aligned} & Z_{Lr} \gg Z_{Cr} + R_r \\ & Z_{2Ccmdc} \ll Z_{Lcmdc} + Z_{LISN\_cm} \\ & Z_{Creturn} \gg Z_{3Cdmac} \end{aligned} \tag{1}$$

Hence, CM equivalent circuit can be simplified to the circuit shown in Fig. 3 (b). The four components L_r, L_{cmac}, $2C_{cmdc}$, and C_{return} establish an impedance bridge. If the impedance bridge meets the relationship

$$\frac{Z_{Lr}}{Z_{Lcmac}} = \frac{Z_{2Ccmdc}}{Z_{Creturn}} \tag{2}$$

The potentials of point A and B are the same (i.e., V_{AB} =0). Thus, CM current flowing through the AC side motor can be theoretically zero. Eq. (2) can be simplified, yielding

$$\frac{L_r}{L_{cmac}} = \frac{C_{return}}{2C_{cmdc}} \tag{3}$$

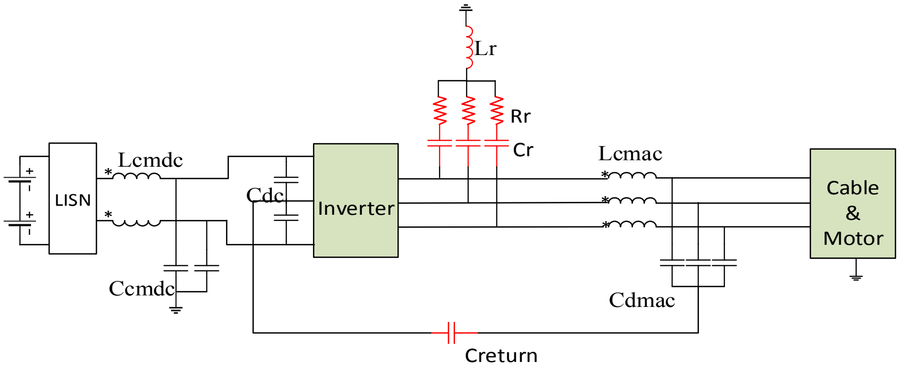
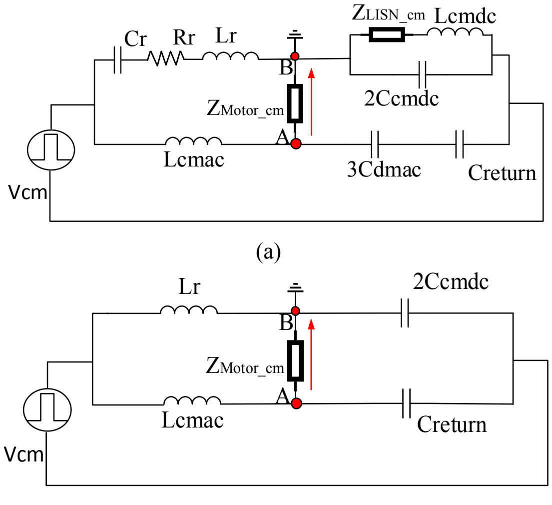


Fig. 3. Proposed impedance balancing circuit for DC-fed motor drives.



(a)

(b)

Fig. 4. (a) CM equivalent circuit. (b) Simplified CM equivalent circuit.

Therefore, for AC side CM noise reduction, the impedance balancing circuit parameters should meet (3) to maximize the CM noise reduction performance. Note that the motor CM impedance is not in one of the branches establishing the impedance bridge as shown in Fig. 4. The noise reduction performance of the impedance balancing circuit is only determined by L_r, L_{cmac}, C_{cmdc} and C_{return}. Hence, the CM noise reduction performance is not dependent on motor and cable models. It is not necessary that the motor CM model must behave like a constant capacitance in a wide frequency range.

Next, an investigation of the influence of the proposed impedance balancing circuit on the DC LISN side CM noise current is conducted. Without the impedance balancing circuit, the CM current path flowing through the LISNs is shown in Fig. 5(a). With the impedance balancing circuit, in ideal case, the impedance bridge is perfectly balanced, and no current will flow through motor CM impedance. The motor CM impedance branch can be considered as open circuit. Then, CM current path flowing through the LISNs is shown in Fig. 5(b). To reduce CM current flow to the LISNs, the propagation path impedance with the impedance balancing circuit should be larger than that without the impedance balancing circuit,

$$Z_{Lr} > Z_{Lcmac} + Z_{Motor\_CM} \tag{4}$$

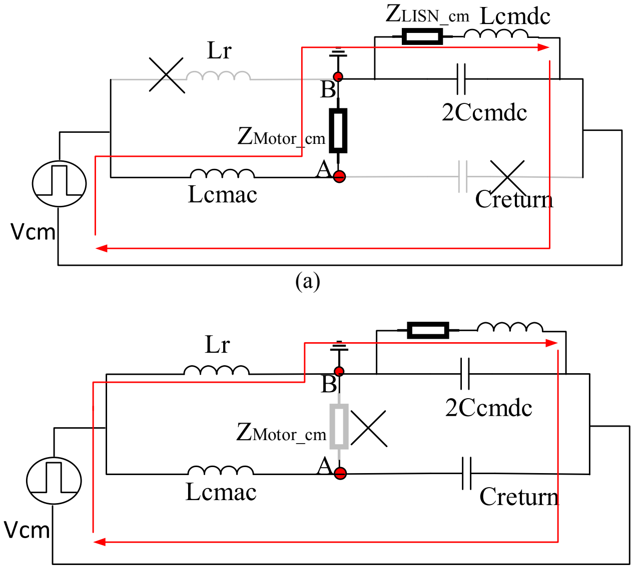
Define the impedance balancing circuit ratio n as

$$n = \frac{L_r}{L_{cmac}} = \frac{C_{return}}{2C_{cmdc}} \tag{5}$$

To meet (4), the ratio n should meet

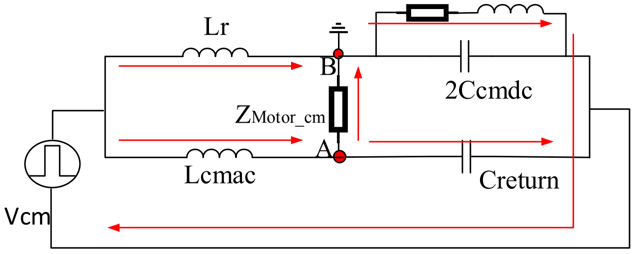
$$n > 1 \tag{6}$$

With larger n, CM current which flows to the DC side LISNs will be smaller. Considering that the impedance balancing bridge may not be perfectly balanced over all the frequency range, there is CM current flowing through the motor CM impedance. Then, the CM current path flowing through the LISNs is shown in Fig. 5(c). The capacitor C_{return} will help to bypass CM current. With larger n, C_{return} is larger, more CM current will be bypassed by C_{return}. Therefore, with larger impedance balancing circuit ratio n, L_r and C_{return}, which both help to reduce CM noise flowing through the LISNs, will be larger, then better DC side CM noise reduction can be achieved.



(a)

(b)



(c)

Fig. 5. (a) LISNs CM current conduction path w/o balancing circuit; (b) LISNs CM current conduction path w/ balancing circuit; (c) LISNs CM current conduction path considering the impedance bridge is not perfectly balanced.

Therefore, for DC side CM noise reduction, the impedance balancing circuit parameters should meet (6) and better DC side CM noise reduction performance can be obtained with larger impedance balancing circuit ratio n.

In conclusion, the proposed impedance balancing circuit can reduce both the AC motor side and the DC LISN side CM noise if the design criteria are met. The AC side motor CM impedance is in the middle of the impedance bridge, and no CM current circuit flows to the motor since CM current of the impedance bridges branches cancel with each other if the bridge is well balanced. The impedance bridge also changes the propagation path impedance of the CM noise current flowing to the LISNs, and thus reduce the DC side CM noise. The proposed circuit is suitable for motor drive system where both the DC and AC sides need to meet EMI standard. As the impedance balancing circuits are not in the main current conduction path and only conduct CM noise current, their loss and weight are very small.

III. EXPERIMENTAL VERIFICATION

A silicon carbide device based three-phase neutral point clamped inverter is constructed for experimental verification. The switching frequency is 280 *kHz* and inverter AC output fundamental frequency is 3 *kHz*. The inverter conventional CM filter structure is the same as the structure shown in Fig. 3. The CM filter parameters are: L_{cmac}=500 *uH*, L_{cmdc}=2.1 *mH* and C_{cmdc}=2 *nF*. Fig. 6 shows the inverter output voltage and current waveform which is the operating point for EMI noise testing.

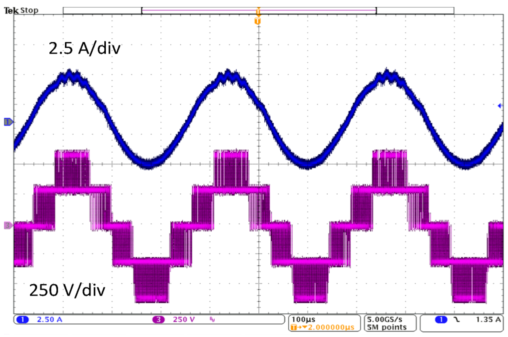
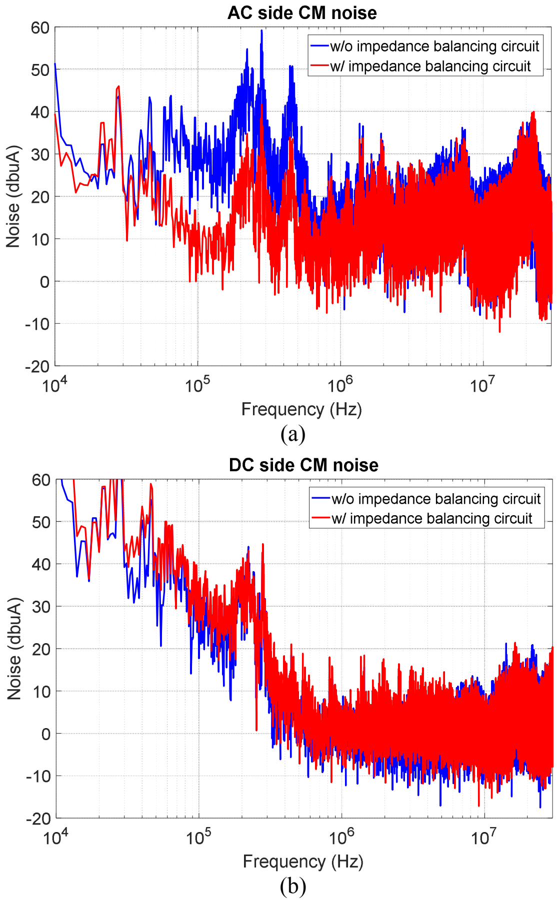


Fig. 6. Inverter output voltage and current waveform.

According to the analysis, (3) should be met for the AC motor side CM noise reduction, and both (3) and (6) should be met for the DC LISN side CM noise reduction. To verify this analysis, the impedance balancing circuit ratio is first selected as n=1. Then, the impedance balancing circuit parameters are determined as L_r=500 *uH* and C_{return}=4 *nF*. In this case, the AC side CM noise attenuation can be expected and the DC side CM noise will not be decreased. The comparison experiments are conducted without the impedance balancing circuit (having only the conventional CM filter L_{cmac}, L_{cmdc} and C_{cmdc} as shown in Fig. 3) and with the impedance balancing circuit (having the conventional CM filter L_{cmac}, L_{cmdc}, C_{cmdc} and the added two impedance balancing circuit branches L_r and C_{return} as shown in Fig. 3). The CM EMI noise test results are shown in Fig. 7. From Fig. 7(a), when the impedance balancing circuit is applied, 10~20 dB AC side CM noise attenuation has been achieved in the 150 *kHz* to 1 *MHz* frequency range, and around 18 dB attenuation is obtained at switching frequency noise peak. In the lower frequency range from 10 *kHz* to 150 *kHz*, the impedance balancing circuit also helps to reduce CM noise. From Fig. 7(b), no CM noise attenuation can be observed in the DC side. These results match the theoretical analysis.



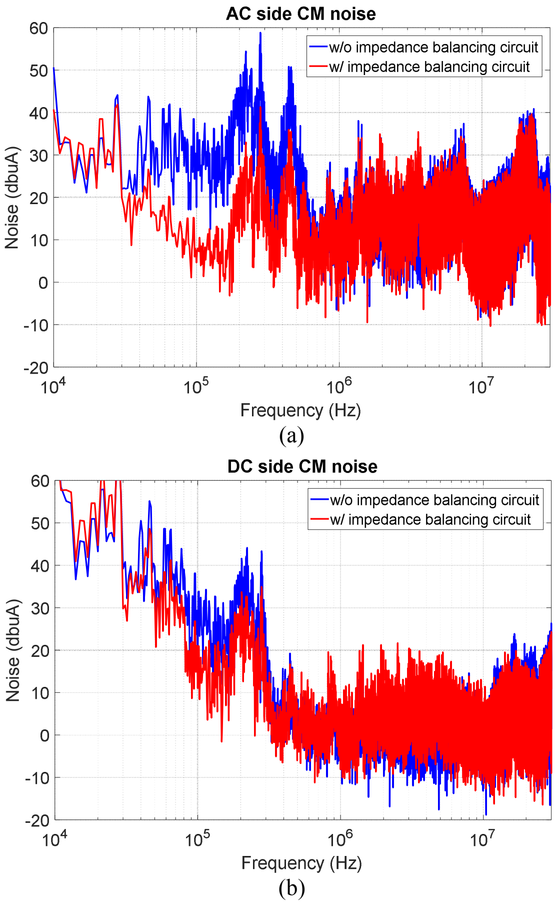
(a)

(b)

Fig. 7. CM EMI noise w/ and w/o the impedance balancing circuit at n=1. (a) AC side, (b) DC side.

To demonstrate the DC side CM noise attenuation, the impedance balancing circuit ratios is then selected as n=4. So, the impedance balancing circuit parameters are determined as

L_r=2 mH and C_{return}=16 nF. The comparison experiments are also conducted. Fig. 8(a) shows the AC side CM noise current spectrum. Similarly, as previous case where n=1, 10~20 dB noise attenuation has been achieved in the 150 kHz to 1 MHz frequency range, and around 18 dB attenuation is obtained at switching frequency noise peak when the impedance balancing circuit is applied. Fig. 8(b) shows the DC side CM noise current spectrum. With the impedance balancing circuit, 5~15 dB noise attenuation has been achieved in the 150 kHz to 1 MHz frequency range, and around 10 dB attenuation is obtained at switching frequency noise peak. These results also match the theoretical analysis.



(a)

(b)

Fig. 8. CM EMI noise w/ and w/o the impedance balancing circuit at n=4. (a) AC side, (b) DC side.

From Fig. 7 and Fig. 8, it can be found that the AC side impedance balancing circuit nearly does not change the EMI noise level above 1 MHz frequency. This is because in the MHz frequency range, the adverse effect of the power stage parasitic capacitances begins to influence balancing performance of the impedance bridge. Also, the parasitics of EMI filters in the impedance bridge, such as the equivalent parallel parasitic capacitance (EPC) of the CM inductor, cannot be neglect in the high frequency range. For example, Fig. 9 shows the measured impedance curve of the AC side CM inductor L_{cmac} and the uniformed auxiliary inductor of the impedance balancing circuit L_r/n. From Fig. 9, the impedance difference of the two inductors begin to increase at the frequency range above 2 MHz. The impedance bridge is not balanced well and (3) is not met in the high frequency range. To improve the high frequency performance of the impedance balancing circuit, from physical design point of view, the power stage parasitic capacitance and passive filter parasitics need to be well controlled and reduced.

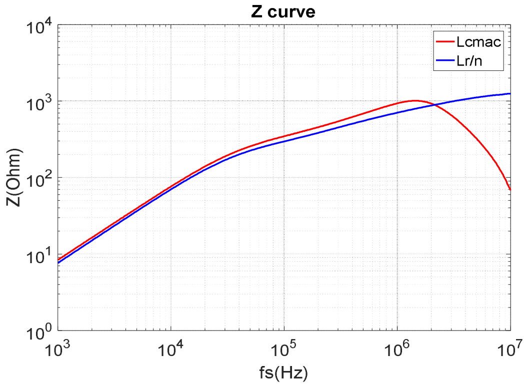


Fig. 9. Impedance comparison of the AC side CM inductor and the auxiliary inductor.

IV. CONCLUSION

This paper proposes an impedance balancing circuit for CM noise reduction in DC-fed motor drives where both the DC and AC sides need EMI filters. The design criteria and CM noise reduction mechanisms are presented. The proposed impedance balancing circuit can reduce both the DC LISN side and the AC motor side CM noise current, and the CM noise reduction performance does not depend on the motor and cable models. Experiment results show that both the AC and DC side can achieve 10~20 dB CM noise attenuation in the 150 kHz to 1 MHz frequency range. Specifically, at the switching frequency noise peak, 18 dB AC side attenuation and 10 dB DC side attenuation have been achieved when impedance balancing circuit ratio is selected as n=4. The proposed impedance balancing circuits are not in the main power current conduction path and conduct only the CM noise current, so their loss and weight are very small compared to conventional CM filters. The required CM inductance of conventional CM inductors in both the DC and AC side can be significantly reduced when the impedance balancing circuit is applied.

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