A Design of PWM Inverter Passive Filter Based on CM Transformer

Yugang Yang, Lei Wang, and Heming Sun

***Abstract*—The negative effects of the PWM inverter are mainly as follows: the high dv/dt value of the DM(differential mode) and the CM(common mode) voltage will cause an impact on the insulation layer of the motor winding; the current generated by the CM voltage on the motor bearing will corrode the bearing and reduce motor life; electromagnetic interference caused by high frequency CM leakage current will affect the stability of the system. Based on the CM transformer, a new passive filter topology is proposed, this filter uses the coupling function of the CM transformer to suppress the CM voltage and the leakage inductance of the CM transformer as the DM filter inductor, which can effectively suppress the dv/dt values of the DM and CM voltages, it can also effectively reduce the RMS value of the CM voltage. In this paper, the winding method of CM transformer windings is improved, each winding is divided into two parts in series and distributed symmetrically on the iron core, which makes the leakage inductance and coupling coefficient between the windings of the transformer more symmetrical, which enhances the filtering effect. The effectiveness of the filter is verified by simulation and experiment.**

***Index Terms*—CM transformer, CM voltage, DM voltage, passive filter, PWM inverter.**

I. Introduction

WITH the wider application range of PWM inverters, the range of influence caused by its negative effects has also expanded, and it has become a new research hotspot to discover and suppress its negative effects. The high-speed turn-on and turn-off of the inverter switch tube will cause the dv/dt value of the inverter output voltage to be large. When the PWM inverter directly drives the motor load, the insulation layer of the motor winding will be greatly impacted[1]-[3]; The high-frequency CM voltage of the inverter output will also generate shaft voltage and shaft current on the motor bearing through the parasitic capacitance inside the motor. The shaft current will gradually corrode the motor bearing, causing damage of the motor bearing and affecting the life of the motor[4]-[6]; The high-frequency CM voltage is affected by parasitic capacitance, which will generate high-frequency ground leakage current, which will cause electromagnetic interference to other electrical equipment in the system and affect the stable operation of the system[7]-[9]. In order to suppress these negative effects of the inverter, passive filters are often used to suppress these negative effects as a lower cost and better solution.

The literature [10] first proposed the concept of CM transformer, which adds a fourth winding to the three-phase CM inductor, and a resistor in series with the fourth winding eliminates the energy of the CM current, which can effectively suppress the CM interference; The literature [11] uses the parasitic parameters of the cable as the inductance of the RLC filter, which effectively reduces the loss, but it is limited by the value of the parasitic parameters, and the filtering effect is general; The literature [12] uses an integrated method to achieve LC filtering, it can increase the pulse rise time and reduce the dv/dt value, but does not have the function of suppressing the CM voltage; The literature [13] uses the SiC inverter to drive the high speed motor, and uses the RLC structure to realize the dv/dt filtering effect, it has high efficiency, but the DM and CM voltage suppression effect is general; The literature [14] uses the LC filter's filter inductor to achieve a multi-coupling structure, which has a good suppression of the DM voltage, but the CM voltage suppression effect is general.

This paper proposes a new PWM inverter output passive filter topology based on the traditional four-winding CM transformer. This filter uses the coupling effect of the CM transformer to suppress the CM voltage, and utilize the leakage inductance of the CM transformer as a DM filter inductor, the DM voltage of SPWM can be effectively filtered into a standard sine wave, the dv/dt value and the effective value of the CM voltage are simultaneously reduced. In addition, this paper also improves the winding mode of CM transformer windings. Each winding is divided into two parts in series, which makes the leakage inductance and coupling coefficient of the transformer more uniform and improves the filtering effect. The effectiveness of the filter is verified by simulation and experiment.

II. PWM Inverter Generates CM Voltage Analysis

A. CM Voltage Definition

Fig. 1 is a schematic diagram of the PWM inverter directly connected to the load.

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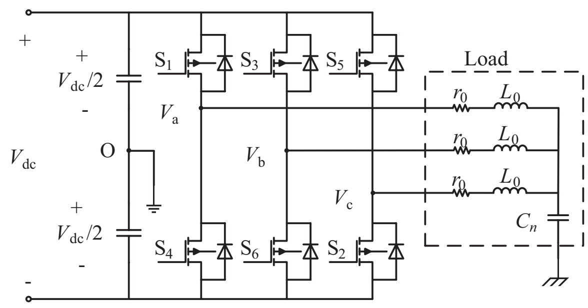


Fig. 1. PWM inverter directly connected to the load.

Since the inverter has eight turn-on and turn-off states during normal operation, the voltage at the midpoint of the inverter output to the ground is defined as the CM voltage, that is the zero-sequence voltage of the inverter output.

$$V_{cm} = \frac{V_a + V_b + V_c}{3} \tag{1}$$

Where V_a, V_b, and V_c are the phase voltages of the PWM inverter output.

B. Value of CM Voltage

It can be known from (1) that if the load is not connected through the inverter but directly connected to the three-phase sinusoidal voltage, the CM voltage on the load is zero, and the system is not affected by the CM voltage[2]. In the case of a load directly driven by a PWM inverter, the six switching tubes have eight switching states, as shown in Fig. 2, taking the first switch state in Fig. 2 as an example, the three single-phase voltages of the inverter are $-V_{dc}/2$, $-V_{dc}/2$, and $-V_{dc}/2$, respectively. According to (1), the CM voltage is $-V_{dc}/2$, and so on. The CM voltages in the eight switching states are as shown in (2).

$$V_{cm} = \begin{cases} \dfrac{V_{dc}}{2} & S_7 \\ -\dfrac{V_{dc}}{2} & S_0 \\ \dfrac{V_{dc}}{6} & S_3, S_5, S_6 \\ -\dfrac{V_{dc}}{6} & S_1, S_2, S_4 \end{cases} \tag{2}$$

The waveform of the CM voltage can be obtained according to Fig. 2 and (2), as shown in Fig. 3.

III. Filter Characteristics Analysis

According to the negative effects of PWM inverter, this paper proposes a novel PWM inverter output passive filter, the topology is shown in Fig. 4.

The PWM inverter output filter in Fig. 4 is composed of

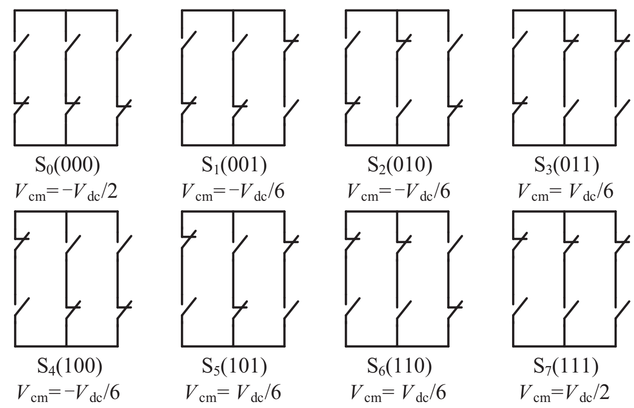


Fig. 2. Eight switch states of the inverter.

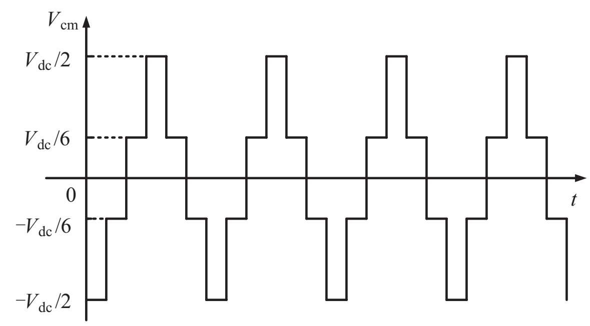


Fig. 3. CM voltage waveform.

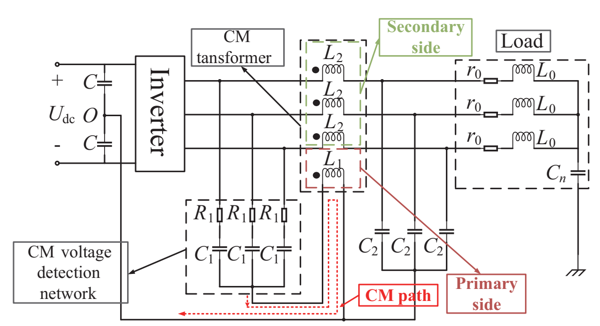


Fig. 4. The passive filter topology of the PWM inverter output proposed in this paper.

a CM voltage detection network and a filter circuit. The CM voltage detection network consists of resistors R_1 and capacitors C_1, the filter circuit is composed of a CM transformer and three capacitors C_2. The function of the CM voltage detection network is to detect the CM voltage (V_{cm}) from the inverter, the function of the filter circuit is to suppress the DM and the CM voltage, so the filter circuit is further divided into a DM filter circuit and a CM filter circuit. The DM filter circuit is composed of a leakage inductance L_s of the CM transformer and three capacitors C_2 for suppressing the DM voltage, the CM filter circuit is composed of the CM voltage detection network and the CM transformer, and the CM voltage is suppressed by the coupling action of the CM transformer.

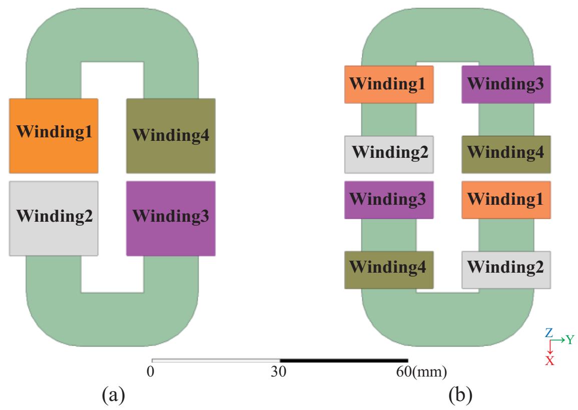


Fig. 5. Two winding methods of CM transformer. (a) Ordinary winding method. (b) New winding method.

TABLE I
COUPLING COEFFICIENT BETWEEN WINDINGS OF FIG.5(A)

	Winding 1	Winding 2	Winding 3	Winding 4
Winding 1	1	0.768	0.747	0.841
Winding 2	0.768	1	0.841	0.747
Winding 3	0.747	0.841	1	0.768
Winding 4	0.841	0.747	0.768	1

TABLE II
COUPLING COEFFICIENT BETWEEN WINDINGS OF FIG.5(B)

	Winding 1	Winding 2	Winding 3	Winding 4
Winding 1	1	0.848	0.881	0.849
Winding 2	0.848	1	0.849	0.881
Winding 3	0.881	0.849	1	0.848
Winding 4	0.849	0.881	0.848	1

A. Winding Design of CM Transformer

The winding mode of the CM transformer proposed in literature [15] is shown in Fig. 5(a), since the winding position is not completely symmetrical, the coupling coefficient between the windings is not uniform. The coupling coefficient is obtained by ANSYS Maxwell simulation, as shown in Table I, it can be seen that the coupling coefficient between the windings differs by a maximum of 0.1. In this case, if the mutual inductance is assumed to be equal when analyzing the transformer, it will cause a large error, as a result, the theoretical design does not match the actual situation. On this basis, this paper proposes a new CM transformer winding method, which divides each winding of the CM transformer into two parts in series, and its structure is shown in Fig. 5(b).

The coupling coefficient between the windings is obtained by simulation, as shown in Table II, it can be seen that the coupling coefficient between the windings differs by a maximum of 0.03, which can reduce the error to a large extent compared with the ordinary winding method. This makes the theoretical design more in line with the actual situation, and thus improves the filtering effect.

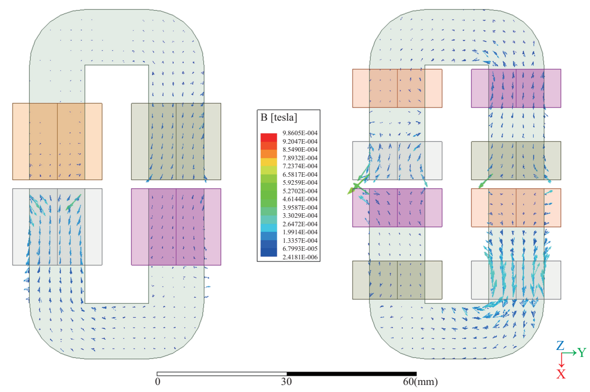


Fig. 6. Apply DM current excitation to the windings.

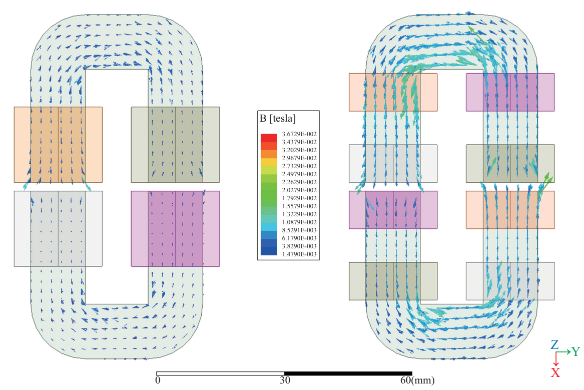


Fig. 7. Apply CM current excitation to the windings.

In order to verify the effect of the new winding method of the CM transformer winding, the simulation is verified by ANSYS Maxwell software, and the DM current and the CM current are respectively input to the CM transformer windings of the two winding methods, and the magnetic density vector cloud diagram is as follows Fig. 6 and 7.

It can be seen from Fig. 6 that when the CM transformer windings is connected to the three-phase DM current, since the vector sum of the three-phase DM current is close to zero at any time, the magnetic fluxes generated by the three-phase DM current cancel each other, the total magnetic flux density of the transformer core is very small, at this time, the leakage inductance of the CM transformer is equivalent to a DM filter inductor. As can be seen from Fig. 7, when the CM transformer winding is connected to the CM current, the magnetic fluxes generated by the windings are superimposed on each other and evenly distributed in the core of the transformer, at this time, the CM transformer exhibits a high inductive reactance to the CM current, and thus has a strong suppression effect on the high frequency CM component. In addition, it can be clearly seen that regardless of the DM current or the CM current flowing through the CM transformer windings, The flux density of the improved CM transformer core is larger than that of the unmodified one, which means that the CM and DM performance of the filter is enhanced.

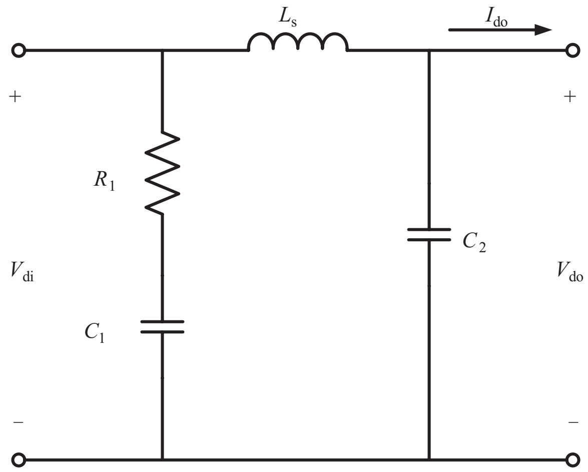


Fig. 8. DM single-phase equivalent circuit.

B. DM Equivalent Circuit Analysis

For the DM voltage component of the inverter output, its induced voltage on the inductor L_1 is zero, which is equivalent to the resistance R_1 and the capacitor C_1 are directly connected to the midpoint of the DC bus, thereby obtaining the DM equivalent circuit is shown in Fig. 8.

The transfer function of the circuit shown in Fig. 8 is

$$H(s) = \frac{V_{do}(s)}{V_{di}(s)} = \frac{1}{s^2 L_s C_2 + 1} \tag{3}$$

(3) can be written as

$$H(j\omega_c) = \frac{1}{-\omega^2 L_s C_2 + 1} \tag{4}$$

The equation for calculating the cutoff angle frequency is

$$H(j\omega_c) = \left| \frac{1}{-\omega^2 L_s C_2 + 1} \right| = \frac{1}{\sqrt{2}} \tag{5}$$

Calculate the cutoff angle frequency according to (5)

$$\omega_c = \sqrt{\frac{1+\sqrt{2}}{L_s C_2}} \tag{6}$$

It can be seen from (4) that the DM equivalent circuit of the filter is equivalent to an LC filter, so the leakage inductance L_s and the value of the filter capacitor C_2 of the CM transformer can be calculated according to the LC filter design criteria[16], as shown in (7).

$$\begin{cases} L_s = \dfrac{V_{do}}{I_{do}\omega_c^2}\sqrt{\omega_c^2 + \omega_1^2} \\ C_2 = \dfrac{1+\sqrt{2}}{\omega_c^2 L_s} \end{cases} \tag{7}$$

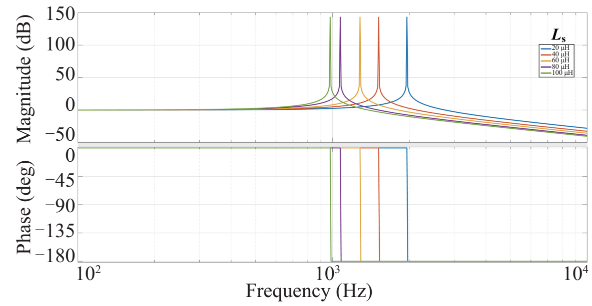


Fig. 9. Bode diagram under different L_s parameters.

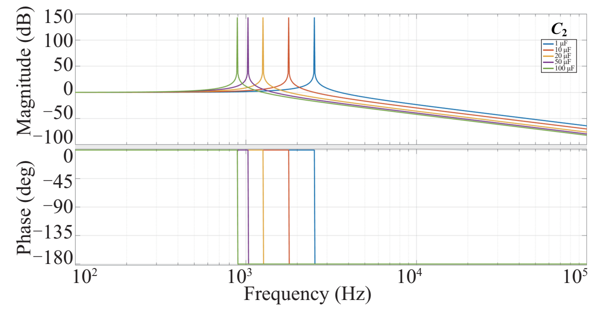


Fig. 10. Bode diagram under different C_2 parameters.

ω_1 is the fundamental angle frequency of the inverter, V_{do} is the output voltage of the DM single-phase equivalent circuit, and I_{do} is the output current of the DM single-phase equivalent circuit.

In order for the filter to effectively filter out high frequency harmonic components in the inverter output voltage, the cutoff angle frequency should be much smaller than the switching frequency of the inverter.

$$\omega_c \ll 2\pi f_s \tag{8}$$

f_s is the switching frequency of the inverter, and ω_c is the cutoff angle frequency of the inverter.

The cutoff frequency in this paper is selected as 1/10 of the switching frequency, that is 1 kHz, which can satisfy (8). At this time, the filter circuit has good low-pass characteristics and can effectively suppress high-frequency harmonic components.

Fig. 9 is a Bode diagram of (3) under different L_s parameters, and Fig. 10 is a Bode diagram of (3) under different C_2 parameters.

It can be seen from Fig. 9 that the value of the inductor L_s will affect the cut-off frequency of the DM filter circuit. The larger the value of the inductor, the smaller the cut-off frequency, and the better the filtering effect. Similarly, it can be seen from Fig. 10 that with the increase of capacitor C_2, the cut-off frequency of the circuit will also decrease accordingly, so there will be a better filtering effect. However, the inductance L_s and the capacitance C_2 are not as large as possible. The inductance L_s is the leakage inductance of the CM transformer, when the leakage inductance is too large, it will not only increase the loss, but also cause interference to other components in the circuit. The capacitance C_2 is filter

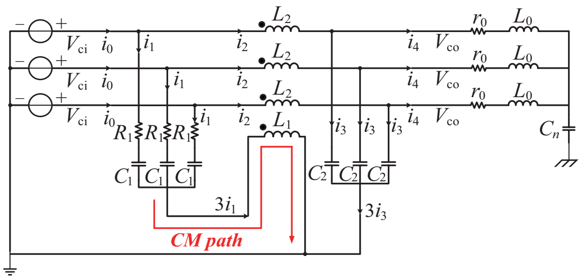


Fig. 11. CM equivalent circuit of filter.

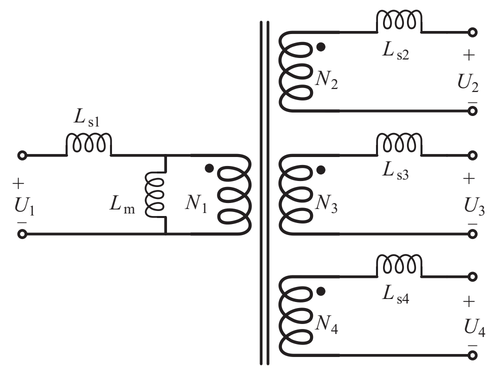


Fig. 12. Model of CM transformer.

capacitor, when the capacitor is too large, not only the safety risk will be increased, but its parasitic parameters will also increase. Therefore, we need to determine the parameters of the leakage inductance L_s and the capacitance C_2 by combining various factors. This paper combines the simulation and experimental data to select the leakage inductance $L_s = 79.5$ μH and the capacitance $C_2 = 22$ μF.

C. CM Equivalent Circuit Analysis

The CM equivalent circuit of the passive filter at the output of the PWM inverter is analyzed. The voltage source is used to equivalent the CM voltage of the PWM inverter output, and the equivalent circuit of Fig. 4 is obtained, as shown in Fig. 11.

$3i_1$ in Fig. 11 is the input current of the primary winding of the CM transformer, and i_2 is the input current of the secondary winding of the CM transformer.

Firstly, the CM transformer is analyzed, and the CM transformer is equivalent to the form of the coupled inductor. The four windings of the CM transformer have the same number of turns.

$$N_1 = N_2 = N_3 = N_4 = N \tag{9}$$

Therefore, the self-inductance of each winding of the transformer is also the same.

$$L_1 = L_2 = L_3 = L_4 = L \tag{10}$$

Since the windings of the CM transformer are wound by the method proposed in this paper, the coupling coefficients of the windings are approximately equal, that is the mutual inductance M between the windings is approximately equal.

$$\begin{aligned} M = M_{12} = M_{13} = M_{14} = M_{21} = M_{23} = M_{24} \\ = M_{31} = M_{32} = M_{34} = M_{41} = M_{42} = M_{43} \end{aligned} \tag{11}$$

Fig. 12 is a model of a CM transformer, where L_{s1}–L_{s4} are the leakage inductances of the windings of the CM transformer, and $L_{s1} = L_{s2} = L_{s3} = L_{s4} = L_s$, and L_m is the excitation inductance of the transformer.

From Fig. 11 and 12, and according to the circuit principle, the voltage equation of the CM transformer can be obtained, as shown in (12).

$$\left\{\begin{aligned}
U_1 &= \left[L_s \cdot \frac{d3i_1}{dt} + \left(\frac{N_1}{N_1}\right)^2 \cdot L_m \cdot \frac{d3i_1}{dt}\right] + \frac{N_1 \cdot N_2}{N_1^2} \cdot L_m \cdot \frac{di_2}{dt} \\
&\quad + \frac{N_1 \cdot N_3}{N_1^2} \cdot L_m \cdot \frac{di_2}{dt} + \frac{N_1 \cdot N_4}{N_1^2} \cdot L_m \cdot \frac{di_2}{dt} \\
U_2 &= \frac{N_2 \cdot N_1}{N_2^2} \cdot L_m \cdot \frac{d3i_1}{dt} + \left[L_s \cdot \frac{di_2}{dt} + \left(\frac{N_2}{N_1}\right)^2 \cdot L_m \cdot \frac{di_2}{dt}\right] \\
&\quad + \frac{N_2 \cdot N_3}{N_2^2} \cdot L_m \cdot \frac{di_2}{dt} + \frac{N_2 \cdot N_4}{N_2^2} \cdot L_m \cdot \frac{di_2}{dt} \\
U_3 &= \frac{N_3 \cdot N_1}{N_3^2} \cdot L_m \cdot \frac{d3i_1}{dt} + \frac{N_3 \cdot N_2}{N_3^2} \cdot L_m \cdot \frac{di_2}{dt} \\
&\quad + \left[L_s \cdot \frac{di_2}{dt} + \left(\frac{N_3}{N_1}\right)^2 \cdot L_m \cdot \frac{di_2}{dt}\right] + \frac{N_3 \cdot N_4}{N_3^2} \cdot L_m \cdot \frac{di_2}{dt} \\
U_4 &= \frac{N_4 \cdot N_1}{N_4^2} \cdot L_m \cdot \frac{d3i_1}{dt} + \frac{N_4 \cdot N_2}{N_4^2} \cdot L_m \cdot \frac{di_2}{dt} \\
&\quad + \frac{N_4 \cdot N_3}{N_4^2} \cdot L_m \cdot \frac{di_2}{dt} + \left[L_s \cdot \frac{di_2}{dt} + \left(\frac{N_4}{N_1}\right)^2 \cdot L_m \cdot \frac{di_2}{dt}\right]
\end{aligned}\right. \tag{12}$$

U_1–U_4 are the voltages of the four windings of the CM transformer, L_s is the leakage inductance of each winding, L_m is the excitation inductance of the transformer, $3i_1$ is the input current of the primary winding of the CM transformer, and i_2 is the input current of the secondary windings, N_1–N_4 are the number of turns of each winding of the CM transformer.

According to literature [17], it can be known that, for multi-winding coupled inductors, the self-inductance and mutual inductance can be expressed as (13). The four winding CM transformer in this paper can be equivalent to a multi-winding coupled inductor, so its self-inductance and mutual inductance can be expressed by (13).

$$\left\{\begin{aligned}
L_i &= L_{si} + \left(\frac{N_i}{N_1}\right)^2 \cdot L_m \\
M_{ij} &= M_{ji} = \frac{N_i \cdot N_j}{N_1^2} \cdot L_m
\end{aligned}\right|_{\substack{i = 1,2,\ldots,n \\ j = 1,2,\ldots,n \\ i \neq j}} \tag{13}$$

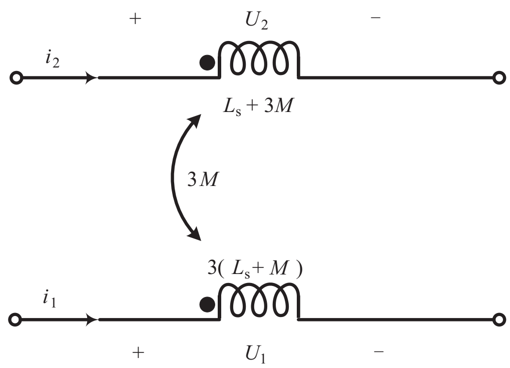


Fig. 13. CM transformer single-phase equivalent circuit.

Simultaneously, (9) to (13) can be obtained as (14).

$$\begin{cases} U_1 = 3(L_s + M)\dfrac{di_1}{dt} + 3M\dfrac{di_2}{dt} \\ U_2 = 3M\dfrac{di_1}{dt} + (L_s + 3M)\dfrac{di_2}{dt} \\ U_3 = 3M\dfrac{di_1}{dt} + (L_s + 3M)\dfrac{di_2}{dt} \\ U_4 = 3M\dfrac{di_1}{dt} + (L_s + 3M)\dfrac{di_2}{dt} \end{cases} \tag{14}$$

U_1–U_4 are the voltages of the four windings of the CM transformer, L_s is the leakage inductance of each winding, M is the mutual inductance between the windings, $3i_1$ is the input current of the primary winding of the CM transformer, and i_2 is the input current of the secondary windings.

Since the three-phase load at the output of the PWM inverter is symmetrical, a single-phase equivalent circuit of the CM transformer can be obtained according to Fig. 12, (14) and Thevenin's theorem, as shown in Fig. 13.

By bringing the single-phase equivalent circuit of the CM transformer in Fig. 13 into Fig. 11, a single-phase equivalent circuit of the filter under the CM voltage can be obtained, as shown in Fig. 14(a). Further eliminating the coupling inductance, the equivalent circuit can be obtained as shown in Fig. 14(b).

The transfer function of Fig. 14(b) is:

$$H(s) = \frac{Ds^2 + Es + 1}{As^4 + Ds^3 + Cs^2 + Es + 1} \tag{15}$$

Among them

$$\begin{cases} A = 12ML_sC_1C_2 + 3L_s^2C_1C_2 \\ B = 3MRC_1C_2 + RL_sC_1C_2 \\ C = L_sC_2 + 3L_sC_1 + 3MC_2 + 3MC_1 \\ D = 3L_sC_1 \\ E = RC_1 \end{cases}$$

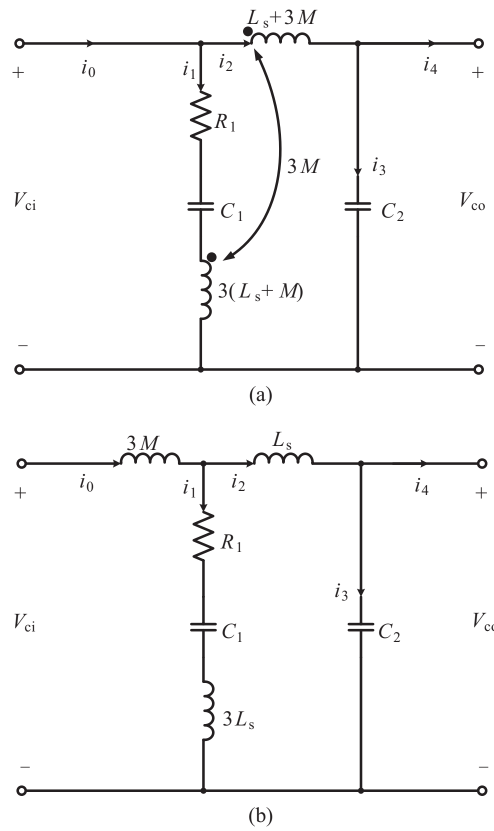


Fig. 14. CM single phase equivalent circuit of filter. (a) Coupled equivalent circuit. (b) Decoupling equivalent circuit.

Since (15) is too complicated, it is analyzed by Matlab. It can be known from (7) that if the leakage inductance and filter capacitance of the CM transformer are to be calculated, the cutoff frequency and the fundamental frequency of the inverter need to be determined. According to (8), the cutoff frequency is 1 kHz and the fundamental frequency is 50 Hz, so the leakage inductance L_s and filter capacitance C_2 of the CM transformer can be calculated, and then the mutual inductance of the transformer can be calculated according to the coupling coefficient k of the CM transformer. On the basis of this, the values of variables R and C_1 in (15) is calculated by the controlled variable method, keep variables R and C_1 unchanged respectively, change other variables, use Matlab to calculate the transfer function, and get the value range of R and C_1.

First, the resistance of the damping resistor R is kept constant, and only change the capacitance of C_1, The Bode diagram of the (15) is shown in Fig. 15. It can be seen from Fig. 15 that holding the damping resistance R unchanged, and only change the value of C_1, the cutoff frequency of the system increases with the decrease of the C_1 capacitance value. When the C_1 capacitance value is too small, the cutoff frequency will exceed the selected value 1 kHz, which does not meet the filtering requirements, when the value of C_1 is too large, the current of the RC_1 branch will be too large, which will cause large loss. Therefore, it is necessary to select the capacitance value according to the actual situation, in this paper, the C_1 capacitance value is 2 μF, which can meet the filtering requirements and has a small loss.

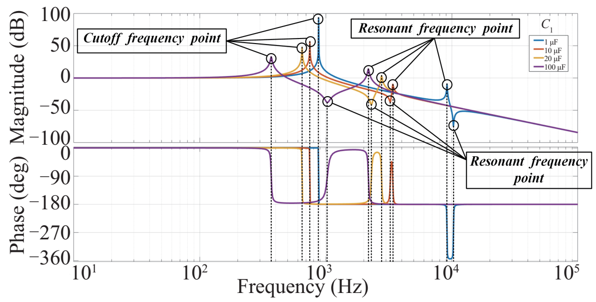


Fig. 15. Bode diagram of (15) with different C_1 values.

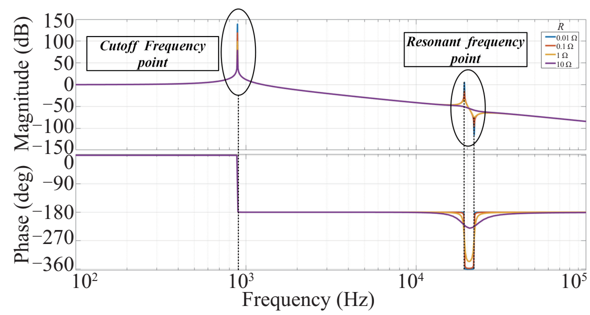


Fig. 16. Bode diagram of (15) with different R values.

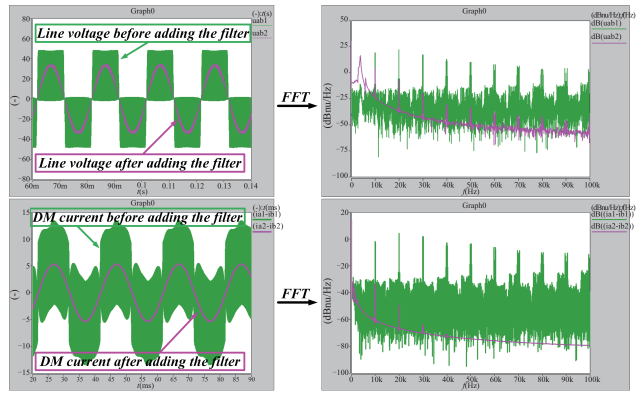
When the capacitance value of C_1 is 2 μF, and only change the resistance value of the damping resistor R, it can be seen from Fig. 16 that the cutoff frequency point and the resonance frequency point of the system do not change at this time, and changing the damping resistance only affects the amplitude at the cutoff frequency and the amplitude & phase angle at the resonant frequency. At the cutoff frequency and the resonant frequency, the larger the damping resistance is, the smoother the system is, the stability of the system is also better. However, the excessive resistance causes the CM voltage detection malformation, which affects the suppression effect of the CM voltage, so it needs to be considered comprehensively. In this paper, the resistance of R is 0.1 Ω, which has better filtering effect and system stability.

IV. Simulation and Experimental Analysis

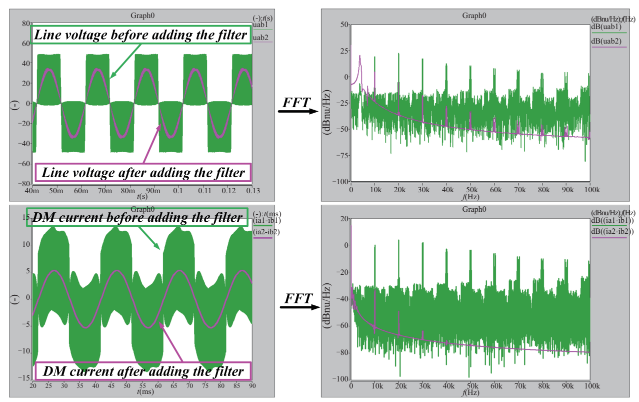
A. Simulation Analysis

In order to verify the correctness and superiority of the proposed theory, the saber simulation software is used to simulate and verify the filtering effects of the RCTC filter of the traditional CM transformer and the RCTC filter of the improved CM transformer. Set the DC bus voltage of the two filters to 48 V, the inverter switching frequency to 10 kHz, the resistor R_1 to 0.1 Ω, the capacitor C_1 to 2 μF, and the capacitor C_2 to 22 μF. The CM transformer has a self-inductance of 530 μH and the number of turns for 50. The simulation comparison results are shown in Fig. 17 and 18.

Fig. 17 is a comparison of the DM suppression effect of different CM transformers in the same RCTC filter topology. Fig. 17(a) is a time-domain and frequency-domain analysis



(a)

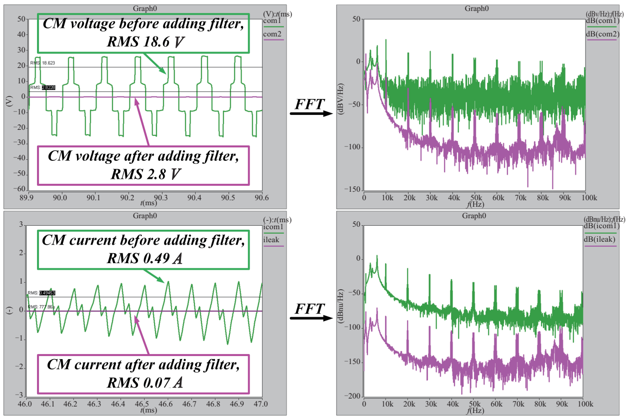


(b)

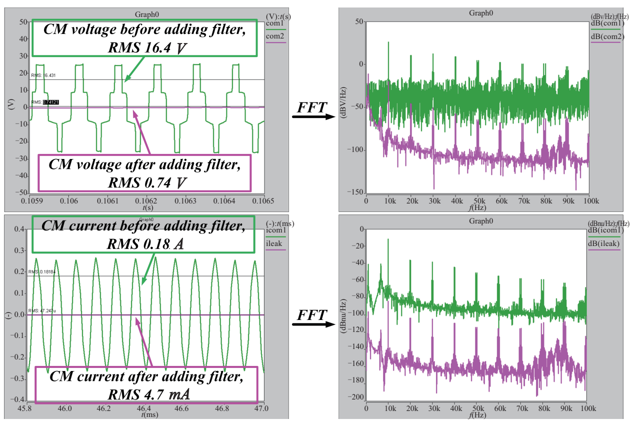
Fig. 17. DM filtering effect simulation comparison. (a) Traditional CM transformer. (b) Improved CM transformer.

of the DM suppression effect of the filter under the traditional CM transformer, including analysis of DM voltage and current; Fig. 17(b) is a time-domain and frequency-domain analysis of the DM suppression effect of the filter under the improved CM transformer, which also includes DM voltage and current. Comparing Fig. 17(a) and (b), we can find that the DM suppression effect of the filters under the two CM transformers is similar, and both have good differential mode suppression effects.

Fig. 18 is a comparison of the CM suppression effect of different CM transformers in the same RCTC filter topology. Fig. 18(a) is a time-domain and frequency-domain analysis of the CM suppression effect of the filter under the traditional CM transformer, including analysis of CM voltage and current; Fig. 18(b) is a time-domain and frequency-domain analysis of the CM suppression effect of the filter under the improved CM transformer, which also includes CM voltage and current. Comparing Fig. 18(a) and (b), we can find that in the time domain, the improved CM transformer has better suppression effect than the traditional CM transformer, and the traditional CM transformer can suppress 85% CM voltage and 85.7% CM current, and the improved CM transformer can suppress 95.5% CM voltage and 97.4% CM current; In the frequency domain, The dB value of the improved CM transformer is larger than the traditional one, which can suppress the CM interference to a greater extent.



(a)



(b)

Fig. 18. CM filtering effect simulation comparison. (a) Traditional CM transformer. (b) Improved CM transformer.

In order to further verify the feasibility of the scheme, the branch currents of i_1 and i_3 in Fig. 11 are given to verify the effectiveness of the scheme.

It can be seen from Fig. 19 that the CM detection branch current of the improved CM transformer is smaller, which shows that under the same circumstances, the improved CM transformer can reduce losses. In the simulation, the resistance of the branch where the i_1 current is located is 0.1 Ω. Compared with the traditional and improved CM transformers, the improved one has an 8.6% lower loss than the traditional one. However, the branch where i_3 is located has no resistance, and only the resistance of the wire exists, the difference between the two currents is very small, so they can be regarded as approximately equal, but the resistance of wire is very small, so it can be approximately ignored.

From the simulation results above, it can be seen that the RCTC filter proposed in this paper has a better effect in suppressing DM and CM interference. After improving the CM transformer, the effect of CM suppression becomes better and the loss is also reduced to a certain extent.

B. Experiment Analysis

In order to further verify the effectiveness of the proposed scheme, an experimental platform was built based on EG8030. The AMCC32 iron-based amorphous magnetic core was selected as the core of the CM transformer. The other parameters were set according to the simulation parameters. The prototype is shown in Fig. 20, the experimental results are shown in Fig. 21-26. Includes a comparative analysis of the filter's DM voltage and current, CM voltage and current, and branch currents i_1 and i_3.

First, the DM filtering effect of the RCTC filter is analyzed, it can be seen from Fig. 21 that the filter has a good DM voltage filtering effect, the traditional CM transformer and the improved CM transformer have similar effects; The output filter also has a good filtering effect on the DM current, and the effects of the two CM transformers are still similar, so it can be seen that the improvement of the CM transformer has little effect on the suppression of DM interference. And then, the CM filtering effect of the filter is analyzed, as can be seen from Fig. 23 and 24, the RCTC filter has a better filtering effect on the CM voltage, and the improved CM transformer can not only detect the CM voltage more accurately, its filtering effect is also 4.8% higher than the traditional one, from Fig. 25, we can see that the RCTC filter has a better filtering effect on the

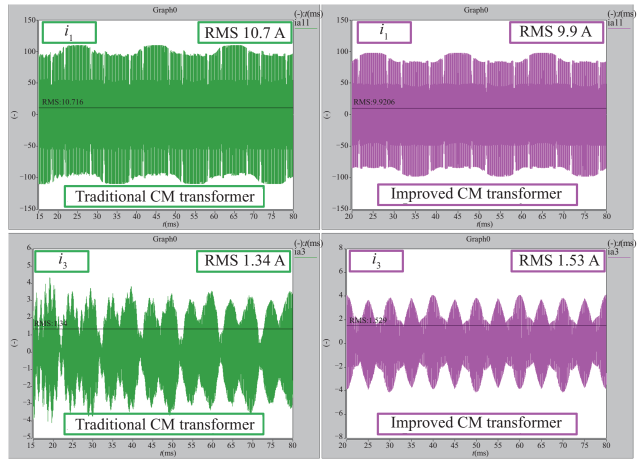


Fig. 19. Simulation comparison of branch currents i_1 and i_3.

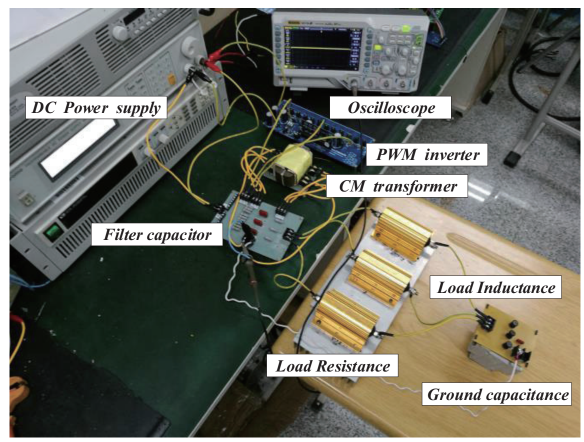


Fig. 20. Experimental prototype.

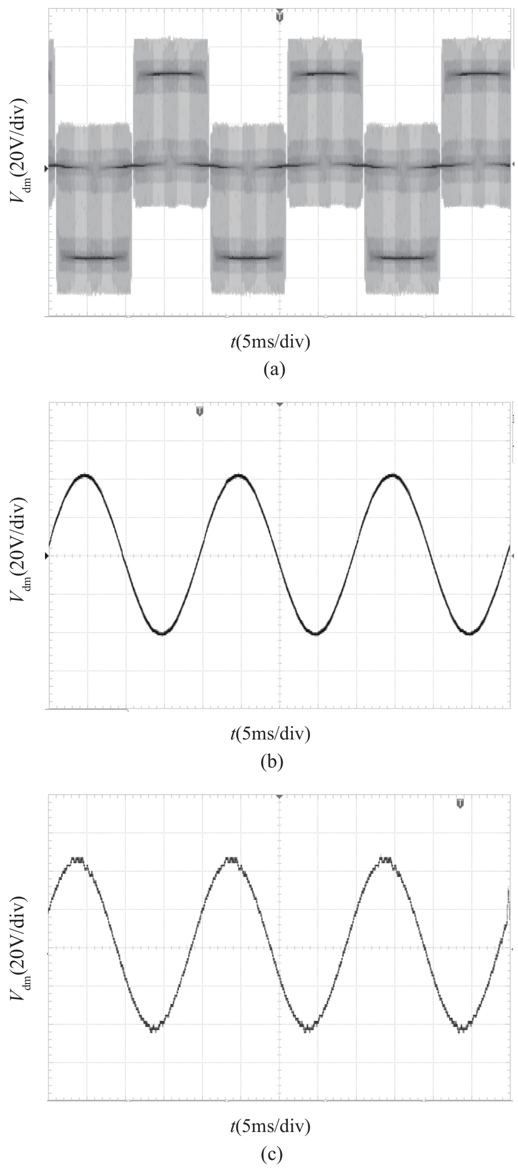


Fig. 21. Comparison of line voltage filtering effect. (a) No filter. (b) Traditional CM transformer. (c) Improved CM transformer.

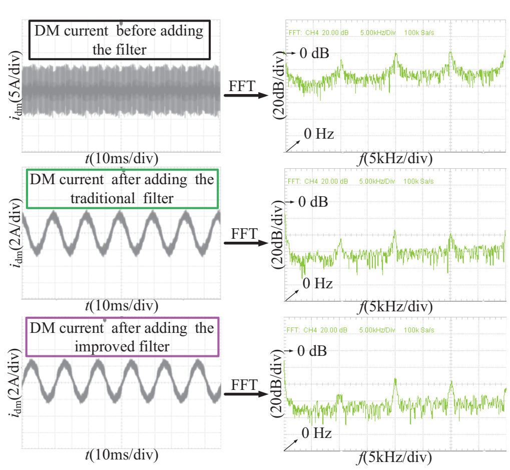


Fig. 22. Comparison of DM current filtering effect.

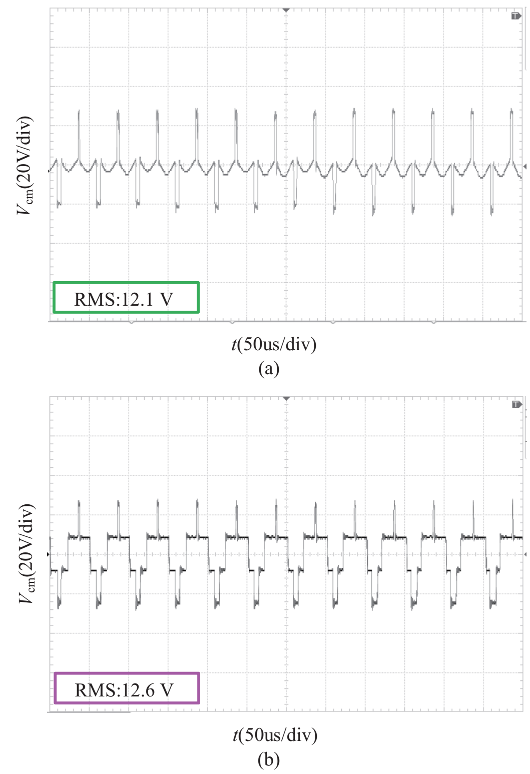


Fig. 23. CM voltage detection effect experimental comparison chart. (a) Traditional CM transformer. (b) Improved CM transformer.

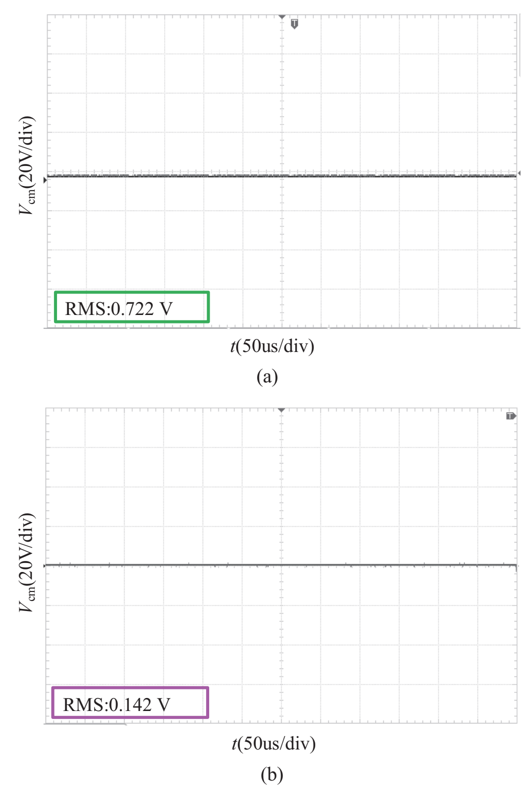


Fig. 24. Comparison of CM voltage filtering effect (CM voltage here is the voltage of capacitor C_n to ground). (a) Traditional CM transformer. (b) Improved CM transformer.

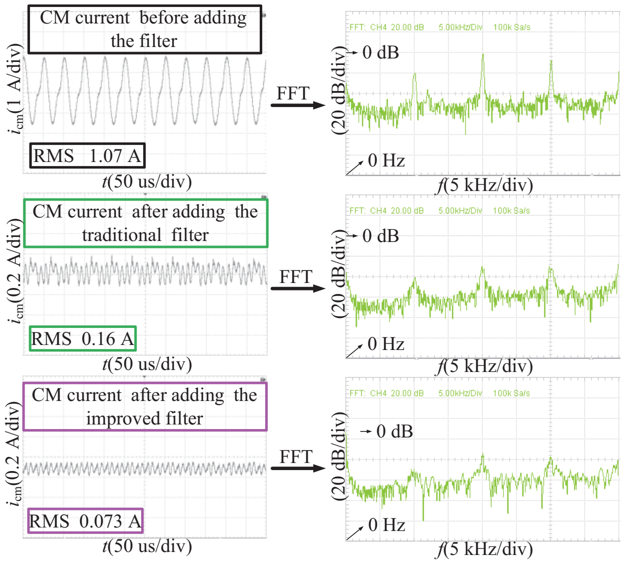


Fig. 25. Comparison of CM current filtering effect.

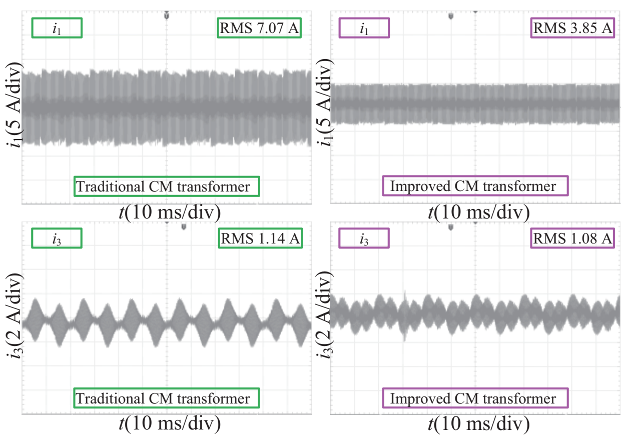


Fig. 26. Experimental comparison of branch currents i_1 and i_3.

CM current, and the improved CM transformer is better than the traditional filtering, its filtering effect is 8.1% higher than the traditional one.

It can be seen from Fig. 26 that the i_1 of the RCTC filter under the improved CM transformer is smaller than the traditional one, the resistance of the branch where i_1 is located is 0.1 Ω. So, the loss under the traditional CM transformer is 4.99 W, and the loss under the improved CM transformer is 1.48 W. The loss of the improved CM transformer is 70.3% lower than the traditional one; Similarly, the current i_3 of the filter branch is the same, the resistance of the filter branch is the wire resistance, and its value is very small, i_3 under the two CM transformers is approximately equal, so the loss here can be approximately ignored.

It can be seen from the above experimental results that the RCTC filter proposed in this paper has a good effect in suppressing DM and CM interference. In addition, the improved CM transformer has better CM rejection and lower losses than traditional CM transformers.

V. Conclusion

This paper proposes a new topology of passive filter for PWM inverter output based on CM transformer, the filter uses an RC branch to detect the CM voltage, and then uses the coupling of the CM transformer to suppress the CM voltage. The leakage inductance of the CM transformer is used to replace the DM filter inductor, thus reducing the number of cores used. This filter can simultaneously implement the functions of dv/dt filter and sine filter, and can also reduce the CM leakage current. In addition, this paper also improves the winding method of the traditional CM transformer, the windings of the CM transformer are divided into two parts in series and distributed symmetrically on the iron core, which improves the CM filtering effect and reduce the loss to a certain extent. Finally, the correctness and effectiveness of the proposed scheme are demonstrated by simulation and experiments.

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