An Active Cancellation Method for the Common Mode Current of the Three-Phase Induction Motor Drives

3상 유도전동기 구동장치의 동상모드 전류 능동 제거법

Tawfique Uzzaman, Unghoe Kim and Woojin Choi
Department of Electrical Engineering, Soongsil University

Abstract

Pulse Width Modulation (PWM) is a widely adopted technique to drive the motor using the voltage source inverters. Since they generate high frequency Common Mode (CM) Voltage, a high shaft voltage in induction motor is induced which leads to parasitic capacitive currents causing adverse effects such as premature deterioration of ball bearings and high levels of electromagnetic emissions. This paper presents an Active Cancellation Circuit (ACC) which can significantly reduce the CM voltage hence the common mode current in the three phase induction motor drives. In the proposed method the CM voltage is detected by the capacitors and applied to the frame of the motor to cancel the CM voltage hence the CM current. Unlike the conventional methods the proposed method does not insert the transformer in between the inverter and motor, a high power rating three phase transformer is not required and no losses associated with it. In addition the proposed method is applicable to any kind of PWM motor drives regardless of their PWM methods. The effectiveness of the proposed method is proved by the experiments with a three phase induction motor (1.1kW 415V/60Hz) combined with a three phase voltage source inverter modulated by the Space Vector Modulation (SVM).

1. Introduction

Now-a-days Electric Vehicles (EVs) are spreading widely all over the world due to environmental concerns. A lot of researches are being conducted on the three-phase inverter with induction motors to make the EV as a better option by improving its robustness and reliability [1]. Due to the fast switching devices in inverter, voltage variation in switches also increases, leading to a greater current with high frequency, called Common-mode (CM) current. Therefore, a voltage with large step size is created called CM voltage passing through the motor drives relative to the inverter ground [2].

Many kinds of the methods have been proposed to reduce the unwanted CM voltage and hence the CM current in PWM motor drives. Some of them employs switching patterns to reduce the CM voltage while the other used RLC filter, CM chokes, however, the amplitude of the compensated CM voltage remains unchanged [3]. Active compensation circuit for CM voltage is typically smaller in size as compared to the passive filters. When the CM voltage transformer is used, both rms and peak values of the leakage current can be reduced with a small core. In [4], an active cancellation circuit for CM voltage compensation is proposed. However, since the method requires a high magnetizing current for the transformer, a larger size core should be used for the circuit.

In this paper an active cancellation method for the common mode current of the three-phase induction motor drives is proposed. In the proposed method the common mode current cancellation is achieved by applying the sensed CM voltage to the motor frame after amplifying it. Therefore the voltage difference between the neutral point of the motor and frame becomes zero and hence the CM current is eliminated. The Cancellation circuit consists of three Y-connected capacitors, two-complimentary Darlington-pair transistors and a CM transformer. The validity of the proposed method can be demonstrated by an experimental setup with a three-phase two-level inverter and a three-phase induction motor (1.1kW 415V/60Hz).

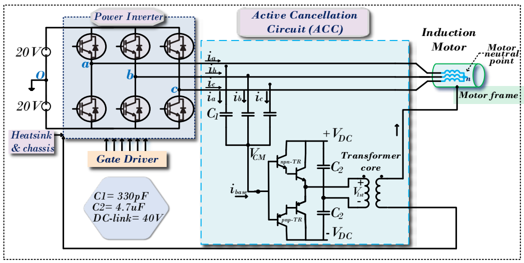

Fig. 1. An active CM voltage cancellation circuit with three-phase two-level inverter.

2. Principle of Active Cancellation Circuit (ACC)

Fig. 1. shows the proposed method where transformer secondary output is connected to the motor frame to compensate for the CM voltage at the motor neutral point. In the proposed method the CM voltage is detected by three Y-connected capacitors. The circuit is called active because transistor needs additional power supply and transistors connected in complementary position behaving as a push-pull emitter follower. The detected CM voltage is reproduced by the push-pull emitter follower at the primary winding of the transformer and imposed to the motor frame by the secondary winding of the CM transformer to compensate for the CM voltage at the motor neutral point. It is natural that the CM current can also be eliminated because there is no voltage difference in between the motor neutral point and the frame. Therefore the current flowing through the CM transformer is very small and the core size of it can be very small, thereby achieving a low-cost solution for the CM current cancellation. Two dc side capacitors are employed in the proposed method to balance the neutral point as well as to block dc components. As compared to the conventional methods the proposed method is simple and low in cost, volume and power loss.

2.1 Sensing Capacitor Selection

The detection of CM voltage can be done by using resistors or capacitors in Y-connection at the inverter output terminal. However, the capacitor bank should be selected to avoid power losses and to get better CM voltage detection without affecting to the motor current. Hence the maximum value for detection capacitor C_1can be calculated as followings.

$$I_{\max} = C_{1\max} \frac{V_{phase-to-neutral}}{100ns} = 1275\,pF \tag{1}$$

Where, $V_{phase-to-neutral} = 26.67V$, rise and fall time of the switch is $100ns$ and $I_{max} = 0.34A$, is the maximum current passing through the capacitor. In this experiment, three 330pF capacitors are used with Y-connection.

2.2 Selection of the Transistors

For the CM voltage amplification circuit, two complimentary Darlington-pair transistors are used as a push-pull emitter follower. When the CM voltage passing through the push-pull circuit, the current-gain can be expressed as Eq. (2).

$$i_e = (\beta_1 \beta_2) i_{base} \tag{2}$$

where, i_e the is emitter output current, i_{base} is the base input current and β_1 & β_2 is the 1st and 2nd transistor current gain of the Darlington-pair, respectively. On the other hand, the difference between sensing voltage and the reproduced voltage in the transformer primary winding can be derived as following Eq. (3).

$$V_{error} \approx 0.7 + \frac{1}{3C_1} \int i_{base} dt \tag{3}$$

By analyzing the Eq. (3), it can be easily found that the voltage error also depends on the value of C_1 and it should be chosen carefully for the perfect common-mode voltage detection.

2.3 Selection of the DC-side Capacitors

If any dc-components are existed in the push-pull emitter follower output, then it will create an excessive current flowing through the CM Transformer, hence the voltage variation at the midpoint should be maintained constant. In the circuit two $4.7\mu F$ capacitors are used so that the voltage variation can be restricted.

2.4 Design of the CM Transformer

The CM transformer is designed with an E-type core and two windings, where the primary winding is connected to the push–pull output and the secondary winding is connected to the motor frame. The relationship between the reproduced voltage V_{1st} and the base current i_{base} can be derived as in eqs. (4) and (5).

$$\frac{V_{1st}}{L_m} = \frac{d}{dt} i_e \tag{4}$$

$$\frac{d}{dt} i_{base} = \frac{V_{1st}}{(\beta_1 \beta_2) L_m} \tag{5}$$

So, the higher the values of transistors gain β and CM transformer inductance L_m are smaller the values of base current i_{base} and error voltage in the transformer primary winding. Therefore a large inductance value of L_m should be selected for the better CM voltage compensation. Considering the maximum conduction time of the transistor as 10^{-4}s, Eq. (6) can be obtained by applying Faraday's law.

$$v = n \frac{d\varphi}{dt} \qquad v = nA_e \frac{db}{dt} \qquad v = 4B_{\max} N A_e f_{sw} \times 10^{-4} \tag{6}$$

Where, v is the CM voltage and n is the no. of turns in the primary winding. For better CM voltage cancellation, 3.2mH of the magnetizing inductance is selected. With m=1 and $A_L = 3.58\mu$, No. of turns of the transistor can be calculated as Eq. (7).

$$L_m = mA_l N^2 \qquad N = \sqrt{L_m / A_l} \tag{7}$$

3. Simulation and Experiment Results

Simulations and experiments are carried out with a 1.1kW, 380-416 L-L voltage, 2.4A current induction motor with three-phase two-level inverter to evaluate the performance of the proposed CM voltage compensation method. In experimental setup, dc-link voltage was 40V and motor was run at 10Hz fundamental frequency. Fig. 2(a) shows the error-voltage and Fig. 2(b) shows the detected CM voltage at wye-connected capacitor point in inverter output.

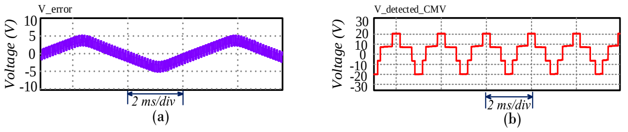

Fig. 2. Simulation Results (a) Voltage error in the transformer primary winding, (b) Detected CM voltage

Fig. 3(a) and 3(b) show the compensated CM voltage and CM current in simulation, respectively. The compensated CM voltage is reduced from 40V to 6V in peak-to-peak value. Fig. 4(a) and 4(b) show the experimental waveforms of Darlington-pair transistor output waveforms and transformer-primary winding input respectively. It can be observed that both waveforms are well each other with a transformer turn ratio 1:1 and the CM current is less than 14mA.

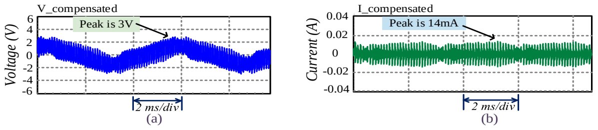

Fig. 3. Simulation results with the proposed compensation circuit (a) CM voltage at the motor neutral point (b) CM current passing through the inverter chassis

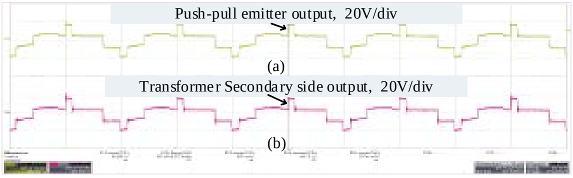

Fig. 4. Experimental results without the proposed circuit (a) Output voltage at the Darlington-pair transistor, (b) Output voltage at the transformer secondary winding

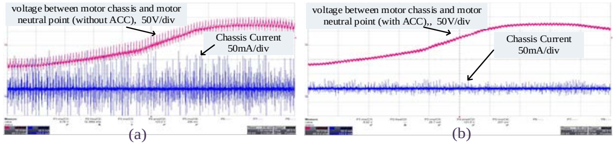

Fig. 5. Experimental results before and after the compensation with the proposed circuit (a) CM voltage and current before the compensation (b) CM voltage and current after the compensation

By comparing the experimental waveforms in Fig. 5(a) and 5(b), it can be concluded that the proposed topology is effective in cancellation of common mode voltage and hence the CM current, which can reduce the induced shaft voltage in the induction motor.

3. Conclusion

In this paper an active cancellation method for the CM current of the three-phase induction motor drives has been proposed and its effectiveness has been verified through the experiments. In the proposed method the detected CM voltage is applied to the motor frame and the CM current can be successively reduced. Since the proposed method does not insert the CM transformer in between the inverter and motor the size of the transformer can be significantly reduced and the loss can also be significantly reduced. In addition the shaft voltage, the bearing current, and the conducted EMI can also be reduced simultaneously.

Reference

[1] A. K. Singh, A. Dalal, and P. Kumar, "Analysis of induction motor for electric vehicle application based on drive cycle analysis," *in 2014 IEEE PEDES.*, pp. 1–6, Dec. 16–19, 2014

[2] G. Grandi, D. Casadei, and U. Reggiani, "Common- and differential-mode HF current components in acmotors supplied by voltage source inverters," *IEEE Trans. Power Electron*, vol. 19, no. 1, pp. 16–24, Jan. 2004

[3] Xiyou Chen, Dianguo Xu, Fengchun Liu, Jianqiu Zhang "A Novel Inverter-Output Passive Filter for Reducing Both Differential- and Common-Mode dvdt at the Motor Terminals in PWM Drive Systems,", *IEEE Trans. Ind. Appl.*, vol. 54, no. 1, pp. 419-426, Feb. 2007

[4] S. Ogasawara, H. Ayano, H. Akagi, "An Active Circuit for Cancellation of Common-Mode Voltage Generated by a PWM Inverter", *IEEE Trans. Power Electron.*, vol. 13, no. 5, pp. 835–841, Sep. 1998