Article

Shaft Voltage Reduction Method Using Carrier Wave Phase Shift in IPMSM

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Abstract: Common-Mode Voltage (CMV) induces shaft voltage and bearing current due to the electrical interaction with the parasitic capacitance of the motor. CMV, shaft voltage, and bearing current are considered the major causes of bearing fault. Motor fault in a traction system poses a risk of accidents. Therefore, it is necessary to reduce the CMV and the shaft voltage to ensure the reliability of the bearing. However, some existing CMV reduction methods are based on asynchronized space vector pulse width modulation (SVPWM), which will cause unacceptable harmonic distortion at a low switching frequency. Alternatively, some CMV reduction methods based on synchronized SVPWM burden the processor because they require a lot of calculation. In this paper, the method to reduce CMV and shaft voltage is proposed using carrier wave phase shift in SVPWM. CMV is explained in traditional SVPWM, and CMV is reduced by shifting the carrier wave phase of one phase. The simulation model is constructed through MATLAB/SIMULINK and Maxwell 2D/Twin Builder. Considering the proposed method, CMV, shaft voltage, and bearing current are analyzed by an equivalent circuit model. Moreover, the output torque behaviors with different input currents are analyzed through the simulation.

Keywords: pulse width modulation inverters; space vector pulse width modulation; bearing faults; fault tolerance

Citation: Im, J.-H.; Lee, Y.-K.; Park, J.-K.; Hur, J. Shaft Voltage Reduction Method Using Carrier Wave Phase Shift in IPMSM. *Energies* **2021**, *14*, 6924. <https://doi.org/10.3390/en14216924>

Academic Editors: Nicola Bianchi, Ludovico Ortomina and Adolfo Dannier

Received: 6 October 2021

Accepted: 18 October 2021

Published: 21 October 2021

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1. Introduction

The interior permanent magnet synchronous motor (IPMSM) with pulse width modulated (PWM) inverter has been used in a wide range of applications because of its high efficiency, better performance, and ability to control a wide area. It is especially used in traction systems such as electric vehicles, urban air mobilities, and electric ships. In these systems, motor faults can lead to accidents, and accidents can lead to huge damage such as casualties or property damage. That is why the reliability of the motor is very important. Thus, research on motor faults should be carried out for reliability.

There are four main types of faults of IPMSM such as inter-turn faults [1,2], demagnetization [3,4], eccentricity faults [5,6], and bearing faults [7,8]. Among them, bearing faults are the most frequent type of faults in IPMSM. During operation, fatigue cracks occur on the bearing surface until metal pieces fall due to overload. Generalized-roughness defects are those that significantly degrade, rough, or deform the bearing surface. Common causes of this type of fault include contamination, lack or loss of lubricant, and misalignment [9–11]. Therefore, studies of bearing faults have received a lot of attention to prevent motor efficiency reduction and increase reliability.

As shown in Figure 1a, common-mode voltage (CMV) does not occur in the ideal three-phase power source. However, in practice, the PWM inverter generates CMV, as shown in Figure 1b. The CMV occurring at this time interacts with the component of the parasitic capacitance of the motor to induce shaft voltage and bearing current. They are noted

as important factors in bearing faults [12–14]. Therefore, research to reduce CMV, shaft voltage, and bearing current is required to improve the reliability of the bearing system.

Figure 1. Common Mode Voltage (a) at ideal power source (b) at PWM inverter.

In [15], the shaft is directly grounded using a special ring to lower the shaft voltage. In [16], The electromagnetic shielding slot wedge (ESLW) is proved to be an efficient method to attenuate the discharging bearing current in motors fed by PWM inverters. In [17], the electric shield is used to reduce the shaft voltage. Another study [18] reduces the parasitic capacitances using the winding technique. However, most previous studies propose the shaft voltage reduction method by modifying the motor structure. It is necessary to analyze CMV, shaft voltage, and bearing current in a basic three-phase motor driving system without any deformation of the motor.

In [19–25], numerous PWM strategies are proposed to reduce CMV. In [19], a reduced CMV PWM strategy is designed by employing dual carrier to replace single carrier. The peak value of CMV can be effectively reduced to 1/6 of the DC link voltage. However, there are intervals in which the maximum CMV is half the DC link voltage. Because of the use of sinusoidal PWM (SPWM), the maximum voltage usage is only 78.6%. In [20], a remote state PWM (RSPWM) is presented to reduce CMV by utilizing three odd or even voltage vectors. However, this method can only suppress CMV at a low modulation index. To reduce CMV in a wide range of modulation indexes, some reduced CMV strategies are proposed, including active zero-state PWM (AZSPWM) and near-state PWM (NSPWM) methods [21–23]. However, these CMV reduction methods, which are based on asynchronized space vector PWM (SVPWM), will cause unacceptable current distortion including large low-order harmonics and subharmonics. In [24], a modified selective harmonic elimination PWM (M-SHEPWM) for CMV reduction is proposed, which can effectively suppress the CMV by eliminating the lower order harmonics of the output line-line voltage. However, the complicated arithmetic calculations of phase angle greatly increase the computational burden of processors. The reduced common-mode voltage model preemptive control (RCMV-MPC) methods are used to reduce CMV [25]. However, the cost function is calculated at every sampling period, increasing the computational burden on the processor and it is parameter sensitive.

This paper presents a method for reducing CMV and shaft voltage through a carrier wave phase shift (CPS) in IPMSM using SVPWM. First, the switch state and CMV are analyzed in SVPWM. It removes the zero-voltage state using only CPS in the traditional SVPWM. Comparisons of changes in the shaft voltage and bearing current due to CMV changed through simulation are included. Comparisons of input current and output torque in the proposed method are also included. Finally, validation through experiments is shown.

2. CMV and Switching States

The CMV of a three-phase inverter is generally defined as the electric potential difference between the neutral point of inverter output and reference ground:

$$V_{CMV} = \frac{V_a + V_b + V_c}{3} \quad (1)$$

where V_{CMV} is the common-mode voltage. V_a , V_b , and V_c are the input voltages in the three-phase motor, respectively. Table 1 show the CMV according to the switch state in the SVPWM of the three-phase inverter. As shown in Table 1, CMV has a maximum at V_0 and V_7 which are zero-voltage states. Figure 2 shows the space vector application process in SVPWM, where t_z , t_k and t_n are the duration of V_0 , V_k and V_n . T_s is the switching cycle. S_a , S_b and S_c refer to the switch state of each phase. The expression for the t_z , t_n and t_k is:

$$\begin{cases} t_k = \frac{2}{T_s \sqrt{3}} m_s \sin(\theta_n - \theta) & k, n = 1, 2 \dots 6 \\ & \theta_n > \theta > \theta_k \\ t_n = \frac{2}{T_s \sqrt{3}} m_s \sin(\theta - \theta_k) \dots & n - k = 1 \\ t_z = \frac{1 - (t_m + t_n)}{T_s} & \theta_n - \theta_m = \frac{\pi}{3} \end{cases} \quad (2)$$

where θ_k and θ_n is the angle of V_k and V_n , θ is the angle of the reference vector, and m_s is the modulation index in SVPWM.

Table 1. CMV According to switching states.

Space Vector	Switch State	Load Phase Voltage			CMV
		V_{an}	V_{bn}	V_{cn}	
V_0	[0 0 0]	0	0	0	$-\frac{1}{2}V_{dc}$
V_1	[1 0 0]	$\frac{2}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$	$-\frac{1}{6}V_{dc}$
V_2	[1 1 0]	$\frac{1}{3}V_{dc}$	$\frac{1}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$	$\frac{1}{6}V_{dc}$
V_3	[0 1 0]	$-\frac{1}{3}V_{dc}$	$\frac{1}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$	$-\frac{1}{6}V_{dc}$
V_4	[0 1 1]	$-\frac{1}{3}V_{dc}$	$\frac{1}{3}V_{dc}$	$\frac{1}{3}V_{dc}$	$\frac{1}{6}V_{dc}$
V_5	[0 0 1]	$-\frac{1}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$	$\frac{1}{3}V_{dc}$	$-\frac{1}{6}V_{dc}$
V_6	[1 0 1]	$\frac{1}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$	$\frac{1}{3}V_{dc}$	$\frac{1}{6}V_{dc}$
V_7	[1 1 1]	0	0	0	$\frac{1}{2}V_{dc}$

Figure 2. Space vector application process in SVPWM.

CMV has the maximum value in the zero-voltage vector state, and the zero-voltage state vector should be avoided as much as possible. As shown in Equation (2), t_z is affected by m_s , θ , and T_s . T_s is a constant that does not change once the system is determined. In PMSM, m_s changes according to the back EMF of the motor. Therefore, changes according to m_s and θ should be considered. Figure 3 shows the t_z according to modulation index

and rotor angle when T_s is normalized to 1. As shown in Figure 3, it can be seen that the larger the m_s , the shorter the duration of the CMV peak value, and the smaller the m_s , the longer the duration of the CMV peak value. It can be seen that as the back EMF of the motor increases, the duration of the CMV peak value becomes longer.

Figure 3. Three-dimensional surface plot of t_z according to angle and modulation index in SVPWM.

3. Carrier Wave Phase Shift in SVPWM

Figure 4 shows the switching state and CMV in traditional SVPWM as well as in the proposed methods. The peak-to-peak value of CMV can be reduced by removing the zero-voltage state from the traditional SVPWM. Previous studies changed the SVPWM method to reduce the zero-voltage state [19–25]. As a result, the input voltage was distorted, and the output of the motor was affected. CPS has no change in input reference voltage and has the same phase voltage. As shown in Figure 4b, if the carrier of one phase has the opposite phase, the zero-voltage state disappears in all states. In that case, the phase of the voltage on phase C is slightly different. However, the same effect can be obtained by shifting the phase of the carrier wave by 180 degrees unless the input reference voltage of the SVPWM is changed.

Figure 4. Switch state and CMV (a) in traditional SVPWM (b) in SVPWM with CPS.

4. Equivalent Circuit Model

A shaft voltage equivalent circuit model is constructed to confirm the change in the shaft voltage for the change in CMV. The circuit model schema in the motor driving system is shown in Figure 5. The inverter, which uses the PWM control method, supplies power through the winding of the motor and simultaneously generates CMV. The generated CMV interacts with parasitic capacitance components caused by the motor's winding, stator, rotor, and bearing, resulting in shaft voltage and bearing current. The shaft voltage is the voltage between the shaft and the frame. The bearing current is the current between the bearing and the shaft.

Figure 5. System schema and motor structure with parasitic capacitance.

The structure of the motor with the parasitic capacitance of the motor is shown in Figure 5. Parasitic capacitance is classified into four main types: C_{ws} is the parasitic capacitance between the winding and the stator; C_{wr} is the parasitic capacitance between the winding and the rotor; C_{sr} is the parasitic capacitance between the stator and the rotor; and C_b is the parasitic capacitance between the bearing and the shaft [26].

The simulation equivalent model for comparing the shaft voltage and bearing current is shown in Figure 6. It is assumed that the parasitic capacitance of the winding is affected in the middle of the winding. Therefore, $La1$ and $La2$ are the same phase winding, and so are other windings. In this paper, SVPWM is used, but other PWM methods can also be applied. This paper constructed the simulation using the parasitic capacitance equations of motor derived from previous studies [19,26,27].

Figure 6. Shaft voltage and bearing current simulation equivalent circuit model.

For a comparison of THE output torque and input current, an IPMSM co-simulation model using SVPWM is constructed using ANSYS Maxwell 2D and Twin Builder, as shown in Figure 7. The values of the parameters used in this paper are shown in Table 2.

Figure 7. Maxwell 2d-Twin Builder co-simulation for output torque and input current.

Table 2. Name of parameters and the motor structure dimensions.

Item	Appearance	Value	Units
p	No. of poles	6	
S	No. of slots	9	
V_{DC}	DC Link voltage	60	V
F_s	Switching Frequency	15	kHz
ω	Rated Speed	3500	RPM
T	Rated Torque	1.3	N·m
P	Rated Power	400	W
I	Rated Current	10.32	Arms
R	Stator resistance	0.07	ohm
C_{ws}	Parasitic capacitance between winding and stator	79.98	pF
C_{wr}	Parasitic capacitance between winding and rotor	8.73	pF
C_{sr}	Parasitic capacitance between stator and rotor	61.1	pF
C_b	parasitic capacitance between bearing and shaft	186.8	pF

5. Simulation Results

The parameters of the motor and inverter used in the simulation are shown in Table 2. The control method is used current control at a constant speed to compare CMV, shift voltage, and bearing current. Depending on the PWM modulation index, the duration of each space vector varies. Since the modulation index of the input reference voltage in the IPMSM depends on the magnitude of the back EMF, it is performed at various speeds. A comparison of CMV, shaft voltage, and bearing current at each speed is included. Finally, the changes of the output torque and the THD of the input current are checked.

A. Shaft Voltage and Bearing Current

Figure 8 shows the simulation results of CMV, shift voltage, and bearing current at 500 rpm and 3500 rpm in the traditional SVPWM. Figure 9 shows the simulation results of CMV, shift voltage, and bearing current at 500 rpm and 3500 rpm in the proposed method. Table 3 shows the experimental result values above. It can be seen that 500 rpm has a low modulation index, a long duration of zero voltage state, a high modulation index of 3500 rpm, and a short time of zero voltage state. In the proposed method, it is confirmed that the maximum CMV is reduced to $1/6$ Vdc. In the traditional SVPWM, the duration of the maximum of CMV at low speed is long, but in the proposed method, it is same at high speed. In the traditional method, the RMS of CMV is large at low speed with a low modulation index. However, the proposed method has the same RMS value. Similar to the results of CMV, the shaft voltage also decreases. Compared to the conventional SVPWM, the bearing current of the proposed method is small in both the low-speed and high-speed regions in the proposed method

B. Changes of input and output

Figure 9 shows the input current and its FFT waveform through co-simulation for the traditional SVPWM and the proposed method, respectively. In the proposed method, the high order harmonics of the current increase compared to the traditional method. The low order harmonic is almost similar. The THD of the input current increases little in

the proposed method. Figure 10 shows the comparison result of the output torque of the co-simulation. Although the torque ripple is increased, the average torque is similar.

Figure 8. CMV, shaft voltage, and bearing current in the traditional SVPWM (a) at 500 rpm (b) at 3500 rpm.

Figure 9. CMV, shaft voltage, and bearing current in the proposed method (a) at 500 rpm (b) at 3500 rpm.

Table 3. Simulation results values in traditional SVWPM and in the proposed method.

		Traditional		Proposed Method	
		500 rpm	3500 rpm	500 rpm	3500 rpm
CMV	Peak-to-peak	60 V	60 V	20 V	20 V
	RMS	28.12 V	17.95 V	9.42 V	9.42 V
Shaft Voltage	Peak-to-peak	5.28 V	5.28 V	1.72 V	1.72 V
	RMS	2.48 V	1.58 V	0.87 V	0.81 V
Bearing Current	Peak-to-peak	6.1 mA	5.4 mA	3.2 mA	3.1 mA
	RMS	0.19 mA	0.18 mA	0.15 mA	0.13 mA

Figure 10. Input current waveform and FFT in the (a) traditional SVPWM (b) with CPS.

6. Experiment Results

Figure 11 shows the experimental setup used for verification. The motor shown in Table 2 is used. The frame of the motor and the inverter are grounded, and the CMV is measured by connecting the neutral point and ground of the motor. The slip ring is installed on the shaft to measure the shaft voltage. Furthermore, the connection point is made on the outer race of the bearing, as shown in Figure 11. The bracket is made of plastic and the bearings are electrically insulated from the frame. A wire is connected between the connection point and the motor frame. The bearing current is determined by measuring the current in the wire using a current probe. However, it is impossible to accurately measure bearing current because it is different from the real bearing. Therefore, the comparison of the bearing current is relative to the peak-to-peak magnitude.

Figure 11. Experimental setup and method to measure bearing current.

Figure 12 shows the experimental results of CMV, shaft voltage, and bearing current in the traditional SVPWM. Figure 13 shows the experimental results of CMV, shaft voltage and bearing current in the proposed method. The proposed method reduced the peak-to-peak value of CMV by 1/3. As a result, the shaft voltage is also reduced, and the peak-to-peak bearing current is reduced. Additionally, in the proposed method, it is confirmed that the RMS values of the CMV and the shaft voltage do not change according to the speed.

Figure 12. CMV, shaft voltage, and bearing current in the traditional SVPWM (a) at 500 rpm (b) at 3500 rpm.

Figure 13. CMV, shaft voltage, and bearing current in the proposed method (a) at 500 rpm (b) at 3500 rpm.

7. Conclusions

In this paper, a CMV and shaft voltage reduction method through carrier wave phase shift in traditional SVPWM is proposed. This is done by configuring CMV and shaft voltage simulation through MATLAB/SIMULINK. CMV, shaft voltage, and bearing current are checked in the proposed method. Through the co-simulation of ANSYS MAXWELL 2D and Twin Builder, the output torque behaviors with changes in input current are confirmed in the proposed method. Finally, experimental results for verification are included. Both the simulation and experimental results are provided to verify the performance of the proposed method. The proposed method reduces CMV and shaft voltage by 1/3. The THD of the input current and the output torque ripple show little increase.

Author Contributions: Methodology, simulation, and writing—original draft preparation by J.-H.I.; conceptualization, writing—review and editing by Y.-K.L. project administration by J.-K.P.; funding acquisition, review, and formal analysis by J.H. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by Industrial Strategic Technology Development Program of Korea Evaluation Institute of Industrial Technology (KEIT) (No. 20010132, 20011437).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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