

Compensation for Harmonic Flux and Current of Permanent Magnet Synchronous Motor by Injected Harmonic Voltage

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Abstract—High-order harmonic flux and current of permanent magnet synchronous motor (PMSM) are generated by the distortion of air-gap magnetic field and the nonlinear characteristics of inverter, resulting in the ripple of electromagnetic torque. In this paper, a novel harmonic compensation algorithm was proposed to solve this problem. Based on the harmonic model of the PMSM, harmonic voltage is injected to reduce harmonic components of the motor flux and current. By extraction of harmonic flux/current and injection of harmonic voltage in real-time, high-order harmonics of flux generated by the distortion of air-gap magnetic field and the nonlinear characteristics of inverter is counteracted. Thereby, distortion of motor current is reduced. The effectiveness of the algorithm is validated by simulation and experimentation.

Keywords—harmonic compensation; flux and current; PMSM; injected harmonic voltage.

I. INTRODUCTION

Stability of electromagnetic torque is important for motor control [1], influenced by high-order harmonic flux and current. Excitation magnet filed of rotor is not sinusoidal with odd harmonics in PMSM, especially in interior PMSM [2]. For suppression of harmonic components, improvement on structure design is researched for ideal excitation magnet filed using finite element analysis [3-8]. But it leads to limited effect and higher manufacturing cost. Other studies are focused on harmonic currents caused by nonlinear characteristic of switch device of inverter such as voltage drop and dead-time. Some methods are presented including non dead-time control [9], time compensation [10] and voltage compensation based on current feedback [11]. But effect is limited due to difficulty in current zero-cross detection, additional hardware, complicated algorithm and low adaptability [12].

Since harmonics are generated in different factors and vary with the motor operating point, the traditional harmonic compensation is very complex and its effect is not ideal. A novel harmonic compensation algorithm is proposed so that not only particular but also almost harmonic components are suppressed in the entire governing system. Effect of this method is validated through simulation and experimentation. In the experimental platform of vector control of a 400 watt PMSM, DSP-TMS28068M and Intelligent Power Module (IPM) is

used as the controller and the inverter, respectively. The harmonic component and total harmonic distortion (THD) of motor current are compared and analyzed before and after using this method without load.

II. PMSM HARMONIC MODEL

In PMSM steady operation, the motor current is distorted and contains 5th, 7th, 11th, 13th harmonics because of air-gap magnetic field distortion, inverter voltage drop, dead time and other factors. The motor torque ripple and flux distortion are caused by these harmonics, especially 5th and 7th harmonic by which 6th torque/flux harmonic is generated [13].

In static three phase coordinate, 5th harmonic voltage vector rotates at speed of 5ω in the reverse direction of fundamental voltage vector. 7th harmonic voltage vector rotates at speed of 7ω in the same direction of fundamental voltage vector. 5th and 7th harmonics of PMSM three phase voltages are expressed in equation 1:

$$\begin{cases} u_a = u_1 \sin(\omega t + \theta_1) + u_5 \sin(-5\omega t + \theta_2) + u_7 \sin(7\omega t + \theta_3) + \dots \\ u_b = u_1 \sin(\omega t + \theta_1 - \frac{2\pi}{3}) + u_5 \sin(-5\omega t + \theta_2 - \frac{2\pi}{3}) + u_7 \sin(7\omega t + \theta_3 - \frac{2\pi}{3}) + \dots \\ u_c = u_1 \sin(\omega t + \theta_1 + \frac{2\pi}{3}) + u_5 \sin(-5\omega t + \theta_2 + \frac{2\pi}{3}) + u_7 \sin(7\omega t + \theta_3 + \frac{2\pi}{3}) + \dots \end{cases} \quad (1)$$

According to the principle of coordinate transformation from a-b-c to d-q, the vector rotating at the same speed and in the same direction of d-q synchronous rotating coordinate is a direct component. Thus, in d-q coordinate of 5th harmonic, 5th harmonic is a direct component while fundamental and other harmonics are all alternate components, as the same in 7th coordinate. Voltage and flux with harmonic components in d-q coordinate of 5th harmonic is respectively shown in equation 2 and equation 3.

$$\begin{cases} u_d^* = -\omega L_q i_{q1} \sin(6\omega t + \theta_4) + R_s i_{d1} \cos(6\omega t + \theta_4) + 5\omega L_q i_{q5th} + R_s i_{d5th} \\ \quad - 7\omega L_q i_{q7} \sin(12\omega t + \theta_6) + R_s i_{d7} \cos(12\omega t + \theta_6) + \dots \\ u_q^* = \omega L_d i_{d1} \sin(6\omega t + \theta_4) + R_s i_{q1} \cos(6\omega t + \theta_4) + 5\omega L_d i_{d5th} + R_s i_{q5th} \\ \quad + 7\omega L_d i_{d7} \sin(12\omega t + \theta_6) + R_s i_{q7} \cos(12\omega t + \theta_6) + \dots \end{cases} \quad (2)$$

$$\begin{cases} \psi_d^* = L_d i_d + \psi_f - \psi_{d6} \cos(6\omega t) \\ \psi_q^* = L_q i_q + \psi_{q6} \sin(6\omega t) \end{cases} \quad (3)$$

III. HARMONIC REDUCTION ALGORITHM

A. Extraction model of harmonic flux

Harmonic components are added into three phase reference voltages of PMSM so that flux/current harmonics are reduced. As shown in Figure 1, an algorithm is designed for harmonic flux/current extracted from actual current.

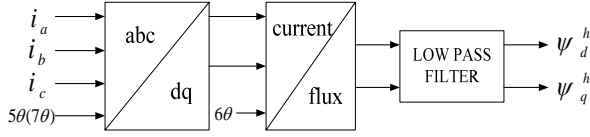


Figure 1. Extraction algorithm of 5th and 7th current harmonics

In corresponding d-q coordinates, 5th and 7th harmonics are respectively direct components while fundamental and other harmonics are all alternate components. Thus, these two harmonics can be extracted by low-pass filter.

B. Compensation model of harmonic flux

According to equation 4 and 6, Compensation model of harmonic flux using 5th and 7th current harmonics is shown in Figure 2.

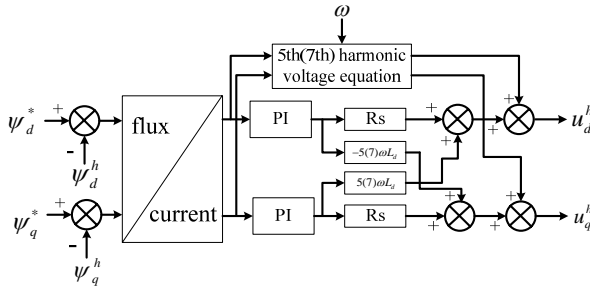


Figure 2. Reduction algorithm of 5th and 7th current harmonics

In PMSM steady-state harmonic voltage equations, d-axis and q-axis voltages are respectively affected by q-axis and d-axis currents. According to these equations, a PI controller with cross-product term is designed so that accurate harmonic voltages can be obtained in any PMSM with different parameters and operating points.

C. Coordinate transformation of harmonic voltage

The harmonic voltages calculated by harmonic reduction algorithm are inversely transformed and accumulated. The compensation in static three phase coordinate is shown in Figure 3.

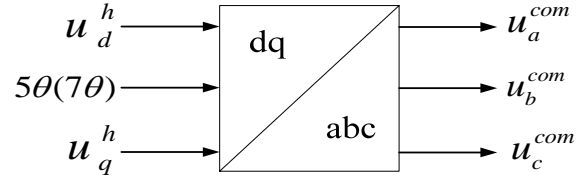


Figure 3. Transformation of harmonic voltages form d-q to a-b-c

IV. ANALYSIS OF SIMULATION AND EXPERIMENTATION

A. Analysis of simulation

The simulation result of Matlab/Simulink is analyzed and compared so that effect of compensation of harmonic flux and current can be validated. In simulation, harmonic current is deliberately generated for validation through the setting of voltage drop and dead time of inverter. Since the motor model with distorted air-gap magnetic field is very complicated, the harmonic current caused by this factor is not considered. Parameters of PMSM are given in Table I.

TABLE I. PARAMETERS OF PMSM

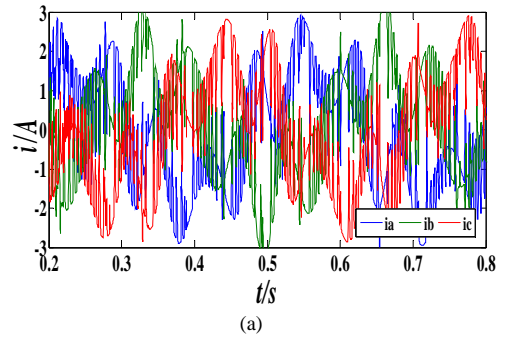
Parameter	Value	Parameter	Value
Load torque Tm/(Nm)	0	Rs/ohm	2.657
Ld/mH	6.7	Lq/mH	6.7
Inertia J/(Kgm2)	0.006	Pair of poles	1

In simulation, harmonic current is deliberately generated for validation through the setting of voltage drop and dead time of inverter. Parameters of inverter are given in Table II.

TABLE II. PARAMETERS OF INVERTER

Parameter	value	Parameter	value
Udc/V	300	Carrier frequency f/KHz	11.7
Carrier period T/us	85.5	Dead time td/us	4
IGBT on-time ton/us	1	IGBT off-time toff/us	2

As shown in Figure 4 and Figure 5, simulation results before and after using harmonic compensation algorithm are compared when PMSM operates in no-load, 180r/min and 3Hz current fundamental frequency.



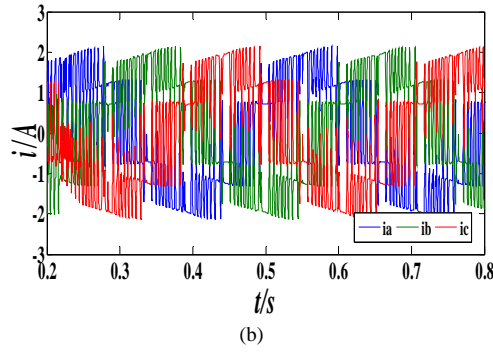


Figure 4. Phase current before and after algorithm

Current harmonic gets heavy and shows the wave seriously distorted without applying harmonic reduction algorithm as shown in Figure 4(a). After utilizing harmonic reduction algorithm, motor currents get obviously improved for standard sine as shown in Figure 4(b).

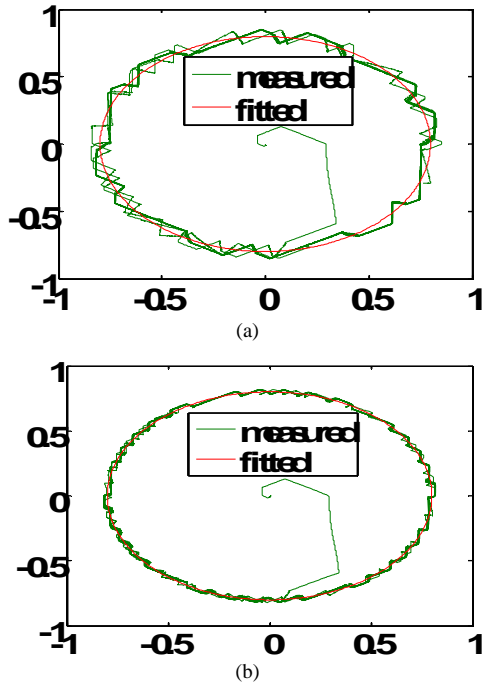


Figure 5. Flux trajectory before and after algorithm

In Figure 5, flux trajectory is reduced in distortion and fits to a standard circle. RMS is 0.0301 and 0.0124 before and after getting improved, respectively.

B. Analysis of experimentation

In the experimental platform of vector control of a 400 watt PMSM, DSP-TMS28068M and Intelligent Power Module (IPM) is used as the controller and the inverter respectively, as shown in Figure 6.

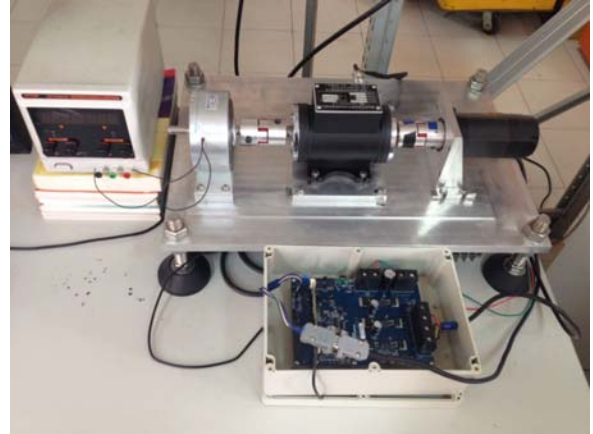


Figure 6. Photo of experimental platform

Rated parameter of PMSM is : $P_N=400W$, $U_N=60V$, $L=0.2mH$, rotor flux= $0.08Wb$, $R_S=300m\Omega$, $n_N=3000r/min$, pair of poles is 1. Parameter of inverter is: PWM carrier frequency is 2.95kHz, dead time is 3.85us, IGBT forward voltage drop is 2.3V, IGBT reverse voltage drop is 3.7 V. As shown in Figure 7 and Figure 8, the harmonic component and THD of motor current before and after using this method are compared and analyzed when PMSM operates in no-load, 180r/min and 3Hz current fundamental frequency.

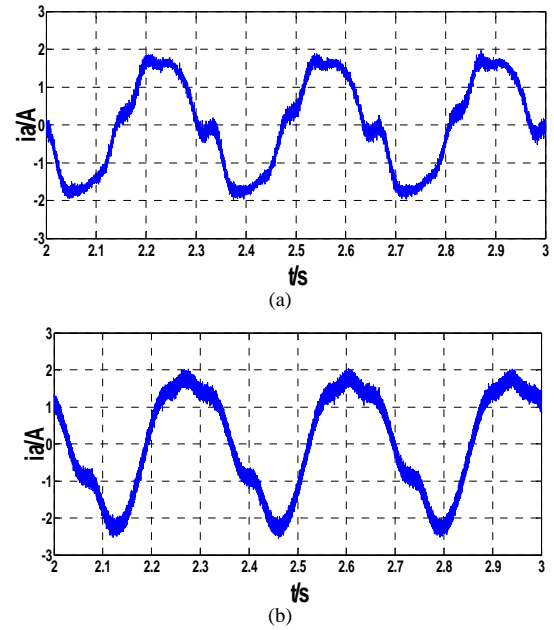


Figure 7. Phase current before and after algorithm

Current harmonic gets heavy and shows the wave seriously distorted without applying harmonic reduction algorithm as shown in Figure 7(a). After utilizing harmonic reduction algorithm, motor currents get obviously improved for standard sine as shown in Figure 7(b).

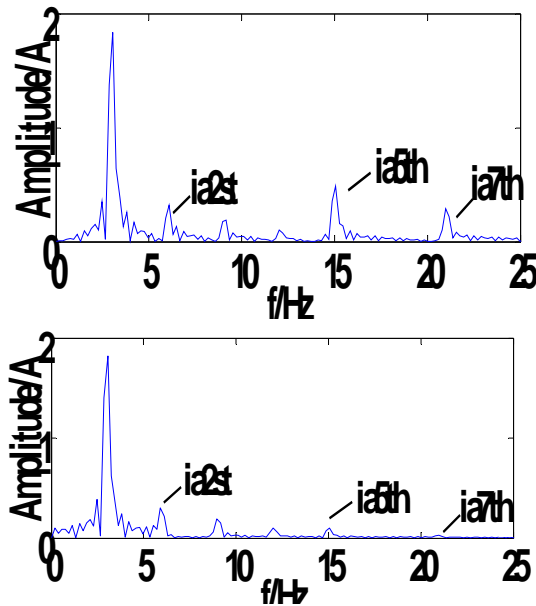


Figure 8. Frequency spectrum of phase current before and after algorithm

Figure 8 shows the amplitude of 5th and 7th current harmonics go obviously down in their corresponding d-q synchronous rotating coordinate. 5th and 7th current harmonics drop from 18.60% to 2.91%, from 6.98% to 1.67%, respectively. Total harmonic distortion (THD) gets down from 26.54% to 5.39%. 5th and 7th harmonics are therefore suppressed with the use of harmonic compensation algorithm. Compared with simulation result, other high-order harmonics such as 2nd harmonic appear in addition to 5th and 7th harmonics as shown in figure 8. It results from the distortion of air-gap magnetic field and the nonlinear characteristics of inverter that can't be included in simulation model. Therefore, reduction of 5th and 7th current harmonics caused by these factors is validated.

However, 5th and 7th current harmonics are not kept to zero strictly both in simulation and in experimentation since real-time and accurate rotor position is needed for harmonic reduction algorithm. Method for decreasing its influence to the effect of harmonic reduction algorithm will be presented for further research.

V. CONCLUSIONS

In this paper, a novel harmonic compensation algorithm was proposed to achieve a stable running of PMSM without torque ripple caused by flux/current harmonics. Simulation and experimentation have proved that flux/current

harmonics existed in governing system are reduced. Mathematic models of 5th and 7th harmonics deduced in this paper can be used for accurate analysis of voltage and current harmonics in governing system. To reduce the harmonics generated by IGBT dead time and voltage drop, harmonic compensation is used without complication of zero-crossing current detection in traditional method. It is also validated that the harmonics caused by distortion of air-gap magnetic field are suppressed.

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