

Voltage-Injection Method for Mitigating Harmonic Currents in Open-Ended Winding Permanent Magnet Synchronous Motors

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Abstract - Since the advantages of multilevel output, voltage utilization rate and enhanced tolerant capacity, the open-end winding permanent magnet synchronous motor (OEW-PMSM) with common DC bus has received increasing research focus. Due to the distortion of air-gap magnetic field and nonlinear factors, different order harmonic currents are introduced to distort the current. Besides, due to the existence of the common DC bus, the 3rd order harmonic voltage would distort the fundamental currents more obviously. In the OEW-PMSM drive system, the disturbances caused by the harmonic currents would reduce the output performance. In this paper, by establishing harmonic mathematical model, a harmonic voltage injection method is proposed. The variables of the corresponding d-q coordinate system are decoupled. And the injection voltages are calculated by the reference currents, which are generated by simple closed-loop controllers. Simulation and experimental results are expressed to verify the proposed method.

Key Words: Open-end winding permanent magnet synchronous motor (OEW-PMSM), common DC bus, harmonic voltage injection, harmonic current suppression.

1.INTRODUCTION

PMSM is used in many applications such as electric vehicles, precise motors and industrial use due to its high power density and efficiency. The OEW-PMSM was proposed to improve the drive system dependability, multilayer modulation, control strategy adaptability and bus voltage utilisation efficiency. This type has a better prospect of utilisation in electric automobiles, electric aeroplanes and marine propulsion systems [1, 2, 3]. The OEW-PMSM is supplied by a dual inverter system. Furthermore, dual inverter architecture provides more flexibility in control and fault tolerance [4], [5]. According to the number of isolated sources, two types of structures can be classified, two sources [6] or one source [7]. The dual inverter system is composed of two different DC sources that can feed the motor with different voltage levels.

If you look at it in terms of volume and cost, the system with one power source is figuratively better than the dual inverter that uses two separate sources. In this method, the common bus allows the passage of the third order harmonic current or zero-sequence current. The third-order harmonic current is caused by the third electromotive force, voltage drop across the switch, deadtime phenomena and the dual inverter, which in turn cause torque fluctuations and system inefficiencies. Many control techniques have been suggested for the OEW-PMSM in an effort to enhance the efficiency of the motor. The strategies include field orientated control, direct torque control, model predictive control etc. The proportion of 3rd-order harmonics is far bigger than the other harmonic currents. To reduce harmonics, some research have reported the attenuation of the third order harmonic current in the OEW-PMSM drive. The third order harmonic voltage of the active vector can be eliminated by merging vectors with the same common mode voltage. This type of PWM modification is a common way to remove the third order harmonics.

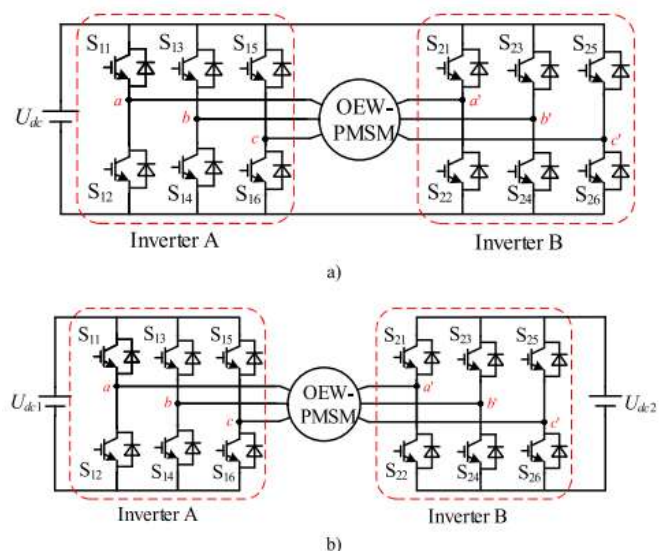


Fig 1. OEW-PMSM drive. (a) With common bus. (b) With isolated buses.

modulation. Changing the phase angle to 120° will not affect the performance of the procedure. These methods remove the third order harmonics of the modulation. However, this technique includes third-order harmonic

voltages due to factors such as deadtime effects, switch voltage loss and the third electromotive force. The third-order harmonic voltage generated by these elements is very noticeable, because the third-order circuit has a low impedance. Hence, the third-order harmonics are reduced by rearranging the zero vectors as in [8] and [15]. The third-order harmonic voltage is produced by adjusting the timing of the two inverters, V0 and V7, to decrease the third-order harmonic current. The third order harmonic current is eliminated by redistribution of the active vectors as explained in [9] and the reference voltage needed for mitigation of the third order harmonic current in the third order harmonic current controller is determined. Moreover, the increase of the switching frequency in [9] reduces the switching losses of the system. A closed-loop controller creates the zero-sequence reference voltage by default. The considered controllers are proportional resonant (PR) controller [8], model predictive control [17] and proportional integral (PI) controller [16]. Compared to PI and model predictive control, the PR controller has effective suppression capabilities and simple design. Therefore, in this study a PR controller is used to generate the reference vector to eliminate the third order harmonic current.

The present scenario is to have 5th, 7th and higher order harmonics in the OEW-PMSM drive because to production imperfections, nonlinearity of the dual inverter, deadtime effects and numerous disturbances. These harmonic currents cause also torque fluctuations and large losses [18], [19]. In the typical control of PMSM drives, a resonant controller is usually employed to reduce these harmonics [20]. The regulators restrict the current in some orders of the harmonic spectrum. In references [21] and [22], a notch filter is employed to remove the specific order harmonic current. The next step in an effort to reduce harmonics is to establish a reference voltage. The mitigation of the associated harmonic current to lessen the torque variation is performed in [23], [24], [25], [26], [27] and [28]. The direct current component is derived by a type-II Chebyshev filter as described in [25].

This allows one to attenuate the direct current signal. In [26] an extended state observer (ESO) is designed to reduce the harmonic current of a dual three-phase PMSM. The effect of harmonic currents increases with decreasing motor inductance. In [27] authors propose a method for mitigation of harmonic currents using deadbeat predictive current regulation. A current is

injected to rectify the adaptive harmonic reference . The ability of OEW-PMSM drive system to suppress these harmonic currents together hasn't been well discussed. Therefore, in this paper, a voltage injection is proposed to reduce the effect of third, fifth and seventh order harmonic currents on the OEW-PMSM drive system. The system uses closed loop controllers to measure third, fifth and seventh order voltages. The mathematical model is used to calculate the compensation voltages of 5th and 7th coordinate system voltages of dual inverter to improve the suppression effect. The harmonic suppression technique has been verified by simulations and experiments.

2.Voltage Vector of The System

Fig. 1 shows the voltage generated by each winding in the OEW-PMSM drive.

$$\begin{bmatrix} u_a = u_{a1} - u_{a2} \\ u_b = u_{b1} - u_{b2} \\ u_c = u_{c1} - u_{c2} \end{bmatrix} \quad (1)$$

In (1), the output is the difference voltage. In (1), the voltage of the stator U_s in $\alpha\beta$ system can be expressed as

$$U_s = U_{sA} - U_{sB} \quad (2)$$

Therefore, the voltages in d-q axis are

$$\begin{cases} u_d = u_{dA} - u_{dB} \\ u_q = u_{qA} - u_{qB} \end{cases} \quad (3)$$

U_d and u_q are voltages in the d-q axis coordinate system. The voltages of the inverter The voltages of source A are u_{dA} and u_{qA} , the voltages of inverter B are u_{dB} and u_{qB} and the voltages of the d-q axis coordinates of the system are u_d and u_q . With one inverter you can have eight separate voltage vectors. The output voltage is the result of the two inverters combined. There are 64 combinations of vectors conceivable. The different vectors together give one zero vector and eighteen separate effective vectors.

The distribution of the entire space vector is shown in Fig. 2. Like the three-level inverter the system provides a voltage on the output. They are at the vertices of three hexagons A~R. However, some combinations of voltage vectors could cause third order harmonic voltage. The medium vectors are used to construct the reference voltage so as to eliminate the third harmonic voltage produced by the system. Fig. 2. Different pairings of blue vectors. You can find them on the edge of three hexagons. The HJLNQS hexagons have the capacity to bypass the third order harmonic voltage of the dual inverter.

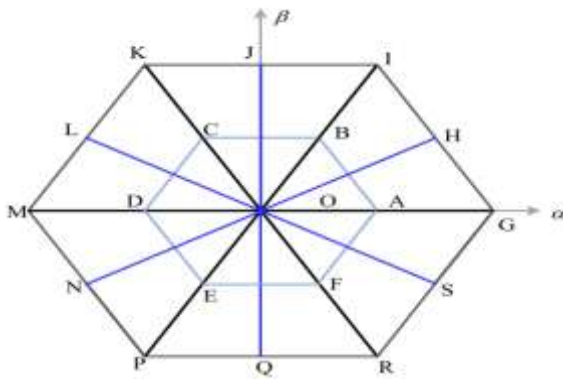


Fig 2. Space voltage vectors of the dual inverter.

2.1. Mathematical Model of OEW-PMSM.

Third Figure 3 shows the third order trajectory of the OEW-PMSM drive with a common bus. The corresponding inductance is called L_0 and the flux linkage of the rotor is 93 Inverter A shows the common mode voltage u_{cmv1} and inverter B shows u_{cmv2} . The voltage differential between them is the inverter introduced third order harmonic voltage. The resistance of the stator is denoted by R_s .

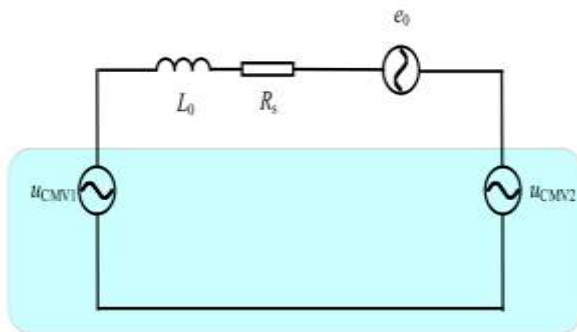


Fig 3. Zero-sequence equivalent circuit.

According to [20], L_0 can be obtained by

$$L_0 = L_s - 2M_s \quad (4)$$

e_0 is the zero-sequence EMF, which is the 3rd order EMF. It can be obtained by

$$e_0 = -3\omega\psi_3 \sin 3\theta \quad (5)$$

Ignoring the torque generated by the high order harmonics, the motor torque generated by the 3rd order harmonic current is

$$T_{e0} = -6\psi_3 \sin(3\theta)i_0 \quad (6)$$

The presence of third-order harmonics leads to torque ripples in the system as illustrated in equation (6). The presence of the common bus makes the third harmonic current ratio higher than the other order harmonics. The third order harmonic current created in the system can be cancelled by using the medium vectors shown in Figure 3. However, in case of applications third order harmonic currents can also be generated due to dead time, voltage drop in the devices, and the third component of the back electromagnetic field. Therefore, closed-loop control is a good way to reduce the third-order harmonic current. According to many studies, the system is subjected to a certain amount of harmonic voltage with the opposite polarity.

Proportional Resonant (PR) controller is often used to reduce third order harmonic current due to its agile capabilities. Furthermore, the motor affects the resonance frequency of the PR controller [8, 10]. B. Fifth and Seventh Frameworks The dead time of the inverters and voltage loss on devices generate the third order harmonics. Moreover, motor output voltage is contaminated by odd multiples of the fundamental current harmonics due to the deadtime and the tube voltage drop as shown in [20]. Therefore, these elements will increase the torque ripples and cause the appearance of fifth, seventh and eleventh-order harmonic currents. The mathematical model for the harmonic mitigation needs to be studied. The OEW-voltages of PMSMs are equal to the voltages of a standard three-phase PMSM connected to a neutral point on the d-q axis. These ideas can be stated as

$$\begin{cases} u_d = R_s i_d + L_d \frac{di_d}{dt} - \omega L_q i_q \\ u_q = R_s i_q + L_q \frac{di_q}{dt} + \omega \psi + \omega L_d i_d \end{cases} \quad (7)$$

Where: $\ddot{u}$ - electrical angular velocity L_d - stator inductance along the d-axis L_q - stator inductance along the q-axis R_s - motor stator resistance. For simplicity of examination, the dynamic parts are ignored. The steady state voltage equations can be written along d-d axis as follows.

$$\begin{cases} u_d = R_s i_d - \omega L_q i_q \\ u_q = R_s i_q + \omega \varphi + \omega L_d i_d \end{cases} \quad (8)$$

Generally the currents and voltages are considered as direct components in the d-q coordinate frame. In the analysis of harmonic elements in phase voltages and currents, it is necessary to include harmonic components in the d-q axis coordinate system. In this research, the only harmonics considered are fifth and seventh order. In the case of fifth order three-phase currents, the harmonic voltage spins anti-clockwise relative to the fundamental wave. However, the rotational direction of the fundamental wave is the same as the seventh order harmonic voltage. The harmonic voltages are given as when converted to three-phase voltages

$$\begin{cases} u_a = U_1 \sin(\omega t + \theta_1) + U_5 \sin(-5\omega t + \theta_5) + U_7 \sin(7\omega t + \theta_7) \\ u_b = U_1 \sin(\omega t + \theta_1 - \frac{2\pi}{3}) + U_5 \sin(-5\omega t + \theta_5 - \frac{2\pi}{3}) \\ \quad + U_7 \sin(7\omega t + \theta_7 - \frac{2\pi}{3}) \\ u_c = U_1 \sin(\omega t + \theta_1 + \frac{2\pi}{3}) + U_5 \sin(-5\omega t + \theta_5 + \frac{2\pi}{3}) \\ \quad + U_7 \sin(7\omega t + \theta_7 + \frac{2\pi}{3}) \end{cases} \quad (9)$$

U_1 , U_5 and U_7 are the amplitudes of the fundamental, fifth and seventh harmonic voltages respectively. The corresponding values of basic phase angle, fifth-order harmonic voltage and seventh-order harmonic voltage are θ_1 , θ_5 and θ_7 respectively. And the matching α - β axis can convert the voltages inside an ABC system.

$$T = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \\ \sqrt{\frac{1}{2}} & \sqrt{\frac{1}{2}} & \sqrt{\frac{1}{2}} \end{bmatrix} \quad (10)$$

They can be transformed to the corresponding d-q axis by transformation formula as follows:

$$T(\theta) = \begin{bmatrix} \cos \theta & \sin \theta & 0 \\ -\sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (11)$$

Then the variables in d-q coordinate system can be obtained. They are

$$\begin{cases} u_d = u_{d1} + U_5 \cos(-6\omega t + \theta_5) + U_7 \cos(6\omega t + \theta_7) \\ u_q = u_{q1} + U_5 \sin(-6\omega t + \theta_5) + U_7 \sin(6\omega t + \theta_7) \end{cases} \quad (12)$$

where u_{d1} and u_{q1} are the fundamental voltages in d-q axis, respectively. In (12), the 5th and 7th order harmonic voltages in ABC coordinate system are sixth ripples in d-q axis.

Similarly, the currents in d-q axis coordinate system can be obtained by

$$\begin{cases} i_d = i_{d1} + I_5 \cos(-6\omega t + \theta_5) + I_7 \cos(6\omega t + \theta_7) \\ i_q = i_{q1} + I_5 \sin(-6\omega t + \theta_5) + I_7 \sin(6\omega t + \theta_7) \end{cases} \quad (13)$$

I_1 , I_5 and I_7 are the amplitudes of the fundamental, fifth and seventh order harmonic currents. The objects of the applicable system, which are steady, are the flows in the corresponding coordinate system. So, the construction of low pass filters for optimising id_{q5} and id_{q7} is an important task.

The reference voltages in d-q coordinate system of fundamental wave space can be expressed as

$$\begin{cases} u_d^* = -\omega L_q i_{q1} + R_s i_{d1} + 5\omega L_q I_5 \sin(-6\omega t + \theta_5) \\ \quad + R I_5 \cos(-6\omega t + \theta_5) - 7\omega L_q I_7 \sin(6\omega t + \theta_7) \\ \quad + R I_7 \cos(6\omega t + \theta_7) \\ u_q^* = \omega L_d i_{d1} + R_s i_{q1} + 5\omega L_d I_5 \cos(-6\omega t + \theta_5) \\ \quad + R I_5 \sin(-6\omega t + \theta_5) + 7\omega L_d I_7 \cos(6\omega t + \theta_7) \\ \quad + R I_7 \sin(6\omega t + \theta_7) \end{cases} \quad (14)$$

In a fifth order coordinate system, the angular velocity is in the opposite direction of the $\ddot{u}$, and harmonic currents are direct ingredients. Therefore, harmonic currents are direct components of the seventh order coordinate system. The angular velocity is along the $\ddot{u}$. The third order current of the three-phase system is equal to the zero-sequence component. It therefore appears at right angles to them. Their relation is seen in Figure 4.

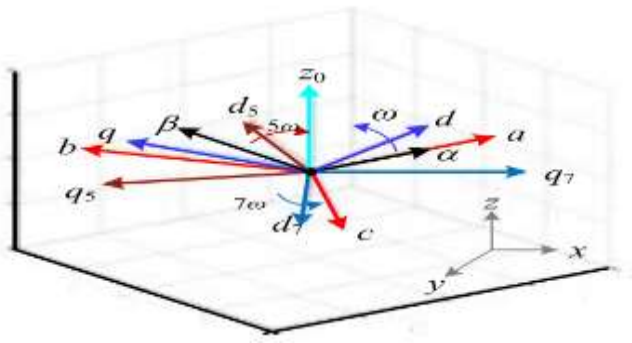


Fig. 4. Relation between various coordinate axes.

The transformation of fifth and seventh order voltages into their corresponding d-q axes will help to reduce the harmonic currents. Except for the communication component, the voltage of this fifth-order d-q coordinate system is .

$$\begin{cases} u_{d5} = 5\omega L_q i_{q5} + R_s i_{d5} \\ u_{q5} = -5\omega L_d i_{d5} + R_s i_{q5} \end{cases} \quad (15)$$

Similarly, the voltages in fifth order d-q coordinate system are

$$\begin{cases} u_{d7} = -7\omega L_q i_{q7} + R_s i_{d7} \\ u_{q7} = 7\omega L_d i_{d7} + R_s i_{q7} \end{cases} \quad (16)$$

2.2. Suppressing of the Harmonics

Figure 5 shows the design that reduces the third order harmonic current. A PR controller is utilised to obtain the third-order reference current. The third order equivalent circuit shows that in an effort to minimise the third order harmonic current, the third order reference current should be multiplied by R_0 and then e_0 should be added to get the third order reference voltage. The dead time effect and voltage reductions in the device generate a third harmonic component that is included in the i_{0ref} .

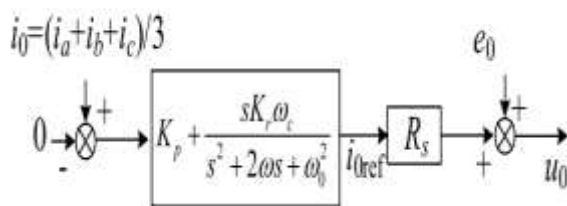


Fig 5. Zero-sequence equivalent circuit

Fig. 6. Inhibiting harmonic framework in the fifth order harmonic coordinate system according to Eqs. (13) and (14). If i_{d5} is not zero, then the PI controller is given a zero input. The reference currents in the fifth-order harmonic coordinate frame are created by the two proportional-integral controllers. The multiplying them with R_s gives the voltage injection. Other u_{d5} elements can be found from the respective branches and equation (14) according to the mathematical framework.

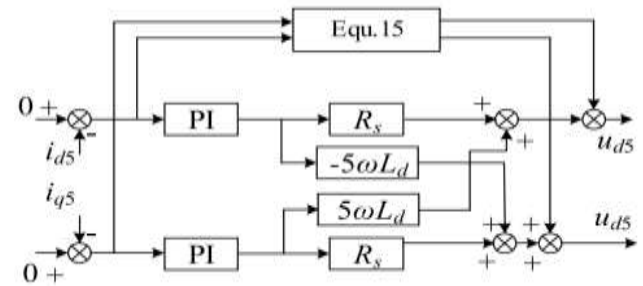


Fig 6. Suppressing structure of the harmonics in the 5th order harmonic coordinate system.

Figure 7 displays the harmonic suppression framework in the seventh-order harmonic coordinate system, as described by equations (13) and (14). The input to the two PI controllers is the difference between i_{d7} and 0. The two PI controllers produce a reference current in the 7th order harmonic system. R_s increases their value. Similarly, the other components of u_{d7} are obtained by using the mathematical structure and the corresponding components of equation (15).

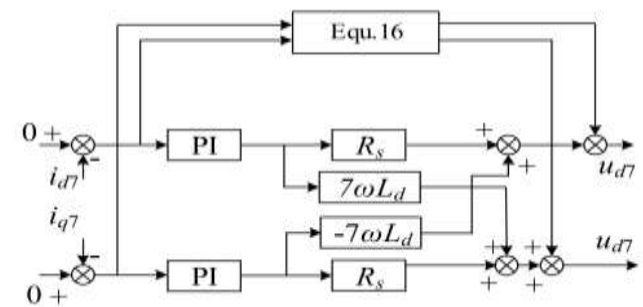


Fig 7. Suppressing structure of the harmonics in the 7th order harmonic coordinate system.

The proposed harmonics mitigation strategy for the OEW-PMSM drive is diagrammed in Fig.8. There is no reference other than zero for any harmonic current. The third order harmonic current is also known as the third order component. It is one-third of the total of the aggregate phase currents. The three existing stages are transformed into corresponding coordinate system using Equ. 10, Equ. 11 and Equ.13. The output currents are provided in the configurations as shown in Figures 5 and 6. The third-order reference voltage for the mitigation of

the third-order harmonics is obtained using the PR controller [29], [30]. The reference voltages of fifth and seventh order are generated by two PI controllers each. Moreover the anti-parker transform them into the coordinate system α - β . The two of inverters in the system must distribute the injection voltage equally. The effect of the modulation factor will thus be reduced to a minimum.

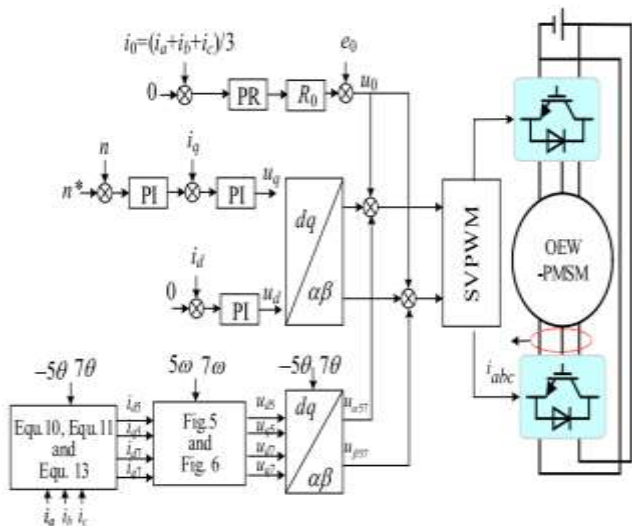


Fig 8. Suppressing structure of the harmonics of the proposed method.

3.Simulation Study Results

In this study, the MATLAB/Simulink simulation environment is developed to investigate the efficiency of the proposed harmonic current suppression approach for OEW-PMSM drives. FAIRCHILD SEMICONDUCTOR's FSBB30CH60C is used. The simulation platform has a perfect mathematics model, except for the deadtime effect and switch voltage drop.

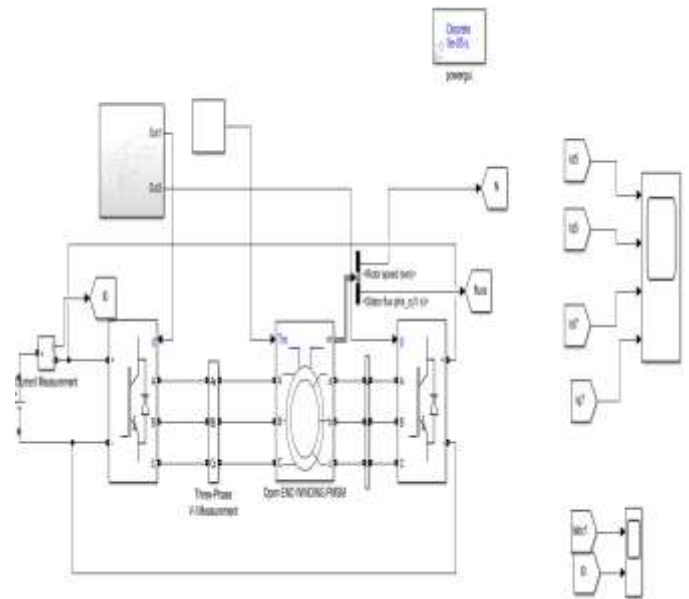


Fig.9. simulation model

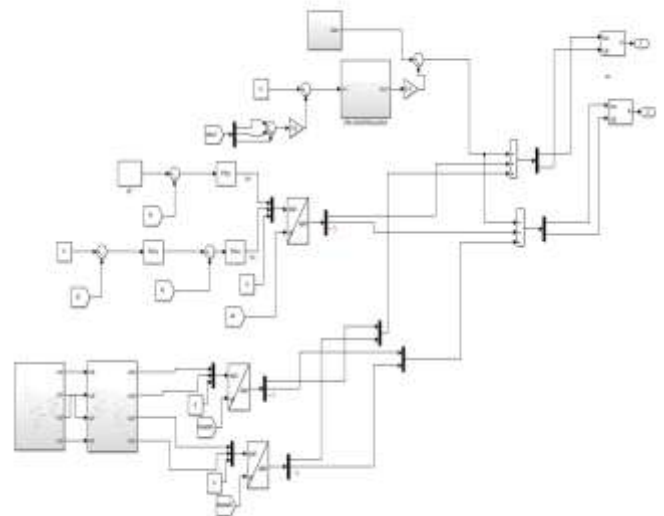
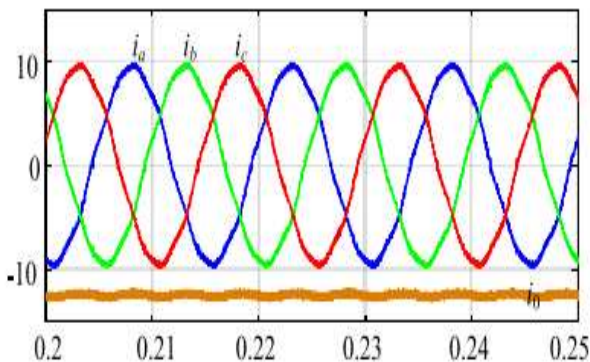


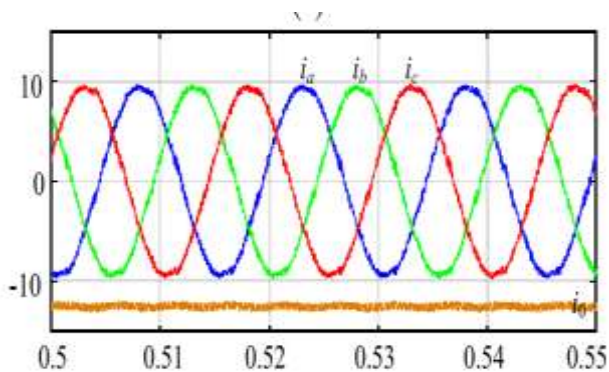
Fig.10. simulation diagram of control system

Figure 9 (a) and Figure 9 (c) presents the simulation results of the working process of the traditional PR controller with 1000 r/min speed and 8 N · m load torque. In most of the investigations, the typical control approach of the OEW-PMSM drive system employs the PR controller as the main method to reduce the 3rd harmonic current. These investigations, however, have no intention of reducing the harmonic currents of the fifth and seventh orders. The simulation results of the proposed strategy for mitigation of harmonic currents are shown in Figure 9 (b) and Figure 9 (d). Figure 9 (a) shows that the third order harmonics are only reduced

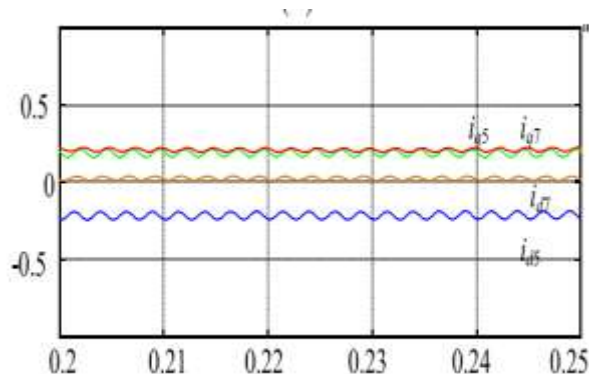
with the usage of the PR controller. A significant reduction of the third-order harmonic current has been observed. The non-zero i_{dq5} and i_{dq7} in Fig. 9(c) are caused by the fifth and seventh order harmonics of the system. The enhancement of the effectiveness of the phase currents as compared with the simulated results in figure 9 (a) without harmonics injection is illustrated in figure 9 (b). In Figure 9 (d) the values of i_{dq5} and i_{dq5} are reduced to practically zero.



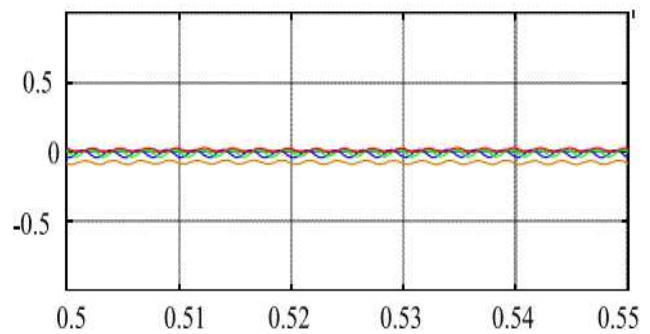
(a)



(b)



(c)



(d)

Fig 11. Simulation results of phase currents, ZSC and currents in d-q axis. (a) and (c) without the proposed method. (b) and (d) with the proposed method

Figure 10 shows the total harmonic distortion (THD) of current harmonics at 1000 r/min and 8 N·m with and without the application of the approach. Most of the disturbance is caused by harmonics of the fifth and seventh orders. Figure 10 (a) shows that the spectrum clearly presents some 5th and 7th order harmonic currents even without voltage injection. The total harmonic distortion (THD) of the current is reduced to 3.26 percent by applying the harmonic voltage. The analysis of the simulation results obtained for different velocities and load torques confirms the proposed technique. The results are shown in Figures 11 (a) and 11 (c) for rotational speeds of 500 r/min and load torques of 8 N·m, respectively. Harmonic voltage injection currents in fifth and seventh order coordinate frames

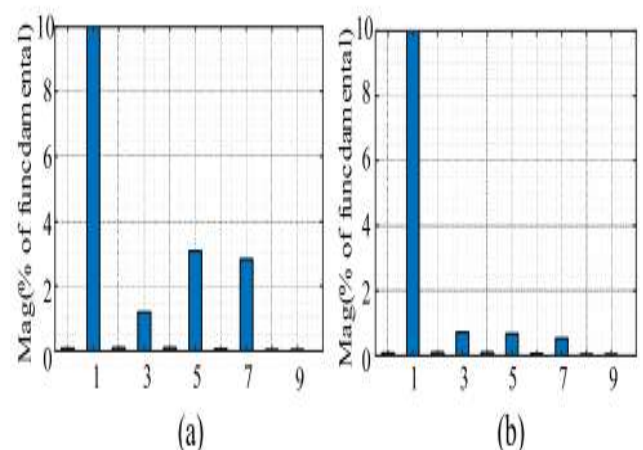


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3. CONCLUSIONS

A method for reducing the harmonic currents in open-end winding PMSMs is proposed by injecting voltage, which enhances the efficiency of the drive without influencing the core component responsible for the generation of torque. The dual-inverter open-end winding arrangement allows for voltage injection to dramatically reduce total harmonic distortion (THD), torque pulsations, acoustic noise, and copper losses, while increasing control flexibility. This approach is well suited for industrial motor drive systems and advanced electric vehicle traction because to its efficiency, responsiveness and dependability in MATLAB/Simulink under different load and speed situations.

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