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TORQUE RIPPLE REDUCTION OF NON-IDEAL PERMANENT MAGNET BRUSHLESS MOTOR BASED ON SELECTIVE TORQUE HARMONIC ELIMINATION USING ONE CYCLE CONTROL STRATEGY

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Abstract

Abstract: Due to some inevitable restrictions during fabrication of permanent magnet brushless (PMBL) motors, some of them have neither sinusoidal nor trapezoidal back-EMF voltages, that we name them as non-ideal PMBL motors. Employing conventional control strategies of permanent magnet synchronous motors (PMSMs) and brushless DC motors (BLDCMs) leads to lower efficiency and performance and causes unwanted torque ripple, vibration and acoustic noises that in unfavourable for special applications. This paper investigates the torque response of non-ideal PMBL motor while is controlled with conventional control strategies and presents a novel torque ripple minimization method. Simulation results indicate the non-ideal PMBL motor by novel proposed method develops smoother torque and lower torque ripple rather than all mentioned control strategies.

Keywords: Electrical drive, Non-ideal permanent magnet brushless motor, One cycle control, Torque ripple, Selective torque harmonic elimination

1. INTRODUCTION

Nowadays, electric motors have been known as one of the major consumers of electric energy. In two past decades and with reducing the price of permanent magnets material, design and manufacture of permanent magnet brushless (PMBL) motors have developed in low power applications. Superior features such as high efficiency, high power and torque density, low maintenance cost, simple structure and ease of control are the reasons for tendency to these motors. Due to mentioned reasons, PMBL motors are considered in high performance and accurate applications as electric transportation, aerospace and military industries or even in domestic and consumer applications [1]. The PMBL motors are divided into two main categories of AC brushless (PMSM) and DC brushless (BLDC). The induced back-EMF voltages in stator windings for PMSMs are quite sinusoidal, whereas for BLDCMs are trapezoidal waveforms with flat portion over a range of 120 degrees as shown in Fig. 1a, b [2, 3]. The difference of back-EMF voltage waveforms causes that the employed control methods to be so different [4]. To develop of a constant instantaneous torque for PMSMs, vector based control such as field oriented control (FOC) or direct torque control (DTC) in two-axis d-q reference frame are usually used. But for BLDCMs, using of vector based methods is not common and their utilization, leads to lots of torque ripple and so, simple quasi-square (six-step) current method is employed [5]. The main advantages of six-step current method for BLDCMs are ease of implementation as same as the current control of DC motors, and no need to costly optical encoders for current commutation. For this purpose, it is sufficient to know only six positions of the rotor per revolution, which can be obtained by three cheap Hall Effect position sensors. Another category of PMBL motors are those that their back-EMF voltages are neither ideal trapezoidal like BLDCMs nor sinusoidal like PMSMs. It is due to the accuracy or restrictions in design or fabrication stages of PMBL motors. The main reasons for this issue are inappropriate distribution of the stator windings, improper form and span of the rotor's permanent magnet and saturation effects. These motors are briefly called non-ideal PMBL motor in this paper. Fig. 1c shows a sample back-EMF voltage of non-ideal PMBL motor. Employing conventional control methods of PMSM and BLDCMs for non-ideal PMBL motors causes significant instantaneous torque ripple that depends directly on the percentage of motor back-EMF voltage waveform distortion ratio to **ideal** sinusoidal **or** trapezoidal waveform [6, 7]. In some of special applications such as military, existence of the torque ripple leads to mechanical vibration or acoustic noise. In general, there isn't any conventional and commercialized method to control these motors without torque pulsation.

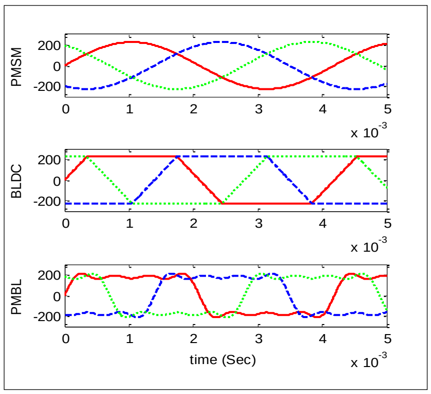


Fig. 1. The Back-Emf Voltage Waveforms Of Different Types Of Permanent Magnet Brushless Motors (PMBL)

This paper proposes a comparative study on the effect of conventional control methods of PMSMs and BLDCMs on the torque ripple of non-ideal PMBL motors. Various methods include; quasi-square current control by dc link current regulation, three-phase quasi-square current regulation, direct torque control, vector control, and pseudo vector control methods are investigated. Afterwards a novel selective torque harmonic elimination based on one cycle control strategy is developed. All mentioned methods are simulated and the results are compared. This paper is organized as follows; in section 2, the dynamic model of non-ideal PMBL motor is developed. In section 3 various mentioned conventional control methods for PMSMs and BLDCMs are studied and then in section 4, the developed selective torque harmonic elimination based on one cycle control strategy is investigated. All simulation results are compared in section 5 and finally conclusions are given in section 6.

2. Dynamic Model of Non-Ideal PMBL Motor

There are two main approaches for dynamic modeling of these motors; (1) modeling in multiple *dq* reference frames (MRF) [5] (2) modeling in stationery three axis abc reference frame. In the modeling based on multiple reference frames, according to harmonic contents of the back-EMF voltage, multiple dq reference frames are considered with speeds equal to available harmonics, and motor quantities include voltages, currents, fluxes are transferred to these multiple *dq* reference frames [8,9].This type of modeling can be useful when the vector control methods are used for the non-ideal PMBL motor that is called pseudo vector control method [19]. Another modeling method of non-ideal PMBL motor is use of the method for modeling of BLDC motor, in *abc* stationary reference frame [10]. Fig. 2 shows the electrical equivalent circuit of dynamic model for non-ideal PMBL motor.

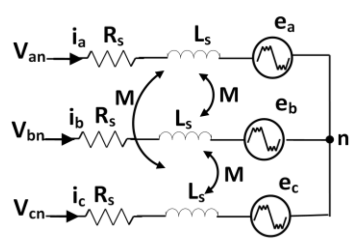


Fig. 2. Electrical Equivalent Circuit Of Dynamic Model Of Three-Phase Non-Ideal Pmbl Motor In abc Reference Frame

The voltage equations of three-phase non-ideal PMBL motor to the motor star Point are expressed as follows:

$$\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \times \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_s\text{-}M & 0 & 0 \\ 0 & L_s\text{-}M & 0 \\ 0 & 0 & L_s\text{-}M \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

That v_{an}, v_{bn}, v_{cn} are the stator terminal voltages to star point, i_a, i_b, i_c are three-phase currents of the motor, e_a, e_b, e_c are the phase back-EMF voltages and L_s and M are self-inductance and mutual inductance of stator phases. Electromagnetic torque is developed from the following:

$$T_{em} = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega_m} \quad (2)$$

In which ω_m is the mechanical speed of the rotor shaft and obeys the rotational motion equation as:

$$T_{em} = T_L + J\frac{d\omega_m}{dt} + B_f \omega_m , \quad (3)$$

That T_L is the load torque and B_f and J are the load friction coefficient and moment of inertia referred to the rotor shaft respectively.

3. THE NON-IDEAL PMBL MOTOR CONTROL

The employed non-ideal PMBL motor has the back-EMF voltage shown in Fig. 1c. It contains the harmonics of order n=1,3,5 and 7 with amplitudes of 100%, 33%, 20% and 13% of base harmonic respectively that has been obtained from FFT analysis of measured phase back-EMF voltage. It is assumed that the harmonic contents are constant over speed range. The motor has rated power of 3hp and at rated speed 1500 rpm and its equivalent circuit parameters are listed in Table 1.

TABLE 1.THE EQUIVALENT CIRCUIT PARAMETERS OF NON-IDEAL PMBL MOTOR

Quantity	Symbol	Value
Resistance per phase	R_s	0.2 Ω
Self-inductance per phase	L_s	0.8 mH
Mutual inductance	M	0.1 mH
Number of poles	P	12
Constant of back-EMF voltage	K_e	0.15 V/(rad/sec)
Moment of inertia	J	0.015 $N.m/s^2$
DC link voltage	V_{dc}	300 V
Rated load torque	T_n	15 N.m

3.1. Quasi-Square Current Control Method Via DC Link Current Regulation

This method that is also known as six-step current control is the most popular and simple control method for BLDC motors. Fig. 3 shows the application of this method for PMBL motor. Like the BLDC motors, it is enough that the DC link current is regulated at desired value, because the current flows in two phases. The reference current is developed via speed controller. An upper and a lower switch always are conducting the current and switching sequence is determined based on the rotor position information obtained from three Hall Effect position sensors. Fig. 4 shows the simulation results under rated torque/speed condition. The acceleration time of reference speed is set to 0.1 sec and the actual speed follows it well. Developed electromagnetic torque contains some ripple that is caused by two different sources; (1) The behavior of freewheeling diodes during commutation instants [11], and (2) the effect of non-ideal phase back-EMF voltage in 120 degrees conduction intervals. Tracking of reference speed is favorable but the torque ripple is high and its value is about 10 N.m or 66% at steady state.

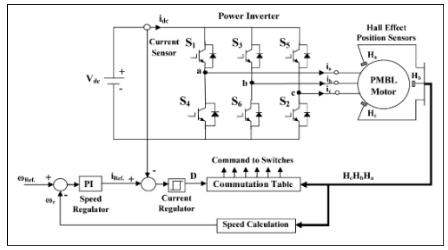


Fig. 3. THE BLOCK DIAGRAM OF NON-IDEAL PMBL MOTOR DRIVE BY QUASI-SQUARE CURRENT CONTROL METHOD VIA DC LINK CURRENT REGULATION

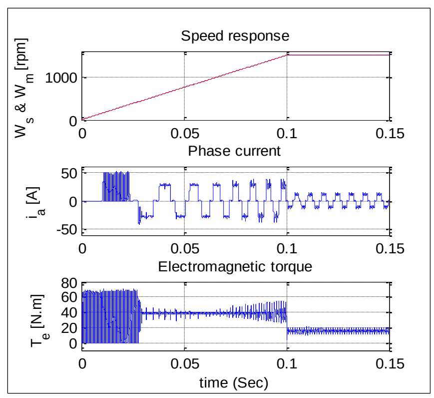


Fig. 4. SIMULATION RESULTS OF QUASI-SQUARE CURRENT CONTROL METHOD VIA DC LINK CURRENT REGULATION FOR NON-IDEAL PMBL MOTOR

3.2. Quasi-Square Current Control Method Via Three-Phase Current Regulation

This control method is an improved form of quasi-square current control method in which the phases' currents are directly controlled at all instants even at commutation times [12]. Fig. 5 shows the block diagram of this control method that three current controllers are used as well as two or three current sensors. Fig. 6 shows the simulation results of this method. The current distortions at commutation instants are lower than the method based on DC-link current regulation method, but there is still the torque ripple due to non-ideal of back-EMF voltage. The torque ripple value is 7 N.m or 46% at steady state.

3.3. Direct Torque Control Of Non-Ideal Pmbl Motor

Direct torque control (DTC) is one of the modern methods that has been well developed during two past decades and commercialized by some electrical dives manufacturers [13].This method was initially expressed for the sinusoidal motors, but the attractiveness and simplicity of implementation was caused to be also used for BLDC motors [14].

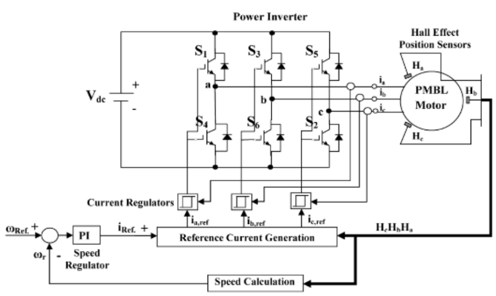


Fig. 5. THE BLOCK DIAGRAM OF NON-IDEAL PMBL MOTOR DRIVE BY QUASI-SQUARE CURRENT CONTROL METHOD VIA THREE-PHASE CURRENT REGULATION

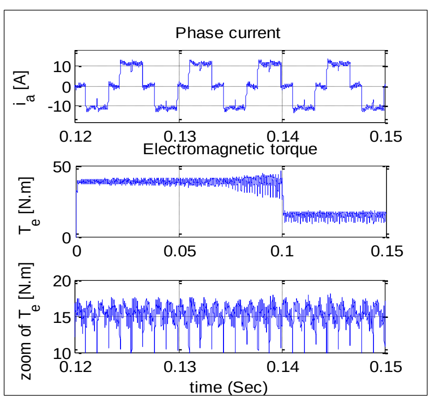


Fig. 6. SIMULATION RESULTS OF QUASI-SQUARE CURRENT CONTROL METHOD VIA THREE-PHASE CURRENT REGULATION FOR NON-IDEAL PMBL MOTOR

In DTC method, torque is directly controlled without controlling of the phases' currents in inner loops. It can be implemented in two ways; three-phase current conduction like to PMSMs and IMs, and two-phase current conduction like BLDCMs. Fig. 7 shows a block diagram of DTC system of non-ideal PMBL motor with two-phase current conduction method [15]. Since Non-ideal PMBL motor does not have sinusoidal back EMF, the stator flux trajectory is not pure circle as in PMSM. Thus, direct stator flux amplitude control in this type of motor is not trivial as in PMSM such that rotor position varying flux command should be considered. However, this is a complicated way to control the stator flux linkage amplitude. So, to choose the voltage vector, only the sign of torque error is considered. The switching table for controlling the torque is given in reference [16]. In the control of non-ideal PMBL motor by DTC method, the electromagnetic torque should be estimated. The motor torque can be estimated achieved using [17, 9]:

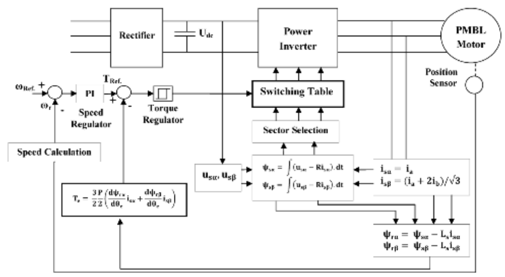


Fig. 7. THE BLOCK DIAGRAM OF NON-IDEAL PMBL MOTOR DRIVE BY DIRECT TORQUE CONTROL METHOD

$$T_{em} = \frac{3}{2}\frac{P}{2\omega_r}\left(\frac{d\psi_{r\alpha}}{dt} i_{s\alpha} + \frac{d\psi_{r\beta}}{dt} i_{s\beta}\right), \tag{4}$$

Where the $\alpha\beta$ components of rotor flux are calculated from the following equations:

$$\psi_{r\alpha} = \int\left(v_{s\alpha} - R_s i_{s\alpha} - L_s \frac{di_{s\alpha}}{dt}\right).dt \tag{5}$$

and

$$\psi_{r\beta} = \int\left(v_{s\beta} - R_s i_{s\beta} - L_s \frac{di_{s\beta}}{dt}\right).dt, \tag{6}$$

The calculation error for estimation of torque has a significant impact on the behavior of the control system and the quality of output torque that may be caused by effect of hysteresis controller, stator resistance variations, switching noises of PWM voltage, and also harmonics superimposed on the back-EMF voltage.

The simulation results of non-ideal PMBL motor with DTC method is shown in Fig. 8 that indicates to high torque ripple due to mentioned reasons. The value of torque ripple is about 12 N.m or 80% that is more than all methods. However, using the PI regulator to control of torque, or three-phase conduction strategy improves the torque response, but there will be still error to estimate of actual torque.

3.4. Vector Control Of Non-Ideal PMBL Motor

The main idea of vector control method for each type of motor is that magnitude of flux vector (rotor, stator or air-gap flux) should remain constant and its orientation is also placed on the d-axis direction in rotating dq reference frame.

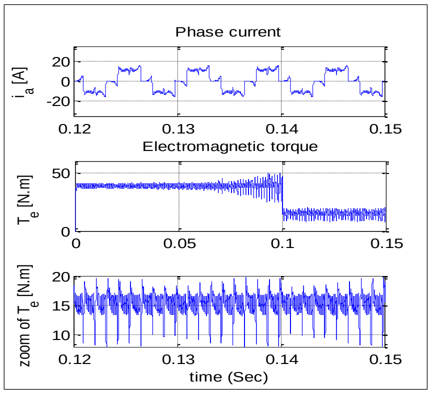


Fig. 8. Simulation Results Of Direct Torque Control Method Based On Two-Phase Conduction For Non-Ideal Pmbl Motor

With this strategy, flux component on the q axis becomes zero and the torque will be proportional to the stator current component i_{qs}. By orientation the flux vector on d axis, the flux amplitude is controlled by regulation of i_{ds} [18]. The torque equation of PMSM in rotating dq reference frame is developed by:

$$T_{em} = \frac{3P}{4}[\lambda_m i_{qs} + \left(L_d - L_q\right) i_{ds} i_{qs}], \qquad (7)$$

It can be realized that i_{ds} should remain zero so that the torque to be independent of flux in speed region lower than the rated speed. So, the reference value of i_{qs} can be obtained from:

$$i_{qs}^* = \frac{4T_{em}^*}{3P\lambda_m}, \qquad (8)$$

Where T_{em}^* the reference torque is developed via speed control loop, λ_m is flux of rotor's permanent magnet, and P is the number of poles. Fig. 9 shows the block diagram of vector control system for non-ideal PMBL motor. Fig. 10 shows the simulation results of non-ideal PMBL motor drive by using vector control method. The torque ripple is about 6 N.m or 40%. The results show that the vector control leads to smoother torque than six-step current control and DTC methods.

3.5. Pseudo Vector Control Of Non-Ideal Pmbl Motor

In view of torque ripple, vector control is the best candidate for PMSM drives. But for non-ideal PMBL motors, the harmonics of back-EMF voltage leads some distortion on the torque. Some of references have used multiple dq reference frames to control of non-ideal PMBL motor. On this way, various harmonic are controlled in individual dq reference frames. This method has very computation and requires powerful processors [19, 20]. The problem of the vector control method for motor with non-sinusoidal back-EMF voltage can be improved with a slight change in the determination of reference currents. This method which is known as the pseudo vector control has been used for vector control of BLDC motors [21, 22].

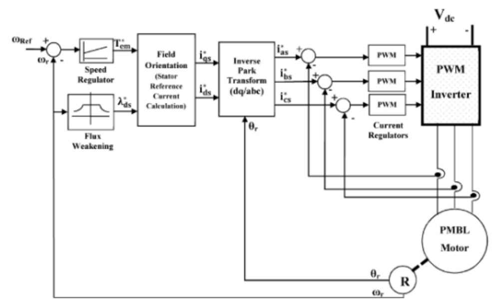


Fig. 9. The Block Diagram Of Non-Ideal Pmbl Motor Drive By Vector Control Method

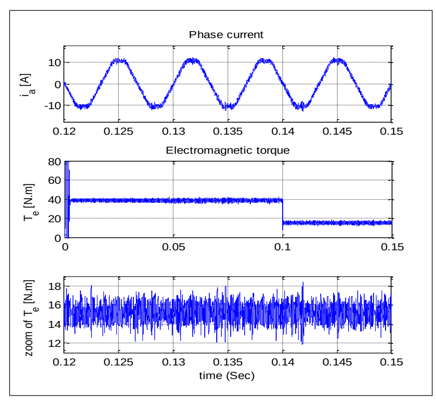
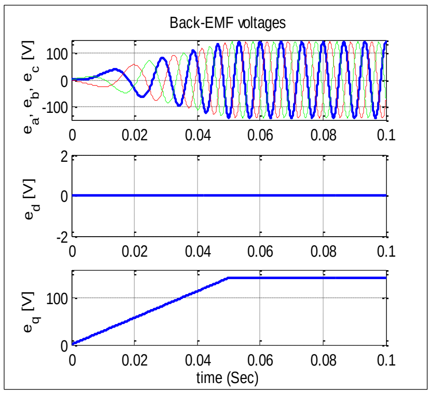


Fig. 10. Simulation Results Of Vector Control For Non-Ideal Pmbl Motor

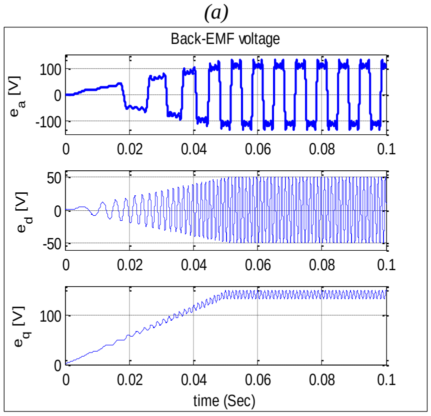
The instantaneous electromagnetic power of non-ideal PMBL motor can be expressed in rotating dq reference frame as:

$$P_{em} = T_{em} \times \omega_m = \frac{3}{2}[e_d i_{ds} + e_q i_{qs} + e_0 i_{0s}], \qquad (9)$$

Where the indexes d, q, 0 represent the variables in d-axis, q-axis and zero-sequence, and ω_m is the mechanical rotor speed. It should be noted that in PMSMs, the instantaneous values of e_d and e_q are constant at any speed, but in the non-ideal PMBL motors the values of e_d and e_q at any fixed speed are varying. Fig. 11 shows the waveforms of phase back-EMF voltages and corresponding e_d and e_q components of a PMSM and non-ideal PMBL motor. At steady state, the values of e_d and e_q are quite constant in PMSM while for non-ideal PMBL motor, they have some oscillation due to higher harmonics of back-EMF voltages.



(a)



(b)

Fig. 11. THE VARIATIONS OF DQ COMPONENTS OF BACK-EMF VOLTAGES (e_d and e_q) DURING ACCELERATION TILL RATED SPEED (a) PMSM, (b) NON-IDEAL PMBL MOTOR

To develop the desired torque with minimum current of the stator, the reference value of i_{ds} is set to zero at region lower than rated speed. The zero-sequence current i_{0s} is also set to zero in balance system. Hence, by using the reference torque from speed controller, the reference value of i_{qs} with having e_q (calculated from park transform of the phases' back-EMF voltages) is obtained from:

$$i_{qs}^{*} = \frac{2\omega_m}{3}\frac{1}{e_q} \times T_{em}^{*}\,, \tag{10}$$

Unlike the vector control method for PMSMs witch i_{qs}^{*} is constant, even under constant load in a fixed speed. Although at speeds higher than rated speed, that the flux-weakening is required, the reference value of i_{ds} is non-zero and is adjusted due to operational speed. So, the reference value of i_{qs} used in (8) is calculated from:

$$P_{em} = T_{em} \times \omega_m = \frac{3}{2}[e_d i_{ds} + e_q i_{qs} + e_0 i_{0s}], \tag{11}$$

Fig. 12 shows the block diagram of pseudo vector control system of the non-ideal PMBL motor. This system is very similar to conventional vector control shown in Fig. 9 It should be noted that the dq reference frame is utilized only for calculating these reference currents, while the phase current control is normally used in abc reference frame. Fig. 13 shows the simulation results of non-ideal PMBL motor drive by using pseudo vector control method. The current of phase 'a' has well followed its reference value. Also, the value of torque ripple is about 3.75 N.m or 25%. Hence it is seen that torque ripple has been significantly reduced rather than to other pervious methods that are often dedicated to BLDCMs and PMSMs.

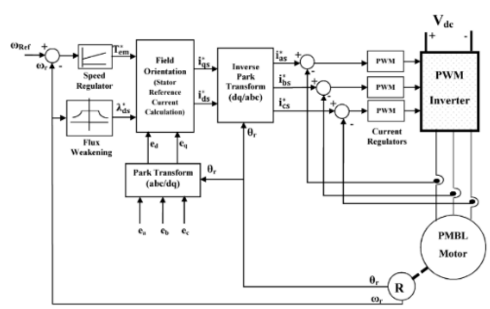


Fig. 12. THE BLOCK DIAGRAM OF NON-IDEAL PMBL MOTOR DRIVE BY PSEUDO VECTOR CONTROL METHOD

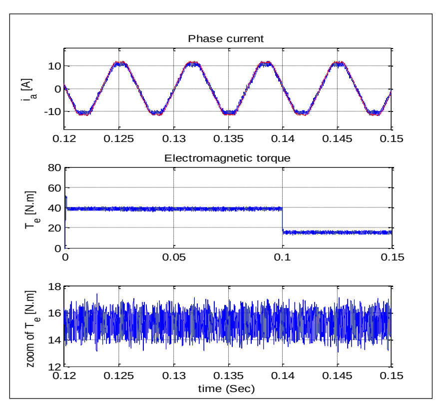


FIG. 13. SIMULATION RESULTS OF PSEUDO VECTOR CONTROL FOR NON-IDEAL PMBL MOTOR

4. SELECTIVE TORQUE HARMONIC ELIMINATION USING ONE CYCLE CONTROL STRATEGY

According to previous section, back-EMF voltage's harmonics should be considered to have suitable torque response. OCC based current control comparing to other control methods, has the following main features: (1) fast dynamic response due to embedded inner current loop in the PWM modulator, (2) simple circuit, and (3) synchronized turn-on time that is suitable for soft switching. OCC is a simple control strategy that has advantages of both PI and hysteresis controllers. As follows, the torque ripple minimization of non-ideal PMBL motor is investigated using selective torque harmonic elimination method in accompany with one cycle control strategy.

4.1. Selective Torque Harmonic Elimination Method For Non-Ideal PMBL Motor

It is possible to remove some arbitrary harmonics of torque waveform by injecting of the suitable reference current. This method has been applied for the BLDC motors and is called selective torque harmonic elimination or harmonic current injection [23, 24]. This method is briefly expressed for non-ideal PMBL motor with phase back-EMF voltage shown in Fig. 1c that contains the harmonics of order h=1,3,5 and 7. Suppose that phase back-EMF voltage of phase 'a' can be rewritten as:

$$e_a(t) = E_1\sin\omega t + E_3\sin 3\omega t + E_5\sin 5\omega t + E_7\sin 7\omega t + ... \tag{12}$$

And the current in phase 'a' is also considered as:

$$i_a(t) = I_1\sin\omega t + I_3\sin 3\omega t + I_5\sin 5\omega t + I_7\sin 7\omega t + \ldots, \tag{13}$$

Thus instantaneous air-gap power of phase 'a' includes an average component and higher order harmonics as:

$$P_a(t) = e_a i_a = P_0 + P_2\sin 2\omega t + P_4\sin 4\omega t + P_6\sin 6\omega t + \ldots, \tag{14}$$

Two phases 'b' and 'c' have the phase shift -120^o and +120^o degrees relative to phase 'a' respectively. So, the total air-gap power will contain an average component and only harmonics of order multiple of six as:

$$P_g(t) = P_0 + P_6\sin 6\omega t + P_{12}\sin 12\omega t + P_{18}\sin 18\omega t + \ldots, \tag{15}$$

$$T_{em}(t) = \frac{P_g}{\omega_m} = T_0 + T_6\sin 6\omega t + T_{12}\sin 12\omega t + T_{18}\sin 18\omega t + \ldots \tag{16}$$

$$T_0 = \frac{3}{2\omega_m}[E_1 I_1 + E_5 I_5 + E_7 I_7] \tag{17}$$

Since the torque is proportional to the product of the counter EMF and the feed current, it is possible to determine an appropriate combination of e and i that reduce the torque ripple to a minimum value for a given average torque T_0. Since, for the given PMBL motor, there are no higher order harmonics than harmonic of order 7 in phase back-EMF voltage waveform, creating harmonic currents with higher order than 7 will be only caused more stator copper losses. Also, the third harmonic of the current doesn't essentially involve in the torque production. Therefore, only the harmonic orders 5 and 7 (I_5, I_7) of phase current are added to fundamental harmonic in which the most important torque harmonics T_6 and T_{12} are cancelled out. So, by solving of following algebraic equation:

$$\begin{bmatrix} E_1 & E_5 & E_7 \\ E_7 - E_5 & -E_1 & E_1 \\ 0 & E_7 & E_5 \end{bmatrix} \times \begin{bmatrix} I_1 \\ I_5 \\ I_7 \end{bmatrix} = \frac{2\omega_r}{3}\begin{bmatrix} T_0 \\ 0 \\ 0 \end{bmatrix} \tag{18}$$

And for given values E_1=100%, E_5=20% and E_7=13%, the feed current harmonics are obtained from:

$$\begin{bmatrix} I_1 \\ I_5 \\ I_7 \end{bmatrix} = \begin{bmatrix} 1.0063 \\ -0.047 \\ 0.0235 \end{bmatrix} \frac{2\omega_r}{3} T_1 \tag{19}$$

By applying three-phase reference currents with the first, fifth and seventh harmonic, the torque ripple due to harmonics of phase back-EMF voltage will be exactly cancelled.

4.2. One Cycle Control Strategy

One-cycle control (OCC) strategy has been widely used in dc-dc conversion and power amplifier [25], and etc. Also, it has been used in electrical drives of induction motors [26, 27], PM synchronous generators [13] and lately in BLDC motor drive [28]. Fig. 15 shows the block diagram of non-ideal PMBL motor drive controlled by selective torque harmonics elimination using one cycle control strategy. Fig. 16 shows the simulation results of motor behavior by this method. The torque ripple value shows a significant improvement rather than all previous methods.

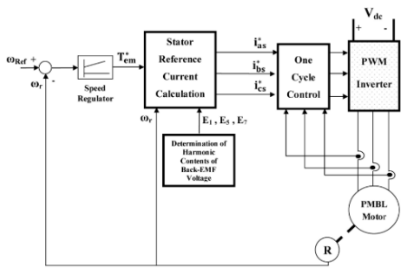


Fig. 15. The Block Diagram Of Non-Ideal Pmbl Motor Drive By Selective Torque Harmonic Method Using One Cycle Control Strategy

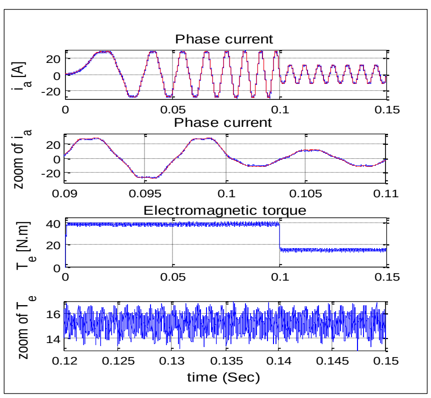


Fig. 16. Simulation Results Of Selective Torque Harmonic Method Using One Cycle Control Strategy For Non-Ideal Pmbl Motor

5. COMPARISON OF SIMULATION RESULTS

In previous sections, the various control methods have been evaluated and applied to a non-ideal PMBL motor for closed-loop speed control. For a better comparison of simulation results, the ratio values of peak-to-peak torque ripple to average torque at rated speed and under rated load torque 15 N.m are summarized in Table 2. Moreover, FFT analysis of electromagnetic torque have been carried out in MATLAB software for four superior control methods that are three-phase quasi-square current control, vector control, pseudo vector control and control by selective harmonic elimination using OCC strategy. The results are given in Table 3. Both results indicate that the selective torque harmonic elimination using OCC have a more appropriate response than other methods. In all performed simulations (except to DTC method) the current-controlled voltage source inverter has been used.

TABLE 2. Comparison Of Relative Torque Ripple Of Non-Ideal Pmbl Motor By Using Different Control Methods Under Rated Load

Control method	Torque ripple
Quasi-square current control with dc link current regulation	66%
Quasi-square current control with three-phase current regulation	46%
Direct torque control	80%
Vector control	40%
Pseudo vector control	25%
Selective torque harmonic elimination using OCC	16%

TABLE 3. Comparison Of FFT Analysis Of Developed Torque By Using Four Superior Methods

Control method	THD of torque
Quasi-square current control with three-phase current regulation	11.3%
Vector control	9%
Pseudo vector control	7%
Selective torque harmonic elimination using OCC	6%

6. Conclusion

In this paper, to reduce the torque ripple caused by non-ideal phase back-EMF voltages of a permanent magnet brushless (PMBL) motor, various control methods of PMSMs and BLDCMs have been studied and simulated. The simulation results show that for a non-ideal PMBL motor, the methods based on three-phase feeding methods are more effective to minimize the torque ripple than two-phase feeding methods. Moreover, to reduce or cancel the torque ripple due to harmonics of back-EMF voltages, the reference currents of *dq* components of stator currents should be adapted with variations of *dq* components of back-EMF voltages. The best torque response was achieved via selective torque harmonic elimination method, in which it is capable to cancel out or minimize the torque ripple by adding certain harmonics of the current. For current regulation of phases, three current controller based on one cycle control strategy were used that leads to zero error of the current. It enjoys all advantages of hysteresis and PI current controllers. The main point for using the lasted method is that the harmonic contents of phase back-EMF voltages should be known. If the harmonic content varies at different speed, it should be considered to calculate of reference current. On this way, an observer may be designed to estimate the phase back-EMF voltages as well as the rotor position and speed to have a sensor less PMBL motor drive with minimum torque ripple.

7. REFERENCES

[1] R. Krishnan, 2002. "Permanent-Magnet Synchronous and Brushless DC Motor Drives", ***John-Willey Press***.

[2] J.F. Gieras, and M. Wing,. 2002. "Permanent Magnet Motor Technology: Design and Applications, Second Edition", ***Marcel Dekker, Inc***.

[3] D.C. Hanselman,. 2006. "Brushless Permanent-Magnet Motor Design", ***Magna Physics Publishing***.

[4] E. Klintberg. 2013. "Comparison of Control Approaches for Permanent Magnet Motors", ***Master of Science Thesis, Department of Energy and Environment, Chalmers University of Technology, G¨oteborg, Sweden***.

[5] P.L. Chapman, S.D. Sudhoff, and C.A. Whitcomb,. 1999. "Multiple reference frame analysis of non-sinusoidal brushless DC drives", ***IEEE Trans. on Energy Conversion***, vol. 14(3), P: 440–446.

[6] T.M. Jahns, and W.L. Soong,. 1996. "Pulsating Torque Minimization Techniques for Permanent Magnet AC Motor Drives-A Review", ***IEEE Trans. on Industrial Electronics***, vol. 43(2), P: 321-330.

[7] N'diaye, C. Espanet, and A. Miraoui,. 2004, "Reduction of the torque ripples in brushless PM motors by optimization of the supply-Theoretical method and experimental implementation", ***IEEE International Symposium on Industrial Electronics***, P: 1345-1350**.**

[8] D. Grenier, and L.A. Dessaint,. 1995. "A Park-like Transformation for the Study and the Control of a Non-Sinusoidal Brushless DC Motor", ***IEEE Industrial Electronics, Control, and Instrumentation Conf. (IECON)***, P: 837-843.

[9] H. Lei, and H.A. Toliyat, 2003. "BLDC motor full speed range operation including the flux-weakening region", ***IEEE Industry Applications Conf***, vol. 1, P: 618-624.

[10] B. K. Lee, B. Fahimi, and M. Ehsani,. 2001. "Dynamic Modeling of Brushless DC Motor Drives", ***Proceedings of the European Conference on Power Electronics and Applications (EPE),*** 2001.

[11] P. Pillay, and R. Krishnan., 1989. "Modeling, simulation, and analysis of permanent-magnet motor drives. II. The brushless DC motor drive", ***IEEE Trans. on Industry Applications***, vol. 25(2), P: 274-279.

[12] G.H. Kim, S.J. Kang, and J.S. Won,. 1992. "Analysis of the commutation torque ripple effect for BLDCM fed by HCRPWM-VSI", ***Proceedings of the IEEE Applied Power Electronics Conference and Exposition (APEC)***, P: 277-284.

[13] ABB Technical Note: Motor Control with DTC, ***TD1 EN Rev. B***, 2007.

[14] S.B. Ozturk, and H.A. Toliyat,. 2011. "Direct Torque and Indirect Flux Control of Brushless DC Motor***", IEEE/ASME Trans. on Mechatronics***, Vol. 16(2), P: 351-360.

[15] Y. Liu, Z.Q. Zhu, and D. Howe,. 2005. "Direct torque control of brushless DC drives with reduced torque ripple", ***IEEE Trans. on Industry Applications***, vol. 41(2), P: 599-608.

[16] G.R. Arab Markadeh, S.I. Mousavi ,S. Abazari, and A. Kargar,. 2008. "Position Sensorless Direct Torque Control of BLDC Motor***, IEEE International Conf. on Industrial Technology***, P: 1-6.

[17] S. B. Ozturk, and H.A. Toliyat,. 2007. "Direct Torque Control of Brushless DC Motor with Non-sinusoidal Back-EMF", ***IEEE International Electric Machines & Drives Conference, IEMDC '07***, P: 165-171.

[18] Freescale Semiconductor: Sensorless PM Sinusoidal Motor Vector Control on MCF51AC256, ***Rev.0, Report DRM109***, 04/2009.

[19] Lidozzi, L. Solero, F. Crescimbini and R. Burgos,. 2008. "Vector Control of Trapezoidal Back-EMF PM Machines Using Pseudo-Park Transformation", ***IEEE Power Electronics Specialists Conference, PESC.*** P: 2167-2171.

[20] Oliveira, Jr. J. R. B. de A. Monteiro, M. L. Aguiar, and D. P. Gonzaga,. 2005. "Extended DQ Transformation for Vectorial Control Applications of Non-sinusoidal Permanent Magnet Synchronous Machines", ***IEEE Power Electronics Specialists Conference***, P: 1807-1812.

[21] F. Bonvin, and Y. Perriard,. 2000. "BLDC motor control in multiple dq axes - Power Electronics and Variable Speed Drives", ***International Conference on IEE***, P: 500-505.

[22] S. Bolognani, L. Tubina, and M. Ziliotto,. 2003. "Sensor less control of PM synchronous motors with non-sinusoidal back EMF for home appliance", ***IEEE Electric Machines and Drives Conference***, P: 1882-1888.

[23] J.Y. Hung, and Z. Ding,. 1993. "Design of currents to reduce torque ripple in brushless permanent magnet motors", ***IEE Proceedings B Electric Power Applications***, vol. 140(4), P: 260-263.

[24] N'diaye, C. Espanet, and A. Miraoui,. 2004. "Reduction of the torque ripples in brushless PM motors by optimization of the supply - Theoretical method and experimental implementation", ***IEEE International Symposium on Industrial Electronics***, pp. 1345-1350.

[25] K.M. Smedley and S. Cuk, 1995. "One-cycle control of switching converters", ***IEEE Transactions on Power Electronics***, Vol. 10(6), P: 625-633.

[26] A.S. Lock, E.R. da Silva, and M.E. Elbuluk,. 2012. "Torque control of induction motor drives based on One-Cycle Control method", ***Proc. IEEE Industry Applications Society Annual Meeting (IAS)***, P: 1-8.

[27] W. Song, K.M. Smedley, and F. Xiaoyun, 2011. "One-cycle Control of induction machine traction drive for high speed railway part II: Square wave modulation region", ***Proc. IEEE Applied Power Electronics Conference and Exposition (APEC)***, P: 1003-1009.

[28] Halvaei Niasar, and E. Boloor Kashani,. 2014. "Implementation of a Novel Brushless DC Motor Drive based on One-Cycle Control Strategy", ***Iranian Journal of Electrical and Electronic Engineering***, vol. 10(3), P: 244-249.