Modified Direct Torque Control System of Five Phase Induction Motor

Namhun Kim† and Minhuei Kim*

Abstract – In this paper, improved direct torque control(DTC) of five-phase induction motor(IM) is proposed. Due to the additional degrees of freedom, five-phase IM drives present unique characteristics. One of them is the ability of enhancing the torque producing capability of the motor. Also five-phase motor drives possess many others advantage compared with the traditional three-phase motor drives. Such as, reducing the amplitude and increasing of frequency of torque pulsation, reducing amplitude of current per phase without increasing the voltage per phase and increasing the reliability. The direct torque control method is advantageous when it is applied to the five-phase IM. Because the five-phase inverter provides 32 space vectors in comparison to 8 space voltage vectors by the three-phase inverter. The 32 space voltage vectors are divided into three groups according to their magnitudes. The characteristics and dynamic performance of traditional five-phase DTC are analyzed and new DTC for five-phase IM is proposed. Therefore, a more precise flux and torque control algorithm for the five-phase IM drives can be suggested and explained. For presenting the superior performance of the proposed direct torque control, experimental results is presented using a 32 bit fixed point TMS320F2812 digital signal processor

Keywords: Direct torque control, Five phase motor, Induction motor, DTC

1. Introduction

In recent years, multi-phase induction motor, five phase, six phase, seven phase motor and so on, has attracted many researcher and is gaining interest at a viable alternative solution to three-phase induction motor system for hybrid electrical vehicle, aircraft and ship propulsion application.

Compared with conventional three-phase induction motors, the used five-phase induction motor in this paper has two significant differences in the view of its structure and input current profiles. First, concentrated windings, instead of sinusoidal winding, are adapted. Second, the third harmonic current component is introduced into the motor currents. As a result, almost rectangular waveform back Electro electromotive force (EMF) is obtained. This not only results in improved iron utilization and higher power density, but also increase the output torque by about 15% for the same amount of copper and iron as in an equivalent three-phase induction motor which has sinusoidal back EMF[1].

The multi-phase motor drive has several advantages compared with conventional three-phase motor drive such as reducing amplitude of torque and current pulsation, increasing the frequency of torque pulsation, reducing the stator current per phase without increasing the stator voltage per phase, lowering the DC link current harmonics and higher reliability and fault tolerance. By increasing number of stator phase it make motor increasing the torque per current of the same volume machines [2, 3, 4, 5]. Due to the abundance of voltage vectors in the multi-phase drive system, steady-state torque and current ripple performance showed considerable improvement over comparable three-phase drives.

For AC motor control, a vector control and direct torque control(DTC) method have been widely used. The DTC method has been gaining more popularity because of its profits due to its exceptional dynamic response and less dependence on machine parameters [6, 7]. Basically, DTC method is based on the instantaneous space vector theory. By optimal selection of the space voltage sectors in each sampling period, the DTC achieves effective control of the stator flux and torque. Thus, the number of space voltage vectors and switching frequency directly influence the performance of DTC control system.

The drawback of a DTC system is high torque and flux ripple. The reason of this disadvantage is that inverter keeps the same switching state as long as the outputs of flux or torque hysteresis controllers keep unchanging. Variable switching frequency is also another disadvantage. In a direct torque controlled drive, the switching frequency varies with speed, load torque, and bandwidth of flux and torque hysteresis controllers. Recently, research has been done on reducing the flux and torque ripple of DTC scheme by employing multilevel inverter which provides more voltage space vectors for controlling the flux and torque [8, 9].

In order to reduce torque ripple instead of DTC look-up table new methods is proposed. Also this proposed control method further can add third harmonic component to maximize output torque. To verify the proposed algorithms, a five-phase inverter system using two three-phase IGBT modules as Fig. 1 and a TMS320C2812 DSP. TMS320C2812

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Received 17 March 2008; Accepted 14 May 2009

have 12 pulse width modulation(PWM) channels and 12 bit on-chip ADC(Analog to digital converter)

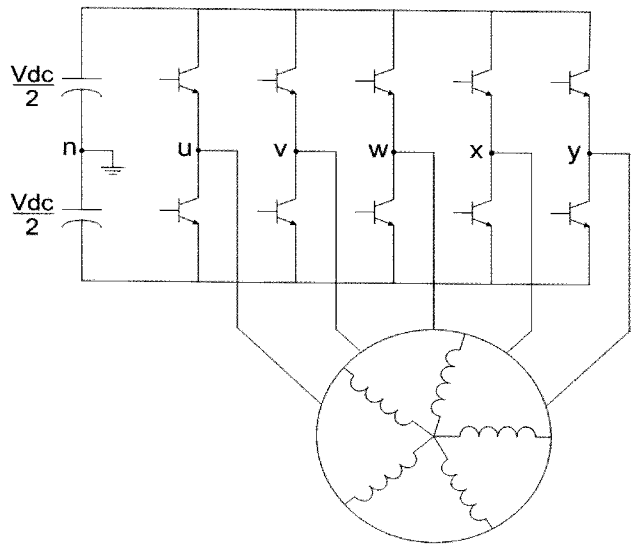
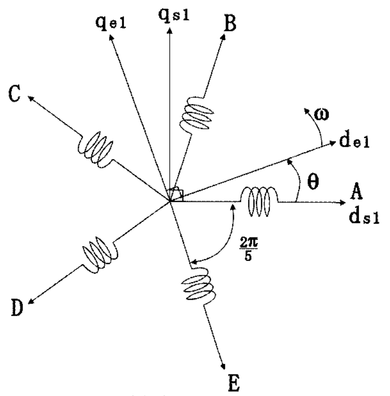


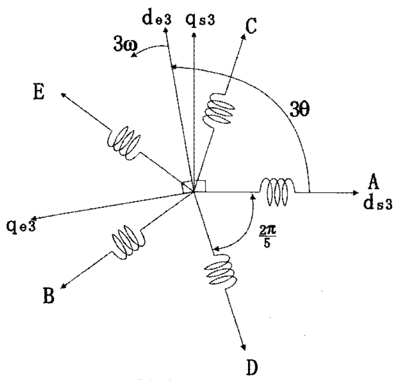
Fig. 1. Five-phase motor drive circuit

2. Five-Phase Motor

The mathematical model of five-phase induction motor in rotational(dq) and stationary($\alpha\beta$) reference frames will be derived.



(a) d1-q1 frame



(b) d3-q3 frame

Fig. 2. The vector diagram of five-phase induction motor

For three-phase motor, fundamental component and all the $6k \pm 1$ ($k = 1,2,3...$) harmonics of three-phase variables are applied to produce a rotating magnetomotive force (MMF) and torque (harmonics produce a torque pulsation). The harmonics $6k \pm 3$ ($k = 1,2,3...$) current corresponding to zero-sequence component are imposed onto the phase current and lead to current deformation and extra copper loss in the motor[11].

Likewise in five-phase motor system, 5-dimensional machine variables can be transformed into $d_1 - q_1$ and $d_3 - q_3$ reference frame and zero sequence variable [10].

The fundamental component and the harmonics of order $10k \pm 1$ ($k = 1,2,3...$) are applied on the $d_1 - q_1$ frame circuit in Fig. 2(a) to produce a rotating MMF and torque (harmonics produce torque pulsation). The harmonics of order $10k \pm 3$ ($k = 1,2,3...$) which are applied onto the remaining $d_3 - q_3$ frame in Fig.2(b). These components can be represented by the following complex space vector on a stationary and rotational reference frame.

$$f_{\alpha\beta 1} = \frac{2}{5}(f_{us} + a_5 f_{vs} + a_5^2 f_{ws} + a_5^3 f_{xs} + a_5^4 f_{ys}) = f_{\alpha 1} + jf_{\beta 1} \quad (1)$$

$$f_{\alpha\beta 3} = \frac{2}{5}(f_{us} + a_5 f_{vs} + a_5^2 f_{ws} + a_5^3 f_{xs} + a_5^4 f_{ys}) = f_{\alpha 3} + jf_{\beta 3} \quad (2)$$

where, $\alpha_5 = \exp(j2\pi/5)$.

The number of subscripts used to differentiate two-spaces means the lowest order among the harmonics equivalently transformed to each space because it is most domestic component of these harmonics. From eq. (1) and (2), the space vectors are synchronously rotation with the frequency of ω and 3ω respectively can be defined as below;

$$f_{dq1} = f_{\alpha\beta 1} \cdot e^{-j\theta} = f_{d1} + jf_{q1} \quad (3)$$

$$f_{dq3} = f_{\alpha\beta 3} \cdot e^{-j3\theta} = f_{d3} + jf_{q3} \quad (4)$$

Using the space vectors of (3) and (4), the fundamental and third harmonics of five-phase variables can be regarded as dc components.

By eq. (1)-(4), voltage equation, as described in stationary and rotational reference frame, can be expressed as following equation in $d_1 - q_1$ and $d_3 - q_3$ reference frame.

$$\begin{bmatrix} v_{\alpha 1} \\ v_{\beta 1} \\ v_{\alpha 3} \\ v_{\beta 3} \end{bmatrix} = \frac{2}{5} \begin{bmatrix} 1 & \cos(\frac{2\pi}{5}) & \cos(\frac{4\pi}{5}) & \cos(\frac{4\pi}{5}) & \cos(\frac{2\pi}{5}) \\ 0 & \sin(\frac{2\pi}{5}) & \sin(\frac{4\pi}{5}) & -\sin(\frac{4\pi}{5}) & -\sin(\frac{2\pi}{5}) \\ 1 & \cos(\frac{6\pi}{5}) & \cos(\frac{2\pi}{5}) & \cos(\frac{2\pi}{5}) & \cos(\frac{6\pi}{5}) \\ 0 & \sin(\frac{6\pi}{5}) & \sin(\frac{2\pi}{5}) & -\sin(\frac{2\pi}{5}) & -\sin(\frac{6\pi}{5}) \end{bmatrix} \begin{bmatrix} v_u \\ v_v \\ v_w \\ v_x \\ v_y \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} v_{d1} \\ v_{q1} \\ v_{d3} \\ v_{q3} \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) & 0 & 0 \\ -\sin(\theta) & \cos(\theta) & 0 & 0 \\ 0 & 0 & \cos(3\theta) & \sin(3\theta) \\ 0 & 0 & -\sin(3\theta) & \cos(3\theta) \end{bmatrix} \begin{bmatrix} v_{\alpha 1} \\ v_{\beta 1} \\ v_{\alpha 3} \\ v_{\beta 3} \end{bmatrix} \quad (6)$$

The electromagnetic torque can be found using the well known magnetic co-energy method as follows.

$$T_{em} = \frac{\partial W_{co}}{\partial \theta_r} \tag{7}$$

It is easy to simplify this equation as

$$\begin{aligned} T_{em} &= \frac{5}{2}\frac{P}{2}(\lambda_d i_q - \lambda_q i_d) \\ &= \frac{5}{2}\frac{P}{2}(\lambda_\alpha i_\beta - \lambda_\beta i_\alpha) \end{aligned} \tag{8}$$

Where, ***P*** is the number of poles.

3. Classic DTC and Proposed DTC

The text must include a citation of each figure and table. Letters in the figure should be large enough to be readily legible when the drawing is reduced. Do not forget to include the label, unit for each axis and the legend when they are required.

Direct torque control(DTC) method produce instantaneous torque control yielding fast torque response and very fast reversing operation. It is theoretically based on the principle of field-oriented control AC motors. The main feature for DTC is that it does not need PWM controller for current control. In such a drive, flux linkage and electromagnetic torque are controlled directly and independently by the selection of optimum inverter switching vectors.

For five-phase IM drives, as shown in figure 2, there are totally thirty active switching vectors and two zero switching vector. All this active switching vectors are divided three groups that are maximum vector, medium vector and minimum vectors. The only difference among the three groups is the length of the sides. The ratio of the amplitudes is $1{:}1.618{:}1.618^2$ from minimum one to maximum one respectively[12]. Therefore, for minimizing the switching loss it is better to use minimum group. The other two groups are being used when finer adjustment of the stator flux and torque are needed. Position information of the stator flux linkages space vector is needed to define the required sector. The proper voltage vector should be applied based on the stator flux and torque errors with respect to their reference values.

For example, suppose that the stator flux linkages vector is in the first sector (Fig. 3) and only the maximum group is considered. Now if the flux has to be increased (FI) and the electromagnetic torque has to be positive (TP), then the switching voltage vector to be selected is V2. On the other hand, if the stator flux linkage has to be increased (FI) and the electromagnetic torque need to be negative (TN), then vector V10 has to be selected. The voltage vectors located on the other two decagons have similar effects with respect to the larger decagon.

The text must include a citation of each figure and table. Letters in the figure should be large enough to be readily legible when the drawing is reduced. Do not forget to include the label, unit for each axis and the legend when they are required.

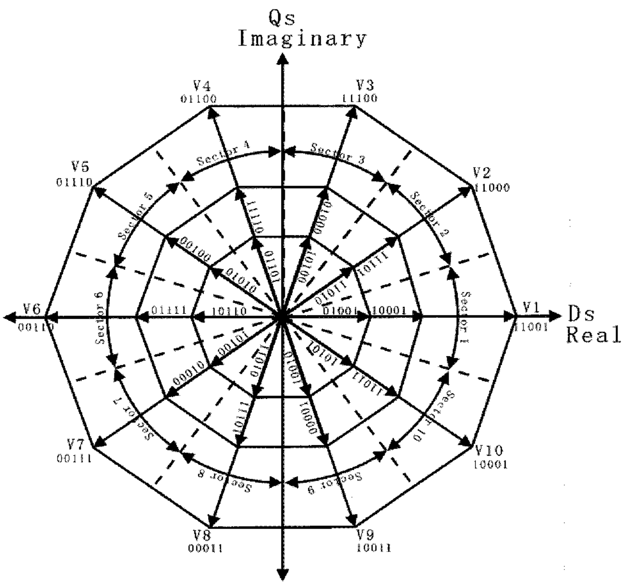


Fig. 3. Switching vectors for the five-phase induction motor drive.

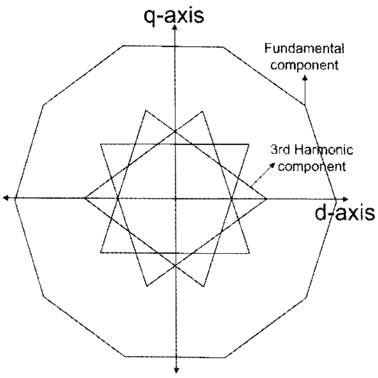
Table 1. Optimum active voltage vector look-up table.

dψ	dt	Sector1	Sector2	Sector3	Sector4	Sector 5	Sector 6	Sector 7	Sector 8	Sector 9	Sector 10
1	1	V2,V12, V22	V3,V13, V23	V4,V14, V24	V5, V15, V25	V6, V16, V26	V7, V17, V27	V8, V18, V28	V9, V19, V29	V10, V20, V30	V1, V11, V21
1	-1	V10,V20, V30	V1,V11, V21	V2,V12, V22	V3, V13, V23	V4, V14, V24	V5, V15, V25	V6, V16, V26	V7, V17, V27	V8, V18, V28	V9, V19, V29
-1	1	V5,V15, V25	V6, V16, V26	V7, V17, V27	V8, V18, V28	V9, V19, V29	V10, V20, V30	V1, V11, V21	V2, V12, V22	V3, V13, V23	V4, V14, V24
-1	-1	V7,V17, V27	V8,V18, V28	V9,V19, V29	V10, V20, V30	V1, V11, V21	V2, V12, V22	V3, V13, V23	V4, V14, V24	V5, V15, V25	V6, V16, V26

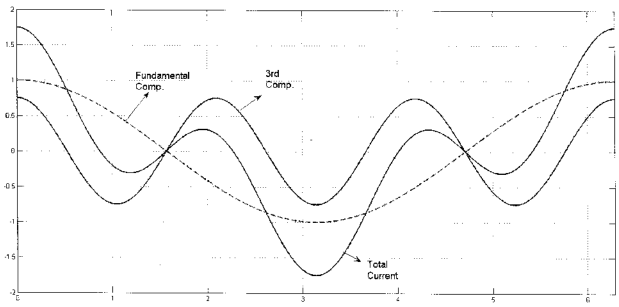
Based on the above, the increased number of space voltage vectors allows the generation of a more elaborate switching vector table in which the selection of the voltage vectors is made according to real-time variation of the stator flux and torque. Moreover, the different amplitudes of voltage vectors provide increased possibility to minimize the ripple in the stator flux and torque. Table 1 shows the optimum switching voltage vector look-up table. In this table, $d\psi = 1$ stands for FI, $d\psi = -1$ for FD, dTe = 1 for TP, and dTe = -1 for TN.

Above mentioned, five-phase motor has equivalent circuits as Fig. 2 and the harmonics component will deform current waveform. Let's suppose to what happens if a single pair of vectors plus harmonics component are used to produce the reference with a circular locus in $d_1 - q_1$

plane. In figure 4(a), the corresponding space vector locus is plotted in the dq_1 and dq_3 frame. The locus shape of dq_3 frame indicates the 3rd harmonics. In the time domain, the 3rd voltage harmonics will superpose onto the fundamental component in $d_1 - q_1$ frame and the phase current will thus be deformed. Since the fundamental voltage and 3rd harmonic voltages apply to different equivalent circuits, the harmonic current will have a different phase shift.



(a)



(b)

Fig. 4. Five phase space vector locus in dq1 and dq3 frame, and corresponding current waveform

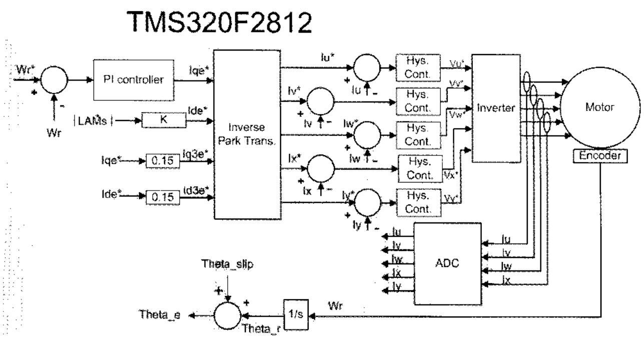


Fig. 5. System configuration of proposed DTC

Also the small impedance without back EMF terms in $d_3 - q_3$ frame circuit induces large magnitude harmonic current which is almost comparable to that of the fundamental, as figure 4(b), so elimination of this harmonics component is necessary from voltage signal, but it is almost impossible to reduce and inject 3rd harmonic component using classic DTC method.

4. Experimental Results

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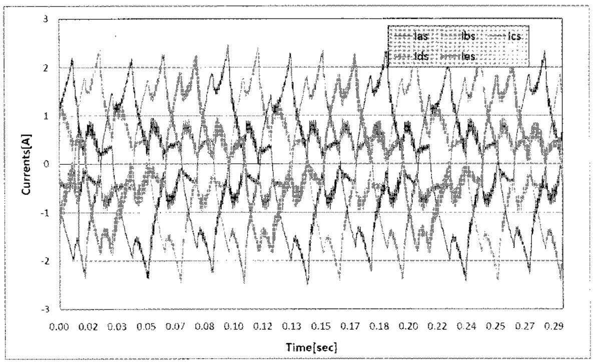
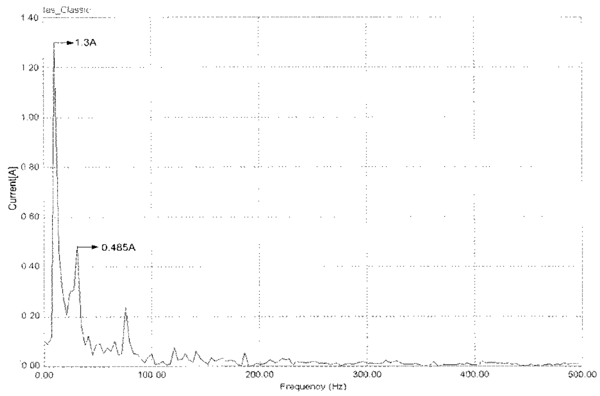
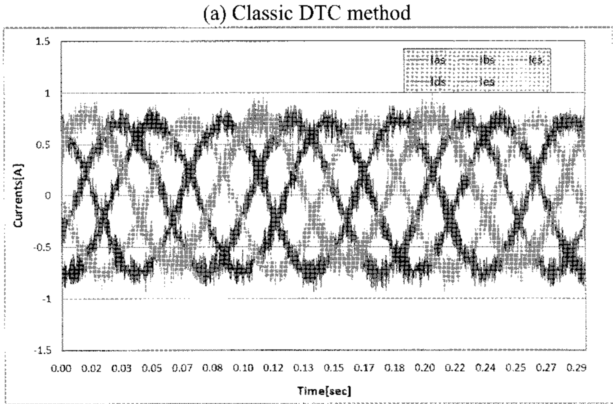
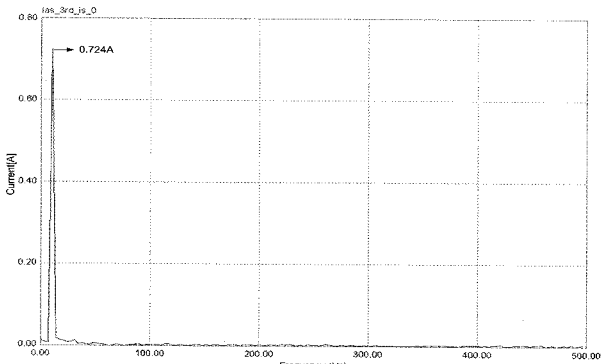
Figure 6(a) shows phase current waveforms and FFT results using look-up table DTC. There is remarkable current distortion because of 3rd harmonic voltage component. Figure 6(b) and 6(c) presents phase current waveform without 3rd harmonic currents control, with 3rd harmonic currents control using proposed DTC. As we can see from FFT results, the case of classic DTC contain that fundamental current is 1.3A and 3rd harmonic current is 0.457A. This outstanding 3rd harmonic component cause acoustic noise and torque pulsation. But the proposed method can control 3rd harmonic current, also suppress acoustic noise and torque pulsation.



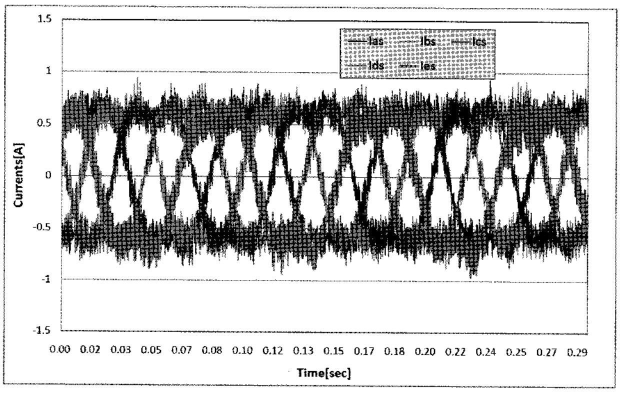


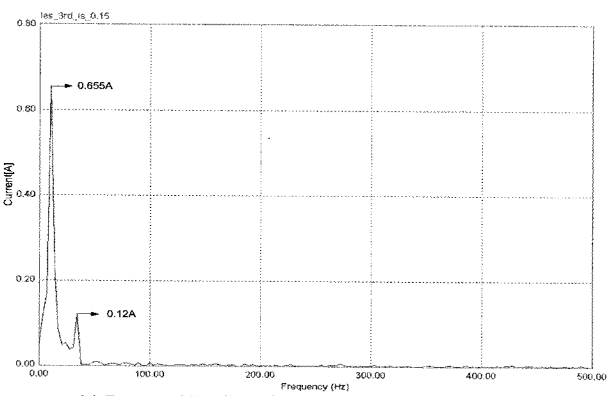
(a) Classic DTC method





(b) Proposed DTC method without 3rd harmonic current





(c) Proposed DTC method with 3rd harmonic current

Fig. 6. Phase current waveform and FFT result using

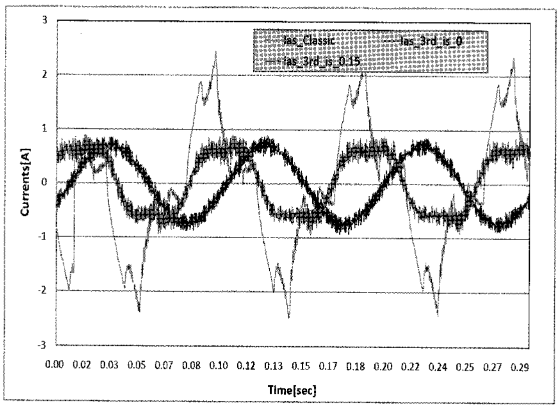
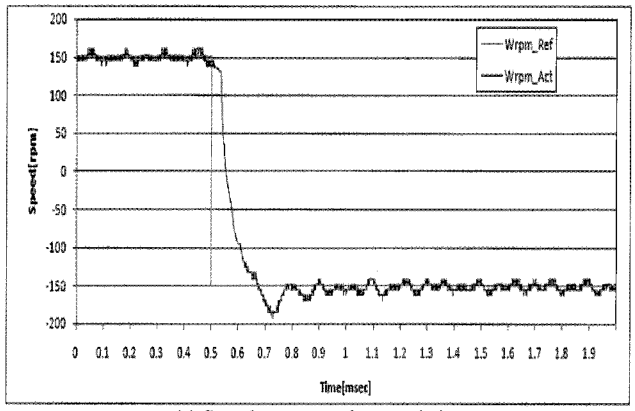
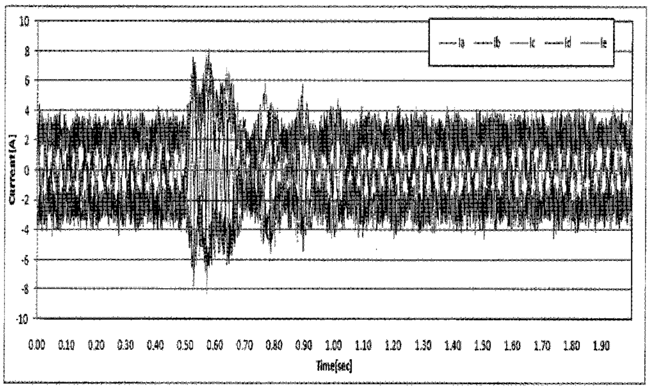


Fig.7. Phase current comparison of classic DTC and proposed DTC

Fig. 7 show phase current comparison of classic DTC with proposed DTC. In order to get same speed, classic DTC need 2.4A and the proposed DTC need just 0.65A. Fig. 8 presents speed control characteristics of the suggested system during low speed region, Fig. 8(a) is speed response characteristics from 150[rpm] to -150[rpm] and Fig. 8(b) is phase current waveform. From experimental results the suggest system have less current harmonic and good dynamic response compare with classic DTC



(a) Speed response characteristics



(b) Phase currents

Fig. 8. Speed control characteristics of the suggested system

5. Conclusion

Five-phase induction motors, which have rectangular back EMF using look-up table DTC method suffer from two drawbacks. The first problem is the larger torque ripple when digital hysteresis implementation is used. The second is that it is almost impossible to inject 3rd harmonic current component for maximizing torque and these harmonic voltage causing 3rd harmonic current can be introduced by the lookup table DTC method. To address these issues, the inverse park transformation and hysteresis controller is extended into a 5-phase system to improve the steady-state performance. Specifically, this paper introduced new DTC schemes to cancel out all possible low frequency voltage harmonics. Detailed experimental results verify the effectiveness of the proposed DTC method in steady-state performance.

References

[1] H.M. Ryu, J.H. Kim, and S.K. Sul, "Analysis of Multiphase Space Vector Pulse-Width Modulation Based on Multiple d–q Spaces Concept," IEEE Trans. on. Power Electronics, vol. 20, No. 6, Nov. 2005

[2] H.A. Toliyat, and T.A. Lipo, "Analysis of a concentrated winding induction motor for adjustable speed drive applications-Motor designand performance," IEEE Trans. on Energy Conversion, Vol. 3. 64, Dec. 1991, pp. 684 -692.

[3] H.A. Toliyat, "Analysis and Simulation of Five-Phase Variable Speed Induction Motor Drives Under Asymmetrical Connections," IEEE Trans. on Power Electronics, Vol. 13, No. 4, pp. 748-756, July 1998.

[4] Huangsheng Xu, Hamid A. Toliyat "Five-phase Induction Motor Drives With DSP-Based control system" IEEE Trans on Power Electronics vol. 13, No.4, July 2002.

[5] H.A. Toliyat, M.M. Rahimian, and T.A. Lipo, "Analysis and modeling of five phase converters for adjustable speed drive applications," Proceedings of the 1993 European Conference on Power Electronics and Applications, Vol. 5, pp. 194 –199.

[6] G.S. Buja and M.P. Kazmierkowski, "Direct torque control of PWM inverter-fed AC motors-a survey," IEEE Trans. on Industrial Electronics, Vol. 51, No. 4, pp. 744-757, Aug. 2004.

[7] I. Takahashi and Y. Ohmori, "High-performance direct torque control of induction motor," IEEE Transactions on Industrial Applications, volume 25, number 2, pp. 257-264, 1989.

[8] Z. Tan, Y. Li, and M. Li, "A direct torque control of induction motor based on three-level inverter" IEEE PESC, Vol. 2, pp. 1435-1439. 2001.

[9] C. Martins, X. Roboam, T. A. Meynard, and A. S. Caryalho, "Switching Frequency Imposition and Ripple Reduction in DTC Drives by Using a Multilevel Converter," IEEE Trans. on Power Electronics, Vol. 17, pp. 286-297, Mar. 2002.

[10] H.A. Toliyat, "Analysis And Simulation of Five-Phase Variable-Speed Induction Motor Drives Under Asymmetrical Connections," IEEE Trans. on Power Electronics, Vol. 13, No.4, pp. 748-756, July 1998.

[11] D. W. Novotny and T. A. Lipo, "Vector Control and Dynamics of AC Drives." Oxford, UK: Oxford Univ. Press, 1996.

[12] L. Parsa and H.A. Toliyat, "Five-phase permanent magnet motor drives for ship propulsion applications," Electric Ship Technologies Symposium 2005 IEEE, pp. 371-378, July 2005.

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