An Improved Stator Flux Estimation in Steady State Operation for Direct Torque Control of Induction Machines

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Abstract- **The paper presents an improved stator flux estimation technique based on a voltage model with some form of low pass filtering. In voltage model-based of stator flux estimation, a low-pass (LP) filter is normally used instead of a pure integrator to avoid integration drift problem due to DC off-set, noise or measurement error present in the back electromotive force (emf). In steady state condition, the LP filter estimator will degrade the performance and efficiency of the direct torque control (DTC) drive system since it introduced magnitude and phase errors thus resulting in an incorrect voltage vector selection. The stator flux steady state error between the LP filter and a pure integrator estimator techniques is derived and its effect on the steady state DTC drive performance is analyzed. A simple method is proposed to compensate for this error which results in a significant improvement in the steady state drive performances. Simulation based on this technique is given and it is verified by experimental results.**

I. INTRODUCTION

An accurate flux estimation in high performance induction motor drive, be it field oriented or direct torque control, is important to ensure proper drive operation and stability. Most of the flux estimation techniques proposed is based on voltage model, current model, or the combination of both [1][2]. The estimation based on current model is normally applied at low frequency, and it requires the knowledge of the stator current and rotor mechanical speed or position. In some industrial applications, the use of incremental encoder to get the speed or position of the rotor is undesirable since it reduces the robustness and reliability of the drive. It has been widely known that even though the current model has managed to eliminate the sensitivity to the stator resistance variation, the use of rotor parameters in the estimation has introduced the sensitivity of the estimation to the rotor parameter variations, especially at high rotor speed [1,2,3]. The voltage model, on the other hand, is normally used in a high speed range since at low speed, some problems arise[3,4,5]. In practical implementation, even a small dc off-set present in the back emf due to noise or measurement error inherently present in the current sensor, can cause the integrator to saturate [4][5]. To overcome this, a low-pass filter is normally used in place of a pure integrator. The voltage model estimation does not require the knowledge of rotor speed, and the only motor parameter used is the stator resistance, which can be measured quite accurately. These can be considered as an advantage of the voltage model-based estimation over the current model-based estimation technique and is also the reason why the former is preferred over the latter in some industrial applications. However, the use of low pass filter in place of a pure integrator reduces the performance of the drive because of the phase and magnitude errors inherent in the LP filter as compared to the pure integrator, particularly at frequencies close to the cut-off. Attempts have been made to improve the estimated stator flux based on LP filter as given by [4]. The proposed method used an adaptive control system which was based on the fact that the back emf is orthogonal to the stator flux. The compensator is adapted for this condition. However, to implement the proposed system requires large processor resource and longer execution time for a slower processor. The implementation of adaptive control will significantly increase the complexity of the control system, hence will outweigh the property of simple control structure inherent in DTC. In this paper, a phase and magnitude compensation for the voltage model-based stator flux estimator with LP filter (which will be referred to as LP filter-based) is proposed. The proposed compensation method is very simple yet it can improve the steady state performance of a DTC drive significantly, particularly at a frequency close to or even smaller than the cut-off frequency. This compensation will extend the range of frequency that can be operated using the LP filter-based estimator.

The rest of the paper is organized as follows. Section II will compare the estimated stator flux based on the voltage model using the pure integrator and the LP filter. The effect of the phase and magnitude errors on the steady state drive performance are analyzed in section III. The proposed compensation method are described in section IV. Section V presents the simulation and experimental result and finally, the conclusions are given in section VI.

II. VOLTAGE MODEL-BASED ESTIMATOR

The stator flux estimation based on voltage model is determined from the stator voltage equation given by:

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$$\bar{v}_s = R_s \bar{i}_s + \frac{d\overline{\Psi}_s}{dt}$$

The stator flux is therefore can be written as:

$$\overline{\Psi}_s = \int (\bar{v} - \bar{i}_s R_s) dt \qquad (1)$$

Under sinusoidal steady state condition, this reduces to:

$$j\omega_e \overline{\Psi}_s = \overline{V}_s - \overline{I}_s R_s$$

$$\overline{\Psi}_s = \frac{\overline{V}_s - \overline{I}_s R}{j\omega_e} \qquad (2)$$

To avoid integration drift problem due to the dc off-set or measurement noise, a low-pass filter is normally used in place of the pure integrator. With a low-pass filter, equation (2) becomes:

$$\overline{\Psi}'_s = \frac{\overline{V}_s - \overline{I}_s R}{j\omega_e + \omega_c} \qquad (3)$$

Where ω_c is the cut-off frequency of the low-pass filter in rad/s and Ψ_s' is the estimated stator flux which is obviously not equal to Ψ_s of equation (2). For a synchronous frequency larger than the cut-off, equations (2) and (3) can be graphically visualized using a phasor diagram as shown in figure 1.

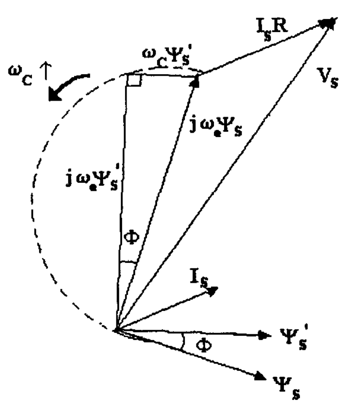


Fig. 1 Phasor diagram for steady state operation of induction machine showing the actual and estimated stator flux based on LP filter.

From equation (2) and (3),

$$j\omega_e \overline{\Psi}_s = j\omega_e \overline{\Psi}'_s + \omega_c \overline{\Psi}'_s$$

$$\overline{\Psi}_s = \overline{\Psi}'_s - j\frac{\omega_c}{\omega_e}\overline{\Psi}'_s \qquad (4)$$

As expected, when $\omega_e >> \omega_c$, the LP filter estimator approaches the pure integrator estimator.

Equation (3) can be written as :

$$\overline{\Psi}'_s = \frac{\overline{V}_s - \overline{I}_s R}{\omega^2_e + \omega^2_c}(\omega_c - j\omega_e) \qquad (5)$$

Substituting ($\overline{V}_s - \overline{I}_s R$) from (2) into (5),

$$\overline{\Psi}'_s = \frac{\overline{\Psi}_s}{\omega^2_e + \omega^2_c} j\omega_e(\omega_c - j\omega_e) \qquad (6)$$

If $\overline{\Psi}'_s = \Psi'_s \angle\theta'$ and $\overline{\Psi}_s = \Psi_s \angle\theta$, then (6) can be written as,

$$\frac{\Psi'_s}{\Psi_s}\angle\theta' - \theta = \frac{\omega_e}{\sqrt{\omega^2_e + \omega^2_c}}\angle\phi \qquad (7)$$

where

$$\phi = \pi/2 - \tan^{-1}(\omega_e/\omega_c)$$

When the cut-off frequency equal to that of the synchronous, the ratio of the estimated to the actual stator flux has a magnitude of $\frac{1}{\sqrt{2}}$ with an angle of π/4. A plot of the ratio of the estimated to the actual stator flux in dB and its corresponding phase difference in degree versus the synchronous speed with the cut-off frequency set to 10 rad/s is shown in figure 2. It can be seen that choosing an appropriate cut-off frequency for the LP filter estimator is very important for an optimum steady state operation, and this depends on the operating frequency. While it is good to set the cut-off frequency as low as possible so that the phase and magnitude errors are minimized, it must be noted that this will reduce the effectiveness of the LP filter-based estimator to filter out the dc offset present in the sensed currents or voltages, which is likely to be true. Choosing a cut-off frequency which is closer to the operating frequency, will reduce the dc offset in the estimated stator flux, which on the other hand will introduce phase and magnitude errors.

III. Effect Of Phase And Magnitude Errors On The DTC Drive Performance

In DTC, the selected voltage vector is based on the calculated or estimated stator flux and torque. The steady state behavior or performance of the DTC drive is influenced by the voltage vector selections [6,7]. As shown above, with the LP filter-based estimator, the magnitude and phase errors exist between the estimated and actual stator flux, which will definitely affect the voltage vector selections. In steady state, the estimated stator flux leads the actual stator flux by an angle given in equation (7). The amount of phase difference depends on the cut-off frequency as well as on the synchronous frequency which will result in an incorrect voltage vectors selected in a particular sector.

The incorrect voltage vectors selected for the actual flux will give a less-than-required radial influence to the flux locus. This occurs at the end of the sector of the actual stator flux or at the beginning of the sector of LP filter-based estimated stator flux. For example, Fig. 3 shows the estimated and actual stator flux in the stator flux plane, which are denoted by ψ'_s and ψ_s respectively. They are assumed to rotate in the counter-clockwise direction with the angle between them denoted by ϕ. Both the estimated and actual stator fluxes are in different sectors as the estimated flux enter a new sector – as shown in Fig. 3, the estimated stator flux is in sector 3 whereas the actual flux is still in sector 2. Accordingly, to increase the flux in sector 3, the controller will select voltage vector 010, however since the actual flux is in sector 2, this voltage vector will cause a decrement rather than increment in the actual stator flux. The actual flux will only be increased with the selected voltage vector once it enter sector 3.

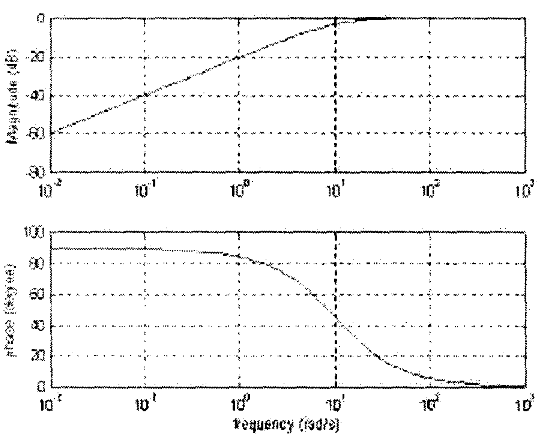


Fig. 2 Magnitude and phase frequency response of the estimated to the actual stator flux ratio.

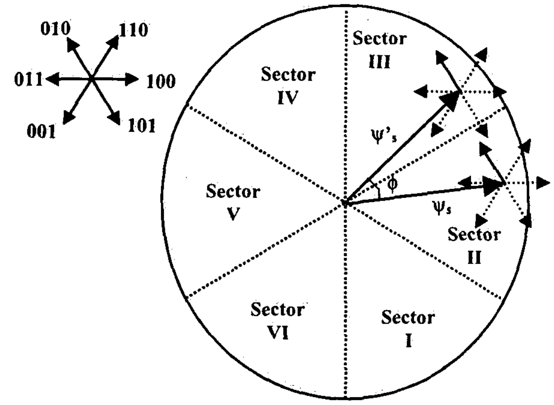


Fig. 3 Effect of phase error on the selected voltage vectors with the actual and estimated stator flux in sector III and II respectively.

From Fig. 2 and equation (7), the magnitude of the estimated stator flux is always less than the actual stator flux. However, the difference is insignificant as $\omega_e >> \omega_c$. Since the controller will force the estimated stator flux to follow the reference, the magnitude of the actual stator flux becomes larger than that of the reference. The estimated torque which is based on the estimated flux will therefore becomes larger than the reference value. At high speed where the problem of flux weakening is not experienced [7], the magnitude of the actual stator flux which is larger than the rated value can results in magnetic flux saturation.

To analyze the effect of phase and magnitude errors on the selection of voltage vectors, the DTC drive is simulated using Matlab/Simulink program . The stator flux used for the DTC controller is estimated using a LP-filter-based estimator with the cut-off frequency set to 5 rad/s. The actual flux – which is based on pure integrator – is also calculated but is not used by the DTC controller. A closed-loop speed control is utilized with the speed reference set to 20 rad/s. The selection of voltage vectors are made as proposed in [8]. Fig. 4 shows the waveform with the time axis zoomed in the vicinity when the stator flux is moving towards sector 3 from sector 2. According to [8], to increase the torque and flux in sectors 2 and 3, voltage vectors 110 and 010 should be selected respectively. Choosing voltage vectors 010 in sector 2 will result in a decrease in stator flux. Since the selection is made based on the estimated stator flux position, the actual stator flux will decrease (when it should be increased) during the period when the estimated and actual flux stator are in different sectors. Consequently, in steady state, particularly at low speed, the magnitude of the actual flux will be reduced and the its locus tend to become hexagonal in shape.

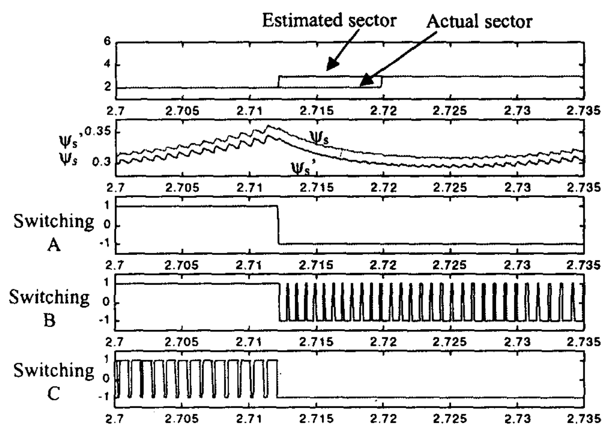


Fig. 4 Simulation results. Trace from top, 1st trace: Actual and estimated sector, 2nd trace: Actual and estimated stator flux, 3rd trace: switching of phase A, 4th trace: switching of phase B, 5th trace: switching of phase C.

IV. Improved Voltage Model-Based Stator Flux Estimator

The purpose of replacing the pure integrator with the LP filter in the stator flux estimator is to avoid integration drift problem due to the DC offsets present in the sensed currents or voltages. It has been shown that the phase and magnitude errors of the estimated stator flux introduced by the LP filter affected the selection of voltage vectors and hence degraded the performance of the DTC drive. The core of the proposed improvement is to provide the magnitude and phase compensations for the estimated flux, under steady state condition, only at the operating frequency thus improving the steady state performance of the DTC drive. In other words, the LP filter action is effective at all frequency except at the operating frequency, that is,

$$\psi'_s = \begin{cases} \dfrac{v - iR}{s} & for \quad \omega = \omega_e \\[2ex] \dfrac{v - iR}{s + \omega_c} & for \quad \omega \neq \omega_e \end{cases} \tag{8}$$

The LP filter action is therefore valid or effective for the DC offsets and low frequency components present in the sensed currents or voltages. This means that integration drift problem is avoided while at the same time good system stability is maintained since the phase and magnitude errors are compensated at the operating frequency. The *d* and *q* axes of the stator flux is compensated at the operating frequency by determining the expressions for the actual stator flux in terms of estimated stator flux.

From the angle relation of equation (7), the *d* component of the actual stator flux is given by:

$$\psi_{sd} = \psi_s \cos(\theta' - \phi), \quad \text{where } \phi = \pi/2 - \tan^{-1}(\omega_e/\omega_c)$$

Let $\phi' = \tan^{-1}(\omega_e/\omega_c)$, hence

$$\psi_{sd} = \psi_s \sin(\theta' + \phi')$$

$$\psi_{sd} = \psi_s (\sin\theta' \cos\phi' + \sin\phi' \cos\theta')$$

$$\psi_{sd} = \psi_s \left(\frac{\psi_q'}{\psi_s'} \frac{\omega_c}{\sqrt{\omega_c^2 + \omega_e^2}} + \frac{\psi_d'}{\psi_s'} \frac{\omega_e}{\sqrt{\omega_c^2 + \omega_e^2}} \right)$$

$$\psi_{sd} = \frac{\sqrt{\omega_c^2 + \omega_e^2}}{\omega_e} \psi_s' \left(\frac{\psi_q'}{\psi_s'} \frac{\omega_c}{\sqrt{\omega_c^2 + \omega_e^2}} + \frac{\psi_d'}{\psi_s'} \frac{\omega_e}{\sqrt{\omega_c^2 + \omega_e^2}} \right)$$

$$\psi_{sd} = \left(\psi_q' \frac{\omega_c}{\omega_e} + \psi_d' \right) \tag{9}$$

Similarly for the q axis,

$$\Psi_{sq} = -\Psi_s \cos(\theta' + \phi')$$

$$\Psi_{sq} = -\Psi_s (\cos\theta' \cos\phi' - \sin\phi' \sin\theta')$$

$$\Psi_{sq} = \Psi_s \left(-\frac{\Psi_d'}{\Psi_s'} \frac{\omega_c}{\sqrt{\omega_c^2 + \omega_e^2}} + \frac{\Psi_q'}{\Psi_s'} \frac{\omega_e}{\sqrt{\omega_c^2 + \omega_e^2}} \right)$$

$$\Psi_{sq} = \frac{\sqrt{\omega_c^2 + \omega_e^2}}{\omega_e} \Psi_s' \left(-\frac{\Psi_d'}{\Psi_s'} \frac{\omega_c}{\sqrt{\omega_c^2 + \omega_e^2}} + \frac{\Psi_q'}{\Psi_s'} \frac{\omega_e}{\sqrt{\omega_c^2 + \omega_e^2}} \right)$$

$$\Psi_{sq} = \left(-\Psi_d' \frac{\omega_c}{\omega_e} + \Psi_q' \right) \tag{10}$$

Equations (9) and (10) gives the relations between *d* and *q* components of the actual stator flux in terms of the *d* and *q* components of the estimated stator flux at the operating frequency. To implement the compensation, we need to know the cut-off frequency of the low pass filter, ω_c and the operating frequency ω_e. The average stator flux frequency, ω_e, is obtained from equation (11) [3,7].

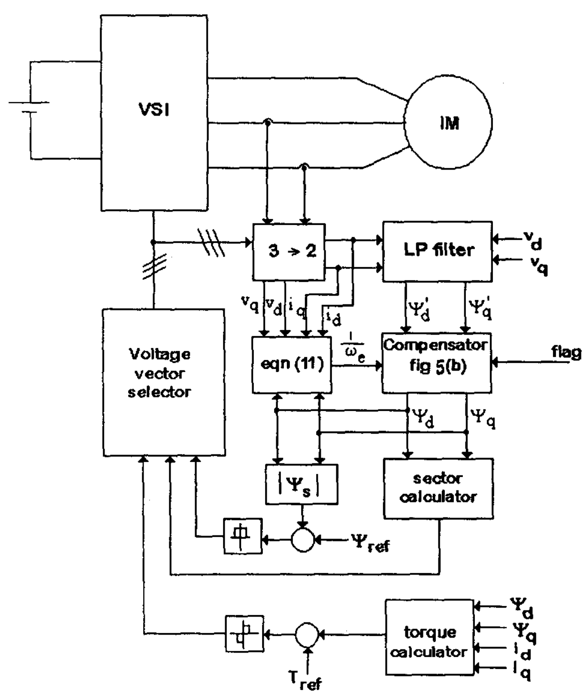
$$\omega_e = -\frac{(\bar{v} - \bar{i}_s R_s)}{\Psi_s^2} \cdot j\bar{\Psi}_s \tag{11}$$

The block diagram of the DTC drive with the compensation scheme in detail is as shown in figure 5(a) and

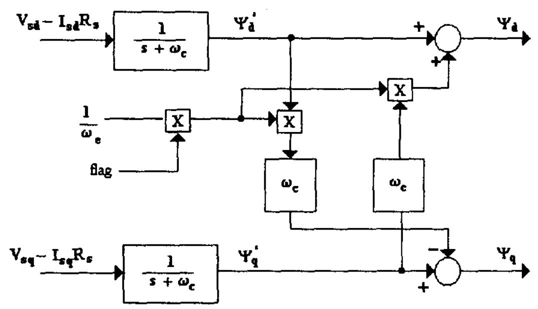
5(b). When activated, the flag will equal to 1, otherwise it will equal to zero. With zero flag, $\Psi_d' = \Psi_d$ and $\Psi_q' = \Psi_q$. The flag can be manually activated or it can be automatically activated based on the steady state speed or synchronous speed.

V. Simulation And Experimental Results

To verify the proposed stator flux estimator, simulations and experiments on the DTC induction motor drive were carried out. The simulations were conducted using Matlab/SIMULINK simulation package, while the implementation was carried out using a dSPACE DS1102 controller board centered around TMS320C31 digital signal processor. To minimize the sampling period, the voltage vectors selection table, blanking time of the VSI and the over–current protections were implemented using the XILINX FPGA. All other control algorithm, including the stator flux LP filter-based estimation technique, were implemented within the software. The experimental set-up is shown in Fig 6. The DTC drive for both simulation and experiment were run without the speed loop. In the experiment set-up, a DC machine is used to load the drive. The torque command is set to 0.2 N-m and the machine is loaded to give a steady state speed of 20 rad/s. The compensation is applied at t=5s for the simulation and at the instant the flag signal becomes 'high' for the experimental results.



(a)



(b)

Fig. 5 Block diagram of the improved stator flux estimator. (a) DTC drive incorporating the flux compensator, (b) stator flux compensator in detail

Fig. 7 shows the simulation results of the actual *d* and *q* axes of the stator flux, and the magnitude of the stator flux before and after the compensation is applied (for ω_c = 5 rad/s). Before the compensation, the stator flux shows some weakening due to the incorrect voltage vector selection as discussed earlier. The shape of the stator flux locus before the compensation is approaching that of the hexagonal as shown in Fig. 8a. After the compensation, the circular locus of the stator flux is restored with its magnitude increased (Fig. 8b). Due to the hexagonal shape of the stator flux, the actual torque pulsate at 6^{th} harmonic fundamental frequency. The estimated torque is maintained constant by the controller as shown by the simulation results of Fig. 9.

Experiments were carried out under the same condition as the simulation. Fig. 10 shows the *d* and *q* axes of the estimated stator flux and the magnitude of the stator flux using the compensated stator flux, while Fig 11 a and b shows the stator flux locus before and after the compensation respectively. Fig 12 shows the estimated torque, which is calculated using the compensated stator flux, and the estimated torque which is used by the controller. The former closely approximates the actual torque, which cannot be measured in the experiments.

V. Conclusions

The paper has presented the effect of using a LP filter in place of a pure integrator in the voltage-model based stator flux estimator to the steady state performance of the DTC of IM drive system. A compensation scheme to eliminate the phase and magnitude errors for the stator flux estimation under steady state condition is proposed. The validity of the proposed compensation scheme is supported with the extensive simulation and experimental results. It is shown that the simple proposed compensation scheme results in an improved stator flux and torque responses of the DTC drive under steady state condition.

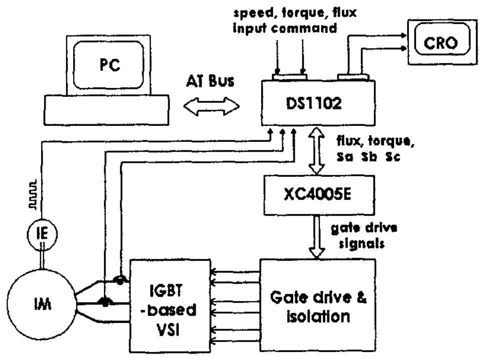


Fig. 6. Experimental set-up

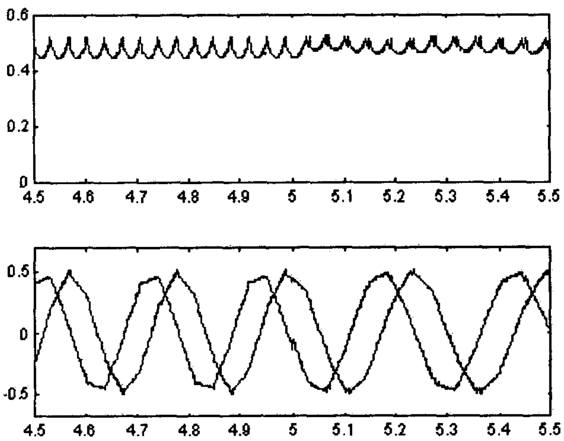
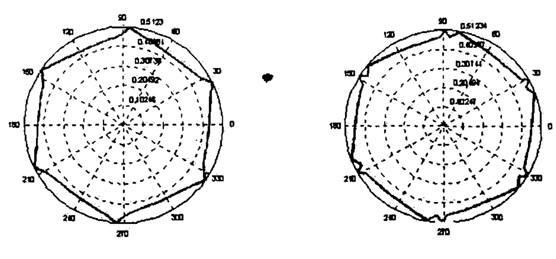


Fig.7 Simulation results. Top trace: actual stator flux, bottom trace: d and q axes of estimated stator flux with ω_c= 5 rad/s.



(a) (b)

Fig. 8 Simulation results with ω_c = 5 rad/s. Stator flux locus (a) before compensation, (b) after compensation.

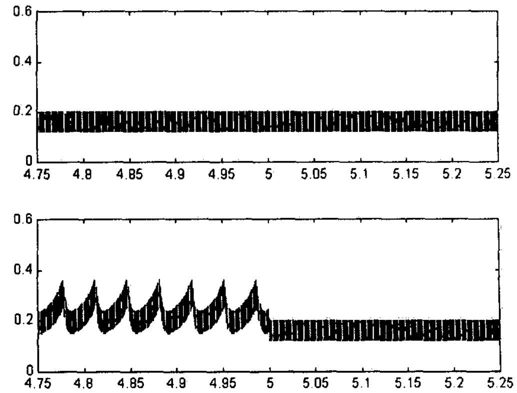


Fig. 9 Simulation results. Top trace:estimated torque, bottom trace: actual torque. ω_c= 5 rad/s.

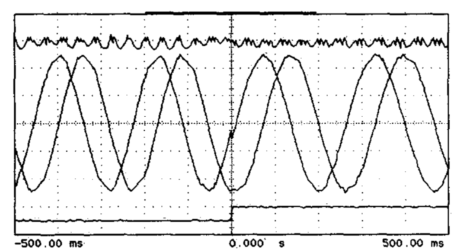
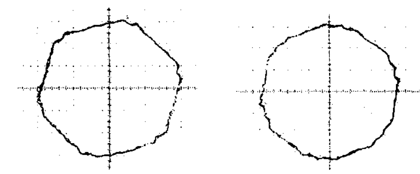


Fig. 10 Experimental results. Top trace: Stator flux magnitude(0.1Wb/div), middle trace: estimated stator flux d and q axes (0.2Wb/div), bottom trace: flag signal. ω_c= 5 rad/s.



(a) (b)

Fig. 11 Experimental results, ω_c= 5 rad/s. Stator flux locus (a) before compensation, (b) after compensation.

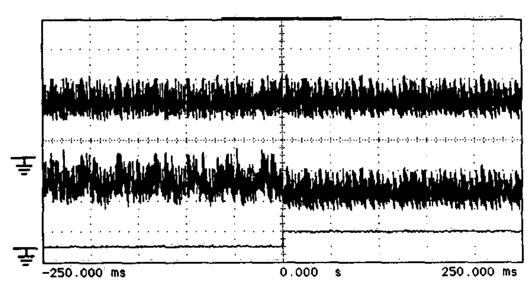


Fig. 12 Experimental results. Top tace: estimated torque used by the controller(0.1 N-m/div), bottom trace: estimated torque calculated using the compensated stator flux (0.1 N-m/div). ω_c = 5 rad/s.

APPENDIX

Motor parameters used for the simulation and experiment.

Rs = 10.9 Ω Rr = 9.25 Ω	Lr = 0.858792 H
Ls = 0.858792 H	Lm = 0.828981 H

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