

Study on Nonlinear Perpendicular Flux Observer for Direct-torque-controlled Induction Motor

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(Received 8 February 2008, accepted 13 May 2008)

Abstract: Flux observation is one of the key to keeping high performance of a direct-torque-controlled drive system. In this paper a nonlinear perpendicular flux observer with feedback compensation model is proposed, and combined with DTC for induction motor control. The flux observer can ensure flux linkage to be perpendicular to back electromotive force, so that the stator flux linkage can be estimated accurately over a wide speed range. The feasibility and correctness were verified by experiment results.

Keywords: nonlinear perpendicular; flux observer; direct torque control

1 Introduction

Accurate estimation of flux linkage including its amplitude and phase angle is very important in realization of high performance motor drives. There are, in general, three methods for flux linkage estimation: the first one is based on direct calculation [1,2], the algorithm of which is easy to implement and the dynamic response is relatively quick. However the first problem associated with this algorithm is that it requires many motor parameters, which change with motor operation condition, e.g., variations in moment of inertia and magnetic saturation level. The second problem associated is that the algorithm is only based on open-loop estimation, without feedback compensation. As a result, these problems mentioned above will lead to inaccurate estimation of the flux. The second method for flux estimation is based on different type state observers [3,4,5], i.e. in general, two kinds of observers: full-order one and reduced-order one. To obtain global stability, different gain matrices are required to estimate system states when the motor operates in different speed ranges. The problem associated is still that it requires too many motor parameters, which again change with motor operation condition. In order to overcome these problems, an on-line motor parameter identification scheme should be adopted, which increases the complexity of the drive system. The third method for flux estimation is based on integrating back electromotive force (emf) [6,7]. The only motor parameter required in this scheme is the stator winding resistance, which can be easily obtained and in most cases can be roughly considered as a constant. Although this algorithm is very easy to implement, but the motor operation performance during very low speed is very bad.

The basic principle of designing flux observer is to require a few of or even no motor parameters, due to that they change with motor operation condition, which severely affects the estimation result. In literature [8], three modified methods for integrating back emf are proposed. The first algorithm in literature [8] still has dc drift problems during operation. The second algorithm must pay special attention to setting a proper limiting level in a nonlinear saturation block, and is only suitable for application where the motor flux is not required to vary during operation. Therefore the algorithm can not meet the practical operation demand. The third algorithm is not suitable for Direct Torque Control (DTC) application at all since the algorithm does

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not consider back emf under DTC operation as a non-continuous signal. Furthermore, both PI regulator and nonlinear saturation block are included, which increases debugging difficulties.

DTC of Induction Machine (IM) has its peculiar operation property. To obtain quickly dynamic torque response, different space voltage vectors are selected during different control period for the purpose of driving stator flux changing quickly. Therefore the space voltage vectors applied to the IM under DTC system are not continuous but discrete signals. Due to stator winding inductances, stator current is a continuous signal, and, naturally, the voltage drop across stator resistance is also continuous, which leads to a non-continuous back emf. Therefore flux estimation result via conventional flux observer is not available for DTC application. To overcome this difficulty, a new nonlinear perpendicular stator flux observer with feedback compensation, suitable for IM DTC, was proposed in this paper.

2 CONVENTIONAL BACK EMF INTEGRATION AND IMPROVED ALGORITHM

The conventional back emf integration approach of flux estimation can be expressed as

$$\vec{\psi}_s = \int_0^t (\vec{u}_s - R \vec{i}_s) d\tau \quad (1)$$

Where \vec{u}_s, \vec{i}_s are stator voltage vector, current vector. The algorithm is very easy to implement and the dynamic response is satisfactory, in which the only motor parameter required is the stator winding resistance. However, due to the existence of noise measured and error, flux estimation result will include dc flux component, and thus stator flux locus is not a circle centered at origin, which leads to dc current component and severely affects motor operation. Furthermore, whether initial flux vector is estimated accurately or not also affects flux estimation.

A simple method to remove the dc component from estimated flux, caused by pure integration algorithm, is to filter calculating results of (1) by a high-pass filter, which can be illustrated by Fig. 1.

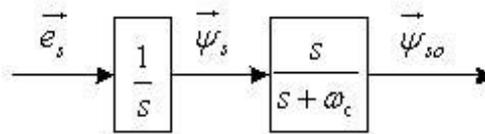


Figure 1: High-pass filter of flux linkage

In the Fig.1, $\vec{e}_s = \vec{u}_s - R \vec{i}_s$ is the measured back emf; $\vec{\psi}_{so}$ is the estimating flux. By combination of the pure integrator block and high-pass filter block in Fig.1 together, a low-pass filter is formed, as shown in Fig.2.

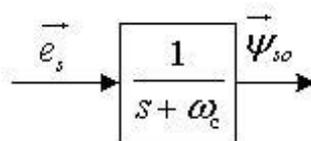


Figure 2: Low-pass filter of back emf

Fig.2 can be expressed as

$$\vec{\psi}_{so} = \frac{1}{s + \omega_c} \vec{e}_s \quad (2)$$

where $\omega_c = 1/\tau$ is the cut-off frequency, τ is the time constant, which directly affects attenuation speed of the dc flux component. Fig.2 illustrates the estimated flux can be acquired by simply getting the back emf pass through a one-order low-pass filter.

Amplitude and phase response of the one-order high-pass filter are expressed as

$$|G(j\omega)| = \frac{\tau\omega}{\sqrt{1+(\tau\omega)^2}} \quad , \quad \angle G(j\omega) = \frac{\pi}{2} - \arctan \omega\tau \quad (3)$$

Equ.(3) shows that when the frequency of the stator flux is very high, the amplitude attenuation and phase shift are not serious, and the flux can be estimated accurately, thus the motor operation behavior is good. But if the motor operates at an extremely low speed, the flux amplitude attenuation and phase shift become very serious which leads to inaccurate estimation of flux and deteriorating DTC operation performance. Therefore the amplitude and phase of the flux must be well compensated during low speed operation, as illustrated in Fig.3

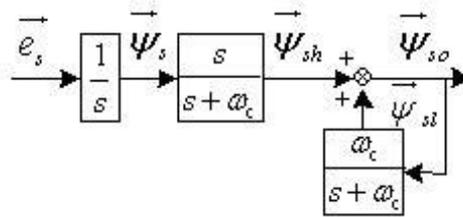


Figure 3: flux observer with low-pass compensation

In Fig.3, $\vec{\psi}_s$, $\vec{\psi}_{sh}$, $\vec{\psi}_{sl}$, $\vec{\psi}_{so}$ are real flux, high-pass filter output flux, low-pass filter output flux and flux estimation value, respectively. During digital control period, the process shown in Fig.3 should be expressed in a discrete form as

$$\vec{\psi}_{so} = \vec{\psi}_s \frac{s}{\omega_c + s} + \frac{\omega_c}{\omega_c + s} \vec{\psi}_{so(k-1)} \quad (4)$$

where $\vec{\psi}_{so(k-1)}$ is the flux estimation value at the previous period. Only if $\vec{\psi}_{so(k-1)} \approx \vec{\psi}_{so}$, then $\vec{\psi}_{so} = \vec{\psi}_s$, which means the flux can be estimated accurately. However, under DTC operation, quite different space voltage vectors are selected during two adjacent control periods to obtain quickly dynamic torque response, which will cause considerable phase difference for these two voltage vectors, i.e., $\vec{\psi}_{so(k-1)} \neq \vec{\psi}_{so}$, $\vec{\psi}_{so} \neq \vec{\psi}_s$. To solve the problem of inaccurate flux estimation mentioned above, a new flux observer with one-order low-pass filter and compensation should be put forward to ensure flux accurate estimation for IM DTC application.

3 NONLINEAR PERPENDICULAR FLUX OBSERVER WITH FEEDBACK COMPENSATION

The flux estimation algorithm suitable for PMSM DTC application can be formulated as

$$\vec{\psi}_{so} = \frac{\vec{e}_s}{s + \omega_c} + \frac{\omega_c}{s + \omega_c} z \quad (5)$$

where z is feedback compensation flux. If $z=0$, equ.(5) performs one-order low-pass function, as shown in Fig.1; if $z = \vec{\psi}_{so}$, equ.(5) performs pure integration function. As a result, if z is properly chosen, the proposed new flux observer will possess better performance than those algorithms mentioned above. Parameter z can be expressed as

$$Z = s_{com} \vec{\psi}_{so} \quad (6)$$

where s_{com} is the flux compensation coefficient, determined by perpendicular degree of $\vec{\psi}_{so}$ with \vec{e}_s , and can be further expressed as

$$s_{com} = \frac{e_\alpha \cdot \psi_{\alpha o} + e_\beta \cdot \psi_{\beta o}}{|\vec{e}_s| \cdot |\vec{\psi}_{so}|} \tag{7}$$

where e_α, e_β are two components of \vec{e}_s in the two-phase stationary reference reframe. Accordingly, $\psi_{\alpha o}, \psi_{\beta o}$ are the corresponding components of $\vec{\psi}_{so}$. The numerator of (7) represents dot product of $\vec{\psi}_{so}$ and \vec{e}_s , and the denominator represents product of their amplitude. Therefore, s_{com} is the cosine of angle between vector $\vec{\psi}_{so}$ and \vec{e}_s , which should be a continuous value. However during IM DTC operation, e_α, e_β are non-continuous signals, which makes it impossible to obtain a continuous s_{com} directly via (7). Therefore, a low-pass filter block could be set behind the back emf block to make the back emf continuous which is essential for calculating dot product of flux and back emf vector. However this measure will cause back emf to have a phase shift. To balance or compensate this phase shift, the same low-pass filter block must be set behind the flux estimator as well to hold the same phase shift as back emf, and the corresponding quantities e'_α, e'_β and $\psi'_{\alpha o}, \psi'_{\beta o}$ can then obtained. After such processing, equ.(7) can be rewritten as

$$s_{com} = \frac{e'_\alpha \cdot \psi'_{\alpha o} + e'_\beta \cdot \psi'_{\beta o}}{|\vec{e}'_s| \cdot |\vec{\psi}'_{so}|} \tag{8}$$

which will be used to judge the perpendicular degree of flux with emf. Consequently[10], a new nonlinear perpendicular flux observer with feedback compensation, suitable for IM DTC application, is formed as shown in Fig.4,

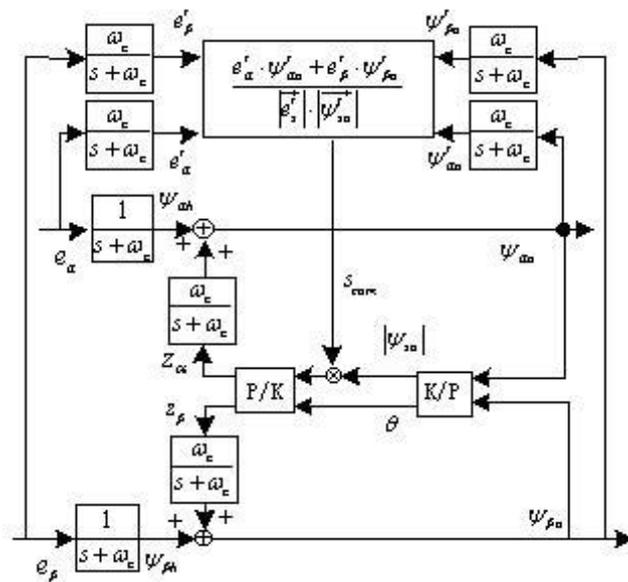


Figure 4: Nonlinear perpendicular flux observer

In Fig.4 it is clearly shown that the amplitude $|\psi_{so}|$ and phase angle θ of the estimated stator flux during the previous period is obtained after the K/P (Cartesian to Polar) transformation, the amplitude of feedback compensation flux z is successively obtained by implementing $s_{com} \times |\psi_{so}|$ and, finally, the compensation flux z_α, z_β , which is obviously determined by perpendicular degree of back emf with flux vector, is obtained by implementing inverse transformation P/K (Polar to Cartesian).

If the flux is perpendicular to back emf, the angle θ between them should be in 90 electrical degrees and accordingly the cosine value will be zero, i.e., $s_{com} = 0, z_\alpha = 0, z_\beta = 0$, no compensation flux required,

which means the flux linkage has been estimated accurately. Otherwise, if the flux is not perpendicular to back emf, $s_{com} \neq 0$, $z_{\alpha} \neq 0$, $z_{\beta} \neq 0$ will occur, which indicates that flux estimation is not accurate and flux compensation must be applied. Therefore the proposed observer is capable of ensuring flux linkage to be perpendicular to back emf and the stator flux linkage can then be estimated accurately over a wide speed range. Besides, this observer is very simple in structure, neither PI regulator nor nonlinear saturation limiter block included, robust to motor parameter uncertainty, suitable for application where the motor flux is required to vary or not to vary during operation and easy to implement in the practical application.

4 EXPERIMENTAL STUDY

The proposed observer was successfully implemented in a 1.1 kw IM setup via a digital signal processor (TMS320F240 DSP). Motor Parameters: $p=2$, $n=1500$ r/min, $R_s=5.739\Omega$, $R_r=3.421\Omega$, $L_m=0.363$ H, $L_r=L_s=0.386$ H, Fig. 5~7 show the experimental results when motor runs at a wide range from extremely low speed to the rated speed. Fig. 5 shows the stator flux, torque and speed response at extremely low speed of 15 r/min with load torque of 5 N.m, and the motor operates quite well. Fig.6 shows the stator flux, torque and speed response at low speed of 125 r/min, from which it can be seen that the sine degree of flux waveform is improved with increase of speed. Fig.7 shows the stator flux, torque and speed response at the rated speed 1000 r/min. Fig.8 shows torque response and enlarged torque response, which demonstrates that the torque can track the reference quickly, and the response time is only 1.2 ms. Hence, the IM DTC system using the proposed new observer not only operates well over a wide speed range, but also holds the merit of quickly dynamic torque response which is inherent for DTC, and robustness to parameter uncertainty.



Figure 5: Flux linkage, Torque and Speed response at the speed of 15 r/min and load torque of 5 N.m



Figure 6: Flux linkage, Torque and Speed response at the speed of 125 r/min and load torque of 5 N.m

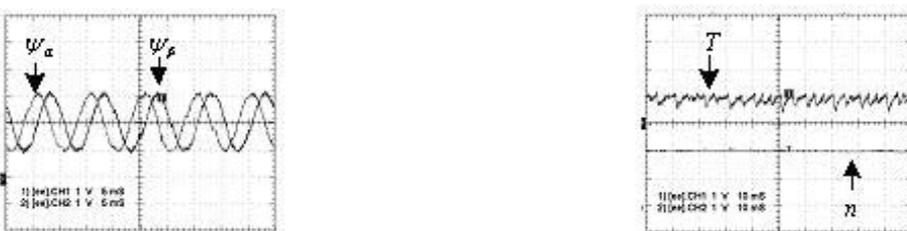


Figure 7: Flux linkage, Torque and Speed response at the speed of 1000 r/min and load torque of 5 N.m



Figure 8: Torque variation from 5 N.m to -5 N.m and back to 5 N.m and the enlarged torque waveform

5 CONCLUSION

Firstly, to obtain quickly dynamic torque response in a IM DTC system, the applied two adjacent space voltage vectors during two contiguous control periods have quite large phase angle difference, which will cause the back emf to be non-continuous. Conventional flux observers did not consider the peculiar property, which leads to considerable flux estimation error.

Secondly, to ensure flux estimation correct over a wide speed range, it is important to make the back emf be perpendicular to the stator flux, which can be reached by flux compensation approach. However, back emf is non-continuous, and a low-pass filter must be set behind the back emf block to make it continuous which is essential to perform dot product of flux vectors with back emf vector. The perpendicular degree of flux with back emf vector can be checked and controlled by a compensation coefficient, which is usually used to form a closed-loop control in the new stator flux observer.

Lastly, the proposed flux observer can estimate accurately the stator flux linkage including its amplitude and phase angle even if the motor runs at a very low speed. The observer still keeps the merits of quickly dynamic torque response and robustness to uncertainty. The high performance operation for IM DTC using proposed flux observer has been achieved with satisfaction in the practical operation.

References

- [1] Marchesoni M, Segarich P, Soressi E.: A simple approach to flux and speed observation in induction motor drives. *IEEE Trans. Industrial Electronics*.4(4):528-535(1997)
- [2] Maidu M, Bose B K: Rotor position estimation scheme of a permanent magnet synchronous machine for high performance variable speed drive. *IEEE IAS annual meeting*.1:48-53(1992)
- [3] Youn-Ok Choi, Kang-Yeon Lee: Performance analysis of the DTC using a closed loop stator flux observer for induction motor in the low speed range. *ICEMS 2001*.1:89- 93(2001)
- [4] Yu Tao, Zhu Shouzhen, Shen Shande et al: Extended state observer based nonlinear robust coordinated control of power systems. *Proceedings of the CSEE*.24(4):1-5(2004)
- [5] Zhang Changfan, Wang Yaonan, He Jing: Variable structure intelligent control for PM synchronous servo motor drive. *Proceedings of the CSEE*.22(7):13-17(2002)
- [6] Hu Yuwen, Tian Cun, Gu Yikang: In-depth research on direct torque control of permanent magnet synchronous motor. *IECON 02 Industrial Electronics Society*.2:1060 -1065(2002)
- [7] Lianbing Li, Hexu Sun, Xiaojun Wang: A high-performance direct torque control based on DSP in permanent magnet synchronous motor drive. *ICA 2002. Proceedings of the 4th World Congress*.2:1622-1625(2002)
- [8] Jun Hu, Bin Wu: New integration algorithms for estimating motor flux over a wide speed range. *IEEE Trans. Power Electronics*.13(5):969- 977(1998)
- [9] Lixin Tian, Gaogao Dong: Predictive Control of Sudden Occurrence of Chaos. *International Journal of Nonlinear Science*.5(2):99-105(2008)