Discrete Current Vector Control —A New Positioning Control Method of PMSM

Yan Dong, He-xu Sun, Zhao-ming Lei, Li-jun Yun

Department of Automation, Hebei University of Technology, Tianjin, PR.China 300130

dongyan73@sohu.com

Abstract

In this paper, a new simple position control method of PMSM which is similar to step motor is proposed. In the method, the previous control pattern is changed, the current input to the three-phase stator windings is not the continuous sinusoidal wave but the stepped wave current, the step magnetomotive force is appeared, discrete torque is produced that is more suitable to the position control. In this paper, the relation between torque-angle and positioning is analyzed. The positioning performance is proved by simulation and experimental results.

Keyword: discrete current vector, torque-angle, PMSM

I. Introduction

PMSM is widely applied in manufacture, industrial robot, military and many other fields as control motor because of its simple structure, low cost and high performance. At present, there are two main advanced control methods for PMSM: Vector Control (VC) and Direct Torque Control (DTC).

In 1971, German engineer F.Blaschke proposed the Vector Control for asynchronous motor for the first time. In the VC of PMSM the torque-angle δ is kept 90º, the continuous control of torque is realized by controlling q-axis current i_q. The merits of VC are good torque response and accurate speed control. The drawback of VC is depending on the accurate model of the motor. The system control performance can be affected easily by parameter changing and the robust performance is not ideal. In 1985, the Direct Torque Control approach is proposed by M. Depenbroch[1]. DTC is a close-loop control of stator flux and torque. Because the controlled variable is stator flux but the rotor flux, DTC is not influenced by the rotor parameters. However, the torque ripple is large, which limits the system dynamic performance. So，a lot of scholars have make plenty of studies, in order to resolve the problems of VC and DTC above[2,3].

In this paper, on the basis of DTC and VC， a new position control method for PMSM based on Discrete Current Vector Control (DCVC) is proposed. The key of the method is to control the torque-angle. Constant stator magnetomotive force is gotten by keeping magnitude of stator current as a constant. The torque is controlled by regulating sin δ. To be adapted to the position control system, the stator current is transformed from sine wave to stepped wave and the continuous circle rotating magnet field is transformed into discrete polygonal magnet field. As a result, the discrete torque is produced. This control method is more suitable to the position control compared with the continuous torque control of VC and the two-point torque control of DTC.

II. Characteristics of Torque-angle

When the symmetrical three-phase sinusoidal current is input in the stator windings, the three-phase basic wave magnetomotive force vectors are as follow:

$$\begin{aligned} F_a(t) &= 0.5F_a(e^{j\omega t} + e^{-j\omega t}) \\ F_b(t) &= 0.5F_a(e^{j\omega t}e^{-j2\pi/3^{\circ}} + e^{-j\omega t}e^{j2\pi/3}) \\ F_c(t) &= 0.5F_a(e^{j\omega t}e^{j2\pi/3^{\circ}} + e^{-j\omega t}e^{-j2\pi/3}) \end{aligned} \quad \textbf{(1)}$$

Where $\boldsymbol{F_a}$ is magnetomotive force vector of phase-a; its phase is in the same direction with the phase-a winding axes.
If the magnitude of stator current is constant the synthesized stator magnetomotive force of three-phase forms a circle rotating magnet field.

$$\sum F_s = 1.5F_a e^{j\omega t} \quad \textbf{(2)}$$

According to the motor's common principle, the electromagnetic torque is:

$$T_e = C_T F_s F_r \sin\delta \quad \textbf{(3)}$$

Where

$\boldsymbol{F_s}$=stator magnetomotive force;

$\boldsymbol{F_r}$= rotor magnetomotive force;

$\delta=\theta_s-\theta_r$ torque-angle which is the electrical degree between $\boldsymbol{F_s}$ and $\boldsymbol{F_r}$.

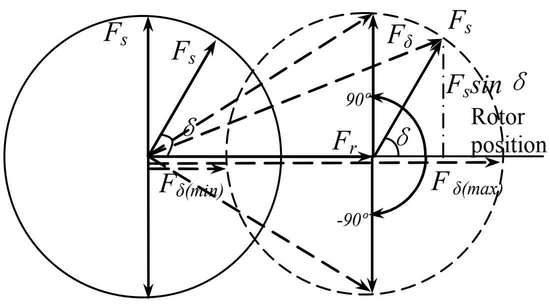

Fig. 1. The characteristics of the torque-angle. In this figure, rotor position is taken for reference axis. $\boldsymbol{F_\delta}$=$\boldsymbol{F_s}$+$\boldsymbol{F_r}$ is the synthesized magnetomotive force vector by stator magnetomotive force vector and rotor magnetomotive force vector.

Because the rotor of PMSM is made of permanent magnet materials, rotor's magnetomotive force is a constant. If the stator's magnetomotive force is also a constant, the electromagnetic torque $T_e \propto \sin\delta$. The DCVC method of PMSM is proposed on this basis. That is to say that to control the electromagnetic torque by controlling the torque-angle δ. The torque-angle characteristics are shown in Fig.1.Viz., the torque T_e is positive while the stator's magnetomotive force exceeds the rotor's δ($0^o \leq \delta \leq 90^o$), the motor is in the state of running ; the torque T_e is negative while the stator's magnetomotive force lags the rotor's δ($0^o \leq \delta \leq 90^o$),the motor is in the state of braking; the motor is in the state of speed regulation by flux reduction when $\delta > 90^o$.

Torque-angle δ	$sin\delta$	Torque T_e	Motor Running State
$0^o \leq \delta \leq 90^o$	$0 \leq sin\delta \leq 1$	$T_e > 0$	motor
$-90^o \leq \delta \leq 0^o$	$-1 \leq sin\delta \leq 0$	$T_e < 0$	brake
$\delta > 90^o$	$0 \leq sin\delta \leq 1$	$T_e > 0$	Lower-magnetism raising speed

Table 1. The relation between torque-angle and motor running state. From Fig.1 we can see that the working states of the motor varies with the torque-angle changed in the different ranges.

III. Discrete Current Vector Control

A. Theoretical Foundation of DCVC

In this method, the current input to the three-phase stator windings is not the continuous sinusoidal wave but the stepped current wave discretized by some certain rule. Here the current is discretized by EDS method [4]. The discrete stator current is shown as below:

$$\begin{aligned} i_a &= I_m \cos[(2\pi / b_H)k] \\ i_b &= I_m \cos[(2\pi / b_H)k - 2\pi/3] \\ i_c &= I_m \cos[(2\pi / b_H)k + 2\pi/3] \end{aligned} \quad \textbf{(4)}$$

Where b_H denotes the number of cycle steps. b_H is a positive integer and each period of the current is divided into b_H parts. For three-phase motors, b_H should be multiple times of 6 to keep the symmetry of three-phase currents. b_H correspond to the number of cycle steps of ring-shape allotter in step motor, which denotes the number of steps that the rotor runs two pole pitch 2τ. And k is an integer, which denotes the number of steps in the full control process. With the output of each step, the current shown in equation (4) will be transformed accordingly. The stator magnetomotive force has a series of setting positioning-points along the circle. So the track of magnetomotive force polygon is formed.

$$\sum F_s = 1.5 F_a e^{j\frac{2\pi}{b_H}k} \quad \textbf{(5)}$$

According to this, stator magnetomotive force is transformed from continuous function to discrete function, just like step motion. The angle between two adjacent magnetomotive forces is called step angle θ_b=360º/b_H. So the reset torque between $\boldsymbol{F_s}$ and $\boldsymbol{F_r}$ is:

$$T_e = -T_{\max} \sin(k\theta_b - p\theta) \quad \textbf{(6)}$$

Where

θ is mechanical angle of the rotor real position;
p is pairs of poles.
We analyze the positioning characteristics of the motor using the torque vector theory.

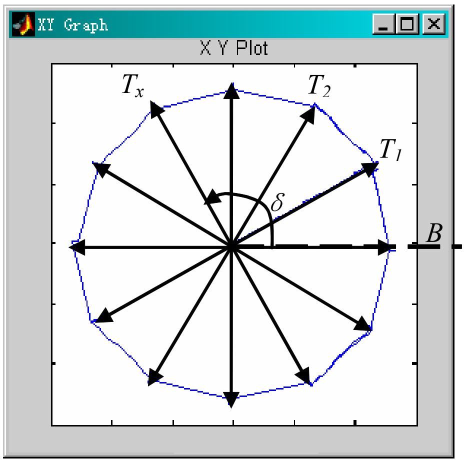

Fig. 2. The torque vector. In the figure, b_H is set 12, the track of the stator magnetomotive force is given by simulation.

The torque vector figure is shown in Fig.2.

1) When the stator magnetomotive force is fixed at the position 1. That is the initial state when k=1. A reset electromagnet torque T_1 is produced with the motion of rotor pole B.

2) When k=x, stator magnetomotive force is fixed at the position x. When the rotor pole B departures from position x, a reset torque T_x is produced. T_x will force the pole B to return to the position x. And so the stator magnetomotive force is traced and the torque-angle δ=0.

3) Point at the position of the stator magnet motive force in the space, which are the set position points. The position of the line B denotes the middle line of the rotor pole.
By setting the number of steps k, the point position control can be realized.

B. Control of Current Vector

In the DCVC, the control of stator current vector is the most important. In recent years, many authors have made great efforts to research the current tracking control method with the Voltage-source inverter [5]. However, the current hysteresis-band approach proposed by A.B. Plunkett and the synchronized on-off method are still most widely used in this field [6]. The hysteresis-band current control approach is easy to implement, but its switch frequency varies. In synchronized on-off control the current sample interval correspond to the width of hysteresis-band in the hysteresis-band control. The increasing of sampling frequency can improve precision of the current control, but the sampling frequency is restricted by the maximal switch frequency of the switch device. So the direct current control driven by voltage vector is used [7].

The one phase voltage equation of PMSM can be written as below:

$$u = Ri + L\frac{di}{dt} + e \qquad \textbf{(7)}$$

Where

u is phase voltage;

i is phase current;

R is stator equivalent resistance;

L is stator equivalent inductance;

E is EMF.

For using the voltage-source inverter, each phase voltage is a constant ($\pm 1/3U_{DC}$ or $\pm 2/3U_{DC}$). Since the sampling time of the current is much shorter than the motor time constant T, the discrete equation can be written as below:

$$i(n+1) = i(n)(1-\frac{T_s}{T}) + \frac{T_s}{L}u(n) \qquad \textbf{(8)}$$

Where

$\boldsymbol{i}(n)$ is current vector at the beginning (n);

$\boldsymbol{i}(n+1)$ is current vector at the end of the interval (n+1);

$\boldsymbol{u}(n)$ is voltage vector at the beginning (n).

In the most cases, the Ts/T is so small that it can be neglected.
Modern DSP is capable of performing fast on-line calculations and can be used for the current control. In the equation above, the vector is decomposed into a stationary reference frame. The previous equation can be rewritten as below.

$$i_{\alpha,\beta}(n+1) = \underbrace{i_{\alpha,\beta}(n)(1-\frac{T_s}{T})}_{i_{0\alpha,\beta}(k+1)} + \underbrace{\frac{T_s}{L}u_{\alpha,\beta}(n)}_{i_u\alpha,\beta(k+1)} \qquad \textbf{(9)}$$

Where

$i_{0\alpha,\beta}(n+1)$ is naturally decreased current;

$i_{u\alpha,\beta}(n+1)$ is current increment caused by the application of voltage during the sampling interval.

The current at the end of the interval depends on the radial naturally decreased current and the current increment caused by the application of the voltage during the sampling interval. Therefore, by choosing the appropriate active or zero voltage vectors, the current can be driven into the any possible direction (see also Fig.3)

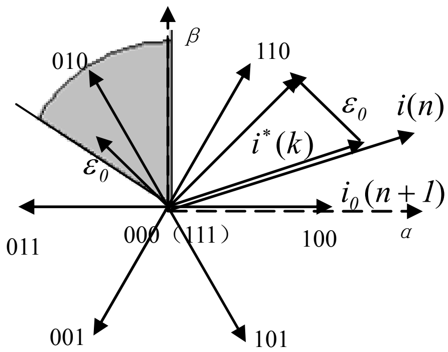

Fig. 3. Relation between the voltage vector and the current vector

Where both voltage components at time n can take the following values:

$$
\begin{aligned}
u_{\alpha,\beta}(n) &= \frac{2}{3}U_d \begin{bmatrix} K_{U\alpha}(n) \\ K_{U\beta}(n) \end{bmatrix} \\
&= \frac{2}{3}U_d \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} s_1 \\ s_3 \\ s_5 \end{bmatrix}
\end{aligned} \tag{10}
$$

s_1, s_3, and s_5 denote the transistor states (0 or 1) that depend on the selected voltage vector at time n. In Fig.3, after calculating $\boldsymbol{i}_0$, the voltage vector closest to the direction of the error $\boldsymbol{\varepsilon}_0$ between the reference current vector $\boldsymbol{i}_0(n)$ and $\boldsymbol{i}_0(n+1)$ is chosen. The combination of the upper transistors 010(voltage vector $\boldsymbol{u}_{010}$) is selected; the switch devices2, 3 and 4 are on.

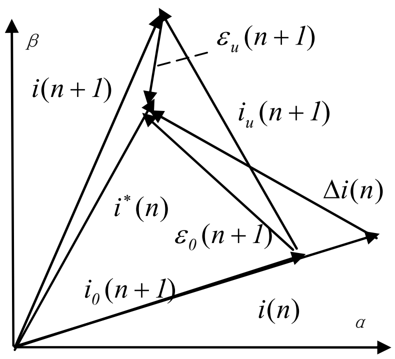

Fig. 4. Current vector and corresponding errors

Where

$\boldsymbol{i}(n)$ is current at the beginning (n);

$\boldsymbol{i}_0(n)$ is naturally decreased current from the beginning to the end in the interval ;

$\boldsymbol{\varepsilon}_0(n+1)$ is error between the reference current vector $\boldsymbol{i}_0(n)$ and $\boldsymbol{i}_0(n+1)$;

$\boldsymbol{i}_u$(n+1) is current increment caused by the applied constant voltage during the sampling interval;

$\boldsymbol{i}(n+1)$ is current at the end of the interval (n+1)

ε_u $(n+1)$ is error between the reference current $\boldsymbol{i}^*(n)$ and $\boldsymbol{i}$ $(n+1)$;

$\Delta\,\boldsymbol{i}(n)$ is error between the reference current $\boldsymbol{i}^*(n)$ and $\boldsymbol{i}$ (n).

From equation (10) we can predict the current behavior. The current vector and its errors are shown in Fig.3, while the active voltage vector (010) is applied.

$$\varepsilon_{0\alpha,\beta}(k+1) = i^*_{\alpha,\beta}(k) - i_{0\alpha,\beta}(k+1) \tag{11}$$

$$\begin{aligned}\varepsilon_{u\alpha,\beta}(k+1) &= i^*_{\alpha,\beta}(k) - i_{\alpha,\beta}(k+1)\\ &= \varepsilon_{0\alpha,\beta}(k+1) - i_{u\alpha,\beta}(k+1)\end{aligned} \tag{12}$$

$$\Delta i_{\alpha,\beta}(k) = i^*_{\alpha,\beta}(k) - i_{\alpha,\beta}(k) \tag{13}$$

In the control process, there are two the possibilities:
1) The best fitting voltage vector (including the natural current decreasing) to obtain final error $\boldsymbol{\varepsilon}_{u\alpha,\beta}$ $(n+1)$;
2) The zero vector (allowing the current to decrease naturally), to obtain final error $\boldsymbol{\varepsilon}_{0\alpha,\beta}$ $(n+1)$.
The second option is chosen if its final error is smaller than the error of the first one:

$$\varepsilon_u^{\ 2} > \varepsilon_0^{\ 2} \tag{14}$$

IV. Position control

To be strictly, the position control method can be considered a kind of open-loop control. System architecture is shown in Fig.5.For a given position θ^*, firstly, a three-segment position-speed (θ-ω) curve is programmed as shown in Fig.6.

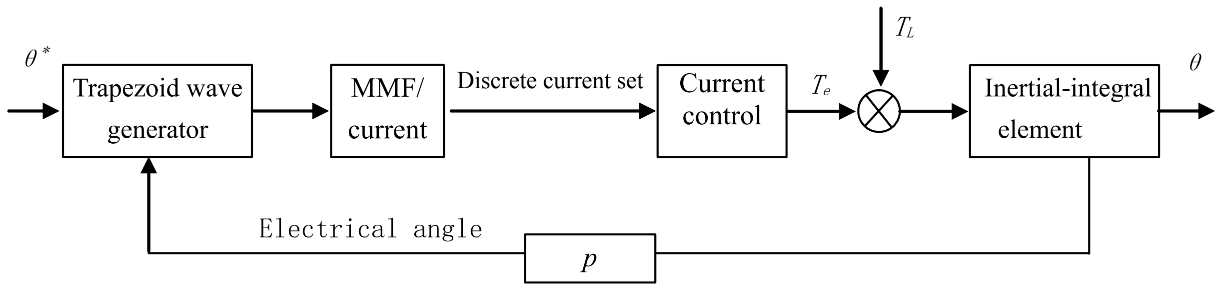

Fig.5. System architecture

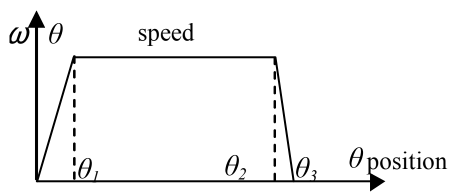

Fig. 6. The ideal three-segment position-speed curve

Where

θ is position of rotor;

ω is motor speed;

$0 \sim \theta_1$ is accelerated starting period;

$\theta_1 \sim \theta_2$ is constant-speed running period;

$\theta_2 \sim \theta_3$ is decelerated braking period.

1) Accelerated starting period

In the accelerated starting period, the motor starts with the maximum torque. When the torque-angle δ is 90°, the value of $sin\ \delta$ is 1 as shown in equation (3), and so the maximum torque is got. In the control process, the rotor position is measured on real-time, and the given stator current in the next step is deduced according to the rotor position. In the starting period, if three-step stator current vector ahead of rotor is kept, the motor is started with maximum electromagnet torque.

2) Constant-speed running period

When the set position θ_1 in the programmed curve is reached, the motor should run at the constant speed. If the load change is small, the torque-angle δ be kept constant (load angle). When the speed fluctuates because of the change of load, based on the load angle regulating the δ properly can make the motor run at the set speed stably.

3) Braking period

When the rotor position exceeds θ_2, the system should decelerate and break. In order to get the maximum breaking torque, the torque-angle δ is -90°, the value of $sin\delta$ is -1. If $b_H=12$, then stator current vector lagging rotor three-step angle is given.

In the position control system, the three-segment θ-ω curve should be figured out first according to the stable constant speed and deceleration when the desired position is given. In order to get high position precision, θ-ω curve must be programmed dynamically in this period. Speed decreases to zero when rotor reaches the set position. The relations of speed and position are shown below:

$$\frac{d\theta}{dt} = \omega, \frac{d\omega}{dt} = a, d\theta = \omega dt, d\omega = adt, d\theta = \omega \frac{d\omega}{a} \quad \textbf{(15)}$$

$$\int_{\theta_2}^{\theta'} a d\theta = \int_{\omega_2}^{\omega'} \omega d\omega, \omega'^2 = 2a(\theta' - \theta_2) + \omega_2^2, \quad \textbf{(16)}$$

Where

a is constant;

$\theta^{'}$ is real position of rotor;

$\omega^{'}$ is corresponding set speed under position θ'.

In order to decrease the calculating process of the processor, the curve of position-square of speed (θ-ω^2) is adopted in the actual system. As shown in equations above, the $\omega^{'}$ at a given position $\theta^{'}$ is used to make the computing easy to implement. The error between real speed and set speed can be regulated dynamically by change the torque-angle.

4) Positioning

Assume the set position is θ^*, then the given step counts of the stator's magnetomotive force is $k^* = Int(p\frac{\theta^*}{\theta_b})$. When the system decelerates almost to zero in term of the θ-ω^2 curve, the stator's current （magnetomotive force）is given according to the step k^* and kept, then the reset torque $T_e=T_{max}sin(k^*\theta_b-p\theta)$, will try to force the rotor back to the position $k^*\theta_b$. So $\theta=k^*\theta_b$. Thus the position control is realized and the error of the system is less then one step angle θ_b.

V. Experimental Results

The experimental system is composed of a PMSM and an inertia wheel. The PMSM is 1.6KW M205B style made in KOLLMONGEN of USA. The inertia wheel is a steel disk with its equivalent moment of inertia: 3.08×10^{-2} kg/m^2. The gear ratio is 1920. The equivalent load torque converted to the motor side is almost zero.

Position precision: At the load side 0.2mil. At the motor side position precision is 23° mechanical degree. The time running 30° at the load side is less than 4.9sec. (At the motor side: 57600°/4.9s).

Fig. 7. Experimental device

Results from the experiments indicate that the running time is less than 4.85s and the position error is less than 15º when the given position is θ^*=57600° and the stable speed is 3200r/min. The speed and position curves are shown in Fig.8 (a).

In the braking period, in order to ensure the position precision, according to the three-segment curve, the point at which the motor begin to decelerate should be calculated first under the current set speed. Then at each interruption the set speed is calculated. Here, the square of speed is used to replace the speed i.e. the $\omega^2=f(\theta)$ curve. Fig.8 (b) is the curve set speed and real speed. It is obvious that the real speed follows accurately the set speed.

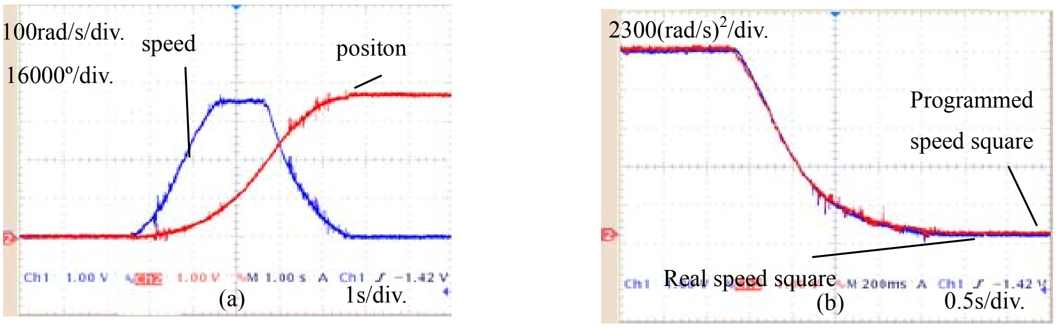

Fig. 8. (a) Three-segment speed and position curves;(b) The compared curves of speed square

The DCVC is adopted to fulfill rotor position tracking by the given discrete stator magnetomotive force, as shown in Fig.9 (a). Continuous current is transformed to discrete current. Here, b_H is 12. In order to express the tracking performance of the current, the real current curve is moved down a grid artificially. Fig.9 (b) shows the curve that real current tracks the given current. Fig.9 (b) proves the good current tracking performance.

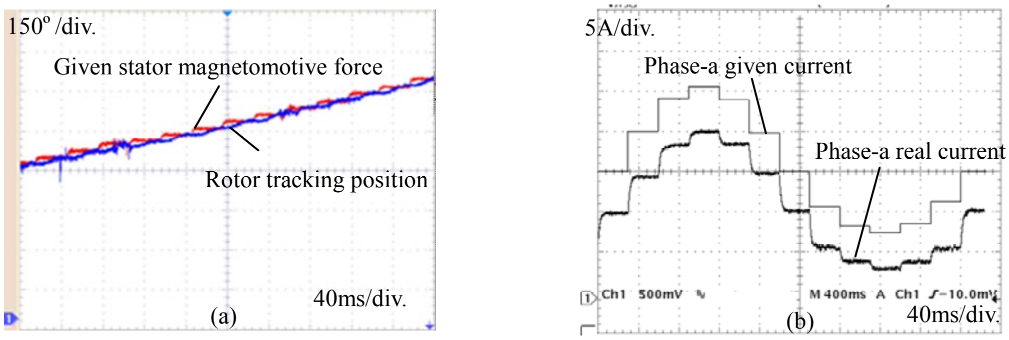

Fig. 9. (a)The rotor motion curve tracking the stator force ;(b) The phase-a current tracking curve

VI. Conclusion

In this paper, on the base of analyzing the torque-angle characteristics of PMSM, the DCVC theory is proposed and used in PMSM position control system. Very good current tracking performance is gotten and then the DCVC is analyzed in each period: accelerated install period, stable period, running period, braking period and positioning period. In the experiments, the DCVC method is proved that it has many merits such as fast torque response, easy to implement, less affected by motor parameters, good robustness, and torque ripple can be diminished by setting b_H high number.

References

[1] Depenbrock M,"Direkte Selbstregelung (DSR) für Hochdynamische mit Umrichtersptisun", ETZ-Archiv, vol.7,1985, pp211-218.

[2] Weizhe Qian, Sanjib K. Panda, Jian-Xin Xu, "Torque Ripple Minimization in PM Synchronous Motors Using Iterative Learning Control", IEEE Transactions on power electronics, vol. 19, 2004, pp272-279.

[3] Romeral Luis, Arias Antoni; Aldabas, Emiliano; Jayne, Marcel G. "Novel direct torque control (DTC) scheme with fuzzy adaptive torque-ripple reduction"; Transactions on Industrial Electronics, vol.50, June, 2003, pp 487-492.

[4] Sun Hexu. "AC Step drive system", Beijing, China Machine Press. 1996.

[5] B.K.Bose, "An adaptive hysteresis-band current control technique of a voltage-fed PWM inverter for machine drive system, IEEE Trans.Ind. Electron, vol37,1990,pp402-408.
[6] Vanja Ambrožič. Rastko Fišer. David Nedeljković, "Direct current control –a new current regulation principle", IEEE Trans. Vol.18, 2003, pp495-503.

Yan Dong, female, 1973, Ph.D. candidate. Her research interest is power electronics and power drive.

He-xu Sun, male, 1956, Ph.D., professor, IEEE senior member, tutor (Ph.D., Hebei University of Technology). His research interests include modern drive, CIMS.

Zhao-ming Lei, male, 1974, Ph.D. candidate. His research interest is power electronics and power drive.

Li-jun Yun, male, 1973, Ph.D. candidate, his research interests include motion control, computer control and application.