**ISSN** 1749-3889 (print), 1749-3897 (online)
**International Journal of Nonlinear Science**
Vol.8(2009) No.1,pp.110-116

# Study on Improved Nonlinear Hysteresis Controller for Direct Torque Control of Induction Motor

Shibo Li *
Institute of Power and Energy Engineering, Yangzhou University, Yangzhou,225009 China

*(Received 4 June 2009, accepted 30 July 2009)*

**Abstract:**For solving high torque ripple in low speed of classic direct torque control(DTC), a novel nonlinear double-level hysteresis controller of flux and torque of direct torque control for induction motor drives was proposed ,which based on analyzing the rule of torque varying ,and the influence on torque changing of different voltage vectors. The proposed method is simple and eased to realize. The feasibility and correctness were verified by the DTC controller in a 1.1 kw IM setup via a digital signal processor (DSP). Simulation and experimental results indicate that the nonlinear hysteresis controller extends the range of low speed operation and reduces the torque ripple, and increases the low speed torque while maintains the dynamic performance.

**Keywords:**nonlinear hysteresis controller; DTC; induction motor

## 1 Introduction

There are six active voltage vectors and two zero voltage vectors by using voltage source inverter in classic direct torque control (DTC) for induction motor (IM) drives. The stator flux and torque could be restrained in hysteresis through selecting proper voltage vector. The hysteresis controller lie at the heart of DTC scheme, determining not only the appropriate voltage vector selection but also the period of the voltage vector remains selected. At present, voltage vectors are selected commonly in DTC by classic switch table [1, 4], torque self-control [2, 3] and space vector modulation [5] etc.. As the method of switch selecting table being simply and easy to realize, so researches and applications of this strategy are more widely.

However a serial of problems would be caused by using classic switching table. For example, switching frequency would varies both with motor speed and different hysteresis width of flux and torque, and different voltage vectors lead to different torque change in same switching period. So problems, such as torque pulsations, would be caused. For enhancing torque performance of DTC in low speed, based on analysis of torque varying rule, the effect on torque by positive vector and back vector, and zero vector in same operation condition should be to analyze. The classic switching table should be improved, and the classic comparators of flux and torque were replaced by two-level nonlinear hysteresis in this paper. The proposed scheme, digital simulations, implementation data, and test results with improved DTC are given and discussed.

## 2 Torque Varing Rule of DTC

### 2.1 Induction Motor Model

Only the dc-link voltage and two line currents are measured. The IM model in stationary frame is:

$$\omega_s = R_s i_s + \frac{d\psi_s}{dt} \tag{1}$$

---

[*] *E-mail address*: lsb@yzu.edu.cn ; Tel. : +86-514-87978339; Fax: +86-514-87971315.

$$0 = R_r i_r + \frac{d\psi_r}{dt} - j\omega_r \psi_r \tag{2}$$

$$\psi_s = L_s i_s + L_m i_m \tag{3}$$

$$\psi_r = R_r i_r + L_m i_s \tag{4}$$

where $u_s$ is stator voltage, $i_s$, $i_r$ are stator and rotor current, $R_s$, $R_r$, $L_s$, $L_r$, $L_m$ are the motor parameters, $\omega_r$ is the motor speed.

The electromagnetic torque is:

$$T_e = \frac{3}{2} P \frac{L_m}{\sigma L_s L_r} \vec{\psi}_s \times \vec{\psi}_r = \frac{3}{2} P \frac{L_m}{\sigma L_s L_r} |\vec{\psi}_s| \cdot |\vec{\psi}_r| \sin\gamma \tag{5}$$

with the $p$ is number of pole pairs, $\gamma$ is the is the angle between rotor and stator fluxes, $\sigma = (L_s L_r - L_m^2)/(L_s L_r)$ is motor Leakage coefficient.

## 2.2 Torque Varying Rule of DTC [7, 8]

Assume sampling period $T_s$ is very small, discrete state equations can be obtained based on IM equations (1)-(5). The stator and rotor flux in $t_{k+1}$ can be expressed as below

$$\vec{\psi}_{sk+1} = \vec{\psi}_{sk}(1 - \frac{R_s}{\sigma L_s} T_s) + \vec{\psi}_{rk} \frac{L_m R_s}{\sigma L_s L_r} T_s + \vec{\nu}_{sk} T_s \tag{6}$$

$$\vec{\psi}_{rk+1} = \vec{\psi}_{rk} + \vec{\psi}_{rk}(j\omega_{rk} - \frac{R_r}{\sigma L_r} T_s) + \vec{\psi}_{sk} \frac{L_m R_r}{\sigma L_s L_r} T_s \tag{7}$$

Stator flux varying rule caused by stator voltage vector $\nu_{sk}$ during $t_k$ $t_{k+1}$ is described through equation (6). If stator resistance $R_s$ is omitted, equation (8) can be obtained.

$$\vec{\psi}_{sk+1} \approx \vec{\psi}_{sk} + \vec{\nu}_{rk} T_s \tag{8}$$

It is known that stator flux will track along with the direction of the stator voltage vector $\vec{\nu}_{sk}$ . So stator flux may move in fixed trace by selecting proper voltage vector. The torque discrete equation also can be obtained according to equation (5):

$$T_{ek+1} = \frac{3}{2} P \frac{L_m}{\omega L_s L_r} \vec{\psi}_{sk+1} \times \vec{\psi}_{rk+1} = \frac{3}{2} P \frac{L_m}{\sigma L_s L_r} \vec{\psi}_{sk+1} \bullet j\vec{\psi}_{rk+1} \tag{9}$$

Put equation (6) and (7) into equation (9), and neglect the square of $T_s$ , the torque in $k_{t+1}$ is expressed as below

$$T_{ek+1} = T_{ek} + \Delta T_{ek} = T_{ek} + \Delta T_{ek1} + \Delta T_{ek2} \tag{10}$$

where $\Delta T_{ek}$ is torque increment, including $\Delta T_{ek1}$ and $\Delta T_{ek2}$, the detailing expressions of two increments are deduced as follows:

$$\Delta T_{ek1} = -T_{ek}(\frac{R_s}{\sigma L_s} + \frac{R_r}{\sigma L_r}) T_s \tag{11}$$

$$\begin{aligned} \Delta T_{ek2} &= \frac{3}{2} P \frac{L_m}{\sigma L_s L_r} [(\vec{\nu}_{sk} - j\omega_{rk} \vec{\psi}_{sk} \bullet j\vec{\psi}_{rk})] T_s = \frac{3}{2} P \frac{L_m}{\sigma L_s L_r} (\vec{\nu}_{sk} \bullet j\vec{\psi}_{rk} - \omega_{rk} \vec{\psi}_{sk} \bullet \vec{\psi}_{rk}) T_s \\ &= \frac{3}{2} P \frac{L_m}{\sigma L_s L_r} [-\nu_{dsk} \psi qrk + \nu_{qsk} \psi_{drk} - \omega_{rk}(\psi_{dsk} \psi_{drk} + \psi_{qsk} \psi_{qrk})] T \end{aligned} \tag{12}$$

The increment $\Delta T_{ek1}$ is the attenuation of torque caused by resistance of stator and rotor. It is direct proportion to torque $T_{ek}$ in $t_k$ , and having nothing to do with voltage vector $\vec{\nu_k}$ and rotor speed $\omega_r$. The increment $\Delta T_{ek2}$ represents the influence on torque change by voltage vector, which is affected by operation status of IM. It is due to the effect of back electromotive force $\omega_{rk} \vec{\psi}_{sk}$ under the circumstances of given voltage vector.

At steady operation ($T_{ek} > 0$), the quantities of torque varying by selecting zero vector, positive vector and back vector are deduced as below:

1. The torque increment by selecting zero vector.

$$\Delta T_{ek2}^{0} = -T_{ek}[(\frac{R_s}{\sigma L_s}+\frac{R_r}{\sigma L_r})T_s - \frac{3}{2}P\frac{L_m}{\sigma L_s L_r}\omega_{rk}(\psi_{dsk}\psi_{drk}+\psi_{qsk}\psi_{qrk})]T_s \tag{13}$$

   where $\Delta T_{ek2}^{0}$ is the torque attenuation caused by resistance of stator and rotor. The remains is negative torque caused by back emf [6], and its absolute value will increase with the increasing speed.

2. The torque increment by selecting positive vector.

$$\begin{aligned}\Delta T_{ek2}^{+} &= \frac{3}{2}P\frac{L_m}{\sigma L_s L_r}(-\nu_{dsk}\psi_{qrk}+\nu_{qsk}\psi_{drk})T_s \\ &- T_{ek}[(\frac{R_s}{\sigma L_s}+\frac{R_r}{\sigma L_r})T_s - \frac{3}{2}P\frac{L_m}{\sigma L_s L_r}\omega_{rk}(\psi_{dsk}\psi_{drk}+\psi_{qsk}\psi_{qrk})]T_s\end{aligned} \tag{14}$$

   where $\Delta T_{ek2}^{+} = \frac{3}{2}P\frac{L_m}{\sigma L_s L_r}(-\nu_{dsk}\psi_{qrk}+\nu_{qsk}\psi_{drk})T_s > 0$ , this part is thetorque increment caused by positive vector. Moreover, equation (14) also includes negative torque caused by zero vector.

3. The torque increment by selecting back vector.

$$\begin{aligned}\Delta T_{ek2}^{-} &= \frac{3}{2}P\frac{L_m}{\sigma L_s L_r}(-\nu_{dsk}\psi_{qrk}+\nu_{qsk}\psi_{drk})T_s \\ &- T_{ek}[(\frac{R_s}{\sigma L_s}+\frac{R_r}{\sigma L_r})T_s - \frac{3}{2}P\frac{L_m}{\sigma L_s L_r}\omega_{rk}(\psi_{dsk}\psi_{drk}+\psi_{qsk}\psi_{qrk})]T_s\end{aligned} \tag{15}$$

   where $\Delta T_{ek2}^{-} = \frac{3}{2}P\frac{L_m}{\sigma L_s L_r}(-\nu_{dsk}\psi_{qrk}+\nu_{qsk}\psi_{drk})T_s < 0$ , it is due to negative torque caused by back vector. Similarly, equation (15) includes negative torque caused by zero vector too.

The conclusion can be achieved by analyzing of (13)-(15) as follows:

1. Negative torque caused by zero vectors is affected by IM speed. The higher speed will produce bigger negative torque.

2. The value of torque changing caused by positive vector and back vector also is influenced by IM speed. With speed increasing, torque increment caused by positive vector may decrease while torque increment caused by back vector will increase further.

3. At same operation condition, torque decrement caused by back vector is larger than torque increment by positive vector. The difference between them is two times as large as torque decrement caused by zero vector.

$$|\Delta T_{ek}|^{-} - |\Delta T_{ek}|^{+} = 2|\Delta T_{ek}|^{0} \tag{16}$$

## 3 Improved Two-Level Nonlinear Hysteresis Controller of Stator Flux and Torque

Every voltage vector acting time during control period is in classic digital DTC. According to above analysis, back vector will cause high torque change and ripple.

If all back vectors are replaced of zero vectors in classic DTC, the torque ripple will be reduced, but it will lead new problem: When the IM is operating in low speed at zero load or low load, zero vector acts more time, and the lower speed, its acting time will be longer. In this case, the motor current and flux will be weakened, and system can't operate smoothly longer at low speed.

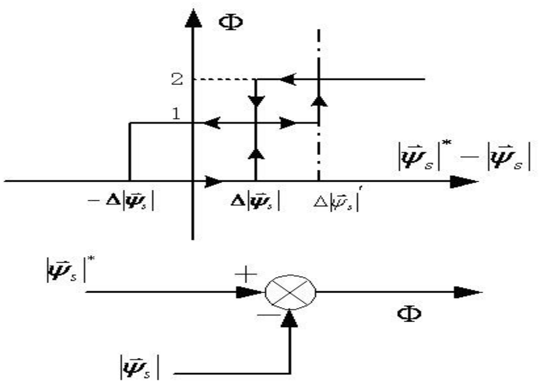


Figure 1: Two-level hysteresis controller of stator flux.

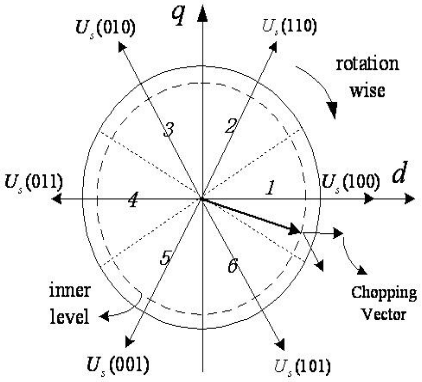


Figure 2: Vector analysis.

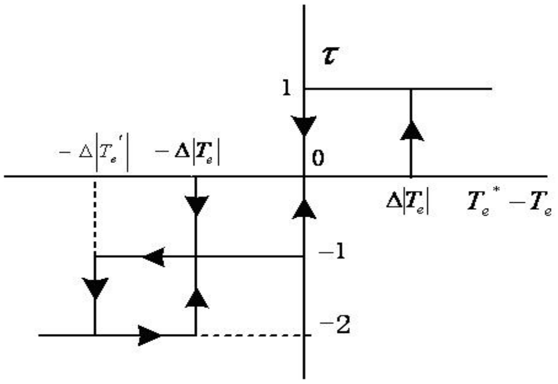


Figure 3: Two-level hysteresis controller of torque.

So an improved two-level hysteresis controller of stator flux method is proposed in this paper. In this way, the classic single-level hysteresis of stator flux was replaced of new two-level hysteresis. On the other hand, the torque was controlled by new two-level hysteresis too, and part of classic switching table was modified correspondingly.

The new stator flux hysteresis is shown in Fig.1.When the difference between the given stator flux and the actual stator flux, is less than outer loop limitation or , the acting manner of improved flux controller is doing like classic method. For reducing torque ripple, the zero vectors substitute for back vectors in modified switching table. When the difference between the given stator flux and the actual stator flux, is more than outer loop limitation or , if the output of torque controller =1, which mean torque needs to increase, the positive vector is selected. And if =0, which mean need keeping torque value, the chopping vector is selected. For example, when the stator flux is in space 1, the chopping vectors are and . Only the chopping vectors, which enlarge flux amplitude, will be selected in proposed system, as shown in Fig.2. The effect of chopping vectors on tangent speed of stator flux is almost as same as zero vectors. So their effect on electromotive torque is like zero vectors basically. If , then the back vectors are replaced of chopping vector. This is similarly as zero vectors substituting for back vector described before.

At lower speed operation, zero vectors acting more time owing to no back vector being adopted, stator flux will be weakened seriously. When stator flux attenuates to inner level (as shown in Fig.2 dashed loop), chopping vector is doing for zero vector, which make flux amplitude increasing rapidly, overcoming shortcoming of zero vector effectively, and keeping advantages of zero vector. As shown in Fig.2, when stator flux rotating to space 1, if it attenuates to inner level, the selecting chopping vector should be , and the selecting positive vector should be .

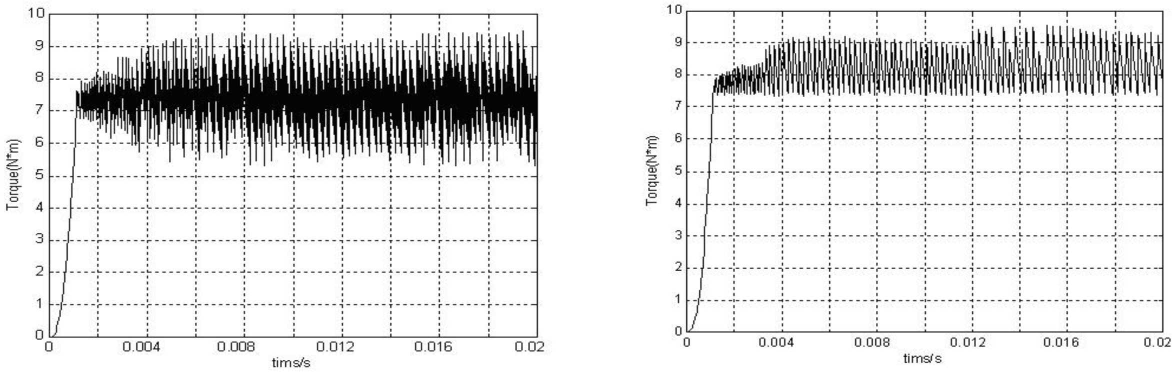
However, if above switching table is adopted completely, other problems will also be produced. Such as, motor can't realize operating in positive and negative turn, and motor decelerating or braking is too slowly. The main reason is due to back vectors removed from classic switching table. Although torque ripple can be reduced, torque decreasing rapidly can't be realized. The eclectically way is employing two-level hysteresis controller of torque. As illustrated in Fig.3, when the output of this hysteresis controller is -2, back voltage vectors begin acting again. When actual torque deviates from outer level, namely =1, 0 or -1, back vector will act no longer.

As known from above analysis, not only torque ripple can be reduced effectively, but also problem of stator flux weakening at low speed is eliminated (or zero speed). On the other hand, torque rapid decreasing is also realized that make motor quickly decelerating and braking.

## 4 Simulation And Experiment Results

### 4.1 Simulation Results

Fig.4 6 show simulation results comparing classic DTC with the improved hysteresis controller presented in this paper. Fig.4 (a) shows torque step response by using back vectors in classic switching table, which torque pulsation reaches to 4N.m. According analysis above, back vector may lead to high torque changing. Fig. 4 (b) shows torque step response, which all back vectors in classic switch table are replaced of zero vectors and torque ripple is restrained to 1.5N.m.



(a) Classic switch table for back vectors.

(b) Zero vectors substitute.

Figure 4: Torque step response

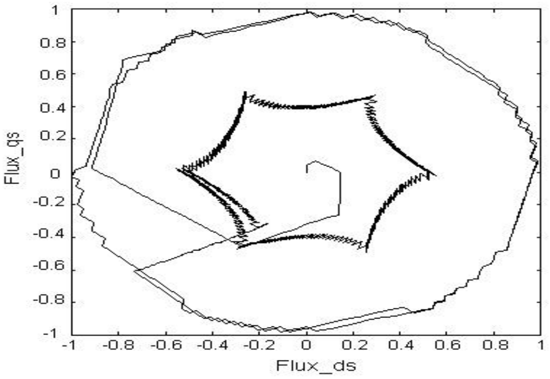


Figure 5: Stator flux linkage of motor in classic DTC.

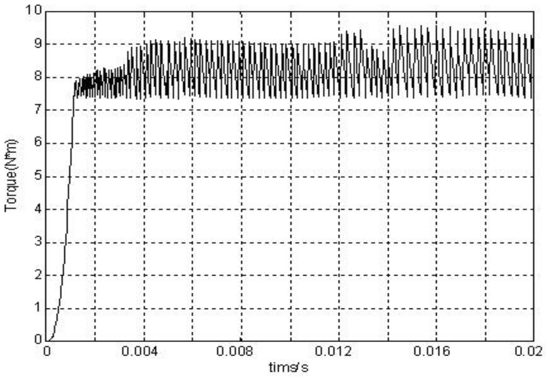
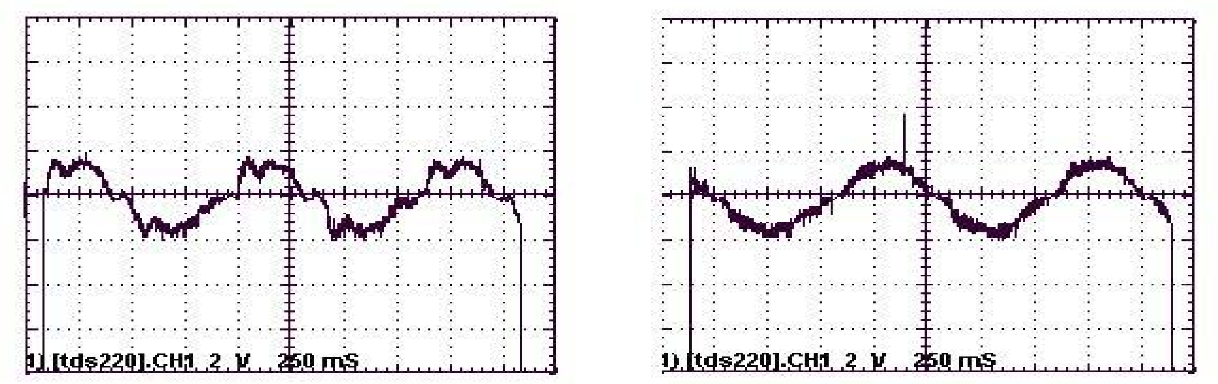


Figure 6: Torque step response by using two-level hysteresis.

Fig.5 shows stator flux linkage simulation curve, which motor starts from 0rad/s to 5rad/s. Stator flux quickly reaches to approximate 1Wb flux circular, but it weaken rapidly to hexagon in steady operation at 5rad/s. And when the motor speed is decreased to 0rad/s, stator flux will attenuate further near to origin. Fig.7 shows torque response by using nonlinear two-level hysteresis controller, which it can be seen that not only torque ripple is reduced to 1.5N.m, but also the problem of stator flux attenuation has been solved.

### 4.2 Experiment Results

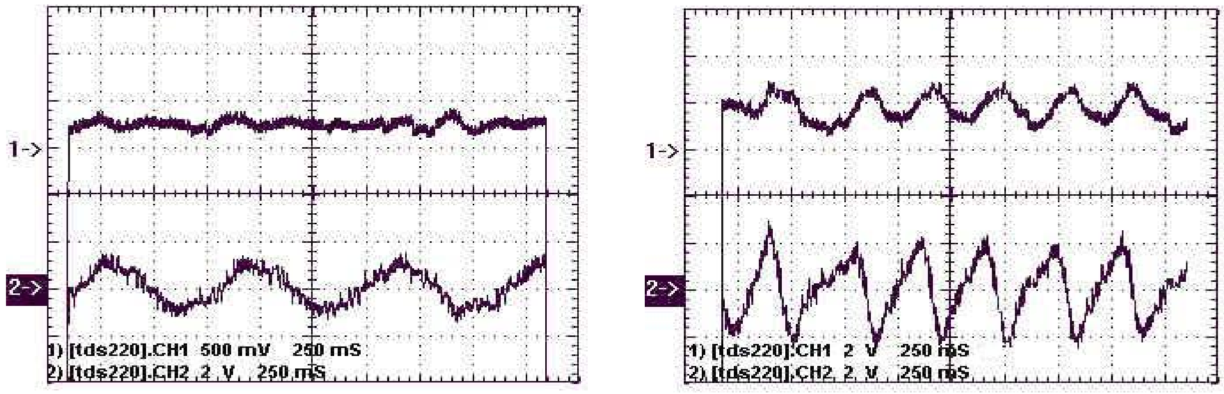
The proposed method was successfully implemented in a 1.1 KW IM setup via a digital signal processor (TMS320LF2407 DSP). Fig. 7 9 show the experimental results when motor runs at low speed. Torque step response by using two-level hysteresis



(a) Classic DTC.

(b) Improved DTC.

Figure 7: Stator phase current at speed of 20rpm



(a) Without load.

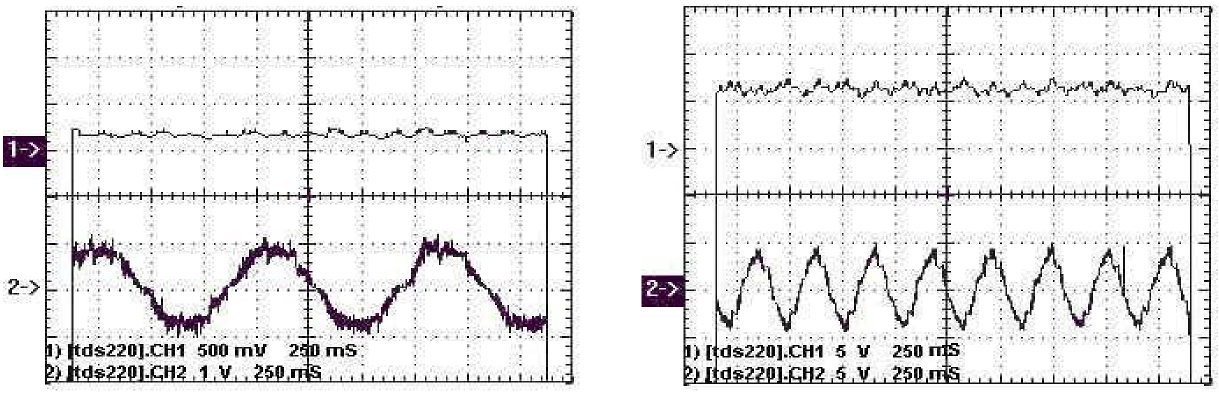
(b) Load torque at 7N.m.

Figure 8: Torque and stator line current in classic DTC at speed of 50rpm (channel 1torque, channel 2stator line current

It can be seen that in proposed system, torque of motor output is steady and powerful, and load torque is overcame effectively to ensuring motor steady operation at command speed.

## 5 Conclusion

The influence of different voltage vector on the torque variation is researched deeply through the theory analysis, and then the classic switching table is replaced with a novel flux and torque two-level switching table. This new switch table is very easy to realize. Simulation and experiment results show that the torque of motor can be improved obviously without degrading dynamic performance of system; the torque ripple and electromagnetic noise is weakened greatly.



(a) Without load. (b) Load torque at 7N.m.

Figure 9: Torque and stator line current in classic DTC at speed of 50rpm (channel 1torque, channel 2stator line current

## References

[1] Isao. Takahashi etc.: A New Quick-Response and High-Efficiency Control Strategy of An Induction Motor. *IEEE Trans. Ind. Application.* 22(5):820-827(1986)

[2] M. Depenbrock: Direct Self-control (DSC) of Inverter-Fed Induction Machine. *IEEE Trans. Ind. Application.* PE-3(4):420-429(1988)

[3] Vanja Ambrozi etc.: Band-Constrained Technique for Direct Torque Control of Induction Motor. *IEEE Trans. Ind. Application.* 51:776-784(2004)

[4] Y.S. Lai and J.H. Chen: A new approach to direct torque control of induction motor drives for constant inverter switching frequency and torque ripple reduction. *IEEE Trans. Energy Conversion.* 16:220-227(2001)

[5] T. G. Habetler, F. Profumno, M. Pastorelli, etc.: Direct Torque control of Induction motor drives using space vector modulation. *IEEE Trans. Ind. Application.* 28(5):1045-1052(1992)

[6] Jiyong Zhang, Hongping Jia: Study on Nonlinear Perpendicular Flux Observer for Direct Torque control of Induction motor. *International Journal of Nonliear Science.* 6(1):73-78(2008)

[7] E. Yusufo glu, A. Bekir: On the Extended Tanh Method Applications of Nonlinear Equations. *International Journal of Nonlinear Science.* 4(1):10-16(2001)

[8] Lixin Tian , Gaogao Dong: Predictive Control of Sudden Occurrence of Chaos. *International Journal of Nonlinear Science.* 5(2):99-105(2008)

## Appendix

Motor Parameters $P_N = 1.1kW$, $p = 2$, $n = 1500r/min$, $R_s = 5.739\Omega$, $R_r = 3.421\Omega$, $L_m = 0.363H$, $L_r = L_s = 0.386H$, $J = 0.0267Kg\dot{m}^2$, $\Psi_s^* = 1Wb$.