A Novel Direct Torque Control of Induction Motor

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Abstract - This paper describes a control scheme for direct torque and flux control of Induction machines using space vector modulation. The proposed predictive flux control scheme has directly calculated the reference voltage space vector based on Stator flux errors in order to control the torque and flux.

This proposed control scheme has not the requirement of a separate current error, thereby improving transient performance and also has the advantage of less torque ripple in steady state with a fixed switching period. The effect of proposed method has been proven by simulations. It is concluded that the proposed control topology produces better results for steady state operation than the classical direct torque control.

Ⅰ.Instruction

In recent years, the application fields of direct torque control of induction machines have greatly increased in the areas of traction, paper and steel industry, and so on.

The direct torque control (DTC) is one of the actively researched control scheme which is based on the decoupled control of flux and torque providing a very quick and robust response with a simple control construction in ac drives. However, Some drawbacks of the conventional DTC strategy using a switching table are the relatively large torque ripple in the steady state and the variation of switching frequency according to the amplitude of hysteresis bands and the motor operating speed [1],[2].

The scheme proposed in this paper is also based on direct control of the torque and flux but has the advantage of a fixed switching period and the minimization of the torque and stator current ripple. With this scheme, the requirement of a separate current regulator and proportional-integral (PI) control of the flux, torque, and/or current error is eliminated, thereby improving transient performance.

This paper introduces a new direct torque and flux control based on SVM for induction motor drives.

The proposed scheme calculates the inverter switching pattern directly in order to control the torque and flux over constant switching period. It is accomplished by calculating the voltage space vector required to control the torque and flux on a cycle-by-cycle basis using the calculated d-axis, q-axis stator flux errors sampled from the previous cycle. The proposed control topologies, digital simulations are given and discussed.

Ⅱ.Proposed Direct Torque Control Strategy

The control block diagram of the proposed DTC is shown in Fig.1. It operates with constant rotor flux, direct stator flux, and torque control. The proposed control block is composed of speed controller, flux observer, reference flux calculator, flux comparator, reference voltage calculator, and space voltage modulation.

The speed controller is a classical proportional-integral (P.I) regulator, which produces the reference torque only.

The stator and rotor flux linkages are calculated from voltage and current models of an IM in flux observer and the reference values of the direct- and the quadrature-axis stator flux are obtained from the torque and the flux commands in the reference flux calculator.

With the results above, the flux comparator produces the flux errors in a stator flux reference frame.

If the switching frequency is constant, the reference voltage vectors can be obtained from stator flux errors with voltage drop terms. The SVM unit produces the inverter control signals which are determined from the reference voltage.

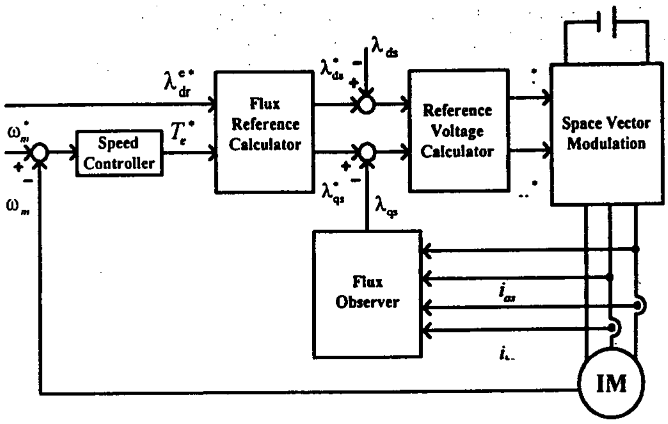


Fig.1 block scheme of the proposed D.T.C

A. Basic Induction Motor Equations

An equivalent circuit in the general rotating reference frame model of inverter-driven induction machine is shown in Fig.2, and the stator and rotor voltage equations are defined in equation (1), (2).

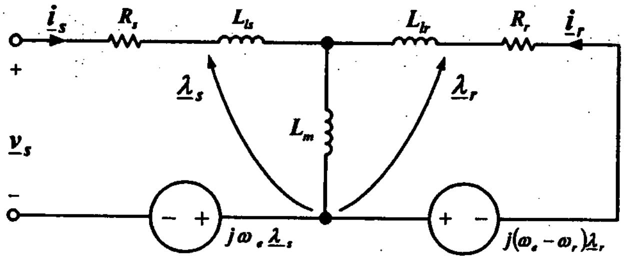


Fig.2. Equivalent circuit in the general rotating reference frame model of inverter-driven induction machine

$$\underline{v}_s = R_s\underline{i}_s + p\underline{\lambda}_s + j\omega_e\underline{\lambda}_s \qquad (1)$$

$$\underline{v}_r = R_r\underline{i}_r + p\underline{\lambda}_r + j(\omega_e - \omega_r)\underline{\lambda}_r \qquad (2)$$

The stator and rotor flux linkage space vector are defined as

$$\underline{\lambda}_s = L_s\underline{i}_s + L_m\underline{i}_r \qquad (3)$$

$$\underline{\lambda}_r = L_r\underline{i}_r + L_m\underline{i}_s \qquad (4)$$

Where $\underline{v}_s$ is the stator voltage vector, $\underline{i}_s$, $\underline{i}_r$ are the stator and rotor currents respectively, $\underline{\lambda}_s$, $\underline{\lambda}_r$ are the stator and rotor flux, respectively, R_s, R_r, L_s, L_r, L_m are the motor parameters. ω_r is the rotor speed, ω_e is the reference frame speed and p is the derivation operator.

The electromagnetic torque can be written in terms of stator and rotor flux as

$$\begin{aligned} T_e &= \frac{3}{2}\frac{P}{2}\frac{L_m}{\sigma L_s L_r}\mathrm{Im}[\underline{\lambda_r^*\lambda_s}] \\ &= \frac{3}{2}\frac{P}{2}\frac{L_m}{\sigma L_s L_r}(\lambda_{dr}\lambda_{qs} - \lambda_{qr}\lambda_{ds}) \\ &= \frac{3}{2}\frac{P}{2}\frac{L_m}{\sigma L_s L_r}|\underline{\lambda_r}||\underline{\lambda_s}|\sin\eta \qquad (5) \end{aligned}$$

Where P is the number of poles of the machine and * denotes the complex conjugate. η is the angle between the stator and the rotor flux-linkage space vectors, as shown in Fig. 3, σ is leakage coefficient with

$$\sigma = (1 - \frac{L_m^{\ 2}}{L_s L_r}) \qquad (6)$$

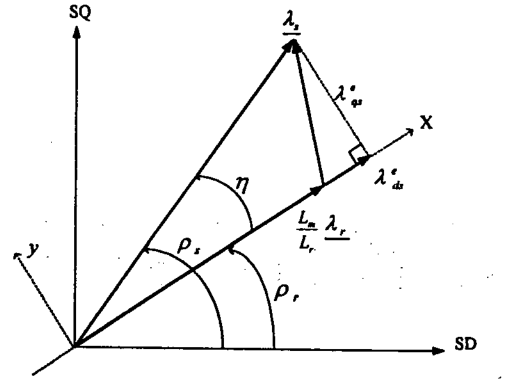


Fig.3. Stator flux-linkage, Rotor flux-linkage space vectors.

Where ρ_s is the angle of the stator flux-linkage space vector with respect to the real-axis of the stationary reference frame.

The rotor time constant of a standard squirrel-cage induction machine is large, thus the rotor flux linkage changes only slowly compared to the stator flux linkage. However, during a short transient, the rotor flux is almost unchanged. Thus rapid changes of the electromagnetic torque can be produced by rotating the stator flux in the required direction, Which is determined by the torque command. It follows from Fig.3 and eqn.(5) that the flux is controlled by the direct-axis stator flux and the torque is controlled by the quadrature-axis stator flux. These two components are directly proportional (stator ohmic drop was neglected) to the components of the stator voltage space vector in the same directions.

B. Flux Observer

The direct- and quadrate-axis stator flux vector are obtained easily from the monitored terminal voltages and or currents by using equation (1). However, achieving high quality torque and flux control in applications requiring both zero and very high speed operation is difficult with this approach. Thus the flux observer utilizing Improved Gopinath Model is adopted to obtain greater accuracy of the flux estimate in wide speed applications in this paper.

The stator flux observer using the Improved Gopinath Model is illustrated in Fig, 3. This flux observer is formed from two open-loop rotor flux observers which are referred to as the voltage and current models.[3]

At high speeds, the voltage model provides an accurate stator flux estimate and the current model estimates an accurate stator flux at a low speed range.

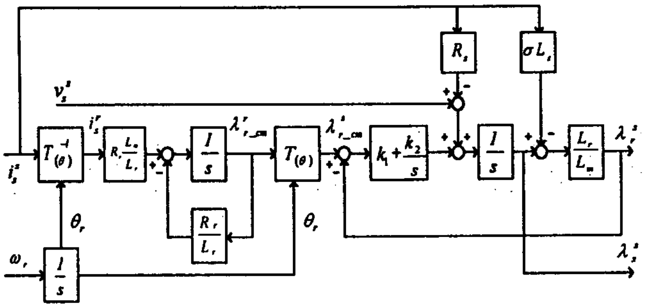


Fig.4. Closed loop stator flux observer based upon Improved Gopinath Model

Rotor flux angle is obtained by the components of rotor flux linkage vector.

$$\theta_e = tan^{-1}\frac{\lambda_{qr}^s}{\lambda_{dr}^s} \qquad (7)$$

C. Flux Reference Calculation

The reference values of the direct- and the quadrature-axis stator flux linkages in the rotor flux reference frame can be calculated from the reference values of the electromagnetic torque and the rotor flux respectively.

The reference value of the quadrature-axis stator flux is determined from the torque command and the rotor flux command by

$$\lambda_{qs}^{e*} = \frac{2}{3}\frac{2}{P}\frac{\sigma L_s L_r}{L_m}\frac{T_e^*}{\lambda_{dr}^{e*}} \qquad (8)$$

The reference value of the direct-axis stator flux is determined from the rotor flux command by

$$\lambda_{ds}^{e*} = \frac{L_m}{L_r}\lambda_{dr}^{e*} + \sigma L_s i_{ds}^{e}$$

$$= \frac{L_m}{L_r}\lambda_{dr}^{e*} + \frac{\sigma L_s}{L_m}(\tau_r p\lambda_{dr}^{e} + \lambda_{dr}^{e}) \qquad (9)$$

The stator flux components in a rotor flux reference frame are transformed into a stator reference frame by

$$\lambda_{ds}^{s*} = \lambda_{ds}^{e*}\cos\theta_e - \lambda_{qs}^{e*}\sin\theta_e$$

$$\lambda_{qs}^{s*} = \lambda_{ds}^{e*}\sin\theta_e + \lambda_{qs}^{e*}\cos\theta_e \qquad (10)$$

D. Flux Comparator and the Reference voltage

Flux comparator compares the reference value of the stator flux vector with the estimated one in the flux observer. The error in the stator flux space vector is readily obtained in flux comparator.

$$\Delta\lambda_{ds}^{s} = \lambda_{ds}^{s*} - \lambda_{ds}^{s}$$

$$\Delta\lambda_{qs}^{s} = \lambda_{qs}^{s*} - \lambda_{qs} \qquad (11)$$

The knowledge of flux error and stator ohmic drop allows the determination of the appropriate voltage space vector which the PWM inverter has to apply to IM during the next sampling period T_s, using the following equation.

$$v_{qs}^{s*} = R_s i_{qs}^{s} + \frac{\Delta\lambda_{qs}^{s}}{T_s}$$

$$v_{ds}^{s*} = R_s i_{ds}^{s} + \frac{\Delta\lambda_{ds}^{s}}{T_s} \qquad (12)$$

Where, T_s is a small control sampling time and it is a half period of the switching frequency. This implies that the torque and flux are controlled twice per switching cycle.

E. Space Vector Modulation

The switching state of the inverter is determined from the reference voltage using space vector PWM[4].

Ⅲ. Simulations of The control scheme

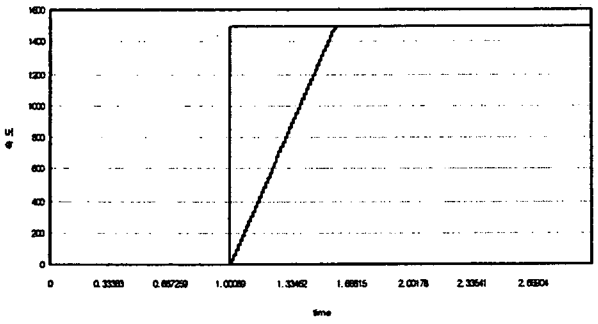
Motor Data

Rated output power	7.5 [kW]
Rated voltage	220[V]
Rated speed	1750[rpm]
Rated torque	39.58[Nm]
Poles	4
Stator resistance	0.15[Ω]
Rotor resistance	0.255[Ω]
Stator self inductance	35[mH]
Rotor self inductance	35[mH]
Mutual inductance	33.9[mH]
Switching frequency	10[kHz]

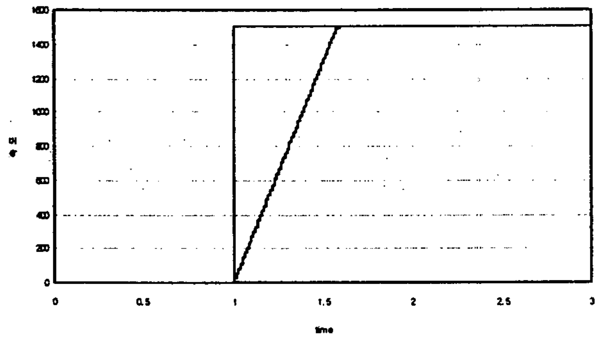
The simulation results illustrate both the steady state and the transient performance of the proposed torque control scheme.

A step change in speed command is presented in Fig.5 and Fig.6 -speed and torque respectively- for proposed DTC and classical DTC.

The torque ripple is drastically reduced, while fast response is preserved.

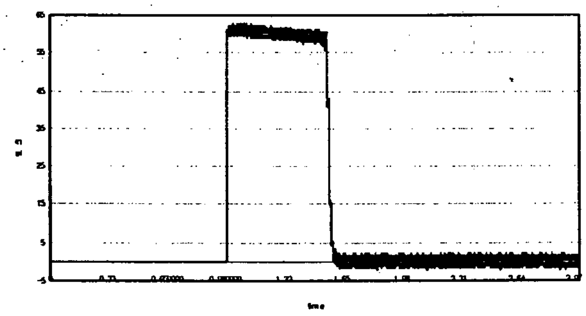


(a) The speed response , in the classical DTC

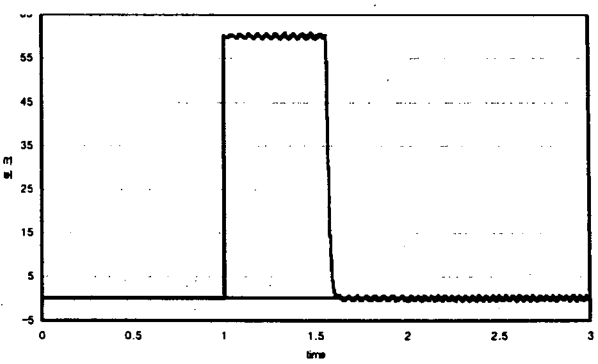


(b) The speed response, in the proposed DTC

Fig. 5) The speed response in a step change of speed command



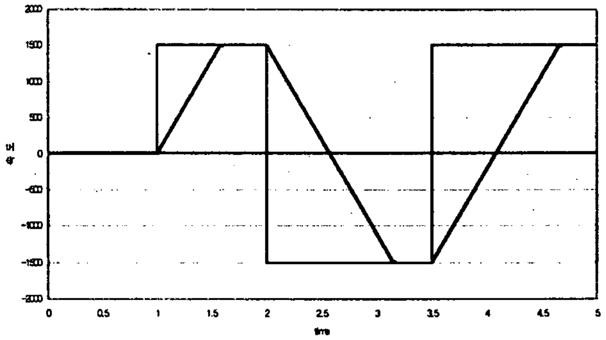
(a) The torque response, in the classical DTC



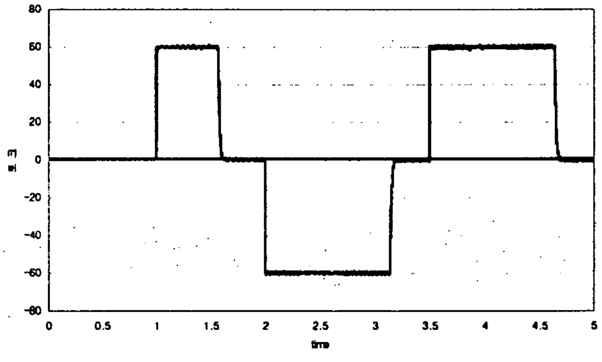
(b) The torque response, The proposed DTC

Fig. 6) The torque response in a step change of speed command

Fig. 7 shows the speed reverse response from 1500[rpm] to -1500[rpm] –speed and torque for proposed DTC.



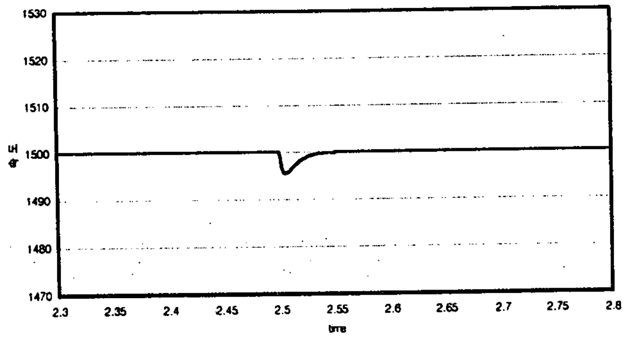
(a) The speed response



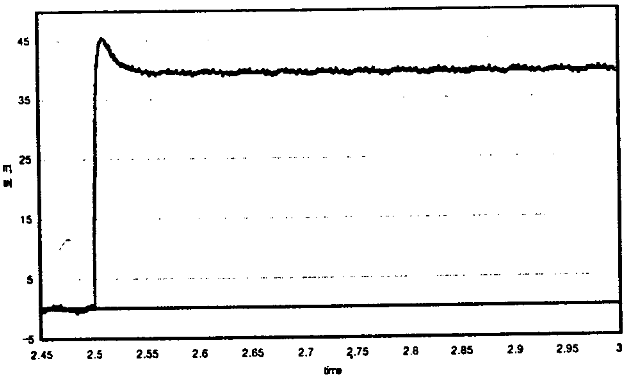
(b) The torque response

Fig.7) The response of the speed reverse command

Only after the application of the load torque, the proposed DTC drive system exhibits a small and fast decreasing speed error in Fig. 8



(a) The speed response



(b) The torque response

Fig. 8) The response of the step injection of load torque

IV.Conclusions

This paper has presented a control scheme for direct torque and flux control of induction machines using space vector modulation. The proposed predictive flux control scheme has directly calculated the reference voltage space vector based on Stator flux errors in order to control the torque and flux.

The main conclusions are as follows.

- The proposed DTC strategy realizes almost ripple free operation for the entire speed range.
- The fast response and robustness merits of the classical DTC are entirely preserved by eliminating PI regulators of flux, torque.
- The switching frequency is constant and controllable by using SVM strategy.

It can be stated that, using the proposed DTC topology, the overall system performance is increased.

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Reference

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