

## A Combined Stator Vector Control – SVM-Direct Torque Control for High Performance Induction Machine Drives

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### Introduction

Electrical drives based on induction motors are the most widely used electromechanical systems in modern industry. Due to their reliability, ruggedness, simple mechanical structure, easy maintenance and relatively low cost, induction motors are attractive for use in a new generation of electrical transportation systems, such as cars, buses and trains. However, from the control point of view, they represent a complex multivariable nonlinear problem and constitute an important area of application for control theory. In fact, induction motors constitute a class of highly coupled and multivariable systems with two control inputs (stator voltages) and two output variables (rotor speed and flux modulus), required to track desired reference signals. Traditionally, rotor field-oriented control (RFOC) has permitted fast transient response by decoupling torque and flux control. This control strategy exploits the fact that in a suitable rotating frame, aligned with the rotor flux space vector, the torque and flux dynamics are decoupled and the induction motor can be efficiently controlled using linear techniques. However, RFOC has several disadvantages such as high computational requirement, high parameter dependence and speed signal for the coordinate transformation. Also, the direct torque control (DTC) technique has gained wide acceptance in motor drive. Although the DTC is a simple control scheme with low computational requirement and has merits like inherent sensorless operation and reduced parameter sensitivity, it has some drawbacks such as operation with variable switching frequency and large torque ripple, due to the hysteresis control and the switching table method. To overcome these problems, the variable switching frequency problem and the torque ripple can be addressed by Proportional-Integral (PI) controllers plus space vector modulation (SVM)]. However, the calculation of the voltage command vector requires the derivative of the stator flux vector, which is kept moving and can be a potential source of errors [1–7].

This paper presents an alternative scheme for torque and stator flux control of an induction machine. The proposed scheme investigates the basic DTC idea, which considers the torque of induction machine proportional with the slip frequency if the amplitude of stator flux vector is kept constant. For that, stator flux orientation technique is used to avoid the requirement of the derivative of stator flux vector and to develop the relationships between the controlled variables and the machine torque. Hence, with the combined stator vector control (SVC) and DTC methods, the torque and stator flux vector can be regulated with PI controllers, and the required voltage vector can be applied to the induction machine by the SVM technique. Furthermore, the estimation of the torque and stator flux is based on voltage mode estimator with minimized sensors numbers. In fact, speed sensor is eliminated and only DC-bus voltage sensor and two AC current sensors are needed.

### Proposed stator vector - direct torque control (SVDTC)

The dynamic model of the induction machine can be represented in the  $(d,q)$  frame as:

$$v_{ds,qs} = R_s i_{ds,qs} + \frac{d\psi_{ds,qs}}{dt} \mp \omega_s \psi_{qs,ds}, \quad (1)$$

$$0 = R_r i_{dr,qr} + \frac{d\psi_{dr,qr}}{dt} \mp \omega_{sl} \psi_{qr,dr}, \quad (2)$$

$$\psi_{ds,qs} = L_s i_{ds,qs} + L_{sr} i_{dr,qr}, \quad (3)$$

$$\psi_{dr,qr} = L_r i_{dr,qr} + L_{sr} i_{ds,qs}, \quad (4)$$

$$T_{em} = p(\psi_{ds} i_{qs} - \psi_{qs} i_{ds}). \quad (5)$$

where  $(v_{ds}, v_{qs})$  – stator voltages;  $(\psi_{ds}, \psi_{qs})$  – stator fluxes;  $(\psi_{dr}, \psi_{qr})$  – rotor fluxes;  $(i_{ds}, i_{qs})$  – stator currents;  $(i_{dr}, i_{qr})$  – rotor currents;  $R_s$  and  $R_r$  – stator and rotor resistances;  $L_s$  and  $L_r$  – stator and rotor inductances;  $L_{sr}$  – mutual inductance;  $p$  – number of pole pairs;  $\omega_s$  and  $\omega_m$  – stator

and rotor angular speed;  $\omega_{sl}$  – slip angular speed ( $\omega_s - \omega_m$ );  $T_{em}$  – electromagnetic torque.

It is known that the stator field-orientation method is based on the alignment of stator flux vector with the  $d$ -axis and setting the stator flux to be constant equal to its rated value, which means:

$$\psi_{ds} = \psi_s; \psi_{qs} = 0. \quad (6)$$

Then, (1) and (5) can be simplified to:

$$v_{ds} = R_s i_{ds} + \frac{d\psi_s}{dt}, \quad v_{qs} = R_s i_{qs} + \omega_s \psi_s, \quad (7)$$

$$T_{em} = p\psi_s i_{qs} \quad (8)$$

and the rotor currents and rotor fluxes can be expressed as:

$$i_{dr} = \frac{1}{L_{sr}} (\psi_s - L_s i_{ds}), \quad i_{qr} = -\frac{L_s}{L_{sr}} i_{qs}, \quad (9)$$

$$\psi_{dr} = \frac{L_r}{L_{sr}} (\psi_s - \sigma L_s i_{ds}), \quad \psi_{qr} = -\frac{\sigma L_r L_s}{L_{sr}} i_{qs}, \quad (10)$$

where  $\sigma = 1 - L_{sr}^2 / (L_s L_r)$  – the total leakage constant.

By substituting (9) and (10) in (2) and considering the Laplace operator ( $s = d/dt$ ), (11) can be obtained:

$$\begin{cases} \psi_s(s) = \frac{\sigma T_r L_s}{1 + T_r s} \left[ \left( \frac{1}{\sigma T_r} + s \right) I_{ds}(s) + I_{qs}(s) \omega_{sl}(s) \right], \\ I_{qs}(s) = \frac{\sigma T_r \omega_{sl}(s)}{1 + \sigma T_r s} \left( \frac{1}{\sigma L_s} \psi_s(s) - I_{ds}(s) \right), \end{cases} \quad (11)$$

where  $T_s = L_s / R_s$  and  $T_r = L_r / R_r$  – the stator and rotor time constant, respectively.

Thus, by expressing  $I_{ds}$  and  $I_{qs}$  according to the stator flux, the stator voltages become:

$$\begin{cases} V_{ds}(s) = \frac{\psi_s(s)}{G_{\psi s}(s)} + E_d(s), \\ V_{qs}(s) \approx \omega_s(s) \psi_s(s), \end{cases} \quad (12)$$

where

$$\begin{cases} G_{\psi s}(s) = \frac{T_s (1 + \sigma T_r s)}{1 + (T_r + T_s)s + \sigma T_r T_s s^2}, \\ E_d(s) = -\frac{\sigma R_s T_r}{1 + \sigma T_r s} I_{qs}(s) \omega_{sl}(s). \end{cases} \quad (13)$$

Hence, it can be seen that the stator flux can be regulated by the  $d$ -component of stator voltage. Fig. 1 shows the relationship between  $\psi_s$  and  $V_{ds}$ ; a second-order equivalent system with a disturbance  $E_d$ .

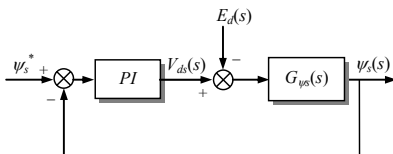


Fig. 1. Closed-loop control of stator flux

From (11), the  $q$ -component of stator current can be expressed as:

$$I_{qs}(s) = \frac{K_\sigma \psi_s(s) \omega_{sl}(s)}{(1 + \sigma T_r s)^2 + (\sigma T_r \omega_{sl}(s))^2}, \quad (14)$$

where  $K_\sigma = (1 - \sigma)T_r / L_s$ .

Hence, (8) becomes:

$$T_{em}(s) = \frac{pK_\sigma \psi_s^2(s) \omega_{sl}(s)}{(1 + \sigma T_r s)^2 + (\sigma T_r \omega_{sl}(s))^2}. \quad (15)$$

From the basic DTC principle, if the amplitude of stator flux vector is kept constant and equal to its reference value  $\psi_s^*$ , the machine torque is proportional with the slip angular speed. Therefore, with the small values of the slip angular speed, (15) can be simplified to:

$$T_{em}(s) = G_{Tem}(s) (\omega_s(s) - \omega_m(s)), \quad (16)$$

where

$$G_{Tem}(s) = \frac{pK_\sigma (\psi_s^*)^2}{(1 + \sigma T_r s)^2}. \quad (17)$$

Thus, the machine torque can be regulated by controlling the rotating speed of the stator flux vector. Fig. 2 shows the relationship between  $T_{em}$  and  $\omega_s$ ; a second-order equivalent system with a disturbance  $\omega_m$ .

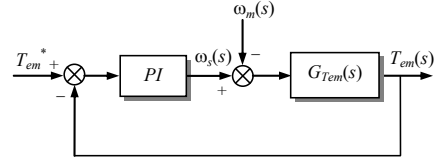


Fig. 2. Closed-loop control of electromagnetic torque

### Space vector pulse-width modulation technique (SVM)

Since the controllers produce the voltage command vector, appropriate space voltage vector can be generated with Space Vector Modulation (SVM) and fixed switching frequency can be achieved. The SVM technique is used to create a reference vector by modulating the cyclic ratios of switches in each of the six sectors shown in Fig. 3.

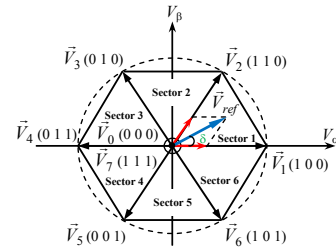


Fig. 3. Switching states of space vector modulation

However, with the SVM method, the reference voltage should be limited to ensure that the voltage command is lower or equal to the maximum inverter voltage:



## Conclusion

This paper has provided a novel direct torque control method to improve high performance drive of an induction machine. The proposed control combines the basic ideas of both stator vector control (SVC) and direct torque control (DTC). With SVC, the amplitude of stator flux vector is kept constant and the relationship between the machine torque and the slip angular speed is fully developed. Thus, the electromagnetic torque can be regulated as in the case of direct torque control, and the PI controllers and SVM technique can be used to obtain a fixed switching frequency and low torque ripple. Furthermore, the estimation of the machine torque and stator flux is based on voltage mode estimator with minimized sensors numbers, and only DC-bus voltage sensor and two AC current sensors are needed.

The simulation results indicate that SVDTC of induction machine can achieve precise control of the stator flux and machine torque. Compared to conventional DTC, presented method is easily implemented, and the steady performances of ripples of both torque and flux are considerably improved.

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**M. Bounadja, B. Belmadani, A. W. Belarbi. A Combined Stator Vector Control – SVM-Direct Torque Control for High Performance Induction Machine Drives // Electronics and Electrical Engineering. – Kaunas: Technologija, 2009. – No. 8(96). – P. 51–54.**

In this paper, a novel direct torque control method has been proposed for high performance induction machine drives. The control system enjoys the advantages of stator vector control and direct torque control and avoids some of the implementation difficulties of either of the two control methods. The stator flux orientation is used to keep constant the amplitude of stator flux vector, and to develop the relationship between the machine torque and the slip angular speed. At this stage, the electromagnetic torque can be regulated as in the case of direct torque control. The proportional–integral controllers and space vector modulation technique are used to obtain a fixed switching frequency and low torque ripple. Simulation experiments results indicate that, with the proposed scheme, a precise control of the stator flux and machine torque can be achieved. Compared to conventional direct torque control, presented method is easily implemented, and the steady performances of ripples of both torque and flux are considerably improved. Ill. 5, bibl. 7 (in English; summaries in English, Russian and Lithuanian).

**М. Боинадья, Б. Белмадани, А. В. Беларби. Применение комбинированного контроля вектора статора для прямого контроля момента вращения в индукционных машинах большой производительности // Электроника и электротехника. – Каунас: Технология, 2009. – № 8(96). – С. 51–54.**

Предложен новый способ контроля прямого момента вращения. Система обеспечивает контроль управления вектором статора и момента прямого вращения. В результате отпадают трудности при реализации одного из двух методов контроля. Для поддержания направления потока статора используется постоянная амплитуда вектора потока статора. Это используется и при исследовании связей между моментом вращения машины и угловой скоростью. Электромагнитный момент можно корректировать, так же как и момент вращения при прямом управлении. Пропорциональное интегральное управляющее устройство. Из результатов моделирования следует, что при применении предлагаемой системы обеспечивается необходимый контроль потока статора и момента вращения. Илл. 5. библи. 7 (на английском языке; рефераты на английском, русском и литовском яз.).

**M. Bounadja, B. Belmadani, A. W. Belarbi. Kombinuotosios statoriaus vektoriaus kontrolės tyrimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2009. – Nr. 8(96). – P. 51–54.**

Pasiūlytas naujas tiesioginio sukimo momento kontrolės būdas. Kontrolės sistema sudaryta iš statoriaus vektoriaus valdymo ir kontroliuojamo tiesioginio sukimo momento, todėl išvengiama tam tikrų sunkumų įgyvendinant vieną iš dviejų kontrolės metodų. Statoriaus srauto kryptį palaikyti naudojama pastovi statoriaus srauto vektoriaus amplitudė, susiejanti mašinos sukimo momentą ir kampinį greitį. Elektromagnetinis momentas gali būti koreguojamas taip pat kaip ir tiesioginio valdymo sukimo momentas. Proporcinis integralinis valdiklis ir erdvinė vektorinė moduliavimo technologija taikoma nustatytam perjungimo dažniui ir mažam sukimo momentui gauti. Modeliavimo rezultatai rodo, kad, taikant siūlomą sistemą, užtikrinama tiksli statoriaus srauto ir sukimo momento kontrolė. Il. 5, bibl. 7 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).