

ASYNCHRONOUS MACHINES WITH PWM INVERTERS: A NOVEL APPROACH TO DTC ENHANCEMENT

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Abstract. *This paper presents some methods of direct torque control (DTC) improvement for asynchronous machine (AM) with PWM inverter. Asynchronous machine DTC is recognized to have a straightforward control structure and work similarly to field orientation control (FOC). Two new strategies are presented to retain this control structure while simultaneously improving the switching frequency and stator flux estimate performances of the DTC drive. Finally, some proposed schemes for improved DTC and simulation results are presented.*

Keywords: asynchronous machine, DTC method, PWM inverter, switching frequency, stator flux estimation

1. INTRODUCTION

DTC is one method that variable frequency drives employ to control the torque—and eventually the speed—of AC electric motors. An approximation of the motor's torque and magnetic flux is computed using the voltage and current measurements.

In order to provide a quick and accurate dynamic torque response, DTC was invented. It is a viable substitute for field orientation control (FOC), [1-6]. The DTC system is fairly basic, consisting of a voltage source inverter (VSI), torque and flux calculator, and DTC controller in its basic version. Because there is no frame transformer present, the configuration is far simpler than that of the FOC system. Additionally, it is not necessarily necessary to use a position encoder or pulse width modulator, which cause delays and call for mechanical transducers.

Hysteresis comparators-based DTC drives often have two issues: inaccurate stator flux estimates that might impair drive performance and variable switching frequency caused by the hysteresis comparators, [7-8]. Some techniques to keep the average switching frequency constant are: space vector modulation, predictive control, artificial intelligence. However, the drive system becomes more complex as a result of all these strategies, [9].

This study proposes different ways to replace the traditional 3-level hysteresis comparator with a simple torque controller, maintaining a constant switching frequency. A straightforward compensator based on steady state operations is utilized to offset the magnitude and phase errors related to stator flux calculation, which is based on voltage models.

The basic configuration of a PWM inverter for asynchronous machine with direct torque control is shown in Figure 1, [4],[7]:

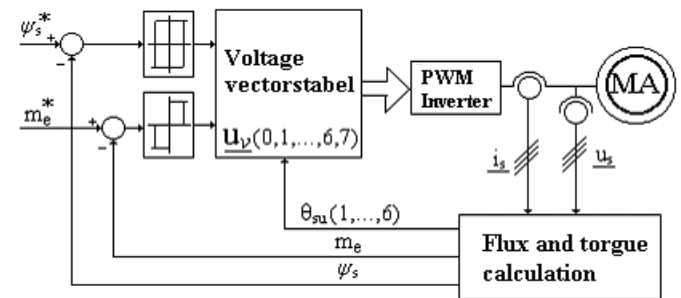


Figure 1. DTC scheme configuration.

This adjusting mode is appropriate for controlling position or speed; it conducts stabilization adjustments up to approximately 0.1 rotations per hour.

This control method has a separate voltage modulator for control of PWM inverter. There are no control loops for the stator current and no axis transform are necessary. Estimating and measuring stator flux and electromagnetic torque is required.

2. METHOD PRESENTATION

Six switching devices within a voltage source inverter can be arranged in eight different ways when coupled to an asynchronous machine. Eight potential input voltage vectors for the induction machine are therefore possible.

The command of the PWM inverter is made with the stator voltage vectors $(\underline{u}_1, \underline{u}_2, \dots, \underline{u}_6, \underline{u}_0, \underline{u}_7)$. It must be seen which is the way of determining of those eight vectors, so that necessary stator flux and electromagnetic torque to be assured.

For selecting the necessary voltage vectors for stator flux control, the equation of stator voltage in fixed $\alpha-\beta$ reference system, by neglecting the stator resistance ($r_s \approx 0$), is:

$$\begin{aligned} d\psi_s^s &\approx \underline{u}_s^s \cdot dt = \underline{u}_{sv} \cdot dt \Rightarrow \\ \Delta \psi_s^s &= \psi_s - \psi_{s0} \approx \underline{u}_{sv} \cdot t \end{aligned} \quad (1)$$

Vector's $\underline{u}_s$ direction is given by $\underline{u}_{sv}(v=1,2,\dots,6,0,7)$, as shown in figure 2.a.

For maintaining the amplitude of stator flux phaser constantly between two limits, proper voltage vector must be applied (figure 2.b.). This vector depends on the initial position $\theta_{su}(N)$ of stator flux phaser $\underline{\psi}_{s0}$.

Orthogonal components of stator flux phaser, in fixed α - β reference system are:

$$\psi_{sa} = \psi_{sa}, \quad \psi_{s\beta} = \frac{1}{\sqrt{3}}(2\psi_{sb} + \psi_{sa}) \quad (2)$$

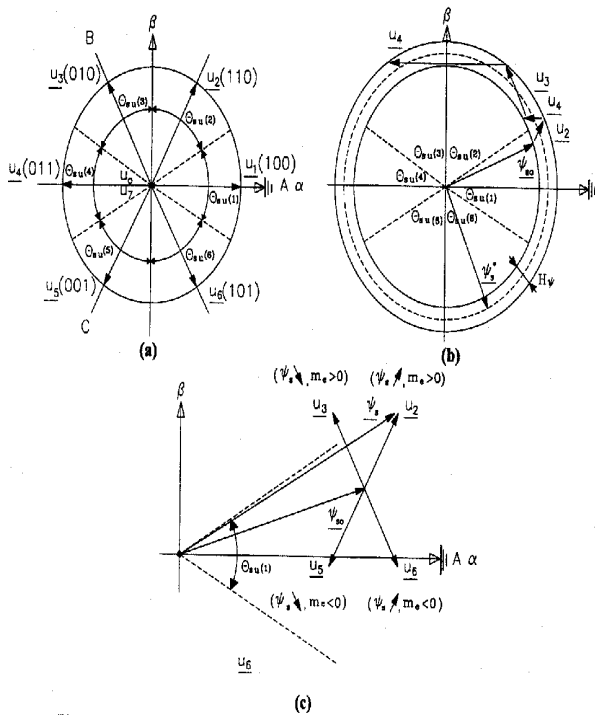


Figure 2. a. Voltage vector direction; b. Maintaining the amplitude of stator flux phaser constantly between two limits; c. Flux error and position information.

Flux error and position information $\theta_{su}(N)$ goes to proper selection of stator voltage vector, which also depends on the electromagnetic torque sign (figure 2.c). With help of the components $\psi_{sa}, \psi_{s\beta}$ and $(\sqrt{3}|\psi_{s\beta}| - |\psi_{sa}|)$ sign, position $\theta_{su}(N)$ is obtained as in the next table:

TABLE 1. Position obtained

sign ψ_{sa}	+	+	-	-	-	+
sign $\psi_{s\beta}$	+, -	+	+	+, -	-	-
sign $(\sqrt{3} \psi_{s\beta} - \psi_{sa})$	-	+	+	-	+	+
$\theta_{su}(N)$	$\theta_{su}(1)$	$\theta_{su}(2)$	$\theta_{su}(3)$	$\theta_{su}(4)$	$\theta_{su}(5)$	$\theta_{su}(6)$

Finally, the table of voltage vectors is obtained, as in figure 3. The variable switching frequency of the voltage source inverter in DTC systems is determined by the existence of hysteresis controllers for torque and flux.

TABLE 2. Voltage vectors

ϕ, τ	$\theta_{su}(1)$	$\theta_{su}(2)$	$\theta_{su}(3)$	$\theta_{su}(4)$	$\theta_{su}(5)$	$\theta_{su}(6)$
$\phi = 1$	$\tau = 1$	$\underline{u}_2$	$\underline{u}_3$	$\underline{u}_4$	$\underline{u}_5$	$\underline{u}_6$
	$\tau = 0$	$\underline{u}_0$	$\underline{u}_7$	$\underline{u}_0$	$\underline{u}_7$	$\underline{u}_0$
	$\tau = -1$	$\underline{u}_6$	$\underline{u}_1$	$\underline{u}_2$	$\underline{u}_3$	$\underline{u}_4$
$\phi = 0$	$\tau = 1$	$\underline{u}_3$	$\underline{u}_4$	$\underline{u}_5$	$\underline{u}_6$	$\underline{u}_1$
	$\tau = 0$	$\underline{u}_7$	$\underline{u}_0$	$\underline{u}_7$	$\underline{u}_0$	$\underline{u}_7$
	$\tau = -1$	$\underline{u}_5$	$\underline{u}_6$	$\underline{u}_1$	$\underline{u}_2$	$\underline{u}_3$

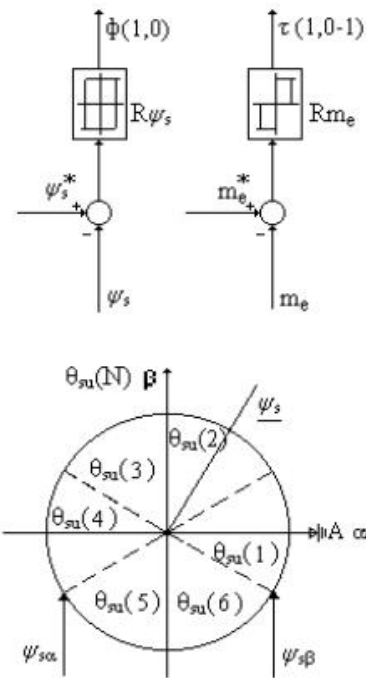


Figure 3. The table of voltage vectors.

There is a high correlation between the amount of accessible voltage vectors and the ability to compensate for torque and flux faults at each cycle phase. According to literature proposals [1–9], non-traditional power circuit topologies can generate a large number of voltage vectors.

In essence, a simplified space vector modulation technique can be introduced while maintaining a typical VSI structure and increasing voltage vectors [10].

The theory of operation states that several voltage vectors at predetermined time intervals can be applied at each cycle period to create new voltage vectors. This method uses a Discrete Space Vector Modulation (DSVM) that just slightly increases computing time [10]. The number of time intervals by which the cycle period

is divided determines the number of voltage vectors that can be generated. It has been confirmed that, without the need for too complicated switching tables, breaking the cycle period into three equal time periods significantly reduces torque and current ripple.

Five voltage vectors are often used in basic DTC methods to adjust for inaccuracies in torque and flux. Nineteen voltage vectors can be employed with three equal time intervals and the DSVM approach. All nineteen voltage vectors should be used to define the voltage vector selection technique.

3. PROPOSED SCHEME FOR IMPROVED DTC

Stator flux and electromagnetic torque errors represent the inputs of the two hysteresis regulators, [6]. Numerical signals, at the outputs of the two regulators, are defined as:

$$\begin{aligned} \text{stator flux regulator } R_\psi \\ \phi = 1, \text{ for } \psi_s^* > \psi_s + H_\psi / 2 \\ \phi = 0, \text{ for } \psi_s^* < \psi_s - H_\psi / 2 \end{aligned} \quad (3)$$

$$\begin{aligned} \text{torque regulator } R_m \\ \tau = 1 \text{ for } m_e^* > m_e + H_m / 2 \\ \tau = 0 \text{ for } m_e^* = m_e \\ \tau = -1 \text{ for } m_e^* < m_e - H_m / 2 \end{aligned} \quad (4)$$

The torque vector-controlled system is presented in figure.4.

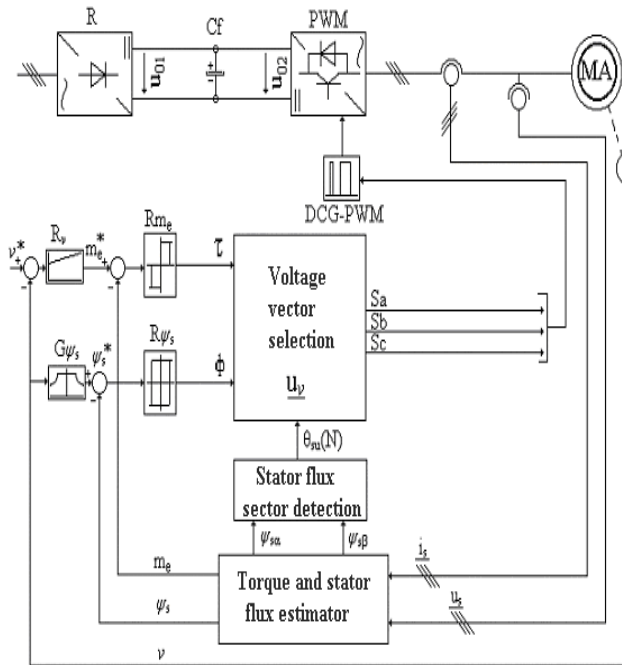


Figure 4. Torque vector-controlled system.

Numerical variables ϕ, τ and $\theta_{su}(N)$ sectors, can create a binary word which can select the proper voltage vector through accessing a memory address (table 2).

Torque and flux components for stator voltage are generated by two regulators, depending on the error between the prescribed torque or flux value and the values obtained at the estimator's output. So, the stator flux is compensated for the d and q components at the operating frequency.

As seen in the figure 5, the adjusted flux can be included in the flux estimator diagram:

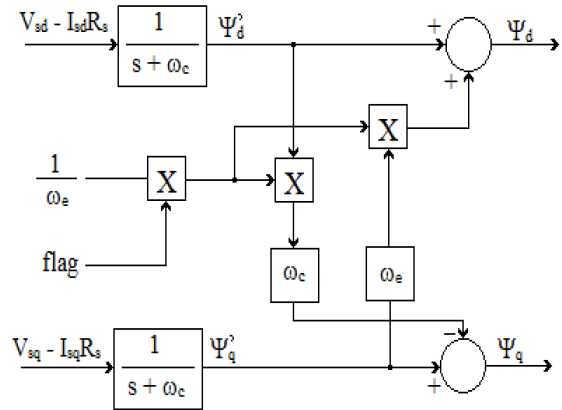


Figure 5. Block diagram of the flux estimator.

The suggested estimation aims to improve the DTC drive's steady state performance.

4. SIMULATION RESULTS

For an induction motor with the stator flux estimator as in figure 5, have been obtained a few simulation results, by using LabVIEW environment.

Figure 6. presents the magnitude of the flux at the top and for the d respective q axis of the stator flux at the bottom.

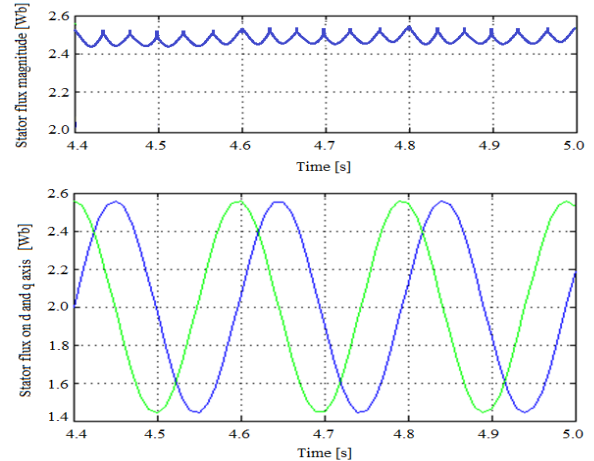


Figure 6. Stator flux magnitude (top); Stator flux d and q axis (bottom).

Other simulation results for the torque are presented in figure 7.

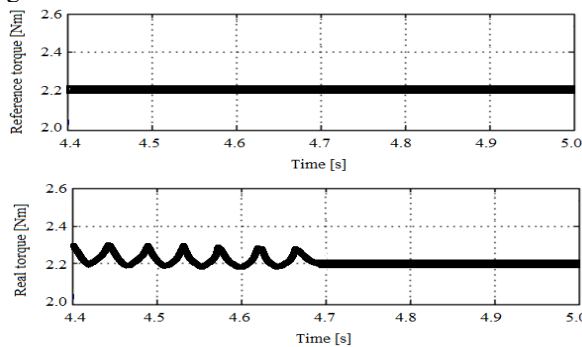


Figure 7. Reference torque (up) and real torque (low).

For DTC based on figure 4, the simulation results are presented in figure 8:

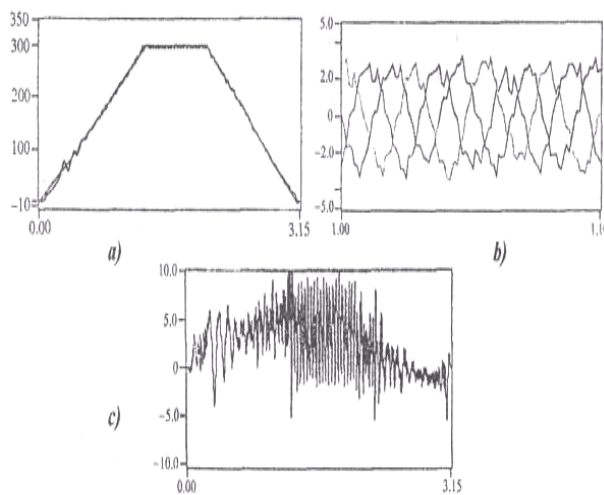


Figure 8. a. Prescribed/obtained speed; b. Phase currents; c. Electromagnetic torque.

No load speed trajectory pursuit at maximum 200 rad/sec with DTC is presented in figure 8. Figure 8.a shows the prescribed/obtained speed, 8.b the phase currents and 8.c the electromagnetic torque.

5. CONCLUSIONS

Physical considerations, analytical advancements, simulations, and experimental results have all been used to analyze the DTC technique for asynchronous machines. The analysis shows how the voltage space vectors can be applied to control the motor torque and the stator flux amplitude.

As in any AM drive without sensors, at low speeds, a DTC drive's performance degrades. It has been demonstrated, therefore, that even under those operating circumstances, the drive performs well when an enhanced flux estimator is used.

For highly dynamic applications, DTC can be the better option than FOC.

This system has a few characteristics:

- Obtaining of sinusoidal currents and flux, content of harmonics been determined of hysteresis band width H_m and H_ψ ;
- Possible functioning with PWM inverter;
- Commutation frequency >2 kHz, which depends on hysteresis band width H_m and H_ψ .

For the proposed scheme, torque and flux components for stator voltage are generated by two regulators, depending on the error between the prescribed torque or flux value and the values obtained at the estimator's output.

For an asynchronous motor with DTC have been obtained a few simulation results under LabVIEW environment. Under steady state conditions, the torque controller ensures a consistent switching frequency. While keeping the DTC drive's straightforward control structure, the DTC's performance is enhanced.

6. CONCLUSIONS

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