Abstract—by principle, Direct Torque Control (DTC) is used to adjust stator flux and electromagnetic torque. Simple structure and very good dynamic behavior are main features of DTC. However classical DTC has some disadvantages, the most important of them is the high ripple torque. In this paper we propose some variety of DTC combined with FOC structures. Hysteresis controllers and switching table are replaced by PI controllers and space vector modulator. Three algorithms work in fixed switching frequency are developed, can overcome the aforementioned drawback.

The proposed schemes are described clearly. Simulation results prove the effectiveness, reliability and correctness of the proposed methods.

Keywords —Direct torque control, Space vector pulse width modulation, Induction motor.

I. INTRODUCTION

A various algorithms of control are implemented and marketed in the industry for induction motor. The most recognized are: Scalar Control (V/f), Field Oriented Control (FOC) and Direct Torque Control (DTC). DTC control was proposed in the middle of 80s by I. Takahashi as alternative for the Field Oriented Control. The DTC strategy proposed to replace motor decoupling and linearization via coordinate transformation, like in FOC, by hysteresis controllers.

The objective of the DTC is to maintain the motor torque and stator flux within a defined band of tolerance by selecting the most convenient voltage vector. The control action is obtained by using hysteresis controllers and switching table [1].

Since it was introduced, a large number of papers appear in the literature to improve the performance of DTC of induction machines [2, 3, 7]. General problems associated with DTC drive are large ripple torque in the steady state and low sampling time that makes his implementation difficult on a digital processor [4].

Many researchers are oriented to combine the principles of DTC and FOC control in the same structure [3, 4, 5, and 6]. The present paper deals this principle. Hysteresis controllers and switching table are replaced by PI controllers and space vector modulator. In this sense, three algorithms are developed. Fundamental theoretical and limits of such approach are presented, discussed and compared with each other. The entire control schemes are simulated with Matlab/Simulink. Some concluding remarks are outlined.

In section 2, mathematical model of induction motor (IM) and three phase inverter with its commands are described. An overview of classical DTC is presented in section 3. The improvements made to conventional DTC are mentioned and detailed in section 4. Section 5, provides digital simulation results and comments. This paper achieved by general conclusion in section 6.

II. MATHEMATICAL MODELS

A. Induction motor model

In Park reference frame (d–q), stator and rotor voltage-flux equations are given as:

$$\begin{align*}
V_s &= R_s I_s + \frac{d\phi_s}{dt} + j\omega_p \phi_s \\
V_r &= R_r I_r + \frac{d\phi_r}{dt} + j(\omega_p - \omega_r) \phi_r
\end{align*}$$

Where $\omega_p$ and $\omega_r$ are respectively Park and rotor pulsations.

The magnetic state of the induction motor is governed by stator and rotor currents and fluxes as given by equation (2). $L_s$ and $L_r$ are stator and rotor flux leakages inductances.

$$\begin{align*}
\phi_s &= L_s I_s + M I_r \\
\phi_r &= L_r I_r + M I_s
\end{align*}$$

The electromagnetic torque generated by the induction machine can be expressed by various equivalent relations. The most popular torque relation is given by (3):

$$T_{em} = p(\phi_{sd} I_{sq} - \phi_{sq} I_{sd})$$
The equation of the dynamic rotor rotation can be expressed as:

$$\frac{d\Omega}{dt} = \frac{1}{J} \left[ T_e - T_L - K_f \Omega \right]$$

(4)

Where: \( T_e \) electromagnetic torque, \( T_L \) load torque, \( K_f \) viscous constant.

In further consideration the friction factor will be negated \((K_f = 0)\).

B. Three phases inverter model

We consider that the machine is feed by a conventional voltage inverter. This converter has only eight possible voltage vectors. Two of them have zero values and the six others are given by (5), where \( V_{dc} \) is the bus voltage supplying the inverter.

$$\begin{cases} \overline{v}_{sk} = \frac{2}{3} V_{dc}e^{j(k-1)\frac{\pi}{6}} & \text{for } k = 1,2,\ldots,6 \\ \overline{v}_{sk} = 0 & \text{for } k = 0 \text{ and } k = 7 \end{cases}$$

(5)

The SVM technique approximates a reference instantaneous voltage \( \overline{v}_{sref} \) by a combination of the switching states corresponding to the basic space vectors. This means that it is required for the average of inverter voltage output to be equal to the reference voltage \( \overline{v}_{sref} \) for any period \( T_s \).

While referring to fig.1 the average value of the voltage applied to the inverter in a switching period is equal to:

$$\overline{v}_{sref} = \frac{\tau_k \overline{v}_k + \tau_{k+1} \overline{v}_{k+1}}{T_s}$$

(6)

\( \tau_k \) and \( \tau_{k+1} \) are the durations for which switching states corresponding to \( \overline{v}_k \), \( \overline{v}_{k+1} \) and \( \overline{v}_0 \) are applied.

$$\overline{v}_k = V_s e^{j\phi_k}, \quad \overline{v}_{k+1} = V_s e^{j\phi_{k+1}}$$

(7)

By involving the amplitudes and phases of vectors \( \overline{v}_k, \overline{v}_{k+1} \) we obtain:

$$\overline{v}_{sref} = V_{sref}e^{j\phi_{sref}} = \sqrt{\frac{2}{3}} V_{dc} \frac{\tau_k e^{j\phi_k} + \tau_{k+1} e^{j\phi_{k+1}}}{T_s}$$

(8)

Separating the real part of the imaginary part in the relationship (8), we find:

$$\begin{cases} \tau_k = \frac{\sqrt{2} V_{sref}}{V_{dc}} T_s \sin\left(\frac{\pi}{3} - \xi\right) \\ \tau_{k+1} = \frac{\sqrt{2} V_{sref}}{V_{dc}} T_s \sin(\xi) \end{cases} ; \xi \in [0, 60^\circ]$$

(9)

The angle \( \xi \) is the angle of \( v_{sref} \) with respect to the considered sector. The coefficient \( \rho_v \) corresponding to the ratio voltage is defined by:

$$\rho_v = \sqrt{\frac{2}{3}} \frac{V_{sref}}{V_{dc}} ; \rho_v \in [0, 1]$$

(10)

Such that the sum \( \tau_k + \tau_{k+1} \) is less than or equal to the switching period \( T_s \) requires that the reference voltage vector is within the circle circumscribing the hexagon in the voltage vectors of the inverter (fig 1). In other words, we must have:

$$V_{sref} \leq \frac{V_{dc}}{\sqrt{2}}$$

(11)

III. OVERVIEW OF THE CLASSIC DTC SCHEME

The block diagram of classical DTC is presented in Fig.2

![Fig.2 Block scheme of the direct torque control method.](image)

The stator flux amplitude \( \phi_{sref} \) and the electromagnetic torque \( T_{sref} \) are the reference signals which
are compared with the estimated $\phi_s$ and $T_e$ values respectively in the stationary frame. The flux, torque errors and stator flux position are the inputs of switching Takahashi Table to deliver an appropriate voltage vector to the inverter.

Equation (1) implies that stator flux vector trajectory in a stationary reference frame verifies:

$$\overline{\phi_s} = \overline{\phi}_{s0} + T_s \overline{v}_s$$  \hspace{1cm} (12)$$

Voltages vectors of inverter are constant during a sampling period $T_s$. In addition, the stator resistance can be assumed constant for a long running time. The equation (12) shows that if the term $R_s \overline{i}_s$ can be neglected, this holds in particular for high speed operating, stator flux variation law becomes a simple Taylor first order series expansion: order series expansion:

$$\Delta \phi_s \approx \Delta \phi_{s0} + T_s \overline{v}_s$$  \hspace{1cm} (13)$$

If we omit the effect of $R_s$ from equations (12) we easily deduce that stator flux magnitude for one switching period can be estimated respectively by:

$$\Delta \phi_s \equiv T_s V_{sd}$$  \hspace{1cm} (14)$$

This equation implies that the flux magnitude is linked to the d-axes voltage component. 
The electromagnetic torque can be expressed by:

$$T_{em} = \frac{p_m}{\ell_s} \phi_s \phi_r \sin (\theta_s - \theta_r)$$  \hspace{1cm} (15)$$

$\theta_s$, $\theta_r$: are the stator and rotor phase.

The amplitude $\phi_s$ and the angle $\theta_s$ of the flux vector can be simultaneously adjusting the electromagnetic torque. The angle $\Theta_s$ is governed by the q-axes voltage component, so we can write:

$$\Delta \Theta_s \equiv T_s \frac{V_{sq}}{\phi_{s0}}$$  \hspace{1cm} (16)$$

The advantages of DTC method are as follows: structure independent on rotor parameters, no coordinate transformation, no current control loops.

The disadvantages of classical DTC are: high switching losses provide by variable switching frequency, difficult implementation due to high sampling frequency (25μs). Therefore, development of new strategy guarantees the proprieties of DTC and benefits of advantages of SVM techniques is preferred.

IV. DIRECT FLUX AND TORQUE CONTROL WITH SPACE VECTOR MODULATION (DTC-SVM).

In this section, different structures of DTC-SVM methods are presented. For each of the control structures, different controller design methods are proposed.

The classical DTC algorithm is based on the instantaneous values and directly calculated the digital control signals for the inverter. DTC-SVM methods are based on averaged values, whereas the switching signals for the inverter are calculated by space vector modulator. This is the main difference between classical DTC and DTC-SVM control methods.

A. DTC-SVM with Closed – Loop Flux Control (DFC)

The DTC-SVM Scheme with Closed – Loop Flux Control is a new method of control for asynchronous machine [3]. This command differs from the conventional DTC by using a vector modulation which ensures constant switching frequency. Switching commands of the inverter are generally derived by SVM modulation which from information flux trends determines the most appropriate switching.

In the fixed reference, the stator flux is obtained from the following equation (17):

$$\overline{\phi}_s = \int (\overline{v}_s - R_s \overline{i}_s) dt$$  \hspace{1cm} (17)$$

In the control structure of Fig. 2, the rotor flux is assumed as a reference. The reference stator flux components defined in the rotor flux coordinates can be calculated from the following equations:

$$\begin{align*}
\phi_{sref} & = \frac{L_s}{M} \phi_{rref} \\
\phi_{qref} & = \frac{\sigma L_r L_s}{pM} T_{ref} \phi_{rref}
\end{align*}$$  \hspace{1cm} (18)$$
It is necessary that the stator flux vector in the fixed reference reaches its reference:

\[ \phi_{ref} = \phi_{ref} e^{j\theta} \]  

(19)

Applying a phase abstraction between the reference and the actual stator flux vector we can estimate the desirable change in stator flux \( \Delta \bar{\phi}_s \).

\[ \bar{\phi}_{ref} - \bar{\phi}_s = \Delta \bar{\phi}_s \]  

(20)

Having the desirable change in stator flux, it is easy to estimate the reference stator voltage vector:

\[ v_{sref} = \frac{\Delta \phi_s}{T_s} + R_s i_{s} \]  

(21)

The reference voltage vector depends on the increment stator flux \( \Delta \bar{\phi}_s \) and voltage drop on the stator winding resistance \( R_s \).

Now, in every sampling time \( T_s \), inverter can produce a voltage vector of any direction and magnitude. That means the changes in stator flux would be of any direction and magnitude and consequently the changes in torque would be smoother.

### B. DTC-SVM operated in stator flux coordinates

1) Description of Parallel structure of DTC-SVM

The method with close-loop torque and flux control in stator flux coordinate system is presented by Fig. 4.

![Fig.4. Parallel structure of DTC-SVM](image)

In this structure, the idea is to control the two important variables of the asynchronous machine: the flux and torque. Their settings are made by control voltages that are generated by proportional integral controllers (PI). These controllers must minimize the error between the mean values of variables and references by imposing a new reference voltage vector at each switching period [19]. SVM command is used to obtain the switching states of the inverter keys. The synoptic DTC-SVM is given in fig.4. Hysteresis controllers and switching table have been eliminated, which eliminates the problems associated with them.

2) Torque and Flux Control in Stator Flux Coordinates

The transfer function of PI controllers is given as follows:

\[ R(s) = K_p + \frac{K_i}{s} = K_p + \frac{T_s}{1 + T_s / s} \]  

(22)

Where: \( K_p, K_i \): controller gain, \( T_i \): controller integrating time.

The developments of systems equations 1 and 2 in stator reference coordinate \( \theta_s \), lead to the following transfer equations linked direct stator voltage \( V_{sd} \) to stator flux \( \phi_s \) and sleep pulsation \( \omega_s = \omega_s - \omega_r \) to electromagnetic torque.

\[ \begin{align*}
V_{sd} &= \frac{\phi_r}{H_{gs}(s)} + E_d \\
(\omega_s - \omega_r) &= \frac{T_e}{H_{Te}(s)}
\end{align*} \]  

(23)

\[ H_{gs}(s) = \frac{\phi_r}{V_{sd}} = \frac{R_r}{s^2 + L_s R_s + R_s L_r} \]  

(24)

\[ E_d = -\frac{\sigma R_s L_{sz} I_{sz}^2 (\omega_s - \omega_r)}{1 + \sigma R_s L_{sz}^2} \]  

(25)

\[ H_{Te}(s) = p (1 - \sigma) \frac{1}{L_s} \frac{1}{\sigma L_s} \frac{1}{\sigma L_s} \]  

(26)

This means that the stator flux is controlled by \( V_{sd} \) and the torque is controlled by the pulse \( (\omega_s - \omega_r) \) so that by the component of stator voltage \( V_{sq} \) as \( V_{sq} = \omega_s \phi_s \).

The control loop of stator flux and electromagnetic torque are given by the diagram in fig.5 and fig.6. \( H_{gs}(s) \) and \( H_{Te}(s) \) are the transfer function and \( R(s) \) represents the controller.
C. Direct Torque Control –Direct Voltage Control (DTC-DVC).

DTC-DVC scheme will be presented which uses a closed loop torque and flux. The block diagram of this scheme is shown by fig 2.

The chosen vector is designated by the integer \( n(t) \) corresponding to the number of the voltage vector to be selected. This integer between 1 and 7 will be selected according to the criteria mentioned by the relation (27):

\[
n(t) \to \min \int \epsilon(t) \, dt = \left( \sqrt{\epsilon_{\text{ref}}^2(t)} - \sqrt{\epsilon(n(t))} \right) \, dt \quad (27)
\]

To minimize the integral of the error, we must find the minimum of the two components of this error:

\[
n(t) \to \min \left( \epsilon(n(t)) \right) = \min \left( \sqrt{\epsilon_{\text{ref}}^2(t)} + \epsilon(n(t)) \right) \quad (28)
\]

V. SIMULATION RESULTS AND COMMENTS

Classical and developed structures are simulated in Matlab/Simulink environment. For a clear and objective comparison, these structures are simulated with same conditions; step reference torque of 5N.m at 0.1s, reference stator flux 1.2Wb (reference rotor flux is 0.8Wb). The sampling time is 50 \( \mu \)s for the basic DTC and 200 \( \mu \)s for the others. Parameters of motor induction are showed in annex.

These figures below prove that the proposed approaches give a good response on the torque and stator flux. The torque ripple of the electromagnetic torque in classic DTC which is resulted by the cyclic sector changes of stator flux vector and produces sharp edges is now eliminated (fig.10, 11, 12). Despite electromagnetic torque is regulated by all structures, it is better in the last method. It can also be seen the improvement in motor acceleration and the change in motor’s torque using DFC, DTC-SVM and DTC-DVC control.

In fig.10 and fig.11, DTC with PI controller shows an overshoot of the electromagnetic torque.

By referring to Figure 12, we can draw the following table.

<table>
<thead>
<tr>
<th>Torque ripple in classic DTC</th>
<th>Torque ripple in DFC</th>
<th>Torque ripple in DTC-SVM</th>
<th>Torque ripple in DTC-DVC</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3N.m</td>
<td>0.2N.m</td>
<td>0.2N.m</td>
<td>0.05N.m</td>
</tr>
</tbody>
</table>

TABLE 1. Comparative analysis of torque ripple
Fig. 8. Simulation of classical DTC: (a) Torque response, (b) stator flux response, (c) Stator voltage in dq axis and (d) rotor speed responses.

Fig. 9. DFC simulations results: (a) Torque response, (b) rotor flux response, (c) Stator voltage in dq axis, (d) rotor speed responses.

Fig. 10 Parallel DTC-SVM simulation results: (a) Torque response, (b) stator flux response, (c) Stator voltage in dq axis, (d) rotor speed responses.

Fig. 11 DTC-DVC simulation results: (a) Torque response, (b) stator flux response, (c) Stator voltage in dq axis, (d) rotor speed response.
V. CONCLUSION

This paper has presented a modified Direct Torque Control methods for PWM-Inverter fed asynchronous motor drive using constant switching frequency. Constant-switching-frequency is achieved by using space vector modulation (SVM).

Direct voltage control (DVC) which has the same meanings as SVM allows reducing ripple torque and minimizing the number of commutation keys SVM. Based DTC-SVM and DTC-DVC system is compared to the classic DTC scheme for torque control. Simulation results obtained for the DTC-SVM and DTC-DVC illustrate a considerable reduction in torque compared to the existing classical DTC system and a good dynamic and static performance.

APPENDIX

Induction Motor Detail

380V, (1.5KW), 1Poles, 2830 rpm
Stator resistance 4 ohm
Stator inductance 0.4334 H
Rotor resistance 4.5328ohm
Moment of inertia 0.0015kg.m²

REFERENCES