Reduction of Torque Ripples of Three-Phase Induction Motors Using Hybrid Vector Control Based on Space Vector Modulation

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Abstract

Three-phase induction motors as widely used electric drives in industry, automation, transportation and electric vehicles are mainly controlled by two conventional methods, vector control (VC) and direct torque control (DTC). The vector control method has a suitable steady state response, but in terms of dynamics and time to reach the steady state, it provides a relatively slower response. In contrast, the direct torque control method works almost the opposite way and provides a better dynamic response. Therefore, providing a control strategy that combines the advantages of the two mentioned methods as much as possible improves the driving performance of the induction motor. This paper presents a hybrid control method based on the optimal keying table to select the appropriate keying modes for the induction motor drive converter to improve the output dynamic response. To reduce current and torque ripples in different operational states, the space vector modulation technique has been used in the proposed drive system. The efficiency of the drive system presented with the hybrid control strategy has been compared with the conventional DTC and VC control methods, and the results illustrate a faster dynamic response of the proposed drive system with less steady-state ripples than the two conventional methods. Modeling and implementation of the proposed drive system have been performed in MATLAB/Simulink software.

Keywords: Hybrid vector control, three-phase induction motor, direct torque control, space vector modulation, torque ripples, switching table.

1. Introduction

In recent years, induction motors have been used only in constant speed applications whereas in variable speed applications, dc motors have been employed. This is due to the fact that the conventional methods of controlling the speed of induction motors have been uneconomical and have low efficiency. The range of speed changes of the motor drive depends on the type of drive application. In some motors, the drive speed must be controlled between the nominal speed and 10% of the nominal speed, and in some other applications, it is necessary to control the engine speed above the base speed. There are also applications in which speed control is performed in a small range, for example, from the base speed to 80% [1]. According to the ideal speed-torque characteristics of a variable speed induction motor drive, the induced voltage is proportional to the flux and speed, and on the other hand, the generated torque is proportional to the flux and current. Therefore, the upper limit of the machine speed is determined by the maximum permissible speed of the rotor assembly or the rated voltage of the motor [2].

So far, several control algorithms have been presented to achieve goals such as response accuracy in steady state, high dynamics, simplicity of the control system, efficiency, low cost, reduction of torque noise and sound [3]. Vector control (VC) and direct torque control (DTC) are two conventional methods for controlling induction motors, of which different types have been presented and used in various applications. The control algorithm of the two mentioned methods is almost similar in some cases and completely different in others. Each of the control methods, due to their general structure, has advantages that lead to a better response compared to other methods [4]. The vector control has a better and more suitable steady state response, which can be due to the existence of direct control over the current. In this way, in the steady state, the amount of output fluctuations is less [5]. The DTC method provides a faster torque response, which is due to the rapid selection of the position of the electronic power switches. In fact, the reason for the fastness of DTC can be seen in the keying table, which, by using this table, instead of the time-consuming and time-consuming method of pulse width modulation (PWM), selects only the predetermined modes for keying. On the other hand, the use of fast hysteresis controllers that make the entries of the keying table also plays an essential role in the fast operation of DTC [6]. The most important drawback of vector control compared to direct torque control is its relatively long dynamic time, which is due to the use of PWM method [7].

If the vector control system can be used together with the switching table, the time to reach the permanent state in the DTC method can be significantly reduced. Therefore, in this paper, in order to improve the performance of the induction motor drive system based on the vector control method, the switching table has been used. In fact, regarding the structure of the presented hybrid control system, it can be noted that this system includes the stator current control similar to the vector control method along with the switchung table similar to the DTC method. Therefore, most of the solutions that have been provided to improve the response of the two mentioned methods can also increase the efficiency of the new system. Among the advantages of the proposed control system, the following can be mentioned:

- Using the optimal switching table in the proposed hybrid control system similar to the DTC method to improve the performance of the drive system.
- VC and DTC control methods at low speeds face the problem of reducing the back EMF, which leads to incorrect estimation of the original waveform. Sensorless vector control is able to work at lower speeds. A hybrid of two estimators such as Kalman filter to estimate rotor flux and speed can be effective in improving system performance at low speeds.
- Using the switching table and hysteresis controllers in the presented hybrid method leads to a reduction in the ripple of the motor output torque.

The rest of the paper is organized as, first, the mathematical equations of the induction motor and the hybrid control system are presented and its modeling is performed in Matlab/Simulink software. Finally, the results obtained for conventional and new induction motor drive methods are illustrated and compared to validate the system performance.

2. Topology and Operation of the Proposed Drive

The six voltage vectors used for torque and flux control in a conventional induction motor are obtained from a three-phase voltage source converter shown in Fig. 1.

From Fig. 1, S_a, S_b, S_c are the modes of the upper switches. The lower switches are always complementary to the upper switches to avoid short circuit. The states of each switches are defined as 1 when the switch is on and 0 when the switch is off. Therefore, there are eight possible outputs for the converter that can feed the induction motor.

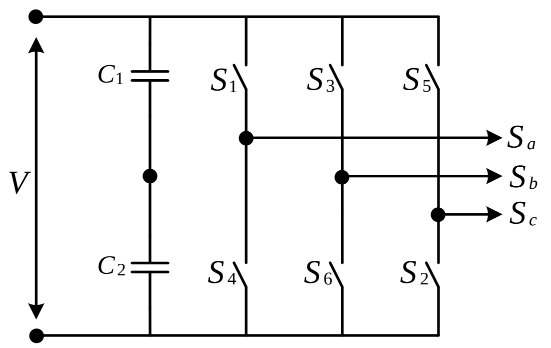

Fig. 1. Three-phase voltage source inverter for induction motor.

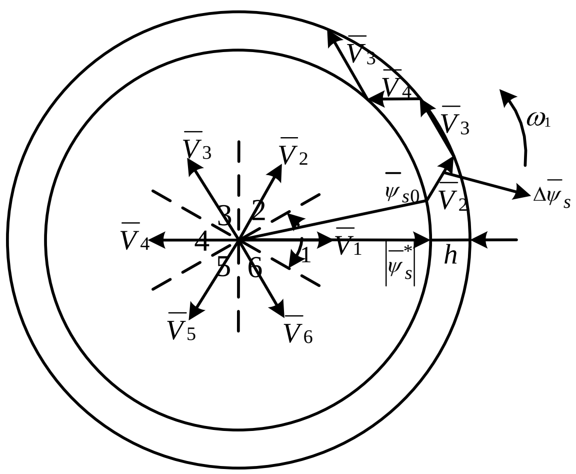

Fig. 2. Applied voltage vectors to induction motor drive.

Considering the drive's inverter feeds a symmetric induction motor with a star connection, the phase voltages V_a, V_b, V_c generated by the converter must meet the following condition

$$V_a + V_b + V_c = 0 \quad (1)$$

By expressing the phase voltages according to the switching modes, the space voltage vector can be obtained as

$$\vec{V}_s = \frac{2}{3} V \left(S_a + S_b e^{j\frac{2\pi}{3}} + S_c e^{-j\frac{2\pi}{3}} \right) \quad (2)$$

As can be observed in Fig. 2, the space voltage vector $\overline{V}_s$ has eight different values $\overline{V}_k$ in which $(k = 0,......,7)$. Though the two space vectors for $k = 0$ and $k = 7$ are zero vectors, the corresponding vectors with $k = 1,2,3,4,5,6$ have amplitudes $2/3V$ and angles $(k-1)(\pi/3)$. As shown in Fig 7, when the flux magnitude needs to be increased; a voltage vector with a phase shift greater than 90 degrees is applied to the existing flux vector $\overline{\psi}_{s0}$. Conversely, if a reduction in flux size is desired; The value of the mentioned phase shift will be less than 90 degrees [8].

Defining the duration of applying each voltage vector is determined based on the hysteresis band related to the hysteresis controllers, and if this duration is constant; The switching frequency will also be constant. Of course, the hysteresis band of two controllers in the DTC method can be adjusted so that the average switching frequency remains constant. The selection of the appropriate voltage vector is done based on the keying table shown in Table 1. The input quantities are the stator flux position and the outputs of two hysteresis comparators [9].

Table 1. The pattern of voltage vectors

Sector		1	2	3	4	5	6
$C_\psi = -1$	$C_T = -1$	$\vec{V}_2$	$\vec{V}_3$	$\vec{V}_4$	$\vec{V}_5$	$\vec{V}_6$	$\vec{V}_1$
	$C_T = 0$	$\vec{V}_7$	$\vec{V}_0$	$\vec{V}_7$	$\vec{V}_0$	$\vec{V}_7$	$\vec{V}_0$
	$C_T = +1$	$\vec{V}_6$	$\vec{V}_1$	$\vec{V}_2$	$\vec{V}_3$	$\vec{V}_4$	$\vec{V}_5$
$C_\psi = +1$	$C_T = -1$	$\vec{V}_3$	$\vec{V}_4$	$\vec{V}_5$	$\vec{V}_6$	$\vec{V}_1$	$\vec{V}_2$
	$C_T = 0$	$\vec{V}_0$	$\vec{V}_7$	$\vec{V}_0$	$\vec{V}_7$	$\vec{V}_0$	$\vec{V}_7$
	$C_T = +1$	$\vec{V}_5$	$\vec{V}_6$	$\vec{V}_1$	$\vec{V}_2$	$\vec{V}_3$	$\vec{V}_4$

2.1. Hybrid Control System

The conventional hybrid control method includes the combination of vector control and direct torque control, which has some advantages and disadvantages. In the previous section, it was shown that there is a direct relationship between the hysteresis control of the stator coupling flux in the DTC method and the direct current axis control in the VC method. Also, the hysteresis control of the electromagnetic torque in the DTC method is proportional to the vertical axis current control. These cases are the main idea of forming a new drive control system based on the common principles of the two methods, so that the new method has a combination of the advantages of the two mentioned methods. In other words, the new control system will not have some problems related to VC and DTC. It is clear that the DTC method provides a faster torque response, which is due to the quick selection of the position of the power electronic switches. In fact, the reason for the speed of DTC can be seen in the switching table, which, by using this table, instead of the time-consuming PWM method, only selects the predetermined modes for switching. According to the above explanations, it seems that the switchig table and hysteresis controllers are among the advantages of the DTC method over the VC, which can be used in the structure of the new system. Fig. 3a shows the part of the switching table and hysteresis controller proposed for the new method.

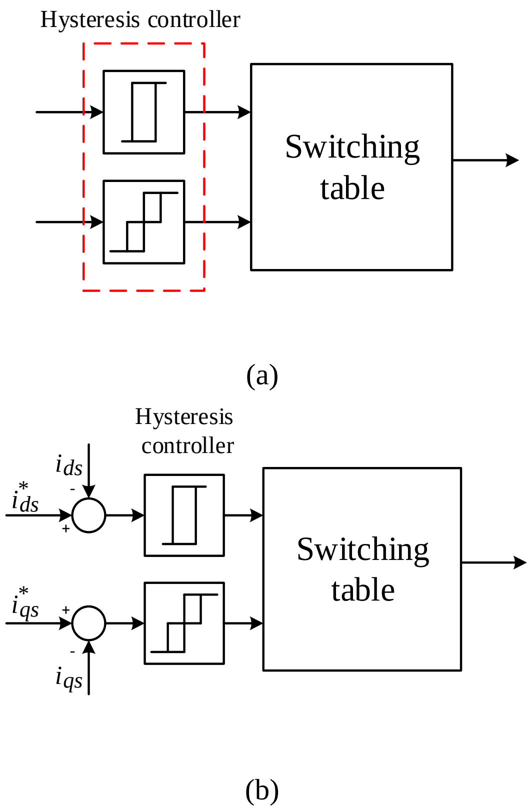

Fig. 3. Block diagram of the torque and flux control; a) based on the switching table and hysteresis controllers, b) combined with stator current control.

In the vector control system, instead of torque and stator flux, the *d* and *q* axis currents of the stator are controlled. In this way, *q*-axis current is used for torque control and *d*-axis current is used for flux control. Therefore, in this method, there is no need to calculate the actual torque and flux. While in the DTC method, to create the inputs of hysteresis controllers, it was necessary to calculate the actual flux and torque separately using the measured parameters and compare them with the reference values. Not needing to calculate torque and flux is an advantage for the vector control method that can be used in the new control system. Fig. 3b shows the block diagram of the combination of VC and DTC methods.

The main idea of the hybrid control system was explained in the previous section and the main part of the structure of this system was also shown in Fig. 3. Fig. 4 shows the drive control system of the induction motor that has hysteresis controllers of *d* and *q* axis current (similar to VC method) and a keying table (similar to DTC method) [10].

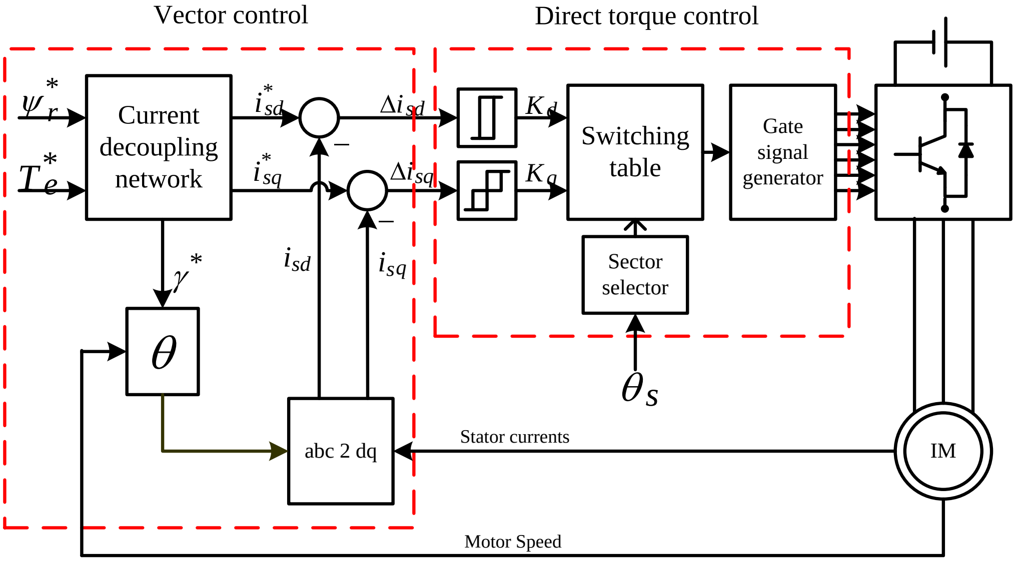

Fig. 4. Block diagram of the hybrid control system.

2.2. Vector Control Part

The current decoupling block is an advanced or indirect method for making the reference flux line, which requires information about the machine parameters as well as simultaneous calculations corresponding to the current separation network. In indirect vector control, the separation of axis current in vector control in the reference frame of the rotor flux is obtained by using Fig. 5 [11].

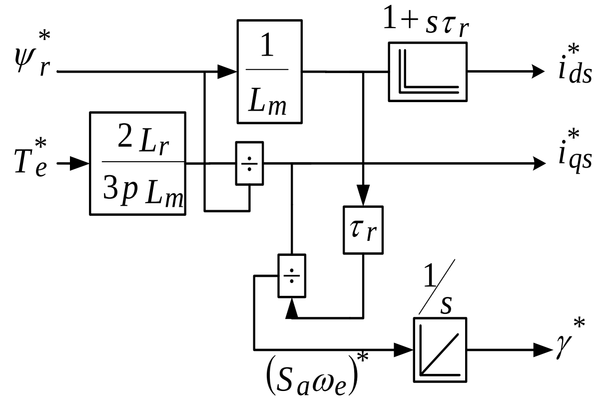

Fig. 5. Block diagram of the current decoupling part.

where in Fig. 5, S_a is motor slip as $S_a = \frac{\omega_e - \omega_r}{\omega_e}$, ω_e and ω_r parameters are the angular speed of the rotor flux and the angular velocity of the rotor, respectively, τ_r is motor time constant, and γ is the difference of the rotor angular position and the rotor flux.

The input angle θ to the reference frame conversion block is the sum of the rotor angle and the sliding speed angle. The rotor angle is obtained by integrating the actual measured speed of the motor and the slip angle is obtained by integrating the slip speed inside the flow separation block (Fig. 5). By combining these two angles, the direction of the reference flux is obtained and by using it, the measured three-phase currents of the stator can be converted into two-phase. In this way, the *d* and *q* axis currents of the stator (real and reference) will be available. The difference of both pairs of corresponding currents forms the outputs of the vector control part, which are used as the input of the DTC part.

2.3. DTC Part of the System

In direct torque control, changes in torque and stator flux were the inputs of hysteresis controllers. In the new control method, there is no need to calculate the actual torque and flux, and the inputs of the hysteresis controllers will be the changes in the currents. In this way, current errors lead to the creation of two switching table entries. The third entry in the above table is the status of the stator current. The position of the stator current input to the switching table is obtained according to the diagram of the current and flux vectors. With the values of currents i_{ds} and i_{qs}, you can easily get the value of angle α. Since the mentioned currents are in the reference frame of the rotor flux, therefore, the mentioned angle will be obtained as follow

$$\alpha = \tan^{-1}\left(\frac{i_{qs}}{i_{ds}}\right) \quad (3)$$

By calculating the above angle and adding it to the angular position of the rotor flux, which was obtained in the vector control part, the third input of the switching table will be available.

Table 2. The pattern of voltage vectors for hybrid control method

Sector		1	2	3	4	5	6
$K_d = -1$	$K_q = -1$	$\vec{V}_2$	$\vec{V}_3$	$\vec{V}_4$	$\vec{V}_5$	$\vec{V}_6$	$\vec{V}_1$
	$K_q = 0$	$\vec{V}_7$	$\vec{V}_0$	$\vec{V}_7$	$\vec{V}_0$	$\vec{V}_7$	$\vec{V}_0$
	$K_q = +1$	$\vec{V}_6$	$\vec{V}_1$	$\vec{V}_2$	$\vec{V}_3$	$\vec{V}_4$	$\vec{V}_5$
$K_d = +1$	$K_q = -1$	$\vec{V}_3$	$\vec{V}_4$	$\vec{V}_5$	$\vec{V}_6$	$\vec{V}_1$	$\vec{V}_2$
	$K_q = 0$	$\vec{V}_0$	$\vec{V}_7$	$\vec{V}_0$	$\vec{V}_7$	$\vec{V}_0$	$\vec{V}_7$
	$K_q = +1$	$\vec{V}_5$	$\vec{V}_6$	$\vec{V}_1$	$\vec{V}_2$	$\vec{V}_3$	$\vec{V}_4$

In order to enter the switching table, the region where $\vec{i}_s$ is located should be determined based on the angle and position of the current, and according to it and the outputs of the two hysteresis controllers, the appropriate voltage vector should be selected. In this way, three entries of the switching table including K_q, K_d and current status are entered into the table. The method of choosing the appropriate voltage vector is completely similar to the DTC method. The switching table selects the appropriate voltage vectors by deciding on the states of the inverter keys. The switching table produces 8 voltage vectors, including two zero vectors. The non-zero voltage vector $\vec{V}_1$ to $\vec{V}_6$ are shown in Fig. 2. Inputs and selected voltages are performed in a combination method according to Table 2.

According to Fig. 4, among the parts that have been removed in the hybrid control system compared to conventional methods, the following can be mentioned:

- PI controller or other current controllers
- Complex and time-consuming PWM method
- Conversion block from two-phase to three-phase frame which is usually needed in VC method.

In fact, it can be noted that the new system is a current vector control system by selecting the DTC voltage vector.

2.4 Space Vector Modulation (SVM)

In the conventional DTC method, the switching frequency changes with the speed change due to the limitation of the torque ripple between two hysteresis bands. In addition, the amount of torque ripple at low speeds is also high. By using a constant switching frequency, the amount of acceptable torque ripples can be achieved in permanent mode and at low speeds. Several methods have been used for this purpose, one of which is SVM. In the SVM method, a predictive method is used in each time interval to obtain the required voltage vector so that the torque and flux errors are accurately compensated. In SVM-DTC method, steady state fluctuations of torque are well improved and the switching frequency is kept constant. SVM is based on the switching between two adjustable boundary active vectors and a zero vector during a keying period, T_z, and for an assumed reference voltage vector in the first region (0-60 degrees) is shown in Fig. 6.

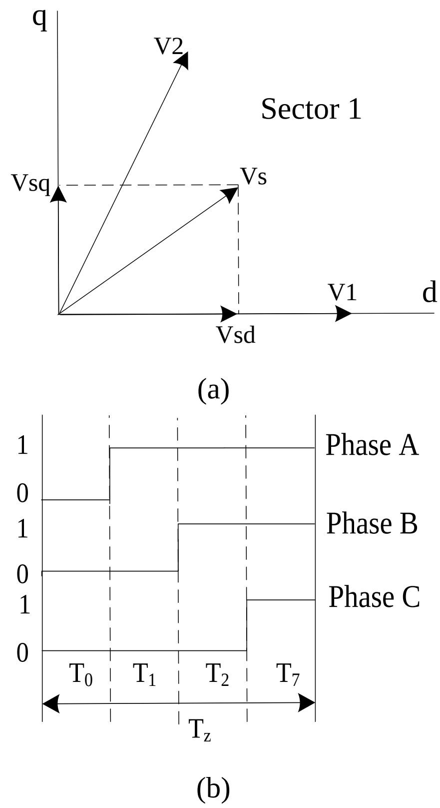

Fig. 6. SVM in first mode; a) switching pattern for three-phase modulation, b) reference voltage vector.

The switching times can be obtained from the following equation:

$$\overline{V}_s^* = V_{sd} + jV_{sq} \quad (4)$$

where V_{sd} and V_{sq} are obtained from the corresponding voltage vectors for each assumed section.

$$T_z\overline{V}_s^* = T_A\overline{V}_1 + T_B\overline{V}_2 \quad (5)$$

$$T_A\sqrt{\frac{2}{3}}V_{dc}\begin{bmatrix}\cos 0\\ \sin 0\end{bmatrix} + T_B\sqrt{\frac{2}{3}}V_{dc}\begin{bmatrix}\cos(\pi/3)\\ \sin(\pi/3)\end{bmatrix} = T_z\sqrt{\frac{2}{3}}V_{dc}a\begin{bmatrix}\cos\gamma\\ \sin\gamma\end{bmatrix} \quad (6)$$

$$T_A = T_z a\frac{\sin(\pi/3-\gamma)}{\sin(\pi/3)} \quad (7)$$

$$T_B = T_z a\frac{\sin(\gamma)}{\sin(\pi/3)} \quad (8)$$

$$T_0 = T_7 = T_z - T_B - T_A \quad (9)$$

$$0 \le \gamma \le \pi/3\,, a = \frac{|\bar{V}_s^*|}{\sqrt{\frac{2}{3}}V_{dc}} \quad (10)$$

The reference vector with constant size and frequency is sampled in constant mode in equal time intervals in T_z. In this sampling interval, the inverter is turned on and placed in different switching positions so that the average space vector produced during the time interval is equal to the sampled value of the reference vector, which is considered to be equal both in terms of size and angle.

The switching positions that can be used in T_z include the zero position and the active positions that are S_A and S_B with the corresponding vectors V_1 and V_2 that form the beginning and end of the region.

Two switching positions S_A and S_B are called active switching positions. S_A shows the switching positions (010), (100) and (001) of the inverter, while S_B shows the positions (011), (110) and (101). The active vector times T_A and T_B are the times that include the switching positions S_A and S_B, respectively. The times of the neutral vector T0 and T1 are also called the times that include the keying positions S0 (000) and S7 (111), respectively. In DTC combined with space vector pulse width modulation, DTC transient mode performance and its continuity are improved and permanent mode fluctuations are significantly reduced. In addition, the inverter's switching frequency is fixed and controllable.

Fig. 7 illustrates the block diagram related to the application of SVM-DTC method in induction motor drive. According to the proposed block diagram, the hysteresis controllers, which were the main cause of steady-state fluctuations, have been removed and replaced by PI controllers. The vector control part has exactly the same characteristics as the previous hybrid control, and the angle is the same as the angle used in the normal hybrid method (stator current vector angle).

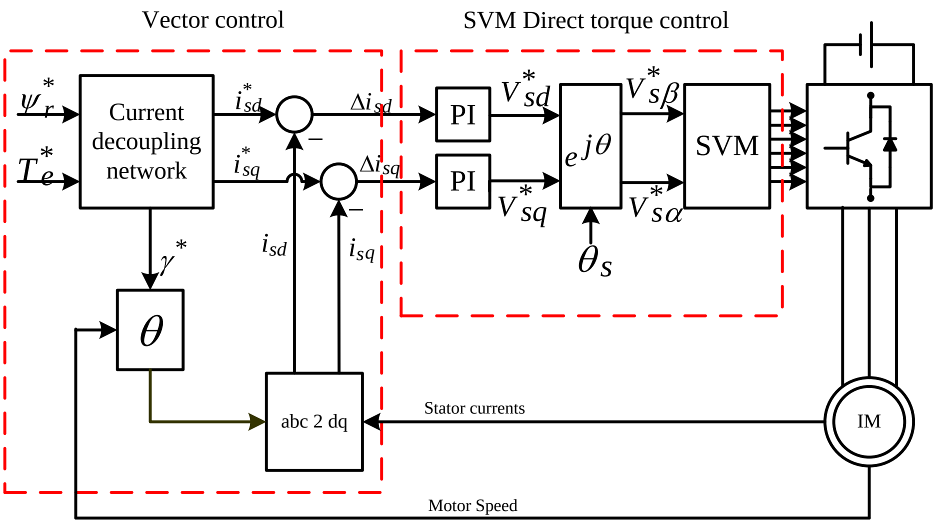

Fig. 7. Block diagram of the hybrid control system with SVM-DTC.

3. Simulation Results

In this section, the simulation results obtained from conventional methods such as VC, DTC, conventional hybrid VC-DTC and the proposed hybrid method with VC-DTC-SVM are compared. These methods have been simulated in the Matlab/Simulink software environment and applied to a three-phase induction motor with the parameters listed in Table 3 [12] under the same conditions.

Table 3. induction motor parameters

Power	200Hp
Line Voltage	460 v
Pole pairs	2
Stator resistance	0.012 Ω
Rotor resistance	0.008 Ω
Stator inductance	0.2 mH
Rotor inductnce	0.2 mH
Mutual inductance	9.5 mH
Inertia	3.1 $kg.m^2$

In this rest, the comparison of the results related to the control methods by applying the same load is performed for them, and in the steady and transient state, as well as under load and speed changes, the advantages and disadvantages of each of them have been investigated and compared with each other.

3.1. Results Under Constant Speed

The four discussed control methods are applied to the induction motor with the parameters listed in Table 3 and by simulating their performance, the obtained results are compared. In all methods, the motor speed is a constant value of 500 rad/s and the motor load is constant. After the motor speed reaches the reference value, the nominal load of the motor is applied at t=0.9s and removed at t=1.2s.

Fig. 8 illustrates the speed of the motor under control methods. In an ideal state, it is desirable that for a set speed, the motor speed remains constant with the change of load torque from no load to full load, but in practice, this is not the case, and as the load increases, the motor speed decreases. From Fig. 8, the dotted graph shows the reference speed and the other graph shows the actual speed. The transient state of the speed occurs in a short period of time at the beginning of the start-up, and after reaching the constant speed, it shows insignificant changes in relation to the application and removal of the load. In all graphs, the actual speed closely follows the reference speed. It is clear that the combined methods are able to control the motor speed like the VC and DTC methods. In all diagrams, at the moment of applying the load, the speed drops by a small amount. The time to reach the final speed for all methods is 0.65 seconds.

The produced torque of the motor is shown in Fig. 9. A load 600 N.m has been applied to the motor at t = 0.9 s for 0.3 seconds. The waveform of the output torque in the control methods is almost the same and they differ only in the amount of ripple and oscillation of the steady state. Due to instant control of the current, the amount of steady-state ripples of current and torque will be low, while in the DTC method, due to the fact that there is no accurate information about the current during control, more fluctuations are seen.

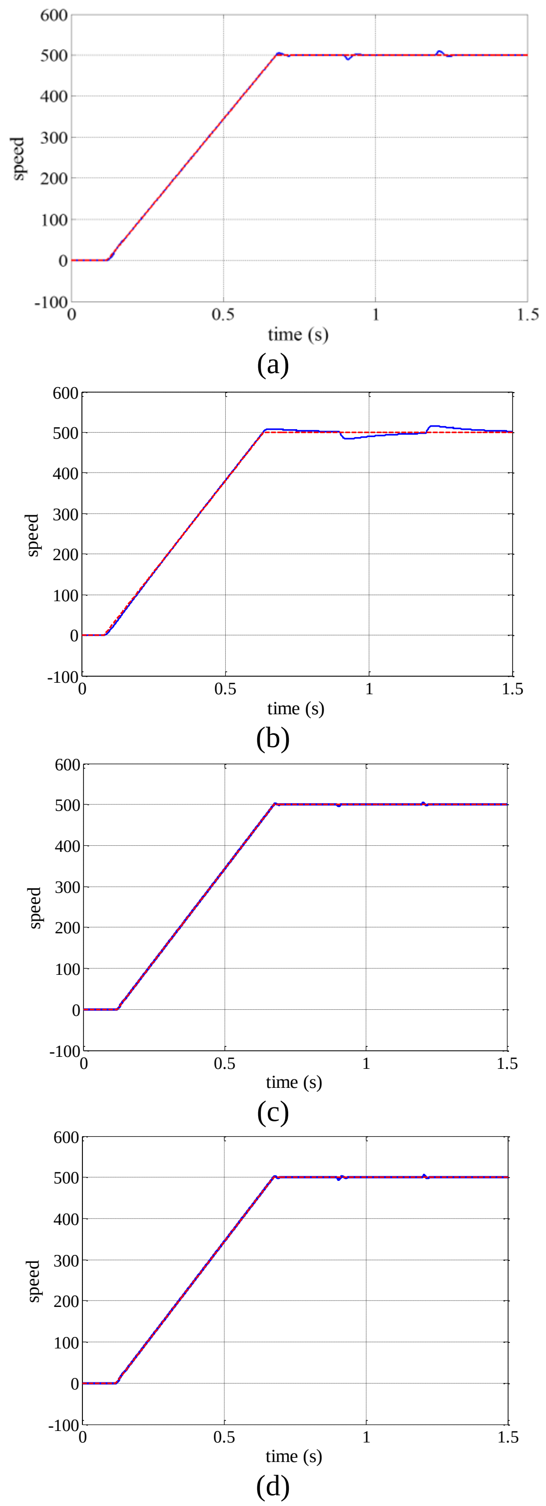

Fig. 8. Motor drive performance during constant speed, a) VC, b) DTC, c) conventional hybrid methof, d) proposed hybrid method with SVM

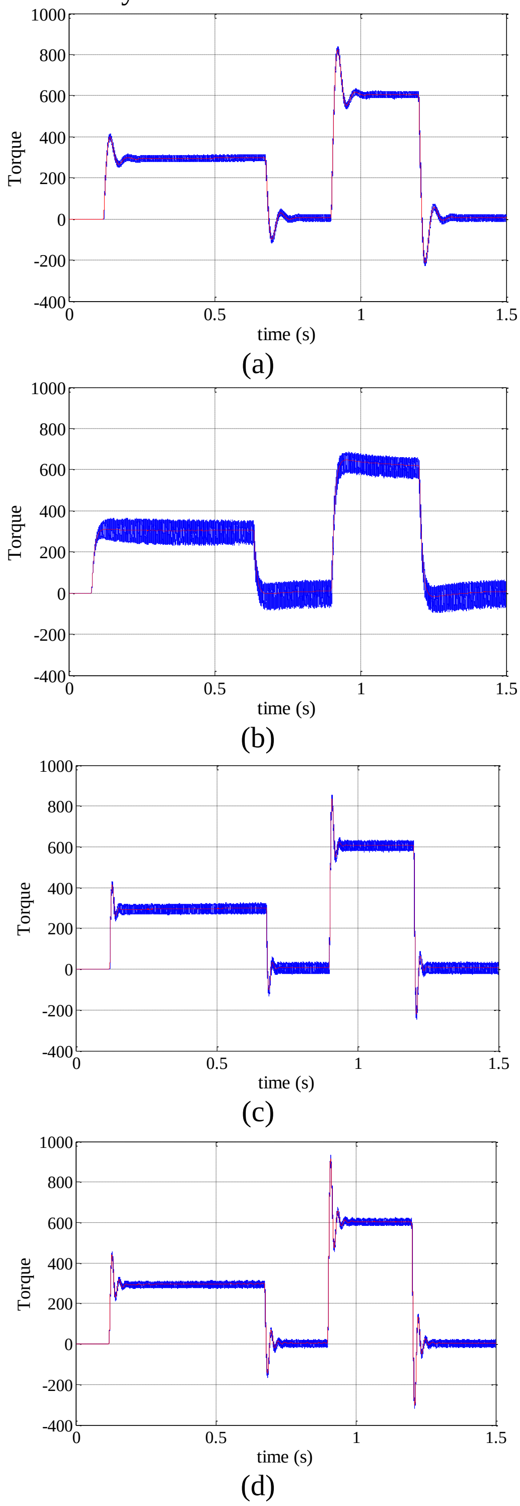

Fig. 9. Torque performance of the drive system during constant speed, a) VC, b) DTC, c) conventional hybrid methof, d) proposed hybrid method with SVM

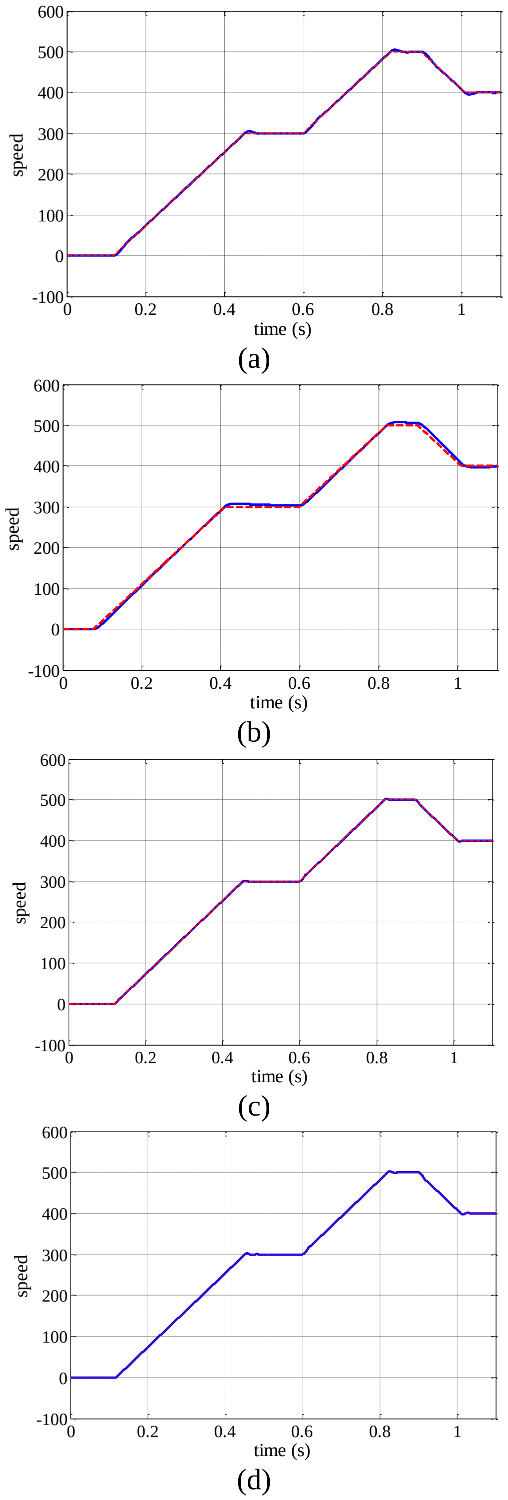

Fig. 10. Motor drive performance during variable speed, a) VC, b) DTC, c) conventional hybrid methof, d) proposed hybrid method with SVM

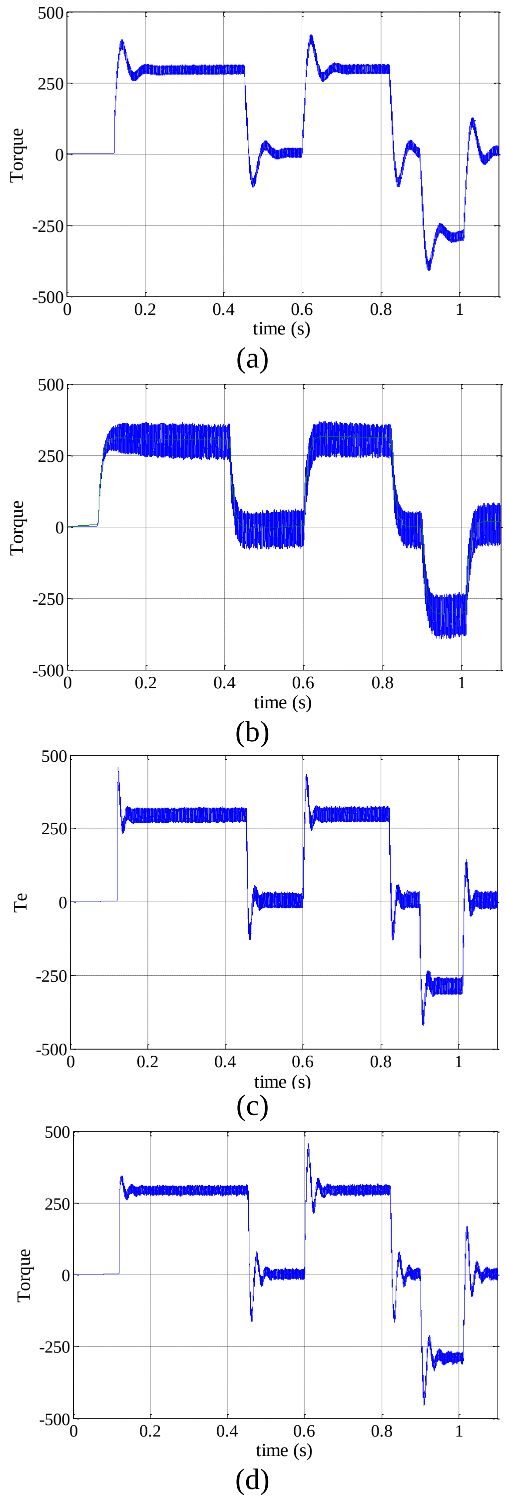

Fig. 11. Torque performance of the drive system during variable speed, a) VC, b) DTC, c) conventional hybrid methof, d) proposed hybrid method with SVM

In the hybrid control system, the torque ripple in steady-state mode is significantly lower than the DTC method. Using the space vector modulation method in DTC helps to reduce the ripple as much as possible.

The torque responses are shown in Fig. 9. After starting the motor and after the motor speed reaches the reference value, a load equal to 600 N.m is applied at t= 0.9s for 0.3 seconds. The responce of the output torque is almost the same and differ only in the amount of ripple and steady state oscillation. In vector control, motor currents are directly controlled. Therefore, due to the moment-to-moment control of the current, the amount of fluctuations in the steady state of current and torque will be low, while in the DTC method, due to the lack of accurate information about the current, more fluctuations in output torque and motor current are created.

3.2. Results Under No-Load Speed

In this subsection, the performance of the motor drive is investigated by the four control methods. At t=0.6s the motor speed is increased from the value of 300 rad/s to 500 rad/s and at t=0.9s it is returned to the speed of 400 rad/s. Fig. 10 shows the response of the motor speed to changes in reference speed. According to these waveforms, in all control methods, the drive system is able to follow the reference speed well and the presented control methods are able to perform the same speed control as other methods.

The torque response of the induction motor for speed changes is shown in Fig. 11. After the speed reaches the nominal value, the motor continues to work with zero torque and a speed of 300 rad/s until the speed increases to 500 rad/s at 0.6 s. When the speed reaches the desired value, the torque becomes zero again until the speed is returned to the initial value of 400 rad/s once again and this time at 0.9 s. After this time, a positive torque is applied until the motor reaches the desired speed.

4. Conclosions

In this paper, by examining the common principles of VC and DTC methods in induction motor drives, a new control system was introduced that has a relatively simple structure and has better performance than conventional methods. This system uses a type of current vector control with DTC based on switching table. In the hybrid method, it was tried to combine the advantages of each of the VC and DTC methods to form a better control system. Despite the fact that the combined system has a better response compared to the first methods, it is still possible to reduce the amount of steady state ripple and transient duration with other methods. By using the space vector modulation, which has led to the elimination of the switching table and hysteresis controllers, the amount of steady state ripples is significantly reduced. The comparison of the performance of the motor shows that the response of the new hybrid control method has faster dynamics than conventional control with less steady state ripple than the DTC method.

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