Analysis and Performance Comparison of Vector Control Method with Direct Torque Control to Reduce Current and Speed ripples of Three-Phase Induction Motors

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Abstract

Today, three-phase induction motors are widely used in industry due to advantages such as lower maintenance requirements, higher reliability, lower design costs, and the ability to operate in dusty and explosive environments. Vector control and direct torque control are two common methods for controlling induction motors. The control algorithm of the two methods is almost the same in some cases and completely different in others. Each of the control methods has advantages due to their general structure, which lead to a better response compared to other methods. The vector control method contains a good steady state response however offers relatively less speed dynamic responses and steady state time. Several methods have been proposed to solve this problem. In this paper, a switching table is used to select the appropriate switching modes for the induction motor drive to improve the output dynamic response. Comparison of the results obtained from the performance of the drive under test with the vector control and direct torque control methods illustrates that the response of the drive system to the vector control includes faster dynamics with less constant state fluctuations. In order to validate the performance of the drive system, MATLAB software has been utilized for modeling and simulation.

Keywords: Induction motor, vector control, direct torque control, current ripples, voltage vector.

1. Introduction

Recently, improvements in the capabilities of the new generation of power electronic switches and a reduction in the cost of power transistors and GTOs leads to the possibility of designing variable speed drives using three-phase induction motors which are surpassing the dc motor drives in terms of cost and performance in some cases. Induction motors, especially the squirrel cage rotor type, have advantages such as lower maintenance, higher reliability, lower cost and inertia, and the ability to operate in harsh environments than dc motors. As a result, the drives of three-phase induction motors have been employed in some variable speed applications instead of dc drives [1]. Induction motors are more widely used in variable speed drives in addition to the constant speed actuators. Several control algorithms have been proposed to achieve goals such as steady-state response accuracy, high dynamics, control system simplicity, low cost, torque and noise reduction [4-2].

Voltage-frequency (v/f) open-loop control or scalar control lacks closed-loop control over speed or position, so despite operating in a wide range of speed changes, it includes low dynamics and slow speed characteristics [5]. Having fast torque dynamics and precise speed control requires closed loop control. In closed loop (speed or position) control, mechanical sensors can be used over a wide range of speeds, although at very low speeds the sensors are inefficient and the required position can be estimated by measuring other parameters such as voltage and current. In voltage vector-based control methods, stator quantities (flux, current, voltage) are decoupled into components that rotate synchronously with the rotor flux. In an induction machine, unlike a synchronous machine, the rotor currents are not applied directly, but these currents are induced in the rotor due to the sliding of the rotor to the rotating flux wave caused by the stator currents [7]. In torque-based control methods, the generated torque of the machine is directly controlled without the need for current control, and its main advantage over the vector control method is very fast dynamics [8].

Vector control (VC) and direct torque control (DTC) methods are mainly used in induction motor drives, which in specific applications, one of the two methods is selected as appropriate drive. By examining and comparing the common principles of VC and DTC methods in induction motor drives, it is possible to choose a suitable control system that has a relatively simple structure and better performs than conventional methods. The DTC method provides a faster torque response due to the rapid selection of the electronic switch angle of the drive converter [9]. The most important drawback of vector control over direct torque control is its relatively long dynamic response, which is due to the use of pulse width modulation (PWM). If the vector control system can be used along with a switching lookup table, the settling time can be significantly reduced. In this paper, first, the induction motor drive control is fully investigated and its performance is analyzed along with vector control and direct torque control methods. Then, by maintaining the general structure of these control methods, an attempt has been made to enter the switching table into the control system and improve the speed performance.

2. Induction Motor Drive Control

The presence of high-efficiency power switches and fast processors has paved the development and use of induction motor drives. In a typical induction motor drive, the power converter supplies the power into an electric motor. The output characteristic of the power converter can be adjusted so that the converter operates as a current source or voltage source with adjustable amplitude and frequency. Fig. 1 shows the basic block diagram for controlling a three-phase induction motor. The converter generates the power delivered to the motor according to the command applied by the controller. The controller may also perform additional operations such as condition monitoring and protection [10].

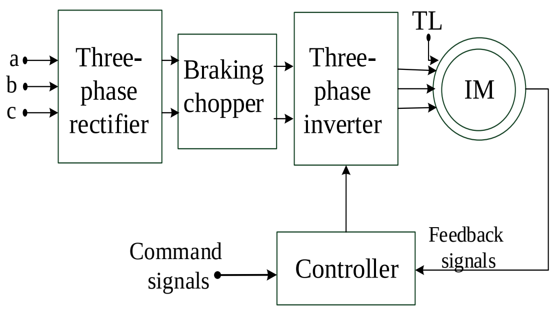


Fig. 1. Typical block diagram of a three-phase induction motor drive.

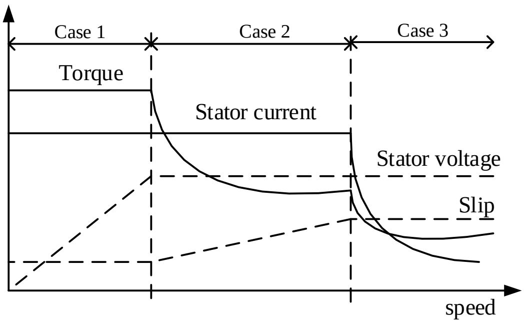


Fig. 2. Operating modes of an induction motor in a wide range of speeds.

Fig. 2 shows typical motor operating strategies over a wide range of speed control intervals [11]. For motor mode, the following three cases can be considered:

Case 1: Keep the slip speed constant and adjust the stator current to obtain a constant torque.

Case 2: Keep the stator voltage constant at its nominal value and adjust the stator current to obtain a constant power.

Case 3: Keep the stator voltage constant at its nominal value and adjust the slip speed so that the slip generated is always less than the slip corresponding to the maximum torque.

Based on Fig. 2, the work strategy is only illustrated in motor operation mode. The braking mode is similar to the motor mode. In braking mode, the upper speed limit in case 1 occurs at a speed higher than the corresponding motor speed, because in braking mode, the voltage drop in the machin is reversed.

2.1. Vector Control (VC)

One of the methods used in controlling the drive of electric motors is vector control. The vector control of induction motors is performed in different ways. However, in all topologies, the torque and coupling flux of the machine are controlled by the stator currents vector. The stator current vector is divided into two components, the torque generator and the flux generator, in the rotating reference frame, so that one component is in line with the coupling flux vector of the machine and the other component is perpendicular to it. In this section, the general method of vector control and its related relationships are briefly reviewed. [12].

The main equations describing the induction motor in the static reference frame areas follows

$$\vec{V}_s = R_s\vec{i}_s + \frac{d\vec{\psi}_s}{dt} \tag{1}$$

$$0 = R_r\vec{i}_r + \frac{d\vec{\psi}_r}{dt} - j\omega_m\vec{\psi}_r \tag{2}$$

$$\vec{\psi}_s = L_s\vec{i}_s + L_m\vec{i}_r \tag{3}$$

$$\vec{\psi}_r = L_m\vec{i}_s + L_r\vec{i}_r \tag{4}$$

In these equations, the parameters R_s and R_r are the stator and rotor resistance, L_s, L_r and L_m are stator inductance, rotor inductance and mutual inductance between rotor and stator, respectively.

The torque equation of the induction motor in the frame of qd0 and in terms of current and flux parameters is calculated as follows

$$T_{em} = \frac{3}{2}P\frac{L_m}{L_r}\left(\psi^e_{dr}i^e_{qs} - \psi^e_{qr}i^e_{ds}\right) \tag{5}$$

where *e* represents the synchronous reference frame. If the rotating coordinate system qd0 is assumed to be such that the d-axis is parallel to the rotor field and the component q of the rotor field, ψ_{qr}^{e}, is selected to be zero in the reference frame, then

$$\psi_{qr}^{e} = L_m i_{qs}^{e} + L_r i_{qr}^{e} = 0 \qquad (6)$$

$$i_{qr}^{e} = -\frac{L_m}{L_r} i_{qs}^{e} \qquad (7)$$

For ψ_{qr}^{e} equal to zero, equation (5) can be rewrite as follow

$$T_{em} = \frac{3}{2} P \frac{L_m}{L_r} \left(\psi_{dr}^{e} i_{qs}^{e}\right) \ \mathrm{N.m.} \qquad (8)$$

The above equation shows that if the rotor flux ψ_{dr}^{e} is not disturbed, the torque can be controlled independently by adjusting the q component of the stator current i_{qs}^{e}.

For ψ_{qr}^{e} to remain zero, $P\psi_{qr}^{e}$ must remain zero. In this case, the voltage equation on the q-axis of the rotor wiring, without applying any voltage to the rotor, is as follows

$$V_{qr}^{e} = R_r i_{qr}^{e} + p\psi_{qr}^{e} + (\omega_e - \omega_m)\psi_{dr}^{e} \qquad (9)$$

In Equation (9), p is operator of derivative. If in this equation, V_{qr}^{e} and $P\psi_{qr}^{e}$ are equal to zero, the slip velocity is obtained as

$$\omega_e - \omega_m = -\frac{R_r i_{qr}^{e}}{\psi_{dr}^{e}} \qquad (10)$$

Moreover, if ψ_{dr}^{e} remains unchanged, $p\psi_{qr}^{e}$ or in other words derivative ψ_{dr}^{e} will also be zero. In this condition, as well as the condition that ψ_{qr}^{e} is zero, it is included that i_{qr}^{e} must be zero as

$$V_{dr}^{e} = R_r i_{dr}^{e} + p\psi_{dr}^{e} - (\omega_e - \omega_m)\psi_{qr}^{e} \qquad (11)$$

When i_{dr}^{e} is zero, $\psi_{dr}^{e} = L_m i_{ds}^{e}$. By replacing this relation in Equation (10) and using Equation (7), the following relation is obtained for the slip velocity and the ratio of the d and q components of the stator flow in a rotating synchronous frame whose axis d is parallel to the rotor field

$$\omega_e - \omega_m = \frac{R_r}{L_r} \frac{i_{qs}^{e}}{i_{ds}^{e}} \qquad (12)$$

The vector control method is divided into two categories: direct and indirect methods. In the direct type, the angle θ_e, as shown in Fig. 3, is measured directly from air gap flux. In the indirect type, the rotor angle is obtained by measuring alternating quantities such as slip velocity. Fig. 4 shows the drive block diagram of the induction motor in which the location of the control block and its relationship to other parts are illustrated [13].

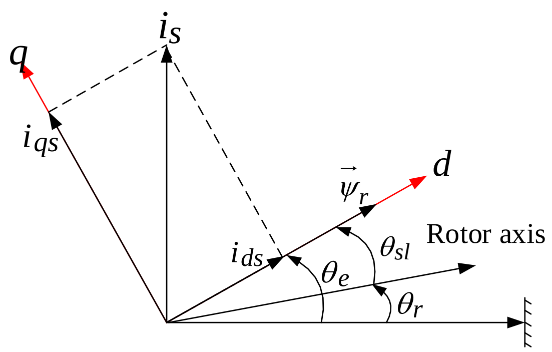


Fig. 3. Rotating synchronous qd0 frame.

In the block diagram (Fig. 4), by measuring the three-phase currents and the motor speed and using the relations running the motor, the electromagnetic torque and the rotor flux as well as the position of the rotor flux angles are calculated. The calculated values of torque and rotor flux are added to the corresponding reference values and passing through a PI controller to produce the required reference stator currents. Using the abc to dq block whose inputs are the three-phase currents i_{abc} and the angle of position of the rotor flux, the actual currents i_{dq} are calculated and entered into the current control block with the corresponding reference values of i^*_{dq}. The outputs of this block generate V_{dq} voltages, which are converted to three-phase V_{abc} voltages to enter the gate signal generator. In this way, the input pulses of a three-phase inverter are obtained to generate and apply appropriate voltages to the stator terminals.

2.2. Direct Torque Control (DTC)

In the direct torque control method, the switching modes of the power converter are selected using the switching table without the use of a current controller and PWM block. Fig. 5 shows the induction motor drive block diagram controlled by the DTC controller [14]. As shown in this figure, the DTC method is very similar to the direct vector control method in many ways. In other words, DTC is a kind of dc current vector control. Both methods require a flow and torque observer, and if the control is sensorless, the use of a speed observer will also be necessary. The DTC method has a real scale and does not require the current PI controllers. The reference frame conversion block and open-loop PWM are also removed and replaced with a lookup table. Therefore, due to these simplifications in the controller structure, the DTC depends on the motor parameters only in the speed-torque-flux observer. In addition, the DTC works with the stator flux, unlike the vector control that works with the rotor flux.

In terms of dynamic characteristics, although the flux dynamics are slower for direct vector control due to the negation of the rotor-component flux component dynamics, the two methods work somewhat similarly. In the diagram block (Fig. 5), fuzzy logic or slip mode control can be used instead of torque and flux hysteresis controllers.

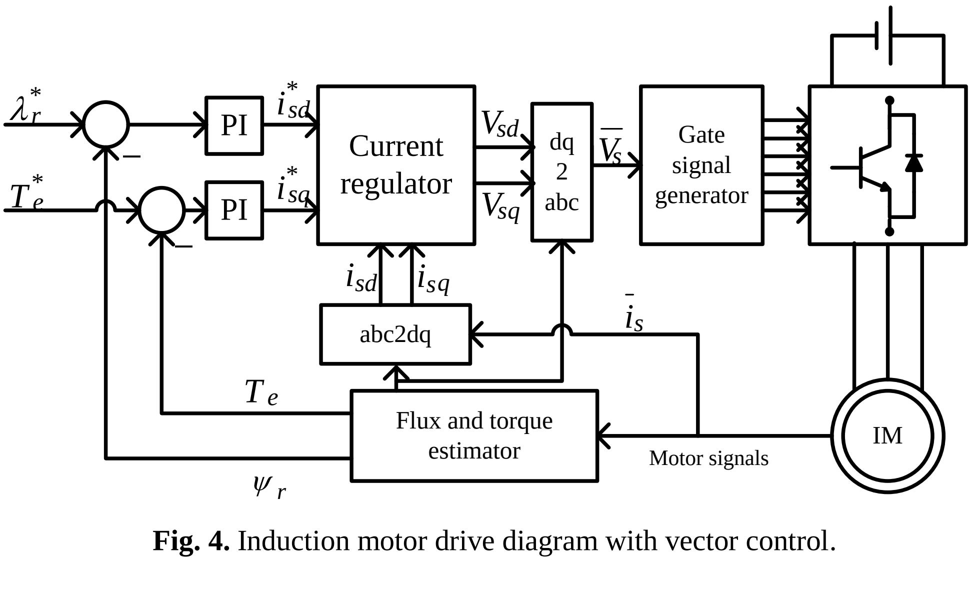


Fig. 4. Induction motor drive diagram with vector control.

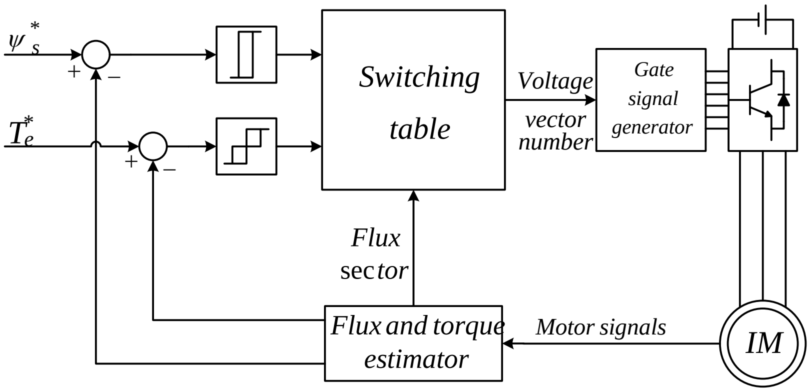
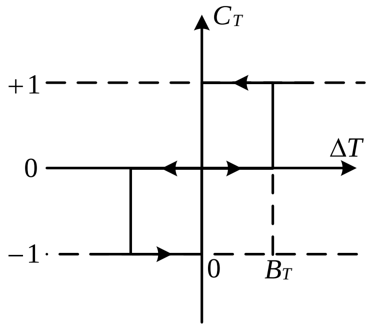


Fig. 5. Induction motor drive diagram based on DTC.

The difference between the estimated torque T_e and the reference torque T_s^* constitutes the three-level hysteresis comparator input, while the difference between the two estimated flux λ_s and the reference flux λ_s^* will also be the two-level comparative inputs. Fig. 6 shows the flux and torque comparators used in the DTC block [15].



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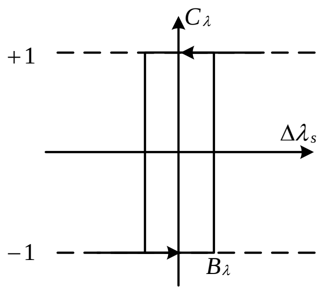


(b)

Fig. 6. a) Torque hysteresis comparator; b) flux hysteresis comparator.

With this relatively simple method, a quick torque response is achieved, but in the steady state, the current, flux, and torque will fluctuate with high ripple. This behavior is due to the lack of information about the values of torque and rotor speed in the voltage vector selection algorithm.

The electromagnetic torque in terms of stator flux and rotor flux as well as the angle between these two vectors, i.e. β, is obtained as follows

$$T_e = \frac{3}{2}P.\frac{L_m}{\sigma L_s L_r}\left|\overrightarrow{\psi_s}\right|.\left|\psi_r\right|\sin\beta \qquad (13)$$

$$\frac{dT_e}{dt} = \frac{3}{2}P.\frac{L_m}{\sigma L_s L_r}\left|\overrightarrow{\psi_s}\right|.\left|\psi_r\right|\frac{d\beta}{dt}\cos\beta \qquad (14)$$

Equation (14) shows the dynamics of the electromagnetic torque produced by the motor depends on the angular variations between the stator and rotor fluxes, and therefore by rapid angular β variations, the torque can be controlled more quickly. Due to such a dependence, the torque can be controlled almost instantaneously by moving the stator flux vector from a distance, approaching or constant relative to the rotor flux vector (which is assumed to be constant during the control operation).

Assuming that the drive's converter 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

$$V_a + V_b + V_c = 0 \quad (15)$$

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

$$\vec{V}_s = \frac{2}{3}V\left(S_a + S_b e^{j\frac{2\pi}{3}} + S_c e^{-j\frac{2\pi}{3}}\right) \quad (16)$$

As can be seen in Fig.7, the space voltage vector $\overline{V}_s$ has eight different values $\overline{V}_k$ in which $(k = 0, \ldots\ldots, 7)$. Although 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.

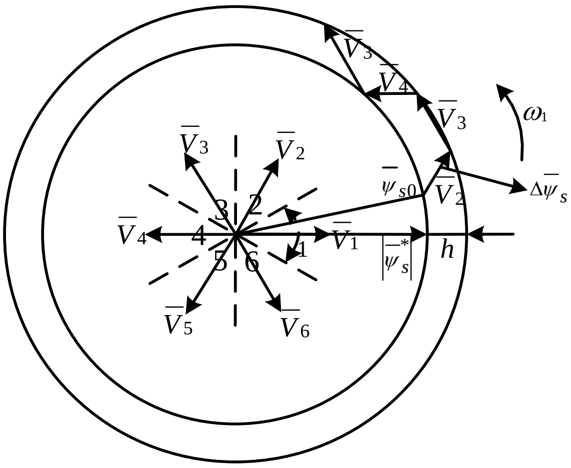


Fig. 7. Voltage vectors applied to the inverter and the path of the stator space flux.

2.3. Comparison of VC with DTC

The comparison of these two methods is important in terms of giving the consumer information on which method can be more efficient in each application. In recent years, many researchers have tried to solve the problems of the DTC method mentioned above. Among the important solutions proposed by some researchers in this field, the following can be listed [16]:

- employing of optimal switching tables;
- Using comparators with or without hysteresis, 2 or 3 levels;
- Applying of DTC methods in fixed switching frequency applications using PWM or SVM methods;
- Applying of fuzzy logic methods or fuzzy systems - neural network;
- Use of complex flux estimators to improve control at low speeds.

All of the proposed methods improve the DTC performance, however they contain a control complexity. Since DTC is essentially a sensorless method; in many ways it is similar to direct vector control. In DTC, based on the error of torque and flux magnitude as well as the position of the stator flux vector in one of the six regions of the periodic cycle, a specific voltage vector or a combination of vectors is applied directly to the inverter for a specified time. The control system needs to estimate the relevant variables in order to detect the stator torque and flux error. Thus all flux or torque estimators as well as velocity detectors used in direct vector control; It is also suitable in DTC.

Parts of the direct vector controller that have been removed from the DTC include [17]:

1- PI controller
2- Reference frame transfer block
3- current regulator
4- PWM signal generator

Therefore, control methods that have the above four conditions are among the direct torque controllers. In order to compare the two methods from a steady state perspective, the existing torque and current ripple can be evaluated for different values of input speed and torque. The effective three-phase current ripple is defined as follows

$$I_{rip,rms} = \sqrt{\frac{1}{T}\int_0^T \left(i_{ripA}^2 + i_{ripB}^2 + i_{ripC}^2\right)} \quad (17)$$

To compare the methods in the transient mode, the transient responses to the torque stepping changes at different rotor speeds are investigated and the results are shown in the simulation results.

3. Simulation Results

The parameters of the three-phase induction motor used in the simulation in Matlab/Simulink software are listed in Table 1 [18].

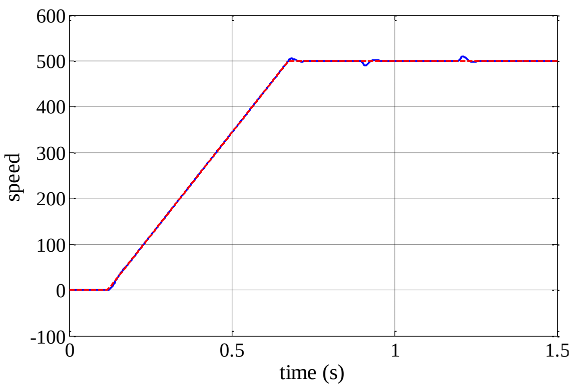
Table 1. induction motor parameters

Power	200Hp
Voltage	460 v(Line-Line)
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 $kg.m^2$

3.1. Load Control Under Constant Speed

The two discussed control methods are applied to the induction motor with the parameters mentioned in Table 1 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 shows the drive speed under control methods. Ideally, for a speed set, the drive speed should remain constant by changing the load torque from no-load to full load, however in practice this is not the case and as the load increases, the motor speed decreases. In these figures, the dot diagram shows the reference speed and the other diagram shows the actual speed. The transient state of speed occurs at the start for a short period of time, and after reaching a constant velocity, it also shows slight changes. In both figures, the actual speed follows the reference velocity well. The time to reach the final speed for both control methods is about 0.65 seconds.



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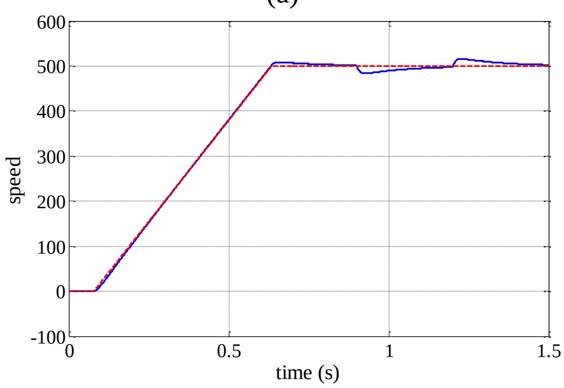

(b)

Fig. 8. Motor speed results, a) VC, b) DTC

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.

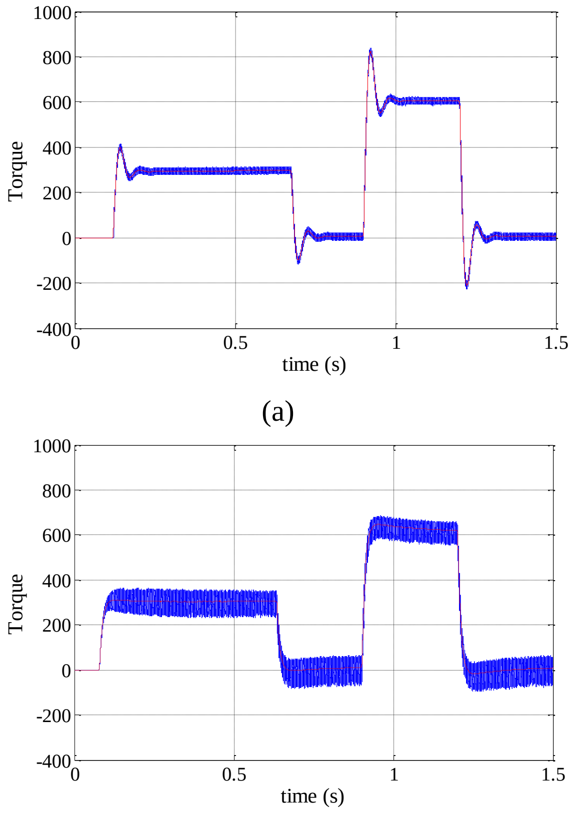

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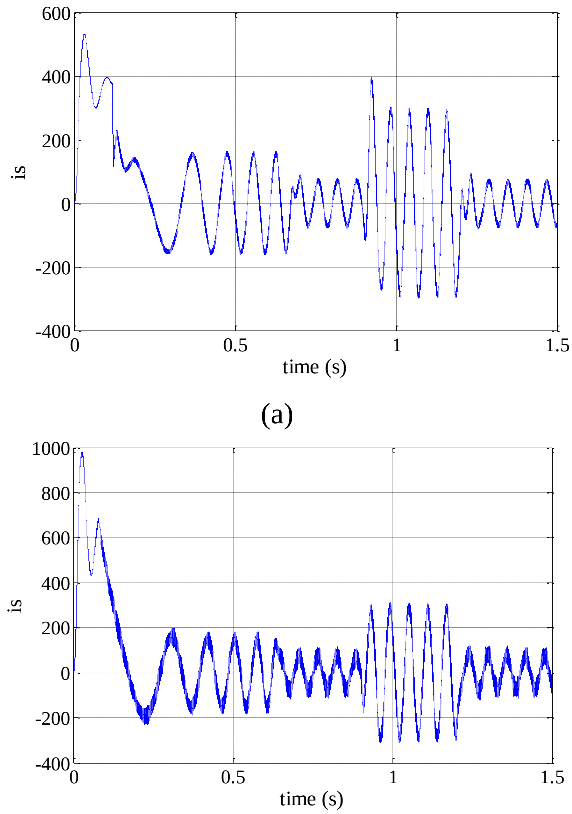
Fig. 9. Motor torque results, a) VC, b) DTC

In order to observe the current waveforms, the three-phase steady state currents for the induction motor under the two control methods are shown in Fig. 10.

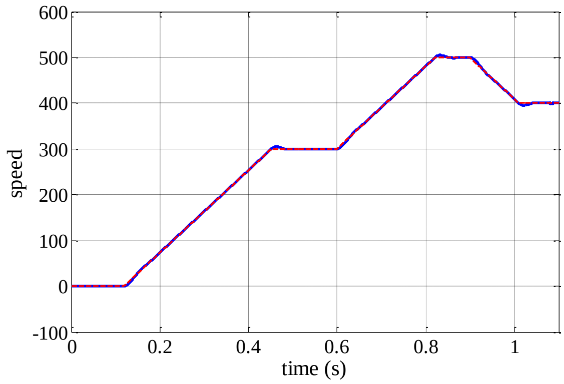


(b)

Fig. 10. Motor phase current, a) VC, b) DTC

3.2. No-Load speed Control

In this subsection, the performance of the motor drive is investigated by the two 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. 11 shows the response of the motor speed to changes in reference speed. According to these curves, 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.



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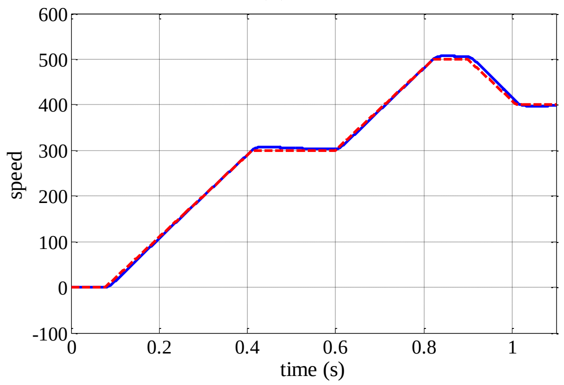
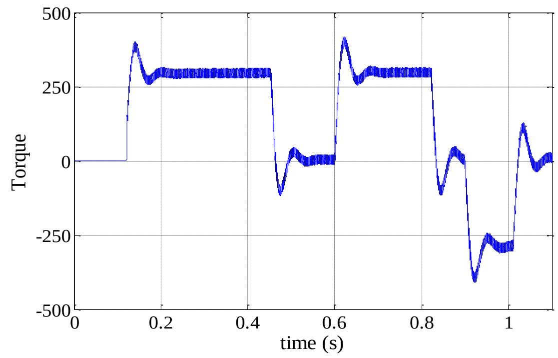


(b)

Fig. 11. Motor speed responces, a) VC, b) DTC

The torque response of the induction motor for speed changes is shown in Fig. 12. After reaching the nominal speed, the motor continues to operate at zero torque and speed 300 rad/s until the speed increases to 50 rad/s at t=0.6s. When the speed reaches the desired value, the torque becomes zero again until it returns to the original value of 400 rad/s again at t=0.9s.

Fig. 13 illustrates the stator phase current. According to the waveforms of the current in the control methods, the current at different operating stages include startup, deceleration, acceleration, and steady state are shown. In all methods at start-up, the current contains a certain amount of jump, which depending on the type of control method used.



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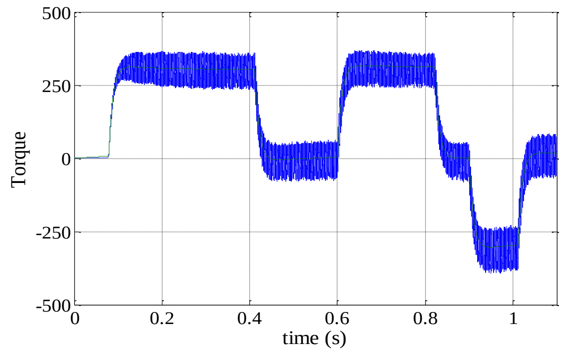

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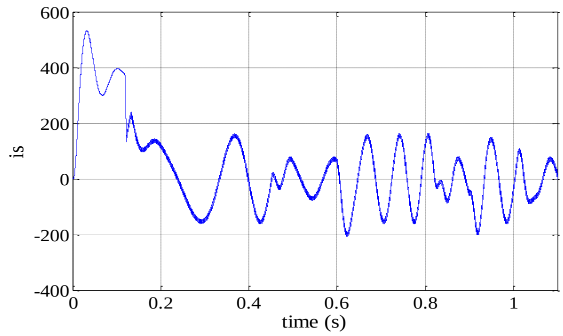
Fig. 12. No-load torque responces during variable speeds, a) VC, b) DTC



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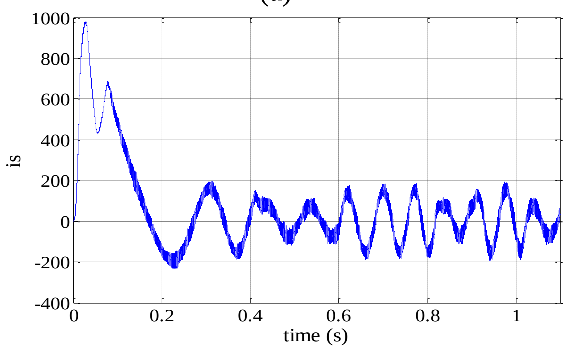

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Fig. 13. No-load current waveforms during variable speeds, a) VC, b) DTC

4. Conclusions

Vector control and direct torque control methods are mainly used in induction motor drives, which in specific applications, one of the two methods is selected as necessary. In this paper, we try to combine the advantages of each of the VC and DTC methods in case of better control system. Presented control systems, although contain better responses than conventional methods, they can still be used with other methods to reduce permanent and transient ripples. Comparison of motor performance under the control of VC and DTC methods with respect to the obtained results shows that the response of DTC method has relatively faster dynamics than vector control and vector control has less steady state fluctuations than DTC method.

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