

A Comparative Performance Analysis of Torque Control Schemes for Induction Motor Drives

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ABSTRACT

This paper presents a comparative study of field-oriented control(FOC), conventional direct torque control(DTC) and proposed space vector modulated direct torque control with low pass filter(SVM-DTC). The main characteristics of FOC, DTC and proposed SVM-DTC schemes are studied by simulation, emphasizing their advantages and disadvantages. The performance of three control schemes is evaluated in terms of torque, current ripples and transient responses. It is shown that the proposed scheme improves the performance by combining a low torque, current ripple characteristics with fast torque dynamics.

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1. INTRODUCTION

The Adjustable Speed Drives (ASD) is generally used in an industry. In most drives Induction Motors (IM) are used. ASDs are widely used in application such as elevators, electric vehicles and hybrid electric vehicles, pumps, robotics, wind generation systems, ship propulsion, etc. [1], [2].

DC machines were used extensively in ASD over the past decades mainly because of the decoupled control of flux and torque that could be achieved by the field and armature current control respectively. They are mostly used in variable speed applications to give a fast and good dynamic torque response because the commutator maintains a fixed torque angle at all time. However, DC machines have the disadvantages of higher cost, higher rotor inertia and maintenance problem with commutator and brushes. In addition they cannot operate in dirty and explosive environments. The induction machines do not have the disadvantages of DC machines. Therefore, in last three decades the DC motors are progressively replaced by AC drives [3].

The control of the IM is not a trivial matter when compared to the DC motor. The invention of Field Oriented Control (FOC) in early 1970 by F.Blaschke enables rugged induction machines to be controlled similar to that of DC machines. FOC provides similar decoupled control of torque and flux, which is inherently possible in the DC machines. Although, the FOC enables an induction machine to attain fast torque response, some problems still exist. An accurate flux estimator had to be employed to ensure the estimated value used in calculation does not deviate from the actual value. Besides, the co-coordinate transformation had increased the complexity of this control method [4]-[5], [13].

Direct Torque Control (DTC) was first introduced by Takahashi in 1986. The principle is based on limit cycle control and it enables both quick response and efficient operation. DTC control the torque and speed of the motor, which is directly based on the electromagnetic state of the motor. It has many advantages compared to FOC, such as less machine parameter dependence, simpler implementation and quicker

response. The configuration of DTC is simpler than the FOC system due to the absence of frame transformer, current controlled inverter and position encoder, which introduces delays and requires mechanical transducer. However, conventional DTC has several disadvantages such as difficulty to control torque and flux at low speed, high current and torque ripple, variable switching frequency and high noise level at low speed [6]-[13].

Since conventional DTC was introduced in 1986, a large number of technical papers appear in the literature mainly to improve the performance of induction motor. Two problems usually associated with DTC drives which are: (i) variable switching frequency due to the hysteresis comparators used for the torque and flux comparators and (ii) inaccurate stator flux estimations which can degrade the drive performance. Some schemes have managed to maintain constant switching frequency and low torque and flux ripples by utilizing space vector modulation with deadbeat torque and flux control [14], multilevel inverter [29], artificial intelligence [26], matrix converter [25], adaptive flux observer [27] and eighteen sector switching strategy [24]. All of these techniques however increase the complexity of the drive systems. Thus, the inherent simple control structure of the conventional DTC drive is lost. In the case of stator flux estimation, it is estimated based on the variation of the two types of estimators, namely, voltage and current models [32, 33]. To maintain a speed sensor less operation, only voltage model has to be used [30]. In voltage model technique, low pass filter (LPF) estimator is normally used in place of a pure integrator to avoid integration drift problem [31].

Thus the objective of this paper is to give a fair comparison between the three schemes, FOC, Conventioanl DTC and proposed SVM-DTC with LPF. The rest of the paper is organized as follows. Section 2 presents the overview of FOC, Coventioanl DTC and proposed SVM-DTC with LPF. Section 3 gives the simulation results of all three schemes both in transient period and steady state period. Section 4 gives the comparisons of three schemes and finally, conclusions are given in section5.

2. IM MODEL

The following equations written in terms of space voltage vector in a stationary reference frame describe the dynamic behavior of an induction motor

$$v_s = R_s i_s + \frac{d\lambda_s}{dt} \quad (1)$$

$$0 = R_r i_r + \frac{d\lambda_r}{dt} - j\omega_r \lambda_r \quad (2)$$

$$\lambda_s = L_s i_s + L_m i_r \quad (3)$$

$$\lambda_r = L_r i_r + L_m i_s \quad (4)$$

Where $v_s = [v_{ds} \quad u_{ds}]^T$ is space vector of stator voltage, $\lambda_s = [\lambda_{ds} \quad \lambda_{qs}]^T$ and $\lambda_r = [\lambda_{dr} \quad \lambda_{qr}]^T$ are respectively the stator and rotor flux vectors,

$i_s = [i_{ds} \quad i_{qs}]^T$ and $i_r = [i_{dr} \quad i_{qr}]^T$ are respectively the stator and rotor current vectors.

(R_m, R_r) and (L_s, L_r) are respectively the stator and rotor resistances and inductances, L_m is mutual inductance, ω_r is motor angular speed in electrical rad/sec.

Also, the motor mechanical equation is

$$\frac{d}{dt} \omega_m = \frac{T_e}{J_m} - \frac{T_i}{J_m} - \frac{B_f}{J_m} \omega_m \quad (5)$$

Where T_{eref} is the motor electromagnetic developed torque which is defined by:

$$T_e = \frac{3P}{2} (\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}) \quad (6)$$

2.1 Principles of FOC

The principle of the FOC is based on an analogy to the separately excited dc motor. In this motor flux and torque can be controlled independently. The control algorithm can be implemented using PI-regulators. In IM independent control of flux and torque is possible in the case of coordinate system is connected with rotor flux vector. A block diagram of FOC scheme is presented in Fig.1.

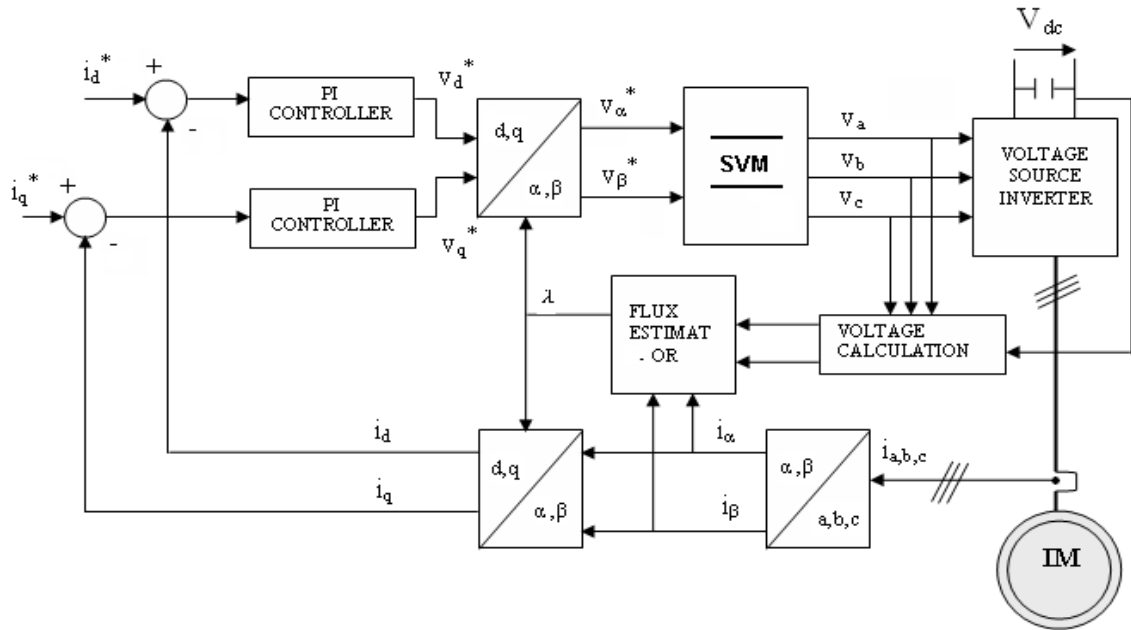


Figure 1 Block Diagram of FOC

The goal of FOC is to maintain the amplitude of the rotor flux linkage Ψ_r at a fixed value, except for field weakening operation or flux optimization, and only modify a torque-producing component in order to control the torque of the ac machine. This control strategy is based on projections. Electromagnetic torque is produced by the interaction of stator flux linkages and stator currents (or rotor flux and rotor current), and can be expressed as a complex product of the flux and current space phasors. In order to gain a complete decoupling of torque and flux, the current phasor i_s is transformed into two components of a rotating reference frame: A flux producing component i_d , aligned with d axis representing the direction of the rotor flux phasor, and a torque producing component i_q , aligned with the q axis perpendicular to the rotor axis. Thus, the electromagnetic torque generated by the motor can be controlled by controlling the q-axis current. This is equivalent to the torque control of a separately excited dc machine.

2.2 Principles of conventional DTC

The basic principle in conventional DTC for IM is to directly select stator voltage vectors by means of a hysteresis stator flux and torque control as in Fig.2.

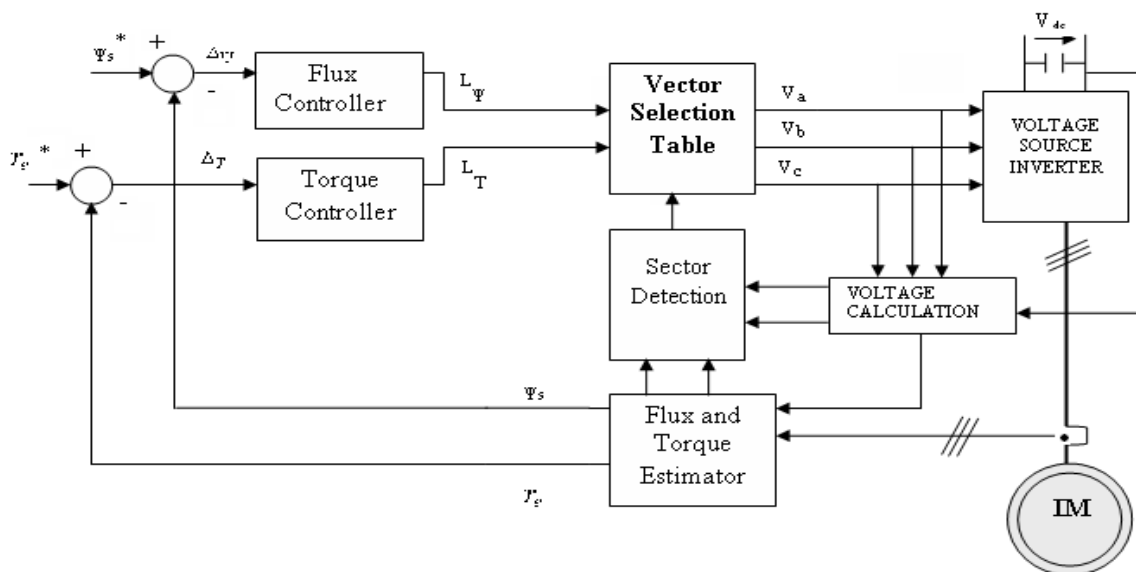


Figure 2 Block diagram of Conventional DTC

Table 1 Switching Table for Conventioanl DTC

Sector		1	2	3	4	5	6
$\Delta_\psi = 1$	Flux						
	Torque						
	$\Delta_T = 1$	V ₂	V ₃	V ₄	V ₅	V ₆	V ₁
$\Delta_\psi = 0$	Flux						
	Torque						
	$\Delta_T = 0$	V ₇	V ₀	V ₇	V ₀	V ₇	V ₀
$\Delta_\psi = -1$	Flux						
	Torque						
	$\Delta_T = -1$	V ₆	V ₁	V ₂	V ₃	V ₄	V ₅
$\Delta_\psi = 0$	Flux						
	Torque						
	$\Delta_T = 1$	V ₃	V ₄	V ₅	V ₆	V ₁	V ₂
$\Delta_\psi = 0$	Flux						
	Torque						
	$\Delta_T = 0$	V ₀	V ₇	V ₀	V ₇	V ₀	V ₇
$\Delta_\psi = -1$	Flux						
	Torque						
	$\Delta_T = -1$	V ₅	V ₆	V ₁	V ₂	V ₃	V ₄

From Fig.2 stator flux Ψ_s^* and torque T_e^* are compared with the corresponding estimated values. Both stator flux and torque errors are processed by means of hysteresis band comparators. In particular, stator flux is controlled by a two level hysteresis comparator, whereas the torque is controlled by a three level comparator. On the basis of the hysteresis comparators and stator flux sector a proper VSI voltage vector is selected by means of the switching table given in Table 1.

2.3 Proposed SVM-DTC with LPF

On the subject of the SVM-DTC with closed-loop torque control, its control objective is to select the exact stator voltage vector, v_s that changes Ψ_s to meet the load angle reference, and so the desired torque while keeping flux amplitude constant. A space vector modulation algorithm is used to apply the required stator voltage vector. It is expected that torque ripple is almost eliminated, while zero steady state error is achieved with fixed switching frequency. The stator flux can be directly obtained from the motor model equation as follows:

$$\hat{\Psi}_s = \int (V_s - R_s I_s) dt \quad (7)$$

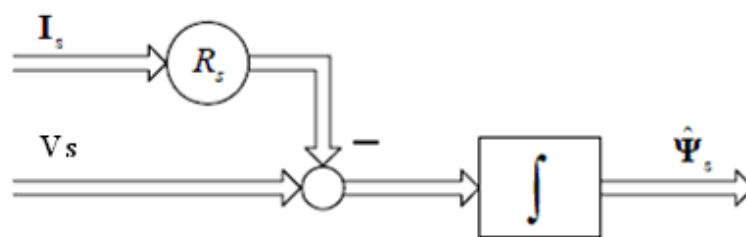


Figure 3 Voltage model based estimator with pure integrator

Fig.3 is a classical voltage model of stator flux vector estimation, which obtains flux by integrating the motor back EMF. The block diagram of this estimator is shown in Fig. This method is sensitive for only one motor parameter, stator resistance. However, the implementation of pure integrator is difficult because of dc drift and initial value problems. In order to eliminate these problems the authors proposed a new flux estimator with low pass filter as shown in Fig.4, which eliminates problems with initial conditions and dc drift, which appear in pure integrator. In this case the equation can be transformed as follows:

$$\frac{d\hat{\Psi}_s}{dt} = (\hat{V}_s - R_s I_s) - \frac{1}{T_F} \hat{\Psi}_s \quad (8)$$

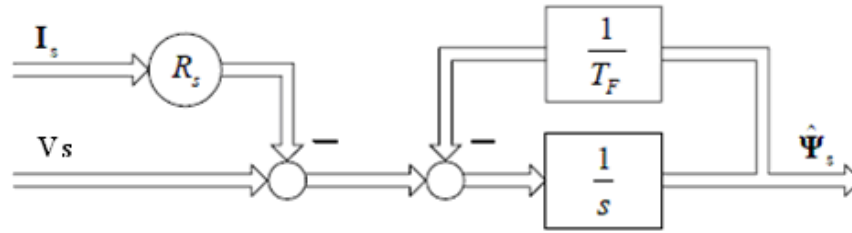


Figure 4 Flux estimator based on voltage model with low pass filter

The block diagram of the method with low pass filter is presented in Fig.5. The estimator stabilization time depends on the low-pass filter time constant T_F .

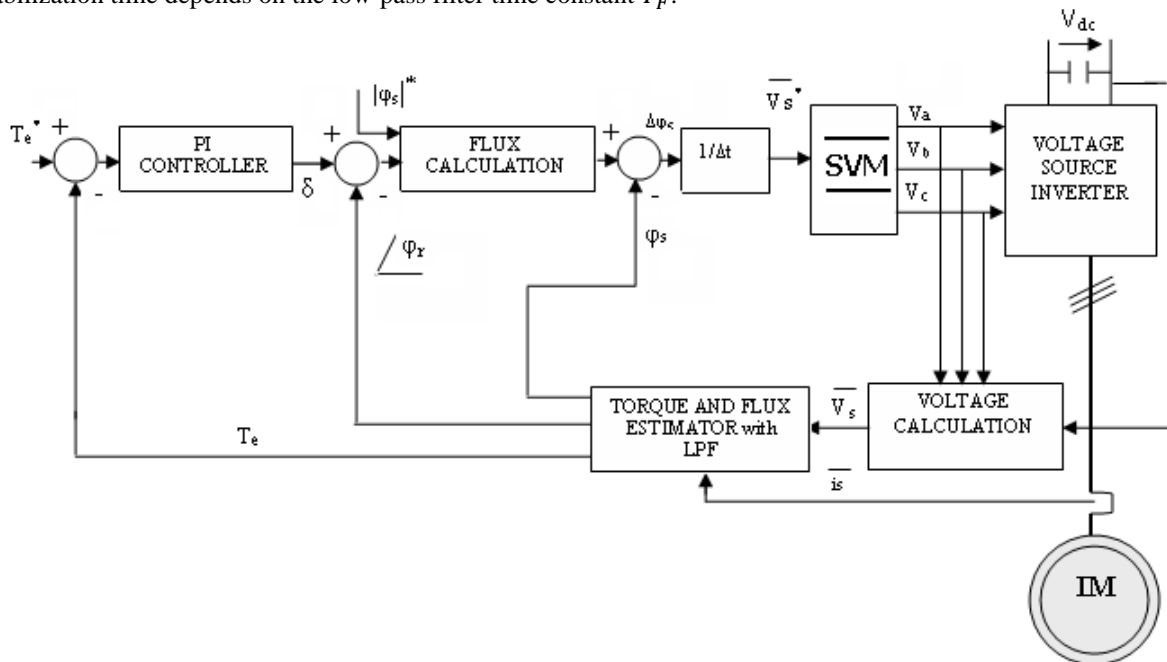


Figure 5 Block scheme of SVM-DTC with Low Pass Filter

3 SIMULATION MODELS AND RESULTS

Each of the three control schemes are simulated using MATLAB/Simulink. The inputs to the simulation model are the applied voltage and rotor speed. The model then calculates the stator current, stator flux, rotor current, rotor flux, and torque. The simulation model is carefully arranged to avoid algebraic loops. These are created when the output of a block is directly dependant on an input and that is obtained via a feedback path directly from the output of that block. These algebraic loops can be avoided by arranging the model such that there is an integral in each of these feedback paths. The dead-time and minimum-on time requirements are also ignored such that the average output voltage produced matches the reference voltage.

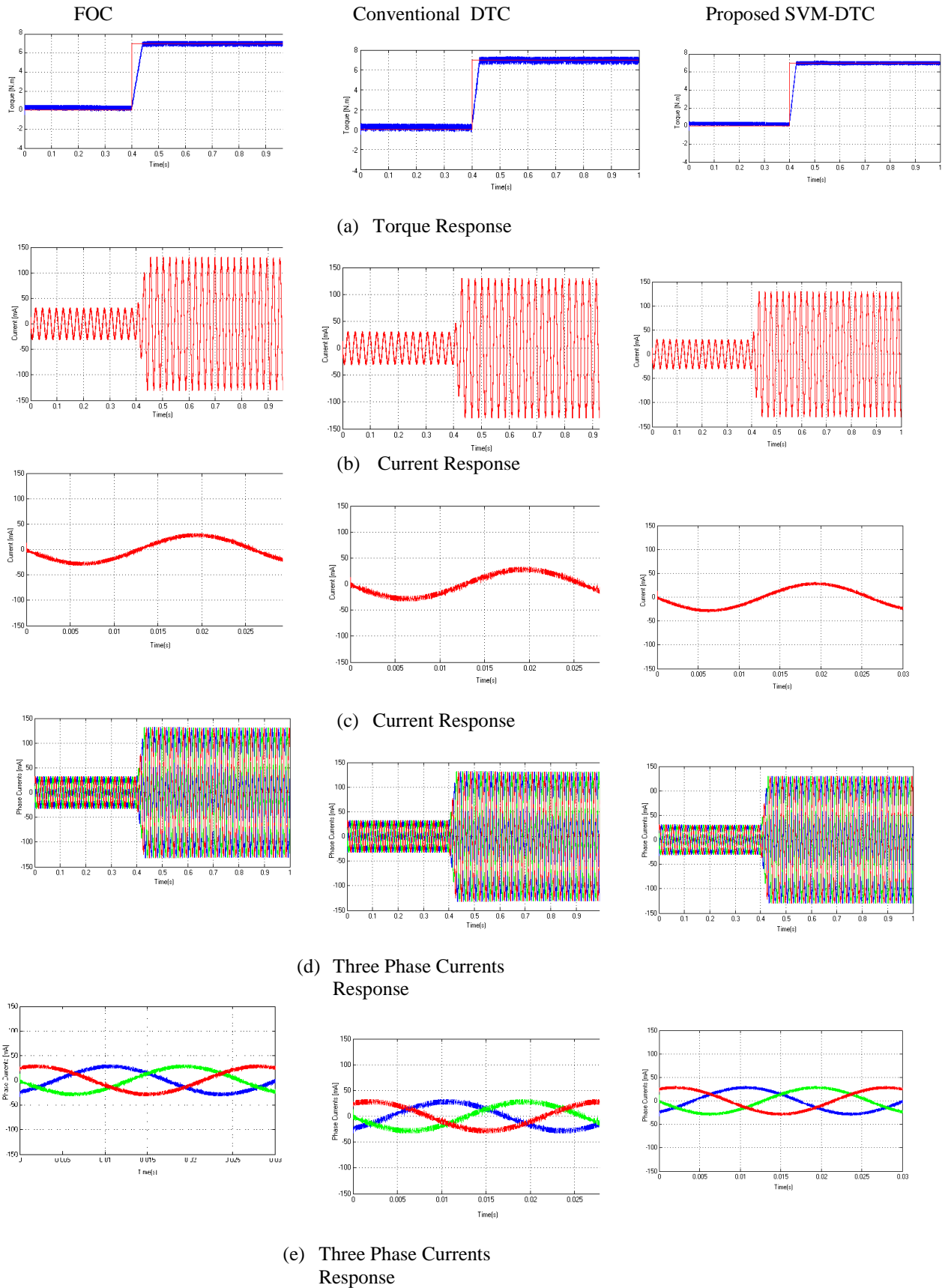


Figure 6 Transient Response of FOC, Conventional DTC and Proposed SVM-DTC with Low Pass Filter at 500 RPM

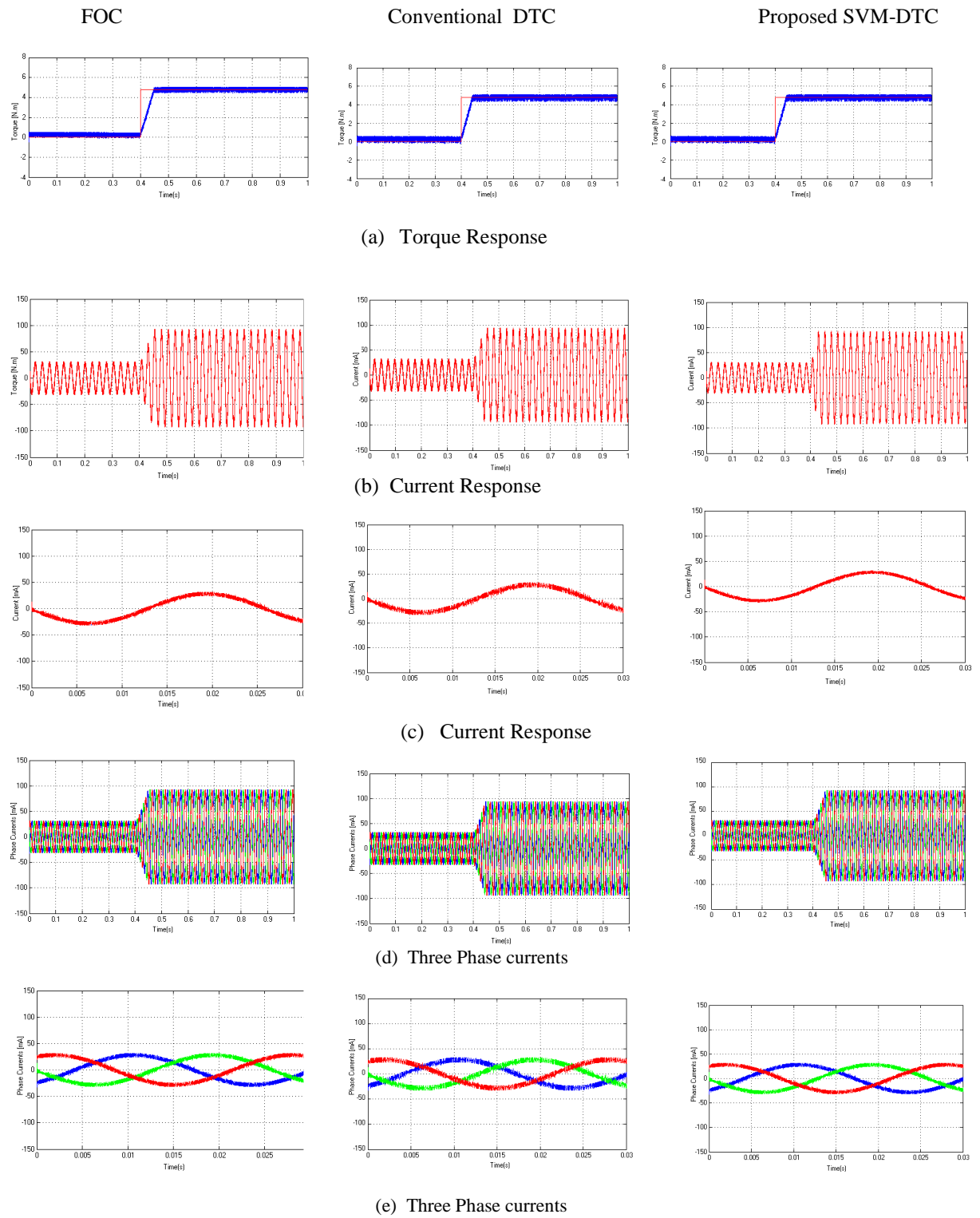


Figure 7 Transient Response at 100RPM

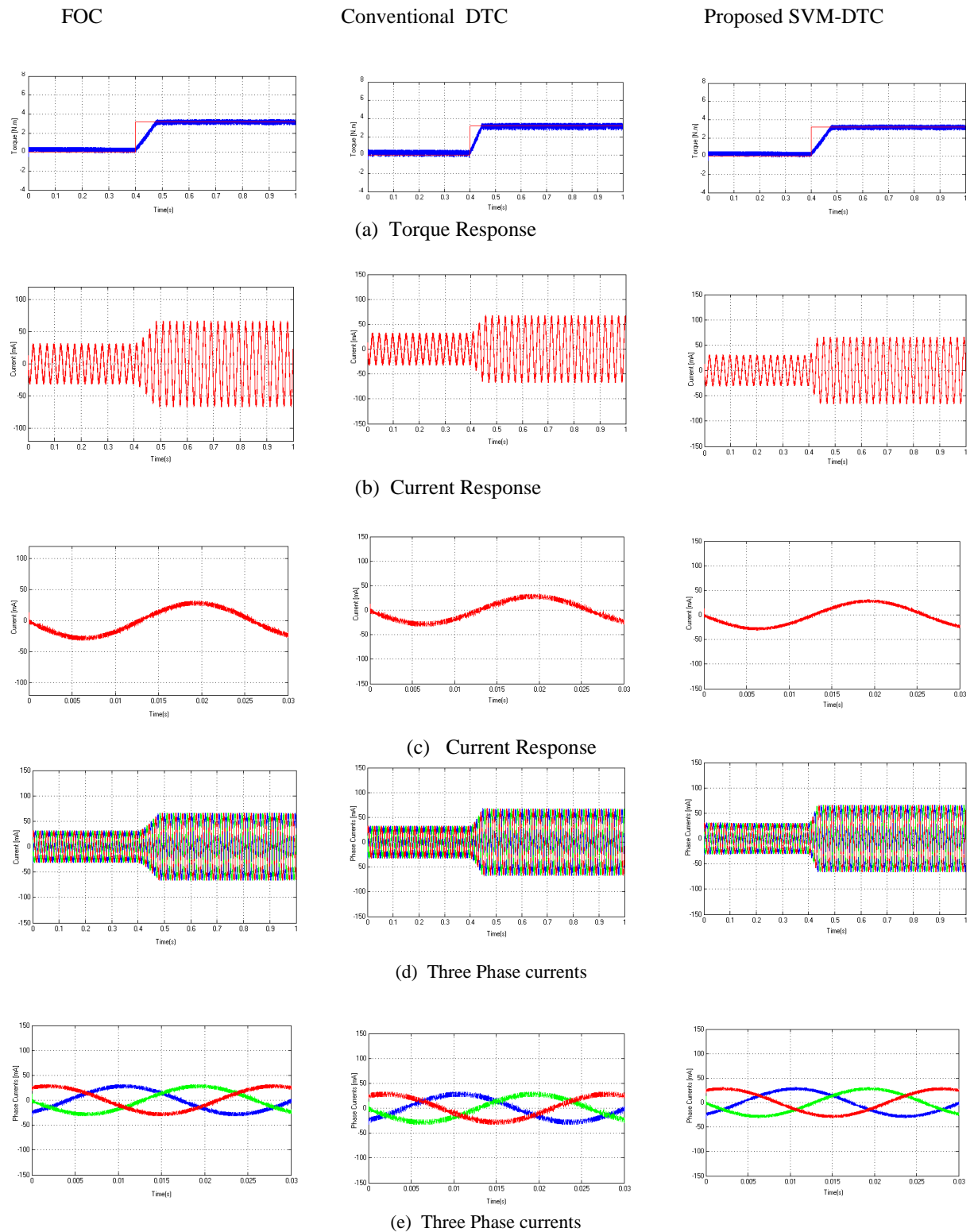


Figure 8 Transient Response at 1500 RPM

3.1 Transient Performance

The transient responses of the three control schemes are evaluated by simulating step changes in the torque responses. Fig.6 (a)-(e) illustrates the torque responses; the current ripples obtained using FOC, conventional DTC and proposed SVM-DTC at 500 rpm. Fig.7 (a)-(e) illustrates the torque responses, current

ripples of FOC, conventional DTC, proposed SVM-DTC at 1000 rpm. Similarly, Fig.8 (a)-(e) illustrates the torque responses, current responses of three control methods at 1440 rpm. The settling time of three control methods are given in Table II.

Table II Settling time of the torque response

	500 rpm	1000 rpm	1440 rpm
FOC	0.038s	0.052s	0.076s
Conventional DTC	0.027s	0.038s	0.056s
Proposed SVM-DTC	0.027s	0.039s	0.057s

3.2 Steady State Performance

The steady state performance of the three control strategies is evaluated based on the torque ripple and on the current distortion. Fig.9 (a)-(e) illustrates the steady state torque ripples, the current ripples obtained using FOC, conventional DTC and proposed SVM-DTC at 500 rpm. Fig.10 (a)-(e) illustrates the torque ripples, current ripples of FOC, conventional DTC, proposed SVM-DTC at 1000 rpm. Similarly, Fig.11 (a)-(e) illustrates the torque ripples, current ripples of three control methods at 1440 rpm. From these figures it can be seen that FOC and proposed SVM-DTC both exhibit very low torque ripple of 0.3Nm and 0.2Nm respectively. This is due to both schemes using space vector modulation to synthesise the voltage.

The average torque ripple for conventional direct torque control was 0.6Nm. The torque ripple of three control strategies is given in Table III.

Table III Torque Ripples

	500 rpm	1000 rpm	1440 rpm
FOC	0.36Nm	0.32Nm	0.29Nm
Conventional DTC	0.46Nm	0.48Nm	0.44Nm
Proposed SVM-DTC	0.32Nm	0.34Nm	0.31Nm

The simulated current waveforms are shown for each method. Again, FOC and proposed SVM-DTC produce very low ripple due to the space vector modulation used to synthesise the voltage. Conventional DTC is slightly more distorted current waveform. The current ripple of three control strategies is given in Table IV.

Table IV Current Ripples

	500 rpm	1000 rpm	1440 rpm
FOC	8.2mA	7.8mA	7.5mA
Conventional DTC	10.2mA	9.9mA	9.2mA
Proposed SVM-DTC	7.2mA	6.9mA	6.6mA

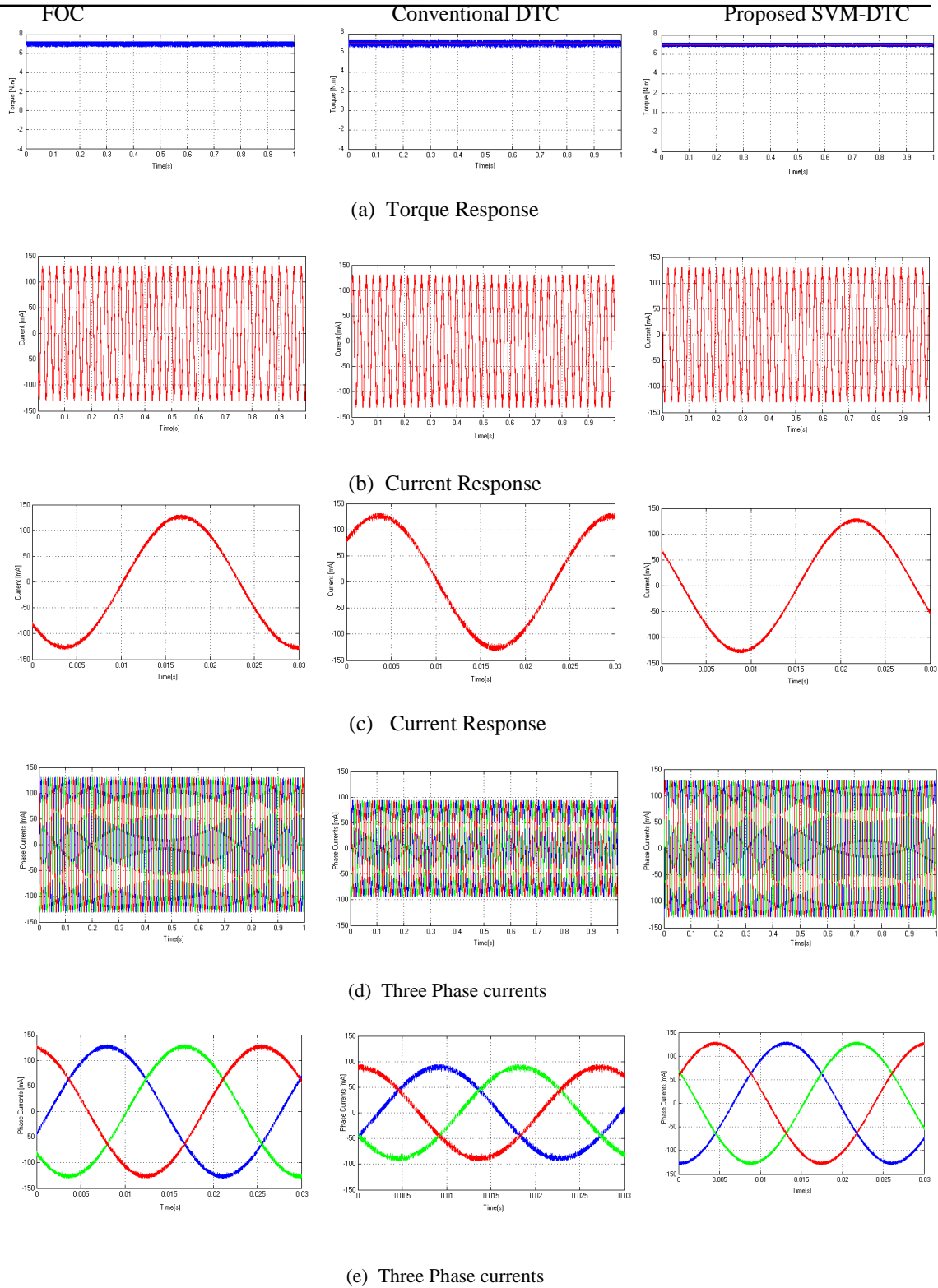


Figure 9 Steady state Response at 500 RPM

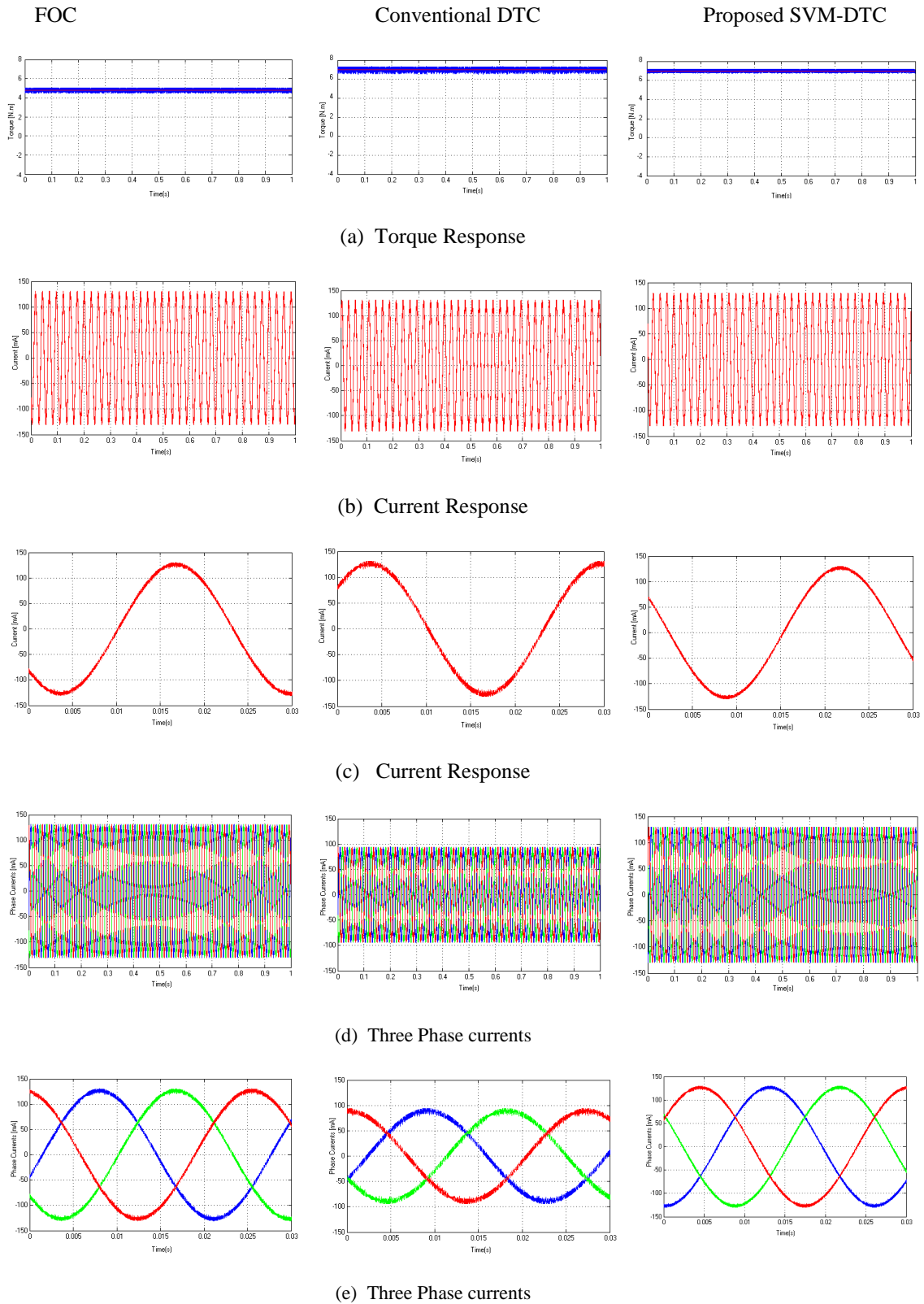


Figure 10 Steady state Response at 1000 RPM

FOC

Conventional DTC

Proposed SVM-DTC

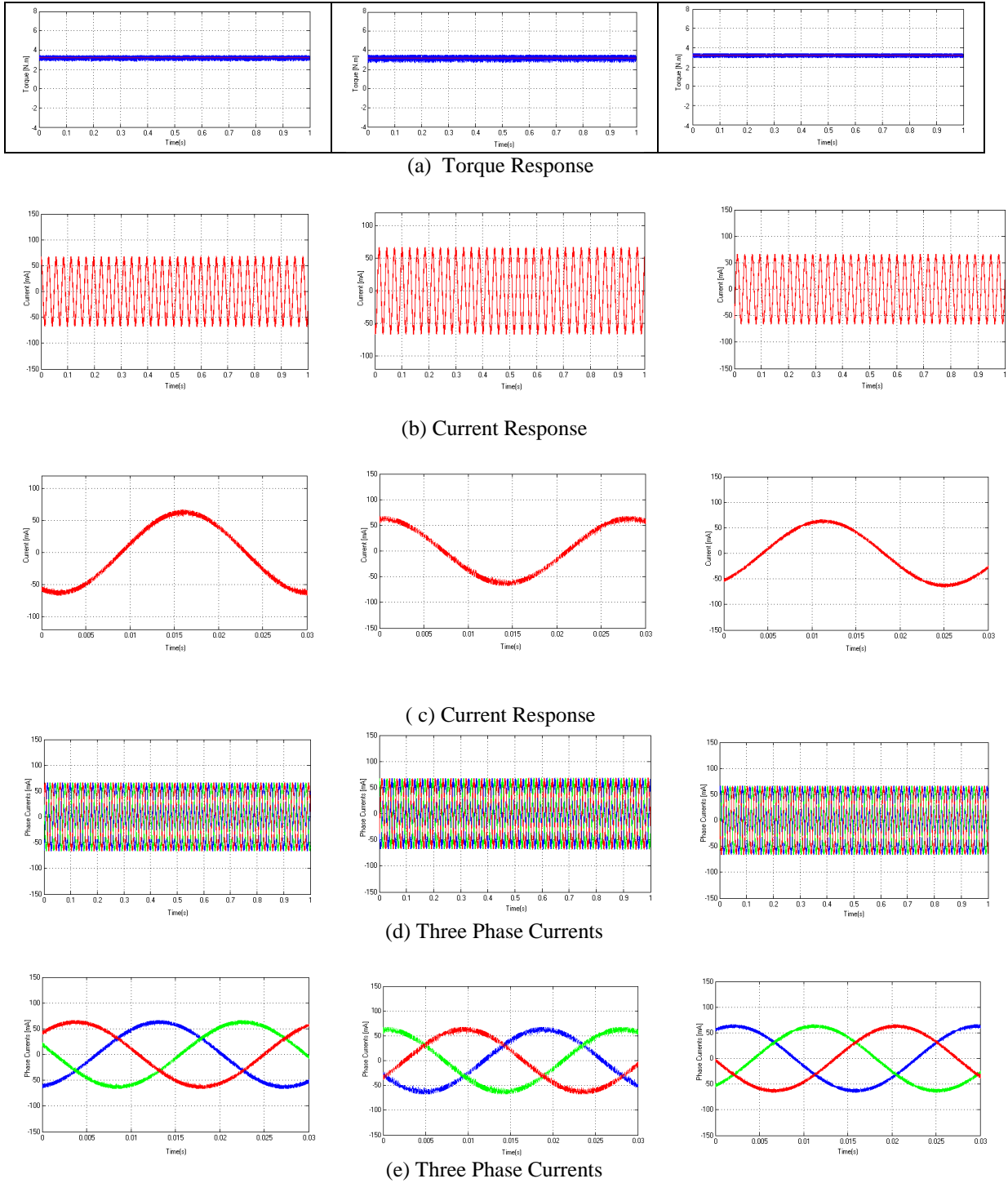


Figure 11 Steady state performace at 1500 RPM

4. COMPARISON OF THE TORQUE CONTROL STRATEGIES

Induction motor torque control has traditionally been achieved using FOC. This is a relatively simple but effective control scheme. Its disadvantages are that it requires an encoder to measure rotor speed, it is sensitive to parameter detuning and the PI controller that regulates the stator current limits the transient response.

The direct torque control scheme was later introduced to control the torque and flux directly based on the instantaneous errors in the torque and flux. It does eliminate the encoder required to measure rotor speed and has significantly higher dynamic performance due to the lack of the PI controller. The hysteresis-based switching of the inverter results in high torque ripple and current distortion.

The proposed SVM-DTC with low pass filter combines the features of FOC and conventional DTC. Like the classical DTC, no encoder is required and the lack of a PI current controller results in a high dynamic performance. The disadvantages of classical DTC are removed by the use of space vector modulation that makes effective use of the inverter, resulting in low torque ripple and current distortion.

5. CONCLUSION

This paper presented a comparison between three torque control methods for induction motor drive. The description of three control schemes and their principle of operation have been presented. DTC was developed as an alternative to FOC that had been in use for a number of years. DTC has the advantage of not requiring speed or position encoders and uses voltage and current measurements only. It also has a faster dynamic response due to the absence of the PI controller. A disadvantage of DTC is its comparatively high current distortion and torque ripple. The proposed SVM-DTC with low pass filter combines the best features of the DTC such as fast dynamic response as conventional DTC and low steady state torque ripple (32% reduced) and current distortion (34% reduced). And compared to FOC the proposed scheme has 24% improved torque response.

Nomenclature

Symbol	Definition
i_{ds}, i_{qs}	d and q components of the stator current in stationary reference frame
i_{dr}, i_{qr}	d and q components of the rotor current in stationary reference frame
L_m	Mutual Inductance
L_s, L_r	Stator and Rotor Self Inductance
R_s, R_r	Stator and Rotor Resistance
V_s	Stator Voltage
V_{ds}, V_{qs}	d and q components of the stator voltage in stationary reference frame
λ_s	Stator magnetic flux
$\lambda_{ds}, \lambda_{qs}$	d and q components of the stator magnetic flux
$\lambda_{dr}, \lambda_{qr}$	d and q components of the rotor magnetic flux

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