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A Simplified Design of Space Vector Modulation for Speed and Torque Control of Induction Motor

Muluneh L. Woldesemayat, K. D. Badgujar, Won Sangchul

Abstract ***−This paper proposes a simplified Space Vector Modulation technique which is used to control an inverter that supplies voltage to an induction motor. A simplified dynamic model of an induction motor model was also designed and voltage is supplied to it using SVM technique. A step by step design procedure with the help of matlab and Simulink made the complexity of the system simpler than existing models. This paper briefly explains design of space vector modulation technique and induction motor modeling. With the help of appropriate interfacing the design method will be used in industrial applications where the space vector modulation technique is used to achieve smooth control of speed and torque. Finally, on-line starting of the designed Induction Motor model was simulated. Moreover comparison of existing and the simplified SVM-based direct torque control method was simulated and results were shown.***

Index Terms − Decoupling, Dynamic Model, Reference frame, Squirrel-cage.

NOMENCLATURE

Symbol	Description	Unit
d_s,α	Direct axis.	
B	Friction Coefficient	N·m·s
DTC	Direct torque control	
i_{dr}	Direct-axis rotor current.	A
i_{ds}	Direct-axis stator current.	A
I_{qr}	Quadrature-axis rotor current.	A
i_{qs}	Quadrature-axis stator current.	A
i_x	Stator current (x=a,b, or c)	A
i_α	Alpha-component of Stationary current	A
i_β	Beta-component of Stationary current	A
J	Moment of inertia.	kg·m^2
k	Position of sector in SVM	
$\square_{ij}$	Flux linkage (i=q or d and j=s or r).	Wb
L_{lr}	Rotor Leakage inductance	H
L_{ls}	Stator leakage inductance	H
L_m	Mutual inductance	H
L_r	Rotor self-inductance	H
L_s	Stator Self-inductance	H
p	Pair of poles	
P	Poles of induction motor	
PI	Proportional and integral	
PWM	Pulsed width modulation	
r	Rotor variable.	
R_r	Rotor resistance.	Ω
R_s	Stator resistance.	Ω
s	Stator Variable.	
SVM	Space Vector Modulation	
SVM-DTC	Space-vector-modulation-based Direct torque control	
T_0	Time duration for applying V_0 or V_7 in SVM	s
T_e	Electrical output torque.	N·m
T_k	Time duration for applying V_k in SVM	s
T_L	Load torque.	N·m
T_s	Switching period of SVM, Sampling Time	s
T_z	Half the switching period	s
v_{dr}	Direct-axis rotor voltage.	V
v_{ds}	Direct-axis stator voltage.	V
V_k	Leg voltage of inverter	V
v_{qr}	Quadrature-axis rotor voltage.	V
v_{qs}	Quadrature-axis stator voltage.	V
v_{xs}	Phase voltage (x=a,b, or c)	V
V_α	Alpha-component of Stationary Voltage	V
V_β	Beta-component of Stationary Voltage	V
w_b	Motor angular electrical base frequency.	rad/s
w_e	Stator angular electrical frequency.	rad/s
w_r	Rotor angular electrical speed.	rad/s
β,q_s	Quadrature axis.	
θ	Sector angle	rad
θ_e	Flux angle	rad

I. INTRODUCTION

Induction motors are used to generate the torque required in many industries and motion control applications. The squirrel-cage induction motor has been widely used in such applications due to its ruggedness, low maintenance cost and high power rating [1]. However, the induction motor principally works on the basis of electromagnetic induction, and this reliance makes the design of speed and torque controller more complex than for

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dc motors [2]. Therefore, the induction machine must be modeled.

A steady-state equivalent circuit of an induction motor [3]-[4], has been used for investigation of speed and torque response, but in these models the effect of saturation which affects the overall performance of speed and torque is negligible and cannot be used for transient response analysis. Therefore to incorporate analysis and design of an induction motor considering saturation effect and transient, dynamic modelling of induction motor is required [5]- [8]. Having the dynamic model the next step is to select a suitable controlling technique so that speed and torque can be controlled regardless of the changes in the system, including transient conditions.

Effective control systems in motion control applications are the main components of systems to achieve a result which is smooth and relatively insensitive to disturbance and noise. Hence, several controller designs have been used for speed and torque control of induction motors. Direct torque control (DTC) is the simplest method but with torque and current ripple. The space vector modulation-based direct torque control (SVM-DTC) [9] minimizes torque ripple by estimating a reference stator voltage, then using SVM to modulate it. This method creates pulse-width-modulated signals (PWMs) with constant switching frequency. These signals are used to drive the gates of the power inverter that supplies voltage to an induction motor.

This paper proposes a simplified Model of Space Vector Modulation (SVM) and Induction Motor Modelling. The SVM technique was used in simulation of online staring of induction motor model and for analysis of Space vector modulation-based direct torque control (SVM-DTC).

II. MATERIALS AND METHODS

These section is comprised of three parts; first a Simplified SVM design will be discussed. Next, the Induction motor Model and the SVM_DTC method will be investigated.

A. *Space Vector Modulation Design*

SVM is a technique to get pulse width modulated signals (PWMs) that trigger the switches of a voltage source inverter (Fig. 1). This method gives PWMs with constant switching frequency, and provide better voltage utilization than sinusoidal modulation technique. Hence it is preferable to the sinusoidal modulation technique [10], [11]. Therefore, in this paper we used [10]-[12] to design a simplified SVM method.

The first step was to have a reference voltage which can be positioned in one of six sectors (Fig. 2). The signal input that is used to reconstruct reference voltage usually obtained from a specific control block used in a given system. In this paper we assumed that a three-phase voltage source is converted to a two- phase equivalent [2], [10] by the following equations:

$$\begin{pmatrix} v\alpha \\ v\beta \end{pmatrix} = \frac{2}{3}\begin{pmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix}\begin{pmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{pmatrix}, \qquad (1)$$

then an angle that can be used to select particular sector in SVM is calculated as

$$\theta = tan^{-1}\left(\frac{v\beta}{v\alpha}\right), \qquad (2)$$

so that leg voltage of the inverter is selected based on the sector obtained (Table I).

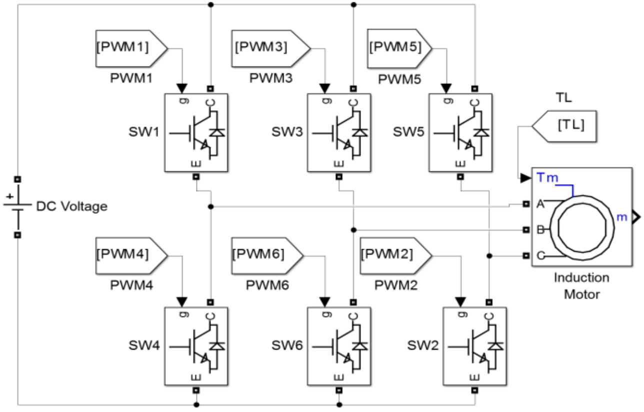

Fig. 1. Inverter and Induction Motor. Components and processes are described in the text.

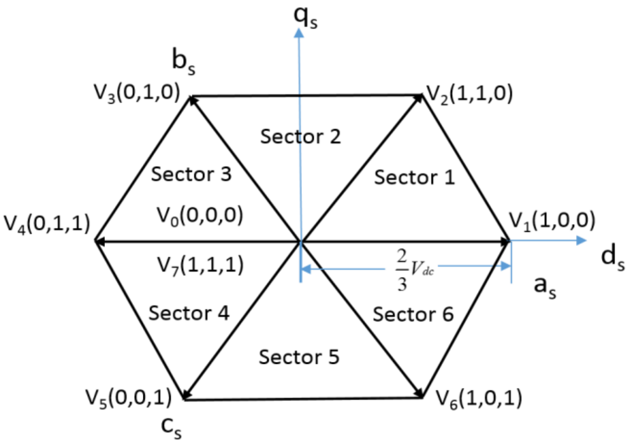

Fig. 2. Space Vectors on d-q frame [11]

Table I

Sector selection and Voltage Vectors

Angle (θ)	Sector	Voltage Vectors (Fig. 2)
$0\leq\theta<60^o$	1	V_1 and V_2
$60\leq\theta<120^o$	2	V_3 and V_2
$120\leq\theta<180^o$	3	V_3 and V_4
$-180\leq\theta<-120^o$	4	V_5 and V_4
$-120\leq\theta<-60^o$	5	V_5 and V_6
$-60\leq\theta<0^o$	6	V_6 and V_0

The next step is to determine the duration for which the leg voltage vectors are applied and obtained from [9]-[11].

Taking a given sector and volt balance,

$$V_sT_z = V_kT_k + V_{(k+1)}T_{(k+1)} + V_0T_0 \qquad (3)$$

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resolving equation (3) into d_s and q_s axes, yields a generalized form (Eq. 4, 5) :

$$\begin{pmatrix} T_k \\ T_{k+1} \end{pmatrix} = \frac{\sqrt{3}}{2}\frac{T_s}{V_d}\begin{pmatrix} \sin\frac{k\pi}{3} & -\cos\frac{k\pi}{3} \\ -\sin\frac{(k-1)\pi}{3} & \cos\frac{(k-1)\pi}{3} \end{pmatrix}\begin{pmatrix} V_\alpha \\ V_\beta \end{pmatrix} \tag{4}$$

and

$$T_0 = T_s - T_1 - T_2 . \tag{5}$$

Therefore, space vectors were obtained from Eq. (3) and the assumption of minimal number of commutations per cycle [10] as:

$$\begin{pmatrix} S_a \\ S_b \\ S_c \end{pmatrix} = \begin{pmatrix} V_k & V_{(k+1)} & V_0 \end{pmatrix}\begin{pmatrix} T_k \\ T_{(k+1)} \\ \frac{T_0}{2} \end{pmatrix} \tag{6}$$

Then comparing with the triangular carrier signal the Space Vector Pulsed wave signals (SVPWMs) were obtained.

Finally, the SVPWM signals were used to synthesize the phase voltages and line voltages, Eq. (7, 8) [11].

$$\begin{aligned} v_{as} &= \frac{V_{dc}}{3}\left(2S_a - S_b - S_c\right) \\ v_{bs} &= \frac{V_{dc}}{3}\left(2S_b - S_c - S_a\right) , \\ v_{cs} &= \frac{V_{dc}}{3}\left(2S_c - S_a - S_b\right) \end{aligned} \tag{7}$$

and

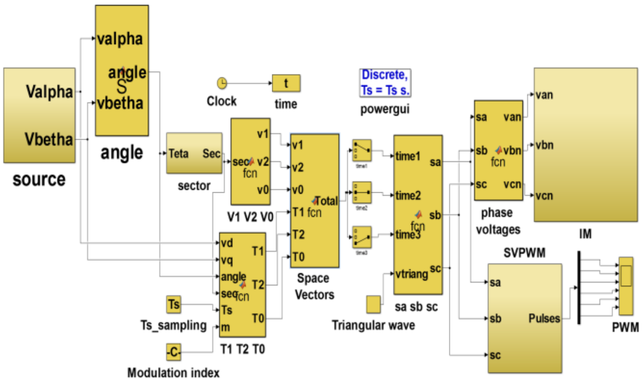


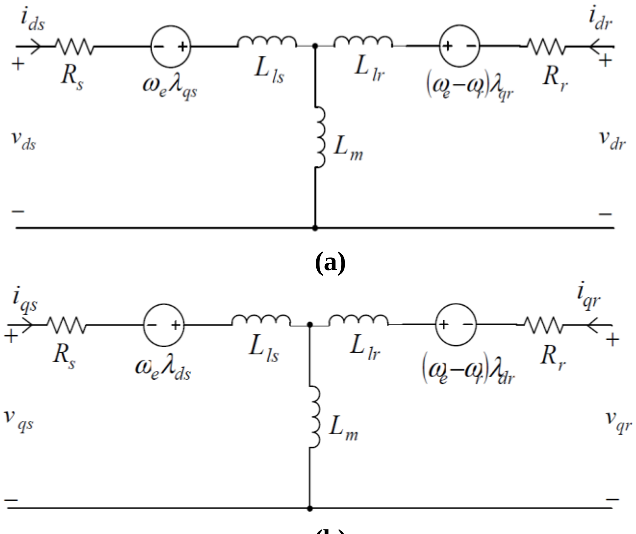
Fig. 3. Block diagram of proposed Space Vector Modulation Model and Induction Motor Model

$$\begin{aligned} V_{ab} &= V_{as} - V_{bs} \\ V_{bc} &= V_{bs} - V_{cs} . \\ V_{ca} &= V_{cs} - V_{as} \end{aligned} \tag{8}$$

Equations (1)-(8) were used to design a simplified Space vector Modulation (Fig. 3) and the phase voltages (Eq. 7) were supplied to an Induction Motor Model which is explained in the next section.

B. Induction Motor Dynamic Model

The d-q equivalent model of an induction motor (Fig. 5) [5], [11] is used in this paper. The dynamic equation of a squirrel cage induction motor in a generalized frame (Eq. 9) is used. In this paper synchronous rotating frame (Eq. 10) was used. From equation (11), equation (12) was used to model dq currents. Supply voltage to the dynamic equivalent circuit was given after coordinate transformation (Eq. 17). Torque and speed were modeled using Eq. (17) and Eq. (18).



(a)

(b)

Fig. 4. (a) d-axis equivalent circuit (b) q-axis equivalent circuit of the Induction Motor [5].

$$\frac{d}{dt}\begin{bmatrix} \lambda_{ds} \\ \lambda_{qs} \\ \lambda_{dr} \\ \lambda_{qr} \end{bmatrix} = \begin{pmatrix} -AR_s & \omega & BR_s & 0 \\ -\omega & -AR_s & 0 & BR_s \\ BR_r & 0 & -AR_r & (\omega-\omega_r) \\ 0 & BR_r & -(\omega-\omega_r) & -AR_r \end{pmatrix}\begin{bmatrix} \lambda_{ds} \\ \lambda_{qs} \\ \lambda_{dr} \\ \lambda_{qr} \end{bmatrix} + \begin{bmatrix} v_{ds} \\ v_{qs} \\ 0 \\ 0 \end{bmatrix} ,(9)$$

$$\frac{d}{dt}\begin{bmatrix} \lambda_{ds} \\ \lambda_{qs} \\ \lambda_{dr} \\ \lambda_{qr} \end{bmatrix} = \begin{pmatrix} -AR_s & \omega_e & BR_s & 0 \\ -\omega_e & -AR_s & 0 & BR_s \\ BR_r & 0 & -AR_r & (\omega_e-\omega_r) \\ 0 & BR_r & -(\omega_e-\omega_r) & -AR_r \end{pmatrix}\begin{bmatrix} \lambda_{ds} \\ \lambda_{qs} \\ \lambda_{dr} \\ \lambda_{qr} \end{bmatrix} + \begin{bmatrix} v_{ds} \\ v_{qs} \\ 0 \\ 0 \end{bmatrix} . (10)$$

The flux linkage in matrix form can be written as

$$\begin{bmatrix} \lambda_{ds} \\ \lambda_{qs} \\ \lambda_{dr} \\ \lambda_{qr} \end{bmatrix} = \begin{pmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{pmatrix}\begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} . \tag{11}$$

The currents in matrix form can be written as:

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$$\begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} = \begin{pmatrix} A & 0 & -B & 0 \\ 0 & A & 0 & -B \\ -B & 0 & A & 0 \\ 0 & -B & 0 & A \end{pmatrix} \begin{bmatrix} \lambda_{ds} \\ \lambda_{qs} \\ \lambda_{dr} \\ \lambda_{qr} \end{bmatrix} , \tag{12}$$

$$L_s = L_m + L_{ls} \ , \tag{13}$$

$$L_s = L_m + L_{ls} \ , \tag{14}$$

$$A = \frac{L_r}{L_r L_s - L_m{}^2} \ , \tag{15}$$

$$B = \frac{L_m}{L_r L_s - L_m{}^2} , \tag{16}$$

$$\begin{pmatrix} v_{ds} \\ v_{qs} \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} v_\alpha \\ v_\beta \end{pmatrix} , \tag{17}$$

$$T_e = \frac{3}{2}\left(\frac{p}{2}\right)\left(\lambda_{ds} * i_{qs} - \lambda_{qs} * i_{ds}\right) \ , \tag{18}$$

$$T_e - T_L - B\omega_r = \left(\frac{2J}{P}\right)\frac{d\omega_r}{dt} \ . \tag{19}$$

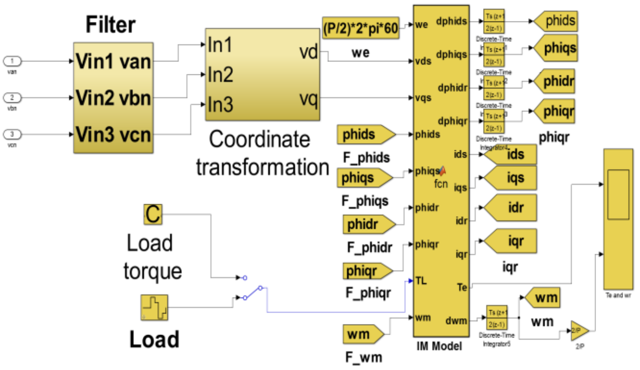

Fig. 5. Detailed Model of Induction Motor

Then, three-phase currents were converted back from dq equivalent (Eq. 12) using transformation eq. (20)-(21).

$$\begin{pmatrix} i_\alpha \\ i_\beta \end{pmatrix} = \begin{pmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} i_{ds} \\ i_{qs} \end{pmatrix} , \tag{20}$$

$$\begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \end{pmatrix} \begin{pmatrix} i_\alpha \\ i_\beta \end{pmatrix} . \tag{21}$$

Finally, using Eq. (8-20) a Matlab function code was used to model the induction motor (Fig. 5).

C. Space Vector Modulation-based direct torque control (SVM-DTC)

Direct torque control of induction motors has gained popularity mainly because of simple control structure [13]-[14]. Similar to dc motor flux and torque references are used and according to [9], the stationary stator fluxes can be calculated as

$$\lambda_{ds} = \int (v_{ds} - R_s i_{ds}) dt \ , \tag{22}$$

$$\lambda_{qs} = \int (v_{qs} - R_s i_{qs}) dt \ , \tag{23}$$

and the resultant stator flux is described by

$$\lambda_s = \sqrt{(\lambda_{ds})^2 + (\lambda_{qs})^2} \ , \tag{24}$$

$$\theta_e = \tan^{-1}\left(\frac{\lambda_{qs}}{\lambda_{ds}}\right) \ , \tag{25}$$

and the torque is estimated using eq. (18)

Utilizing SVM-DTC reduces torque ripple and was used in this paper to compare the speed and torque responses of existing and simplified SVM-DTC (Figs. 6, 7).

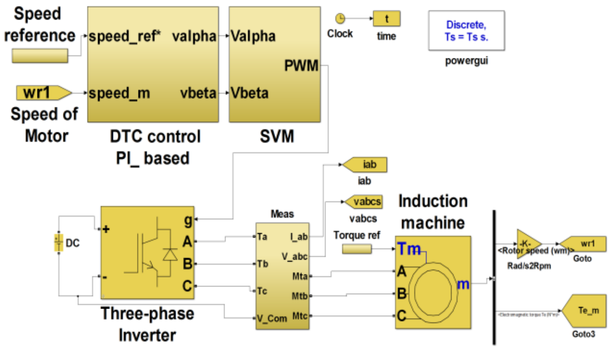

Fig. 6. Matlab/Simulink DTC Model

III. RESULTS

To investigate the overall response of space vector modulation model Fig. 3, the parameters of the motor (Table II), Eq. 6 and Table I were used and space vectors (Fig. 8a) and sector selection (Fig. 8b) were simulated. Then, space vectors and a triangular wave signal of 20 kHz were simulated (Fig. 9). Then SVPWM signals with 10 μs dead-

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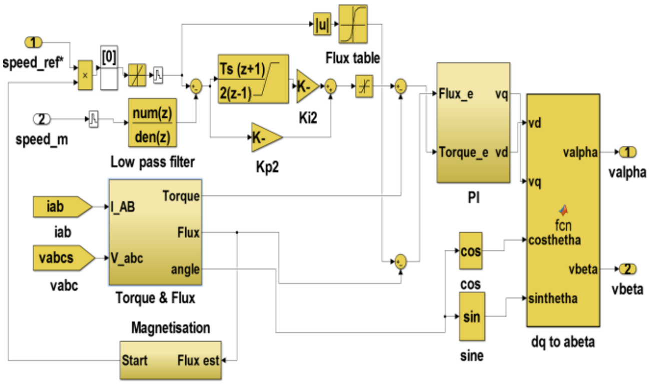

Fig. 7. Detail view of DTC controller

time to avoid short circuit of switches on the same leg, were simulated based on comparison of space vectors and triangular wave (Fig. 10). Line voltages and phase voltages (Eq. 7-8) were simulated from the PWM signals (Fig.11). Then using direct online starting method phase voltages were supplied to the induction motor model (Fig. 5). Reference torque was used (Fig. 12) and speed and torque response of induction motor model (Fig. 13) showed smooth response except small error at transient states (2 s, 3 s, 4 s, 5 s and 6 s). Current response was also simulated (Fig. 14). Magnified current at transient torque condition (400 N·m to 200 N·m and from -200 N·m to 0 N·m) (Fig. 15) was simulated and showed smooth response.

With a 5 kHz SVPWM, the existing SVM-DTC [9] and simplified SVM-DTC were used to investigate speed and torque response of induction motor (Table II). For a given speed reference the response for both existing and simplified SVM-DTC showed similar result (Fig. 16). But torque response in the case of a simplified SVPWM (Fig. 18) showed low overshoot during transient condition (1 s, 2 s, 3 s and 5 s) and less torque ripple than the torque response of existing SVM-DTC (Fig. 17). Furthermore, using simplified SVPWM, a 9 % improvement of torque variation (considering 200 N·m and -200 N·m as a reference) was observed (Figs. 19-20). Torque response of a simplified SVM-DTC was further improved by 14 % (Fig. 21) compared to the torque response of existing SVM-DTC (Fig. 19). The current response using a simplified SVM-DTC (Fig. 22) also showed smooth current during transient condition (1 s and 1.1 s).

Table II
INDUCTION MOTOR PARAMETERS

Power	3.7 kW
Supply Voltage	460 V
Frequency	60 Hz
Stator Resistance, R_s	0.09961 Ω
Rotor Resistance, R_s	0.05837 Ω
Stator self-inductance , L_{ls}	0.867 mH
Rotor self-inductance , L_{lr}	0.867 mH
Mutual inductance, L_m	30.39 mH
Moment of Inertia, J	0.4 kg·m^2
Friction factor, B	0.02187
Pole pairs, p	2

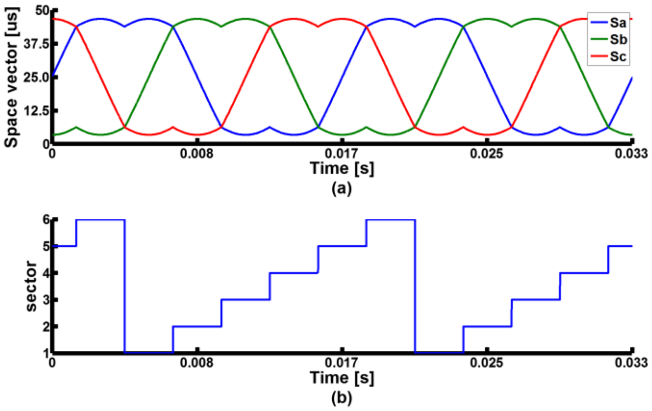

Fig. 8. (a) Space vector vs time and (b) Sector vs time in simulated Space Vector Modulation

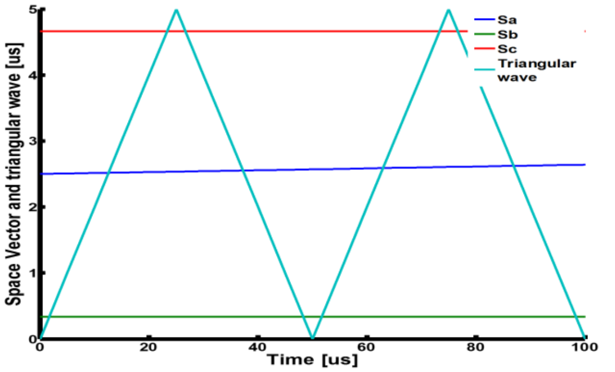

Fig. 9. Space Vectors and Triangular wave vs time of Space Vector Modulation Model

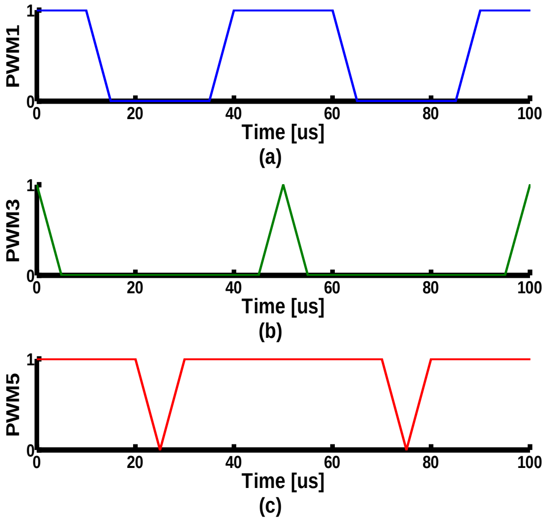

Fig. 10. (a) PWM1 vs time (b) PWM2 vs time (c) PWM3 vs time of the upper leg of inverter in simulated Space Vector Modulation Model

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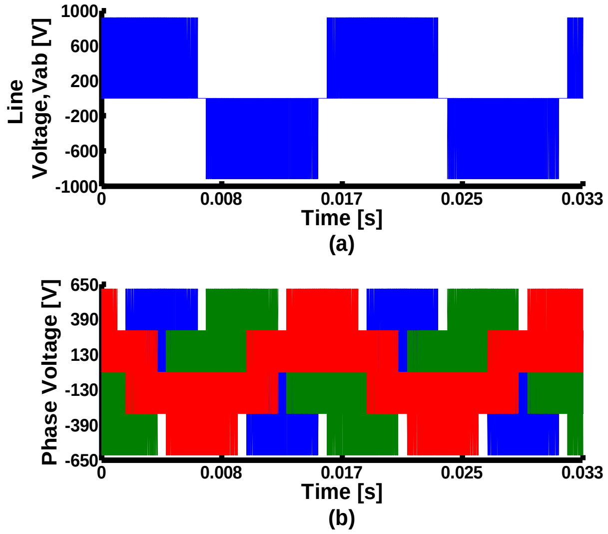

Fig. 11. (a) Line voltage vs time and (b) phase voltage vs time in simulated-dynamic-equivalent circuit based Induction motor Model.

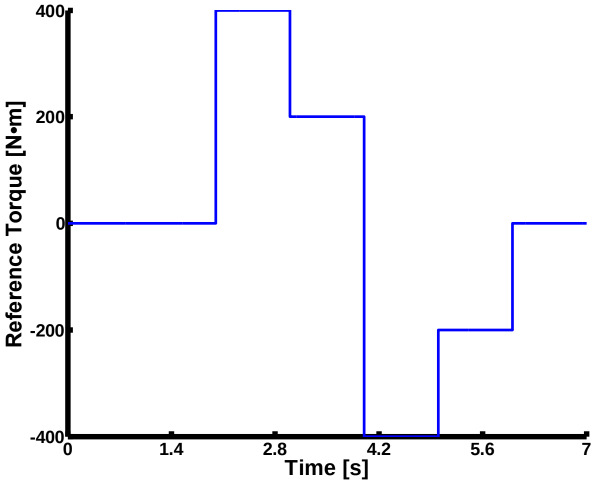

Fig. 12. Reference Torque vs time

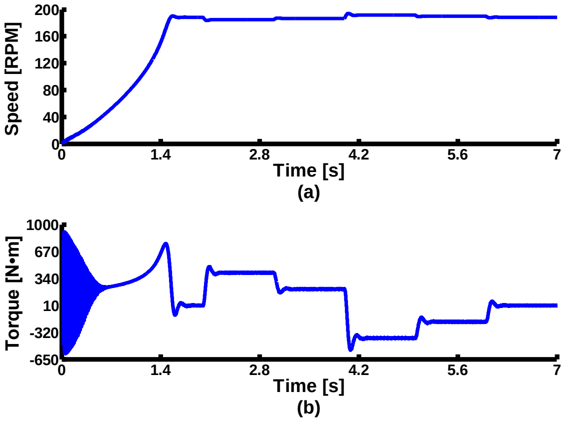

Fig. 13. Speed vs time and Torque vs time in simulated-dynamic-equivalent circuit based Induction motor Model.

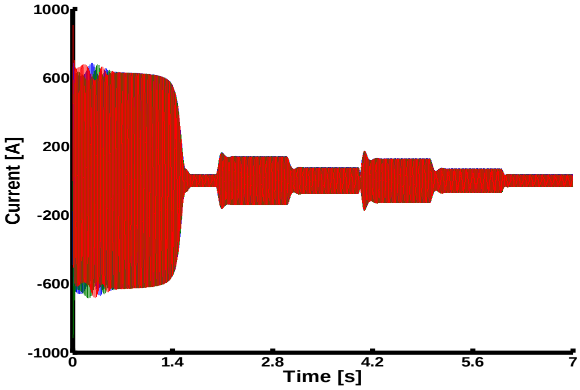

Fig. 14. Current vs time

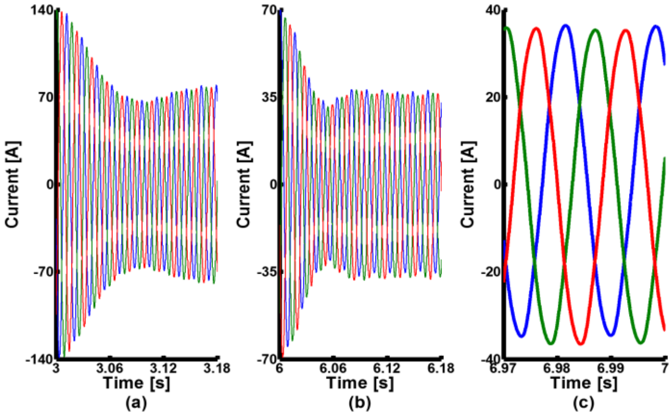

Fig. 15. Current vs time at transient condition simulated induction motor model.

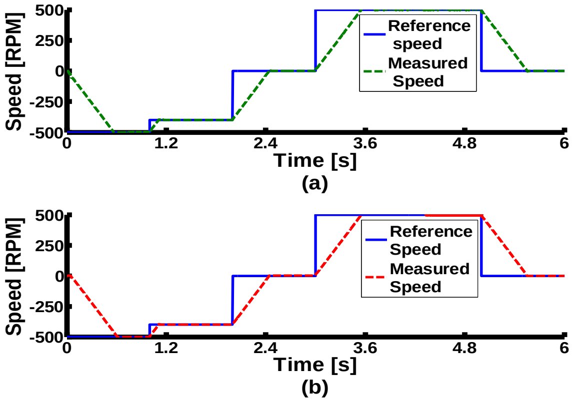

Fig. 16. (a) Speed vs time using existing SVM-DTC and (b) Speed vs time using new SVM-DTC

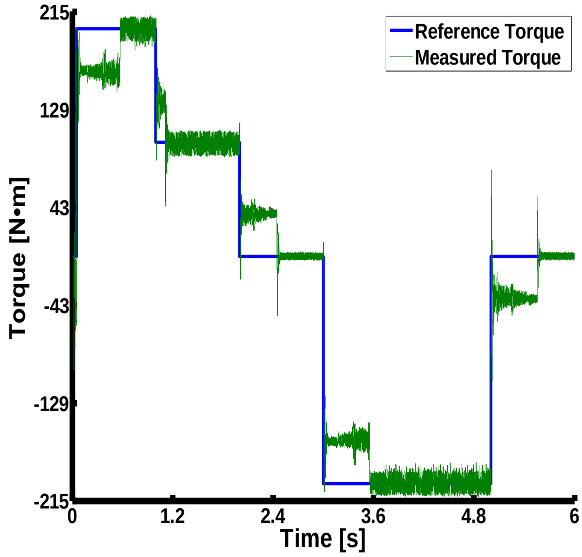

Fig. 17. Torque vs time of SVM-DTC using existing SVM

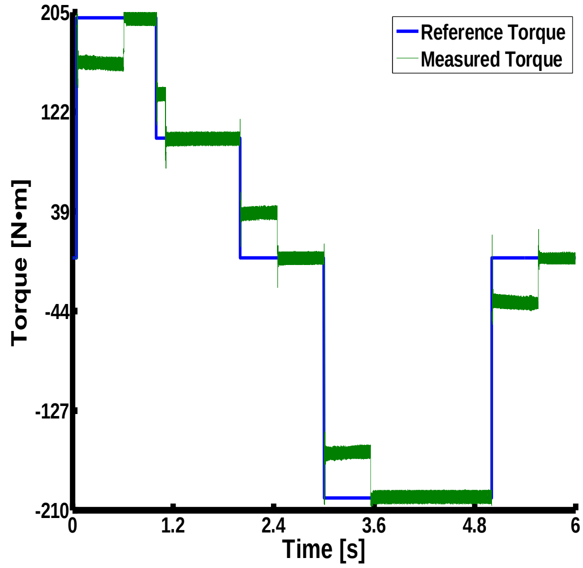

Fig. 18. Torque vs time of SVM-DTC using designed SVM

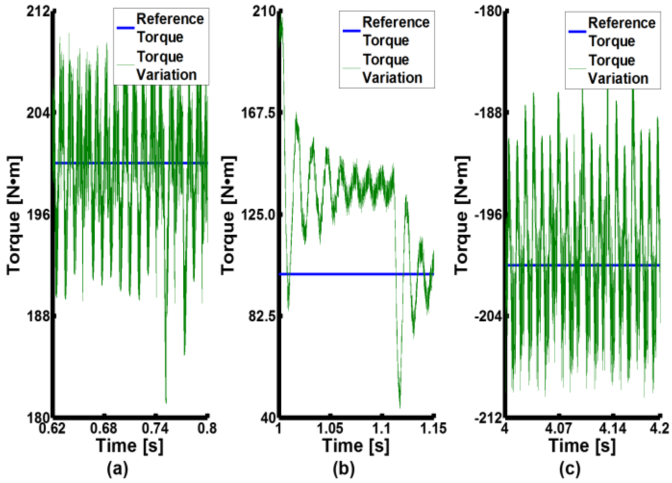

Fig. 19. (a) Torque variation vs time at 200Nm reference (b) Torque vs time overshoot during transient condition (c) Torque vs time at -200 N·m of existing SVM-DTC method

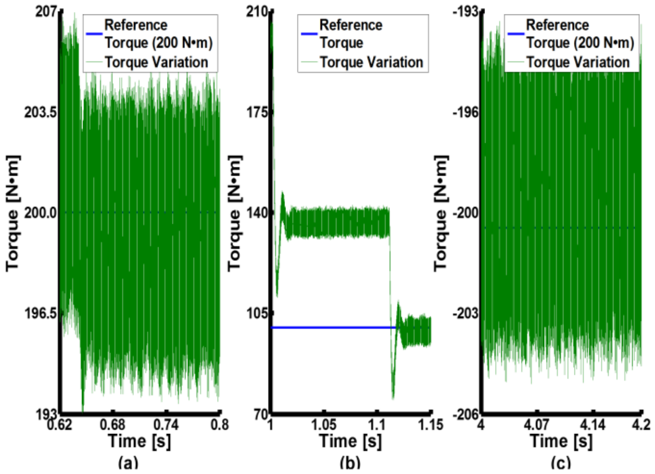

Fig. 20. (a) Torque variation vs time at 200 N·m reference (b) Torque vs time overshoot during transient condition (c) Torque vs time at -200 N·m using designed SVM-DTC method and sampling time of 5 µs

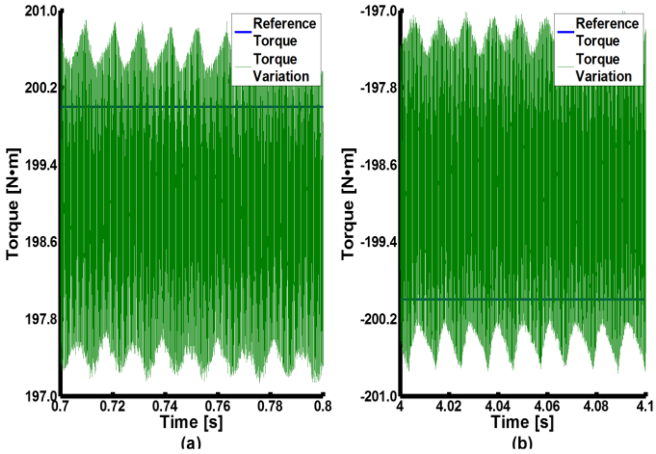

Fig. 21. (a) Torque variation vs time at 200 N·m reference (b) Torque vs time overshoot during transient condition (c) Torque vs time at -200 N·m using designed SVM-DTC method and sampling time of 0.5 µs

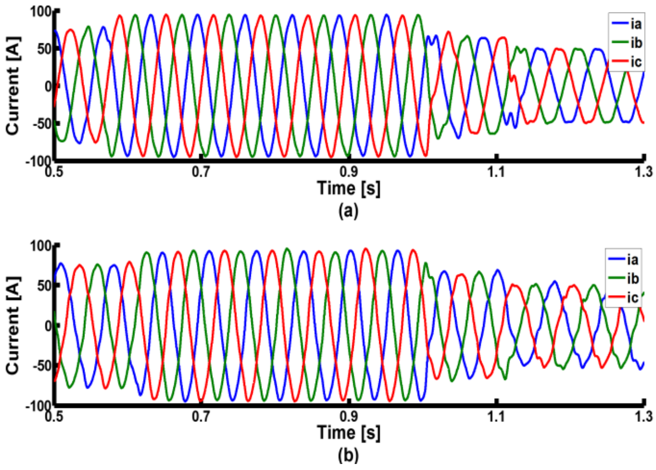

Fig. 22. (a) Current vs time using existing SVM-DTC and (b) Current vs time using designed SVM-DTC

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IV. CONCLUSION

In this study, a simplified Matlab/Simulink-based design of SVM and dynamic modeling of Induction motor was simulated. To study on-line starting and the effect of load torque variation, the designed SVM technique uses PWM signals to synthesize voltage supply to the dynamic model of Induction motor. PI-based simplified SVM-DTC control was also used to compare speed and torque tracking capability with the existing SVM-DTC method. The result demonstrated that with fine tuning of the controller, torque error was reduced (Fig. 21).

Although the torque variation was generally improved with selection of very small sampling time, we observed that the smoothness of current response deteriorated during transient instant compared to existing method that has longer sampling time. To improve the smoothness of current and torque responses, additional study will be conducted using a digital signal processor. Furthermore, variable structure control and other methods can also be adopted to achieve this goal.

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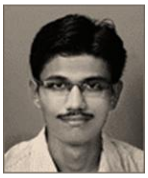

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