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.

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 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

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Muluneh L. Woldesemayat was with Arba Minch University, Arba Minch, Ethiopia. He is now with the Department of Electrical Engineering, Pohang University of Science and Technology, Pohang, South Korea.

K. D. Badgujar is now with the department of Nuclear Engineering, Pohang University of Science and Technology, Pohang, South Korea.

Won Sangchul is Professor of Electrical Engineering, Pohang University of Science and Technology, Pohang, South Korea.

Table of Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>d, α</td>
<td>Direct axis.</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Friction Coefficient</td>
<td>N·m·s</td>
</tr>
<tr>
<td>TDC</td>
<td>Direct torque control</td>
<td></td>
</tr>
<tr>
<td>i_{ds}</td>
<td>Direct-axis rotor current</td>
<td>A</td>
</tr>
<tr>
<td>i_{ds}</td>
<td>Direct-axis stator current</td>
<td>A</td>
</tr>
<tr>
<td>i_{pq}</td>
<td>Quadrature-axis rotor current</td>
<td>A</td>
</tr>
<tr>
<td>i_{pq}</td>
<td>Quadrature-axis stator current</td>
<td>A</td>
</tr>
<tr>
<td>i_s</td>
<td>Stator current (x=a, b, or c)</td>
<td>A</td>
</tr>
<tr>
<td>i_{α}</td>
<td>Alpha-component of Stationary current</td>
<td>A</td>
</tr>
<tr>
<td>i_{β}</td>
<td>Beta-component of Stationary current</td>
<td>A</td>
</tr>
<tr>
<td>J</td>
<td>Moment of inertia</td>
<td>kg·m²</td>
</tr>
<tr>
<td>k</td>
<td>Position of sector in SVM</td>
<td></td>
</tr>
<tr>
<td>i_{dq}</td>
<td>Flux linkage (i=q or d and j=s or r).</td>
<td>Wb</td>
</tr>
<tr>
<td>L_s</td>
<td>Rotor Leakage inductance</td>
<td>H</td>
</tr>
<tr>
<td>L_m</td>
<td>Stator leakage inductance</td>
<td>H</td>
</tr>
<tr>
<td>L_m</td>
<td>Mutual inductance</td>
<td>H</td>
</tr>
<tr>
<td>L_s</td>
<td>Rotor self-inductance</td>
<td>H</td>
</tr>
<tr>
<td>L_s</td>
<td>Stator Self-inductance</td>
<td>H</td>
</tr>
</tbody>
</table>

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_{rs}  | Half the switching period | s |
V_{ds}  | Direct-axis rotor voltage | V |
V_{ds}  | Direct-axis stator voltage | V |
V_{dp}  | Quadrature-axis rotor voltage | V |
V_{dp}  | Quadrature-axis stator voltage | V |
V_{qs}  | Phase voltage (x=a, b, or c) | V |
V_{α}  | Alpha-component of Stationary Voltage | V |
V_{β}  | Beta-component of Stationary Voltage | V |
V_ω  | Motor angular electrical base frequency. | rad/s |
V_r  | Stator angular electrical frequency. | rad/s |
V_r  | Rotor angular electrical speed. | rad/s |
ω_β  | Quadrature axis. |          |
θ   | Sector angle | rad |
ω_e | Flux angle | rad |

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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 storing 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:

$$\begin{bmatrix} v_α \\ v_β \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} \\ \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \end{bmatrix}\begin{bmatrix} v_{αs} \\ v_{βs} \end{bmatrix}$$

(1)

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

$$\theta = \tan^{-1}\left(\frac{v_β}{v_α}\right)$$

(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.](image1)

![Fig. 2. Space Vectors on d-q frame [11]](image2)

<table>
<thead>
<tr>
<th>Sector selection and Voltage Vectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle (θ)</td>
</tr>
<tr>
<td>0°≤θ&lt;60°</td>
</tr>
<tr>
<td>60°≤θ&lt;120°</td>
</tr>
<tr>
<td>120°≤θ&lt;180°</td>
</tr>
<tr>
<td>-180°&lt;θ&lt;120°</td>
</tr>
<tr>
<td>-120°&lt;θ&lt;60°</td>
</tr>
<tr>
<td>-60°≤θ&lt;0°</td>
</tr>
</tbody>
</table>

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,

$$V_i T_z = V_i T_k + V_{(k+1)} T_{(k+1)} + V_0 T_0$$

(3)

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

$$\begin{bmatrix} T_i \\ T_{k+1} \end{bmatrix} = \begin{bmatrix} \frac{\sqrt{3}}{2} T_i \\ -\frac{\sin\left(\frac{k\pi}{3}\right)}{V_o} \end{bmatrix} \begin{bmatrix} -\cos\left(\frac{k\pi}{3}\right) \\ \sin\left(\frac{(k-1)\pi}{3}\right) \end{bmatrix}$$

(4)

and

$$T_0 = T_z - T_1 - T_2$$

(5)
Therefore, space vectors were obtained from Eq. (3) and the assumption of minimal number of commutations per cycle [10] as:

$$\begin{bmatrix}
S_a \\
S_b \\
S_c
\end{bmatrix} = \begin{bmatrix}
V_a \\
V_{(k+1)} \\
V_b
\end{bmatrix} \begin{bmatrix}
T_k \\
T_{(k+1)} \\
T_0/2
\end{bmatrix}$$  \hspace{1cm} (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].

$$v_{as} = \frac{V_{dc}}{3}(2S_a - S_b - S_c)$$

$$v_{bs} = \frac{V_{dc}}{3}(2S_b - S_c - S_a)$$

$$v_{cs} = \frac{V_{dc}}{3}(2S_c - S_a - S_b)$$  \hspace{1cm} (7)

and

$$v_{ab} = v_{as} - v_{bs}$$

$$v_{bc} = v_{bs} - v_{cs}$$

$$v_{ca} = v_{cs} - v_{as}$$  \hspace{1cm} (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).
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\[ B = \frac{L_m}{L_s L_m - L_s^2}, \quad (16) \]

\[ \lambda_s = \sqrt{\lambda_{ds}^2 + \lambda_{qs}^2}, \quad (24) \]

\[ \theta_e = \tan^{-1}\left(\frac{\lambda_{qs}}{\lambda_{ds}}\right), \quad (25) \]

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).

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 \( \mu \)s dead-

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

\[ \lambda_{ds} = \int (v_{ds} - R i_{ds})dt, \quad (22) \]

\[ \lambda_{qs} = \int (v_{qs} - R i_{qs})dt, \quad (23) \]

and the resultant stator flux is described by

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

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

\[ \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ -1/2 & \sqrt{3}/2 & 0 \\ -1/2 & -\sqrt{3}/2 & 0 \end{pmatrix} \begin{pmatrix} i_{\alpha} \\ i_{\beta} \end{pmatrix}. \quad (21) \]

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

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 \( \mu \)s dead-

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).
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**

<table>
<thead>
<tr>
<th>INDUCTION MOTOR PARAMETERS</th>
<th>Power</th>
<th>3.7 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Voltage</td>
<td>460 V</td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>60 Hz</td>
<td></td>
</tr>
<tr>
<td>Stator Resistance, $R_s$</td>
<td>0.09961 Ω</td>
<td></td>
</tr>
<tr>
<td>Rotor Resistance, $R_r$</td>
<td>0.05837 Ω</td>
<td></td>
</tr>
<tr>
<td>Stator self-inductance, $L_{s}$</td>
<td>0.867 mH</td>
<td></td>
</tr>
<tr>
<td>Rotor self-inductance, $L_{r}$</td>
<td>0.867 mH</td>
<td></td>
</tr>
<tr>
<td>Mutual inductance, $L_m$</td>
<td>30.39 mH</td>
<td></td>
</tr>
<tr>
<td>Moment of Inertia, $J$</td>
<td>0.4 kg·m$^2$</td>
<td></td>
</tr>
<tr>
<td>Friction factor, $B$</td>
<td>0.02187</td>
<td></td>
</tr>
<tr>
<td>Pole pairs, $p$</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

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

**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

**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
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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
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.

IV. CONCLUSION

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REFERENCES


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Muluneh L. Woldesemayat obtained B.Sc. degree in Electrical Engineering from Arba Minch University, Ethiopia in 2004 and M.Tech from Indian Institute of Technology Delhi, India in 2009. Since 2004 he has been working in Electrical Engineering department, Arba Minch University with Lecturer rank. He is currently a Ph.D. student in Electrical Engineering, Pohang University of Science and Technology, Korea. His research interest include simulation and control of electrical machines and motion control application of electrical drives.

K. D. Badgujar obtained Bachelor of engineering from university of Pune. He obtained industrial experience from Diebold, ATM manufacturing company. He received his Master of Technology degree, from Indian Institute of Technology, Kanpur (IITK), India. He is currently a Ph.D. student in Division of Advanced Nuclear Engineering department, Pohang University of Science and Technology, Korea.

Won Sangchul obtained the B.S. and M.S. degrees in Electrical Engineering from Seoul National University in 1974 and 1976, respectively, and Ph.D. degree in Electrical Engineering from the University of Iowa in 1985. Dr. Won is now Professor in Electrical Engineering Department, PohangUniversity of Science and Technology, Korea. Dr. Won serves as a Chairman of IFAC MMM Technical Committee and Vice President of Asian Control Association and as an Associate Editor for IEEE Transactions on Industrial Electronics. His research interest include dynamic system modeling and simulation, steel making process control and automation, robot control, time delay system, and linear and nonlinear control system.