Field Oriented Control of PMSM Drive using SVPWM Technique

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Abstract: This paper focuses on the advancement of SVPWM (space vector pulse width modulation) inverter fed permanent magnet synchronous motor (PMSM). The paper deals with a space vector pulse width modulation (SVPWM) algorithm applied to electrical drives. An extensive and detailed study of the space vector pulse width modulation design process has been done, indicating some practical sign for implementation. As an example, the SVPWM is developed for a permanent-magnet synchronous motor drive for speed and current control. In the present work, three closed loop control schemes have been used. Two inner loops are current control feedback loops and another outer feedback loop is used for optimizing the speed of PMSM drive. The proposed field oriented control (FOC) scheme for PMSM drive decouples the torque and flux, which is not only providing the faster response but at the same time makes the control action easy.

Keywords: FOC, MATLAB/Simulink, PMSM, speed control, SVPWM Inverter

1. INTRODUCTION

Over the last three decades, AC machine drives are becoming more and more popular, especially Permanent Magnet Synchronous Machine (PMSM) has been used in many automation fields such as robots, metal cutting machines, precision machining, etc. The PMSM drives are ready to meet sophisticated requirements such as fast dynamic response, high power factor, wide operating speed range and high performance applications, as a result, a gradual gain in the use of PMSM drives will surely be in the future market in low and mid power applications. Recently, PMSM is applied to traction drive for electric vehicles and railway vehicles [1-2].

In the current control for an inverter-fed PMSM drive, there are four main types of control schemes: the hysteresis control, the ramp comparison control, the synchronous frame proportional-integral (PI) control, and the predictive control [3-7].

The hysteresis current controller has advantages such as a fast transient response and simplicity in implementation, but shows a high and non-constant switching frequency in the inverter. The ramp comparison current control method has the advantages of limiting the maximum inverter switching frequency and producing well-defined harmonics [3]. Even though the controller has optimized gains, there are magnitude and phase delay errors in steady state since, the control method has low pass filter characteristics. To overcome such errors, a rotor synchronous frame PI current control has been proposed. In this control method, the current control is carried out in rotor synchronous reference frame. In the SVPWM control scheme, the switching duties of the inverter switches are determined by calculating the required voltages forcing the motor phase currents to follow corresponding references. If the motor and inverter parameters are well known, the SVPWM inverter shows the fast transient response and no steady state error.

2. PMSM MODELING

The mathematical model is similar to that of the wound rotor synchronous motor. Since, there is no external source connected to the rotor side and variation in the rotor flux with respect to time is negligible, there is no need to include the rotor voltage equation. Rotor reference frame is used to derive the modal of the PMSM[9].

The electrical dynamic equation in terms of phase variable can be written as:
\[ V_A = R_A i_A + p \psi_A \] ........................................(1)
\[ V_B = R_B i_B + p \psi_B \] ........................................(2)
\[ V_C = R_C i_C + p \psi_C \] ........................................(3)

Where, \( V_A, V_B \) and \( V_C \) are instantaneous phase voltage, \( i_A, i_B \) and \( i_C \) are instantaneous phase current, \( R \) is phase resistant, \( p \) is derivative operator, \( \psi_A, \psi_B \) and \( \psi_C \) are rotor coupling flux linkage.

While the flux linkage equation are:
\[ \psi_A = L_A i_A + \psi_r \cos \theta \] ........................................(4)
\[ \psi_B = L_B i_B + \psi_r \cos \left( \theta - \frac{2\pi}{3} \right) \] ........................................(5)
\[ \psi_C = L_C i_C + \psi_r \cos \left( \theta + \frac{2\pi}{3} \right) \] ........................................(6)

Where, \( L \) is phase Inductance.

The transformation from 3-phase to 2-phase quantities can be written in matrix form as:
\[
\begin{bmatrix}
V_x \\
V_y
\end{bmatrix} = \sqrt{2 \over 3} \begin{bmatrix}
1 & 1 & -1 \\
1 & 0 & 0 \\
1 & -1 & 0
\end{bmatrix} \begin{bmatrix}
V_A \\
V_B \\
V_C
\end{bmatrix} \] ........................................(7)

Where, \( V_x \) and \( V_y \) are orthogonal space phasor.

The Park Transformation in matrix form can be represented as:
\[
\begin{bmatrix}
V_d \\
V_q
\end{bmatrix} = \begin{bmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{bmatrix} \begin{bmatrix}
V_x \\
V_y
\end{bmatrix} \] ........................................(8)

According to above transformation, \( d - q / abc \) Transformation may be written as:

\[
\begin{bmatrix}
V_d \\
V_q
\end{bmatrix} = \begin{bmatrix}
K_{da} & K_{da} \\
K_{db} & K_{db} \\
K_{ca} & K_{ca}
\end{bmatrix} \begin{bmatrix}
V_A \\
V_B \\
V_C
\end{bmatrix} \] ........................................(9)

\[
\begin{bmatrix}
V_d \\
V_q
\end{bmatrix} = \begin{bmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{bmatrix} \begin{bmatrix}
V_x \\
V_y
\end{bmatrix} \] ........................................(8)

According to above transformation, \( d - q / abc \) Transformation may be written as:
Field Oriented Control of PMSM Drive Using SVPWM Technique

\[
\begin{bmatrix}
V_A \\
V_B \\
V_C
\end{bmatrix} = \sqrt{\frac{2}{3}}
\begin{bmatrix}
\cos \theta & -\sin \theta \\
\cos \left(\theta - \frac{2\pi}{3}\right) & -\sin \left(\theta - \frac{2\pi}{3}\right) \\
\cos \left(\theta + \frac{2\pi}{3}\right) & -\sin \left(\theta + \frac{2\pi}{3}\right)
\end{bmatrix}
\begin{bmatrix}
V_d \\
V_q
\end{bmatrix} \quad \text{(9)}
\]

Simple transformed equation are:

\[V_d = R_s i_d + pL_d i_d + p\psi_r - \omega_L \psi_q \quad \text{(10)}\]
\[V_q = R_s i_q + pL_q i_q + \omega_L \psi_q \quad \text{(11)}\]

Where, \(L_d\) and \(L_q\) are called \(d\)- and \(q\)-axis synchronous inductance respectively, \(\omega_L\) is motor electrical speed.

The produced torque \(T_e\) which is power divided by mechanical speed can be represented as:

\[T_e = \frac{3}{2} p_n (\psi_i i_q + (L_d - L_q) i_d i_q) \quad \text{(12)}\]

Where, \(p_n\) is pole Logarithm.

It is apparent from the above equations that the produced torque is composed of two distinct mechanisms. The first term corresponds to “the mutual reaction torque” occurring between \(i_q\) and the permanent magnet, while the second term corresponds to “the reluctance torque” due to the difference in \(d\)- and \(q\)-axis reluctance [9]. Note that \(L_d = L_q = L_s\) for the motor, so an expression for the torque generated by a PMSM is:

\[T_e = \frac{3}{2} p_n \psi_i i_q \quad \text{(13)}\]

In the presence of a \(d\)-axis stator current, the \(d\)-axis and \(q\)-axis currents are not decoupled, and the model is nonlinear. It has been shown in the torque Eq. (12). Under the assumption that \(i_d = 0\), the system becomes linear and resembles, Thus vector control of PMSM provides approximate desired dynamic characteristics.

In general, the mechanical equation of the PMSM can be represented as

\[T_e = J_M \omega_M + T_d + B_M \omega_M \quad \text{(14)}\]

Where,
\(\omega_M\) = rotor angular speed,
\(J_M\) = motor moment inertia constant,
\(B_M\) = damping coefficient,
\(T_d\) = torque of the motor external load disturbance,
\(T_e\) = electromagnetic torque.

3. SPACE VECTOR PULSE WIDTH MODULATION (SVPWM)

The SVPWM consists of four major process:

i. Sector Identification,
ii. Vector action time,
iii. Computation of switching time
iv. Generation of PWM,

Fig.5 showing the process of generation of SVPWM. Fig.6. shows the space vector of three-phase voltage source inverter (VSI) divided into six sectors based on the six fundamental vectors \(V_x(x=1, 2,\)
3…, 6). Any voltage vectors in this vector space can be synthesized by two fundamental vectors $V_x$ and $V_{x+1}$. For example, the voltage vector in sector I can be represented as a combination of active vectors $V_{1}$ and $V_{2}$. Within a switching cycle $T_s$, the components for each fundamental vector $V_s$ is related to the occupied time $T_n$ and unoccupied time of the null vectors. The locus of the maximum $V_s$ is represented by the envelope of the hexagon formed by the basic space vectors. Thus, the magnitude of $V_s$ must be limited to the shortest radius of this envelope when $V_s$ is revolving, which gives a maximum magnitude of $\frac{V_s}{\sqrt{2}}$ for $V_s$.

![Fig.3. Block Diagram of SVPWM](image)

For the computation of sector and vectors, the three phase a-b-c voltage is transformed to $\alpha$-$\beta$ reference frame using the Clarke Transformations. In Field oriented control of PMSM the $\alpha$-$\beta$ voltages are obtained from the $d$-$q$ voltages.

![Fig.4. Sectors of SVPWM](image)

3.1 Sector Identification

To determine the switching time instants and switching sequence, it is important to know the sector in which the reference vector lies. Following algorithm can be used to determine the sector of the reference output voltage vector. Three intermediate variables are considered as $V_{ref 1}$, $V_{ref 2}$ and $V_{ref 3}$.

\[ V_{ref 1} = V_\beta \]
\[ V_{ref 2} = \frac{\sqrt{3}}{2} V_\alpha - \frac{1}{2} V_\beta \]
\[ V_{ref 3} = -\frac{\sqrt{3}}{2} V_\alpha - \frac{1}{2} V_\beta \]

A, B and C are considered as logical variables which takes the values 0 or 1 depending on the conditions:

- If $V_{ref 1} > 0$, A=1 else A=0
- If $V_{ref 2} > 0$, B=1 else B=0
- If $V_{ref 3} > 0$, C=1 else C=0

Using the logical variables A, B and C, the variable N is identified as:
Values of N is used to map the sector (P) where, the vector lies using the Table 1.

**Table 1. MAPPING OF N TO P**

<table>
<thead>
<tr>
<th>N</th>
<th>3</th>
<th>1</th>
<th>5</th>
<th>4</th>
<th>6</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>

**3.2 Calculation of Action Time T1 and T2 of Basic Voltage Vector**

The action time of two adjacent basic vector in a certain sector is defined as \( t_1 \) and \( t_2 \). In traditional SVPWM algorithm, space angles and trigonometric functions are used to calculate the values of \( t_1 \) and \( t_2 \), which makes the process complex. In this method these values are calculated using the \( V_{\alpha} \) and \( V_{\beta} \). Applying the volt-second balance principle to the orthogonal decomposition rates of the basic vectors, \( t_1 \) and \( t_2 \) can be mapped from Table 2.

Where; X, Y and Z are given by:

\[
X = \frac{\sqrt{3} V_{\beta} T_s}{V_{dc}} ..............................................(21)
\]

\[
Y = \left( \frac{3}{2} V_{\alpha} + \frac{\sqrt{3}}{2} V_{\beta} \right) \frac{T_c}{2V_{dc}} ..............................................(22)
\]

\[
Z = \left( \frac{3}{2} V_{\alpha} + \frac{\sqrt{3}}{2} V_{\beta} \right) \frac{T_i}{2V_{dc}} ..............................................(23)
\]

**Table 2. Mapping X, Y, Z To T1 and T2**

<table>
<thead>
<tr>
<th>sector</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_1 )</td>
<td>-Z</td>
<td>Y</td>
<td>X</td>
<td>Z</td>
<td>-Y</td>
<td>-X</td>
</tr>
<tr>
<td>( T_2 )</td>
<td>X</td>
<td>Z</td>
<td>-Y</td>
<td>-X</td>
<td>-Z</td>
<td>Y</td>
</tr>
</tbody>
</table>

**3.3 Determination of Ta, Tb and Tc:**

\( T_a \), \( T_b \) and \( T_c \) correspond to the time comparison values of each phase. Intermediate variables \( T_{a-on}, T_{b-on} \) and \( T_{c-on} \) are used to map the comparison values from Table 3:

**Table 3. Operation of T_a, T_b, T_c**

<table>
<thead>
<tr>
<th>N</th>
<th>3</th>
<th>1</th>
<th>5</th>
<th>4</th>
<th>6</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_a )</td>
<td>Ta-on</td>
<td>Tb-on</td>
<td>Tc-on</td>
<td>Tc-on</td>
<td>Tb-on</td>
<td>Ta-on</td>
</tr>
<tr>
<td>( T_b )</td>
<td>Tb-on</td>
<td>Ta-on</td>
<td>Tc-on</td>
<td>Tb-on</td>
<td>Tc-on</td>
<td>Tc-on</td>
</tr>
<tr>
<td>( T_c )</td>
<td>Tc-on</td>
<td>Tb-on</td>
<td>Ta-on</td>
<td>Ta-on</td>
<td>Tb-on</td>
<td>Tb-on</td>
</tr>
</tbody>
</table>

**4. FIELD ORIENTED CONTROL (FOC) OF PMSM**

The overall block schematic of FOC of PMSM is shown in Fig. 4. In this control system, stator currents \( i_a\&i_b \) are measured using electric current sensors, and \( i_c \) is calculated with the formula \( i_c = -(i_a+i_b) \). The electric currents \( i_a \), \( i_b \) and \( i_c \) are transformed into the direct component \( i_{d} \) \& \( i_{q} \) in the revolving coordinate system through the Clarke and the Park transformations. Then \( i_{d}, i_{q} \) can be used as the negative feedback quantity of the electric current loop. The deviation between the given speed and the feedback speed \( \omega_{*} \) is regulated through the speed PI regulator. The output is \( q \) axis reference component \( i_{q}^{*} \)– torque component, which is used to control the torque. The deviations between \( i_{q}^{*}, i_{q} \) and current feedback quantity \( i_{q} \) \& \( i_{d} \) is fed to the current PI regulators, and the respective output phase voltage \( V_{q}^{*} \) and \( V_{d}^{*} \) on the \( d-q \) revolving coordinate system. \( V_{q}^{*} \) and \( V_{d}^{*} \) are transformed into the stator phase voltage vector component \( V_a \) and \( V_b \) under \( \alpha-\beta \) coordinate system through inverse Park transformation. If the stator phase voltage vector \( V_a \), \( V_b \) and its sector number is known, the voltage space vector PWM technique can be used to produce PWM signal to control the inverter, so as to achieve closed-loop control of the
Permanent magnet synchronous motor parameter are given in table 5.

<table>
<thead>
<tr>
<th>Name of parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Pole Pair p</td>
<td>4</td>
</tr>
<tr>
<td>Stator Resistance</td>
<td>0.9585Ω</td>
</tr>
</tbody>
</table>
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<table>
<thead>
<tr>
<th>Field</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator Inductance</td>
<td>0.00835H</td>
</tr>
<tr>
<td>Flux Linkage</td>
<td>0.01827 V.S</td>
</tr>
<tr>
<td>Inertia</td>
<td>0.0046329 Kg.m²</td>
</tr>
<tr>
<td>Viscous Damping</td>
<td>0.0003035 N.m.s</td>
</tr>
<tr>
<td>Rotor Type</td>
<td>Round Rotor</td>
</tr>
</tbody>
</table>

Fig. 7 shows the electromagnetic torque of the Permanent magnet synchronous drive. The torque value is stabilize after 0.011 sec.

![Fig.7. Electromagnetic Torque](image)

Fig. 8 shows the speed response of PMSM motor based on SVPWM technique which is used as an inverter fed drive for a reference speed of 300 rpm. No overshoot have been observed. It may be clearly observed that steady state tracking accuracy is high for proposed controller. PMSM drive gave speed range from 0-300 rpm in 0-0.011 sec and then it stabilize at 300 rpm.

![Fig.8. Speed Response](image)

Fig. 9 shows the stator d-q voltage. Stator d-q voltage time axis is shown in mili-second.

![Fig.9. d-q Axis Voltage](image)

Fig.10-fig11 shows the stator current of permanent magnet synchronous motor drive. Fig.10 is showing the d-axis current and fig.11 shows the stator 3-phase a-b-c current.
The input voltage \( V_{ab} \) of permanent magnet synchronous motor has been shown in fig.12. It is the output voltage of the SVPWM inverter. The SVPWM inverter voltage source is 3-phase rectified DC voltage.

The simulation result with SVPWM method are shown in fig.13. The speed and torque characteristics with respect to time axis has been shown. The speed torque characteristic shows no transient for a PMSM and a smooth operation may be observed after 0.011 sec.

6. CONCLUSIONS

This paper present field oriented control (FOC) with space vector pulse width modulation (SVPWM) algorithm for permanent magnet synchronous machine (PMSM). The configuration for the proposed system is designed and simulated using latest MATLAB/Simulink. The paper investigate that the use
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of SVPWM may provide proper switching state of inverter and optimized the switching patterns. The simulation results shows the reduced torque repels and reduced the speed transients, speed is settled at 0.011 sec. SVPWM controller makes the system robust as there is no overshoot present in speed. Simulation result shows the quicker and dynamic response of the system. Hence the SVPWM is feasible and more effective for application point of view.

REFERENCES


