SVPWM Techniques and Applications in HTS PMSM Machines Control

Zheng-Guang Wang, Jian-Xun Jin, You-Guang Guo, and Jian-Guo Zhu

Abstract—This paper introduces the principle of space vector pulse width modulation (SVPWM), and discusses a method for implementing the SVPWM based on MATLAB/SIMULINK, as well as modeling of AC servo system with permanent magnet synchronous motor (PMSM). Simulation results show that the model is effective, and the method provides a frame of reference for software and hardware designs which can be applied in high temperature superconducting (HTS) flywheel energy storage system (FESS) and linear motor (LM).

Index—Flywheel energy storage system (FESS), linear motor (LM), modeling and simulation, permanent magnet synchronous motor (PMSM), space vector pulse width modulation (SVPWM).

1. Introduction

Digital control techniques of AC motors, such as the space vector pulse width modulation (SVPWM), have been developed with wide range industrial applications. The SVPWM was brought forward in the 1980’s, specifically for the frequency varying and speed regulation of AC motors. It controls the motor based on the switching of space voltage vectors, by which an approximate circular rotary magnetic field is obtained. In other words, the inverter is controlled to output an “appropriate” voltage waveform. This forms the basis of the magnetic flux linkage tracking pulse width modulation [1]-[6].

The basis of SVPWM is different from that of sine pulse width modulation (SPWM). SPWM aims to achieve symmetrical 3-phase sine voltage waveforms of adjustable voltage and frequency, while SVPWM takes the inverter and motor as a whole, using the eight fundamental voltage vectors to realize variable frequency of voltage and speed adjustment. If the voltage drop across stator resistance is ignored, when the stator windings are supplied with perfect sine waveform voltages, a rotating voltage space vector is formed with constant magnitude and hence the airgap flux density rotates with constant speed and circular track [7],[8].

2. HTS PMSM Machines

The flywheel energy storage system (FESS) has features of high energy density, high power density, high efficiency, long life and no pollution, etc. High temperature superconducting (HTS) materials have brought great opportunity to this technology [7]. With the rapid development of high-intensity fibers, power electronic devices, rare-earth permanent magnet materials, microcomputer technology, and control theory, the practical applications of the HTS FESS will be used in various areas, such as electrical power peaking modulation, UPS, electric automobile battery, control of satellite attitude, and electromagnetic cannon requesting short-time large-power supply [10],[11]. HTS linear motor (LM) is another related HTS application, which can be applied to maglev driving systems and also the electromagnetic cannons with high efficiency.

Due to a number of merits of the HTS permanent magnet synchronous motor (PMSM), it has become the best choice for the FESS which requires the electric machine featuring small volume, light weight, high efficiency, small moment of inertia, and high reliability. The PMSM is also suitable to develop a HTS LM.

A HTS FESS consists of high speed flywheel, bearing support system, electromotor/dynamo, power electronic converter, electronic control equipment, and extra equipment such as vacuum chamber, etc. It is a kind of integrated building block systems.

FESS has three operation modes as follows:
1) Flywheel charge mode: AC supply offers power supply to the flywheel controller, which controls the input of electrical energy that flywheel runs at the maximal rating rotary speed.
2) Flywheel energy maintenance mode: FESS depends on the least AC current input which keeps flywheel at the maximal rotary speed.
3) Flywheel discharge mode: when the AC supply is off, the flywheel offers power supply to the flywheel controller, which feeds UPS and user load. Then, the flywheel rotary speed decreases.

The HTS PMSM AC servo mathematical model is able to realize digitization control of the HTS FESS and LM. The models are built as shown in Fig. 1 and Fig. 2.
3. Principle of SVPWM

SVPWM aims to generate a voltage vector that is close to the reference circle through the various switching modes of inverter. Fig. 3 is the typical diagram of a three-phase voltage source inverter model. For the on-off state of the three-phase inverter circuit, every phase can be considered as a switch $S$. Here, $S_a(t)$, $S_b(t)$ and $S_c(t)$ are used as the switching functions for the three phases, respectively.

The space vector of output voltage of inverter can be expressed as

$$V(S_a, S_b, S_c) = 2V_{dc} (S_a + \alpha S_b + \alpha^2 S_c)/3$$

where $V_{dc}$ is the DC bus voltage of inverter and $\alpha = e^{j120}$. If we express the on state of the upper-arm with “1” and the off state with “0”, the on-off states of three phases have eight combinations, correspondingly forming eight voltage space vectors, as shown in Fig. 4. $T$ refers to the operation times of two adjacent non-zero voltage space vectors in the same zone. Both $V_s(000)$ and $V_s(111)$ are called the zero voltage space vector, and the other six vectors are called the effective vector with a magnitude of $2V_{dc}/3$. For example, when the output voltage vector $V_s$ is within zone one, it is composed of $V_s$, $V_s$, $V_s$, and $V_s$, and can be obtained by

$$V_{out} = T_{s} V_{dc} + T_{o} V_{o}$$

The eight on-off states of inverter are listed in Table 1.

Table 1: Eight on-off states of the inverter

<table>
<thead>
<tr>
<th>Inverter State</th>
<th>$S_a$</th>
<th>$S_b$</th>
<th>$S_c$</th>
<th>$V_a/V_{dc}$</th>
<th>$V_b/V_{dc}$</th>
<th>$V_c/V_{dc}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>-1/3</td>
<td>-1/3</td>
<td>2/3</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1/3</td>
<td>1/3</td>
<td>1/3</td>
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<tr>
<td>3</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>-1/3</td>
<td>2/3</td>
<td>-1/3</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1/3</td>
<td>-2/3</td>
<td>1/3</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>-1/3</td>
<td>1/3</td>
<td>-2/3</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1/3</td>
<td>1/3</td>
<td>-2/3</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Fig. 4. Diagram of voltage space vector.

4. SIMULINK Simulation of SVPWM

Based on the principle of SVPWM, the simulation models for generating SVPWM waveforms mainly include the sector judgment model, calculation model of operation, time of fundamental vectors, calculation model of switching time, and generation model of SVPWM waveforms.

4.1 Sector Judgment

For applying the technology of SVPWM, firstly it is requested to determine the sector which the voltage vector is within. Considering that the expression of vector in the $\alpha-\beta$ coordinate is suitable for controlling implementation, the following procedure is used for determining the sector.

When $V_{\beta} > 0$, $A = 1$; when $\sqrt{3} V_{\alpha} < V_{\beta} > 0$, $B = 1$; when $\sqrt{3} V_{\alpha} + V_{\beta} < 0$, $C = 1$. Then, the sector containing the voltage
vector can be decided according to $N = A + 2B + 4C$, listed in Table 2. Fig. 5 shows the corresponding model.

Table 2: The sector containing the voltage vector versus $N$

<table>
<thead>
<tr>
<th>Sector</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>3</td>
<td>1</td>
<td>5</td>
<td>4</td>
<td>6</td>
<td>2</td>
</tr>
</tbody>
</table>

Fig. 5. Model of sector judgment.

4.2 Calculation of Operation Times of Fundamental Vectors

Table 3 lists the operation times of fundamental vectors against $N$, where $T_1$ and $T_m$ refer to the operation times of two adjacent non-zero voltage space vectors in the same zone. Fig. 6 shows the calculation model, where $Z = T(\sqrt{3} V_a + V_b)/(\sqrt{2} V_{dc})$, $Y = T(\sqrt{3} V_a + V_b)/(\sqrt{2} V_{dc})$, $X = 2T[V_b/(\sqrt{2} V_{dc})]$. The sum of $T_1$ and $T_m$ must be smaller than or equal to $T$ (PWM modulation period). The over saturation state must be judged: if $T_1 + T_m + T$, take $T_1 = T/[(T_1 + T_m)]$, $T_m = T_m /[T/(T_1 + T_m)]$. Fig. 7 illustrates the SIMULINK-based model.

Table 3: Operation time of fundamental vector

<table>
<thead>
<tr>
<th>$N$</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>$-Z$</td>
<td>$-X$</td>
<td>$X$</td>
<td>$-Y$</td>
</tr>
<tr>
<td>$T_m$</td>
<td>$Y$</td>
<td>$-X$</td>
<td>$X$</td>
<td>$Z$</td>
<td>$-Y$</td>
<td>$-Z$</td>
</tr>
</tbody>
</table>

Fig. 6. Model for counting $X$, $Y$ and $Z$.

Fig. 7. Calculation model of operation times of fundamental vectors.

4.4 Generation of SVPWM Waveform

The relation between $N$ and switch operation times is shown in Table 4 and realized in Fig. 8 and Fig. 9, where $T_a = (T - T_1 - T_m)/4$, $T_b = T_a + T_3/2$, and $T_c = T_b + T_m/2$, $T_{cm1}$, $T_{cm2}$ and $T_{cm3}$ are the operation times of the three phases respectively.

Table 4: Relation between $N$, $T_{cm1}$, $T_a$, $T_b$, and $T_c$

<table>
<thead>
<tr>
<th>$N$</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{cm1}$</td>
<td>$T_a$</td>
<td>$T_b$</td>
<td>$T_c$</td>
<td>$T_a$</td>
<td>$T_b$</td>
<td>$T_c$</td>
</tr>
<tr>
<td>$T_{cm2}$</td>
<td>$T_a$</td>
<td>$T_b$</td>
<td>$T_c$</td>
<td>$T_a$</td>
<td>$T_b$</td>
<td>$T_c$</td>
</tr>
<tr>
<td>$T_{cm3}$</td>
<td>$T_a$</td>
<td>$T_b$</td>
<td>$T_c$</td>
<td>$T_a$</td>
<td>$T_b$</td>
<td>$T_c$</td>
</tr>
</tbody>
</table>

Fig. 8. Model of switch operation time.

4.3 Calculation Model of Switch Operation Time

By comparing the computed $T_{cm1}$, $T_{cm2}$ and $T_{cm3}$ with the equilateral triangle diagram, a symmetrical space vector PWM waveform can be generated and its model is shown in Fig. 10. The waveforms of PWM2, PWM4 and PWM6 are obtained by reversing those of PWM1, PWM3 and PWM5, respectively. The PMSM is controlled by switching on or off the power electronic parts. Fig. 11 illustrates the overall model of SVPWM.
Fig. 9. Relation between $N$, $T_{cm1}$, $T_{cm2}$, and $T_{cm3}$.

Fig. 10. Generation model of SVPWM waveforms.

5. PMSM Simulation Model

The PMSM simulation model of closed loop system can be built by connecting the above-mentioned sub-models. Because the measured rotor angle and speed are in mechanic degrees, but in the actual coordinate transform the electrical angle is adopted, the measured angle and speed are multiplied by the number of pole-pairs of the motor. The simulation model of the control system is shown in Fig. 12.

6. Simulation Results

When the sampling period of PWM is 0.0001 s, the DC bus voltage is 310 V, the carrier frequency of PWM waveform is 10 kHz, the dead zone time is 4 μs, the SVPWM waveform in a sampling period is shown in Fig. 13. $T_s$ refers to sampling time, $T_0$ refers to the time of zero vector operation, $T_k$ and $T_{k+1}$ refer to the operation times of two adjacent non-zero voltage space vectors in the same zone, then the resultant torque increases to $\sqrt{3}$ times. The phase is switched to the next in every 60 electrical degrees.

The operation duration of each power electronic part is 120 electrical degrees. The exciting duration of each winding is 240 electrical degrees: including 120 degrees for positive direction and 120 degrees for negative direction.

When the parameters of speed regulator are set as $K_p=1.5$, $K_i=10.5$; the q-axis current regulator is set as $K_p=3$, $K_i=1$; the d-axis current regulator is set as $K_p=3$, $K_i=1$, the simulated current, rotor speed, torque and rotor angle of the PMSM are shown in Fig. 14. It can be seen that the simulations agree with common operational characteristics, proving the validity of the presented model.

The simulation reference speed is set as 200 rad/s, the simulation step is 0.0001 s, and the simulation time is 0.4 s. At $t=0$ s, the motor starts up with no-load; at $t=0.2$ s, a load torque of 3 Nm is applied. From the simulations, it can be seen that the startup speed of motor is fast and is able to follow the reference speed. With load torque, the fluctuation of rotary speed waveform is very small. The PMSM used in the simulation model is TYB55-4, whose major parameters are listed in Table 5.

![Overall model of SVPWM](image-url)
be seen that the voltage vector rotates anticlockwise in proper order, i.e. III (011), I (001), V (101), IV (010), VI (110), II (010). Fig. 18 accords with Fig. 13 and Table 2.

![Diagram](image)

**Fig. 12. Simulation model of control system of PMSM.**

**Fig. 13. SVPWM waveform in a single sampling period.**

**Table 5: Major parameter of a PMSM**

<table>
<thead>
<tr>
<th>Item</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power range</td>
<td>110 W to 550 W</td>
</tr>
<tr>
<td>Moment of inertia</td>
<td>0.8 kgm²</td>
</tr>
<tr>
<td>Rated torque</td>
<td>3.5 Nm</td>
</tr>
<tr>
<td>Voltage range</td>
<td>76 V to 380 V</td>
</tr>
<tr>
<td>Rated current</td>
<td>1.5 A</td>
</tr>
<tr>
<td>Stator resistance</td>
<td>2.875 Ω</td>
</tr>
<tr>
<td>Stator inductance</td>
<td>8.5 mH</td>
</tr>
<tr>
<td>Rated speed</td>
<td>1500 rpm</td>
</tr>
<tr>
<td>Frequency varying range</td>
<td>10 Hz to 50 Hz</td>
</tr>
</tbody>
</table>

Fig. 15 shows the simulated waveforms of d-q axis stator currents. When $t=0.2$ s, a torque of 3 Nm is applied from no-load. It can be observed that the q-axis current is directly proportional to the torque, while the d-axis current is nearly zero. It can be concluded that the three-phase stator currents have well been decoupled.

With a reference speed of 200 rad/s, the simulated line-to-line voltage (A-B) and phase voltage waveforms are shown in Fig. 16 and Fig. 17, respectively. The section transform of the voltage vector is shown in Fig. 18. It can
From the rotor speed response curve, it is observed that after starting-up, the motor accelerates to a stable value quickly. Similarly, the electromagnetic torque and the three phase currents maintains at the steady values with small fluctuation shortly.

7. Conclusion

Comparing with the SPWM, the main SVPWM advantage is that it has a 15% higher utilization ratio of voltage. SVPWM is achieved by implementing the zero voltage space vectors in the phase modulation wave of SPWM. SPWM is easier to be realized in hardware circuit, while SVPWM is more suitable for digital control system. Based on the rotor field orientation control of PMSM, this paper presents the MATLAB/SIMULINK-based simulation model by adopting the classical double closed loops of speed and current and vector control method. The simulation results reveal that the waveforms are in accord with theoretical analysis, the system can operate stably with fairly good steady-state and dynamic characteristics, providing sound bases for developing both software and hardware to realize HTS FESS and LM machines[18]-[21].

References


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