Application of space vector pulse width modulation algorithm based on programmable logic array in power system

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Abstract—In the traditional power system, the voltage regulation and frequency modulation control method used for boiler induced draft fan is limited in control accuracy. With the improvement of furnace pressure change accuracy, higher requirements are put forward for motor control algorithm. This paper studies permanent magnet synchronous motor (PMSM) as the executive part of induced draft fan servo control system, and adopts FOC control method based on space vector pulse width modulation (SVPWM). Firstly, the simulation model of SVPWM pulse width modulation algorithm is established by MATLAB to provide theoretical support for the subsequent debugging algorithm; When using FPGA to realize SVPWM modulation algorithm, FPGA has the advantages of high reliability and high real-time processing, which provides theoretical support and application guidance for the realization of high-precision motor control of boiler induced draft fan in power system.

1. Introduction

The boiler air flow classifier is mainly composed of secondary air, tertiary air, impeller, transmission system, etc. During the operation of the production line, the materials enter through the feed pipe of the classifier under the attraction of the induced draft fan. At the same time, the air enters the scouring area through the secondary air inlet evenly distributed on the cone under the attraction of the induced draft fan, and the coarse and fine mixed powder is used for air screen scouring. In order to improve the air classification accuracy of the boiler, it is necessary to improve the permanent magnet synchronous motor of the induced draft fan control accuracy and control stability of the drive system.

There are three main PMSM control strategies: voltage regulation and frequency modulation control (VF), direct torque control (DTC) and vector control (FOC). The VF control method is open-loop control, which has simple control and low precision. Motor out of step will occur under heavy load. This is the traditional motor control method of boiler induced draft fan\textsuperscript{[1]}. DTC control realizes high-performance dynamic control through direct tracking of flux linkage amplitude and torque. It does not need complex calculation formulas such as complex spatial coordinate changes, and is insensitive to motor parameters. It has simple structure, fast torque response and good robustness. However, it is protected by intellectual property rights. At present, only ABB company applies this control method\textsuperscript{[2]}. FOC control is to add phase control on the basis of controlling the voltage and current of three-phase AC, detect the magnetic pole position of motor rotor in real time to determine the voltage phase of three-phase stator winding, and realize current control torque. FOC control is a closed-loop control with high control accuracy and flexible control modes (including \(id = 0\) control;
maximum torque current ratio control, constant flux control, flux weakening control, etc.), but the
calculation of FOC control is complex and requires a variety of spatial coordinate transformations [3].

In this paper, the simulation model of SVPWM is established by establishing simulink of
MATLAB, and the "three loop" control simulation of PMSM is completed, which provides a
theoretical basis for circuit debugging. According to the simulation results, the motor selection and
drive circuit design are completed. The SVPWM control algorithm is realized through anti fuse FPGA
to complete the bottom drive control of permanent magnet synchronous motor.

2. Principle of space vector pulse width modulation
The essence of SVPWM pulse width modulation is the modulation mode of ideal sine wave and ideal
third harmonic. On the one hand, this modulation mode ensures the maximum voltage utilization; On
the other hand, most motors are three-phase windings with a winding subspace angle of 120°, and the
third harmonic of phase voltage does not affect the line voltage, and such modulation mode will not
affect the synthetic magnetomotive force of the motor [4]. Figure 1 shows a voltage waveform
(approximately trapezoidal) consisting only of fundamental wave and third harmonic:

![Figure 1. Ideal SVPWM modulation waveform](image)

The SVPWM method adopts the average equivalent principle, that is, the average value is equal to
the given voltage vector by combining the basic voltage vector in one switching cycle. At a certain
time, the voltage vector is obtained by different combinations of two adjacent non-zero vectors and
zero vectors in time. The action time of each voltage vector is controlled in a sampling period to make
the voltage space vector close to rotating according to the circular track, and the actual flux generated
by different switching states (Sa, Sb, Sc) of the inverter approaches the ideal flux circle.

3. Simulation Implementation of space vector pulse width modulation algorithm and analysis of
vector control simulation results
The implementation of SVPWM algorithm is mainly divided into several steps: sector judgment
calculation, voltage vector selection and action time calculation, sector vector switching point
calculation and three-phase PWM pulse trigger.

3.1 Sector judgment of reference voltage vector
According to figure 2, \( U_\alpha \) and \( U_\beta \) are the components of the reference voltage \( U_{OUT} \) on the \( \alpha \) axis
and \( \beta \) axis. Further simplify the analysis of the above conditions. The sector where the reference
voltage vector \( U_{OUT} \) is located can be judged by the three formulas \( U_\beta, \sqrt{3} U_\alpha - U_\beta, -\sqrt{3} U_\alpha - U_\beta \).

\[
\begin{align*}
U_1 &= U_\beta \\
U_2 &= \frac{\sqrt{3}}{2} U_\alpha - \frac{U_\beta}{2} \\
U_3 &= -\frac{\sqrt{3}}{2} U_\alpha - \frac{U_\beta}{2}
\end{align*}
\]

If \( U_1 > 0 \), \( a = 1 \), otherwise \( a = 0 \);
If \( U_2 > 0 \), then \( B = 1 \), otherwise \( B = 0 \);
If \( U_3 > 0 \), then \( C = 1 \), otherwise \( C = 0 \);
Define the number of sectors \( N=4C+2B+A \) to obtain the corresponding relationship between the number of sectors \( N \) and the sector where the actual \( U_0 \) is located, as shown in Table 1:[5]

| \( N \) | 3 | 1 | 5 | 4 | 6 | 2 |
|-------|---|---|---|---|---|---|
| Fan area code | I | II | III | IV | V | VI |

3.2 calculation of sector voltage vector action time
According to the principle of space voltage vector action equivalence, taking \( U_{OUT} \) in sector I as an example, the action time of adjacent non-zero voltage vector \( T_4, T_6 \), zero voltage vector \( T_0, T_7 \) and in sector I is sorted out, as shown in equation (2)[6]:

\[
\begin{align*}
T_4 &= \frac{3U_o T_a}{2U_o} - \frac{1}{2} T_a = \frac{3U_o T_a}{2U_o} - \frac{1}{2} \sqrt{3} U_o T_6 = \sqrt{3} T_6 \left( \frac{\sqrt{3} U_o}{2} - \frac{U_o}{2} \right) = \sqrt{3} T_6 U_o; \\
T_6 &= \frac{\sqrt{3} U_o T_a}{U_o} = \sqrt{3} T_6 U_i; \\
T_7 &= T_a = \frac{T_a - T_4 - T_b}{2} \\
\end{align*}
\]

Where is the \( U_{dc} \) bus voltage and \( T_s \) is the time period, \( U_1, U_2, U_3 \) which is determined by equation (3).

\[
\begin{align*}
U_1 &= U_\beta \\
U_2 &= \frac{\sqrt{3}}{2} U_a - \frac{U_\beta}{2} \\
U_3 &= -\frac{\sqrt{3}}{2} U_a - \frac{U_\beta}{2} \\
\end{align*}
\]

Similarly, the action time of different voltage vectors in other sectors can be calculated.

3.3 determination of sector vector switching point
According to the average value equivalence principle in sector I, the switching time of different voltage vectors in sector I is shown in equation (4).

\[
\begin{align*}
T_a &= \frac{T_a - T_4 - T_b}{4} \\
T_b &= \frac{T_a + T_4}{2} \\
T_c &= \frac{T_a + T_b}{2} \\
\end{align*}
\]

The relationship between three-phase voltage switching time switching points \( T_{cm1}, T_{cm2} \) and \( T_{cm3} \) and each sector number \( N \) is shown in the table below:

| \( N \) | 1 | 2 | 3 | 4 | 5 | 6 |
|-------|---|---|---|---|---|---|
| \( T_{cm1} \) | \( T_b \) | \( T_a \) | \( T_a \) | \( T_c \) | \( T_c \) | \( T_b \) |
| \( T_{cm2} \) | \( T_a \) | \( T_c \) | \( T_b \) | \( T_b \) | \( T_a \) | \( T_c \) |
| \( T_{cm3} \) | \( T_c \) | \( T_b \) | \( T_c \) | \( T_a \) | \( T_b \) | \( T_a \) |

3.4. Simulation modeling and results of space vector pulse width modulation
The overall model of space vector control SVPWM is established in Simulink of MATLAB, as shown in Figure 2, which includes four parts: sector judgment, calculation of action time of basic voltage vector, determination of sector vector switching point and three-phase voltage generation module.
Figure 2. Simulink modeling of SVPWM

The simulation results are shown on left, where Fig. 2 is the sector number N on right is the voltage vector switching time point.

Figure 3. Simulation results of SVPWM module

4. Implementation of programmable logic array for space vector pulse width modulation
According to the Top-Down design idea, each functional module of SVPWM in quartus environment is designed. Combined with the in-depth analysis of SVPWM principle, the top-level design file of SVPWM algorithm will call each functional module. The system structure is shown in Figure 4.

FPGA top-level file uses MATLAB to generate simulated three-phase sinusoidal periodic angle data of motor winding to make DDS file, which is realized by clarke transform module, sector selection module, vector action time calculation module, switch selection module and so on.
The low-speed start of the motor is realized through the acceleration and deceleration module in FPGA. In the design process, the carrier frequency is set to 500Hz, the data period of three-phase winding angle is 0.1024s, and the motor speed is calculated to be 150r/min combined with the time sampling point. The simulation results of the SVPWM control algorithm implemented by FPGA are shown in Figure 5, including sinusoidal two-phase voltage inputs $U_a$ and $U_b$, three-way switch switching action time and triangular carrier setting.

It can be seen from Figure 5 that in FPGA simulation, the cycle alternation of sector n is $3 \rightarrow 1 \rightarrow 5 \rightarrow 4 \rightarrow 6 \rightarrow 2$, and the saddle shaped modulation waveform is realized through SVPWM algorithm to realize the accurate control of permanent magnet synchronous motor.

5. Conclusion
In this paper, the space voltage vector SVPWM model is built by Matlab / Simulink. At the same time, the SVPWM control algorithm is realized by software program and hardware circuit design on FPGA to complete the bottom drive control of permanent magnet synchronous motor. The motor control of induced draft fan in power system adopts FPGA to realize the bottom control algorithm, which has the advantages of high real-time and high reliability. In the future, the motor closed-loop control algorithm can be integrated in FPGA. At the same time, the device adopts anti fuse FPGA to improve the control accuracy, control reliability and real-time of the whole control system and meet the control requirements of various induced draft fans in the future.
Reference

[1] Wang Yang. Design of AC voltage regulation and frequency modulation control elevator system based on PLC [D]. Jiangsu: Suzhou University, 2011.

[2] Pan Feng, Yan Gelong, Yuan Wei Hua, et al. Direct torque control of permanent magnet synchronous motor based on double sliding mode [J]. Journal of electrotechnics, December 2018, Vol. 33, supplement 2:427-433.

[3] Cai Gang. Design and implementation of motor drive system for four rotor UAV Based on FOC [D]. Shaanxi: Chang'an University, 2016.

[4] Li Jinying, Fu Chengyu, Chen Xinglong, et al. Permanent magnet synchronous motor drive controller and modulation mode [J]. Motor and control applications, 2010, Vol. 37, No. 7: 28-31.

[5] Peng Bo, Xiao Dengming, long Bo. Simulation implementation of three-phase inverter SVPWM based on Simulink [J]. Industrial control computer, 2011, Vol. 24, No. 7: 90-92.

[6] Xiao Chunyan. Research and implementation of voltage space vector pulse width modulation technology [M]. Jiangxi: School of information engineering, Nanchang University, 2005.