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Spec No: 002-05407

Spec Title: AN205407 FM3 MICROCONTROLLER SERVO CONTROL ALGORITHM FOR PMSM

Replaced by: None

AN205407

FM3 Microcontroller Servo Control Algorithm for PMSM

Target Products: Refer to Section 2

This application note describes a servo control solution for a brushless PMSM. The control algorithm presented is field oriented control.

Contents

1 Introduction

1.1 Purpose

This application note describes a servo control solution for a brushless PMSM. The control algorithm presented is field oriented control.

1.2 Definitions, Acronyms and Abbreviations

PMSM Permanent Magnet Synchronous Motor

PID Proportion, Integration, and Derivation Regulator

QPRC Quadrature Position/Revolution Counter

1.3 Document Overview

The rest of document is organized as the following:

Chapter 2 explains the mathematical models of the PMSM.

Chapter 3 explains the realization of FOC scheme.

Chapter 4 shows the experiment result of the design control system.

2 Target products

This application note is described about below products;

(TYPE0)

Series	Product Number (not included Package suffix）
MB9B500A	MB9BF504NA,MB9BF505NA,MB9BF506NA MB9BF504RA,MB9BF505RA,MB9BF506RA
MB9B400A	MB9BF404NA,MB9BF405NA,MB9BF406NA MB9BF404RA,MB9BF405RA,MB9BF406RA
MB9B300 A	MB9BF304NA,MB9BF305NA,MB9BF306NA MB9BF304RA,MB9BF305RA,MB9BF306RA
MB9B100A	MB9BF102NA,MB9BF104NA,MB9BF105NA,MB9BF106NA MB9BF102RA,MB9BF104RA,MB9BF105RA,MB9BF106RA
MB9A100A	MB9AF102NA,MB9AF104NA,MB9AF105NA MB9AF102RA,MB9AF104RA,MB9AF105RA

3 PMSM Model

Mathematical models of the PMSM

3.1 Overview

It is possible to generate a magnetic rotating field by applying sinusoidal voltages to the 3 stator phases. The sinusoidal current flows in the coils and generate the rotating stator flux. The rotor rotates because of the attraction between the permanent rotor flux and the stator flux.

3.2 Motor Model

Figure 1. Equivalent circuit of PMSM motor

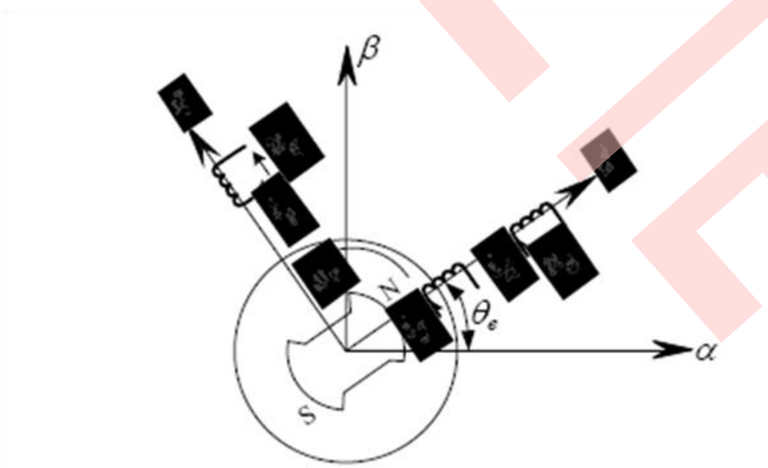


Figure 1 shows the equivalent model in rotational d-q axis. The direction of d-axis is identical to the rotor flux of permanent magnet synchronous motor. The q-axis is 90 degree leading for d-axis.

3.3 Mathematical Equations

In d-q axis, the motor model is as follows.

Stator flux equation:

$$\begin{bmatrix}\Psi_d\\ \Psi_q\end{bmatrix}=\begin{bmatrix}L_d & 0\\ 0 & L_q\end{bmatrix}\begin{bmatrix}i_d\\ i_q\end{bmatrix}+\begin{bmatrix}\Psi_f\\ 0\end{bmatrix}$$

Stator voltage equation:

$$\begin{bmatrix}u_d\\ u_q\end{bmatrix}=r\begin{bmatrix}i_d\\ i_q\end{bmatrix}+\begin{bmatrix}L_d & 0\\ 0 & L_q\end{bmatrix}p\begin{bmatrix}i_d\\ i_q\end{bmatrix}+\omega_r\begin{bmatrix}0 & -L_q\\ L_d & 0\end{bmatrix}\begin{bmatrix}i_d\\ i_q\end{bmatrix}+\omega_r\begin{bmatrix}0\\ \Psi_f\end{bmatrix}$$

Torque equation:

$$T_e=\frac{3}{2}P_n(\Psi_d i_q-\Psi_q i_d)=\frac{3}{2}p[\Psi_f i_q+(L_d-L_q)i_d i_q]$$

Where,

P_n: Motor pole pairs

Ψ_f: Rotor flux

4 Field Oriented Control for PMSM

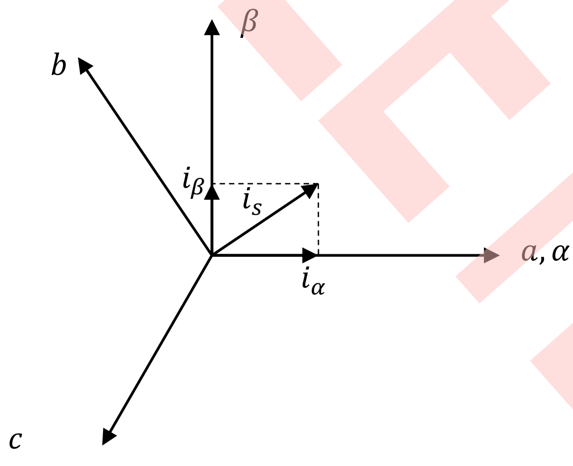
This chapter introduces Field Oriented Control algorithm and realization.

4.1 Coordinate Transform

4.1.1 Clarke Transform

The Clarke transform is that 3-phase stator current is transformed to 2-phase stationary axes α-β. This transformation is illustrated in Figure 2

Figure 2. Clarke Transform



$$i_a+i_b+i_c=0$$

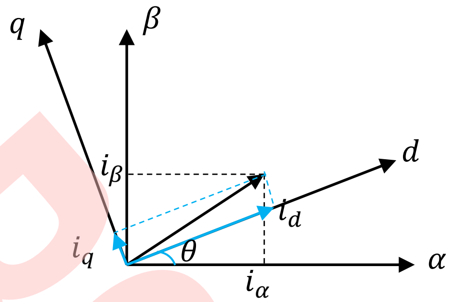
$$i_\alpha=i_a$$

$$i_\beta=\frac{i_a+2i_b}{\sqrt{3}}$$

4.1.2 Park Transform

The Park transform is that 2-phase stationary axes α-β is transformed to 2-phase rotating d-q axes. This transformation is illustrated in Figure 3

Figure 3. Park Transform



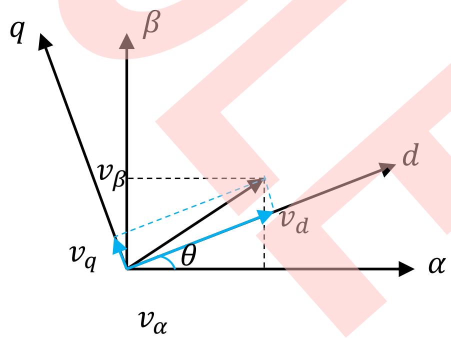
$i_d = i_\alpha cos\theta + i_\beta sin\theta$

$i_q = -i_\alpha sin\theta + i_\beta cos\theta$

4.1.3 Inverse Park

Inverse Park transforms from the two axis rotating d-q frame to the two axes stationary frame α-β. This transformation is illustrated in Figure 4

Figure 4. Inverse Park Transform



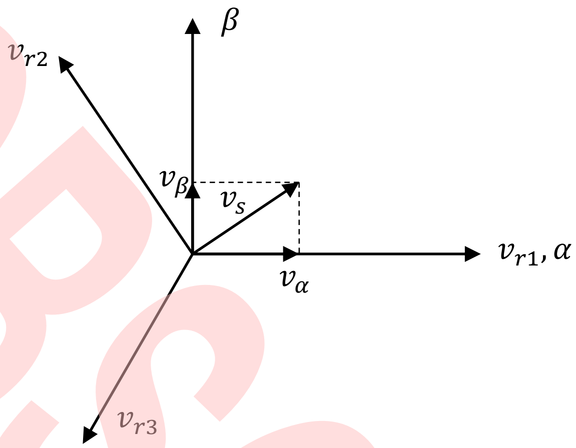
$v_\alpha = v_d cos\theta - v_q sin\theta$

$v_\beta = v_d sin\theta + v_q cos\theta$

4.1.4 Inverse Clarke

The Inverse Clarke is to transform form the stationary two axes α-β to the stationary three axes, which is illustrated in Figure 5

Figure 5. Inverse Clarke Transform



$$v_{r1} = v_\beta$$

$$v_{r2} = \frac{-v_\beta + \sqrt{3} * v_\alpha}{2}$$

$$v_{r3} = \frac{-v_\beta - \sqrt{3} * v_\alpha}{2}$$

4.1.5 Space Vector Modulation

The Space Vector Modulation is used to generate pulse width modulation signals for the 3-phase motor voltage signals. It uses a special scheme to switch the power transistors to generate sinusoidal currents in the stator phases.

Each of the three inverter outputs can be in one of two states. The inverter output can be connected to either the positive bus or the negative bus, which allows for 8 possible states.

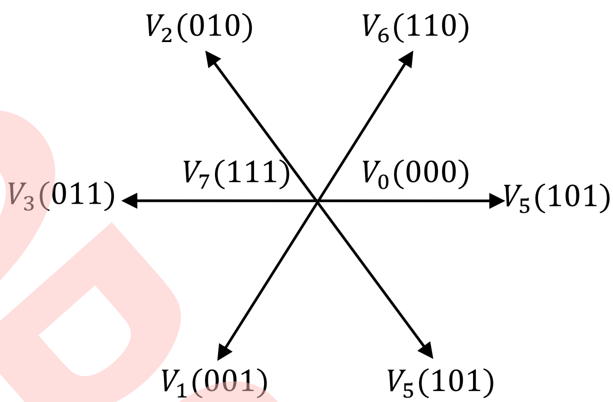
It is possible to express each phase to neutral voltages, for every combination of the power transistors as listed in Table 1. Power Bridge Output Voltage

Table 1. Power Bridge Output Voltage

Phase A	Phase B	Phase C	V_{AN}	V_{BN}	V_{CN}
0	0	0	0	0	0
0	0	1	$-V_{DC}/3$	$-V_{DC}/3$	$2V_{DC}/3$
0	1	0	$-V_{DC}/3$	$2V_{DC}/3$	$-V_{DC}/3$
0	1	1	$-2V_{DC}/3$	$V_{DC}/3$	$V_{DC}/3$
1	0	0	$-2V_{DC}/3$	$-V_{DC}/3$	$-V_{DC}/3$
1	0	1	$V_{DC}/3$	$-2V_{DC}/3$	$V_{DC}/3$
1	1	0	$V_{DC}/3$	$V_{DC}/3$	$-2V_{DC}/3$
1	1	1	0	0	0

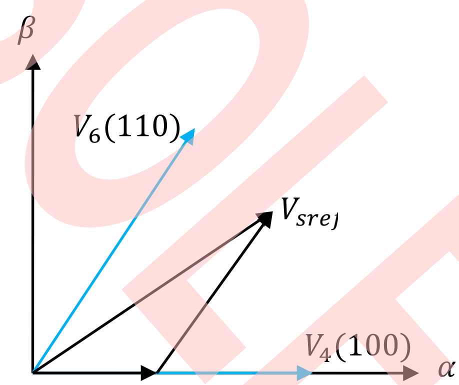
The eight voltage vectors defined by the combination of the switches are represented in Figure 6

Figure 6. Voltage Vector



The method used to approximate the desired stator reference voltage with only eight possible states of switches is to combine adjacent vectors of the reference voltage and to modulate the time of application of each adjacent vector.

Figure 7. Projection of the Reference Voltage Vector



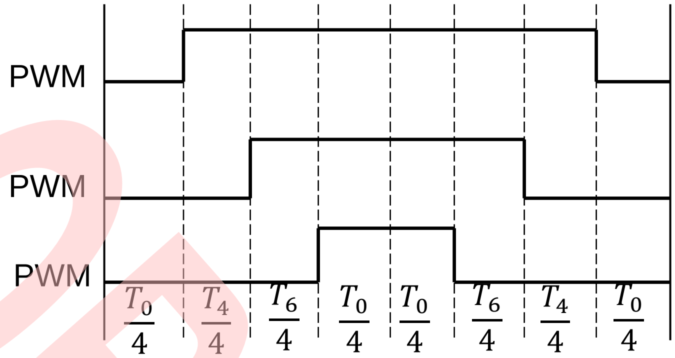
In エラー! 参照元が見つかりません。, the reference voltage V_{sref} is in the third sector and the application time of each adjacent vector is given by:

$$T = T_4 + T_6 + T_0$$

$$V_{sref} = \frac{T_4}{T} V_4 + \frac{T_6}{T} V_6$$

In Figure 8 for the PWM period T, the vector T_4 is output for $\frac{T_4}{T}$ and vector T_6 is output for $\frac{T_6}{T}$, the remain time is output for vector T_0.

Figure 8. PWM Patterns and Duty Cycles



4.2 Position and Speed Sensing

In electric motors, mechanical and electrical position is usually defined. The mechanical position is related to the rotation of the rotor shaft. The electrical position of the rotor is related to the rotation of the rotor magnetic field.

The relationship between electrical position and mechanical position is,

$$\theta_e = \theta_m * p$$

The relationship between electrical speed and mechanical speed is,

$$\omega_e = \omega_m * p$$

Where p is the number of pole pairs.

Fujitsu FM3 series contain QPRC modules, which is commonly used for position and speed sensing. AIN and BIN are incremental encoder output pulses. QPRC module counts each rising and falling edge.

4.2.1 Position Sensing

After configuration of QPRC module, the position counter starts to count the pulse edge. In order to find the relationship between rotor and position counter, searching encoder zero is necessary. Give a rotational magnetic field, the rotor rotates, record the position counter value when electrical position is 0 degree. The rotor position can be calculated as follows

$$\theta_m = \frac{x - x_0}{4 * N} * 360^{\circ}$$

Where,

x: QPRC position counter current value,

x_0: QPRC position counter initial value when electrical position is 0 degree,

N: Incremental encoder lines.

4.2.2 Speed Sensing

There are three ways to measure speed: M method, T method and M/T method.

1. M method

Count encoder output pulses in a fixed sample period. This method is suitable for high speed, because speed error is large in low speed.

The mechanical speed can be calculated as follows,

$$n = \frac{60 * M1}{4N * T_c}$$

Where,

N: Incremental encoder lines.

T_c: A fixed sample period

$M1$: Position counter changed value in a fixed sample period

2. T method

Use high frequent pulse, measure time interval of encoder output pulse. In low speed, this method has high precision, but as the speed increase, the error increases.

The mechanical speed can be calculated as follows,

$$n = \frac{60 * f_{clk}}{N * M2}$$

Where,

N: Incremental encoder lines.

f_{clk}: High frequent pulse input

$M2$: High frequent pulse count value

3. M/T method

M/T method combines the merits of M method and T method. It is an excellent method in measuring wide speed range.

The mechanical speed can be calculated as follows,

$$n = \frac{60 * M1 * f_{clk}}{4N * M2}$$

Where,

N: Incremental encoder lines.

f_{clk}: High frequent pulse input

$M1$: Position counter changed value in a fixed sample period

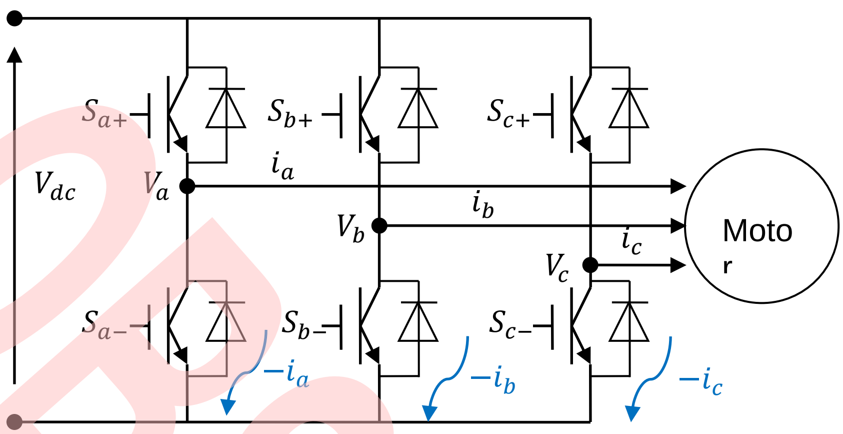
$M2$: High frequent pulse count value in a fixed sample period

4.3 Current Sensing

4.3.1 Current Sensing Theory

Hall component or current transformer can be used to measure motor winding current, but isolation circuit is required to handle the high common mode voltage and switching frequency at the motor windings. In order to reduce cost, the motor winding currents are measured by synchronizing the sampling of the current in the dc link shunt with the power inverter switching. Compared the motor winding current, the sample current is inverted. Figure 9 shows the current flow.

Figure 9. Three-phase Inverter Circuit

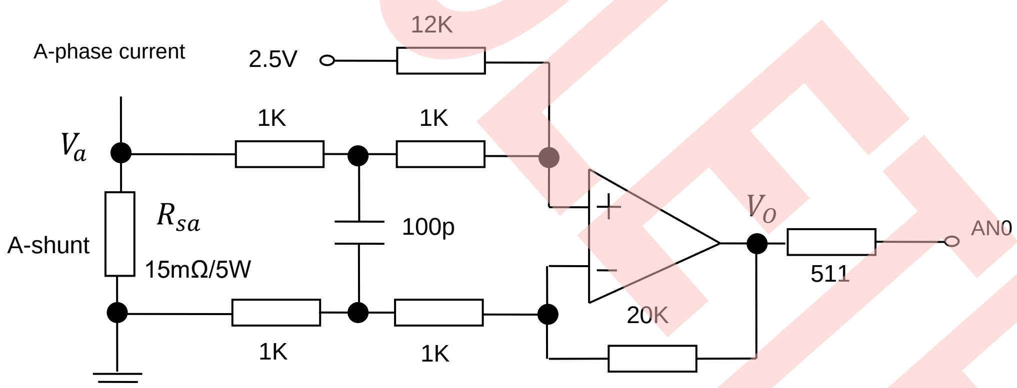


4.3.2 Current Sensing Circuit

The sample resistance converts current information into voltage information. The amplify circuit regulate voltage to MCU acceptable voltage. The voltage is sampled and converted to digital value by the AD converter integrated in MCU. Figure 10 gives the actual current sensing circuit. The amplifier output is expressed as follows,

Figure 10. Current Sensing Circuit

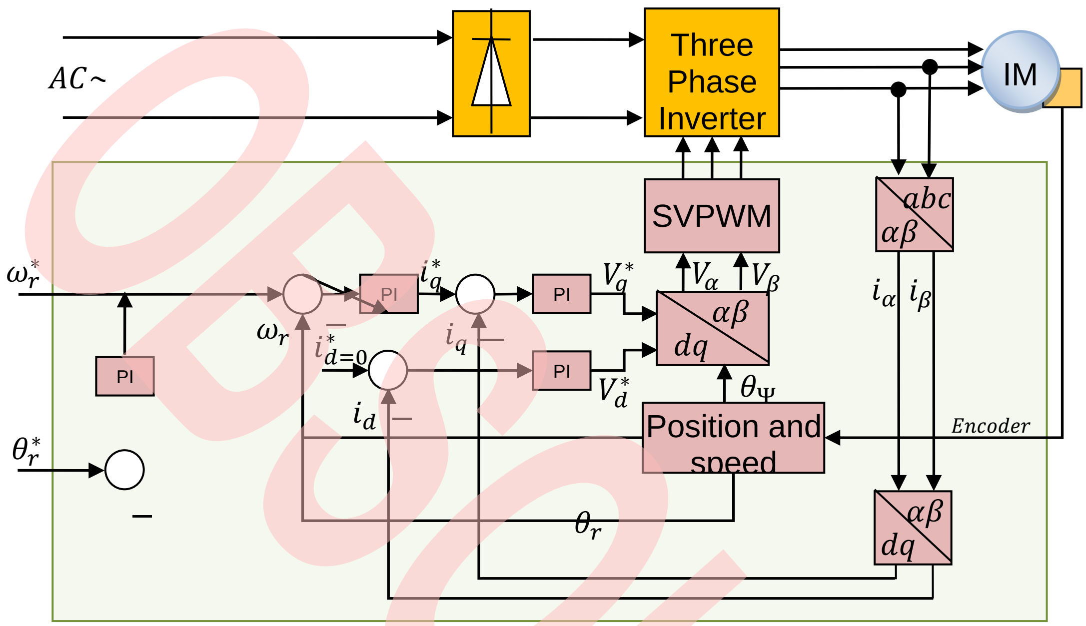
$$V_o = 2.5 + 10 * V_a$$



4.4 PMSM Control Block Diagram

The control block diagram for the PMSM servo control is shown in Figure 11

Figure 11. FOC Control for PMSM



5 Experimental Result

This section provides the experiment result of the design control system.

5.1 Requirements

Take camera servo controller as an example, which is shown in Table 2

Table 2. Servo Controller Requirements

Item	Value	Unit
Motor speed	1500	rpm
Motor angular velocity	4500	deg/s
Motor angular acceleration	4000	deg/s^2
Minimum motor angular velocity	0.01	deg/s
Positioning accuracy	±0.01	deg
Dome encoder	9000	lines
Motor output torque	0.2873	N·m
Motor rotor inertia	2.7	kg*cm^2

5.2 Experimental Result

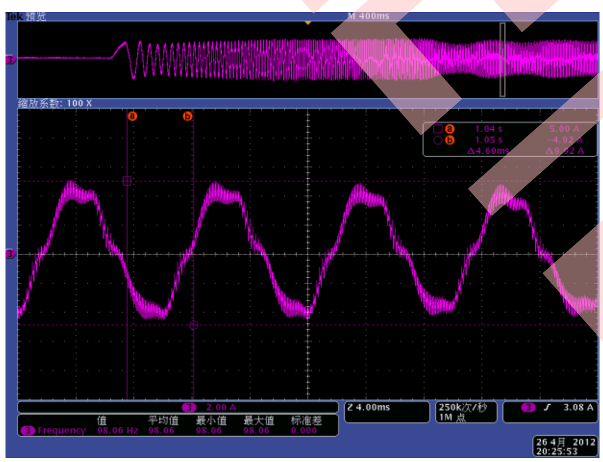
The servo controller experimental platform is shown in Figure 12. Servo Controller Experimental Platform. The DC bus voltage is +48V.

Figure 12. Servo Controller Experimental Platform

5.2.1 High Speed

Figure 13 shows the motor phase current waveform when running on high speed. The speed reference is set to 1500rpm.

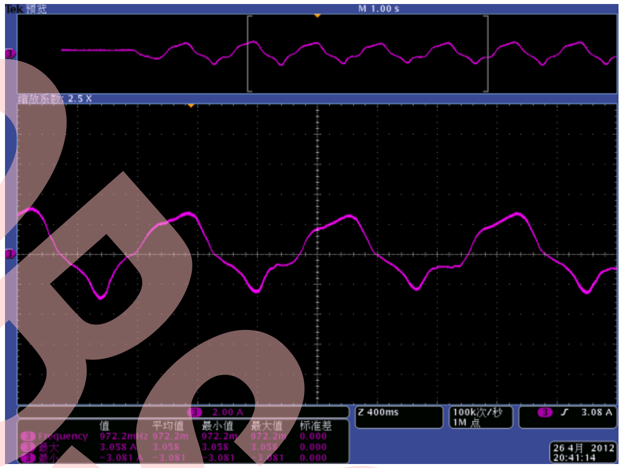
Figure 13. Running on High Speed



5.2.2 Low Speed

Figure 14 shows the motor phase current waveform when running on low speed. The speed reference is set to 15rpm.

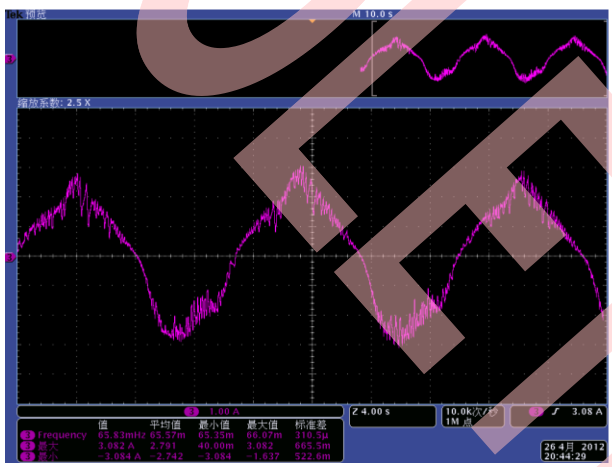
Figure 14. Running on Low Speed



5.2.3 Very Low Speed

Figure 15 shows the motor phase current waveform when running on very low speed. The speed reference is set to 1rpm. In this mode, position reference is changed at a given time interval. It is similar to step motor.

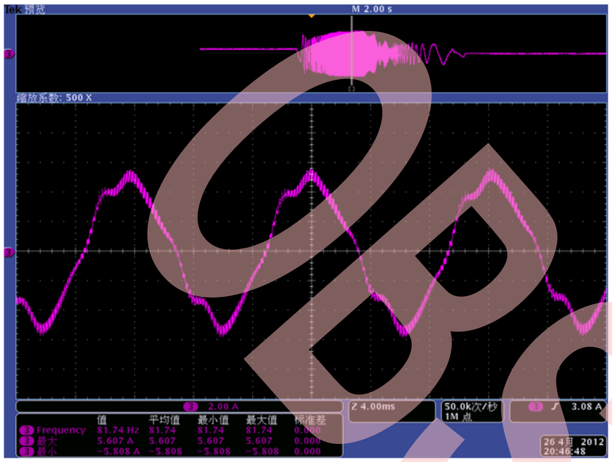
Figure 15. Running on Very Low Speed



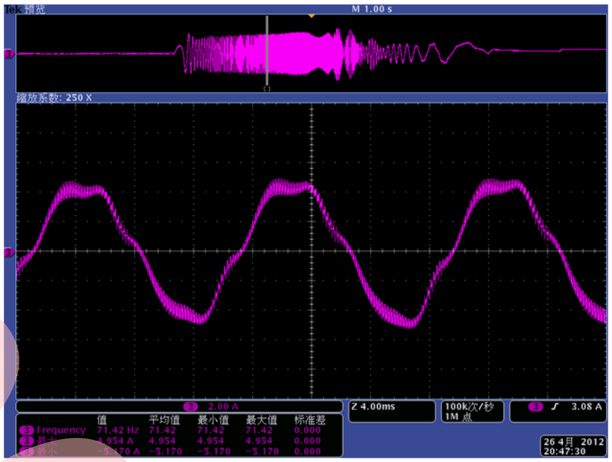
5.2.4 Running on Bi-direction

Figure 16 shows the motor phase current waveform when running on bi-direction. From the waveform, we can see that the current peak value is different when running on different direction.

Figure 16. Running On Bi-direction



(a). clockwise



(b). anti-clockwise

5.2.5 Position Accuracy

On the motor side, the positioning accuracy can reach 0.1˚. On the dome side, the positioning accuracy can reach ±0.01˚.

6 Additional Information

For more Information on Cypress semiconductor products, visit the following websites:

http://www.spansion.com/Products/microcontrollers/Pages/default.aspx

7 Document History

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Revision	ECN	Orig. of Change	Submission Date	Description of Change
**	–	WJLV	12/10/2012	Initial release
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*B	6329251	SSAS	10/02/2018	Obsoleted

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