

FM3 Family 3-Phase PMSM FOC Control**Associated Part Family: FM0+ / FM3 / FM4 Series**

This application note describes the FOC control of a 3-phase PMSM which includes, the structure of a 3-phase PMSM and motor driving principle, FOC control system, Core modules and Mathematical model of a 3-phase PMSM.

Contents

1	Introduction.....	1	4	Core Modules	7
1.1	Purpose	1	4.1	Coordinate Transformation	7
1.2	Definitions, Acronyms and Abbreviations.....	1	4.2	PI Regulator	9
1.3	Document Overview.....	1	4.3	SVPWM	10
2	Structure of a 3-Phase PMSM and Motor Driving Principle.....	2	4.4	Sensor-less Position Observer	16
2.1	Motor Category	2	5	Mathematical Model of a 3-Phase PMSM	17
2.2	Structure of a 3-Phase PMSM	2	6	Additional Information.....	17
2.3	Driving principle of 3-Phase PMSM	3		Document History.....	18
3	FOC Control	5			

1 Introduction**1.1 Purpose**

This document describes the FOC control of a 3-phase PMSM. The following contents are included:

- The structure of a 3-phase PMSM and motor driving principle
- FOC control system
- Core modules
- Mathematical model of a 3-phase PMSM

1.2 Definitions, Acronyms and Abbreviations

PMSM	Permanent Magnetic Synchronous Motor
SVPWM	Space Vector Pulse Width Modulation
FOC	Field Oriented Control

1.3 Document Overview

The rest of document is organized as the following:

Section 1 explains Introduction.

Section 2 explains Structure of a 3-Phase PMSM and Motor Driving Principle.

Section 3 explains FOC Control.

Section 4 explains Core Modules.

Section 5 explains Mathematical Model of a 3-Phase PMSM.

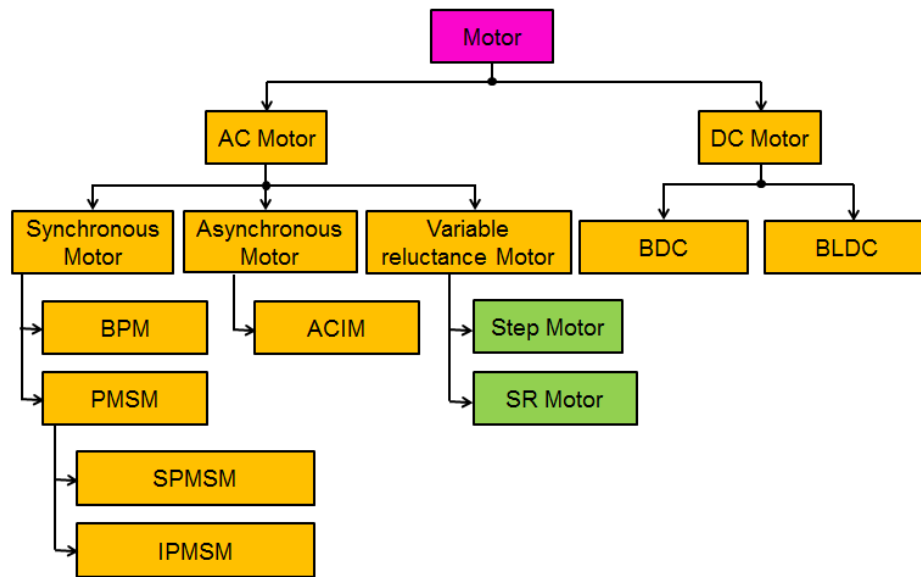
Section 6 explains Additional Information.

2 Structure of a 3-Phase PMSM and Motor Driving Principle

2.1 Motor Category

Synchronous motors can be divided into several different types. The figure below shows a simple classification tree of electric motors. In this document, the FOC control of 3-phase PMSM is to be introduced, which is highlighted with the green color in below figure.

Figure 1. Motor Category



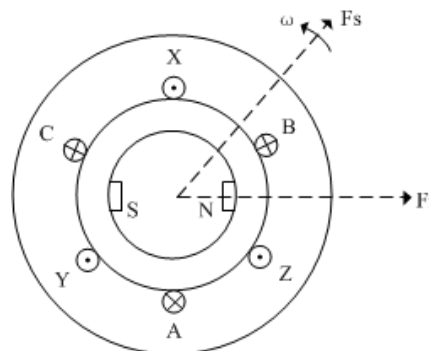
2.2 Structure of a 3-Phase PMSM

A 3-phase PMSM is mainly composed of two parts: the stator and the rotor.

At stator side, the 3-phase windings are coiled on the stator core. The windings of 3 phases are separately placed by the rule of 120 degrees angle to generate a round rotating magnetic field (F_s) when a 3-phase AC current goes through the 3-phase winding. The separated 3-phase winding placed by the rule of 120 degrees angle is named as 3-phase symmetric winding.

At rotor side, one or more pairs of permanent magnetic poles are mounted to offer a constant rotor magnetic field (F_r).

Figure 2. Structure of a 3-phase PMSM



Because F_s is a rotating magnetic field, the F_r will be dragged and follow the F_s . If the F_r cannot catch up with F_s , the rotor will rotate continuously. If the 3-phase current in 3-phase windings disappears, the F_s will disappear at the same time, and the rotor will stop.

2.3 Driving principle of 3-Phase PMSM

To keep rotor rotating, a continuous rotating stator magnetic field is necessary. Assume the 3-phase AC current can be expressed as:

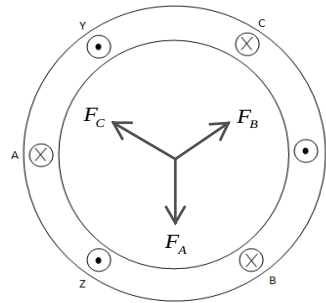
$$i_{AX} = I_m \sin(\omega t) \dots (2.3 - 1)$$

$$i_{BY} = I_m \sin(\omega t - 120^\circ) \dots (2.3 - 2)$$

$$i_{CZ} = I_m \sin(\omega t - 240^\circ) \dots (2.3 - 3)$$

The 3-phase AC current goes through stator 3-phase winding, so three magnetic fields are created. By the formula of $F = Ni$, the three magnetic fields can be expressed as:

Figure 3. Stator Magnetic Field of A 3-phase PMSM



$$F_A = F_{AX} = NI_m \sin(\omega t) \dots (2.3 - 4)$$

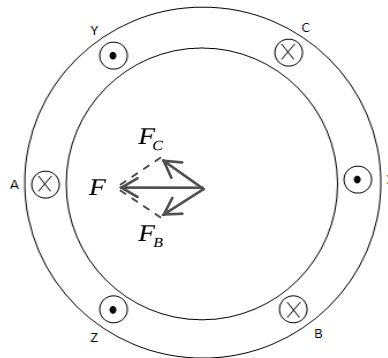
$$F_B = F_{BY} = NI_m \sin(\omega t - 120^\circ) \dots (2.3 - 5)$$

$$F_C = F_{CZ} = NI_m \sin(\omega t - 240^\circ) \dots (2.3 - 6)$$

By observing the synthesis magnetic F in different timing modes, which is combined by F_A, F_B , and F_C , it is easy to understand the rotating principle of stator magnetic field.

1. $\omega t = 0^\circ$

Figure 4. Stator Magnetic Field of a 3-Phase PMSM When $\omega t = 0^\circ$



$$F_A = F_{AX} = 0 \dots (2.3 - 7)$$

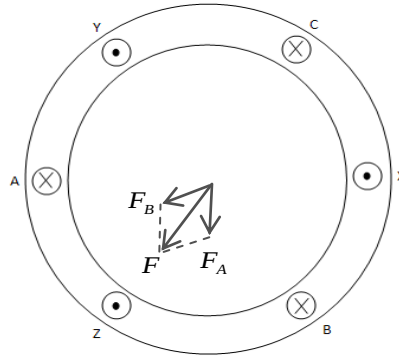
$$F_B = F_{BY} = -\frac{\sqrt{3}}{2}NI_m \dots (2.3 - 8)$$

$$F_C = F_{CZ} = \frac{\sqrt{3}}{2}NI_m \dots (2.3 - 9)$$

$$F = \frac{3}{2}NI_m, \text{ (the direction is shown in figure above) } \dots (2.3 - 10)$$

2. $\omega t = 60^\circ$

Figure 5. Stator Magnetic Field of a 3-Phase PMSM When $\omega t = 60^\circ$



$$F_A = F_{AX} = \frac{\sqrt{3}}{2}NI_m \dots (2.3 - 11)$$

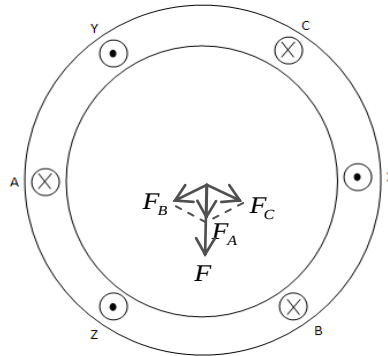
$$F_B = F_{BY} = -\frac{\sqrt{3}}{2}NI_m \dots (2.3 - 12)$$

$$F_C = F_{CZ} = 0 \dots (2.3 - 13)$$

$$F = \frac{3}{2}NI_m, \text{ (the direction is shown in figure above) } \dots (2.3 - 14)$$

3. $\omega t = 90^\circ$

Figure 6. Stator Magnetic Field of a 3-Phase PMSM When $\omega t = 90^\circ$



$$F_A = F_{AX} = NI_m \dots (2.3 - 15)$$

$$F_B = F_{BY} = -\frac{1}{2}NI_m \dots (2.3 - 16)$$

$$F_C = F_{CZ} = -\frac{1}{2}NI_m \dots (2.3 - 17)$$

$$F = \frac{3}{2}NI_m, \text{ (the direction is shown in figure above) } \dots (2.3 - 18)$$

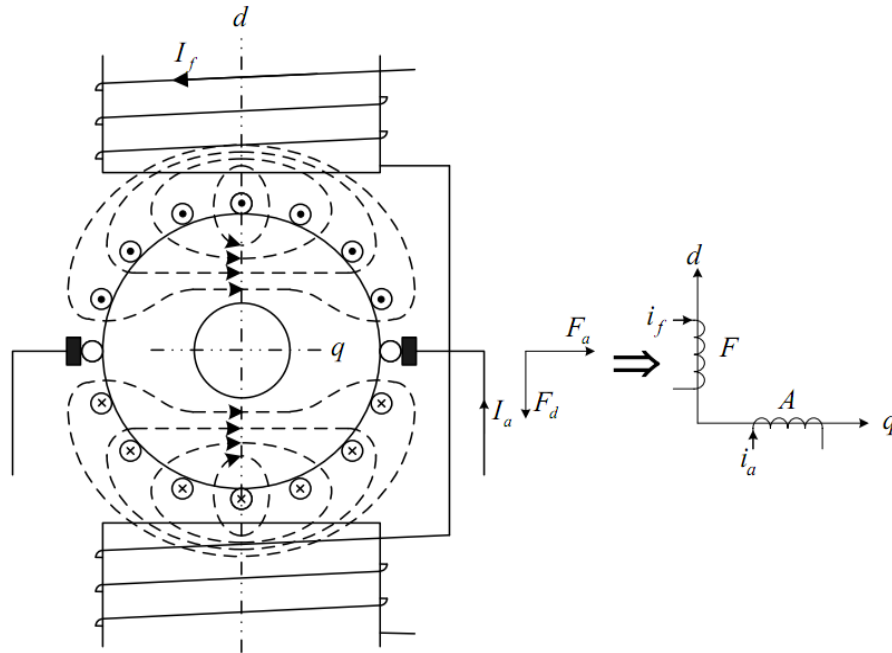
From the synthetic magnetic field F in different timing modes, it is obviously known that F is a rotating vector and furthermore the magnitude of F is a constant ($\frac{3}{2}NI_m$). Now we can get a conclusion that a round rotating magnetic field is created if a 3-phase AC current goes through a 3-phase symmetric winding.

3 FOC Control

3.1.1 FOC Principle

Brush DC motor is the conventional DC motor with a long history. A big advantage of the brush DC motor is that its torque control and magnetizing control are decoupled, which makes brush DC motor easy to control. The brush DC motor decoupled control is shown in below figure.

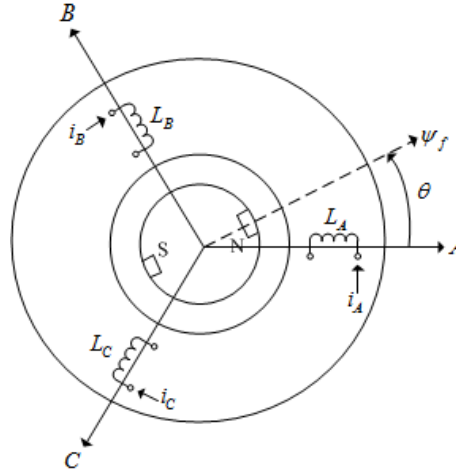
Figure 7. Brush DC Motor Decoupled Control



The magnetizing is controlled by magnetizing current (I_f), and the torque is controlled by torque current (I_a). The direction of the magnetizing magnetic field is parallel with d-axis (vertical direction), and the direction of the torque magnetic field is parallel with q-axis (horizontal direction). So these two magnetic fields do not influence each other. That is to say, it is decoupled between the 2 magnetic fields and motor's magnetizing and torque can be adjusted individually. For example, the torque control formula is $T_e = C_m \Phi I_a$, which means torque is only controlled by torque current I_a .

The condition of PMSM motor control is much more complex than a brush DC motor. The magnetic field of a 3-phase symmetry winding is a coupled magnetic field. We can discover the complex coupled relationship from the torque control formula.

Figure 8. The Coupled Magnetic Flux of A PMSM



$$T_e = \frac{1}{2} n_p [I_{ABC}]^T \frac{\partial [L_{ABC}]}{\partial \theta} [I_{ABC}] \dots (3.1.1 - 1)$$

$$[L_{ABC}] = \begin{bmatrix} L_A & M_{AB} & M_{AC} \\ M_{BA} & L_B & M_{BC} \\ M_{CA} & M_{CB} & L_C \end{bmatrix} (M \text{ is mutual inductance}), [I_{ABC}] = \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix}$$

From the expression of T_e , it is easy to understand that the torque is determined by all 3-phase inductances (including self-inductance and mutual-inductance) and currents. Obviously, the torque control seems much more complex than a brush DC motor.

Coordinate transformation is just the way to simplify the PMSM torque control. By coordinate transformation, a PMSM control model is converted from A-B-C coordinate to d-q coordinate. The torque control formula is also converted into d-q coordinate, the formula is:

$$T_e = \frac{3}{2} n_p \psi_d I_q \dots (3.1.1 - 2)$$

The simple formula in d-q coordinate makes the PMSM torque control as easy as a brush DC motor.

3.1.2 FOC Control Structure

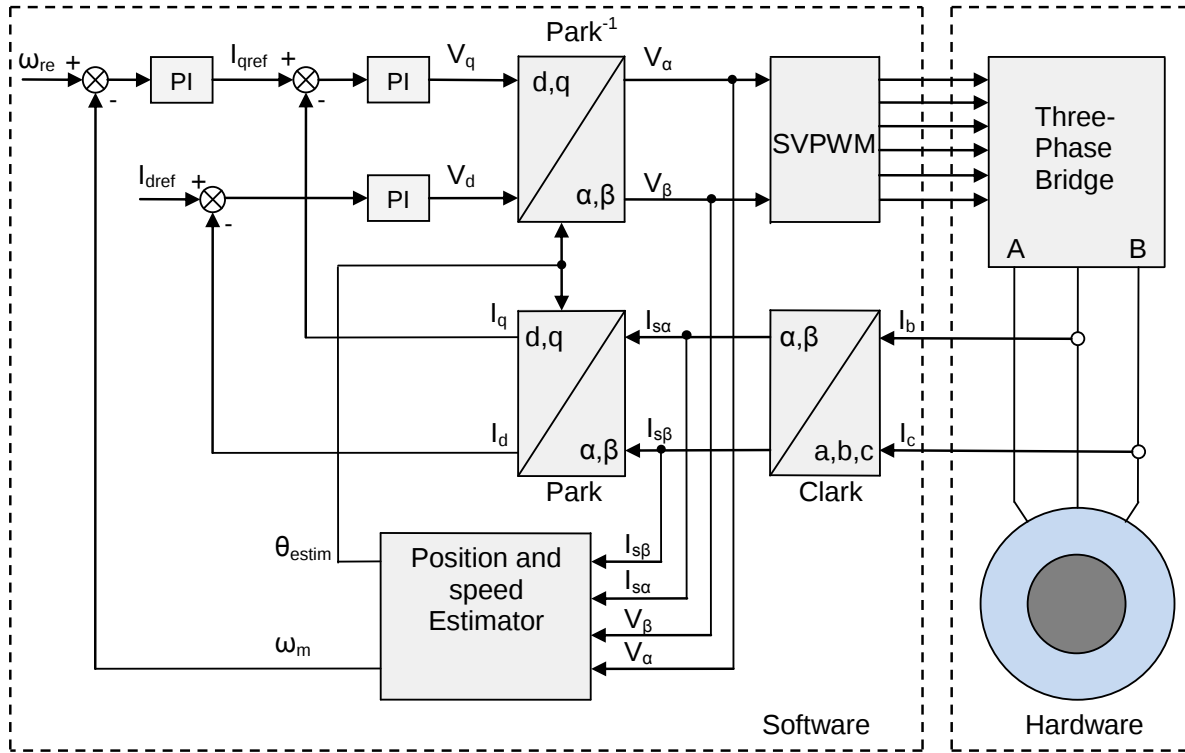
From the description above, the FOC core thinking is to make the torque control of PMSM as easy as a DC brush motor by a motor rotor magnetic field orientation technology. In the technology, the coordinate transformation method turns the motor module from the u-v-w coordinate to the rotational d-q coordinate, and the d-q coordinate rotational speed is the same as the stator magnetic field rotational speed. Then the control of a PMSM is simplified and the control performance is almost same as a DC brush motor.

Some PID regulators are added to adjust the motor output following the given input. By setting different PID parameters, system gets different dynamic and static performance.

SVPWM technology is applied to accept the driving voltage in α - β coordinate and output a set of switching instruction to control the 6 switches in full bridge inverter.

Position and speed estimator is designed to observe the real time motor speed through the motor driving voltage and current. The estimated motor speed is compared with the expected speed, and the comparison result serves as the input of the speed PI regulator. The estimated rotor position angle is used by the coordinate transformation unit.

Figure 9. FOC Control Diagram



4 Core Modules

4.1 Coordinate Transformation

The coordinate transformation includes Clark transformation and Park transformation. On the contrary, the inverse coordinate transformation includes inverse Clark transformation and inverse Park transformation.

1. Clark transformation

It changes a quantity in A-B-C coordinate to α - β coordinate.

$$\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \frac{1}{\sqrt{3}} & \frac{2}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} x_A \\ x_B \end{bmatrix} \dots (4.1 - 1)$$

2. Park transformation

It changes a quantity in α - β coordinate to d-q coordinate.

$$\begin{bmatrix} x_d \\ x_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} \dots (4.1 - 2)$$

3. Inverse Clark transformation

It changes a quantity in α - β coordinate to A-B-C coordinate.

$$\begin{bmatrix} x_A \\ x_B \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} \dots (4.1 - 3)$$

$$x_C = -x_A - x_B \dots (4.1 - 4)$$

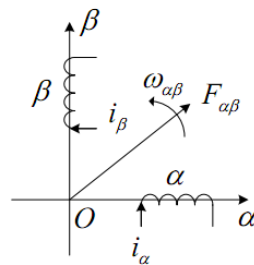
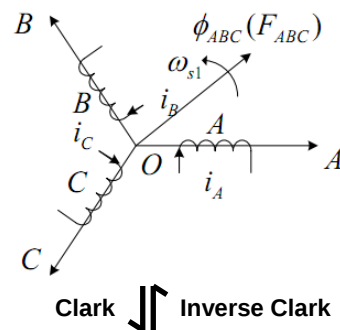
4. Inverse Park transformation

It changes a quantity in d-q coordinate to α - β coordinate.

$$\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} x_d \\ x_q \end{bmatrix} \dots (4.1 - 5)$$

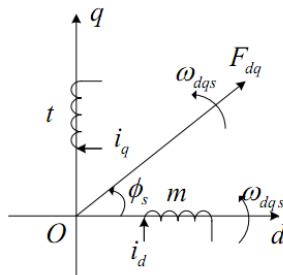
The following figures show the progress of coordinate transformation.

Figure 10. Coordinate Transformation



1. $F_{ABC}, F_{\alpha\beta}, F_{dq}$ -- Synthesis magnetic field
2. $\omega_{s1}, \omega_{\alpha\beta}, \omega_{dqs}$ -- Magnetic field rotating speed
3. $\omega_{s1} = \omega_{\alpha\beta} = \omega_{dqs}$

Park ⇄ Inverse Park



4.2 PI Regulator

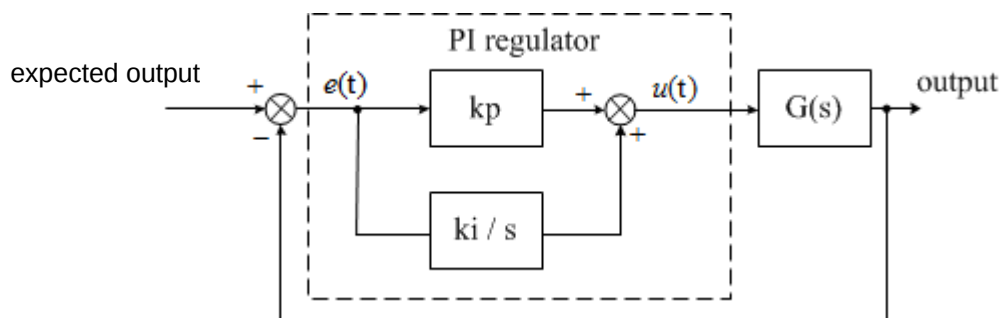
4.2.1 Introduction

The PI regulator is composed of a proportional regulator and an integral regulator, which mainly has two functions:

1. To assure a fast response when the input is changed;
2. To assure the output follows the given input.

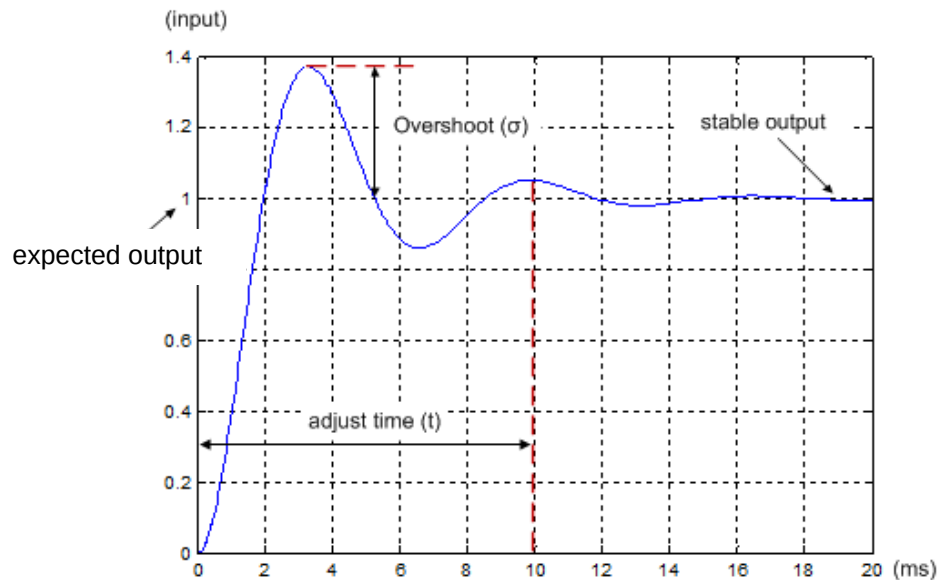
The PI regulator keeps the output follow the expected output by a comparing error between the expected output and the real output. The P-value is to make a fast output response to the comparing error, and the I-value is to decrease the stable output error. Its transfer function can be expressed as follows.

Figure 11. PI-regulator Transfer Function



PI regulator causes a fluctuating output, fluctuating amplitude is decreasing. After some regulating periods, the output follows the expected output with a very small fluctuation around the expected output value.

Figure 12. Output of PI Regulator



4.2.2 Formula

The mathematic formula of PI regulator is:

$$u(t) = k_p e(t) + k_i \int_0^t e(\tau) d\tau \dots (4.2 - 1)$$

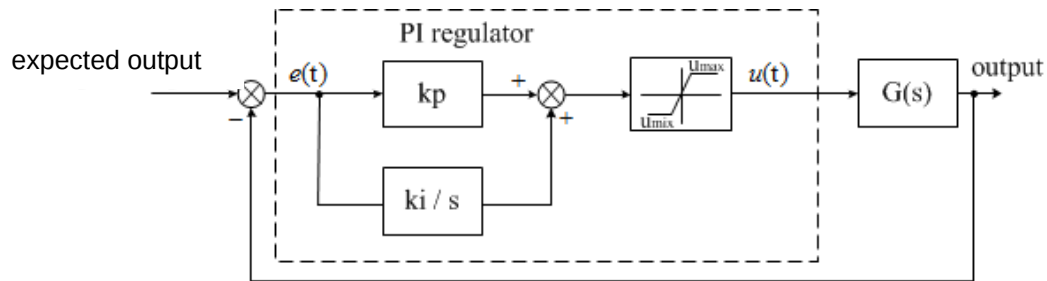
Usually the formula can be changed to the discrete field and expressed by the incremental algorithm.

$$\Delta u(k) = k_p [e(k) - e(k - 1)] + k_i e(k) \dots (4.2 - 2)$$

$$u(k) = u(k - 1) + \Delta u(k) \dots (4.2 - 3)$$

Generally, an output limitation is defined to limit the output into a legal range.

Figure 13. PI Regulator with Output Limitation



$$u(k) = u(k - 1) + \Delta u(k) \dots (4.2 - 4)$$

$$u(k) = u_{max}, \text{ if } u(k) > u_{max} \dots (4.2 - 5)$$

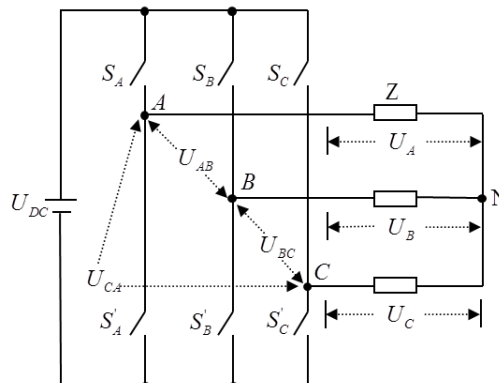
$$u(k) = u_{min}, \text{ if } u(k) < u_{min} \dots (4.2 - 6)$$

4.3 SVPWM

4.3.1 Synthesis of a Space Vector

SVPWM is a method to generate a round rotational voltage vector by controlling the status of 6 switches ($S_A, S'_A, S_B, S'_B, S_C, S'_C$) in the 3-phase full bridge inverter.

Figure 14. 3-phase Full Bridge Inverter



Below figure lists 8 switching statuses (1 – switch is closed, 0 – switch is opened) and the relative voltages.

Table 1. Eight Switching Statuses and Voltages

S_A	S_B	S_C	U_A	U_B	U_C	U_{AB}	U_{BC}	U_{CA}	Vector
0	0	0	0	0	0	0	0	0	0_{000}
1	0	0	$2U_{DC}/3$	$-U_{DC}/3$	$-U_{DC}/3$	U_{DC}	0	$-U_{DC}$	U_0
1	1	0	$U_{DC}/3$	$U_{DC}/3$	$-2U_{DC}/3$	0	U_{DC}	$-U_{DC}$	U_{60}
0	1	0	$-U_{DC}/3$	$2U_{DC}/3$	$-U_{DC}/3$	$-U_{DC}$	U_{DC}	0	U_{120}
0	1	1	$-2U_{DC}/3$	$U_{DC}/3$	$U_{DC}/3$	$-U_{DC}$	0	U_{DC}	U_{180}
0	0	1	$-U_{DC}/3$	$-U_{DC}/3$	$2U_{DC}/3$	0	$-U_{DC}$	U_{DC}	U_{240}
1	0	1	$U_{DC}/3$	$-2U_{DC}/3$	$U_{DC}/3$	U_{DC}	$-U_{DC}$	0	U_{300}
1	1	1	0	0	0	0	0	0	0_{111}

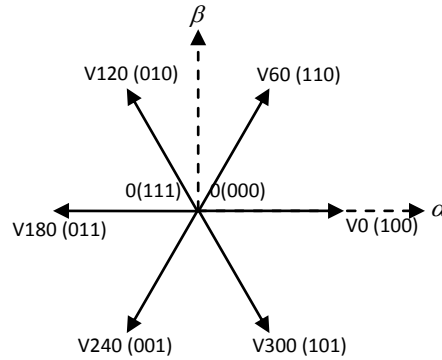
Through the Clark transformation, those voltages are equally converted to α - β coordinate.

Table 2. Voltages in α - β Coordinate

S_A	S_B	S_C	U_α	U_β	Vector
0	0	0	0	0	0_{000}
1	0	0	$2U_{DC}/3$	0	U_0
1	1	0	$U_{DC}/3$	$U_{DC}/\sqrt{3}$	U_{60}
0	1	0	$-U_{DC}/3$	$U_{DC}/\sqrt{3}$	U_{120}
0	1	1	$-2U_{DC}/3$	0	U_{180}
0	0	1	$-U_{DC}/3$	$-U_{DC}/\sqrt{3}$	U_{240}
1	0	1	$U_{DC}/3$	$-U_{DC}/\sqrt{3}$	U_{300}
1	1	1	0	0	0_{111}

Then 6 basic voltage vectors and 2 zero vectors are got.

Figure 15. Basic Voltage Vectors



Because motor is driven by a magnetic field created by the 3-phase stator winding, let's see the relationship between the voltage and the magnetic field. A winding follows below voltage-flux formula.

$$\vec{u}_s = R_s \vec{i}_s + \frac{d\vec{\psi}_s}{dt} \dots (4.3.1 - 1)$$

For the motor winding, if the motor rotational speed is not very low, the formula above can be simplified as:

$$\vec{v}_s = \frac{d\vec{\psi}_s}{dt} \dots (4.3.1 - 2)$$

So we can get:

$$\vec{\psi}_s = \int_0^t \vec{v}_s d\tau \dots (4.3.1 - 3)$$

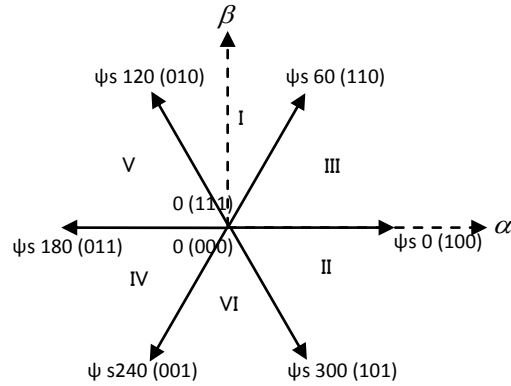
From the table of 'voltages in α - β coordinate', it is easy to know all the basic voltages vectors are constants. So the formula above can become:

$$\vec{\psi}_s = \int_0^T \vec{v}_s dt = \vec{v}_s \int_0^T dt = \vec{v}_s \times T \dots (4.3.1 - 4)$$

It means that the stator magnetic field is created by the voltage added in motor stator winding. Furthermore, a longer time of voltage applying on winding causes a bigger magnetic field.

In Figure 15, 6 basic voltage vectors divide the space into 6 numbers. It is numbered as follows (Voltage vectors are expressed as magnetic vectors).

Figure 16. Sector Numbers



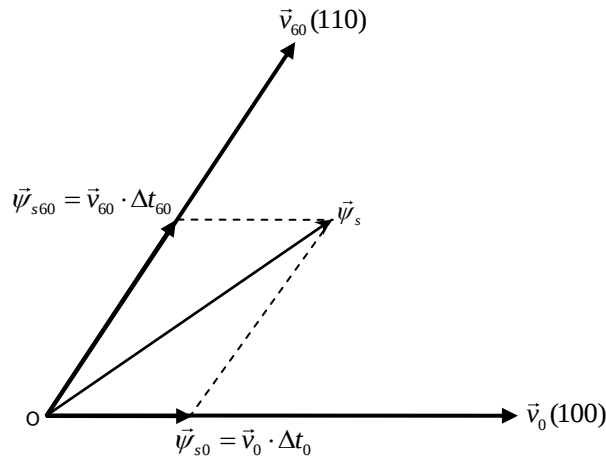
$$\vec{\psi}_k = \vec{V}_k \times T \quad (k = 0, 60, 120, 180, 240, 300) \dots (4.3.1 - 5)$$

In a control period T , if we divide the T into 3 parts: ΔT_0 (action time of V_0), ΔT_{60} (action time of V_{60}), ΔT_{null} (the zero vectors action time), a magnetic field can be expressed as:

$$\vec{\psi}_s = \vec{V}_0 \times \Delta T_0 + \vec{V}_{60} \times \Delta T_{60} = \vec{\psi}_{s0} + \vec{\psi}_{s60} + \vec{\psi}_{null} \dots (4.3.1 - 6)$$

Below figure shows the synthesis magnetic vector.

Figure 17. Vector Synthesis

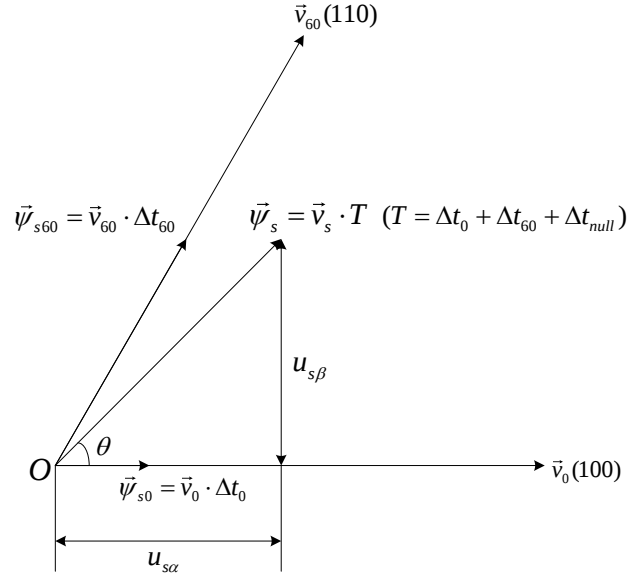


In above figure, it shows the synthesis vector in sector III. By the same way, the synthesis magnetic $\vec{\psi}_s$ of any direction in every sector can be composed of the adjacent 2 basic vectors and the zero vectors.

4.3.2 Basic Vector Conduction Time

Assuming the synthesis vector locates in the sector III, the conduction time can be calculated by the following method.

Figure 18. Conduction Time of Basic Vectors



From the table of Eight Switching Statuses and Voltages, It is easy to know the basic vector amplitude is a constant ($|\vec{v}_0| = |\vec{v}_{60}| = \frac{2}{3}V_{DC}$).

The synthesis vector $\vec{\psi}_s$ is composed of $\vec{\psi}_{s0}$ and $\vec{\psi}_{s60}$.

$$\begin{cases} |\vec{v}_s| \cdot T \cdot \cos \theta = |\vec{v}_0| \cdot \Delta t_0 \cdot \cos 0^\circ + |\vec{v}_{60}| \cdot \Delta t_{60} \cdot \cos 60^\circ \\ |\vec{v}_s| \cdot T \cdot \sin \theta = |\vec{v}_0| \cdot \Delta t_0 \cdot \sin 0^\circ + |\vec{v}_{60}| \cdot \Delta t_{60} \cdot \sin 60^\circ \\ |\vec{v}_0| = |\vec{v}_{60}| = \frac{2}{3}V_{DC} \\ u_{s\alpha} = |\vec{v}_s| \cdot T \cdot \cos \theta \\ u_{s\beta} = |\vec{v}_s| \cdot T \cdot \sin \theta \end{cases} \quad \dots (4.3.2 - 1)$$

It can be simplified as

$$\begin{cases} \frac{\Delta t_0}{T} = \frac{\frac{3}{2}u_{s\alpha} - \frac{\sqrt{3}}{2}u_{s\beta}}{V_{DC}} \\ \frac{\Delta t_{60}}{T} = \frac{\frac{\sqrt{3}}{2}u_{s\beta}}{V_{DC}} \end{cases} \quad \dots (4.3.2 - 2)$$

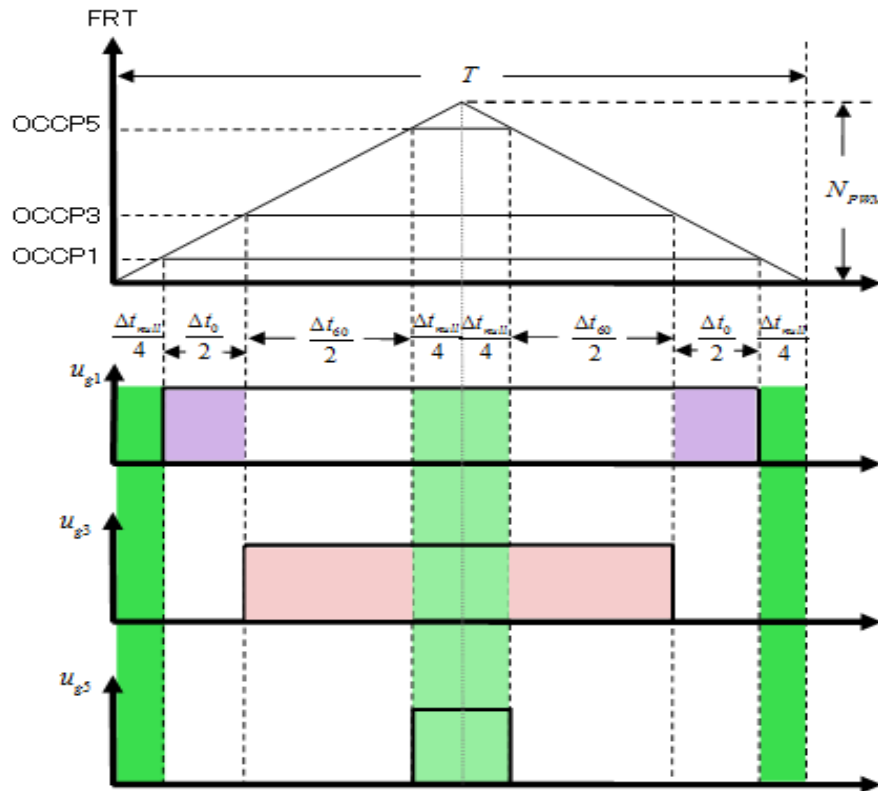
It means that the conduction time of basic vectors can be calculated from $u_{s\alpha}$, $u_{s\beta}$ and V_{dc} .

If $T > \Delta t_{60} + \Delta t_0$, the rest time is filled by the zero vectors.

For other sectors, the conduction time of basic vectors can be got similarly.

The condition time control of basic vectors can be done by the timer in MCU. Generally MCU offers an up-down counter. According to the counting value, we control the full bridge switches to assign the conduction time for each basic vector.

Figure 19. Assign the Conduction Time of Basic Vectors by an Up-down Counter



FRT is an up-down counter in FMx series MCU. Npwm is FRT's counting top value.

u_{g1} controls S_A and S'_A . OCCP1 is the u_{g1} toggle time.

u_{g3} controls S_B and S'_B . OCCP3 is the u_{g3} toggle time.

u_{g5} controls S_C and S'_C . OCCP5 is the u_{g5} toggle time.

4.3.3 Sector Number Calculation

According to the sector division, the sector number can be judged by the following table.

Table 3. Sector Number Calculation

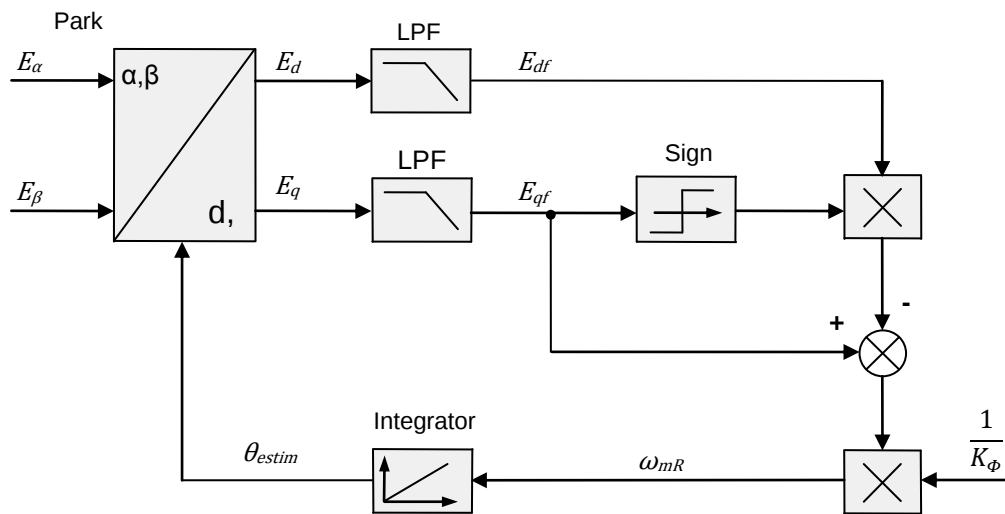
Sector	Condition
I	$v_\beta > 0, \frac{v_\beta}{ v_\alpha } > \sqrt{3}$
II	$v_\alpha > 0, v_\beta < 0, -\frac{v_\beta}{v_\alpha} < \sqrt{3}$
III	$v_\alpha > 0, v_\beta > 0, \frac{v_\beta}{v_\alpha} < \sqrt{3}$
IV	$v_\alpha < 0, v_\beta < 0, \frac{v_\beta}{v_\alpha} < \sqrt{3}$

Sector	Condition
V	$v_\alpha < 0, v_\beta > 0, -\frac{v_\beta}{v_\alpha} < \sqrt{3}$
VI	$v_\beta < 0, -\frac{v_\beta}{ v_\alpha } > \sqrt{3}$

4.4 Sensor-less Position Observer

The estimator has PLL structure. Its operating principle is based on the fact that the d-component of the Back Electromotive Force (BEMF) must be equal to zero at a steady state functioning mode. The block diagram of the estimator is presented in below figure.

Figure 20. PLL Estimator's Block Schematic



Starting from the closed loop shown in Figure 4-2, the estimated speed ($\omega_m R$) of the rotor is integrated in order to obtain the estimated angle, as shown in Equation 4.4-1:

$$\text{Equation 1: } \theta_{estim} = \int \omega_m R dt \dots (4.4 - 1)$$

The estimated speed, $\omega_m R$, is obtained by dividing the q-component of the BEMF value with the voltage constant, K_Φ , as shown in Equation 4.4-2.

$$\text{Equation 2: } \omega_m R = \frac{1}{K_\Phi} (E_{qf} - \text{sign}(E_{qf}) \cdot E_{df}) \dots (4.4 - 2)$$

Considering the initial estimation premise (the d-axis value of BEMF is zero at steady state) shown in Equation 2, the BEMF q-axis value, E_{qf} , is corrected using the d-axis BEMF value, E_{df} , depending on its sign. The BEMF d-q component's values are filtered with a first order filter, after their calculation with the Park transform, as indicated in Equation 4.4-3.

$$\text{Equation 3: } \begin{cases} E_d = E_\alpha \cos(\theta_{estim}) + E_\beta \sin(\theta_{estim}) \\ E_q = E_\beta \cos(\theta_{estim}) - E_\alpha \sin(\theta_{estim}) \end{cases} \dots (4.4 - 3)$$

With the fixed stator frame, Equation 4.4-4 represents the stators circuit equations.

$$\text{Equation 4: } \begin{cases} E_\alpha = V_\alpha - R_s I_\alpha - L_s \frac{dI_\alpha}{dt} \\ E_\beta = V_\beta - R_s I_\beta - L_s \frac{dI_\beta}{dt} \end{cases} \dots (4.4 - 4)$$

In Equation 4, the terms containing $\alpha - \beta$ were obtained from the three-phase system's corresponding measurements through Clarke transform. L_s and R_s represent the stator inductance and resistance per phase respectively, considering Y (star) connected stator phases. If the motor is Δ (delta) connected, the equivalent Y connection phase resistance and inductance should be calculated and used in the equations above.

5 Mathematical Model of a 3-Phase PMSM

FOC is a control theory based on coordinate transformation. In the d-q coordinate, the PMSM mathematical model can be described as below.

$$v_d = R_s i_d + \frac{d\psi_d}{dt} - \omega_r \psi_q \dots (5-1)$$

$$v_q = R_s i_q + \frac{d\psi_q}{dt} + \omega_r \psi_d \dots (5-2)$$

$$T_e = \frac{3}{2} n_p (\psi_d i_q - \psi_q i_d) \dots (5-3)$$

$$\psi_d = L_d i_d + \lambda_m \dots (5-4)$$

$$\psi_q = L_q i_q \dots (5-5)$$

Where,

v_d – voltage of d axis

v_q – voltage of q axis

i_d – current of d axis

i_q – current of q axis

L_d – inductance of d axis

L_q – inductance of q axis

ψ_d – magnetic linkage of d axis

ψ_q – magnetic linkage of q axis

R_s – motor stator phase resistor

ω_r – rotor rotational speed

λ_m – permanent magnetic linkage of rotor

n_p – pole pairs

In FOC method, it always keeps i_d to zero so that the motor mathematical model can be simplified in the steady status.

$$v_d = \frac{d\psi_d}{dt} - \omega_r \psi_q \dots (5-6)$$

$$v_q = R_s i_q + \frac{d\psi_q}{dt} + \omega_r \psi_d \dots (5-7)$$

$$T_e = \frac{3}{2} n_p \psi_d i_q \dots (5-8)$$

$$\psi_d = \lambda_m \dots (5-9)$$

$$\psi_q = L_q i_q \dots (5-10)$$

From the equation above, the following results can be deduced:

1. The magnetic exciting is independently determined by the permanent magnetic linkage (λ_m);
2. Torque is independently determined by the current on q axis (i_q);

So we can adjust only the current on q axis (i_q) to control the torque which determines the motor rotational speed.

6 Additional Information

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

www.cypress.com/cypress-microcontrollers

Document History

Document Title: AN204469 - FM3 Family 3-Phase PMSM FOC Control

Document Number: 002-04469

Revision	ECN	Orig. of Change	Submission Date	Description of Change
**	—	SHEY	02/26/2015	Initial release
*A	5232902	SHEY	04/21/2016	Migrated Spansion Application Note from FM3_ AN709-00015-1v0-E to Cypress format
*B	5795967	AESATMP8	07/03/2017	Updated logo and Copyright.

Worldwide Sales and Design Support

Cypress maintains a worldwide network of offices, solution centers, manufacturer's representatives, and distributors. To find the office closest to you, visit us at [Cypress Locations](#).

Products

ARM® Cortex® Microcontrollers	cypress.com/arm
Automotive	cypress.com/automotive
Clocks & Buffers	cypress.com/clocks
Interface	cypress.com/interface
Internet of Things	cypress.com/iot
Memory	cypress.com/memory
Microcontrollers	cypress.com/mcu
PSoC	cypress.com/psoc
Power Management ICs	cypress.com/pmic
Touch Sensing	cypress.com/touch
USB Controllers	cypress.com/usb
Wireless Connectivity	cypress.com/wireless

PSoC® Solutions

[PSoC 1](#) | [PSoC 3](#) | [PSoC 4](#) | [PSoC 5LP](#) | [PSoC 6](#)

Cypress Developer Community

[Forums](#) | [WICED IOT Forums](#) | [Projects](#) | [Videos](#) | [Blogs](#) | [Training](#) | [Components](#)

Technical Support

cypress.com/support

All other trademarks or registered trademarks referenced herein are the property of their respective owners.



© Cypress Semiconductor Corporation, 2014-2017. This document is the property of Cypress Semiconductor Corporation and its subsidiaries, including Spanion LLC ("Cypress"). This document, including any software or firmware included or referenced in this document ("Software"), is owned by Cypress under the intellectual property laws and treaties of the United States and other countries worldwide. Cypress reserves all rights under such laws and treaties and does not, except as specifically stated in this paragraph, grant any license under its patents, copyrights, trademarks, or other intellectual property rights. If the Software is not accompanied by a license agreement and you do not otherwise have a written agreement with Cypress governing the use of the Software, then Cypress hereby grants you a personal, non-exclusive, nontransferable license (without the right to sublicense) (1) under its copyright rights in the Software (a) for Software provided in source code form, to modify and reproduce the Software solely for use with Cypress hardware products, only internally within your organization, and (b) to distribute the Software in binary code form externally to end users (either directly or indirectly through resellers and distributors), solely for use on Cypress hardware product units, and (2) under those claims of Cypress's patents that are infringed by the Software (as provided by Cypress, unmodified) to make, use, distribute, and import the Software solely for use with Cypress hardware products. Any other use, reproduction, modification, translation, or compilation of the Software is prohibited.

TO THE EXTENT PERMITTED BY APPLICABLE LAW, CYPRESS MAKES NO WARRANTY OF ANY KIND, EXPRESS OR IMPLIED, WITH REGARD TO THIS DOCUMENT OR ANY SOFTWARE OR ACCOMPANYING HARDWARE, INCLUDING, BUT NOT LIMITED TO, THE IMPLIED WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE. To the extent permitted by applicable law, Cypress reserves the right to make changes to this document without further notice. Cypress does not assume any liability arising out of the application or use of any product or circuit described in this document. Any information provided in this document, including any sample design information or programming code, is provided only for reference purposes. It is the responsibility of the user of this document to properly design, program, and test the functionality and safety of any application made of this information and any resulting product. Cypress products are not designed, intended, or authorized for use as critical components in systems designed or intended for the operation of weapons, weapons systems, nuclear installations, life-support devices or systems, other medical devices or systems (including resuscitation equipment and surgical implants), pollution control or hazardous substances management, or other uses where the failure of the device or system could cause personal injury, death, or property damage ("Unintended Uses"). A critical component is any component of a device or system whose failure to perform can be reasonably expected to cause the failure of the device or system, or to affect its safety or effectiveness. Cypress is not liable, in whole or in part, and you shall and hereby do release Cypress from any claim, damage, or other liability arising from or related to all Unintended Uses of Cypress products. You shall indemnify and hold Cypress harmless from and against all claims, costs, damages, and other liabilities, including claims for personal injury or death, arising from or related to any Unintended Uses of Cypress products.

Cypress, the Cypress logo, Spanion, the Spanion logo, and combinations thereof, WICED, PSoC, CapSense, EZ-USB, F-RAM, and Traveo are trademarks or registered trademarks of Cypress in the United States and other countries. For a more complete list of Cypress trademarks, visit cypress.com. Other names and brands may be claimed as property of their respective owners.