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3-Phase PM Synchronous Motor Vector Control using DSP56F80x

Design of Motor Control Application Based on Motorola's Software Development Kit

Libor Prokop, Pavel Grasblum
Motorola Czech System Laboratories

1. Introduction of Application Benefit

This Application Note describes the design of a 3-phase Permanent Magnet (PM) synchronous motor drive based on Motorola's DSP56F80x dedicated motor control device. The software design takes advantage of the SDK (Software Development Kit) developed by Motorola.

PM synchronous motors are very popular in a wide application area. The PM synchronous motor lacks a commutator and is therefore more reliable than the DC motor. The PM synchronous motor also has advantages when compared to an AC induction motor. Because a PM synchronous motor achieves higher efficiency by generating the rotor magnetic flux with rotor magnets, a PM synchronous motors is used in high-end white goods (such as refrigerators, washing machines, dishwashers); high-end pumps; fans; and in other appliances which require high reliability and efficiency.

The concept of the application is a speed closed-loop PM synchronous drive using a Vector Control technique. It serves as an example of a PM synchronous motor control design using a Motorola DSP with SDK support. It also illustrates the use of the SDK's dedicated motor control libraries.

This Application Note includes basic motor theory, system design concept, hardware implementation and software design, including the PC master software visualization tool.

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2. Motorola DSP Advantages and Features

The Motorola DSP56F80x family is well suited for digital motor control, combining the DSP's calculation capability with the MCU's controller features on a single chip. These DSPs offer many dedicated peripherals, such as Pulse Width Modulation (PWM) module(s), an Analog-to-Digital Converter (ADC), Timers, communication peripherals (SCI, SPI, CAN), on-board Flash and RAM.

As an example, one member of the family, the DSP56F805, provides the following peripheral blocks:

- Two Pulse Width Modulator modules (PWMA & PWMB), each with 6 PWM outputs, 3 Current Sense inputs, and 4 Fault inputs; fault tolerant design with deadtime insertion, supporting both center- and edge-aligned modes
- Twelve-bit Analog-to-Digital Converters (ADCs), supporting 2 simultaneous conversions with dual 4-pin multiplexed inputs; the ADC can be synchronized by PWM modules
- Two Quadrature Decoders (Quad Dec0 & Quad Dec1), each with 4 inputs, or 2 additional Quad Timers A & B
- Two dedicated General Purpose Quad Timers totaling 6 pins: Timer C with 2 pins and Timer D with 4 pins
- CAN 2.0 A/B Module with 2-pin ports used to transmit and receive
- Two Serial Communication Interfaces (SCI0 & SCI1), each with 2 pins, or 4 additional GPIO lines
- Serial Peripheral Interface (SPI), with configurable 4-pin port, or 4 additional GPIO lines
- Computer Operating Properly (COP) timer
- Two dedicated external interrupt pins
- Fourteen dedicated General Purpose I/O (GPIO) pins, 18 multiplexed GPIO pins
- External reset pin for hardware reset
- JTAG/On-Chip Emulation (OnCE)
- Software-programmable, Phase Lock Loop-based frequency synthesizer for the DSP core clock

Table 2-1. Memory Configuration

	DSP56F801	DSP56F803	DSP56F805	DSP56F807
Program Flash	8188 x 16-bit	32252 x 16-bit	32252 x 16-bit	61436 x 16-bit
Data Flash	2K x 16-bit	4K x 16-bit	4K x 16-bit	8K x 16-bit
Program RAM	1K x 16-bit	512 x 16-bit	512 x 16-bit	2K x 16-bit
Data RAM	1K x 16-bit	2K x 16-bit	2K x 16-bit	4K x 16-bit
Boot Flash	2K x 16-bit	2K x 16-bit	2K x16-bit	2K x 16-bit

In addition to the fast Analog-to-Digital converter and the 16-bit Quadrature Timers, the most interesting peripheral, from the PM synchronous motor control point of view, is the Pulse Width Modulation (PWM) module. The PWM module offers a high degree of freedom in its configuration, allowing efficient control of the PM synchronous motor.

The PWM has the following features:

- Three complementary PWM signal pairs, or 6 independent PWM signals
- Features of complementary channel operation
- Deadtime insertion
- Separate top and bottom pulse width correction via current status inputs or software
- Separate top and bottom polarity control
- Edge-aligned or center-aligned PWM signals
- 15 bits of resolution
- Half-cycle reload capability
- Integral reload rates from 1 to 16
- Individual software-controlled PWM outputs
- Mask and swap of PWM outputs
- Programmable fault protection
- Polarity control
- 20mA current sink capability on PWM pins
- Write-protectable registers

The PM synchronous motor control utilizes the PWM block set in the complementary PWM mode, permitting generation of control signals for all switches of the power stage with inserted deadtime. The PWM block generates three sinewave outputs mutually shifted by 120 degrees.

The Analog-to-Digital Converter (ADC) consists of a digital control module and two analog sample and hold (S/H) circuits. ADC features:

- 12-bit resolution
- Maximum ADC clock frequency is 5MHz with 200ns period
- Single conversion time of 8.5 ADC clock cycles (8.5 x 200 ns = 1.7µs)
- Additional conversion time of 6 ADC clock cycles (6 x 200 ns = 1.2µs)
- Eight conversions in 26.5 ADC clock cycles (26.5 x 200 ns = 5.3µs) using simultaneous mode
- ADC can be synchronized to the PWM via the sync signal
- Simultaneous or sequential sampling
- Internal multiplexer to select 2 of 8 inputs
- Ability to sequentially scan and store up to 8 measurements
- Ability to simultaneously sample and hold 2 inputs
- Optional interrupts at end of scan, if an out-of-range limit is exceeded, or at zero crossing
- Optional sample correction by subtracting a preprogrammed offset value
- Signed or unsigned result
- Single-ended or differential inputs

The application utilizes the ADC block in simultaneous mode and sequential scan. It is synchronized with PWM pulses. This configuration allows the simultaneous conversion within the required time of required analog values, of all phase currents, voltage and temperature.

The Quadrature Timer is an extremely flexible module, providing all required services relating to time events. It has the following features:

- Each timer module consists of four 16-bit counters/timers
- Count up/down
- Counters are cascadable
- Programmable count modulo
- Maximum count rate equals peripheral clock/2 when counting external events
- Maximum count rate equals peripheral clock when using internal clocks
- Count once or repeatedly
- Counters are preloadable
- Counters can share available input pins
- Each counter has a separate prescaler
- Each counter has capture and compare capability

The PM synchronous motor vector control application utilizes four channels of the Quadrature Timer module for position and speed sensing. A fifth channel of the Quadrature Timer module is set to generate a time base for speed sensing and a speed controller.

The Quadrature Decoder is a module providing decoding of position signals from a Quadrature Encoder mounted on a motor shaft. It has the following features:

- Includes logic to decode quadrature signals
- Configurable digital filter for inputs
- 32-bit position counter
- 16-bit position difference counter
- Maximum count frequency equals the peripheral clock rate
- Position counter can be initialized by software or external events
- Preloadable 16-bit revolution counter
- Inputs can be connected to a general purpose timer to aid low speed velocity.

The PM synchronous motor vector control application utilizes the Quadrature Decoder connected to Quad Timer module A. It uses the decoder's digital input filter to filter the encoder's signals, but does not make use of its decoding functions, freeing the decoder's digital processing capabilities to be used by another application.

3. Target Motor Theory

3.1 Permanent Magnet Synchronous Motor

The PM synchronous motor is a rotating electric machine with a classic 3-phase stator like that of an induction motor; the rotor has surface-mounted permanent magnets (see **Figure 3-1**).

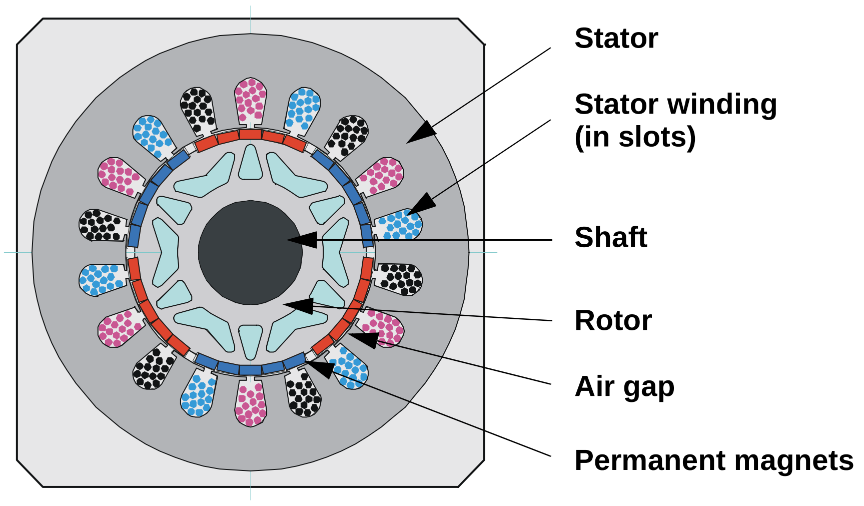


Figure 3-1. PM Synchronous Motor - Cross Section

In this respect, the PM synchronous motor is equivalent to an induction motor, where the air gap magnetic field is produced by a permanent magnet, so the rotor magnetic field is constant. PM synchronous motors offer a number of advantages in designing modern motion control systems. The use of a permanent magnet to generate substantial air gap magnetic flux makes it possible to design highly efficient PM motors.

3.2 Mathematical Description of PM Synchronous Motor

The model used for vector control design can be understood by using space vector theory. The three-phase motor quantities (such as voltages, currents, magnetic flux, etc.) are expressed in terms of complex space vectors. Such a model is valid for any instantaneous variation of voltage and current and adequately describes the performance of the machine under both steady-state and transient operation. The complex space vectors can be described using only two orthogonal axes. We can look at the motor as a two-phase machine. Using a two-phase motor model reduces the number of equations and simplifies the control design.

3.2.1 Space Vector Definition

Assume i_{sa}, i_{sb}, i_{sc} are the instantaneous balanced three-phase stator currents:

$$i_{sa} + i_{sb} + i_{sc} = 0 \qquad \text{(EQ 3-1.)}$$

Then we can define the stator current space vector as follows:

$$\bar{i}_s = k(i_{sa} + a i_{sb} + a^2 i_{sc}) \qquad \text{(EQ 3-2.)}$$

where a and a^2 are the spatial operators, $a = e^{j2\pi/3}$, $a^2 = e^{j4\pi/3}$ and k is the transformation constant, chosen as $k=2/3$. Figure 3-2 shows the stator current space vector projection:

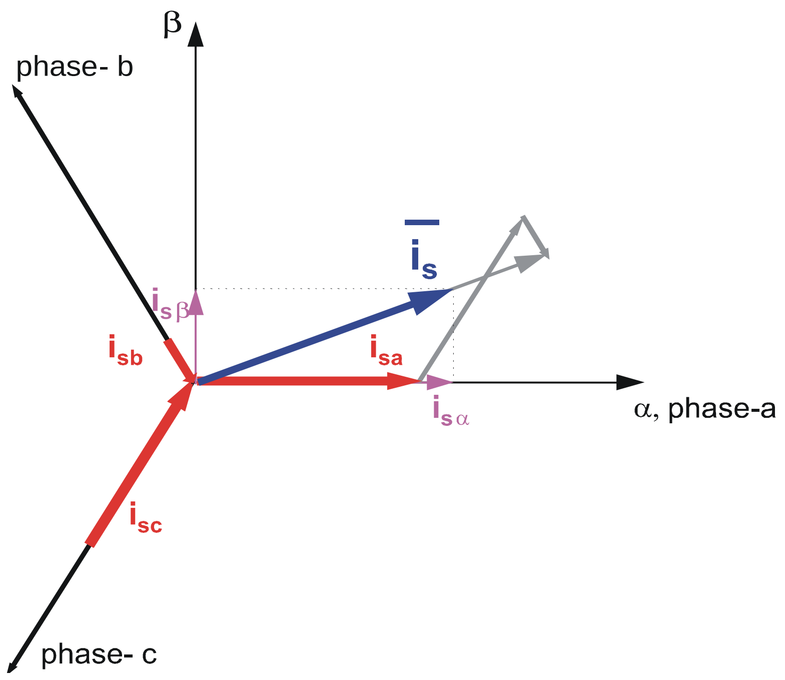


Figure 3-2. Stator Current Space Vector and Its Projection

The space vector defined by **(EQ 3-2.)** can be expressed utilizing two-axis theory. The real part of the space vector is equal to the instantaneous value of the direct-axis stator current component, $i_{s\alpha}$, and whose imaginary part is equal to the quadrature-axis stator current component, $i_{s\beta}$. Thus, the stator current space vector, in the stationary reference frame attached to the stator can be expressed as:

$$\bar{i}_s = i_{s\alpha} + j i_{s\beta} \qquad \text{(EQ 3-3.)}$$

In symmetrical three-phase machines, the direct and quadrature axis stator currents $i_{s\alpha}$, $i_{s\beta}$ are fictitious quadrature-phase (two-phase) current components, which are related to the actual three-phase stator currents as follows:

$$i_{s\alpha} = k\left(i_{sa} - \frac{1}{2}i_{sb} - \frac{1}{2}i_{sc}\right) \qquad \text{(EQ 3-4.)}$$

$$i_{s\beta} = k\frac{\sqrt{3}}{2}(i_{sb} - i_{sc}) \qquad \text{(EQ 3-5.)}$$

where $k=2/3$ is a transformation constant.

The space vectors of other motor quantities (voltages, currents, magnetic fluxes etc.) can be defined in the same way as the stator current space vector.

For a description of the PM synchronous motor, the symmetrical three-phase smooth-air-gap machine with sinusoidally-distributed windings is considered. The voltage equations of stator in the instantaneous form can then be expressed as:

$$u_{SA} = R_S i_{SA} + \frac{d}{dt}\psi_{SA} \tag{EQ 3-6.}$$

$$u_{SB} = R_S i_{SB} + \frac{d}{dt}\psi_{SB} \tag{EQ 3-7.}$$

$$u_{SC} = R_S i_{SC} + \frac{d}{dt}\psi_{SC} \tag{EQ 3-8.}$$

where u_{SA}, u_{SB} and u_{SC} are the instantaneous values of stator voltages, i_{SA}, i_{SB} and i_{SC} are the instantaneous values of stator currents, and ψ_{SA}, ψ_{SB}, ψ_{SC} are instantaneous values of stator flux linkages, in phase SA, SB and SC.

Due to the large number of equations in the instantaneous form, the equations **(EQ 3-6.)**, **(EQ 3-7.)** and **(EQ 3-8.)**, it is more practical to rewrite the instantaneous equations using two axis theory (Clarke transformation). The PM synchronous motor can be expressed as:

$$u_{S\alpha} = R_S i_{S\alpha} + \frac{d}{dt}\Psi_{S\alpha} \tag{EQ 3-9.}$$

$$u_{S\beta} = R_S i_{S\beta} + \frac{d}{dt}\Psi_{S\beta} \tag{EQ 3-10.}$$

$$\Psi_{S\alpha} = L_S i_{S\alpha} + \Psi_M \cos(\Theta_r) \tag{EQ 3-11.}$$

$$\Psi_{S\beta} = L_S i_{S\beta} + \Psi_M \sin(\Theta_r) \tag{EQ 3-12.}$$

$$\frac{d\omega}{dt} = \frac{p}{J}\left[\frac{3}{2}p(\Psi_{S\alpha} i_{S\beta} - \Psi_{S\beta} i_{S\alpha}) - T_L\right] \tag{EQ 3-13.}$$

where:	
α,β	is the stator orthogonal coordinate system
$u_{S\alpha,\beta}$	is the stator voltage
$i_{S\alpha,\beta}$	is the stator current
$\Psi_{S\alpha,\beta}$	is the stator magnetic flux
Ψ_M	is the rotor magnetic flux
R_S	is the stator phase resistance
L_S	is the stator phase inductance
ω / ω_F	is the electrical rotor speed / fields speed
p	is the number of poles per phase
J	is the inertia
T_L	is the load torque
Θ_r	is the rotor position in α,β coordinate system

The equations **(EQ 3-9.)** through **(EQ 3-13.)** represent the model of PM synchronous motor in the stationary frame α, β fixed to the stator.

Besides the stationary reference frame attached to the stator, motor model voltage space vector equations can be formulated in a general reference frame, which rotates at a general speed ω_g. If a general reference frame is used, with direct and quadrature axes x,y rotating at a general instantaneous speed $\omega_g = d\theta_g/dt$, as shown in **Figure 3-3**, where θ_g is the angle between the direct axis of the stationary reference frame (α) attached to the stator and the real axis (x) of the general reference frame, then **(EQ 3-14.)** defines the stator current space vector in general reference frame:

$$\overline{i_{sg}} = \bar{i}_s e^{-j\theta_g} = i_{sx} + j i_{sy} \qquad \text{(EQ 3-14.)}$$

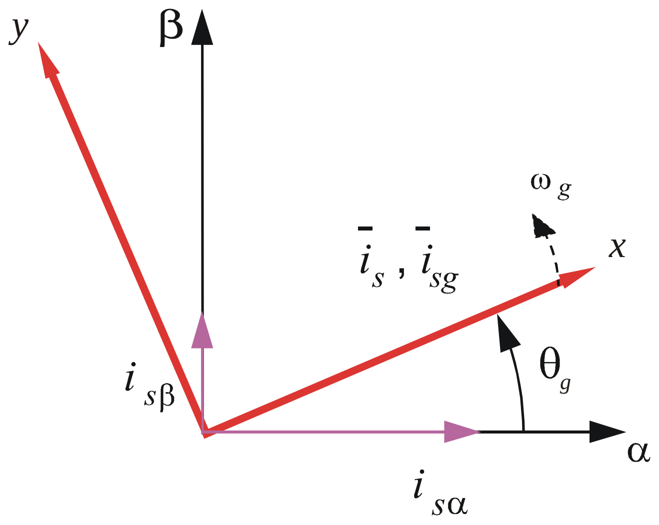


Figure 3-3. Application of the General Reference Frame

The stator voltage and flux-linkage space vectors can be similarly obtained in the general reference frame.

Similar considerations hold for the space vectors of the rotor voltages, currents and flux linkages. The real axis (rα) of the reference frame attached to the rotor is displaced from the direct axis of the stator reference frame by the rotor angle θ_r. Since it can be seen that the angle between the real axis (x) of the general reference frame and the real axis of the reference frame rotating with the rotor (rα) is θ_g-θ_r, in the general reference frame, the space vector of the rotor currents can be expressed as:

$$\overline{i_{rg}} = \bar{i}_r e^{-j(\theta_g - \theta_r)} = i_{rx} + j i_{ry} \qquad \text{(EQ 3-15.)}$$

where $\bar{i}_r$ is the space vector of the rotor current in the rotor reference frame.

The space vectors of the rotor voltages and rotor flux linkages in the general reference frame can be similarly expressed.

The motor model voltage equations in the general reference frame can be expressed by utilizing introduced transformations of the motor quantities from one reference frame to the general reference frame. The PM synchronous motor model is often used in vector control algorithms. The aim of vector control is to implement control schemes which produce high dynamic performance and are similar to those used to control DC machines. To achieve this, the reference frames may be aligned with the stator flux-linkage space vector, the rotor flux-linkage space vector or the magnetizing space vector. The most popular reference frame is the reference frame attached to the rotor flux linkage space vector, with direct axis (*d*) and quadrature axis (*q*).

After transformation into *d-q* coordinates, the motor model as follows:

$$u_{Sd} = R_S i_{Sd} + \frac{d}{dt}\Psi_{Sd} - \omega_F \Psi_{Sq} \qquad \text{(EQ 3-16.)}$$

$$u_{Sq} = R_S i_{Sq} + \frac{d}{dt}\Psi_{Sq} + \omega_F \Psi_{Sd} \qquad \text{(EQ 3-17.)}$$

$$\Psi_{Sd} = L_S i_{Sd} + \Psi_M \qquad \text{(EQ 3-18.)}$$

$$\Psi_{Sq} = L_S i_{Sq} \qquad \text{(EQ 3-19.)}$$

$$\frac{d\omega}{dt} = \frac{p}{J}\left[\frac{3}{2}p(\Psi_{Sd} i_{Sq} - \Psi_{Sq} i_{Sd}) - T_L\right] \qquad \text{(EQ 3-20.)}$$

By considering that below base speed $i_{sd}=0$, the equation **(EQ 3-20.)** can be reduced to the following form:

$$\frac{d\omega}{dt} = \frac{p}{J}\left[\frac{3}{2}p(\Psi_M i_{Sq}) - T_L\right] \qquad \text{(EQ 3-21.)}$$

From the equation **(EQ 3-21.)**, it can be seen that the torque is dependent and can be directly controlled by the current i_{sq} only.

3.3 Digital Control of PM Synchronous Motor

In adjustable-speed applications, the PM synchronous motors are powered by inverters. The inverter converts DC power to AC power at the required frequency and amplitude. The typical 3-phase inverter is illustrated in **Figure 3-4.**

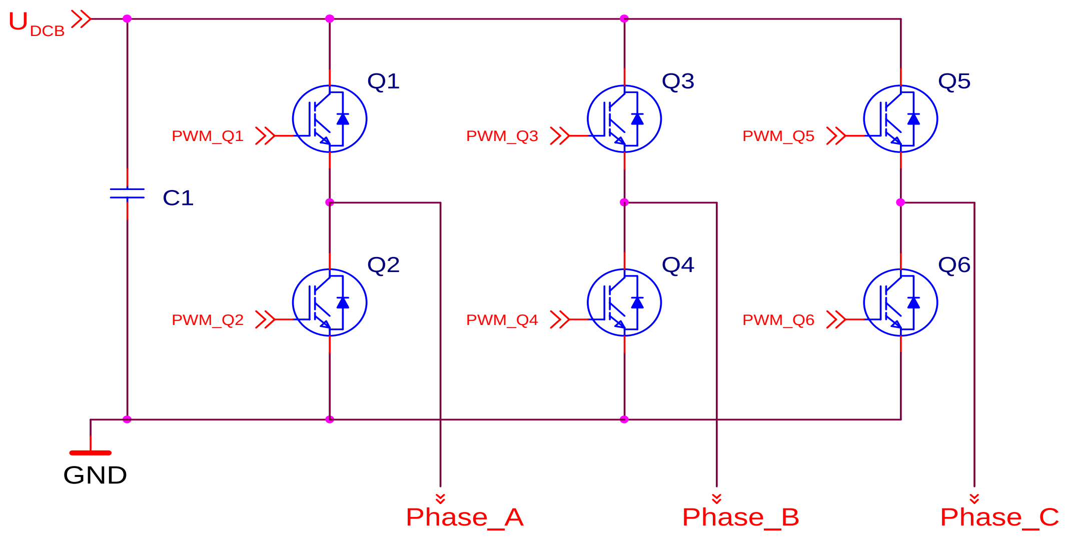


Figure 3-4. 3- Phase Inverter

The inverter consists of three half-bridge units where the upper and lower switches are controlled complementarily, meaning when the upper one is turned on, the lower one must be turned off, and vice versa. Because the power device's turn off time is longer than its turn on time, some deadtime must be inserted between the turn off of one transistor of the half-bridge, and the turn on of its complementary device. The output voltage is mostly created by a pulse width modulation (PWM) technique, where an isosceles triangle carrier wave is compared with a fundamental-frequency sine modulating wave, and the natural points of intersection determine the switching points of the power devices of a half bridge inverter. This technique is shown in **Figure 3-5**. The 3-phase voltage waves are shifted 120^{o} to each other and, thus, a 3-phase motor can be supplied.

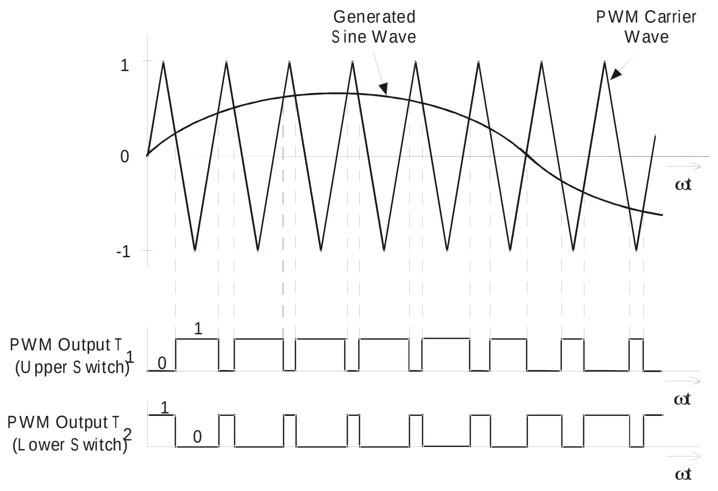


Figure 3-5. Pulse Width Modulation

The most popular power devices for motor control applications are Power MOSFETs and IGBTs.

A Power MOSFET is a voltage-controlled transistor. It is designed for high-frequency operation and has a low voltage drop; thus, it has low power losses. However, the saturation temperature sensitivity limits the MOSFET application in high-power applications.

An insulated-gate bipolar transistor (IGBT) is a bipolar transistor controlled by a MOSFET on its base. The IGBT requires low drive current, has fast switching time, and is suitable for high switching frequencies. The disadvantage is the higher voltage drop of a bipolar transistor, causing higher conduction losses.

3.3.1 Vector Control of PM Synchronous Motor

Vector Control is an elegant control method of a PM synchronous motor, where field-oriented theory is used to control space vectors of magnetic flux, current, and voltage. It is possible to set up the coordinate system to decompose the vectors into a magnetic field-generating part and a torque-generating part. The structure of the motor controller (Vector Control controller) is then almost the same as for a separately-excited DC motor, which simplifies the control of PM synchronous motor. This Vector Control technique was developed specifically to achieve a similarly dynamic performance in PM synchronous motors.

As explained in **Section 4.2**, we chose a widely used speed control with inner current closed-loop, where the rotor flux is controlled by a field-weakening controller.

In this method, we must break down the field-generating and torque-generating parts of the stator current to be able to separately control the magnetic flux and the torque. In order to do so, we need to set up the rotary coordinate system connected to the rotor magnetic field; this system is generally called a “d-q coordinate system”. Very high CPU performance is needed to perform the transformation from rotary to stationary coordinate systems. Therefore, the Motorola DSP56F80x is very well suited for use in a Vector Control algorithm. All transformations which are needed for Vector Control will be described in the next section.

3.3.2 Block Diagram of Vector Control

Figure 3-6 shows the basic structure of Vector Control of the PM synchronous motor. To perform Vector Control, follow these steps:

- Measure the motor quantities (phase voltages and currents)
- Transform them into the two-phase system (α,β) using Clarke transformation
- Calculate the rotor flux space vector magnitude and position angle
- Transform stator currents into the d-q coordinate system using Park transformation
- The stator current torque- (i_{sq}) and flux- (i_{sd}) producing components are controlled separately by the controllers
- The output stator voltage space vector is calculated using the decoupling block
- The stator voltage space vector is transformed back from the d-q coordinate system into the two-phase system and fixed with the stator by inverse Park transformation
- Using sinewave modulation, the output 3-phase voltage is generated

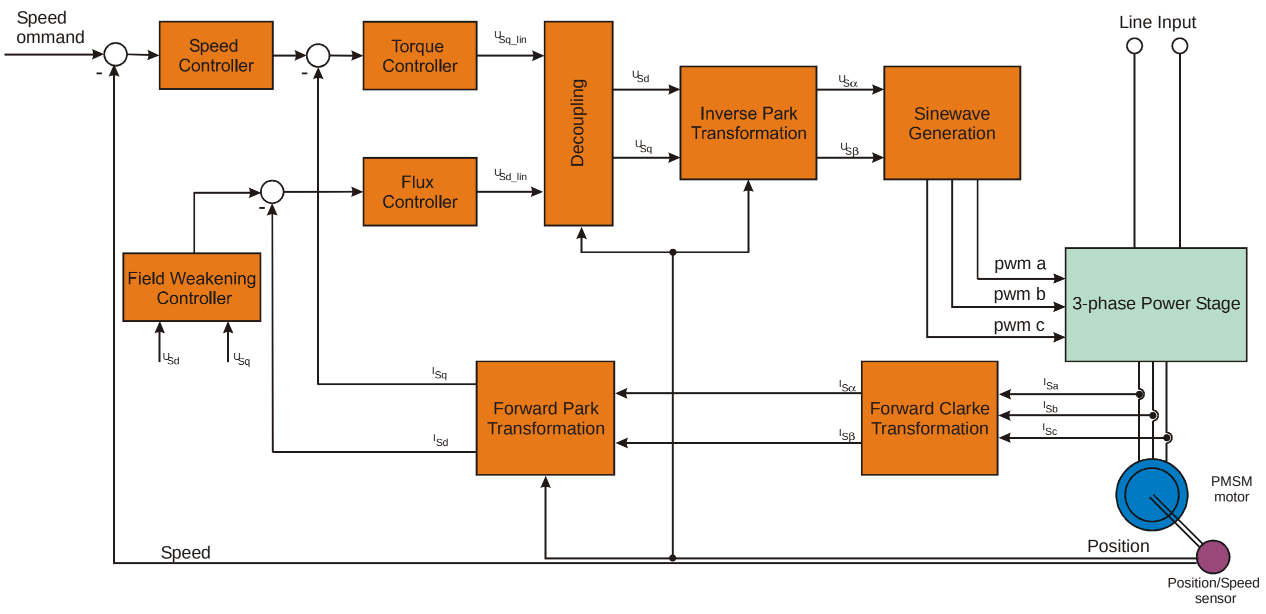


Figure 3-6. Block Diagram of PM Synchronous Motor Vector Control

3.3.3 Vector Control Transformations

Transforming the PM synchronous motor into a DC motor is based on points of view. As shown in **Section 3.3.2**, a coordinate transformation is required.

The following transformations are involved in Vector Control:

- Transformations from a 3-phase to a 2-phase system (Clarke transformation)
- Rotation of orthogonal system
  - — α,β to d-q (Park transformation)
  - — d-q to α,β (Inverse Park transformation)

3.3.3.1 Clarke Transformation

Figure 3-7. shows how the three-phase system is transformed into a two-phase system.

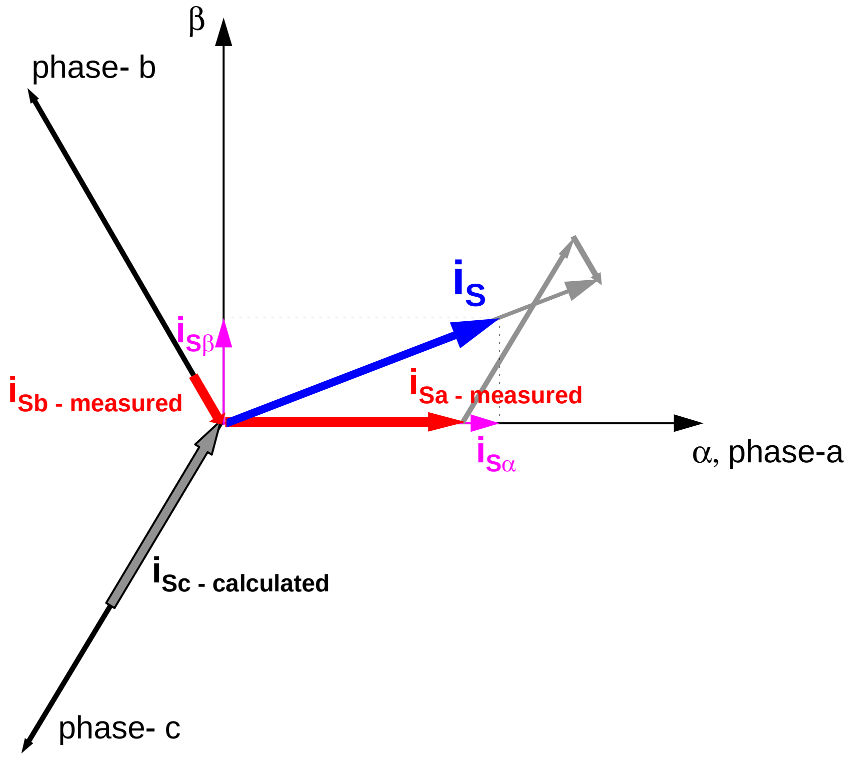


Figure 3-7. Clarke Transformation

To transfer the graphical representation into mathematical language:

$$\begin{bmatrix}\alpha\\ \beta\end{bmatrix} = K\begin{bmatrix}1 & -\frac{1}{2} & -\frac{1}{2}\\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}\end{bmatrix}\begin{bmatrix}a\\ b\\ c\end{bmatrix} \quad \text{(EQ 3-22.)}$$

In most cases, the 3-phase system is symmetrical, which means that the sum of the phase quantities is always zero.

$$\alpha = K\left(a - \frac{1}{2}b - \frac{1}{2}c\right) = |\ a + b + c = 0\ | = K\frac{3}{2}a \quad \text{(EQ 3-23.)}$$

The constant "*K*" can be freely chosen and equalizing the α-quantity and a-phase quantity is recommended. Then:

$$\alpha = a \ \Rightarrow\ K = \frac{2}{3} \quad \text{(EQ 3-24.)}$$

We can fully define the Park-Clarke transformation:

$$\begin{bmatrix}\alpha\\ \beta\end{bmatrix} = \begin{bmatrix}\frac{2}{3} & -\frac{1}{3} & -\frac{1}{3}\\ 0 & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}}\end{bmatrix}\begin{bmatrix}a\\ b\\ c\end{bmatrix} = |\ a + b + c = 0\ | = \begin{bmatrix}1 & 0 & 0\\ 0 & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}}\end{bmatrix}\begin{bmatrix}a\\ b\\ c\end{bmatrix} \quad \text{(EQ 3-25.)}$$

3.3.3.2 Transformation from α,β to d-q Coordinates and Backwards

Vector Control is performed entirely in the d-q coordinate system to make the control of PM synchronous motors elegant and easy; see **Section 3.3.2**.

Of course, this requires transformation in both directions and the control action must be transformed back to the motor side.

First, establish the d-q coordinate system:

$$\Psi_M = \sqrt{\Psi_{M\alpha} + \Psi_{M\beta}} \quad \text{(EQ 3-26.)}$$

$$\sin\vartheta_{Field} = \frac{\Psi_{M\beta}}{\Psi_{Md}}$$
$$\cos\vartheta_{Field} = \frac{\Psi_{M\alpha}}{\Psi_{Md}} \quad \text{(EQ 3-27.)}$$

Then transform from α,β to d-q coordinates:

$$\begin{bmatrix}d\\ q\end{bmatrix} = \begin{bmatrix}\cos\vartheta_{Field} & \sin\vartheta_{Field}\\ -\sin\vartheta_{Field} & \cos\vartheta_{Field}\end{bmatrix}\begin{bmatrix}\alpha\\ \beta\end{bmatrix} \quad \text{(EQ 3-28.)}$$

Figure 3-8. illustrates this transformation.

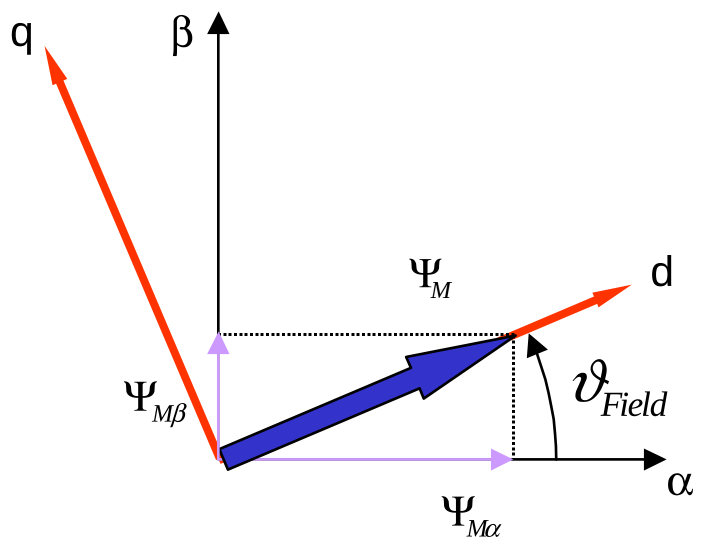


Figure 3-8. Establishing the d-q Coordinate System (Park Transformation)

The backward (Inverse Park) transformation (from d-q to α,β) is:

$$\begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \begin{bmatrix} \cos\vartheta_{Field} & -\sin\vartheta_{Field} \\ \sin\vartheta_{Field} & \cos\vartheta_{Field} \end{bmatrix} \begin{bmatrix} d \\ q \end{bmatrix} \qquad \text{(EQ 3-29.)}$$

3.3.4 PMSM Vector Control and Field-Weakening Controller

This section describes the control regarding the required stator current vectors i_{sd}, i_{sq}.

There are two speed ranges (shown in **Figure 3-9**), which differ by controlled current vector:

- Control in Normal Operating Range is a control mode for a speed required below nominal motor speed
- Control in Field-Weakening Range is a control mode for a speed required above nominal motor speed

3.3.4.1 Control in Normal Operating Range

Assume an ideal PM synchronous motor with constant stator reluctance, L_s = const. The equations **(EQ 3-17.)**, **(EQ 3-18.)** and **(EQ 3-19.)** can then be written as:

$$u_{Sq} = R_S i_{Sq} + L_S \frac{d}{dt} i_{Sq} + \omega_F (L_S i_{Sd} + \Psi_M) \qquad \text{(EQ 3-30.)}$$

As demonstrated from PM synchronous motor equations, the maximum efficiency of the ideal PM synchronous motor is obtained when maintaining the current flux-producing component i_{sd} at zero. Therefore, in the drive from **Figure 3-6**, the Field-Weakening Controller sets $i_{sd} = 0$ in the normal operating range. The speed regulator controls the current torque-producing component i_{sq}.

A real 3-phase power inverter has voltage and current rating limitations:

1. The absolute value of stator voltage u_s is physically limited according to DCBus voltage to *u_sdq_max* limit
2. The absolute value of the stator current i_s should be maintained below a limit of *I_SDQ_MAX* given by the maximum current rating

In the normal operating range, the current torque-producing component i_{sq} can be set up to *I_SDQ_MAX*, since $i_{sd} = 0$.

Due to the voltage limitation, the maximum speed in the normal motor operating range is limited for $i_{sd} = 0$, to a nominal motor speed as shown in **Figure 3-9** and **(EQ 3-30.)**.

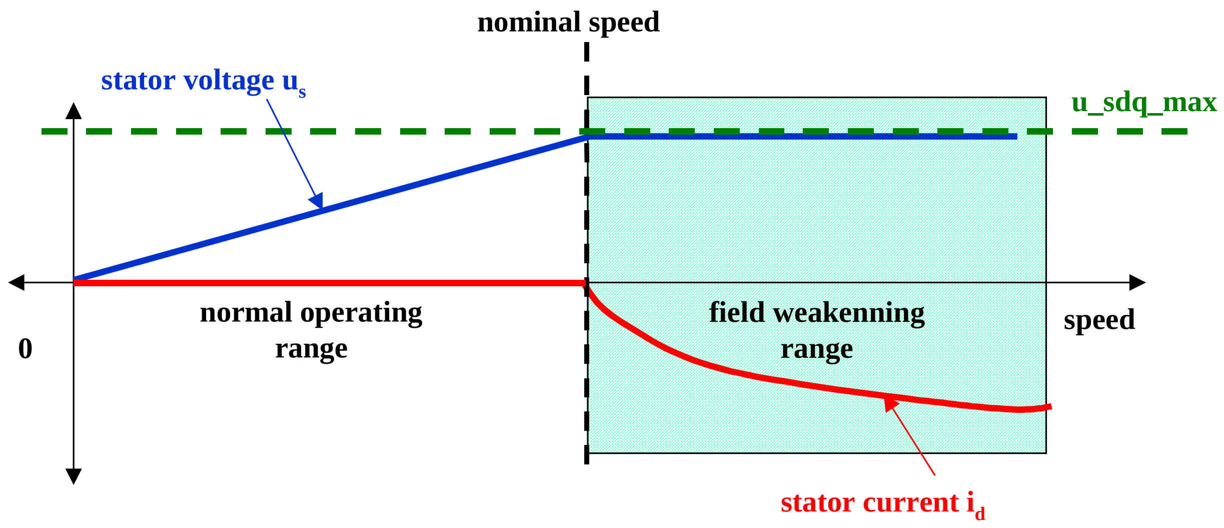


Figure 3-9. Normal Operation and Field-Weakening

3.3.4.2 Control in Field-Weakening Range

Where a higher maximum motor speed is required, the field-weakening technique must be used. That is provided by maintaining the flux-producing current component i_{sd}, in the field-weakening range, as shown in **Figure 3-9**.

Due to the limitation of absolute current value, the current torque-producing component i_{sq}, then must be maintained below a limited value.

$$i_{Sq} < \sqrt{\mathrm{I\_SDQ\_MAX}^2 - i_{Sd}^2} \qquad \text{(EQ 3-31.)}$$

One possibility to maintain the flux-producing current component i_{sd} for field weakening is to use a look-up table.

A more-progressive method uses a Field-Weakening Controller, which generates a negative current flux-producing component i_{sq}, whenever the absolute value of stator voltage exceeds *u_S_max_FWLimit*. The field-weakening limit *u_S_max_FWLimit* is set to be close to the maximum voltage limit of the 3-phase power inverter *u_sdq_max* with some reserve for regulation. Since the DCBus voltage determines the *u_sdq_max* limit, the *u_S_max_FWLimit* is set according to the DCBus. The *u_S_max_FWLimit* can be a constant or it can be calculated from a measured DCBus voltage. The Field-Weakening controller is described in **Section 6.2.5.4**.

4. System Concept

4.1 System Specification

The motor control system is designed to drive a 3-phase PM synchronous motor in a speed closed-loop. The application meets the following performance specifications:

- Vector control of PM motor using the quadrature encoder as a position sensor
- Targeted for DSP56F80xEVM
- Running on a 3-phase PM synchronous motor control development platform at variable line voltage 110 - 230V AC
- Control technique incorporates:
  - Vector Control with speed closed-loop and field-weakening
  - Rotation in both directions
  - Motoring and generator mode with brake
  - Start from any motor position with rotor alignment
  - Minimum speed of **50**rpm
  - Maximum speed of **3000**rpm at input power line 230V AC
  - Maximal speed of **1500**rpm at input power line 115V AC
- Manual interface (Start/Stop switch, Up/Down push button control, LED indicator)
- PC master software control interface (motor start/stop, speed set-up)
- PC master software remote monitor
- Power stage board identification
- Overvoltage, undervoltage, overcurrent and overheating fault protection

The PM synchronous drive introduced here is designed to power a high-voltage PM synchronous motor with a quadrature encoder. It has the following specifications:

Table 1: High Voltage Hardware Set Specifications

Motor Characteristics:	Motor Type	6 poles, 3-phase, star connected, BLDC motor
	Speed Range	2500rpm (at 310V DCBus)
	Maximum Electrical Power:	150 W
	Phase Voltage	3*220V
	Phase Current	0.55A

Table 1: High Voltage Hardware Set Specifications (Continued)

Drive Characteristics:	Speed Range	< 3000rpm
	Input Voltage	310V DC
	Maximum DCBus Voltage	380V
	Control Algorithm	Speed Closed-Loop Control
	Optoisolation	Required

4.2 Vector Control Drive Concept

A standard system concept is used with this drive; see **Figure 4-1**. The system incorporates the following hardware parts:

- Three-phase PM synchronous motor high-voltage development platform
- Feedback sensors for:
  - — Position (quadrature encoder)
  - — DCBus voltage
  - — Phase currents
  - — DCBus overcurrent detection
  - — Temperature
- Three DSP56F80x Evaluation Modules:
  - — DSP56F803EVM
  - — DSP56F805EVM
  - — DSP56F807EVM

The drive can be controlled in two different operational modes:

In the **Manual** operational mode, the required speed is set by the Start/Stop switch and the Up/Down push buttons.

In the **PC master software** operational mode, the required speed and Start/Stop switch are set by the PC.

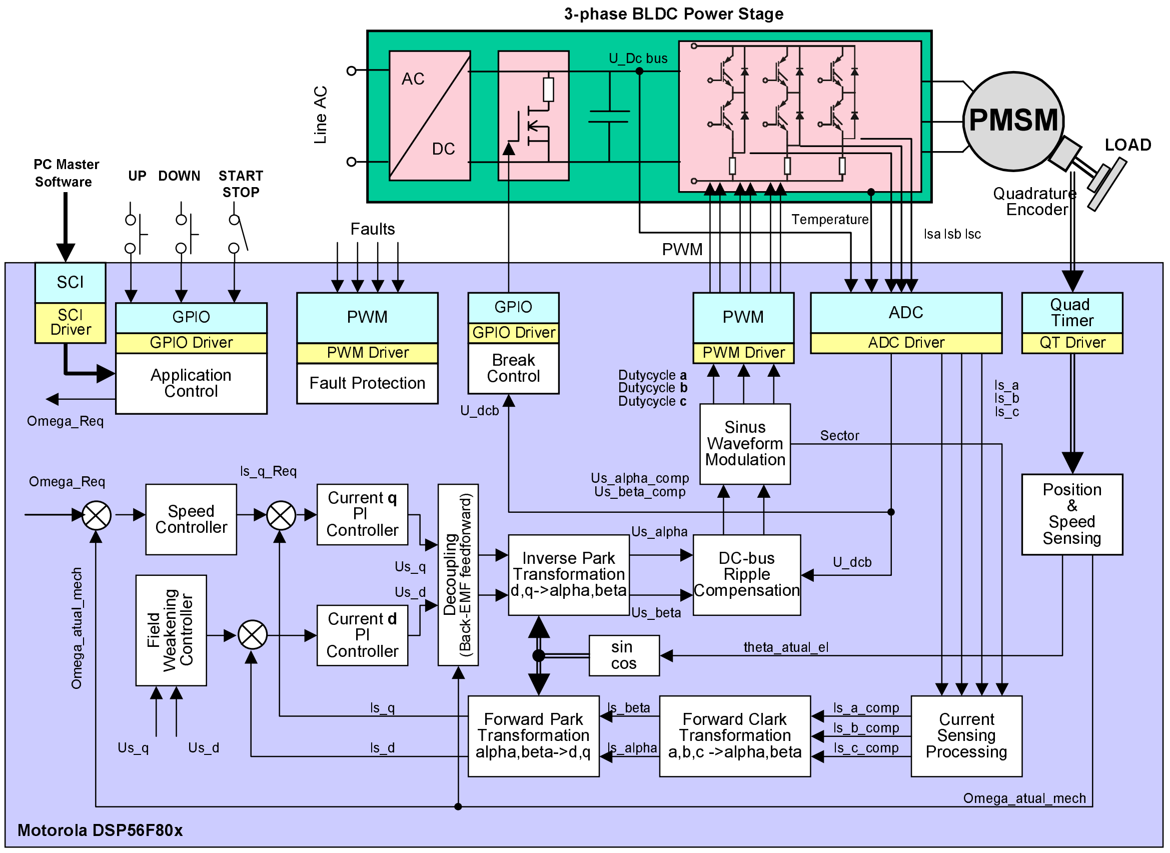


Figure 4-1. Drive Concept

The **control process** is as follows:

When the Start command is accepted (using the Start/Stop Switch or PC master software command), the required speed is calculated according to the Up/Down push buttons or PC master software commands. The required speed proceeds through an acceleration/deceleration ramp, and a reference command is put to the speed controller. The actual speed is calculated from the pulses of the quadrature encoder. The comparison between the required speed command and the actual measured speed generates a speed error. Based on the error, the speed controller generates a current, *Is_qReq*, which corresponds to torque. A second part of stator current *Is_dReq*, which corresponds to flux, is given by the Field-Weakening Controller. Simultaneously, the stator currents *Is_a*, *Is_b*, and *Is_c* are measured and transformed from instantaneous values into the stationary reference frame α, β, and consecutively into the rotary reference frame d-q (Park - Clarke transformation). Based on the errors between required and actual currents in the rotary reference frame, the current controllers generate output voltages *Us_q* and *Us_d* (in the rotary reference frame d-q). The voltages *Us_q* and *Us_d* are transformed back into the stationary reference frame α, β and, after DCBus ripple elimination, are recalculated to the 3-phase voltage system, which is applied to the motor.

Beside the main control loop, the DCBus voltage, DCBus current and power stage temperature are measured during the control process. They are used for overvoltage, undervoltage, overcurrent and overheating protection of the drive. The undervoltage and overheating protection is performed by software, while the overcurrent and overvoltage fault signal utilizes a fault input of the DSP.

If any of the previously-mentioned faults occur, the motor control PWM outputs are disabled in order to protect the drive, and the fault state of the system is displayed by the on-board LED.

A hardware error is also detected if the wrong power stage is used. Each power stage contains a simple module generating a logic sequence unique for that type of power stage. During chip initialization, this sequence is read and evaluated according to the decoding table. If the correct power stage is identified, the program can continue. In the case of wrong hardware, the program stays in an infinite loop, displaying the fault condition.

4.3 System Blocks Concept

4.3.1 Position and Speed Sensing

All members of Motorola’s DSP56F80x family, except the DSP56F801 device , have a quadrature decoder. This peripheral is commonly used for position and speed sensing. The quadrature decoder position counter counts up/down each edge of Phase A and Phase B signals according to their order. On each revolution, the position counter is cleared by an index pulse; see **Figure 4-2**.

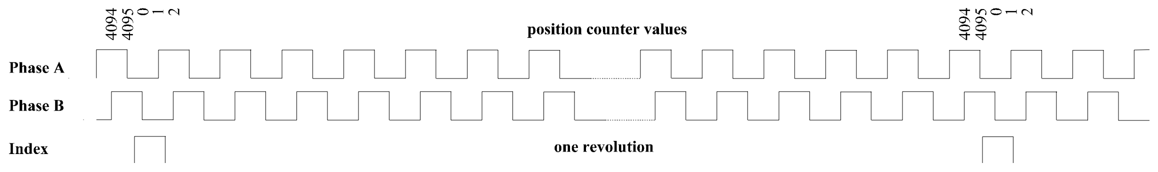


Figure 4-2. Quadrature Encoder Signals

This means that the zero position is linked with the index pulse, but Vector Control requires the zero position, where the rotor is aligned to the *d* axis; see **Section 4.3.1.3**. Therefore, using a quadrature decoder to decode the encoder’s signal requires either the calculation of an offset which aligns the quadrature decoder position counter with the aligned rotor position (zero position), or the coupling of the zero rotor position with the index pulse of a quadrature encoder. To avoid the calculation of the rotor position offset, the quadrature decoder is not used in this application. The decoder’s digital processing capabilities are then free to be used by another application and the application presented can then run on the DSP56F801, which lacks a quadrature decoder.

In addition to the quadrature decoder, the input signals (Phase A, Phase B and Index) are connected to quad timer module A. The quad timer module consists of four quadrature timers. Due to the wide variability of quad timer modules, it is possible to use this module to decode quadrature encoder signals, sense position, and speed. A configuration of the quad timer module is shown in **Figure 4-3**.

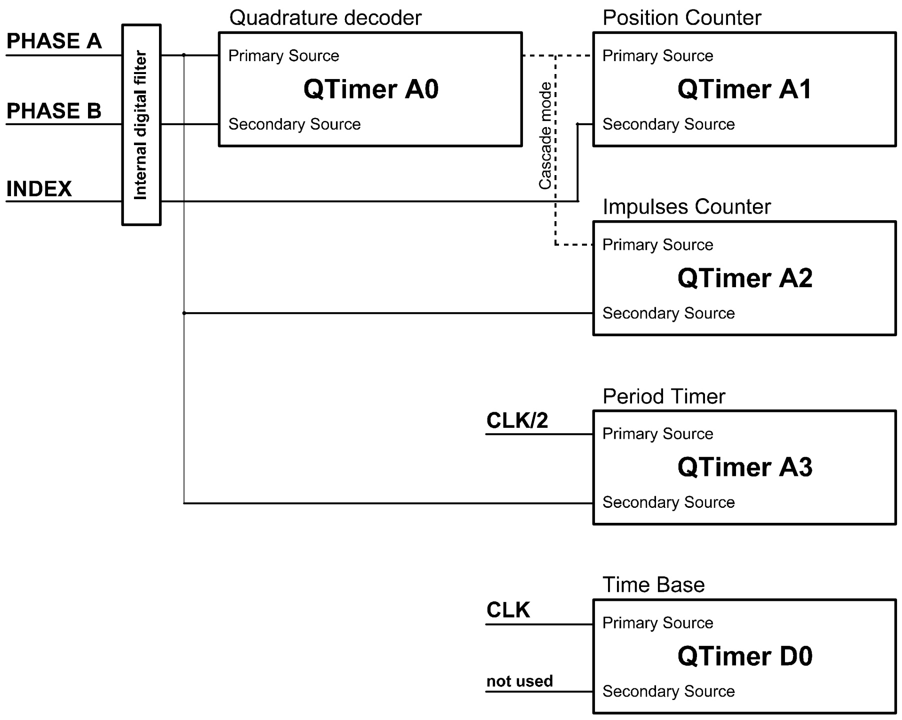


Figure 4-3. Quad Timer Module A Configuration

4.3.1.1 Position Sensing

The position and speed sensing algorithm uses all of the timers in module A and an additional timer as a time base. Timers A0 and A1 are used for position sensing. Timer A0 permits connection of three input signals to the quadrature timer A1, even if timer A1 has only two inputs (primary and secondary), accomplished by using timer A0 as a quadrature decoder only. It is set to count in the quadrature mode, count to zero, and then reinitialize. This timer setting is used to decode quadrature signals only. Timer A1 is connected to timer A0 in cascade mode. In this mode, the information about counting up/down is connected internally to timer A1; thus, the secondary input of timer A1 is free to be used for the index pulse. The counter A1 is set to count to +/- ((4*number of pulses per revolution) - 1) and reinitialize after compare. The value of the timer A1 corresponds to the rotor position.

The position of the index pulse is sensed to avoid the loss of some pulses under the influence of noise during extended motor operation, which can result in incorrect rotor position sensing. If some pulses are lost, a different position of the index pulse is detected, and a position sensing error is signaled. If a check of the index pulse is not required, timer A1 can be removed and timer A0 set as the position counter A1. The resulting value of timer A1 is scaled to range <-1; 1), which corresponds to <-π; π).

4.3.1.2 Speed Sensing

There are two common ways to measure speed. The first method measures the time between two following edges of quadrature encoder, and the second method measures a position difference (a number of pulses) per constant period. The first method is used at low speed. At the moment when the measured period is very short, the speed calculation algorithm switches to the second method.

The proposed algorithm combines both methods. The algorithm simultaneously measures the number of quadrature encoder pulses per constant period, and an accurate time interval between the first and last pulse is counted during that constant period. The speed can then be expressed as:

$$speed = \frac{k \cdot N}{T}$$

(EQ 4-1.)

where:

speed	calculated speed
k	scaling constant
N	number of pulses per constant period
T	accurate period of *N* pulses

The algorithm requires two timers for counting pulses and measuring their period, and a third timer as a time base; see **Figure 4-3**. Timer A2 counts the pulses of the quadrature encoder, and timer A3 counts a system clock divided by 2. The values in both timers can be captured by each edge of the Phase A signal. The time base is provided by timer D0, which is set to call the speed processing algorithm every 900μs. An explanation of how the speed processing algorithm works follows.

First, the new captured values of both timers are read. The difference in the number of pulses and their accurate time interval are calculated from actual and previous values. The new values are then saved for the next period, and the capture register is enabled. From that moment, the first edge of Phase A signal captures the values of both timers (A2, A3) and the capture register is disabled. This process is repeated on each call of the speed processing algorithm; see **Figure 4-4**.

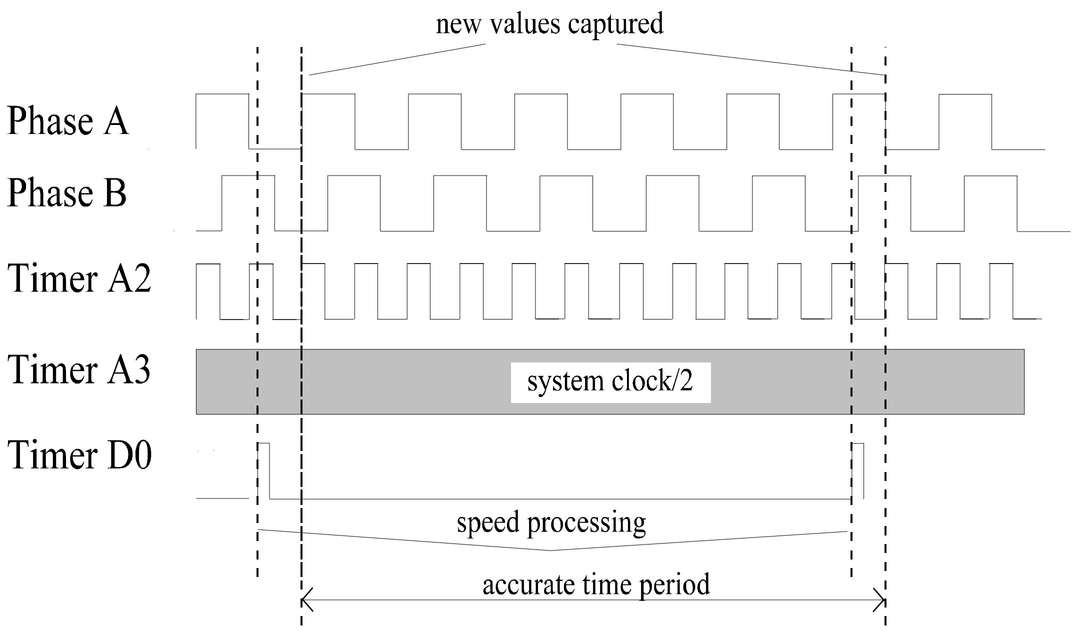


Figure 4-4. Speed Processing

4.3.1.2.1 Minimum and Maximum Speed Calculation

The minimum speed is calculated with the following equation:

$$\omega_{min} = \frac{60}{4NT_{calc}} \qquad \text{(EQ 4-1.)}$$

where:

ω_{min}	Minimum obtainable speed [rpm]
N	Number of pulses per revolution [1/rev]
T_{calc}	Period of speed measurement (calculation period) [s]

In the application, the quadrature encoder has 1024 pulses per revolution and a calculation period of 900µs was chosen on the basis of a motor mechanical constant. Thus, **(EQ 4-1.)** calculates the minimum speed as 16.3 rpm.

The maximum speed can be expressed as:

$$\omega_{max} = \frac{60}{4NT_{clkT2}} \qquad \text{(EQ 4-2.)}$$

where:

ω_{max}	Maximum obtainable speed [rpm]
N	Number of pulses per revolution [1/rev]
T_{clkT2}	Period of input clock to timer A2 [s]

Substitution in **(EQ 4-2.)** for N and T_{clkT2} (timer A2 input clock = system clock 36 MHz/2) yields a maximum speed of 263672rpm. As demonstrated, the algorithm can measure speed across a wide range. Because such high speed is not practical, the maximum speed can be reduced to a required range by the constant k in **(EQ 4-1.)**. The constant k can be calculated as:

$$k = \frac{60}{4NT_{clkT2}\omega_{max}} \qquad \text{(EQ 4-3.)}$$

where:

k	Scaling constant in **(EQ 4-1.)**
ω_{max}	Maximum of the speed range [rpm]
N	Number of pulses per revolution [1/rev]
T_{clkT2}	Period of input clock to timer A2 [s]

In this application, the maximum measurable speed is limited to 6000rpm.

Note: To ensure an accurate speed calculation, you must choose the input clock of timer A2 so that the calculation period of speed processing (in this case, 900µs) is represented in timer A2 as a value lower than 0x7FFFH ($900.10^{-6}/T_{clkT2}$<=0x7FFFH).

4.3.1.3 Position Reset with Rotor Alignment

After reset, the rotor position is unknown, because a quadrature encoder does not give an absolute position until the index pulse arrives. As shown in **Figure 4-5**, the rotor position must be aligned with the *d* axis of the d-q coordinate system before a motor begins running. The alignment algorithm is shown in **Figure 4-6**. First, the position is set to zero, independent of the actual rotor position. (The value of the quadrature encoder does not affect this setting). Then the I_d current is set to alignment current. The rotor is now aligned to the required position. After rotor stabilization, the encoder is reset to the zero position, then the I_d current is set back to zero, and alignment is finished. The alignment is executed only once during the first transition from the Stop to Run state of the Run/Stop switch.

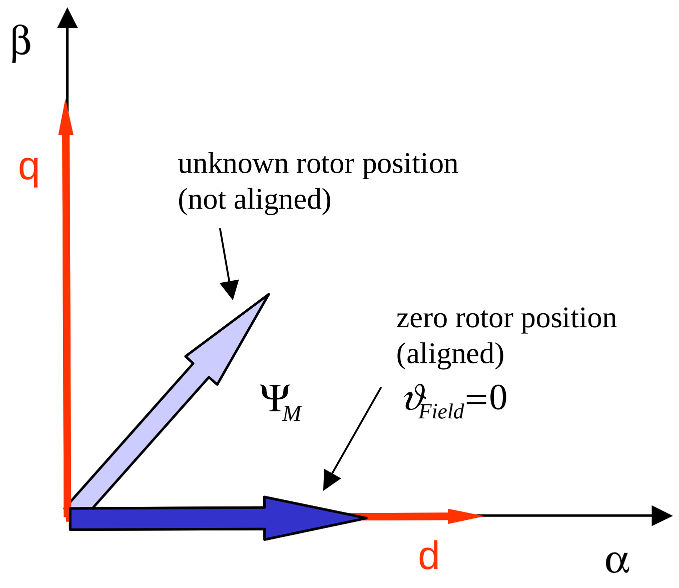


Figure 4-5. Rotor Alignment

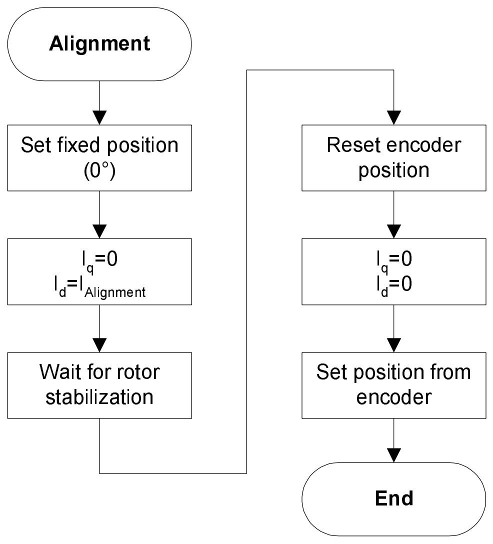

Alignment
Set fixed position (0°)
$I_q=0$ $I_d=I_{Alignment}$
Wait for rotor stabilization
Reset encoder position
$I_q=0$ $I_d=0$
Set position from encoder
End

Figure 4-6. Rotor Alignment Flow Chart

4.3.2 Current Sensing

Phase currents are measured by a shunt resistor in each phase. A voltage drop on the shunt resistor is amplified by an operational amplifier, and shifted up by 1.65V. The resultant voltage is converted by an A/D converter (see **Figure 4-7** and **Figure 4-8**).

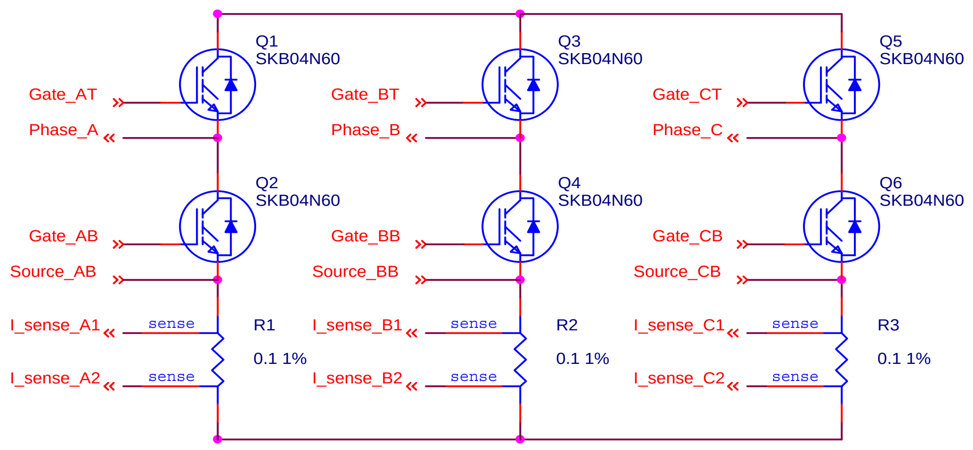


Figure 4-7. Current Shunt Resistors

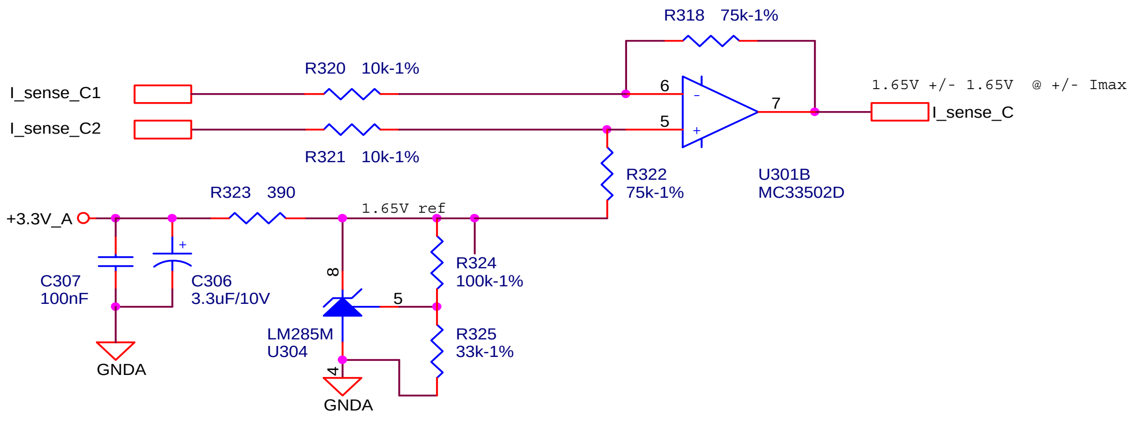


Figure 4-8. Current Amplifier

As shown in **Figure 4-7**, the currents cannot be measured at any moment. For example, the current flows through Phase A (and shunt resistor R1) only if transistor Q2 is switched on. Likewise, the current in Phase B can be measured if transistor Q4 is switched on, and the current in Phase C can be measured if transistor Q6 is switched on. To get a moment of current sensing, a voltage shape analysis must be done.

The voltage shapes of two different PWM periods are shown in **Figure 4-11**. The voltage shapes correspond to center-aligned PWM sinewave modulation. As shown, the best moment of current sampling is in the middle of the PWM period, where all bottom transistors are switched on.

To set the exact moment of sampling, the DSP56F80x family offers the ability to synchronize ADC and PWM modules via the SYNC signal. This exceptional hardware feature, patented by Motorola, is used for current sensing. The PWM outputs a synchronization pulse, which is connected as an input to the synchronization module TC2 (Quad Timer C, counter/timer 2). A high-true pulse occurs for each reload of the PWM, regardless of the state of the LDOK bit. The intended purpose of TC2 is to provide a user-selectable delay between the PWM SYNC signal and the updating of the ADC values. A conversion process can be initiated by the SYNC input, which is an output of TC2. The time diagram of the automatic synchronization between PWM and ADC is shown in **Figure 4-9.**

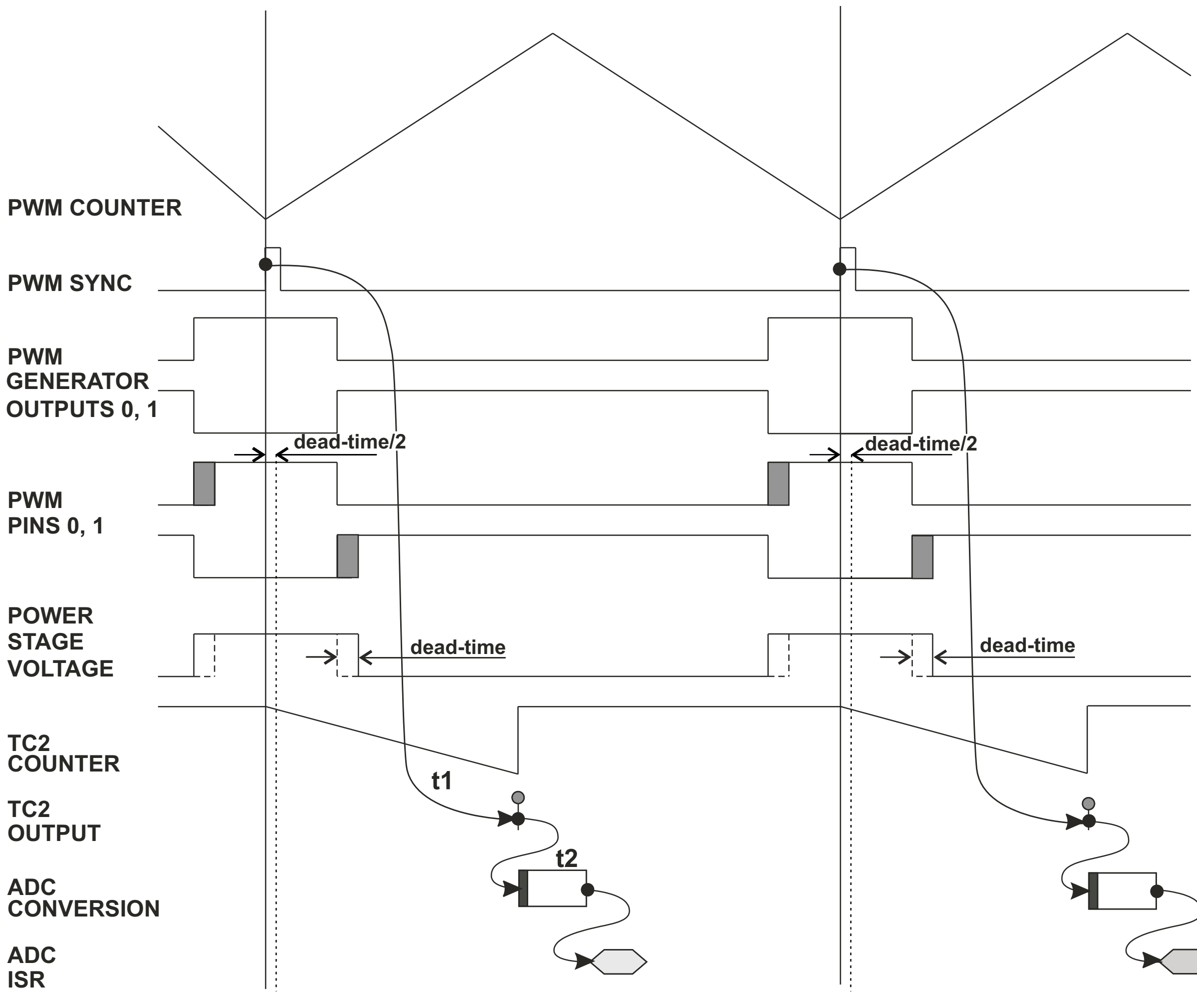


Figure 4-9. Time Diagram of PWM and ADC Synchronization

However, all three currents cannot be measured from one voltage shape. The PWM period II in **Figure 4-11** shows a moment when the bottom transistor of Phase A is switched on for a very short time. If the on-time is shorter than a critical time, the current can not be accurately measured. The critical time is given by hardware configuration (transistor commutation times, response delays of the processing electronics, etc.). Therefore, only two currents are measured and a third current is calculated from the following equation:

$$0 = i_A + i_B + i_C \qquad \text{(EQ 4-4.)}$$

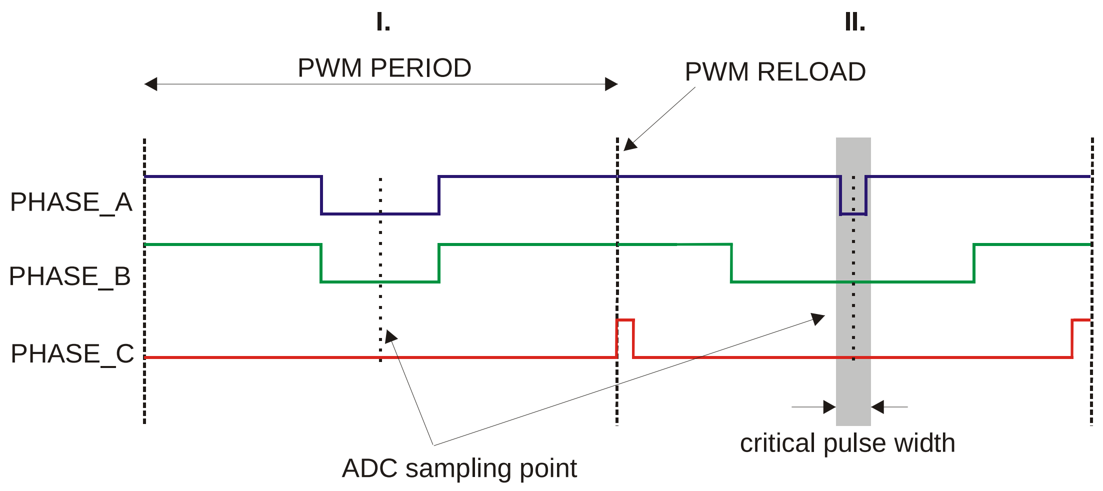


Figure 4-10. Voltage Shapes of Two Different PWM Periods

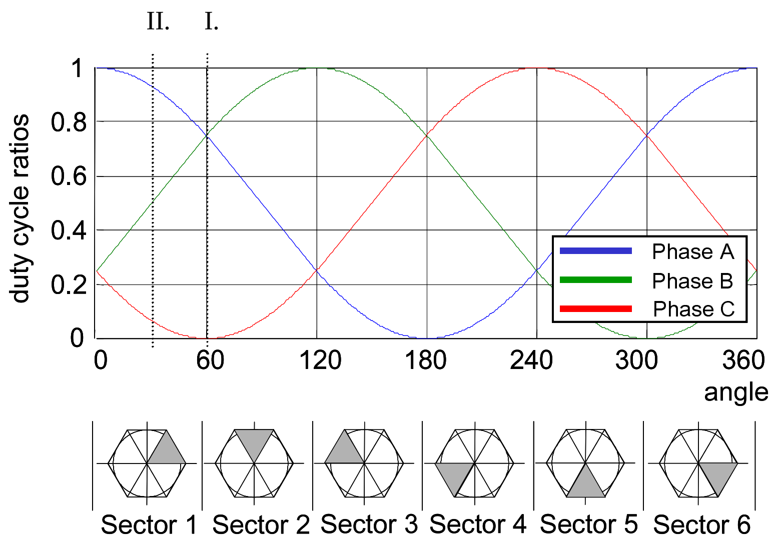


Figure 4-11. 3-phase Sinewave Voltages and Corresponding Sector Value

A decision must now be made about which phase current should be calculated. The simplest technique is to calculate the current of the most positive voltage phase. For example, Phase A generates the most positive voltage within section 0 - 60°, Phase B within section 60° - 120°, and so on; see Figure 4-11.

In this case, the output voltages are divided into six sectors, as shown in Figure 4-11. The current calculation is then made according to the actual sector value.

Sectors 1 and 6:

$$i_A = -i_B - i_C \qquad \text{(EQ 4-5.)}$$

Sectors 2 and 3:

$$i_B = -i_A - i_C \qquad \text{(EQ 4-6.)}$$

Sectors 4 and 5:

$$i_C = -i_B - i_A \qquad \text{(EQ 4-7.)}$$

Note: The sector value is used for current calculation only, and has no other meaning in the sinewave modulation. But if we use any type of space vector modulation, we can get the sector value as part of space vector calculation.

4.3.3 Voltage Sensing

The DCBus voltage sensor is represented by a simple voltage divider. The DCBus voltage does not change rapidly. It is nearly constant, with the ripple given by the power supply structure. If a bridge rectifier is used for rectification of the AC line voltage, the ripple frequency is twice the AC line frequency. If the power stage is designed correctly, the ripple amplitude should not exceed 10% of the nominal DCBus value.

The measured DCBus voltage must be filtered to eliminate noise. One of the easiest and fastest techniques is the first order filter, which calculates the average filtered value recursively from the last two samples and coefficient C:

$$u_{DCBusFilt}(n+1) = (Cu_{DCBusFilt}(n+1) - Cu_{DCBusFilt}(n)) - u_{DCBusFilt}(n) \qquad \text{(EQ 4-8.)}$$

To speed up the initialization of the voltage sensing (the filter has exponential dependency with constant of 1/N samples), the moving average filter, which calculates the average value from the last N samples, can be used for initialization:

$$u_{DCBusFilt} = \sum_{n=1}^{-N} u_{DCBus}(n) \qquad \text{(EQ 4-9.)}$$

4.3.4 Power Module Temperature Sensing

The measured power module temperature is used for thermal protection The hardware realization is shown in **Figure 4-12**. The circuit consists of four diodes connected in series, a bias resistor, and a noise suppression capacitor. The four diodes have a combined temperature coefficient of 8.8 mV/°C. The resulting signal, *Temp_sense*, is fed back to an A/D input, where software can be used to set safe operating limits. In this application, the temperature, in Celsius, is calculated according to the conversion equation:

$$temp = \frac{Temp\_sense - b}{a} \qquad \text{(EQ 4-10.)}$$

where:

temp	Power module temperature in centigrades
Temp_sense	Voltage drop on the diodes, which is measured by ADC [V]
a	Diodes-dependent conversion constant (*a* = -0.0073738)
b	Diodes-dependent conversion constant (b = 2.4596)

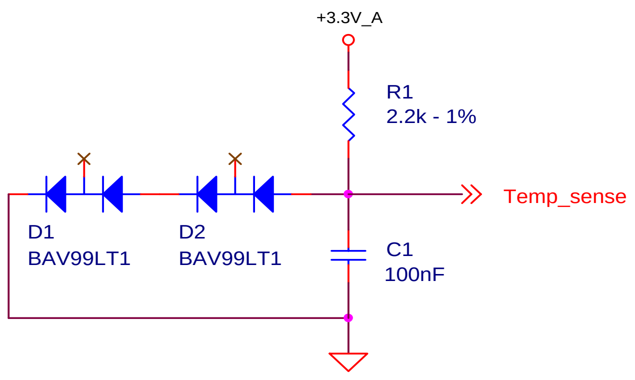


Figure 4-12. Temperature Sensing

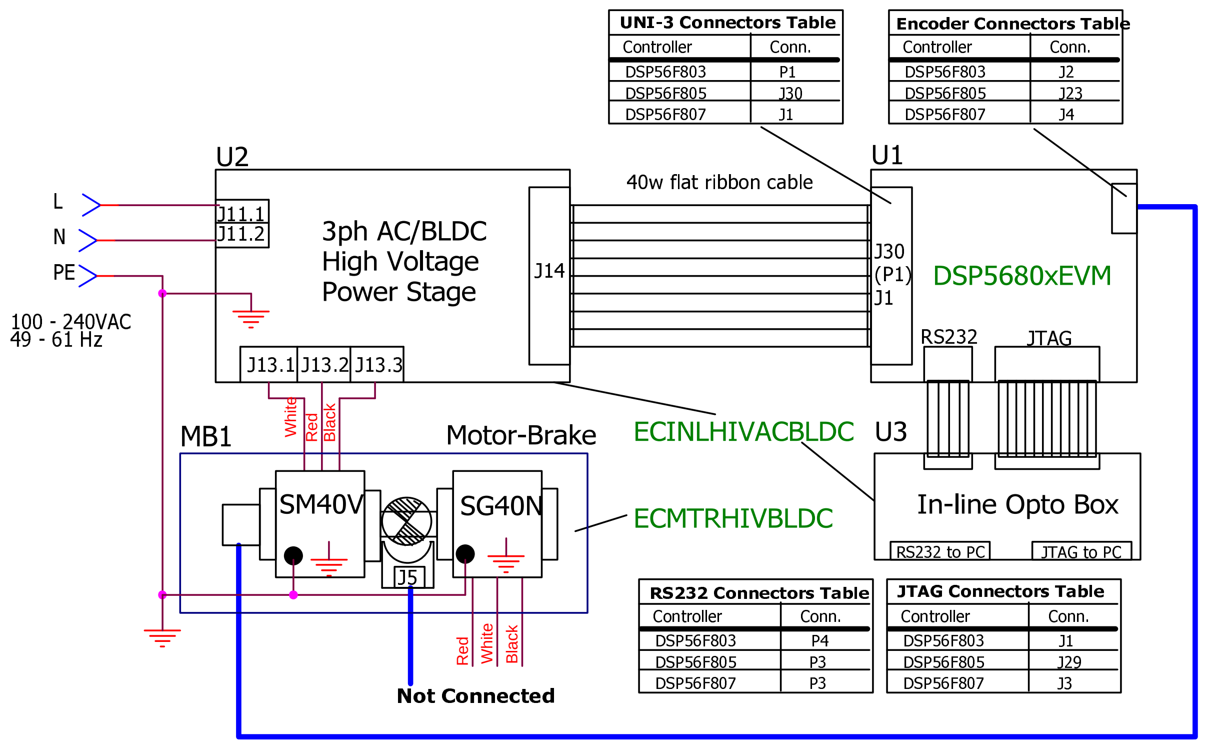
5. Hardware Implementation

5.1 Hardware Set-up

The application can run on Motorola's motor control DSPs using the DSP56F803EVM, DSP56F805EVM, or DSP56F807EVM, Motorola's 3-Phase AC/BLDC high voltage power stage and the BLDC high voltage motor with a quadrature encoder and integrated brake. All components are an integral part of Motorola's embedded motion control development tools. Application hardware set-up is shown in **Figure 5-1**.

The system hardware set-up for a particular DSP varies only by the EVM Board used. The application level of the software is identical for all DSPs. The EVM and chip differences are handled by the off-chip software drivers for the particular DSP EVM board.

Detailed application hardware set-up can be found in the **Targeting Motorola DSP5680x Platform** manual.



UNI-3 Connectors Table	
Controller	Conn.
DSP56F803	P1
DSP56F805	J30
DSP56F807	J1

Encoder Connectors Table	
Controller	Conn.
DSP56F803	J2
DSP56F805	J23
DSP56F807	J4

RS232 Connectors Table	
Controller	Conn.
DSP56F803	P4
DSP56F805	P3
DSP56F807	P3

JTAG Connectors Table	
Controller	Conn.
DSP56F803	J1
DSP56F805	J29
DSP56F807	J3

Figure 5-1. High-Voltage Hardware System Configuration

All system parts are supplied and documented in these references:

- **U1 -** Controller Board for the:
  - — DSP56F803
    - — Supplied as DSP56F803EVM
    - — Described in the **DSP56F803 Evaluation Module Hardware User's Manual**
  - — DSP56F805
    - — Supplied as DSP56F805EVM
    - — Described in the **DSP56F805 Evaluation Module Hardware User's Manual**
  - — DSP56F807
  - — Supplied as DSP56807EVM
  - — Described in **DSP56F807Evaluation Module Hardware User's Manual**
- **U2 -** 3-phase AC/BLDC High-Voltage Power Stage
  - — Supplied in a kit with the In-Line Optoisolation Box (Order #ECINLHIVACBLDC)
  - — Described in the **3-phase Brushless DC High Voltage Power Stage Manual**
- **U3 -** In-Line Optoisolation Box
  - — Supplied in a kit with the 3-phase AC/BLDC High Voltage Power Stage (Order #ECINLHIVACBLDC) or solo (Order #ECOPTINL)
  - — Described in the **In-Line Optoisolation Box Manual**

WARNING: It is strongly recommended to use an In-line Optoisolation Box during development to avoid any damage to the development equipment.

- **MB1** Motor-Brake SM40V + SG40N
  - Supplied as Order #ECMTRHIVBLDC

Note: The application software is targeted for a PM synchronous motor with sinewave Back-EMF shape. In this demo application, a BLDC motor is used instead, due to the availability of the BLDC motor (MB1). Although the Back-EMF shape of this motor is not an ideal sinewave, it can be controlled by the application software. The drive parameters will be ideal with a PMSM motor with an exact sinewave Back-EMF shape.

A detailed description of the individual board can be found in the appropriate **DSP56F80x Evaluation Module User's Manual**, or on the Motorola web site, **http://-www.motorola.com**. The User's Manual includes the schematic of the board, description of individual function blocks, and a bill of materials. The individual boards can be ordered from Motorola as standard products.

6. Software Design

This section describes the design of the drive's software blocks. The software description comprises these topics:

- Main Software Flow Chart
- Data Flow
- State Diagram

For more information on the system blocks used, refer to **Section 4.3**.

6.1 Main Software Flow Chart

The main software flow chart incorporates the Main routine entered from Reset (see **Figure 6-1**) and Interrupt states (see **Figure 6-2**, **Figure 6-3**). The Main routine includes the initialization of the DSP and the main loop.

The software consist of processes: Application Control, PM Synchronous Motor (PMSM) Control, Analog sensing, Position and Speed Measurement, Fault Control, and Brake Control.

The Application Control process is the highest software level which precedes settings for other software levels. The input of this level is the Run/Stop switch, Up/Down buttons for manual control, and PC master software (via the registers shown in **Section 6.2**). This process is handled by Application Control Processing called from Main; see **Figure 6-1**.

The PMSM (PM Synchronous Motor) Control process provides most of the motor control functionality. It is split into Current Processing and Speed Processing. Current Processing is called from ADC Complete Interrupt (see **Figure 6-2**) once per two PWM reloads, with a period 125µs. It can also be set to each PWM reload (62.5µs), but the PC master software recorder *pcmasterdrvRecorder()* must be removed from the code. Speed Processing is called from the Quadrature Timer D0 Interrupt (see **Figure 6-3**) with the period PER_TMR_POS_SPEED_US (900µs). The advantage of splitting the current and the speed control processes is that current control can be executed with a high priority and frequency of calls, while the execution of the speed control is not that highly prioritized.

The Analog sensing process handles sensing, filtering and correction of analog variables (phase currents, temperature, DCBus voltage). It is provided by Analog Sensing Processing (see **Figure 6-2**) and Analog Sensing ADC Phase Set. Analog Sensing ADC Phase Set is split from Analog Sensing Processing because it sets ADC according to the *svmSector* variable, calculated after PMSM Control Current Processing.

Position and Speed Measurement processes are provided by hardware Timer modules and the functions giving the actual speed and position; see **Figure 4.3.1**.

LED Indication Processing is called from Quadrature Timer D0 Interrupt, which provides the time base for LED flashing.

The Fault Control process is split into Background and PWM Fault ISR. Background (see **Figure 6-1**) checks the Overheating, Undervoltage and Position Sensing Faults. The PWM Fault ISR part (see **Figure 6-2**) takes care of Overvoltage and Overcurrent Faults, which causes a PWM A Fault interrupt.

The Brake Control process is dedicated to the brake transistor control, which maintains the DCBus voltage level. It is called from Main (see **Figure 6-1**).

The Up/Down Button and Switch Control processes are subprocesses of Application Control and are described in **Section 7.4**.

The Up/Down Button processes are split into Button Processing Interrupt, called from Quadrature Timer D0 Interrupt (see **Figure 6-3**); Button Processing BackGround (inside Analog Sensing); Interrupt Up Button; and Interrupt Down Button (see **Figure 6-2**).

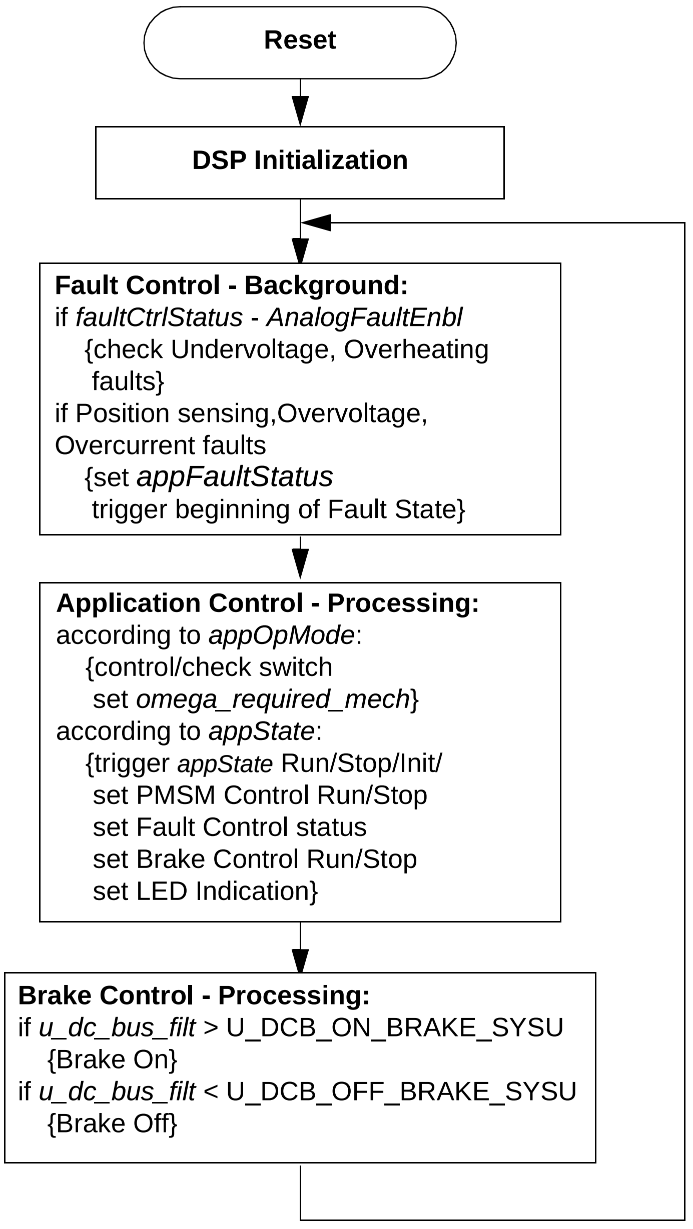

Reset
DSP Initialization
Fault Control - Background:
if *faultCtrlStatus - AnalogFaultEnbl*
{check Undervoltage, Overheating faults}
if Position sensing,Overvoltage, Overcurrent faults
{set *appFaultStatus*
trigger beginning of Fault State}
Application Control - Processing:
according to *appOpMode*:
{control/check switch
set *omega_required_mech*}
according to *appState*:
{trigger *appState* Run/Stop/Init/
set PMSM Control Run/Stop
set Fault Control status
set Brake Control Run/Stop
set LED Indication}
Brake Control - Processing:
if *u_dc_bus_filt* > U_DCB_ON_BRAKE_SYSU
{Brake On}
if *u_dc_bus_filt* < U_DCB_OFF_BRAKE_SYSU
{Brake Off}

Figure 6-1. Software Flow Chart - General Overview I

The Switch process is split into Switch Filter Processing, called from Quadrature Timer D0 Interrupt (see **Figure 6-3**); and Switch Get State, called from Application Control processing, which handles manual switch control, and Switch Get State PC master software (in PC master application operating mode).

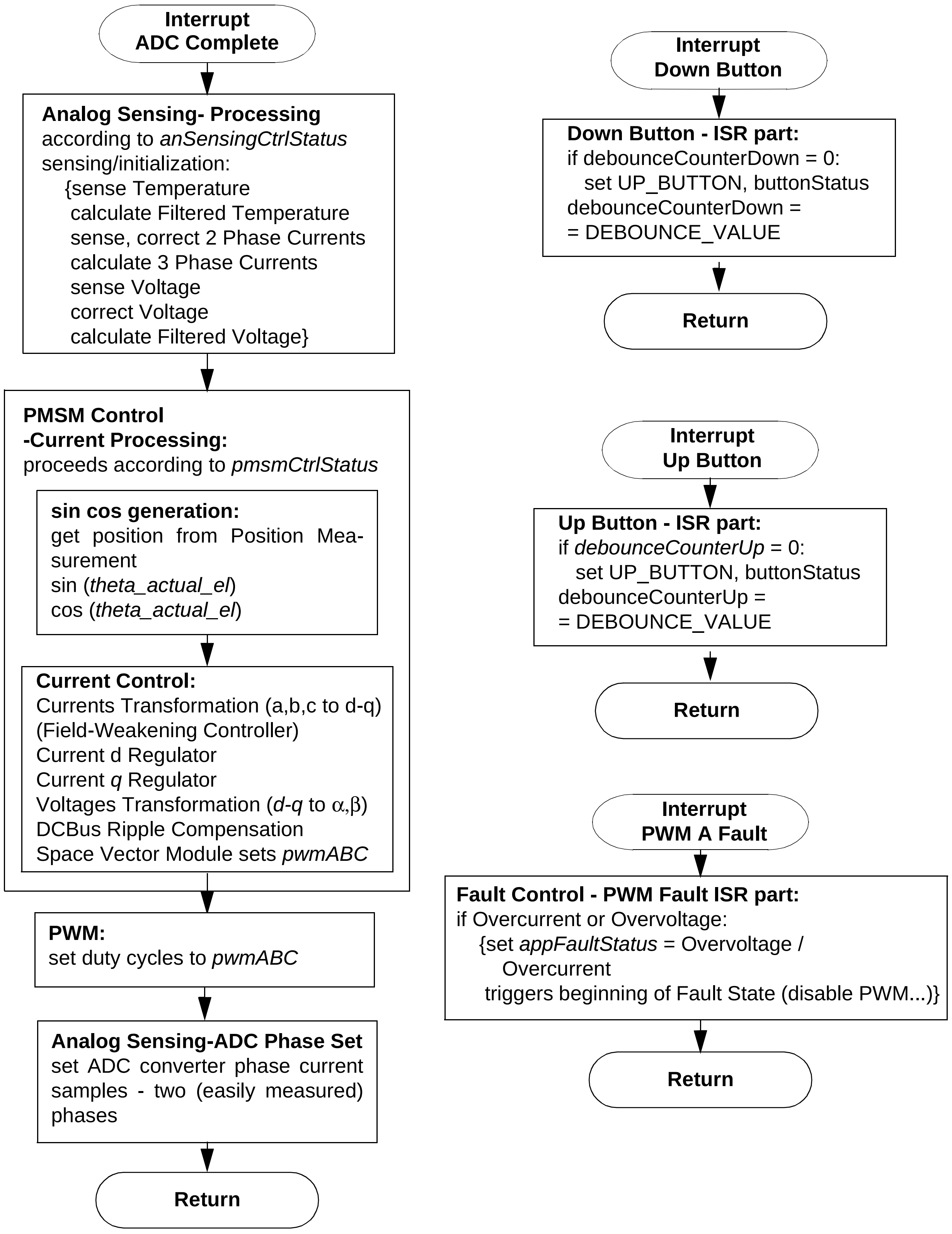

Interrupt
ADC Complete
Analog Sensing- Processing
according to anSensingCtrlStatus
sensing/initialization:
{sense Temperature
calculate Filtered Temperature
sense, correct 2 Phase Currents
calculate 3 Phase Currents
sense Voltage
correct Voltage
calculate Filtered Voltage}
PMSM Control
-Current Processing:
proceeds according to pmsmCtrlStatus
sin cos generation:
get position from Position Measurement
sin (theta_actual_el)
cos (theta_actual_el)
Current Control:
Currents Transformation (a,b,c to d-q)
(Field-Weakening Controller)
Current d Regulator
Current q Regulator
Voltages Transformation (d-q to α,β)
DCBus Ripple Compensation
Space Vector Module sets pwmABC
PWM:
set duty cycles to pwmABC
Analog Sensing-ADC Phase Set
set ADC converter phase current samples - two (easily measured) phases
Return
Interrupt
Down Button
Down Button - ISR part:
if debounceCounterDown = 0:
set UP_BUTTON, buttonStatus
debounceCounterDown =
= DEBOUNCE_VALUE
Return
Interrupt
Up Button
Up Button - ISR part:
if debounceCounterUp = 0:
set UP_BUTTON, buttonStatus
debounceCounterUp =
= DEBOUNCE_VALUE
Return
Interrupt
PWM A Fault
Fault Control - PWM Fault ISR part:
if Overcurrent or Overvoltage:
{set appFaultStatus = Overvoltage / Overcurrent
triggers beginning of Fault State (disable PWM...)}
Return

Figure 6-2. Software Flow Chart - General Overview II

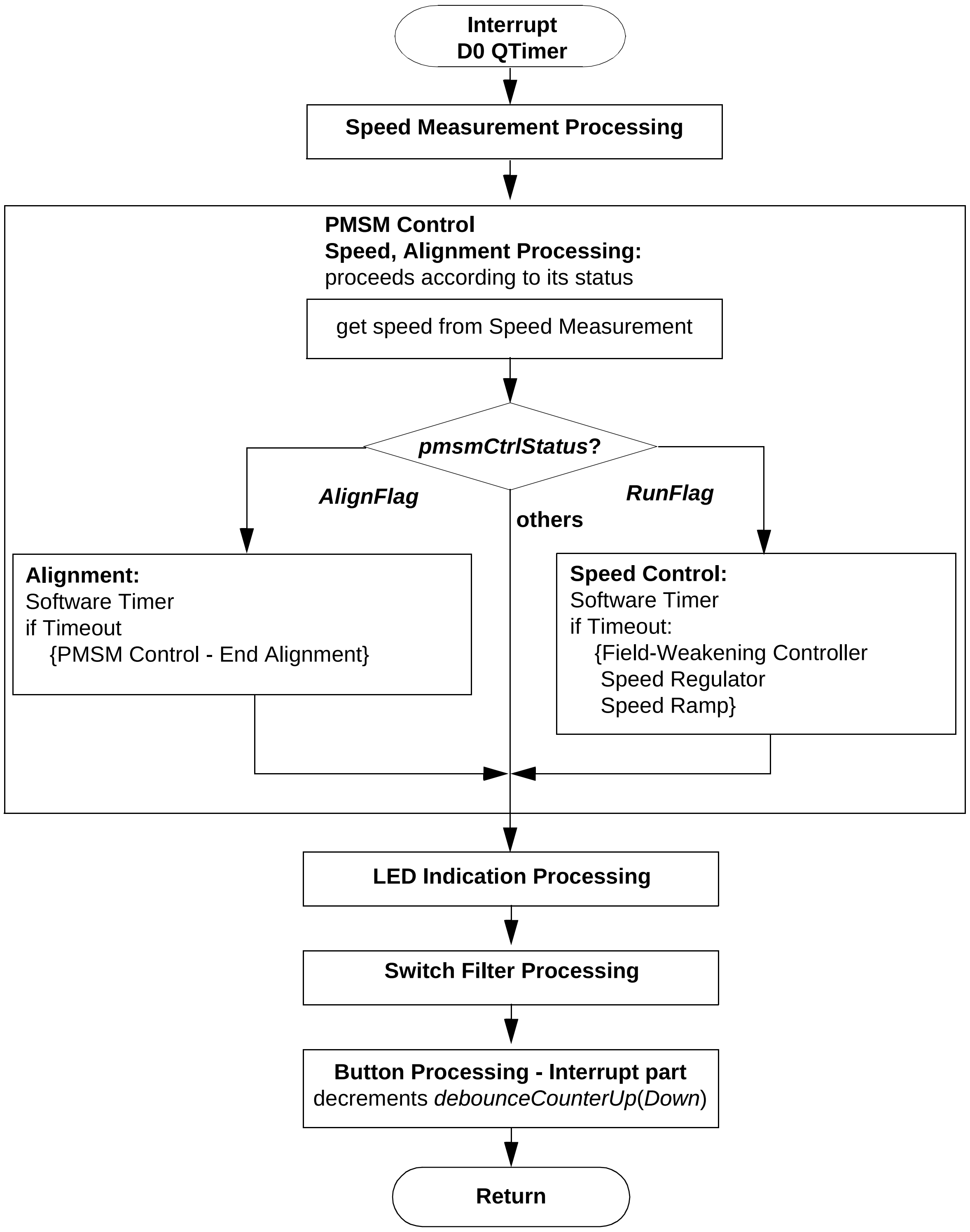

Interrupt
D0 QTimer
Speed Measurement Processing
PMSM Control
Speed, Alignment Processing:
proceeds according to its status
get speed from Speed Measurement
pmsmCtrlStatus?
AlignFlag
others
RunFlag
Alignment:
Software Timer
if Timeout
{PMSM Control - End Alignment}
Speed Control:
Software Timer
if Timeout:
{Field-Weakening Controller
Speed Regulator
Speed Ramp}
LED Indication Processing
Switch Filter Processing
Button Processing - Interrupt part
decrements debounceCounterUp(Down)
Return

Figure 6-3. S/W Flow Chart - General Overview III

6.2 Data Flow

The PM synchronous motor vector control drive control algorithm is described in the data flow charts shown in **Figure 6-4** and **Figure 6-5**. The variables and constants described should be clear from their names.

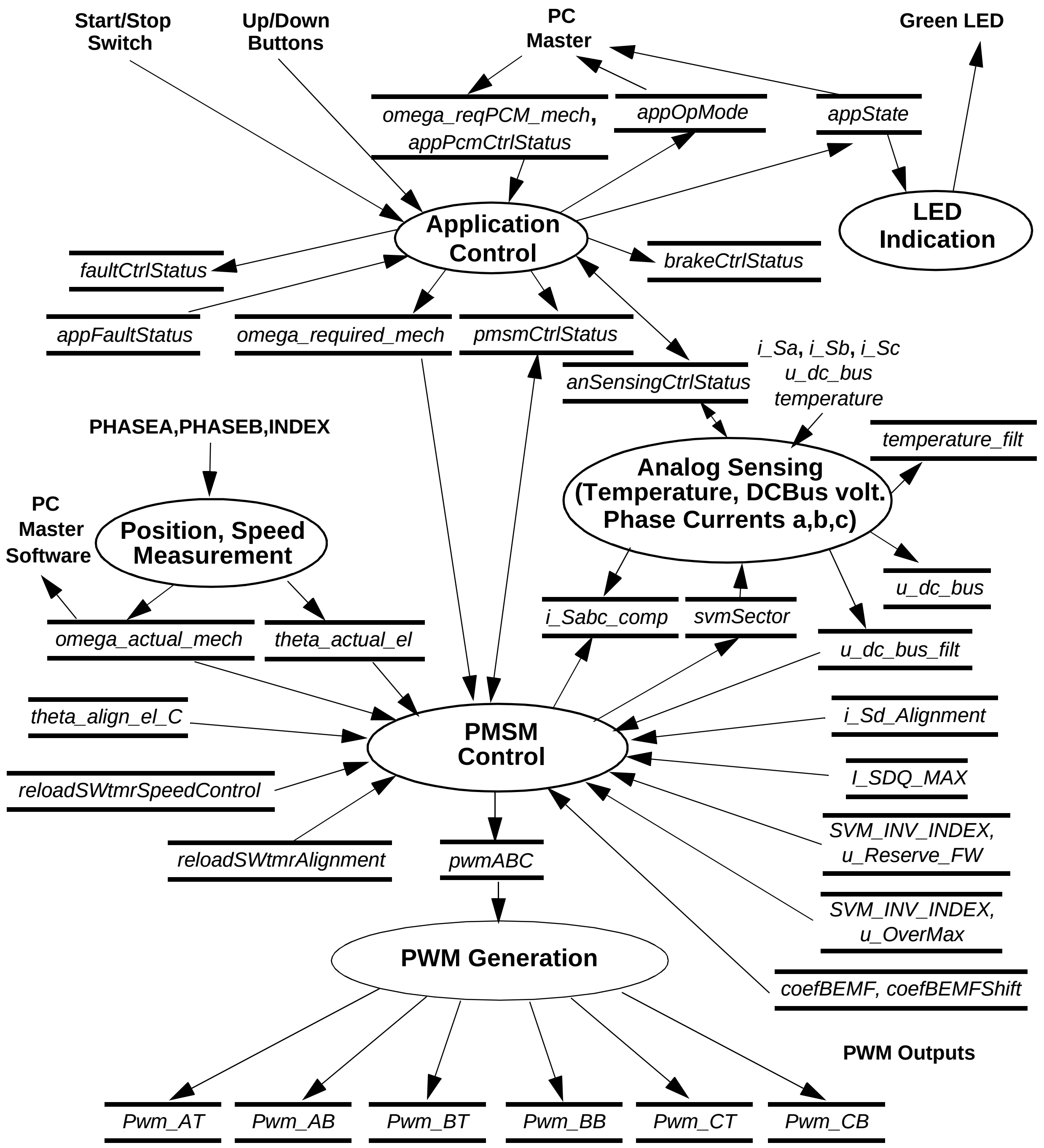


Figure 6-4. Data Flow - Part 1

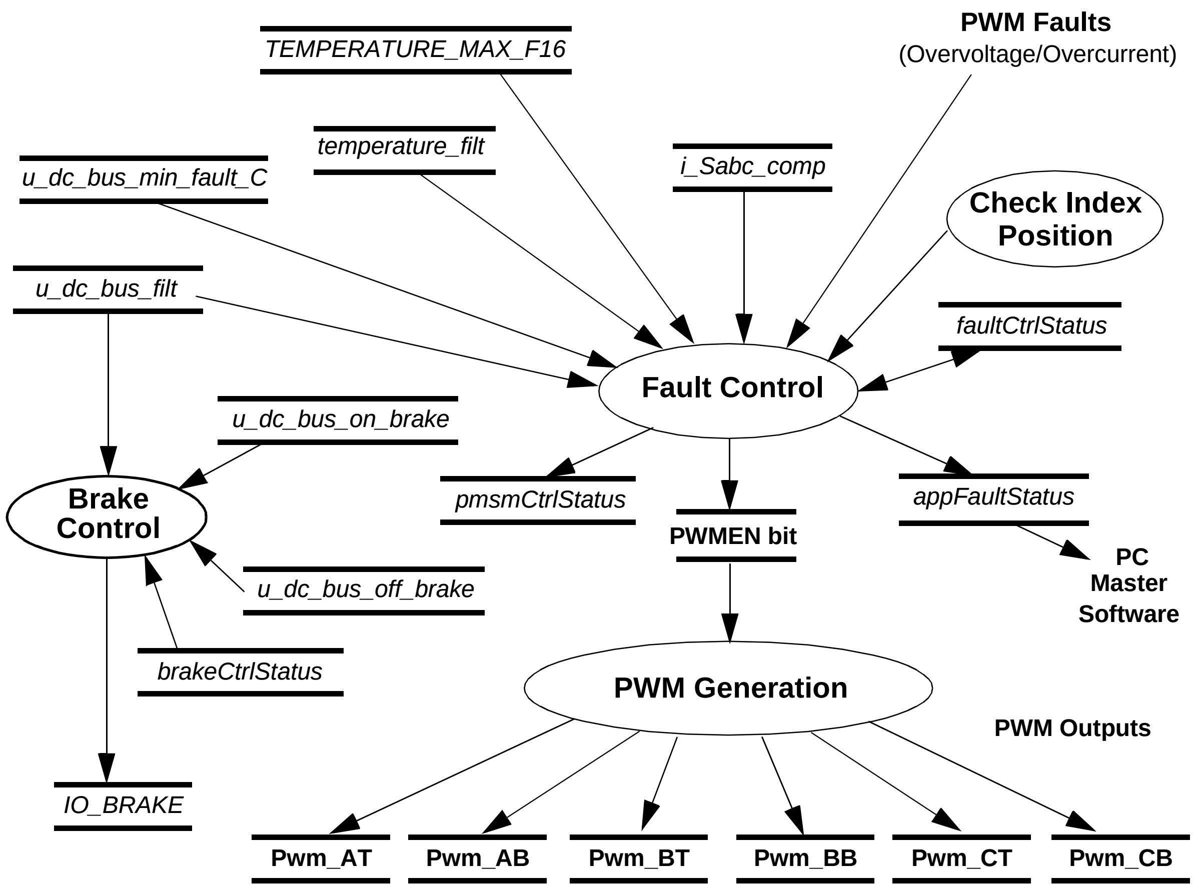


Figure 6-5. Data Flow - Part 2

The data flows consist of the processes described in the following sections.

6.2.1 Application Control Process

The Application Control process is the highest software level, which precedes settings for other software levels.

The process state is determined by the variable *appState*.

The application can be controlled either:

- Manually
- From PC master software

The manual/PC master application operating mode is determined by the setting of *appOpMode*.

For manual control, the input of this process is the Run/Stop switch and Up/Down buttons.

The PC master software communicates via *omega_reqPCM_mech*, which is the required angular speed from PC master software; *appPcmCtrlStatus*, which consists of the flags *StartStopCtrl* for Start/Stop; *RequestCtrl* for changing the application’s operating mode *appOpMode* to manual or PC control; and *appFaultStatus*, indicating faults.

The other processes are controlled by setting *pmsmCtrlStatus*, *omega_required_mech*, *appPcmCtrlStatus*, *brakeCtrlStatus*, *faultCtrlStatus*.

6.2.2 LED Indication Process

This process controls the LED flashing according to *appState*.

6.2.3 Analog Sensing Process

The Analog sensing process handles sensing, filtering and correction of analog variables (phase currents, temperature, DC Bus voltage).

6.2.4 Position and Speed Measurement Process

The Position and Speed Measurement process gives mechanical angular speed *omega_actual_mech* and electrical position *theta_actual_el*.

6.2.5 PMSM (PM Synchronous Motor) Control Process

The PMSM (PM Synchronous Motor) Control process provides most of the motor control functionality.

Figure 6-6 shows the data flow inside the process PMSM Control. It shows essential subprocesses of the process: Sine; Cosine Transformations; Current Control; Speed; Alignment Control; and Field-Weakening.

The Sine and Cosine Transformations generate *sinCos_theta_el* with the components *sine*, *cosine* according to electrical position *theta_actual_el*. It is provided in a look-up table.

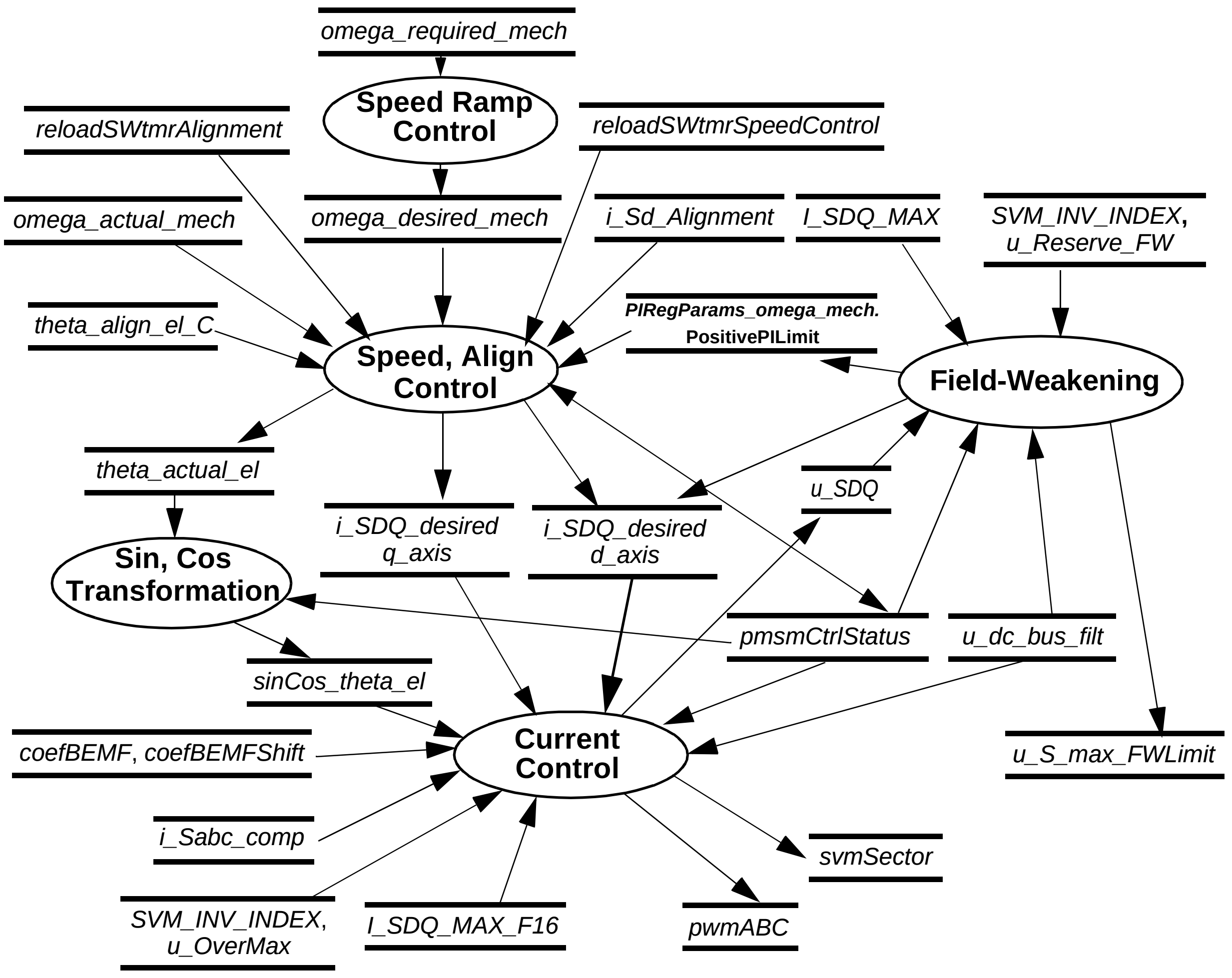


Figure 6-6. Data Flow - PMSM Control

6.2.5.1 Current Control Process

The data flow inside the process Current Control is detailed in **Figure 6-7**. The measured phase currents *i_Sabc_comp* are transformed into *i_SDQ_lin* using *sinCos_theta_el*; see **Section 3.3.3**. Both *d* and *q* components are regulated by independent PI regulators to *i_SDQ_desired* values. The outputs of the regulators are *u_SDQ_lin*.

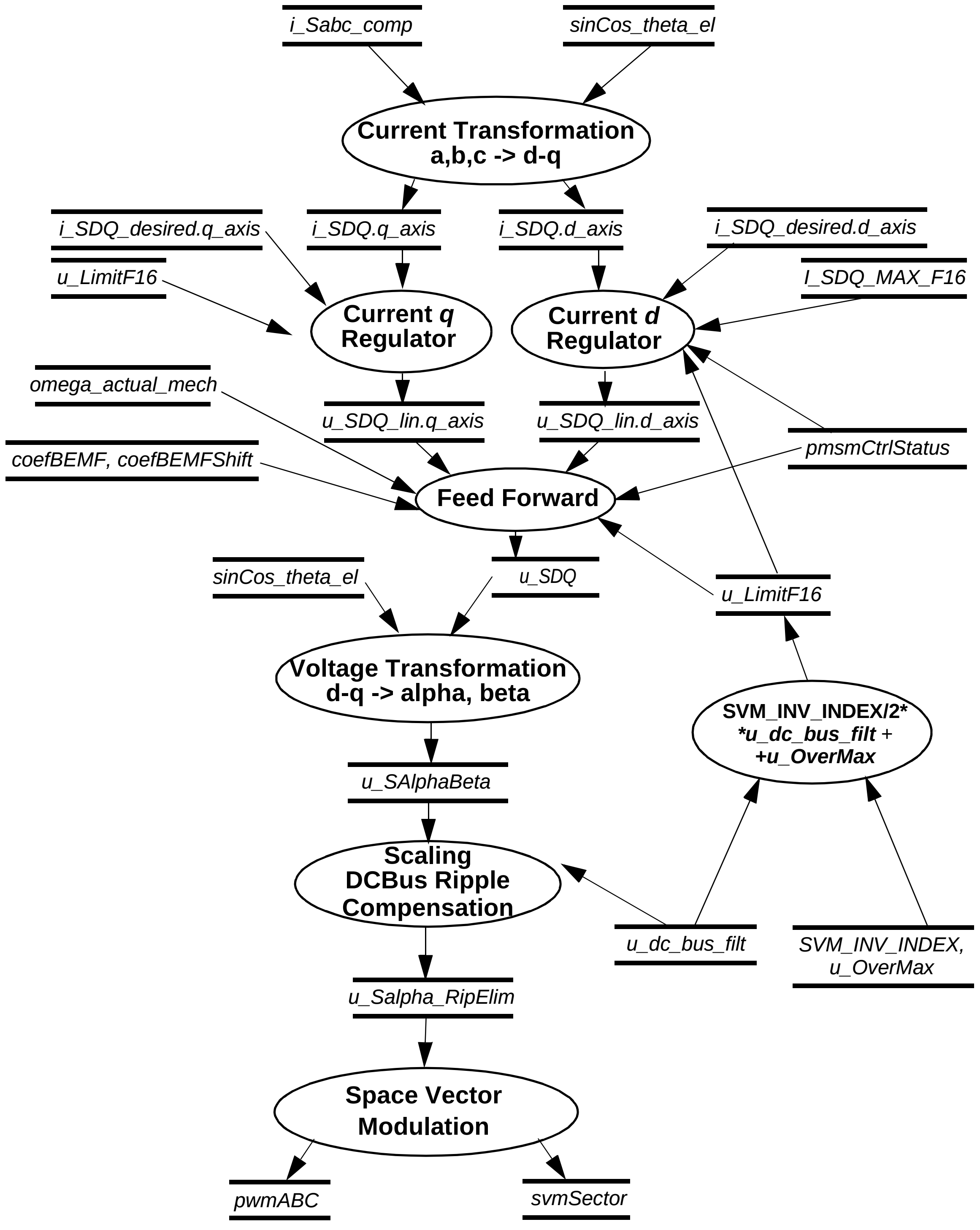


Figure 6-7. Data Flow - PMSM Control - Current Control

The Feed Forward process provides the following calculations:

$$u\_SDQ.q\_axis = coefBEMF \cdot 2^{coefBEMFShft} \cdot omega\_actual\_mech + u\_SDQ\_lin.q\_axis \tag{EQ 6-1.}$$

$$u\_SDQ.d\_axis = u\_SDQ\_lin.d\_axis \tag{EQ 6-2.}$$

The *u_SDQ* voltages are transformed into *u_SAlphaBeta* (see **Section 3.3.3**) by the Voltage Transformation process. The Scaling DCBus Ripple Compensation block scales *u_SAlphaBeta* (according *u_dc_bus_filt*) to *u_Salpha_RipElim*, described in the *svmlimDcBusRip* function in the **Motor Control Library**. The space vector modulation process generates duty cycle *pwmABC* and *svmSector* according to *u_Salpha_RipElim*.

The *u_LimitF16* is a voltage limit for current controllers. The *u_OverMax* constant is used to increase the limitation of *u_SDQ* voltages over maximum *SVM_INV_INDEX/2*u_dc_bus_filt* determined by the DCBus voltage and space vector modulation. Although the *pwmABC* will be limited by the space vector modulation process functions, the reserve is used for field-weakening controller dynamics. In the stable state, the *u_SDQ* voltages vector will not exceed *u_S_max_FWLimit*; see **Section 6.2.5.4**.

6.2.5.2 Speed Ramp

The process generates angular speed *omega_desired_mech* from angular speed *omega_required_mech* with a linear ramp. The speed ramp is implemented so as not to saturate the speed regulator during acceleration.

6.2.5.3 Speed, Alignment Control Process

The process controls the *i_SDQ_desired.q_axis* current according to the PMSM Control Process Status.

For Alignment status, it sets *i_SDQ_desired.d_axis* to *i_Sd_Alignment* and *i_SDQ_desired.q_axis* to 0.

For Run status, it controls the *omega_actual_mech* speed to *omega_desired_mech* by calculation of the PI regulator with *i_SDQ_desired.q_axis* output.

6.2.5.4 Field-Weakening Process

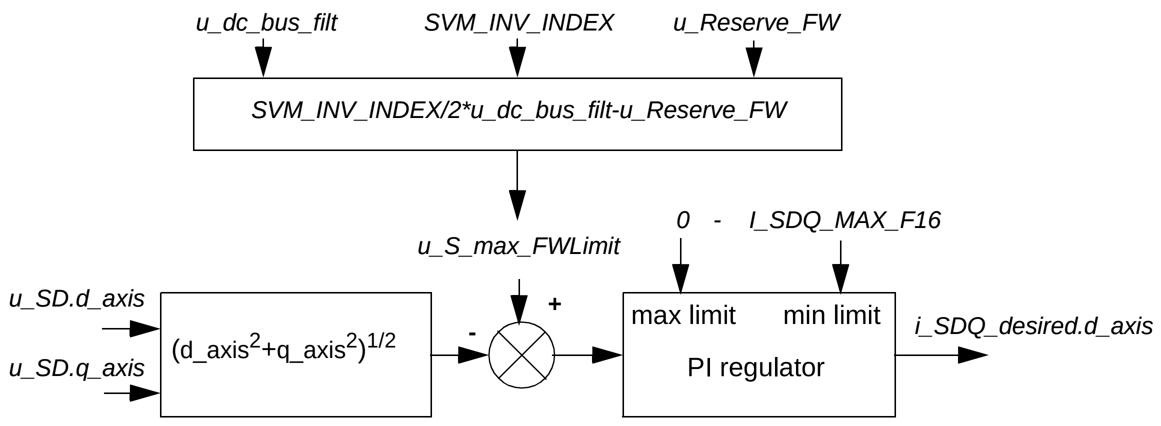


Figure 6-8. Field-Weakening Controller

The field-weakening process provides control of *i_SDQ_desired.d_axis* in order to achieve higher motor speeds by the field-weakening technique. The control algorithm is shown in **Figure 6-8**. The *u_S_max_FWLimit* is computed from *u_dc_bus_filt*. The *u_Reserve_FW* is subtracted, in order to have some voltage reserve, to the maximum *SVM_INV_INDEX/2*u_dc_bus_filt* determined by DCBus voltage and space vector modulation. The reserve is used for field-weakening controller dynamics; in the stable state, the *u_SDQ* voltages vector will not exceed *u_S_max_FWLimit*.

This process also provides voltage limitation $i\_SDQ\_desired.d\_axis^2 + i\_SDQ\_desired.q\_axis^2 < (I\_SDQ\_MAX\_F16)^2$ by setting:

$$\text{PIRegParams\_omega\_mech.PositivePILimit} = \sqrt{\text{I\_SDQ\_MAX\_F16}^2 - i\text{\_SDQ\_desired.d\_axis}^2} \qquad \text{(EQ 6-3.)}$$

$$\text{PIRegParams\_omega\_mech.NegativePILimit} = -\sqrt{\text{I\_SDQ\_MAX\_F16}^2 - i\text{\_SDQ\_desired.d\_axis}^2} \qquad \text{(EQ 6-4.)}$$

6.2.6 Brake Control Process

The brake control process maintains DCBus voltage level via the IO_BRAKE driver, which controls the brake switch. The voltage comparison levels are *u_dc_bus_on_brake*, which is initialized with either the *U_DCB_ON_BRAKE_MAINS230_F16* or *U_DCB_ON_BRAKE_MAINS115_F16* constant according to mains voltage, and *u_dc_bus_off_brake*, initialized with *U_DCB_OFF_BRAKE_MAINS230_F16* or *U_DCB_OFF_BRAKE_MAINS115_F16*.

6.2.7 PWM Generation Process

The PWM generation process controls the generation of PWM signals, driving the 3-phase inverter.

The input is *pwmABC*, with three PWM components scaled to the range <0,1> of type Frac16. The scaling (according to PWM module setting) and the PWM module control (on the DSP) is provided by the PWM driver.

6.2.8 Fault Control Process

The Fault Control process checks the Overheating, Undervoltage, Overvoltage, Overcurrent and Position Sensing faults.

Overheating and Undervoltage are checked by the comparisons *temperature_filt* < *TEMPERATURE_MAX_F16* and *u_dc_bus_filt* < *u_dc_bus_min_fault_C*, where *u_dc_bus_min_fault_C* is initialized with *U_DCB_MIN_FAULT_MAINS230_F16* or *U_DCB_MIN_FAULT_MAINS115_F16*. The Position Sensing fault is checked with the Check Index Position process.

The Overvoltage and Overcurrent faults are set in the PWMA Fault interrupt.

6.3 State Diagram

The software can be split into the processes shown in **Section 6.2**.

The following processes are described below:

- Application Control State Diagram
- PMSM Control State Diagram
- Fault Control State Diagram
- Analog Sensing State Diagram

All processes start with the DSP Initialization state after Reset.

6.3.1 DSP Initialization

The DSP Initialization state:

- Initializes:
  - PWM
  - Application Control
  - PM Synchronous Motor Control
  - Analog Sensing
  - Brake Control
  - Fault Control
  - LED Indication
  - Button Control
- Sets manual application operating mode
- Enables masked interrupts
- Application Control: Initialization Triggers, which set all affected processes to the Begin Application Initialization state

6.3.2 Application Control State Diagram

The Application Control process is detailed in **Figure 6-9**.

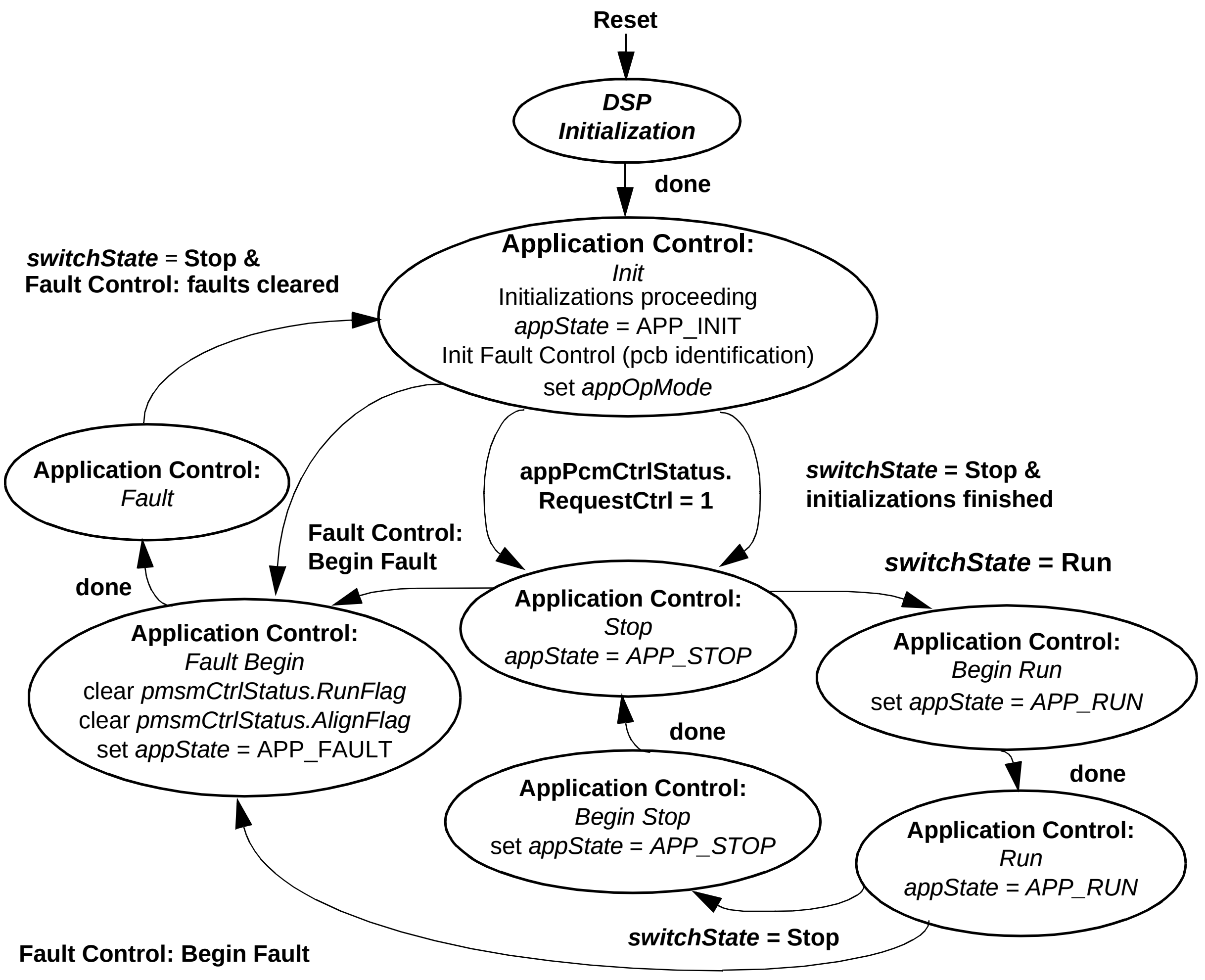

Reset
DSP Initialization
done
Application Control: Init
Initializations proceeding
appState = APP_INIT
Init Fault Control (pcb identification)
set appOpMode
switchState = Stop & Fault Control: faults cleared
Application Control: Fault
appPcmCtrlStatus. RequestCtrl = 1
switchState = Stop & initializations finished
Fault Control: Begin Fault
done
switchState = Run
Application Control: Stop
appState = APP_STOP
Application Control: Fault Begin
clear pmsmCtrlStatus.RunFlag
clear pmsmCtrlStatus.AlignFlag
set appState = APP_FAULT
Application Control: Begin Run
set appState = APP_RUN
done
done
Application Control: Begin Stop
set appState = APP_STOP
Application Control: Run
appState = APP_RUN
switchState = Stop
Fault Control: Begin Fault

Figure 6-9. State Diagram - Application Control

After reset, the DSP Initialization state is entered. The peripherals and variables are initialized in this state, and the application operating mode *appOpMode* is set to *Manual Control*.

When the state is finished, the Application Control Init state follows. As shown in **Figure 6-9**, *appState = APP_INIT*; all subprocesses requiring initialization are proceeding; pcb identification is provided; the PWM is disabled; and so no voltage is applied on motor phases. If the *appPcmCtrlStatus.RequestCtrl* flag is set from PC master software, the application operating mode *appOpMode* is toggled and the application operating mode can only be changed in this state. If the *switchState = Stop*, the Application Control enters the *Stop* state.

The *switchState* is set according to the manual switch on the EVM or PC master software register *AppPcmCtrlStatus.StartStopCtrl*, depending on the application operating mode.

In the Stop state, *appState = APP_STOP* and the PWM is disabled, so no voltage is applied on motor phases. When *switchState = Run*, the Begin Run state is processed. If there is a request to change application operating mode, *appPcmCtrlStatus.RequestCtrl = 1*, the application Init is entered and the application operating mode request can only be accepted in the Init or Stop state by transition to the Init state.

In the Begin Run state, all the processes provide settings to the Run state.

In the Run state, the PWM is enabled, so voltage is applied on motor phases. The motor is running according to the state of all subprocesses. If *switchState* = *Stop*, the Stop state is entered.

If and fault is detected during the Begin Fault state, which is a subprocess of Fault control, the Begin Fault state is entered. It sets *appState* = *APP_FAULT*; the PWM is disabled; and the subprocess PMSM Control is set to Stop. The Fault state can only move onto the Init state when *switchState* = *Stop*, and the Fault Control subprocess has successfully cleared all faults.

6.3.3 PMSM Control State Diagram

A state diagram of the Commutation Control process is illustrated in **Figure 6-10**.

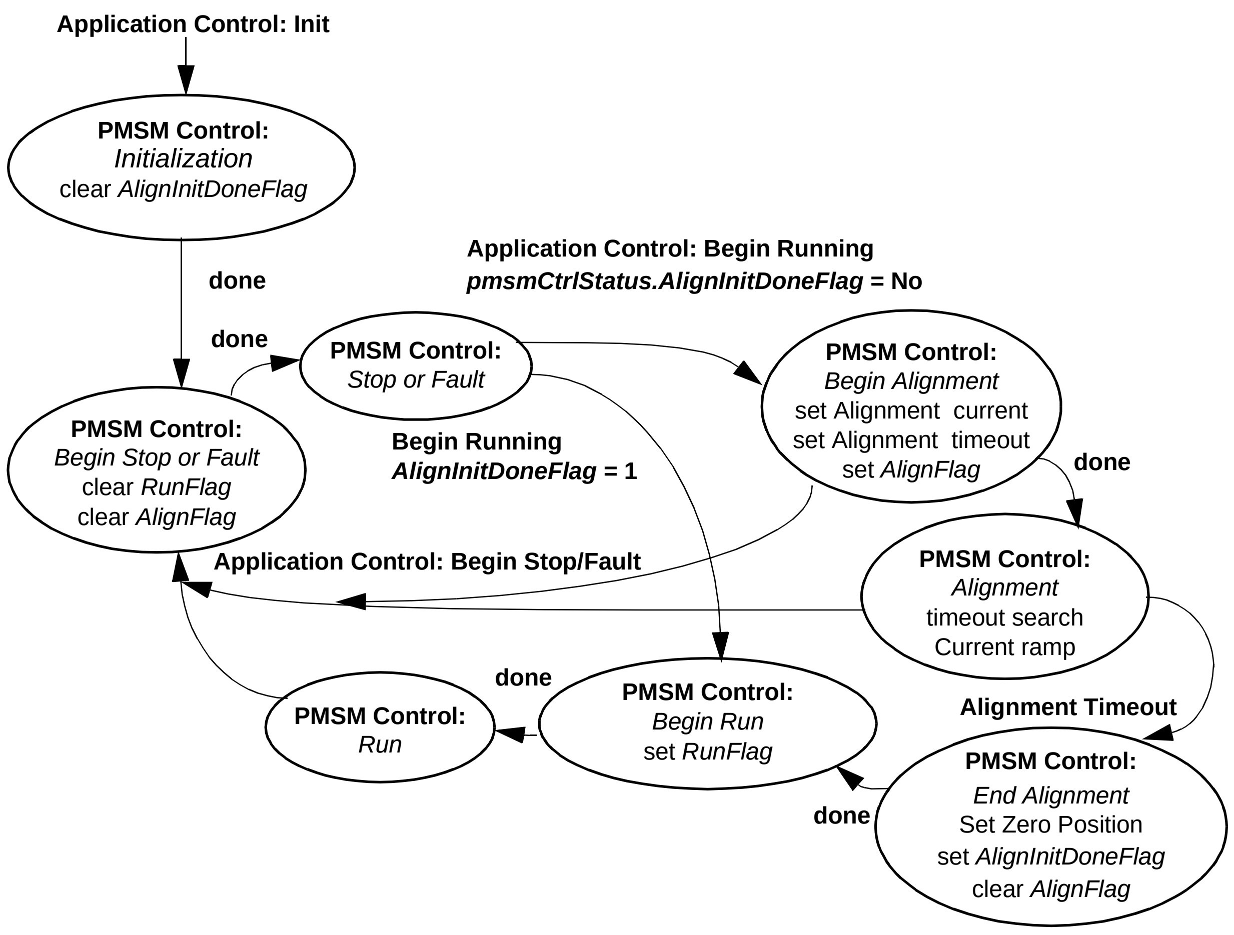

Application Control: Init
PMSM Control: Initialization clear AlignInitDoneFlag
done
Application Control: Begin Running
pmsmCtrlStatus.AlignInitDoneFlag = No
done
PMSM Control: Stop or Fault
PMSM Control: Begin Alignment set Alignment current set Alignment timeout set AlignFlag
PMSM Control: Begin Stop or Fault clear RunFlag clear AlignFlag
Begin Running
AlignInitDoneFlag = 1
done
Application Control: Begin Stop/Fault
PMSM Control: Alignment timeout search Current ramp
done
PMSM Control: Run
PMSM Control: Begin Run set RunFlag
Alignment Timeout
PMSM Control: End Alignment Set Zero Position set AlignInitDoneFlag clear AlignFlag
done

Figure 6-10. State Diagram - PMSM Control

When Application Control initializes, the PMSM Control subprocess initialization state is entered. The *AlignInitDoneFlag* is cleared, which means that alignment can proceed. The next PMSM Control state is *Begin Stop or Fault*. *RunFlag* and *AlignFlag* are cleared and the Stop or Fault state is entered. When Application Control: Begin Run, the PMSM Control subprocess enters the *Begin Alignment* or *Begin Run* state, depending on whether or not the alignment initialization has already proceeded (flagged by *AlignInitDoneFlag*). The alignment state is necessary for setting the zero position of position sensing; see **Section 4.3.1.3**. In the state *Begin Alignment*, the Alignment current and duration are set; the alignment is provided by setting desired current for *d_axis* to *i_Sd_Alignment* and *q_axis* to 0. The alignment state provides current control and timeout search. When alignment timeout occurs, *End Alignment* is entered. In that state, the Position Sensing Zero Position is set, so the position sensor is aligned with the real vector of the rotor flux. When the End Alignment state ends, the PMSM Control enters a regular Run state, where the motor is running at the required speed. If the Application Control state is set to *Begin Stop* or *Begin Fault*, the PMSM Control enters the *Begin Stop or Fault*, then the *Stop or Fault*.

6.3.4 Fault Control State Diagram

The state diagram of the Fault Control subprocess is illustrated in **Figure 6-11**. After the initialization, the fault conditions are searched. If any fault occurs, the *appFaultStatus* variable is set according to detected error; PWM is switched on (PWMEN bit = 0); the Fault state is entered. This state also causes Application Control: Fault state. If the faults are successfully cleared, this is signaled to the Application Control process. The Fault state is left when the Application Control Init state is entered.

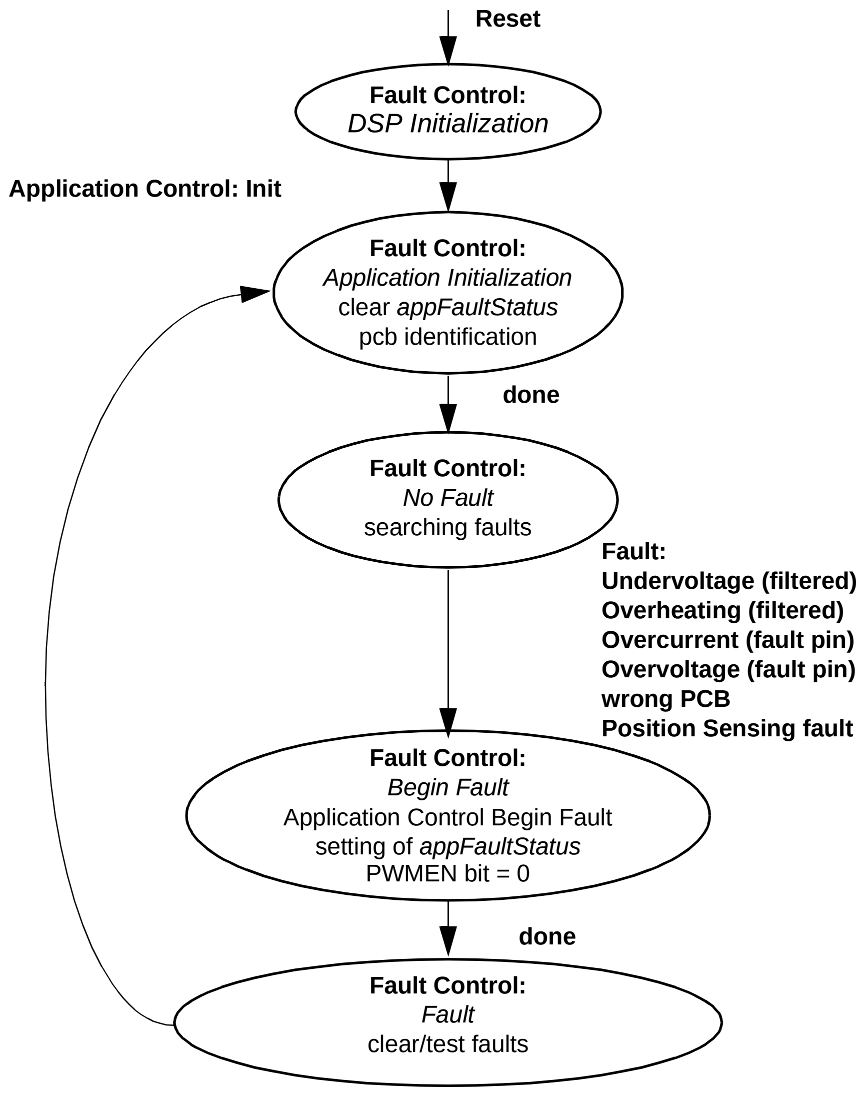

Reset
Fault Control: DSP Initialization
Application Control: Init
Fault Control: Application Initialization clear appFaultStatus pcb identification
done
Fault Control: No Fault searching faults
Fault: Undervoltage (filtered) Overheating (filtered) Overcurrent (fault pin) Overvoltage (fault pin) wrong PCB Position Sensing fault
Fault Control: Begin Fault Application Control Begin Fault setting of appFaultStatus PWMEN bit = 0
done
Fault Control: Fault clear/test faults

Figure 6-11. State Diagram Fault Control

6.3.5 Analog Sensing State Diagram

The state diagram of the Analog Sensing subprocess is shown in Figure 6-12. The DSP Initialization state initializes hardware modules like ADC, synchronization with PWM, etc. In *Begin Init*, Initialization is started, so the variables for initialization sum and the *InitDoneFlag* are cleared. In the *Init Proceed* state, the temperature, DCBus voltage and phase current samples are sensed and summed. After required analog sensing, Init samples are sensed, and the *Init Finished* state is entered. There, the samples' average is calculated, from the sum divided by the number of analog sensing Init samples. According to the phase currents' average value, the phase current offsets are initialized.

All variable sensing is initialized and the state *Init Done* is entered, so the variables from analog sensing are valid for other processes. In this state, temperature and DCBus voltage are filtered in first order filters.

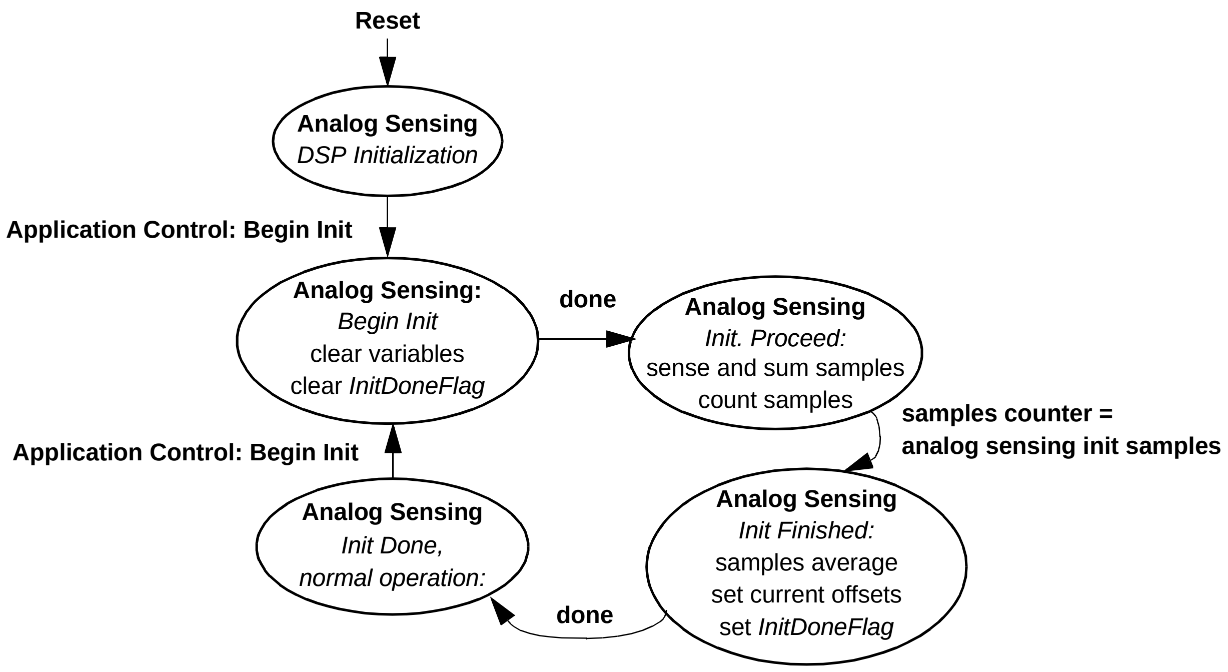


Figure 6-12. State Diagram - Analog Sensing

7. Implementation Notes

7.1 Scaling of Quantities

The PM synchronous motor vector control application uses a fractional representation for all real quantities except time.

The N-bit signed fractional format is represented using 1.[N-1] format (1 sign bit, N-1 fractional bits). Signed fractional numbers (SF) lie in the following range:

$$-1.0 \le \mathrm{SF} \le +1.0 - 2^{-[N-1]} \quad \text{(EQ 7-1.)}$$

For words and long-word signed fractions, the most negative number that can be represented is -1.0, whose internal representation is $8000 and $80000000, respectively. The most positive word is $7FFF or 1.0 - 2^{-15}, and the most positive long-word is $7FFFFFFF or 1.0 - 2^{-31}.

The following equation shows the relationship between the real and fractional representations:

$$\text{Fractional Value} = \frac{\text{Real Value}}{\text{Real Quantity Range Max}} \qquad \text{(EQ 7-2.)}$$

where:

Fractional Value is the fractional representation of the real value [Frac16]

Real Value is the real value of the quantity [V, A, RPM, etc.]

Real Quantity Range Max is the maximum of the quantity range, defined in the application [V, A, RPM, etc.]

The C language standard does not have any fractional variable type defined. Therefore, fractional operations are provided by CodeWarrior intrinsics functions (e.g. mult_r()). As a substitution for the fractional type variables, the application uses types Frac16 and Frac32. These are in fact defined as integer 16-bit signed variables and integer 32-bit signed variables. The difference between Frac16 and pure integer variables is that Frac16 and Frac32 declared variables should only be used with fractional operations (intrinsics functions).

A recalculation from real to a fractional form and Frac16, Frac32 value is made with the following equations:

$$\text{Frac16 Value} = 32768 \cdot \frac{\text{Real Value}}{\text{Real Quantity Range Max}} \qquad \text{(EQ 7-3.)}$$

for Frac16 16-bit signed value and:

$$\text{Frac32 Value} = 2^{31} \cdot \frac{\text{Real Value}}{\text{Real Quantity Range Max}} \qquad \text{(EQ 7-4.)}$$

for Frac32 32-bit signed value.

$$\text{Fractional Value} = \frac{\text{Real Value}}{\text{Real Quantity Range Max}} \qquad \text{(EQ 7-5.)}$$

Fractional form, a conversion from Fraction Value to Frac16 and Frac32 Value can be provided by the C language macro.

7.1.1 Voltage Scaling

Voltage scaling results from the sensing circuits of the hardware used; for details see the **3-Phase AC/BLDC High-Voltage Power Stage User’s Manual**.

Voltage quantities are scaled to the maximum measurable voltage, which is dependent on the hardware. The relationship between real and fractional representations of voltage quantities is:

$$u_{Frac} = \frac{u_{Real}}{\text{VOLT\_RANGE\_MAX}} \qquad \text{(EQ 7-6.)}$$

where:

u_{Frac}	Fractional representation of voltage quantities	[-]
u_{Real}	Real voltage quantities in physical units	[V]
VOLT_RANGE_MAX	Defined voltage range maximum used for scaling in physical units	[V]

In the application, the VOLT_RANGE_MAX value is the maximum measurable DCBus voltage:

VOLT_RANGE_MAX = 407 V

All application voltage variables are scaled in the same way (*u_dc_bus*, *u_dc_bus_filt*, *u_SAlphaBeta*, *u_SDQ*, *u_SAlphaBeta*, and so on).

7.1.2 Current Scaling

Current scaling also results from the sensing circuits of the hardware used; for details see **3-Phase AC/BLDC High-Voltage Power Stage User's Manual**.

The relationship between real and fractional representation of current quantities is:

$$i_{Frac} = \frac{i_{Real}}{\text{CURR\_RANGE\_MAX}} \qquad \text{(EQ 7-7.)}$$

where:

i_{Frac}	Fractional representation of current quantities	[-]
i_{Real}	Real current quantities in physical units	[A]
CURR_RANGE_MAX	Defined current range maximum used for scaling in physical units	[A]

In the application, the CURR_RANGE_MAX value is the maximum measurable current:

CURR_RANGE_MAX = 5.86 A

All application current variables are scaled in the same way (components of *i_Sabc_comp*, *i_SAlphaBeta*, *i_SDQ*, *i_SDQ_desired*, *i_Sd_Alignment* and so forth).

Note: As shown in **3-Phase AC/BLDC High-Voltage Power Stage User's Manual**, the current sensing circuit provides measurement of the current in the range from CURR_MIN = -2.93A to CURR_MAX = +2.93A, giving the voltage for the ADC input ranges from 0 to 3.3V with 1.65V offset. The DSP5680x's ADC converter is able to automatically cancel (subtract) the offset. The fractional representation of the measured current is then in the range <-0.5, 0.5), while the possible representation of a fractional value is <-1,1), as shown in **(EQ 7-3.)**. Therefore, CURR_RANGE_MAX is calculated according to the following equation:

$$\text{CURR\_RANGE\_MAX} = \text{CURR\_MAX-CURR\_MIN} = 2 \cdot \text{CURR\_MAX} \qquad \text{(EQ 7-8.)}$$

7.1.3 Speed Scaling

Speed quantities are scaled to the defined speed range maximum, which should be set lower than all speed variables in the application, so it was set higher than the maximum mechanical speed of the drive. The relationship between real and fractional representation of speed quantities is:

$$\omega_{Frac} = \frac{\omega_{Real}}{\text{OMEGA\_RANGE\_MAX}} \qquad \text{(EQ 7-9.)}$$

where:

ω_{Frac}	Fractional representation of speed quantities	[-]
ω_{Real}	Real speed quantities in physical units	[rpm]
OMEGA_RANGE_MAX	Defined speed range maximum used for scaling in physical units	[rpm]

In the application, the OMEGA_RANGE_MAX value is defined as:

OMEGA_RANGE_MAX = 6000rpm

Other speed variables are scaled in the same way (*omega_reqPCM_mech*, *omega_desired_mech*, *omega_required_mech*, *omega_reqMAX_mech*, *omega_reqMIN_mech*, *omega_actual_mech*).

The relation between speed scaling and speed measurement with encoder is described in **Section 4.3.1.2**. In the final software, the constant OMEGA_SCALE is identical with the scaling constant *k* in equations **(EQ 4-1.)** and **(EQ 4-3.)**, and OMEGA_RANGE_MAX is ω_{Max}.

7.1.4 Position Scaling

Position Scaling is described in **Section 4.3.1.1**

7.1.5 Temperature Scaling

As shown in **Section 4.3.4**, the temperature variable does not have a linear dependency.

7.2 PI Controller Tuning

The application consists of four PI controllers. Two controllers are used for the I_d and I_q currents, one for speed control and the other for field-weakening. The controller’s constants are given by simulation in Mathlab and were experimentally specified. A detailed description of controller tuning is beyond the scope of this application note.

7.3 Subprocesses Relation and State Transitions

As shown in **Section 6.2** and **Section 6.3**, the software is split into subprocesses according to functionality. The application code is designed to be able to extract individual processes, such as Analog Sensing, and use them for customer applications. The C language functions dedicated for each process are located in one place in the software, so they can be easily used for other applications. The function naming usually starts with the name of the process, for example, *AnalogSensingInitProceed()*.

As **Section 6.3** shows, the processes’ or subprocesses’, state transients have some mutual relations. For example, Application Control: Begin Initialization is a condition for transient of the Analog Sensing process: Init Done to Begin Init state. In the code, the interface between processes is provided via “trigger” functions. The naming convention is for these functions is: *<ProcessName><State>Trig()*.

The functionality will be explained in following example:

The "trigger" function *Process1StateTrig()* is called from *process1*. The transient functions of *process2*, *process3*,etc., which must be triggered by *Process1State*, are put inside the Process1StateTrig().

7.4 Run/Stop Switch and Button Control

In the DSP56F805EVM and the DSP56F807EVM, the Run/Stop switch is connected to a GPIO pin. The state of the Run/Stop switch can be read directly from the GPIO Data Register. In the DSP56F803EVM, there are fewer free GPIO pins, so the switch is connected to ADC input AN7 and the switch status is obtained with the AD Converter. The switch logical status is obtained by comparing the measured value with the threshold value.

Also, the buttons are usually connected to GPIO pins. But in this application, the buttons are connected to IQRA and IRQB interrupts to allow the ability to run the same code on the DSP56F803, DSP56F805, and DSP56F807 EVMs. Since the DSP56F803 has no free GPIO pins for user buttons, the application uses buttons connected to IRQA/B pins. The EVM boards do not resolve the button contact bouncing, which may occur while pushing and releasing the button, so this issue must be resolved by software.

The IRQA and IRQB interrupts are maskable interrupts connected directly to the DSP's core. The IRQA and IRQB lines are internally synchronized with the processor's internal clock and can be programmed as level-sensitive or edge-sensitive. The IRQA and IRQB interrupts have no interrupt flag, so this flag is replaced by a software flag. The following algorithm is used to check the state of the IRQ line and is described for one interrupt.

The IRQ interrupt is set to be negative-level-sensitive. When the button is pressed, the logical level 0 is applied on the IRQ line and the interrupt occurs; see **Figure 7-1**. To avoid multiple calls of ISR due to contact bounces, the ISR disables the IRQ interrupt, sets the debounce counter to a predefined value and sets the variable *buttonStatus* to 1. The variable *buttonStatus* represents the interrupt flag. Using the DSP56F80x's software timer, the *ButtonProcessing* function is periodically called, as shown in **Figure 7-1**. The function *ButtonProcessing* decrements the debounce counter and if the counter is 0, the IRQ interrupt is again enabled. The button press is checked by the *ButtonEdge* function; see **Figure 7-2**. When the variable *buttonStatus* is set, the *ButtonEdge* function returns "1" and clears *buttonStatus*. When the variable *buttonStatus* is not set, the *ButtonEdge* function returns "0".

According to the *ButtonProcessing* calling period, the value of the debounce counter should be set close to 180ms. This value is sufficient to prevent multiple IRQ ISR calls due to contact bounces.

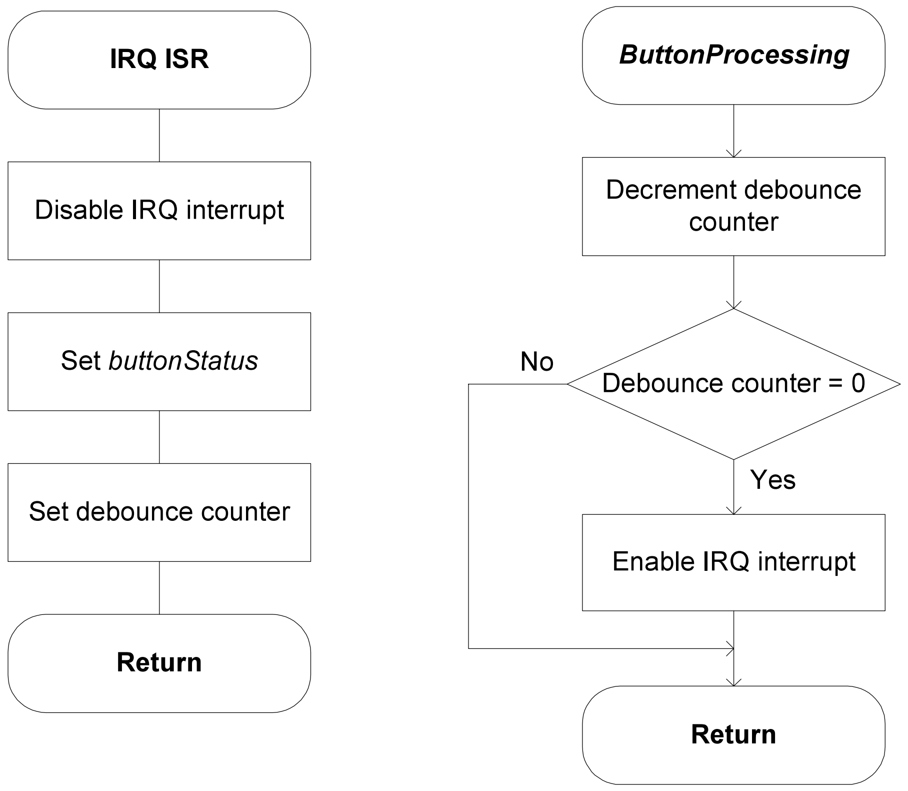


Figure 7-1. Button Control - IRQ ISR and ButtonProcessing

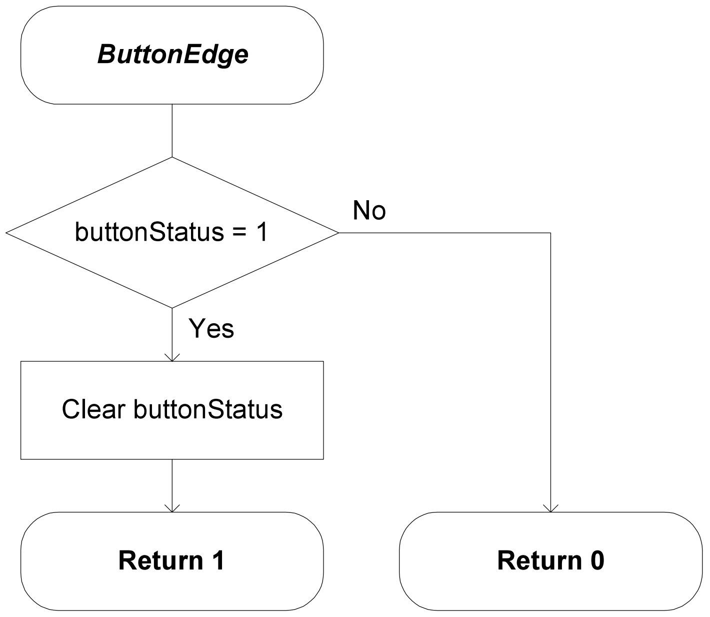


Figure 7-2. Button Control - ButtonEdge

8. SDK Implementation

The Motorola Embedded SDK is a collection of APIs, libraries, services, rules and guidelines. This software infrastructure is designed to let DSP5680x software developers create high-level, efficient, portable code. The application code is available in the SDK. This chapter describes how the PM synchronous motor vector control application is written under the SDK.

8.1 Drivers and Library Function

The PM synchronous motor vector control application uses the following drivers:

- ADC driver
- Quadrature Timer driver
- Quadrature Decoder driver
- PWM driver
- LED driver
- SCI driver
- PC master software driver
- Switch driver (only for DSP56F805EVM and DSP56F807EVM)
- Brake driver

All drivers are included in *bsp.lib* library.

The PM synchronous motor vector control application uses the following library functions:

- *cptrfmClarke* (Clarke transformation, *mcfunc.lib* library)
- *cptrfmPark* (Park transformation, *mcfunc.lib* library)
- *cptrfmParkInv* (Inverse Park transformation, *mcfunc.lib* library)
- *mcElimDcBusRip* (DC bus ripple elimination, *mcfunc.lib* library)
- *mcPwmIct* (3-ph sinewave modulation, *mcfunc.lib* library)
- *rampGetValue* (ramp generation, *mcfunc.lib* library)
- *switchcontrol* (switch control, *mcfunc.lib* library)
- *boardId* (board identification, *bsp.lib* library)

8.2 *Appconfig.h* File

The purpose of the *appconfig.h* file is to provide a mechanism for overwriting default configuration settings, which are defined in the *config.h* file.

There are two *appconfig.h* files. The first *appconfig.h* file is dedicated for External RAM (*..\ConfigExtRam* directory) and second one is dedicated for Flash memory (*..\ConfigFlash* directory). In the PM synchronous motor vector control application, both files are identical, with these exceptions:

- The *appconfig.h* for the ExtRAM target contains a definition of the RAM memory support
- The *appconfig.h* for the Flash target contains a definition of the FLASH support
- The *appconfig.h* for the ExtRAM target contains a PC master software recorder buffer 25000 samples long, while *appconfig.h* for the Flash target contains a PC master software recorder buffer for only 100 samples, due to the limited Flash memory size
- The *appconfig.h* for the DSP56F805EVM and DSP56F807EVM contains the definition of a switch driver, while the *appconfig.h* for the DSP56F803EVM does not

The *appconfig.h* file can be divided into two sections. The first section defines which components of SDK libraries are included in the application; the second part overwrites components' standard setting during their initialization.

8.3 Drivers' Initialization

Each peripheral on the DSP chip or on the EVM board is accessible through a driver. The driver initialization of all peripherals used is described in this section. For a more-detailed description of drivers, see the **Targeting Motorola DSP5680x Platformm** manual.

To use a driver, following these steps:

- Include the driver support to the *appconfig.h*
- Fill the configuration structure in the application code for specific drivers, which depends on driver type
- Initialize the configuration setting in *appconfig.h* for specific drivers, which depends on driver type
- Call the *open* (create) function

Access to individual driver functions is provided by the *ioctl* function call.

8.4 Interrupts

The SDK serves the interrupt routine calls and automatically clears interrupt flags. The user defines the callback functions called during interrupts. The callback functions are assigned during driver initialization--*open()*. The callback function assignment is defined as one item of the initialization structure, which is used as a parameter of the *open()*function. Some drivers define the callback function in the *appconfig.h* file.

8.5 PC Master Software

PC master software was designed to provide a debugging, diagnostic and demonstration tool for development of algorithms and applications. It consists of components running on PCs and parts running on the target DSP, connected by an RS-232 serial port. A small program is resident in the DSP that communicates with the PC master software to parse commands, return status information to the PC, and process control information from the PC. The PC master software executing on a PC uses Microsoft Internet Explorer as a user interface to the PC.

The PC master software application is a part of the Motorola Embedded SDK and may be selectively installed during SDK installation.

To enable the PC master software operation on the DSP target board application, add the following lines to the *appconfig.h* file:

```
#define INCLUDE_SCI          /* SCI support */
#define INCLUDE_PCMASTER     /* PC master software support */
```

It automatically includes the SCI driver and installs all necessary services.

The default baud rate of the SCI communication is 9600 and is set automatically by the PC master software driver.

A detailed PC master software description is provided in the **PC Master Software User's Manual**.

The 3-Phase PM Synchronous Motor Vector Control utilizes PC master software for remote control from a PC. It enables the user to:

- Control the PC master software
- Start/stop control
- Set the motor speed

Variables read by the PC master software as a default and displayed to the user are:

- Required Speed of the motor
- Actual Speed of the motor
- Application status
  - — Init
  - — Stop
  - — Run
  - — Fault
- DCBus voltage level
- Identified line voltage
- Fault Status
  - — No_Fault
  - — Overvoltage
  - — Overcurrent
  - — Undervoltage
  - — Overheating
- Identified Power Stage

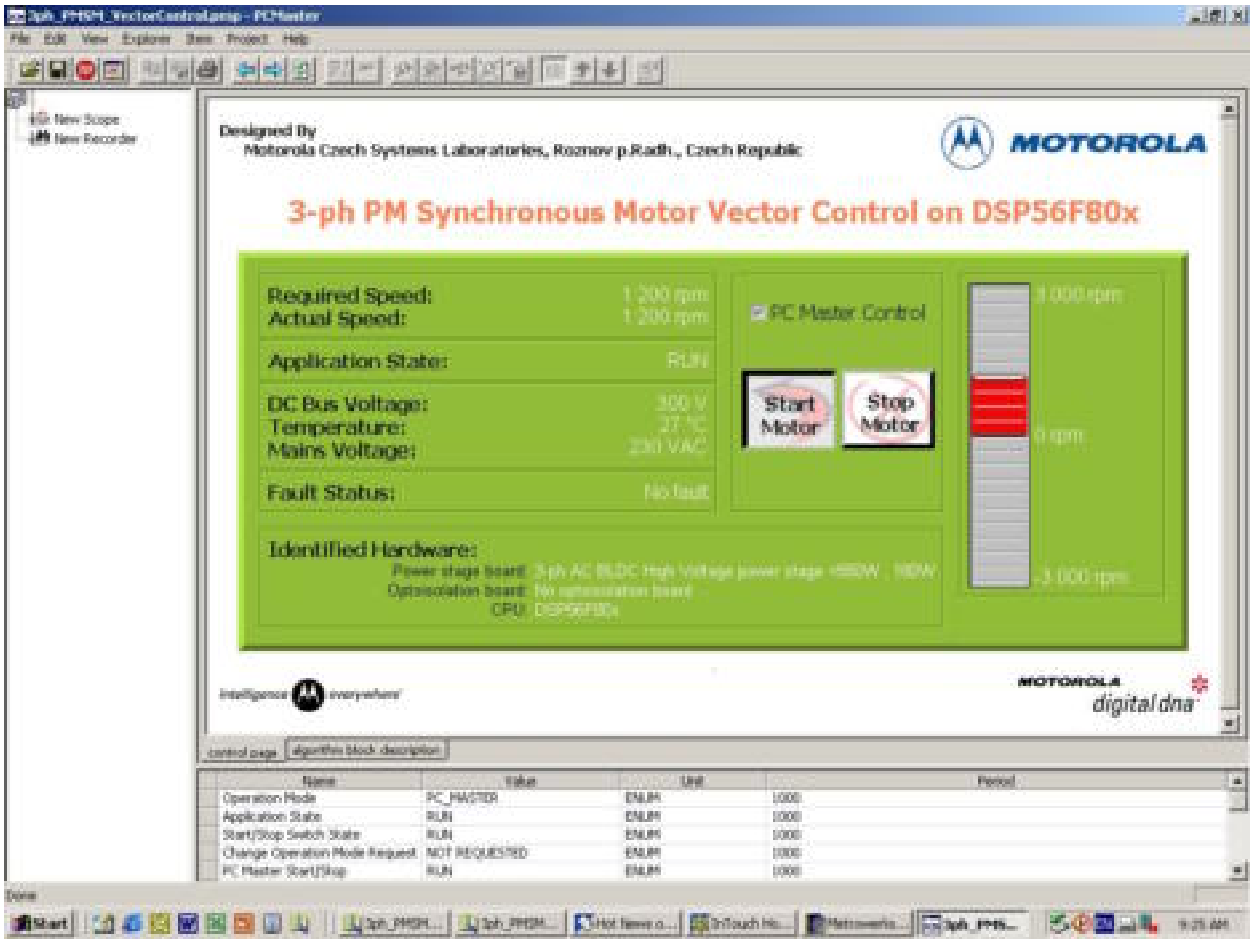
The profiles of required and actual speeds, together with the desired I_d and I_q currents can be seen in the Speed Scope window.

The course of quickly-changing variables can be observed in the Recorder windows, displayed by the PC master's Speed Scope. The Recorder can **only** be used when the application is running from **External RAM**, due to the limited on-chip memory. The length of the recorded window may be set in *Recorder Properties* => bookmark *Main* => *Recorded Samples*. The dedicated memory space is defined in the *appconfig.h* file of the ExtRAM target. The recorder samples are taken every 125µsec.

The following records can be captured:

- Required speed
- Actual speed
- Desired I_d current
- Desired I_q current

The PC master software Control Page is illustrated in **Figure 8-1**. The profiles of the required and actual speeds can be seen in the Speed Scope window.



Designed By
Motorola Czech Systems Laboratories, Roznov p.Radh., Czech Republic

3-ph PM Synchronous Motor Vector Control on DSP56F80x

Required Speed: 1 200 rpm
Actual Speed: 1 200 rpm
Application State: RUN
DC Bus Voltage: 300 V
Temperature: 27 °C
Mains Voltage: 230 VAC
Fault Status: No fault

PC Master Control

Identified Hardware:
Power stage board: 3-ph AC BLDC High Voltage power stage +550W , 180W
Optoisolation board: No optoisolation board
CPU: DSP56F80x

Name	Value	Unit	Period
Operation Mode	PC_MASTER	ENUM	1000
Application State	RUN	ENUM	1000
Start/Stop Switch State	RUN	ENUM	1000
Change Operation Mode Request	NOT REQUESTED	ENUM	1000
PC Master Start/Stop	RUN	ENUM	1000

Figure 8-1. PC Control Window

9. DSP Memory Use

Table 9-1 shows how much memory is needed to run the 3-phase PM Synchronous Vector Control drive using the quadrature encoder. A part of the DSP memory is still available for other tasks.

Table 9-1. RAM and FLASH Memory Use by SDK2.4 and CW4.1

Memory (in 16-bit Words)	Available for DSP56F803 DSP56F805	Available for DSP56F807	Application Used + Stack	Application Used without PC Master Software, SCI
Program FLASH	32K	60K	11520	7740
Data FLASH	4K	8K	617	617
Program RAM	512	2K	36	36
Data RAM	2K	4K	745 + 352 stack	452 + 352 stack

10. References

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