AN2584

Integrated Power Factor Correction (PFC) and Sensorless Field Oriented Control (FOC) System for Microchip 32-bit Microcontrollers

Introduction

In recent years, the motor control industry has been focusing on designing power efficient motor control drives for a wide variety of applications. The consumer demand for improved power quality standards is driving this trend. The power quality can be enhanced by implementing Power Factor Correction (PFC), and efficient control of a motor can be realized using Sensorless Field Oriented Control (FOC) techniques. The appliance industry often requires low-cost implementation of these algorithms. This can be achieved by integrating PFC and Sensorless FOC algorithms on a single microcontroller. Microchip's 32-bit microcontrollers have sufficient computational and peripheral resources to support PFC and Sensorless FOC on a single microcontroller.

This application note describes the process of integrating two complex applications: PFC and Sensorless FOC. These applications are implemented on a Permanent Magnet Synchronous Motor (PMSM). In addition, this application note also describes the integration of the algorithms, lists the necessary hardware requirements, and provides the guidelines to optimize the development procedure.

The integrated solution is based on these application notes:

- AN1106, *Power Factor Correction in Power Conversion Applications Using the dsPIC DSC*
- AN2520, *Sensorless Field Oriented Control (FOC) for a Permanent Magnet Synchronous Motor (PMSM) Using a PLL Estimator and Equation-based Flux Weakening (FW)*

Note: Both of these documents are available for download from the Microchip web site at: www.microchip.com.

The application note AN1106, describes the Power Factor Correction (PFC) method. The application note AN2520, describes the Sensorless Field Oriented Control (FOC) method. The detailed digital design and implementation techniques are provided in these application notes. This application note is an addendum to the application notes listed above.

The low cost and high performance capabilities of the microcontroller (MCU) combined with a wide variety of power electronic peripherals, such as the Analog-to-Digital Converter (ADC), Pulse Width Modulator (PWM), and on-chip Op amps, and Comparator, enable the digital design and the implementation of such a complex application to be simpler and easier.

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1. Digital PFC and Motor Control

The majority of motor control systems often use PFC as the first stage of the system. Without an input PFC stage, the current drawn will have significant harmonic content due to the presence of switching elements of the inverter. In addition, since motor loads are highly inductive, the input currents will induce significant reactive power into the input system, thereby reducing overall efficiency of the system. A PFC stage which is a front-end converter of a motor control application, provides better output voltage regulation and reduces harmonic content of the input current drawn. The standard boost converter topology with average current mode control is the preferred method for implementing digital PFC in these applications.

The PMSM is driven in Speed Control mode using the Dual Shunt Sensorless FOC method. The Sensorless FOC technique overcomes restrictions placed on some applications that cannot deploy position or speed sensors. The speed and position of the PMSM are estimated by measuring phase currents. With a constant rotor magnetic field produced by a permanent magnet on the rotor, the PMSM is very efficient when used in appliances. When compared with induction motors, PMSMs are more powerful for the same given size. They are also less noisy than DC motors, since brushes are not involved. Therefore, the PMSM is chosen for this application.

2. Why Use a 32-bit Microcontroller?

Microchip's 32-bit microcontrollers are ideal for a variety of complex applications running multiple algorithms at different frequencies and using multiple peripherals to drive the various circuits. These applications (for example, washing machines, refrigerators, and air conditioners) use various motor control peripherals to precisely control the speed of the motor at various operating loads.

The following features of Microchip's 32 bit microcontrollers make them an excellent choice for integrated PFC and FOC Motor Control applications:

PIC32MK Family Features:

CPU

- 32-bit MIPS32® microAptiv™ MCU core - 120 MHz (198 DMIPS)
- DSP-enhanced core
- Double-precision Floating Point Unit (FPU) - IEEE 754 Compliant

Analog

- Up to six dedicated 12-bit ADC channels (up to 3.75 msps) plus one shared 12-bit ADC channel
- Up to four on-chip Op amp modules
- Up to five on-chip Analog Comparator modules
- Up to three 12-bit DAC modules

PWM

- Up to 12 PWM pairs (8.33 ns resolution) capable of generating complimentary PWM with dead-time in Edge-Aligned and symmetric/asymmetric Center-Aligned modes
- PWM channels capable of generating precise and synchronized ADC triggers without any software intervention
- Asynchronous Fault inputs allows fast response (50 ns) PWM shutdown under Fault condition without any software intervention

Position Sensing

- On-chip QEI interfaces with incremental encoders to obtain rotor mechanical position

3. System Overview

Figure 3-1 shows a block diagram of the integrated PFC and Sensorless FOC system.

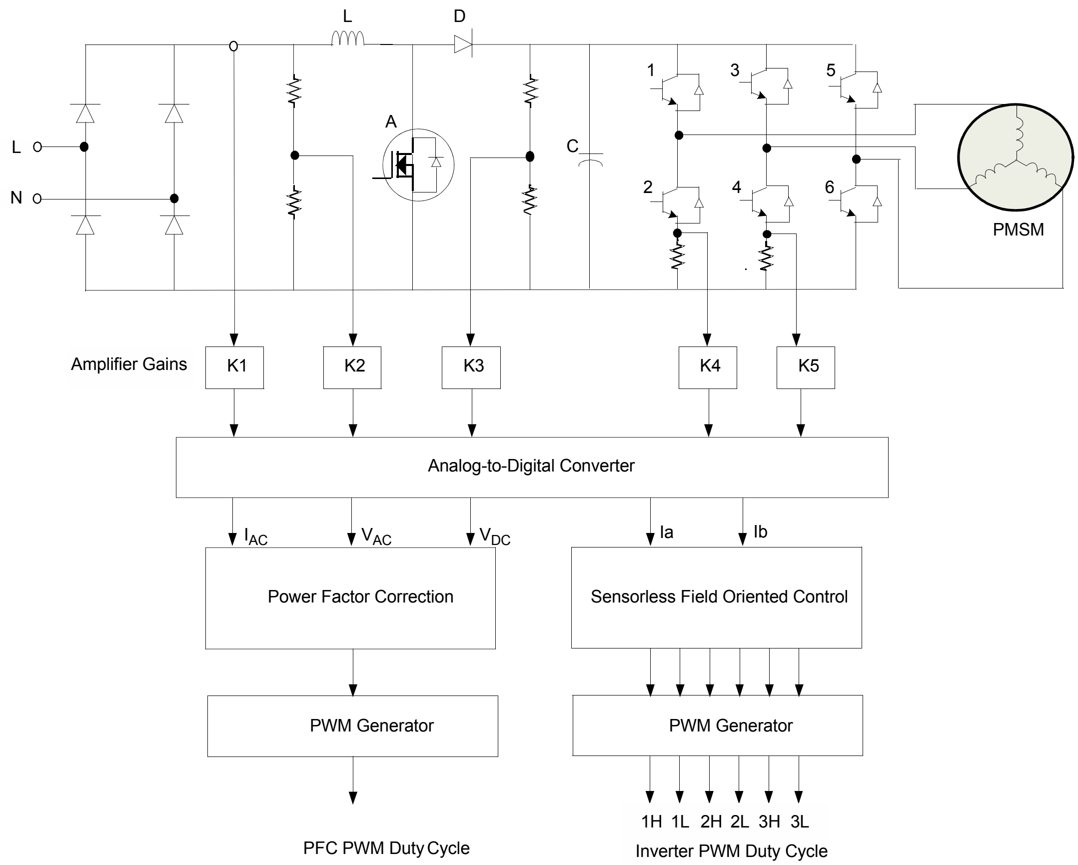
The first stage is a rectifier stage that converts the input line voltage into a rectified AC voltage. The rectified AC voltage is the input to the second stage, which is the boost converter stage.

During the second stage, the boost converter boosts the input voltage and shapes the inductor current similar to that of the rectified AC voltage. This is achieved by implementing digital power factor correction. The Average Current Mode Control method is used to implement PFC. In this control method, the output DC voltage is controlled by varying the average value of the current amplitude signal reference, which is calculated digitally.

The third and the final stage of the integrated system is a three-phase inverter stage that inverts the DC voltage into a three-phase AC voltage. The inverted three-phase AC voltage is the input to the PMSM. This stage is controlled by implementing the Sensorless FOC strategy on the device. The Sensorless FOC controls the stator currents flowing into the PMSM to meet the desired speed and torque requirements of the system. The position and speed information is estimated from the stator currents. Please refer to AN2520, *Sensorless Field Oriented Control (FOC) for a Permanent Magnet Synchronous Motor (PMSM) Using a PLL Estimator and Equation-based Flux Weakening (FW)*, for details on the rotor position estimation using stator currents.

The integrated system uses five compensators to implement PFC and Sensorless FOC technique. The PFC technique uses two compensators to control the voltage and current control loops, and the Sensorless FOC technique uses three compensators to control the speed control loop, torque control loop, and flux control loop. All of the compensators are realized by implementing Proportional-Integral (PI) controllers.

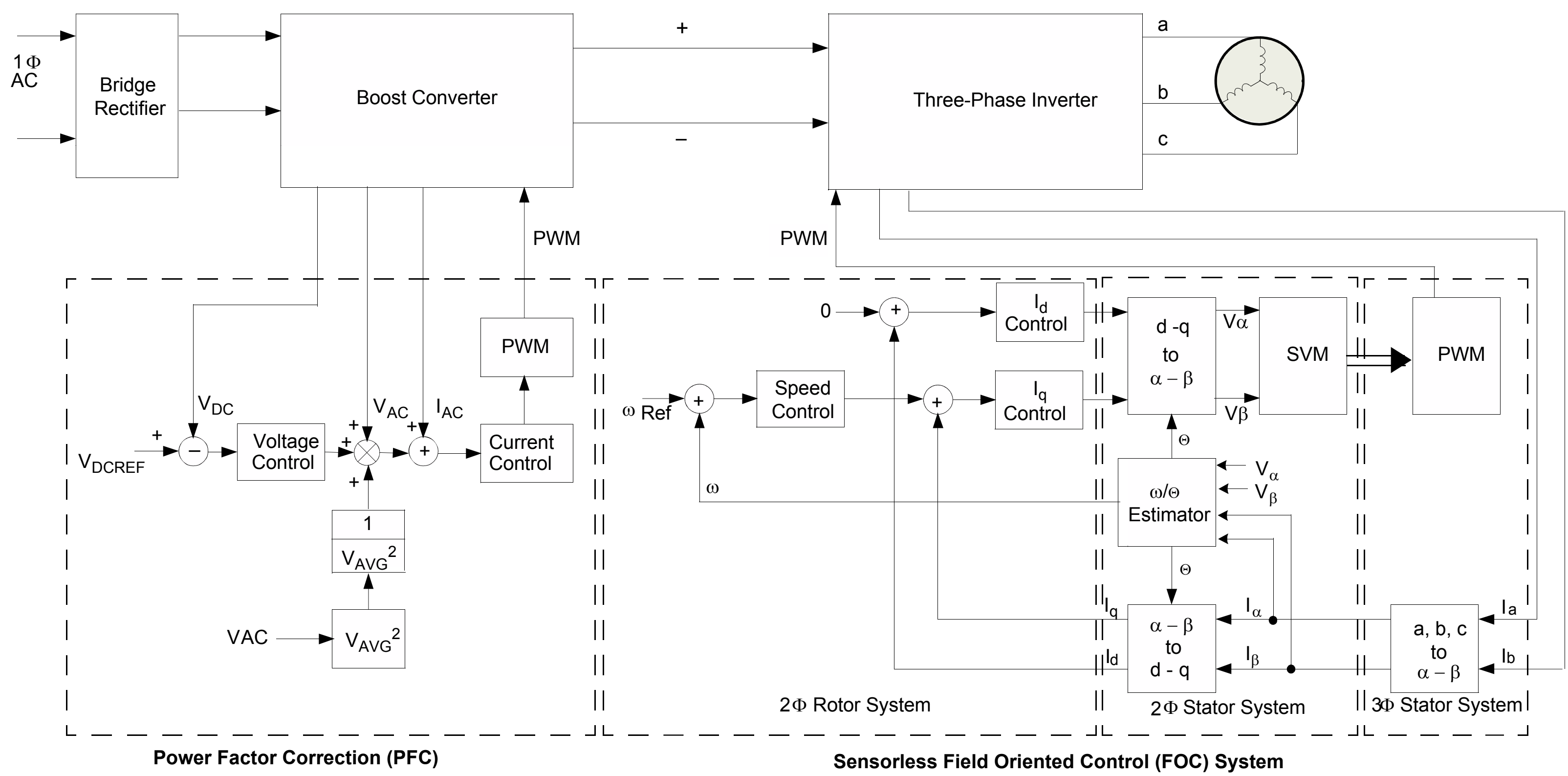
Figure 3-1. Integrated PFC and Sensorless FOC System Block Diagram



4. Digital Implementation of PFC and Sensorless FOC Algorithms

Figure 4-1 shows a block diagram of the PFC and Sensorless FOC control loops implemented digitally using a 32-bit microcontroller.

Figure 4-1. Digital PFC and Sensorless FOC Block Diagram



4.1 Digital Power Factor Correction

The inductor current (I_{AC}), input rectified AC voltage (V_{AC}), and DC Output Voltage (V_{DC}) are used as feedback signals to implement the digital PFC. These signals are scaled by hardware gains set by internal/external differential Op amp gains, and are input to the analog channels of the ADC module.

The PFC algorithm uses three control loops: the voltage control loop, current control loop, and the voltage feed forward control loop.

The voltage compensator uses the reference voltage and actual output voltage as inputs to compute the error and compensate for the variations in output voltage. The output voltage is controlled by varying the average value of the current amplitude reference.

The current amplitude reference is calculated digitally by computing the product of the rectified input voltage, the voltage error compensator output, and the voltage feed-forward compensator output.

The rectified input voltage is multiplied to enable the current reference to have the same shape as the input voltage wave shape. The current signal should match the rectified voltage as closely as possible to have a high power factor.

The voltage feed-forward compensator is essential for maintaining a constant output power for a given load because it compensates for variations in the input voltage. Once the current reference is computed, it is fed to the current compensator. The output of the current compensator determines the duty cycle of the PWM pulses. The boost converter can be driven either by the Output Compare module or the PWM module.

Refer to application note AN1106, *Power Factor Correction in Power Conversion Applications Using the dsPIC®DSC* (DS01106), for information about the system design and digital implementations of this control method.

4.2 Sensorless Field Oriented Control

The phase currents, I_a and I_b, are used as feedback signals to implement the Sensorless FOC technique.

Since the PMSM has a balanced three-phase winding,we know that $I_a + I_b + I_c = 0$. Therefore, we can derive the third-phase current, I_c from I_a and I_b. The three-phase currents are first converted to a two-phase stator system by using Clarke transformation before being converted to a two-phase rotor system by using Park transformation. This conversion provides two computed current components: I_d and I_q. The magnetizing flux is a function of the current Id and the rotor torque is a function of the current I_q.

A position estimator estimates the rotor position and speed information. The motor model uses voltages and currents to estimate the position. The motor model essentially has a position observer to indirectly derive the rotor position. The PMSM model is based on a DC motor model.

After the speed is determined by mathematical estimation, the error between the desired speed and the estimated speed is fed to the speed compensator. The speed compensator produces an output that acts as a reference to the I_q compensator. For a surface mounted permanent magnet synchronous motor, the reference to the Id compensator is zero value. The PI controllers for I_q and I_d compensate errors in the torque and flux, thereby producing V_d and V_q as the output signals respectively.

The Inverse Park transformation and Space Vector Modulation (SVM) techniques are applied to generate the duty cycle for the Insulated Gate Bipolar Transistors (IGBTs). The motor control PWM module is used to generate PWM pulses.

Refer to application note AN1078, *Sensorless Field Oriented Control of PMSM Motors* (DS01078), for information about how to design, implement, and tune the compensator.

The implementation details and the hardware configuration details required to develop the integrated system are discussed in the following sections.

5. Integrated PFC and Sensorless FOC Implementation On a PIC32MK Device

5.1 PWM Configuration

Integrated implementation of PFC and FOC requires four PWM channels. Details of the PWM channel configuration are shown in Table 5-1.

Table 5-1. PWM Configuration for Integrated PFC and FOC Implementation On PIC32MK PIM Using the MCHV-3

Application	Number of PWM Channels	PWM Frequency	PWM Alignment Mode	PWM Output Mode	Control Loop Rate
PFC	1 (PWM5)	80 kHz	Edge-Aligned	Single-Ended	40 kHz
FOC	3 (PWM1, PWM2, PWM3)	20 kHz	Center-Aligned	Complementary	20 kHz

5.2 ADC Configuration

Each PWM channel on a 32-bit microcontroller is capable of independently triggering an ADC conversion on any of the analog input. Integrated PFC and sensorless FOC implementation requires to sense six analog inputs, as shown in Table 5-2. PFC-related analog input conversions are triggered simultaneously by PFC PWM Channel and sensorless FOC-related analog input conversions are triggered simultaneously by any one of the three FOC PWM Channels. Although DC Bus Voltage sensing is required for both PFC and FOC, its analog conversion is triggered by PFC PWM channel as PFC control loop runs at faster rate than FOC control loop.

Table 5-2. ADC Configuration for Integrated PFC and FOC Implementation On the PIC32MK PIM Using the MCHV-3

Analog Input	Application	ADC Module	ADC Trigger	Sample Rate
AC Line Voltage	PFC	ADC4	PFC PWM Channel	40 kHz
PFC Inductor Current	PFC	ADC0	PFC PWM Channel	40 kHz
DC Bus Voltage	PFC/FOC	ADC7 (Shared ADC)	PFC PWM Channel	40 kHz
Phase A Motor Current	FOC	ADC3	FOC PWM Channel	20 kHz
Phase B Motor Current	FOC	ADC1	FOC PWM Channel	20 kHz
Speed Reference Potentiometer	FOC	ADC7(Shared ADC)	FOC PWM Channel	20 kHz

5.2.1 ADC Interrupts

PFC and FOC control loops are executed in their respective interrupt service routines. As PFC control loop executes at a faster rate than FOC control loop, the interrupt service routine for PFC has a higher priority over FOC.

Figure 5-1 shows the timing diagram of the integrated PFC and Sensorless FOC system. Figure 5-2 through Figure 5-4 show the state flow diagrams of the integrated system.

Figure 5-1. Timing Diagram

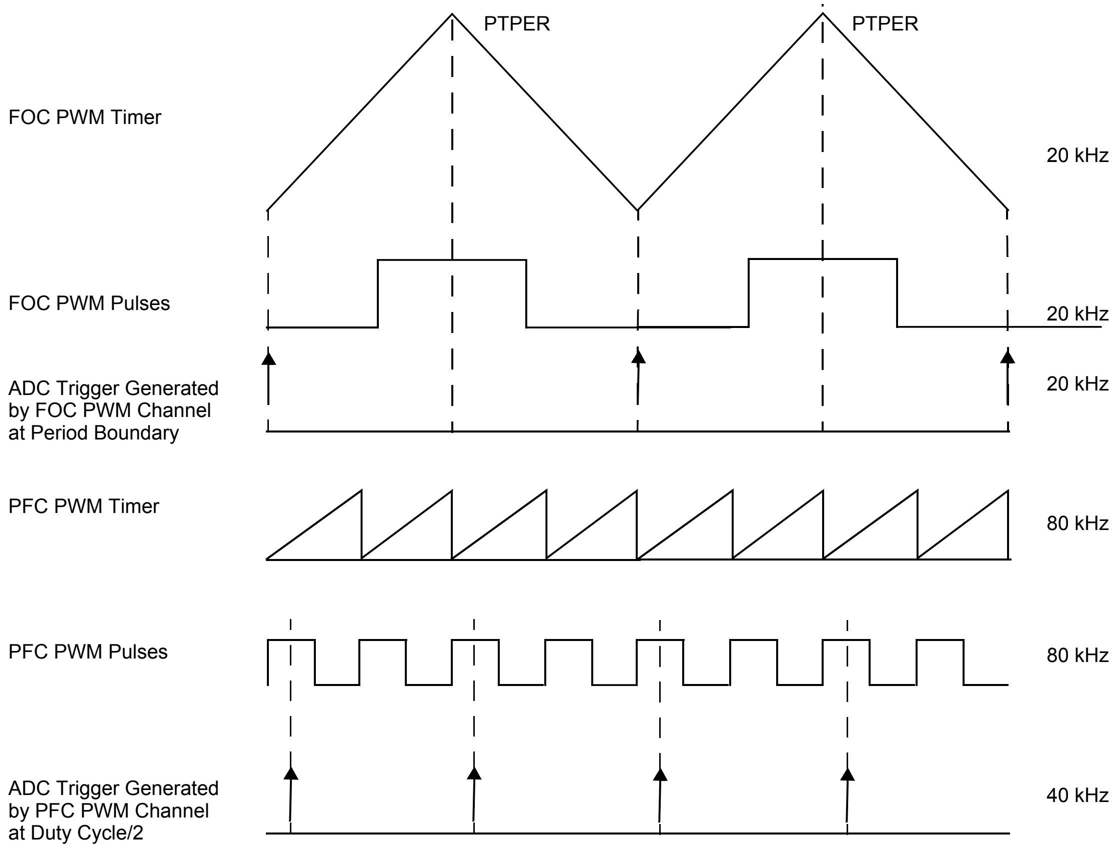


Figure 5-2. State Flow Diagram of Integrated System

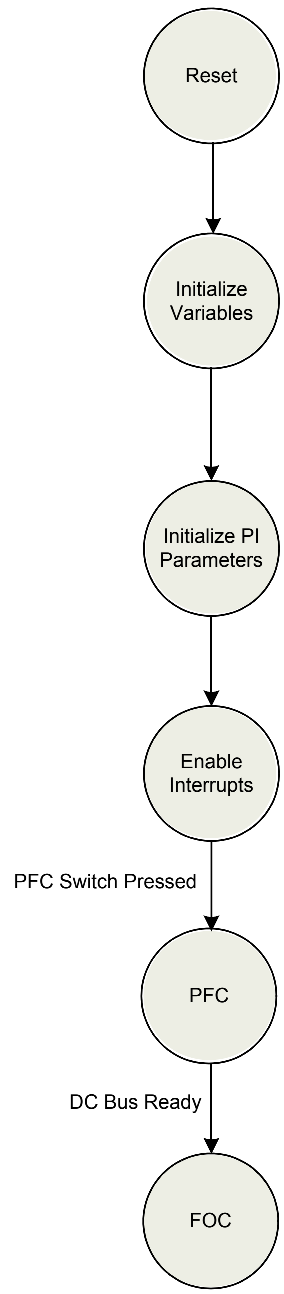


Figure 5-3. State Flow Diagram of Digital PFC

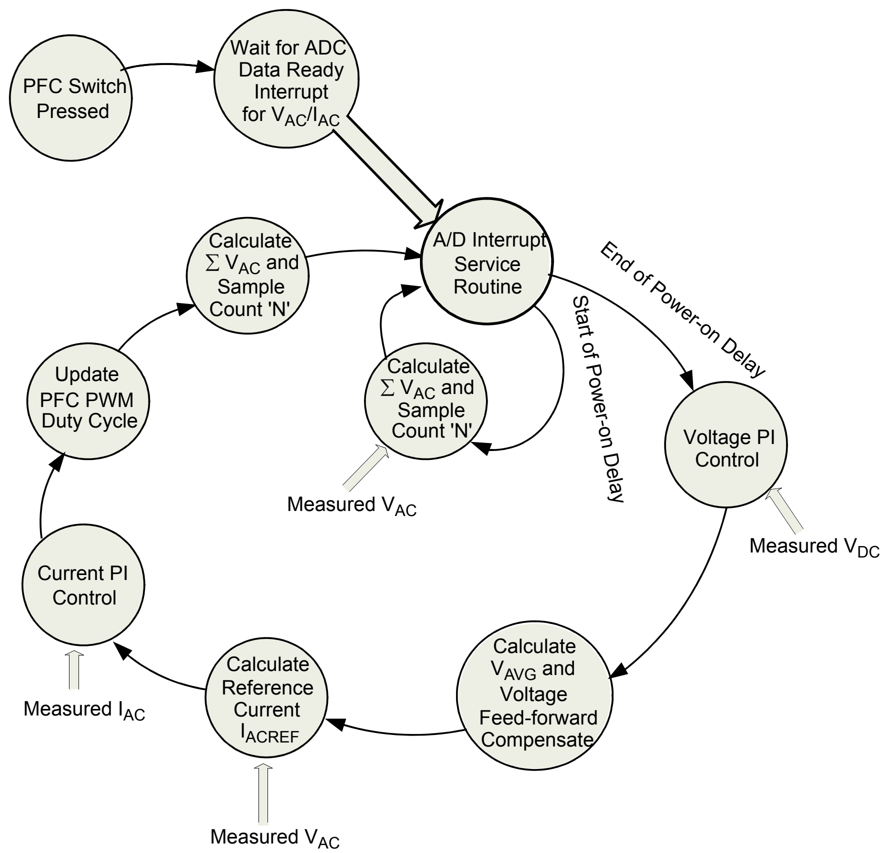
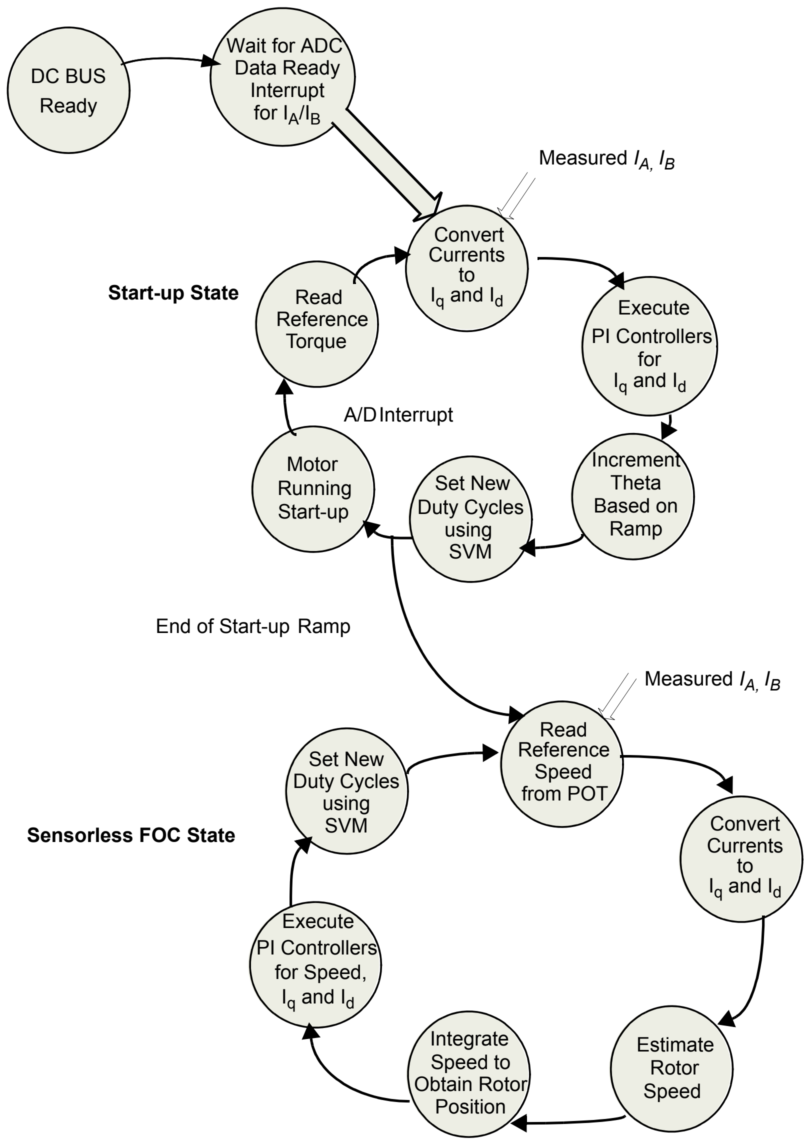


Figure 5-4. State Flow Diagram of Sensorless FOC



6. Development Resources

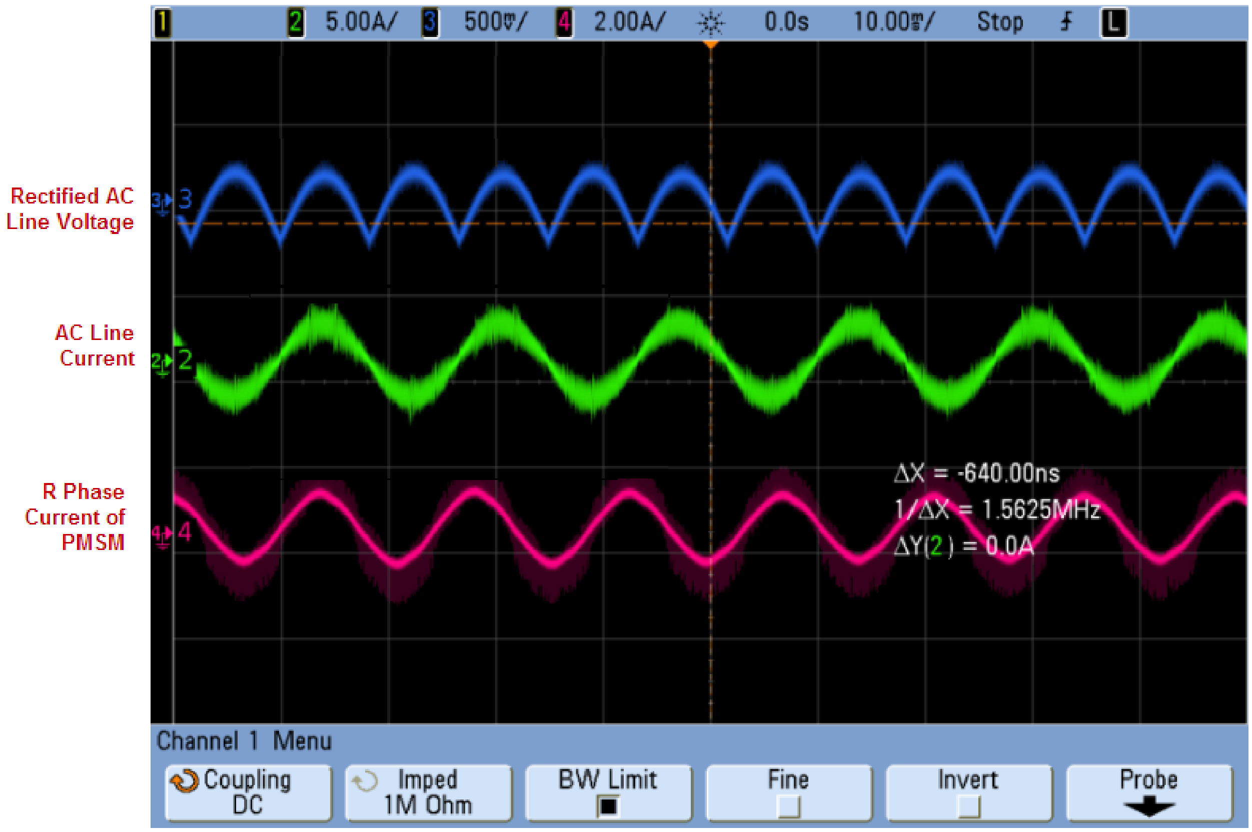
To develop and test the integrated algorithm, the following hardware and software tools are required.

- *Hardware Tools:*
  - dsPICDEM™ MCHV-3 Development Board (High Voltage) (P/N: DM330023-3)
  - PIC32MK1024 Motor Control Plug-in Module (PIM) (P/N: MA320024)
  - Permanent Magnet Synchronous Motor (PMSM)
  - MPLAB® REAL ICE™ Debugger/Programmer
  - 110V, 60 Hz AC power source
- *Software Tools:*
  - MPLAB X IDE - Version 4 (or later)
  - MPLAB XC32 C/C++ Compiler for PIC32 MCUs - Version 1.43 (or later)

7. Laboratory Test Results and Waveforms

The figure below shows the waveforms for rectified line voltage, input current and R phase current of a PMSM when executing the integrated application. This information aids in validating the PFC and sensorless FOC implementation on a 32-bit microcontroller.

Figure 7-1. Rectified Line Voltage, Input Current, and R Phase Current Waveforms



8. Conclusion

Considering the consumer demand for increased efficiency and growing desires for environmental standards, designers are always looking out for new algorithms that can be used to develop low-cost, power efficient motor control systems.

The high processing power and peripheral-rich platform of a Microchip 32-bit microcontroller enable the implementation of complex algorithms on a single chip. The Sensorless FOC process uses three control loops to compensate the current and the speed. The PFC process uses two control loops to compensate the input current and output voltage. All of these compensators use a PI controller to compensate for variations in these parameters, which requires very high processing power and finer control of the system. The 32-bit microcontrollers are best suited to handle the requirements listed above because of the high resolution, good processing speed, availability of advanced analog peripherals, and the variety of instructions that support these functions.

Microchip has various resources to assist you in developing this integrated system. Contact your local Microchip sales office if you would like further support.

9. References

Several application notes have been published by Microchip Technology Inc., which describe the use of our devices for motor control applications.

For ACIM control see:

- AN984, *An Introduction to AC Induction Motor Control Using the dsPIC30FMCU* (DS00984)
- AN908, *Using the dsPIC30F for Vector Control of an ACIM* (DS00908)
- GS004, *Driving an ACIM with the dsPIC DSC MCPWM Module* (DS93004)
- AN1162, *Sensorless Field Oriented Control (FOC) of an AC Induction Motor (ACIM)* (DS01162)
- AN1206, *Sensorless Field Oriented Control (FOC) of an AC Induction Motor (ACIM) Using Field Weakening* (DS01206)

For BLDC motor control see:

- AN901, *Using the dsPIC30F for Sensorless BLDC Control* (DS00901)
- AN957, *Sensored BLDC Motor Control Using dsPIC30F2010* (DS00957)
- AN992, *Sensorless BLDC Motor Control Using dsPIC30F2010* (DS00992)
- AN1083, *Sensorless BLDC Control with Back-EMF Filtering* (DS01083)
- AN1160, *Sensorless BLDC Control with Back-EMF Filtering Using a Majority Function* (DS01160)

For PMSM control see:

- AN1017, *Sinusoidal Control of PMSM Motors with dsPIC30F DSC* (DS01017)
- AN1078, *Sensorless Field Oriented Control of PMSM Motors* (DS01078)
- AN1292, *Sensorless Field Oriented Control (FOC)for a Permanent Magnet Synchronous Motor (PMSM) Using a PLL Estimator and Field Weakening (FW)* (DS01292)
- AN2520, *Sensorless Field Oriented Control (FOC)for a Permanent Magnet Synchronous Motor (PMSM) Using a PLL Estimator and Equation Based Flux - Weakening (FW)* (DS00002520)

For Power Control see:

- AN1106, *Power Factor Correction in Power Conversion Applications Using the dsPIC DSC*(DS01106)

For information on the dsPICDEM MCHV-3 Development Board (High Voltage) see:

- dsPICDEM MCHV-3 (DM330023-3) Development Board User's Guide (DS50002505

These documents are available on the Microchip web site at: www.microchip.com.

10. Source Code

All of the software covered in this application note is available as a MPLAB® Harmony application. This application can be found within the <install_dir>\apps\motor_control folder of your MPLAB Harmony installation.

The MPLAB Harmony Integrated Software Framework is available for download from the Microchip website at: www.microchip.com/harmony.

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