

Design of Indirect Power Factor Correction Using DSP56F80X

Indirect Power Factor Correction Application
Design based on Motorola Software
Development Kit

1. Introduction

This document describes the design of an Indirect Power Factor Correction (Indirect PFC) application. It is based on Motorola's 56F803/805 Digital Signal Processor (DSP), dedicated to motor control applications.

Most practical electronic power supplies consist of a conventional, single-phase, full-bridge rectifier, and filter stages. Already well-established, this type of circuit draws high current levels from the power line, producing a high level of harmonics. This harmonic distortion and low power factor (PF) reduces the maximum power available from power lines, thereby decreasing the efficiency of the electrical power grid. The European Normative EN 61000-3-2 defines the limits of the harmonic content of the input current for the power line supplied equipment. To meet these requirements, new designs require the use of an active power factor correction (PFC) at the input. The PFC emulates the ideal ohmic load through electronically controlled input current drawn from the line.

There are many specific integrated circuits (IC) available on the market to perform a PFC task. However, to perform the PFC task, additional electronic components increasing the system cost and complexity are required. Alternatively, there is a way to implement the PFC control through the DSP in addition to the main control tasks such as motor control. The use of a digital PFC replaces a number of ICs, reducing system cost. Another benefit of the software implementation is the possibility of easy modification without changing the hardware.

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The indirect PFC design featured here satisfies the minimum DSP performance requirements. The design is suitable for applications where the load of the DSP is high and the available resources are low.

This application note presents the concept of the continuous conduction current mode boost power factor corrector (PFC) with nominal output power of 180W. The PFC is digitally controlled by a digital signal processor (DSP).

2. Motorola DSP Advantage and Features

The Motorola DSP56F80x family is well suited for digital motor control, combining the calculation capability of DSPs with MCUs controller features on a single chip. These DSPs offer a rich, dedicated peripherals set like pulse-width-modulation (PWM) unit, analog-to-digital converter (ADC), Timers, communication peripherals (SCI, SPI, CAN), on-board Flash, and RAM. Each family chip is well suited for reliable motor control tasks.

A typical family member, the DSP56F805, provides the following peripheral blocks:

- Two Pulse Width Modulator modules each with six PWM outputs, three Current Sense inputs, and four Fault inputs, fault tolerant design with dead-time insertion; supports both center- and edge-aligned modes
- Two 12-bit Analog-to-Digital Converters (ADC) which support two simultaneous conversions; ADC and PWM modules can be synchronized
- Two Quadrature Decoders each with four inputs or two additional Quad Timers
- Two General Purpose Quad Timers totaling six pins: Timer C with two pins and Timer D with four pins
- CAN 2.0 B Module with 2-pin port for transmit and receive
- Two Serial Communication Interfaces, each with two pins (or four additional GPIO lines)
- Serial Peripheral Interface (SPI) with configurable four-pin port (or four additional GPIO lines)
- 14 dedicated General Purpose I/O (GPIO) pins, 18 multiplexed GPIO pins
- Computer Operating Properly (COP) watchdog timer
- Two dedicated external interrupt pins
- External reset input pin for hardware reset
- External reset output pin for system reset
- JTAG/On-Chip Emulation (OnCE™) module for unobtrusive, processor speed-independent debugging
- Software-programmable, Phase Lock Loop-based frequency synthesizer for the DSP core clock
 - Memory configuration
 - 32252 × 16-bit words of program flash
 - 512 × 16-bit words of program RAM
 - 2K × 16-bit words of data RAM
 - 4K × 16-bit words of data flash
 - 2K × 16-bit words of boot flash

3. Power Factor Correction Theory

The main idea of the power factor correction algorithm is the input current waveform transformation to be a sine signal having the same input voltage frequency. IEC standards do not require ideal sine waveform for compatibility. It is enough to provide simple three-point approximation. In this case the current waveform will be nearly rectangular. This simplification saves processor resources. The hardware control of the inverter power switch is the next step of simplification. For this approach the hardware provides instant value of the PFC input current. Thus, software controls the average value only and does not have direct access to the inverter switch. See [Figure 3-1](#).

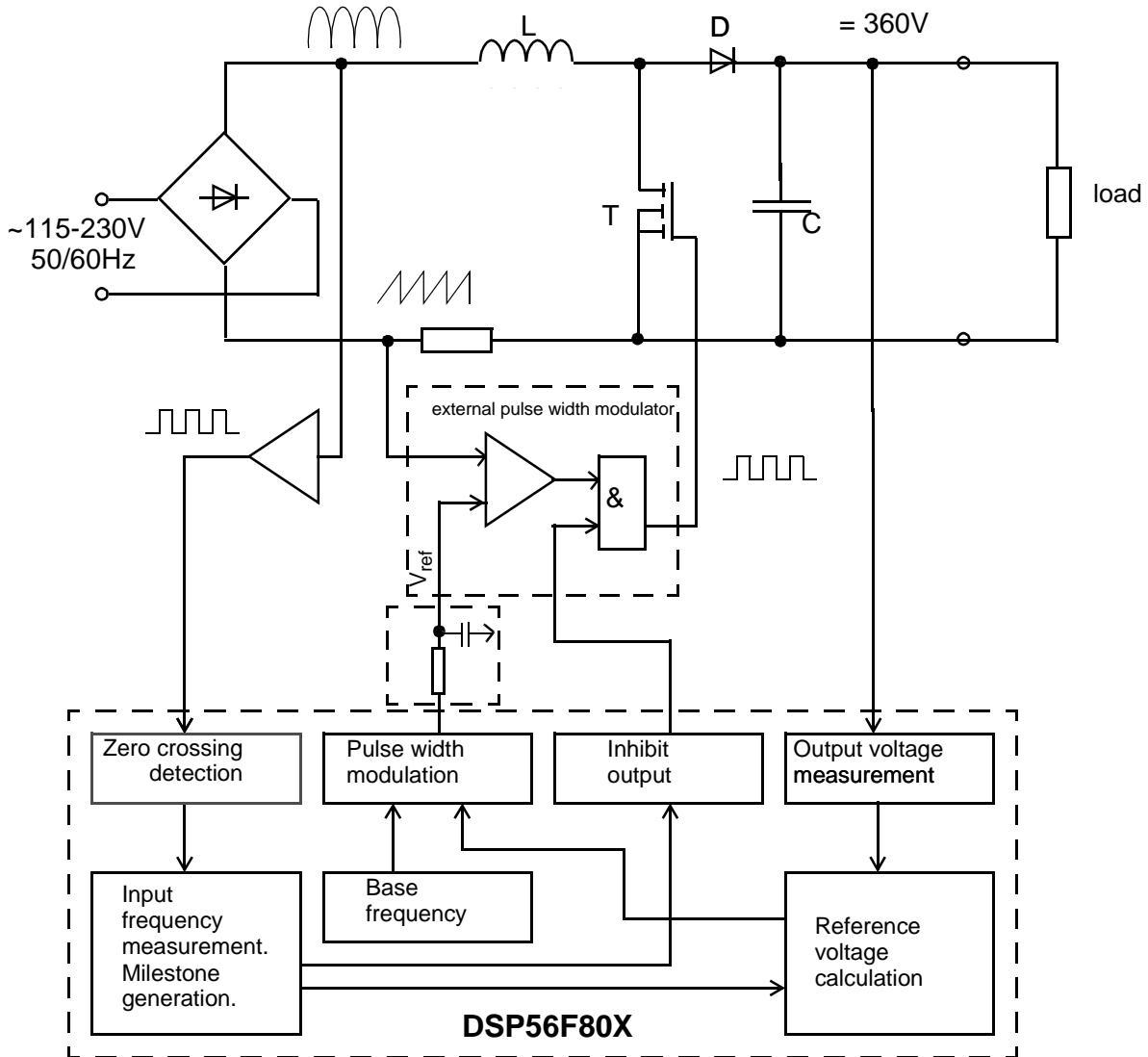


Figure 3-1 System Concept

The system is designed to provide power supply with maximum 180W power. The system incorporates the following hardware circuits:

- Power supply rectifier
- Boost inverter
- Hardware pulse wide modulator
- Zero crossing detector
- Output voltage sensor
- Evaluation board DSP56F803 or DSP56F805

The Control Process

The power factor corrector (PFC) performs correction of the input current waveform. The standard power supply with rectifier and large electrolytic capacitor has excessive peak of input current. This peak appears when voltage from rectifier is greater than voltage on the capacitor (see [Figure 3-2](#)).

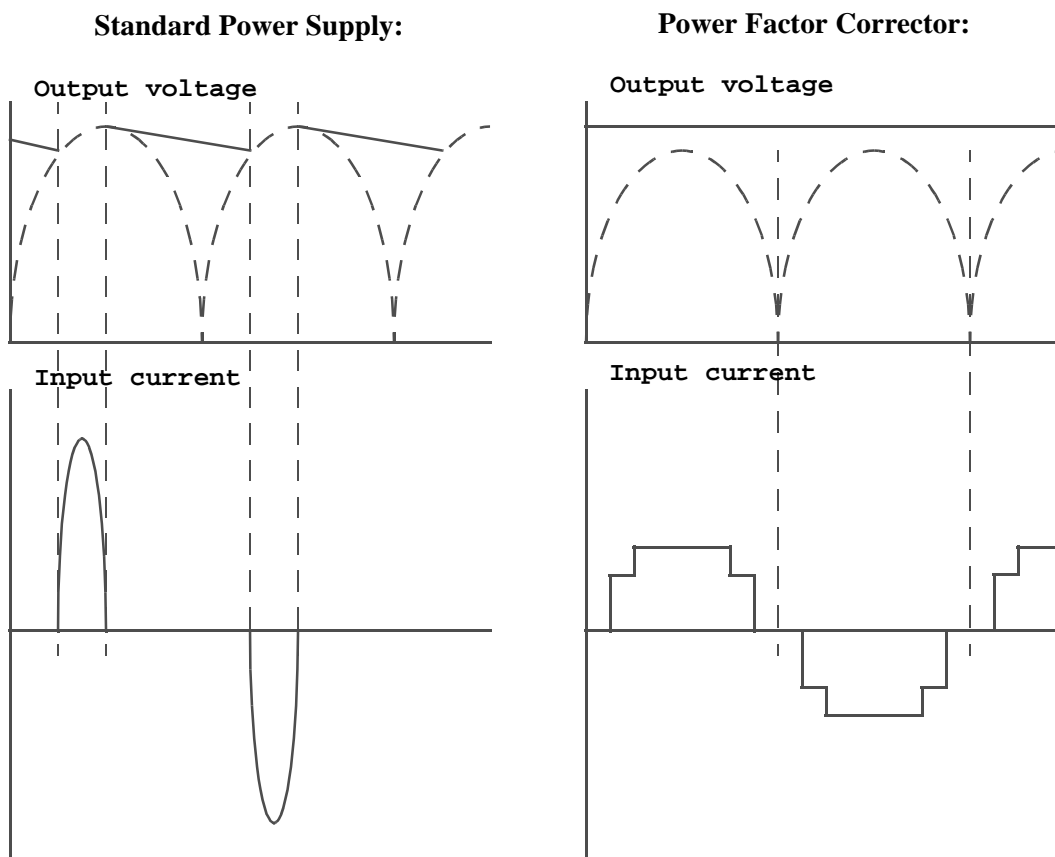


Figure 3-2 Waveforms of Output Voltage and Input Current

To produce the rectangular input current waveform, an active power factor corrector is placed between the rectifier and the filtering capacitor. This is a boost inverter consisting of an inductor (L), diode (D) and chop switcher (T). If switcher (T) is on at any phase position of AC input voltage, the diode is reversed biased, thus isolating the filtering capacitor. In this period, the input supplies energy to inductor (L). When switcher (T) is off, the filtering capacitor is charged from the inductor as well as from the input. Thus providing input current with continuous conduction.

Pulse width modulator generates reference pulses with a frequency of about 20KHz. The duty cycle of PWM pulses can be modified in two points:

1. Average duty cycle (time longer than one period of input voltage) depends on output load. High output load requires longer time of transistor open state to support the constant output voltage.
2. Instant duty cycle (time less than one half of period of input voltage) depends on input voltage. Low input voltage requires longer time of transistor open state to support constant input current.

Rectangular waveform provides a narrow spectrum of noise and lowest peak value of input current because the high frequency part of inverter switching can be filtered easily.

This hardware implementation does not allow direct modification of the pulse duty cycle that feeds to switcher (T). Reference voltage of external pulse width modulator comes from a filtered DSP PWM signal. This DSP PWM signal can be set according to input voltage zero crossing, base frequency, and output voltage. Therefore the only analog feedback for DSP control is output voltage. This implementation is called indirect PFC and can save DSP resources.

The best shape of the input current is the sinusoid. But for reducing complexity and meet standard requirements, this PFC application utilizes simplest 3-points approximation, illustrated in **Figure 3-3**. The desired shape is the result of optimization, and fulfills the following requirements:

- Less complexity, avoiding overloading of the DSP (most part of resources is reserved for motor control)
- Harmonic content complies with standard IEC 1000-3-2

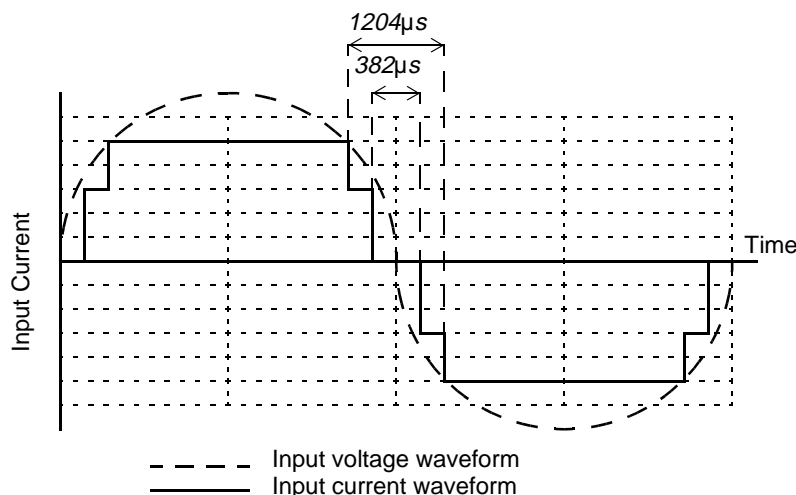


Figure 3-3 Input Current Waveform

4. System Design Concept

The system was designed in accordance with the following performance specifications:

- Targeted for DSP56F803/805EVM platforms
- Input power supply voltage 115-230V AC
- Input power supply frequency 50/60Hz
- Nominal output voltage up to 360V DC

- Nominal output power up to 180W
- Input current harmonic content will comply with standard IEC 1000-3-2

The PFC control algorithm performs the following tasks. See **Figure 4-1**.

- Converts sensed output voltage to a digital value
- Software PID regulator for feedback loop
- Programs the PWM channel, creating a pattern of the input current
- Synchronizes operation to the power line frequency, using mean zero crossing detector

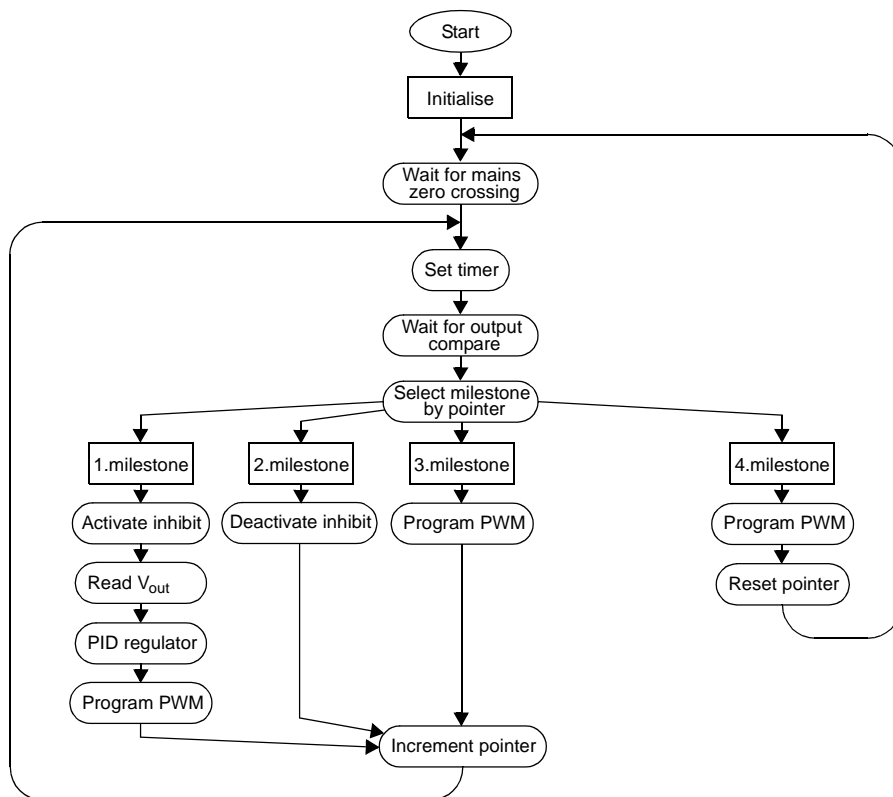


Figure 4-1 Indirect PFC Control Flowchart

Initialization - the on-chip peripherals' initialization, power line voltage and frequency detection.

Input capture ISR - After the initialization the PFC software waits for the power lines zero crossing signal, used for synchronization of the PFC algorithm with the line voltage, the time_base for the milestone table is set.

Output compare ISR - The main task of the function is to define the input current waveform milestones, or time intervals, hence forming the input current waveform. During each step the next output comparison is programmed and the proper input current level is set by programming the PWM duty cycle. Upon reaching a milestone of one of the input current waveform, the output DC bus voltage (V_{out}) is sensed. Sensed voltage is fed into the PID regulator. The nominal output voltage is set to 385 VDC. The output of the voltage regulator represents the amplitude of the input current. The calculated input current is limited to maximum input value and zeroed if negative. The new values

representing the higher and lower level of the input current waveform are calculated, and illustrated in **Figure 3-3**. Reaching milestone four, the algorithm is waiting for the next synchronization signal.

Analog-to-Digital Conversion ISR - The routine reads the output dc-bus voltage. It is required by the PFC algorithm to sense the output voltage regularly with a minimum period of 10ms. The ADC channel can be shared with other applications running on the DSP.

The PWM Signal is generated using quad timer D, channel one, in cascade with channel zero. The output of channel one is connected to the output pin TD1. Placing the timers in cascade mode is necessary to generate a sufficient PWM frequency, and recommended to be higher than 100kHz. After filtering the PWM signal, the analog voltage is obtained. It corresponds with the required input current, fed to the analog comparator (external Pulse Width Modulator) switching the MOSFET.

The control technique is based on the hysteresis current control. The system operates in continuous conduction mode with variable switching frequency (30 - 80kHz). The desired shape of the input current is a staircase waveform. The number and size of the stairs are optimized in order to fulfill these requirements:

- Least complex to get low load of the DSP
- Harmonic currents content complying with standard EN 61000-3-2

To provide a current waveform generation, the PFC hardware has a subsystem detecting input voltage at the zero crossing. This subsystem is the level comparator generating pulses when the input voltage crosses a particular level. This is illustrated in **Figure 4-2**. The center of pulse is shifted from a real zero crossing position because of the comparator hysteresis characteristic. This shift can be recovered by the software. So, a real input voltage zero crossing position can be resolved as the center of zero crossing pulse minus offset value.

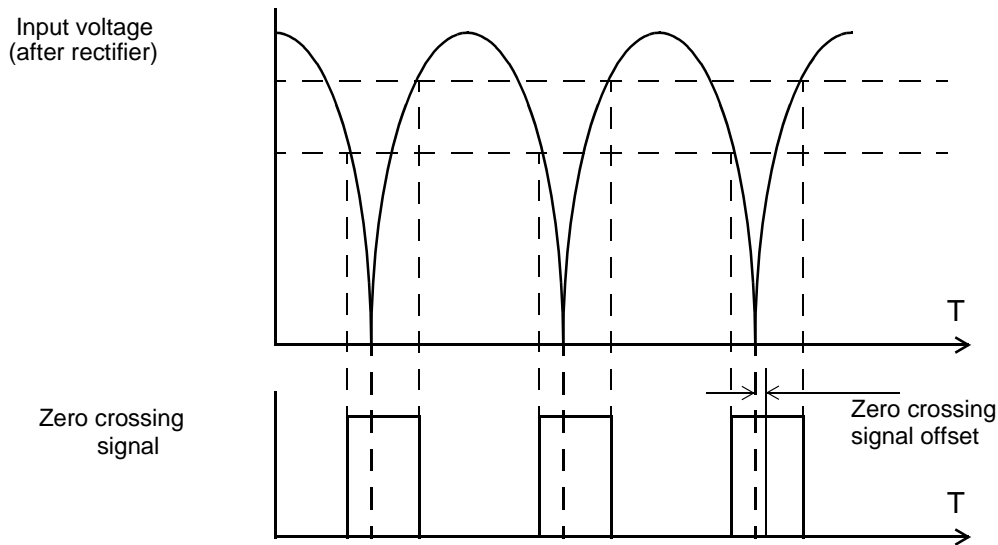


Figure 4-2 Zero Crossing Signal Generation

5. Hardware Implementation

5.1 System Outline

The hardware (HW) system is designed to drive the three-phase AC/BLDC motor. The application note described here is only a PFC application example without motor control. PFC can be easily integrated with any motor control application.

There are software (SW) versions targeted for a real DSP and evaluation module (DSP/EVM):

- DSP56F803
- DSP56F805

The HW setup only depends on the evaluation module (EVM) applied.

The designed software is capable of running only with the high voltage HW set described below.

The HW setup described in **Figure 5-1** below is also described in the documents **Targetting_DSP56803_Platform**, **Targetting_DSP56805_Platform**, both available from Motorola. These documents also contain EVM jumper setting descriptions.

5.2 High Voltage HW Set

The PFC application does not require the motor drive. It provides evaluation of the PFC software only. To enable a PFC converter on the high voltage 3ph AC/BLDC board, the jumper JP201 shall be in *PFC* position. Contacts one and two are closed.

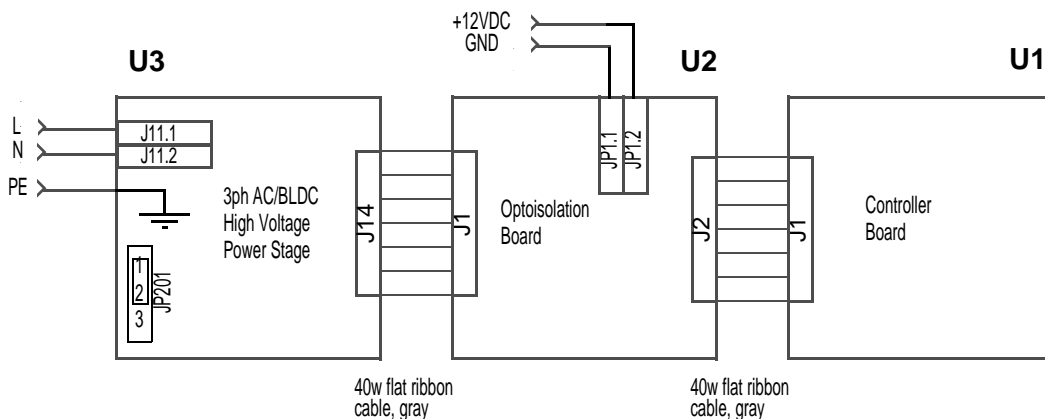


Figure 5-1 High Voltage HW System Configuration

All the system parts are supplied and documented according to the following references:

- U1 - Controller board for DSP56F805:
 - supplied as: DSP56805EVM
 - described in: **DSP Evaluation Module Hardware User's Manual**
- U1 - Controller board for DSP56F803:

- supplied as: DSP56803EVM
- described in: **DSP Evaluation Module Hardware User's Manual**
- U2 - 3 ph AC/BLDC high voltage power stage
 - supplied in kit with optoisolation board as: ECOPTHIVACBLDC
 - described in: **Three Phase Brushless DC High Voltage Power Stage**
- U3 - Optoisolation board
 - supplied with three phase AC/BLDC high voltage power stage as: ECOPTHIVACBLDC
 - or supplied alone as: ECOPT - optoisolation board
 - described in: **Optoisolation Board User's Manual**

Warning: It is strongly recommended to use optoisolation (optocouplers and optoisolation amplifiers) during development to avoid damage to the development equipment.

Note: Information of all mention boards and documents above can be located at:
<http://mot-sps.com/motor/devtools/index.html>.

6. Software Design

This section describes the design of the software blocks of the drive. The software will be described in terms of:

- Reference voltage calculation
- Milestones processing
- State diagram

6.1 Reference Voltage Calculation

PFC software periodically updates reference voltage according to the present value of output voltage. Reference value is calculated as the sum of its average value with difference between measured output voltage and its nominal value, shown in **Figure 6-1**. The structure contains the amplifier model, tasked with performing transformation $u_dif = K * u_dif$. It rescales the output voltage value, measured by the ADC module, to the eight bits range of the PWM. The application uses the PWM output as digital-to-analog convertor.

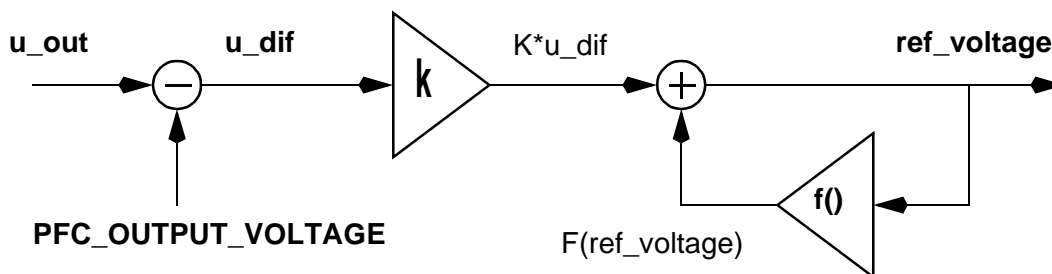


Figure 6-1 Reference Voltage Calculation

The reference voltage calculation algorithm uses the DC bus voltage value, measured by the ADC module in the Motor Control portion of the software. The DC bus value has the following scale:

Table 6-1. DC-Bus Voltage Scale

DC-Bus Voltage	Frac16 u_out	Comments
0 V	0.0	zero level
407 V	1.0	full scale

The function $f()$ is a filter algorithm like a simple RC-circuit. The filter time constant depends on the PFC hardware implementation and defines output characteristic of the PFC output voltage. The smaller time constant value provides a quicker output voltage response, but with less stable behavior.

Warning: Reference voltage calculation coefficients and algorithm directly depend on PFC hardware implementation.

6.2 Milestone Generation

The reference voltage value is corrected during the period of input voltage to provide the input current

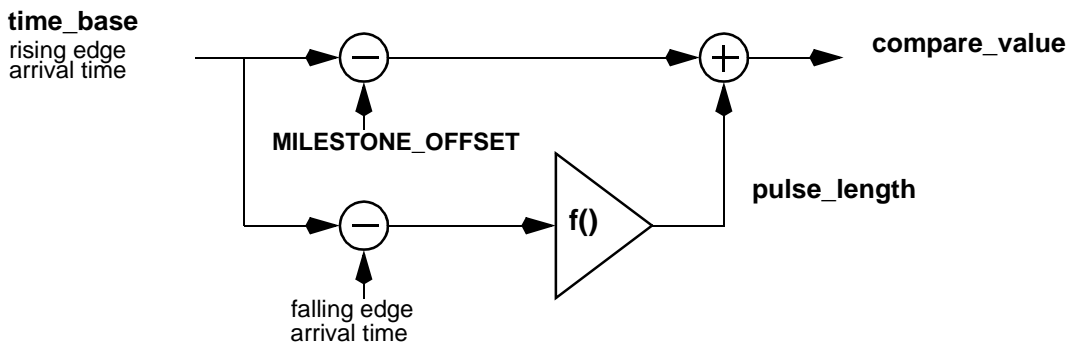


Figure 6-2 Milestones Synchronization Algorithm

waveform illustrated in [Figure 3-1](#). When the zero crossing signal comes, the program calculates the zero crossing pulse length and synchronizes the processes of milestone generation with input frequency (see [Figure 6-2](#)).

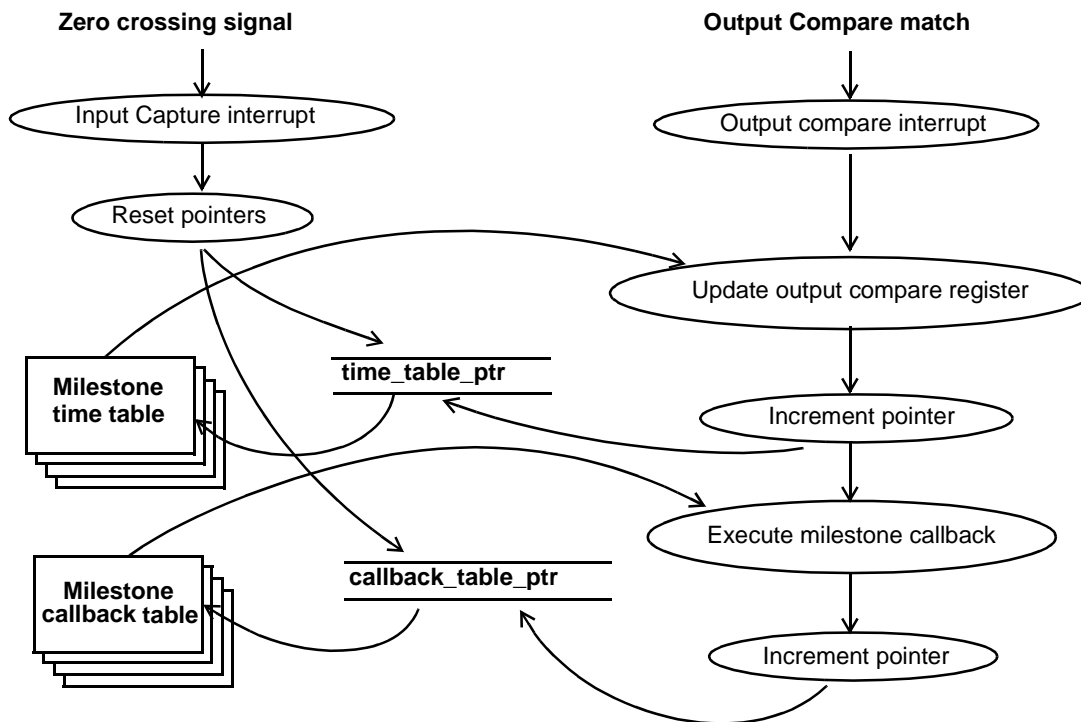


Figure 6-3 Milestone Generation

The resolved value defines first milestone point, a timer interrupt on the output *compare event*. Each time the output compare matches the interrupt, the compare register accrues toward the next milestone. Milestone generation time intervals are stored in the milestone time table. They have constant values during half-period of input voltage. The output interrupt compare service routine invokes function from the milestone callback table. This table performs calculation and correction of PFC reference value or activates inhibit output. This procedure allows easy modification of events sequence.

6.3 State Diagram

The PFC control operates from interrupts, excludes peripheral initialization and DC-bus voltage measurement. The PFC control is developed to easily incorporate motor control applications. Main routine functionality is to call to the PFC initialization function and to pass the measured DC-bus voltage value to the PFC control. This allows DC-bus voltage measurement with different sample rates and ADC modes. This application demonstrates initialization and use the PFC control.

6.3.1 Application State Machine

The Main routine provides:

- Analog-to-digital converter initialization
- POSIX timer initialization
- Switch and LEDs initialization
- Brake control initialization
- PFC initialization routine call
- Application main loop

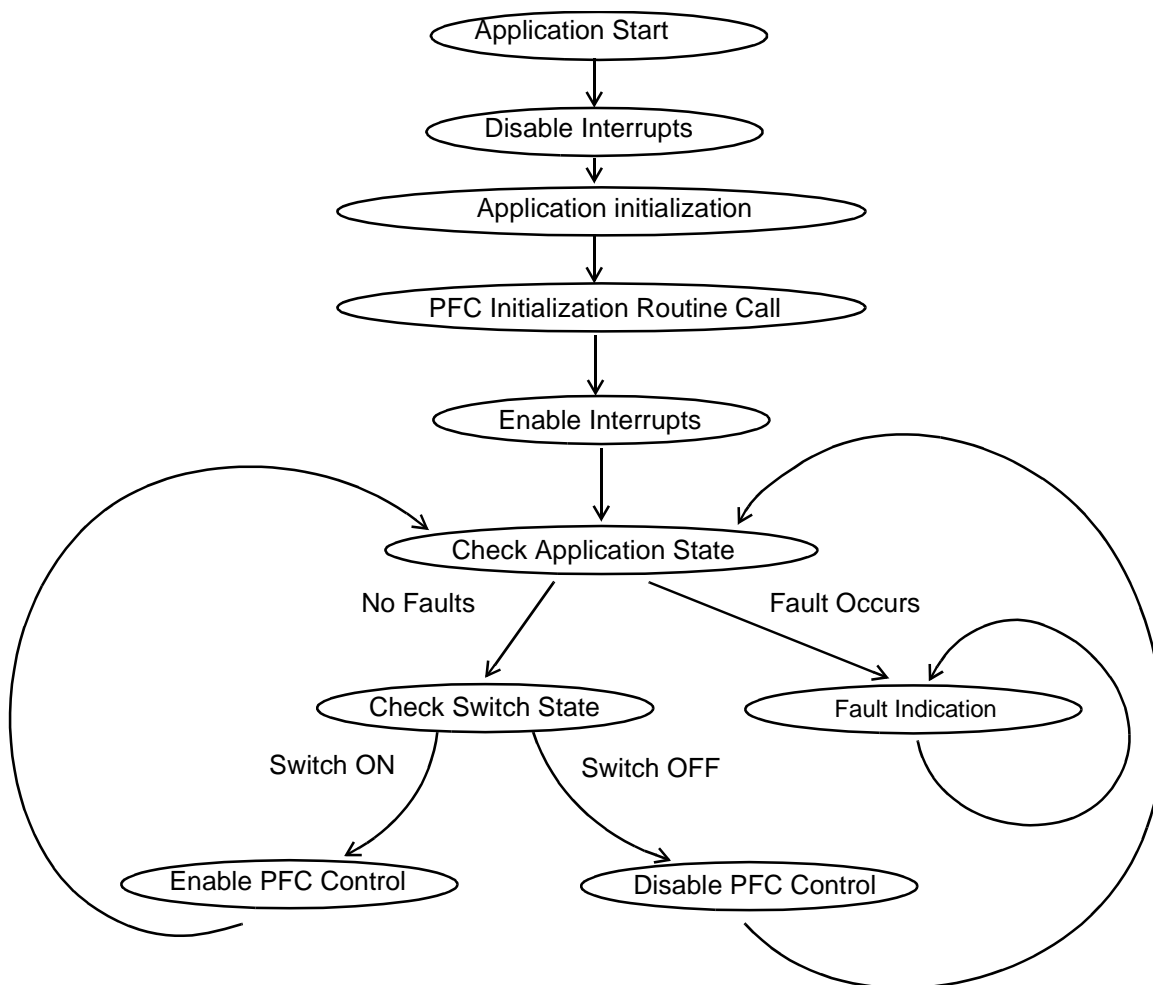


Figure 6-4 Application State Machine

7. 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. This chapter describes how the Digital PFC application is written under SDK version 2.2.

7.1 Files

Application is composed of the following files:

- ...*dsp5680Xevm\nos\application\Digital_PFC\Digital_PFC.c*
(main program)
- ...*dsp5680Xevm\nos\application\Digital_PFC\dpfc.c*
(PFC control program)
- ...*dsp5680Xevm\nos\application\Digital_PFC\Digital_PFC.mcp*
(application project file)

- ...*dsp5680Xevm\nos\applications\Digital_PFC\configflash\appconfig.c*
(application configuration source file for FLASH)
- ...*dsp5680Xevm\nos\applications\Digital_PFC\configflash\appconfig.h*
(application configuration header file for FLASH)
- ...*dsp5680Xevm\nos\applications\Digital_PFC\configflash\linker.cmd*
(linker command file for FLASH)
- ...*dsp5680Xevm\nos\applications\Digital_PFC\configflash\flash.cfg*
(configuration file for FLASH)
- ...*dsp5680Xevm\nos\applications\Digital_PFC\configextram\appconfig.c*
(application configuration source file for external RAM)
- ...*dsp5680Xevm\nos\applications\Digital_PFC\configextram\appconfig.h*
(application configuration header file for external RAM)
- ...*dsp5680Xevm\nos\applications\Digital_PFC\configextram\linker.cmd*
(linker command file for external RAM)

Where X means type of target DSP (dsp56803evm or dsp56805evm)

These files are located in the SDK installation directory.

7.2 Drivers and Library Function

The three-phase AC induction V/Hz close loop motor control application uses the following drivers:

- ADC driver
- Quadrature timer driver
- GPIO driver
- Timer driver
- LED driver
- Switch driver
- Brake driver

All drivers except the timer driver are included in the *bsp.lib* library. The timer driver is included in *sys.lib* library.

Just ADC, MPIO and quadrature timer is necessary to provide PFC functionality. All other peripherals are maintained for example only.

Each peripheral on the DSP chip or on the EVM board is accessible through driver. For detailed description of drivers, see **Embedded SDK (Software Development Kit) Targeting Motorola DSP5680X Platform**.

7.3 Appconfig.h file

The purpose of the *appconfig.h* file is to provide a mechanism for over-writing default static configuration settings, defined in the *config.h* file. There are two *appconfig.h* files.

1. The first is dedicated to external RAM (*..\ConfigExtRam directory*).
2. The second is dedicated for FLASH memory (*..\ConfigFlash directory*).

In the case of digital PFC application, both files are nearly identical. The following lines are included in the *appconfig.h* file to use PFC functionally:

```
#define INCLUDE_USER_TIMER_D_0 0
#define INCLUDE_USER_TIMER_D_1 0
#define INCLUDE_USER_TIMER_D_2 0
#define INCLUDE_USER_TIMER_C_0 0
```

The difference in the two files is the PFC inhibit output. It is connected to multiple purpose input/output (MPIO) pins or to timer dedicated pins for DSP56F805 EVM only.

One interrupt priority level is defined in the *appconfig.h* file. Because milestone generation is a time critical process, one timer interrupt is to have highest interrupt priority; level three for this example:

```
#define GPR_INT_PRIORITY_32 3
```

The ADC initialization and service function sets ADC operating more. This module can be used in the different modes. Application provides sample rate of DC-bus voltage measurement, required to be sufficient for PFC control. Here is an example of ADC settings in *appconfig.h*:

```
/* ADC setting */
#define ADC_SCANMODE ADC_SEQUENTIAL_ONCE
#define ADC_INITIATE_SCAN ADC_INITIATE_SCAN_ON_START
#define ADC_SET_DIVISOR 6
#define GPR_INT_PRIORITY_55 2

/* ADC samples */
#define INCLUDE_ADCA_SAMPLE_0

/* ADC callbacks */
#define ADC_RAW_CONVERSION_COMPLETE_CALLBACK CallbackADC_ISR
```

7.4 PFC Control Constants

This section describes constants, located in the *dpfc.c* file. It defines waveform of PFC input current.

MILESTONE_OFFSET defines the time between the rising edge of zero crossing signal and the first milestone point. This time depends on zero crossing detection subsystem of PFC hardware. It can be measured. MKS_TO_TICK() macro allows definition value in microseconds.

Example:

```
#define MILESTONE_OFFSET MKS_TO_TICK(820L)
```

Milestone50Hz is the array of milestones time intervals. Its values depend on current waveform, to be generated. MKS_TO_TICK() macro allows definition value in microseconds.

Example:

```
const UWord16 Milestone50Hz[] = {
MKS_TO_TICK(411L),
MKS_TO_TICK(382L),
MKS_TO_TICK(411L),
MKS_TO_TICK(10000L),
NULL, /* End of time table */ };
```

MilestoneCallback is the array of pointers to the functions to be executed. Those functions occur after each corresponding time interval is defined in Milestone50Hz[]. This functions controls PFC reference voltage and inhibit output.

Example:

```
/* Forward function declaration */
void PFC_SetLowGain(void);
void PFC_SetHighGain(void);
void PFC_ForceInhibit(void);
```

```

const pfc_tCallback* MilestoneCallback[] = {
    PFC_SetLowGain,
    PFC_ForceInhibit,
    PFC_SetLowGain,
    PFC_SetHighGain,
    NULL,
};
/* End of callback table */;

```

7.5 PFC Control API

This section describes the main PFC control functions, permitting PFC features use in the main code.

7.5.1 PFC_Init

Prototype:

```
void PFC_Init(void);
```

This function performs initialization of the DSP peripherals. It does not include ADC channel initialization for DC bus voltage measurement.

7.5.2 PFC_SetUOut

Prototype:

```
void PFC_SetUOut(UInt16 u_dc_bus);
```

This function allows to pass DC bus voltage value to PFC control. Refresh rate of this value has to be not less than input voltage frequency.

7.5.3 PFC_Enable

Prototype:

```
void PFC_Enable(void);
```

This function enables PFC control to start conversion after first zero crossing pulse.

Notes: Beware to enable PFC control if DC-bus voltage measurement is not complete.

7.5.4 PFC_Disable

Prototype:

```
void PFC_Disable(void);
```

This function disables PFC control to immediately finish PFC conversion.

Notes: After finishing PFC conversion output voltage has no zero level. Its value depends on input voltage and equals about $1.4 \cdot U_{IN}$

7.5.5 PC Master

PC master is designed to provide the profiling, diagnostic and demonstration tool for development of algorithms and application. It consists of components running on a PC and parts running on the target DSP device.

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

To enable the PC master operation on the target board application, the following lines should be added to the *appconfig.h* file:

```
#define SCI_DRIVER
#define INCLUDE_PCMaster
```

These two lines automatically include the SCI driver and install all necessary services for running PC master.

The detailed PC master description is provided by the **PC Master User Manual**. It is stored at the SDK directory as *\sdk\pc_master\dsp_gui_um\dsp_gui_um.pdf*.

8. Memory Usage

Table 8-1 shows the PFC application memory consuming. A part of the DSP memory is still available for other tasks.


Table 8-1. RAM and FLASH Memory Usage for SDK2.2

Memory (In 16 Bit Words)	Available DSP56F803 DSP56F805	Used Application + Stack	Used Application without PC Master, SCI, Ident.
Program FLASH	32K	8572	4395
Data RAM	2K	564+352	196+352

9. References

- DSP56F800 16-Bit Digital Signal Processor, Family Manual, DSP56F800FM/D, Motorola*
- DSP Evaluation Module Hardware User's Manual, DSP56F803EVMUM/D, Motorola*
- DSP Evaluation Module Hardware User's Manual, DSP56F805EVMUM/D, Motorola*
- DSP56F80x 16-Bit Digital Signal Processor, User's Manual, DSP56F801-7UM/D, Motorola*
- DSP56F8XX Software Development Kit, Motorola*
- Optoisolation Board User's Manual, MEMCOBUM/D, Motorola*
- PC Master User Manual, SDK111/D, Motorola*
- Three Phase Brushless DC High Voltage Power Stage, MEMC3BLDCPSUM/D, Motorola*
- Web page: <http://e-www.motorola.com/motor>

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