Simplifying Digital Control of Power Factor Correction with Digital Signal Controllers (DSCs)

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Introduction

Digital control of Power Factor Correction (PFC) delivers significant advantages over analogue methods and allows precise management of performance as well as the ability to integrate different control schemes within a single application. Digital Signal Controllers (DSCs) which integrate peripherals which are optimised for PFC, simplify digital control even in complex systems.

White Paper

PFC has become a vital element for virtually all equipment which is connected to the mains electrical network. Most power-conversion applications demand a DC source, which inherently has a rectification stage. Typically, rectification causes non-sinusoidal line currents to be drawn from the source, due to its non-linear input characteristics. With the steady increase in the use of such equipment, line-current harmonics have become a significant problem. Some adverse effects of poor power factor and high line-current harmonics include overheating of transformers and inductive equipment, degradation of system voltages and increased stress on components due to higher peak currents. Added to this, stringent limits imposed on harmonic currents by international standards and regulatory bodies make the need to improve power quality even more important. The resulting solution to this problem is Power Factor Correction (PFC).

This article will explain PFC, and why it is more important today than ever. The article will review how designers can choose the appropriate converter topology and the best control methodology for the implementation of PFC using a Digital Signal Controller (DSC). Laboratory results will be presented to illustrate this, followed by a discussion of how digital PFC can be integrated into other power- and motor-control applications.

Introduction: What is Power Factor?

In order to understand what power factor is, it is important to know that the total apparent power has two components—active power and reactive power.

Active power is the working component of power that is actually consumed by the system. It performs the actual work, such as creating heat, light and motion. Working power is expressed in Watts and is registered on the electric meter at the utility company in kilowatt hours (kWh).
Reactive power doesn't do any useful work, but it is required to maintain and sustain the electromagnetic field associated with inductive elements and loads. Reactive power is expressed in Volt Amperes Reactive (VAR) and is registered on the electric meter at the utility company in kilo Volt Ampere Reactive (kVAR). The total required power capacity, known as apparent power, is expressed in simply kilo Volt Amperes (kVA).

Using the above power components, power factor is a parameter that can be defined as the amount of working power used by a system, in terms of the total apparent power. Ideally, the power factor for a given system should be unity. However, in actual systems, the power factor deviates from unity for the following reasons:

- Phase shift of current with respect to voltage, which results in displacement. This is sometimes called the “Displacement Factor.”
- Harmonic content present in the current that results in waveform distortion. This can be termed as “Distortion Factor.”

Now, power factor can be alternatively defined as the product of distortion factor and displacement factor. Power factor becomes an important measurable quantity and a figure of merit because it often results in significant economic savings for utility companies.

The objective of PFC is to make the power converter present itself as a linear resistance to the input voltage. If the input voltage has a sine-wave shape, the input current will also have a sine-wave shape. This allows the power distribution system to operate more efficiently, thereby reducing energy consumption.

Cause and Effect of Current Harmonics

Current harmonics are sinusoidal waves that are integral multiples of the fundamental wave. They are altogether different from line disturbances, such as transient distortions and power surges. Current harmonics appear as continuous, steady-state disturbances on the electric network.

Some of the common causes of current harmonics are:

- Power electronic equipment, such as rectifiers, Uninterruptible Power Supplies (UPSs), state converters, thyristor systems, Switch Mode Power Supplies (SMPSs) and SCR-controlled systems, among others.
- Commonly used industrial equipment, such as welding machines, arc furnaces, and mercury vapor lamps.
- Saturable inductive equipment, such as generators, motors and transformers.

The problems caused by current harmonics include:

- Erroneous operation and nuisance tripping of system components, such as circuit breakers, fuses and relays.
- Damage to sensitive electronic equipment.
- Excessive overheating of capacitors, transformers, motors, lighting ballasts and other equipment.
- Interference with neighboring electronic equipment.

To reduce these harmful effects, the current drawn from the input needs to have a similar shape to that of the input-voltage profile.
How Can a Converter be Made to Look Resistive?

The answer to this question lies in the fact that PFC is a low-frequency requirement. This means that the converter does not need to be resistive at all frequencies, provided a filtering mechanism exists to remove the high-frequency ripples. Using the four basic power components—namely, inductor, capacitor, diode and switch—a converter can be made to look resistive. At this point, the reactive energy, which would otherwise cycle back to the utility company or grid, needs to be localized and contained within the PFC converter.

Traditionally, bulk inductors and capacitors were used to compensate for downstream loads, which would be leading or lagging, respectively. The bulk components would store energy over one power cycle. The downside of this approach is increased cost and an inability to correct for harmonics. However, with the advent of DSCs and advanced power electronics, the energy-storage elements can be downsized because they only need to store energy for a small period of time, on the order of a few tens of microseconds. With this approach, the harmonics can also be effectively addressed.

Topological Considerations for PFC

Figure 1 illustrates a basic block diagram of a generic power-converter system with PFC. The rectifier converts the AC input to a unidirectional pulsating output, which acts as the input to the PFC converter. The PFC converter can be one of several different topologies—a Buck converter, a Boost converter or a Buck-Boost converter. The DSC takes the three signals $V_{AC}$, $I_{AC}$ and $V_{DC}$ as feedback for the control loop. The only outputs of the DSC are the PWM pulses for switching the PFC MOSFET.

![Figure 1: Basic Block Diagram of a Power Converter](image-url)

Let us look at the various topologies in order to decide which would suit the PFC application. Figure 2 shows the Buck, Boost and Buck-Boost topologies of power converters. Table 1 compares the three converters, based upon the various parameters. It can be concluded that the Boost converter is best suited for the implementation of PFC because of the absence of crossover distortions and viability of operating the converter in continuous-conduction mode.

There are many ways to control a Boost converter.
In discontinuous conduction mode, the inductor current returns to zero at the end of every switching cycle, thereby having lower switching losses. Since the current goes to zero at each switching cycle, the peak current through the inductor and hence through the switching devices is comparatively more than in continuous-conduction mode.

Critical-conduction mode is the optimization of discontinuous mode to the point of continuous mode operation. Here, peak current and Total Harmonic Distortion (THD) are more than in continuous-conduction mode, but lower than the discontinuous-conduction mode of operation. Critical-conduction mode operates on a variable switching frequency, wherein depending upon the load and input voltage, the switching frequency will vary.

Continuous-conduction mode strives to maintain a non-zero current through the Boost inductor to minimize peak current levels. This will in turn reduce losses when compared to discontinuous-conduction and critical-conduction modes. This mode is more suitable for higher power levels, although the control strategy is more complex.

<table>
<thead>
<tr>
<th>Type of Converter</th>
<th>Output Voltage Polarity</th>
<th>Crossover Distortions</th>
<th>Line Current Shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buck</td>
<td>Positive</td>
<td>Yes</td>
<td>Always Discontinuous</td>
</tr>
<tr>
<td>Boost</td>
<td>Positive</td>
<td>No</td>
<td>Continuous*</td>
</tr>
<tr>
<td>Buck-Boost</td>
<td>Negative</td>
<td>No</td>
<td>Always Discontinuous</td>
</tr>
</tbody>
</table>

*Based upon load conditions and inductor value, continuous currents can be obtained in a Boost converter.

Table 1:  
Comparison of Three Types of PFC Converters
Figure 2:
Power-Converter Topologies

Digital Implementation of Power Factor Correction

Figure 3 illustrates the digital implementation of PFC using a DSC. The method used here is called Average Current-Mode Control. In this method, the average current flowing through the inductor is forced to be a sine wave and the output voltage is regulated. To derive the sine shape for the average inductor current, either a sinusoidal pattern can be generated in software or the rectified voltage, itself, can be used. The scheme here uses the rectified voltage to get the necessary shape of inductor current. $T_S$ is the total PWM switching period, $t_{ON}$ is the MOSFET conduction time and $t_{OFF}$ is the time during which the MOSFET is turned off. The time $t_{ON}$ is controlled by implementing the digital-control system described next, in order to achieve the necessary inductor-current shape.

The following control loops and compensators are implemented digitally, through software:

- **Current Loop**

  The inner loop in the control block forms the current loop. The inputs to the current loop are the reference current signal from the outer loop and the inductor current. The current error compensator is designed to produce a control output such that the inductor current follows the reference current signal. The current loop should run at a much faster rate when compared to the voltage loop. The bandwidth of the current compensator should be higher for correctly tracking the semi-sinusoidal waveform at twice the input frequency, which is 100 Hz or 120 Hz. Usually, the bandwidth of the current compensator is between 5 kHz and 10 kHz for a switching frequency of around 100 kHz.
Component sizes would be small at these switching frequencies. The current controller produces a duty-cycle value to drive the gate of the PFC MOSFET. A proportional-integral controller is used to achieve the current-error compensation.

**Voltage Loop**

The outer loop in the control block forms the voltage loop. The input to the voltage loop is the reference DC voltage and the sensed output voltage. The voltage-error compensator is designed to produce a control output such that the DC output voltage remains constant at the reference value, regardless of variations in the load current and changes in the supply voltage. The voltage controller produces a control signal, which determines the reference current for the inner current loop. The voltage-loop bandwidth is chosen to be 10 Hz. This is selected to be well below the input frequency of 100 Hz or 120 Hz, so that the output voltage remains constant and still maintains the necessary shape of the inductor current, without distorting it. A proportional-integral controller is used to achieve the voltage-error compensation.

**Voltage Feed-Forward Compensator**

If the voltage decreases, the product of $V_{AC}$ and $V_{PI}$, which determines current reference, also proportionally decreases. However, to maintain a constant output power at a reduced input voltage, the current reference must increase. The purpose of having an input voltage feed-forward term is to maintain the output power constant, as determined by the load, regardless of sudden variations in the input-line voltage. This compensator is implemented digitally by calculating the average value of the input-line voltage and using the result as a divider for the current reference. This resulting signal acts as the input to the inner current loop.
Integration of PFC With Other Applications

Most power-conversion applications use PFC as the front-end converter, be it in the area of SMPS or motor-control applications.

Let us consider an integrated application, as in the case of a home air conditioner. Taking a look at the Figure 4, we can see the input converter features an active PFC stage, which helps to meet the stringent regulatory needs stipulated by various countries. The DSC’s Analog-to-Digital Converter (ADC) module measures the required feedback currents and voltages. Based upon these, the PWM module drives the power switch. This on-chip PWM module runs under the two PI controllers in order to maintain a near unity power factor.

Using the same DSC, the sensorless Field Oriented Control (FOC) algorithm takes phase currents as feedback through the ADC module. The same on-chip PWM module is used to drive the inverter’s power switches running under multiple PID controllers for speed and torque control of the air-conditioner compressor.

A single DSC used for the implementation of both PFC and FOC algorithms results in major cost savings over the same implementation using non-DSC-based solutions. This is because the latter require the use of expensive ASICs and fixed-functionality devices. The final goal of reducing the stress on the electric grid using PFC, and at the same time efficiently controlling the air conditioner motor, is facilitated using the DSC.

Many such applications are being integrated with PFC on a single DSC chip, thus making power conditioning an integral part of the system. Some examples include server power supplies, UPSs, telecom rectifier supplies, washing machines, refrigerators, gaming consoles, digital lighting, television sets and many more.

Figure 4:
Integrated PFC and FOC in an Air Conditioner
Conclusion and Experimental Results

The experimental results shown in Figure 5 validate the digital implementation of PFC using a dsPIC® DSC. The yellow waveform is the input current and the blue waveform is the input voltage. This shows that the input current is shaped according to the voltage, resulting in a near-unity power factor. Implementation of PFC enables substantial cost savings for power quality, depending upon the pricing structure provided for the consumer. PFC can also reduce losses for utility companies.

Figure 5:
Input Current and Input Voltage Waveforms with PFC

Summary

PFC is no longer a choice—it has become a requirement for most power-conversion applications. In this article, we have seen some fundamental concepts governing power quality and the issues faced in distribution systems if PFC is not implemented. The digital implementation of PFC proves to be advantageous over analog implementations because it enables precise control of performance and the ability to merge and integrate many control schemes in integrated applications. The advent of DSCs with application-specific peripherals on-chip has made the digital implementation for complex applications with PFC possible for today's and tomorrow's world of power.

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