Increase power factor by digitally compensating for PFC EMI-capacitor reactive current

By Bosheng Sun
Application Engineer, High Power Controller Solutions

Introduction

Many articles have been written on how to improve power factor (PF). For the most part, they focus on power factor correction (PFC) current-loop tuning, or how to match the phase tracking of the PFC inductor current to the input voltage as closely as possible. This article explores a different angle. Poor PF mostly occurs at high line voltage and light load. Under these conditions, the PFC electromagnetic interference (EMI) filter has a big effect on PF. Because traditional current-loop tuning cannot do much to improve PF, a new method is required to deal with this low-PF issue.

PF is defined as the ratio of real power in watts (W) to apparent power, or the product of the root-mean-square (RMS) current and RMS voltage in volt-amperes (VA) as shown by Equation 1.

\[
PF = \frac{\text{Real Power}}{\text{Apparent Power}}
\] (1)

Power factor indicates how efficiently energy is drawn from the AC source. Ideally, PF should be 1, then any electrical load appears as a resistor to the voltage source. However, in practice, electrical loads cause distortions in the current waveforms, resulting in poor PF. With a poor PF, the utility must generate more current than the electrical load actually needs, which causes elements such as breakers and transformers to overheat. In turn, this reduces their lifespan and increases the cost of maintaining public electrical infrastructure.

To attain a good PF, PFC is generally required at the front end of the power supply for electrical appliances with input power levels of 75 W or greater. A typical PFC circuit diagram is shown in Figure 1, which consists of three major parts: an EMI filter, a diode bridge rectifier, and a boost converter.

A power supply with PFC has two purposes. The first is to rectify the AC voltage ($V_{AC}$) into a DC voltage ($V_{OUT}$) and maintain $V_{OUT}$ at a specific level. The second is to control the input current to follow the input voltage so that a good PF can be achieved. With the ever increasing PF requirements, especially in the server and telecommunications industries, it is a design challenge for a PFC to achieve an excellent PF with traditional control methods.

Figure 1 shows a typical EMI filter for PFC. C1, C2, C3 and C4, which are EMI capacitors. Inductors in the EMI filter do not change the phase of the PFC inductor current; therefore, Figure 1 can be simplified as shown in Figure 2. Note that C is the combination of C1, C2, C3 and C4.
The EMI filter’s capacitor causes the AC input current to lead the AC voltage (Figure 3). The PFC inductor current is \( I_L \), the input voltage is \( V_{AC} \), and the EMI-capacitor reactive current is \( I_C \). The total PFC input current is \( I_{AC} \), which is also the current from where the PF is measured. Although the PFC current control loop forces the inductor current, \( I_L \), to follow \( V_{AC} \), the reactive current of \( I_C \) leads \( V_{AC} \) by 90°, which causes the total current, \( I_{AC} \), to lead \( V_{AC} \). The result is a poor PF. This effect is amplified at light loads and high line voltages because \( I_C \) has more weight in the total current. As a result, it is difficult for the PF to meet a rigorous specification.

Traditionally, the poor PF caused by this EMI-capacitor leading current can be improved by forcing the induction current, \( I_L \), to lag \( V_{AC} \) by some degree. To do this, the input AC voltage, \( V_{AC} \), is measured by an analog-to-digital converter (ADC), then delayed for an amount of time, \( \Delta t \). The current reference is derived from this delayed \( V_{AC} \) signal, which deliberately makes the inductor current, \( I_L \), lag \( V_{AC} \). This can compensate the leading EMI-capacitor reactive current, \( I_C \), and improve PF.

However, this method has several limitations. First, the delay period, \( \Delta t \), needs to be dynamically adjusted based on the input voltage and output load. The lower the input voltage and the heavier the load, the smaller the \( \Delta t \). Otherwise the inductor current, \( I_L \), will be over-delayed, making the PF worse than if there was no delay at all. Precisely and dynamically adjusting the delay time, \( \Delta t \), based on the operating condition makes the design complex.

Second, the diode bridge blocks any reverse current, which is caused by a phase difference between voltage and current at AC zero-crossing. As a result, the current-feedback signal is clamped to zero, while the current reference is not zero. The inconsistency between the current feedback and its reference causes the control loop to accumulate to a large value. As a result, a current spike is generated when the diode begins to conduct again. The more PF is increased by the reference delay, the more distortion is generated, causing an increase in total harmonic distortion (THD).

There is a novel method to actively compensate for the reactive current caused by the EMI capacitor. Moreover, the PFC current-loop reference is reshaped at the AC zero-crossing to accommodate for the fact that any reverse current will be blocked by the diode bridge. Both PF and THD are improved as a result.

### A novel EMI-capacitor compensation method

Poor PF is caused mainly by the EMI-capacitor reactive current, which can be calculated for a given EMI-capacitor value and input voltage. Therefore, if this reactive current is subtracted from the total ideal input current to form a new current reference for the PFC current loop, a desirable total input current can be obtained and a good PF achieved. To explain in detail, for a PFC with an ideal PF of one, \( I_{AC} \) is in phase with \( V_{AC} \). The reactive current, \( I_C \), always leads \( V_{AC} \) by 90°.

If \( V_{AC} \) is depicted as:

\[
v_{AC}(t) = V_{AC} \sin(\omega t)
\]

then

\[
i_{AC}(t) = I_{AC} \sin(\omega t)
\]

Since capacitor current is

\[
i_C(t) = C \times \frac{dv_{AC}(t)}{dt}, \text{ then}
\]

\[
i_C(t) = \omega \times C \times V_{AC} \cos(\omega t)
\]

From Figure 2:

\[
i_{AC}(t) = i_L(t) + i_C(t), \text{ so}
\]

\[
i_L(t) = i_{AC}(t) - i_C(t)
\]

Combining equations 3, 4 and 6 gives:

\[
i_L(t) = I_{AC} \sin(\omega t) - \omega \times C \times V_{AC} \cos(\omega t)
\]
If \( i_L(t) \) is calculated as the current reference for the PFC current loop, then the EMI-capacitor reactive current can be fully compensated, which improves PF (Figure 4). The blue waveform is the preferred input current, \( i_{AC}(t) \), which is in-phase with \( V_{AC} \). The green waveform is the capacitor current, \( i_C(t) \), which leads \( V_{AC} \) by 90°. The dotted black waveform is \( i_{AC}(t) - i_C(t) \). The red waveform is the rectified \( i_{AC}(t) - i_C(t) \). The proposed method for EMI-capacitor compensation uses this red waveform as its current reference. In theory, if the PFC current loop uses this as its reference, the EMI-capacitor reactive current can be fully compensated, and the PF can be increased.

The proposed current reference is further improved as shown in Figure 5. Because of the diode bridge rectifier used in the PFC power stage, any reverse current will be blocked by diodes. Referencing Figure 5, during the time period bound by T1 and T2, \( v_{AC}(t) \) is in the positive half cycle, but the expected \( i_L(t) \) (dotted black line) is negative. This is not possible, however, because the negative current will be blocked by the diodes, so the actual \( i_L(t) \) remains zero during this period. Similarly, during the T3-to-T4 time period, \( v_{AC}(t) \) becomes negative, but the expected \( i_L(t) \) is still positive. So it also will be blocked by the diodes, and remains at zero. The red waveform in Figure 5 shows what the actual \( i_L(t) \) would be, which will be used as the current reference for the PFC current loop.

**Implementation**

The proposed compensation method can be easily implemented by a digital PFC controller. In a traditional PFC with average current-mode control, the current reference is generated by:

\[
I_{REF} = A \times B \times C
\]

where \( A \) = voltage loop output, \( B = 1/V_{AC,RMS}^2 \), and \( C \) = the sensed \( V_{AC}(t) \) input voltage.

To use the proposed EMI-capacitor compensation method, the current reference needs to be modified according to Equation 7. The EMI-capacitor reactive current, \( i_C(t) \), needs to be calculated first. With a digital controller, the input AC voltage is sampled by an ADC at a fixed sample rate. Thus, the frequency of an input AC voltage can be determined by calculating how many ADC samples are in two consecutive AC zero-crossings.

To get the cosine waveform, the ADCs input voltage measurements are stored in the random access memory (RAM). Note that the cosine wave leads the sine by 90° (a quarter AC cycle). Therefore, the cosine value of the input voltage can be found by reading from the previously stored ADC measurement, but shifted by a quarter AC cycle. Finally, the EMI-capacitor reactive current, \( i_C(t) \), can be calculated using Equation 4, then subtracted from \( I_{REF} \) to get a new current reference. Special action is taken during subtraction to deal with AC zero-crossing distortion. The following steps outline the details:

1. Store the previous half-AC cycle, \( V_{AC} \) ADC measurements, depicted as \( V_{AC}[0], V_{AC}[1] \ldots V_{AC}[N] \), where \( N \) is the total ADC samples in a half AC cycle.

2. Detect the AC zero-crossing, which corresponds to the T1 time marker in Figure 5.
3. Read from the previously stored ADC values, starting from \( V_{AC}[N/2] \).
4. Calculate \( i_C(t) \) according to Equation 4.
5. Subtract \( i_C(t) \) from \( I_{REF} \) to get the new reference \( I_{REF} \).
   - If \( I_{REF} > |i_C(t)| \), then \( I_{REF} = I_{REF} - i_C(t) \)
   - If \( I_{REF} < |i_C(t)| \), then \( I_{REF} = 0 \), which corresponds to the T1-to-T2 time period in Figure 5.
6. Once reading reaches the end of \( V_{AC}[N] \), then start reading from \( V_{AC}[0] \). This is because the AC waveform is symmetric in each half cycle.
7. Repeat the above for the next half-AC cycle.
Test results
The proposed compensation method for EMI-capacitor reactive current was tested on a modified 360-W, single-phase PFC evaluation module (EVM), UCD3138PFCEVM-026, which was controlled by a UCD3138 digital power controller. The input voltage for the test condition was $V_{IN} = 230\, \text{V}$, 50 Hz. Figure 6 shows the actual PF test results at light load with and without EMI-capacitor compensation. Figure 7 shows the actual THD test results at light-load with and without EMI-capacitor compensation. Both PF and THD are improved with the proposed EMI-capacitor compensation method.

Conclusions
The proposed novel method to compensate EMI-capacitor reactive current reshaped the current reference during the AC zero-crossing area. Test results showed that both PF and THD were improved. Moreover, a digital controller was used to implementing this method, all changes were made in the controller’s firmware, and no extra hardware was needed.

References
2. UCD3138 Digital Power Factor Correction Pre-regulator Evaluation Module, Texas Instruments

Related Web sites
Product information: UCD3138


**TI Worldwide Technical Support**

**Internet**

**TI Semiconductor Product Information Center**

**Home Page**

support.ti.com

**TI E2E™ Community Home Page**

e2e.ti.com

**Product Information Centers**

**Americas**

<table>
<thead>
<tr>
<th>Country</th>
<th>Phone</th>
<th>Toll-Free Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brazil</td>
<td>0800-891-2616</td>
<td></td>
</tr>
<tr>
<td>Mexico</td>
<td>0800-670-7544</td>
<td></td>
</tr>
</tbody>
</table>

**Europe, Middle East, and Africa**

**Phone**

- European Free Call: 00800-ASK-Texas (00800 275 83927)
- International: +49 (0) 8161 80 2121
- Russian Support: +7 (4) 95 98 10 701

**Note:** The European Free Call (Toll Free) number is not active in all countries. If you have technical difficulty calling the free call number, please use the international number above.

**Fax**

+49 (0) 8161 80 2045

**Internet**

www.ti.com/asktexas

**Direct Email**

asktexas@ti.com

**Asia**

<table>
<thead>
<tr>
<th>Country</th>
<th>Phone</th>
<th>Toll-Free Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>1-800-999-084</td>
<td></td>
</tr>
<tr>
<td>China</td>
<td>800-820-8682</td>
<td></td>
</tr>
<tr>
<td>Hong Kong</td>
<td>800-96-5941</td>
<td></td>
</tr>
<tr>
<td>India</td>
<td>00-800-100-8888</td>
<td></td>
</tr>
<tr>
<td>Indonesia</td>
<td>001-803-8861-1006</td>
<td></td>
</tr>
<tr>
<td>Korea</td>
<td>080-551-2804</td>
<td></td>
</tr>
<tr>
<td>Malaysia</td>
<td>1-800-80-3973</td>
<td></td>
</tr>
<tr>
<td>New Zealand</td>
<td>0800-446-934</td>
<td></td>
</tr>
<tr>
<td>Philippines</td>
<td>1-800-765-7404</td>
<td></td>
</tr>
<tr>
<td>Singapore</td>
<td>800-886-1028</td>
<td></td>
</tr>
<tr>
<td>Taiwan</td>
<td>0800-006800</td>
<td></td>
</tr>
<tr>
<td>Thailand</td>
<td>001-800-886-0010</td>
<td></td>
</tr>
</tbody>
</table>

**International** +86-21-23073444

**Fax** +86-21-23073686

**Email** tiasia@ti.com or ti-china@ti.com

**Internet** support.ti.com/sc/pic/asia.htm

**Important Notice:** The products and services of Texas Instruments Incorporated and its subsidiaries described herein are sold subject to TI’s standard terms and conditions of sale. Customers are advised to obtain the most current and complete information about TI products and services before placing orders. TI assumes no liability for applications assistance, customer’s applications or product designs, software performance, or infringement of patents. The publication of information regarding any other company’s products or services does not constitute TI’s approval, warranty or endorsement thereof.

© 2016 Texas Instruments Incorporated. All rights reserved.

E2E is a trademark of Texas Instruments. All other trademarks are the property of their respective owners.
IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, enhancements, improvements and other changes to its semiconductor products and services per JESD46, latest issue, and to discontinue any product or service per JESD48, latest issue. Buyers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All semiconductor products (also referred to herein as "components") are sold subject to TI’s terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its components to the specifications applicable at the time of sale, in accordance with the warranty in TI’s terms and conditions of sale of semiconductor products. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by applicable law, testing of all parameters of each component is not necessarily performed.

TI assumes no liability for applications assistance or the design of Buyers’ products. Buyers are responsible for their products and applications using TI components. To minimize the risks associated with Buyers’ products and applications, Buyers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI components or services are used. Information published by TI regarding third-party products or services does not constitute a license to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of significant portions of TI information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI components or services with statements different from or beyond the parameters stated by TI for that component or service voids all express and any implied warranties for the associated TI component or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

Buyer acknowledges and agrees that it is solely responsible for compliance with all legal, regulatory and safety-related requirements concerning its products, and any use of TI components in its applications, notwithstanding any applications-related information or support that may be provided by TI. Buyer represents and agrees that it has all the necessary expertise to create and implement safeguards which anticipate dangerous consequences of failures, monitor failures and their consequences, lessen the likelihood of failures that might cause harm and take appropriate remedial actions. Buyer will fully indemnify TI and its representatives against any damages arising out of the use of any TI components in safety-critical applications.

In some cases, TI components may be promoted specifically to facilitate safety-related applications. With such components, TI’s goal is to help enable customers to design and create their own end-product solutions that meet applicable functional safety standards and requirements. Nonetheless, such components are subject to these terms.

No TI components are authorized for use in FDA Class III (or similar life-critical medical equipment) unless authorized officers of the parties have executed a special agreement specifically governing such use.

Only those TI components which TI has specifically designated as military grade or “enhanced plastic” are designed and intended for use in military/aerospace applications or environments. Buyer acknowledges and agrees that any military or aerospace use of TI components which have not been so designated is solely at the Buyer’s risk, and that Buyer is solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI has specifically designated certain components as meeting ISO/TS16949 requirements, mainly for automotive use. In any case of use of non-designated products, TI will not be responsible for any failure to meet ISO/TS16949.

### Products

<table>
<thead>
<tr>
<th>Audio</th>
<th><a href="http://www.ti.com/audio">www.ti.com/audio</a></th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplifiers</td>
<td>amplifier.ti.com</td>
</tr>
<tr>
<td>Data Converters</td>
<td>dataconverter.ti.com</td>
</tr>
<tr>
<td>DLP® Products</td>
<td><a href="http://www.dlp.com">www.dlp.com</a></td>
</tr>
<tr>
<td>DSP</td>
<td>dsp.ti.com</td>
</tr>
<tr>
<td>Clocks and Timers</td>
<td><a href="http://www.ti.com/clocks">www.ti.com/clocks</a></td>
</tr>
<tr>
<td>Interface</td>
<td>interface.ti.com</td>
</tr>
<tr>
<td>Logic</td>
<td>logic.ti.com</td>
</tr>
<tr>
<td>Power Mgmt</td>
<td>power.ti.com</td>
</tr>
<tr>
<td>Microcontrollers</td>
<td>microcontroller.ti.com</td>
</tr>
<tr>
<td>RFID</td>
<td><a href="http://www.ti-rfid.com">www.ti-rfid.com</a></td>
</tr>
<tr>
<td>OMAP Applications Processors</td>
<td><a href="http://www.ti.com/omap">www.ti.com/omap</a></td>
</tr>
<tr>
<td>Wireless Connectivity</td>
<td><a href="http://www.ti.com/wirelessconnectivity">www.ti.com/wirelessconnectivity</a></td>
</tr>
</tbody>
</table>

### Applications

| Automotive and Transportation | www.ti.com/automotive |
| Communications and Telecom | www.ti.com/communications |
| Computers and Peripherals | www.ti.com/computers |
| Consumer Electronics | www.ti.com/consumer-apps |
| Energy and Lighting | www.ti.com/energy |
| Industrial | www.ti.com/industrial |
| Medical | www.ti.com/medical |
| Security | www.ti.com/security |
| Space, Avionics and Defense | www.ti.com/space-avionics-defense |
| Video and Imaging | www.ti.com/video |

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265
Copyright © 2016, Texas Instruments Incorporated