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

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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.

$$PF = \frac{\text{Real Power}}{\text{Apparent Power}} \tag{1}$$

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.

Figure 1. Typical power correction supply with PFC

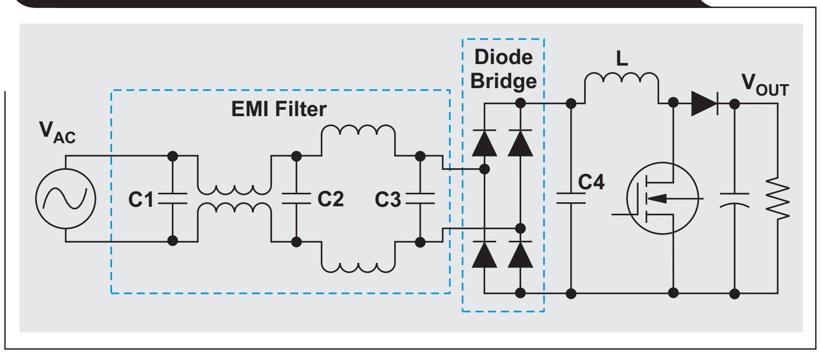
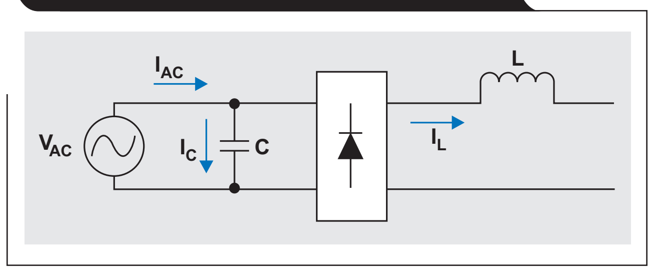


Figure 2. Simplified electromagnetic interference filter



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 $\overrightarrow{I_L}$, the input voltage is $\overrightarrow{V_{AC}}$, and the EMI-capacitor reactive current is $\overrightarrow{I_C}$. The total PFC input current is $\overrightarrow{I_{AC}}$, which is also the current from where the PF is measured. Although the PFC current control loop forces the inductor current, $\overrightarrow{I_L}$, to follow $\overrightarrow{V_{AC}}$, the reactive current of $\overrightarrow{I_C}$ leads $\overrightarrow{V_{AC}}$ by 90°, which causes the total current, $\overrightarrow{I_{AC}}$, to lead $\overrightarrow{V_{AC}}$. The result is a poor PF. This effect is amplified at light loads and high line voltages because $\overrightarrow{I_C}$ has more weight in the total current. As a result, it is difficult for the PF to meet a rigorous specification.

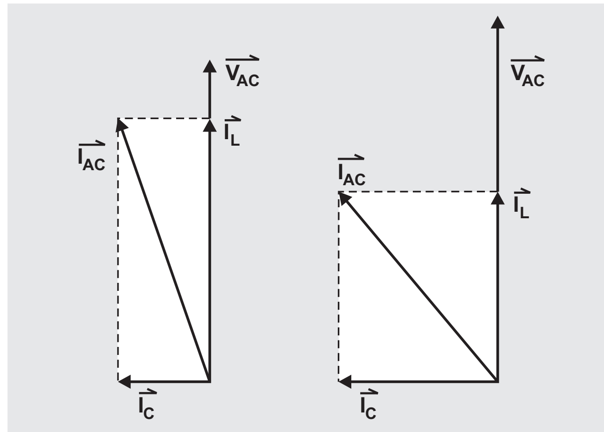
Traditionally, the poor PF caused by this EMI-capacitor leading current can be improved by forcing the induction current, $\overrightarrow{I_L}$, to lag $\overrightarrow{V_{AC}}$ by some degree.[1] To do this, the input AC voltage, $\overrightarrow{V_{AC}}$, is measured by an analog-to-digital converter (ADC), then delayed for an amount of time, Δt. The current reference is derived from this delayed $\overrightarrow{V_{AC}}$ signal, which deliberately makes the inductor current, $\overrightarrow{I_L}$, lag $\overrightarrow{V_{AC}}$. This can compensate the leading EMI-capacitor reactive current, $\overrightarrow{I_C}$, and improve PF.

However, this method has several limitations. First, the delay period, Δt, 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 Δt. Otherwise the inductor current, $\overrightarrow{I_L}$, will be over-delayed, making the PF worse than if there was no delay at all. Precisely and dynamically adjusting the delay time, Δt, 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.

Figure 3. EMI-filter reactive current causes an AC current to lead the AC voltage



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, $\overrightarrow{I_{AC}}$ is in phase with $\overrightarrow{V_{AC}}$. The reactive current, $\overrightarrow{I_C}$, always leads $\overrightarrow{V_{AC}}$ by 90°.

If $\overrightarrow{V_{AC}}$ is depicted as:

$$v_{AC}(t) = V_{AC}\sin(\omega t) \tag{2}$$

then

$$i_{AC}(t) = I_{AC}\sin(\omega t) \tag{3}$$

Since capacitor current is

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

$$i_C(t) = \omega \times C \times V_{AC}\cos(\omega t) \tag{4}$$

From Figure 2:

$$i_{AC}(t) = i_L(t) + i_C(t), \text{ so} \tag{5}$$

$$i_L(t) = i_{AC}(t) - i_C(t) \tag{6}$$

Combining equations 3, 4 and 6 gives:

$$i_L(t) = I_{AC}\sin(\omega t) - \omega \times C \times V_{AC}\cos(\omega t) \tag{7}$$

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 $\overrightarrow{V_{AC}}$. The green waveform is the capacitor current, $i_C(t)$, which leads $\overrightarrow{V_{AC}}$ 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:

$$I_{REF} = A \times B \times C \qquad (8)$$

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 ADC's 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 $V_{AC}[0]$, $V_{AC}[1]$ … $V_{AC}[N]$, where N is the total ADC samples in a half AC cycle.

Figure 4. Proposed current reference curve for PFC current loop

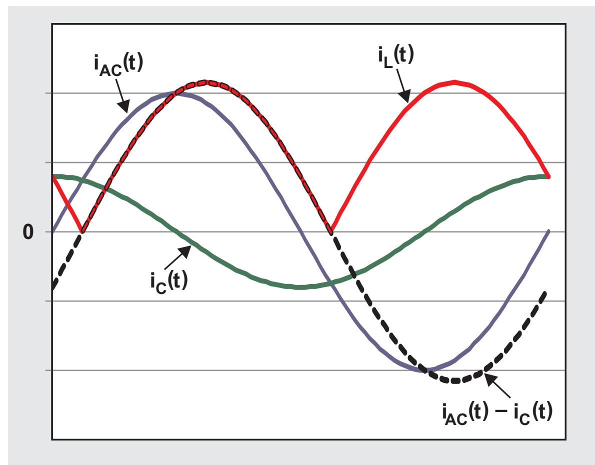
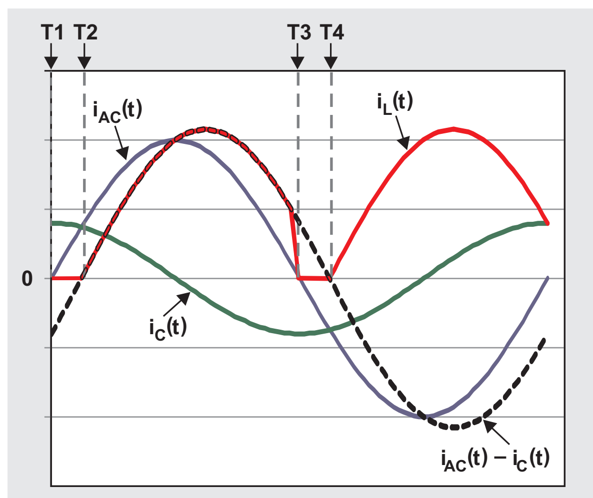


Figure 5. Proposed final current reference curve for PFC current loop



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 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

1. Z. Ye and B. Sun, "Advanced Digital Controls Improve PFC Performance," Darnell's Power China 2012, May 2012
2. UCD3138 Digital Power Factor Correction Pre-regulator Evaluation Module, Texas Instruments
3. "UCD3138 Highly Integrated Digital Controller for Isolated Power," Texas Instruments Data Manual (slusap2f), November 2013

Related Web sites

Product information:
UCD3138

Figure 6. Power factor versus load comparison

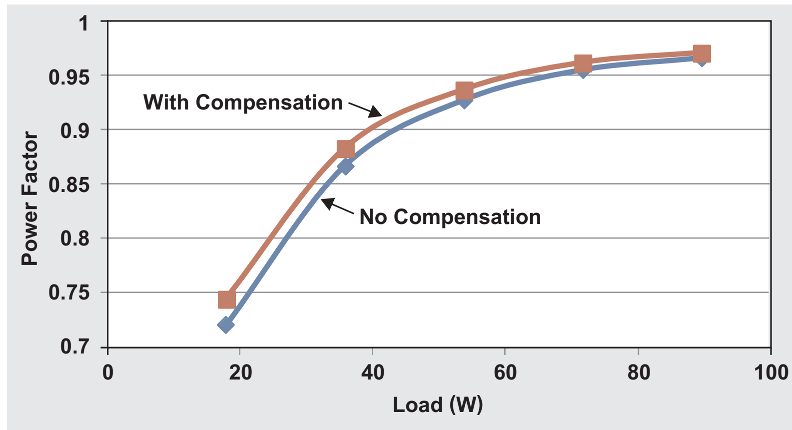
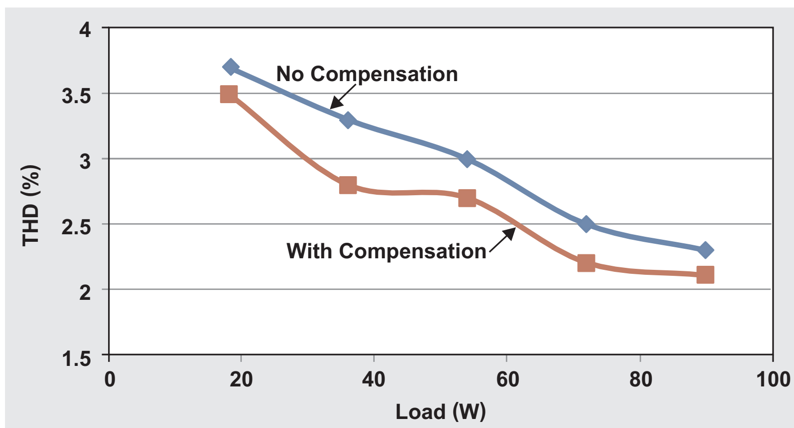


Figure 7. Total harmonic distortion versus load comparison



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