Low-cost solution for measuring input power and RMS current

By Bosheng Sun
Systems Engineer

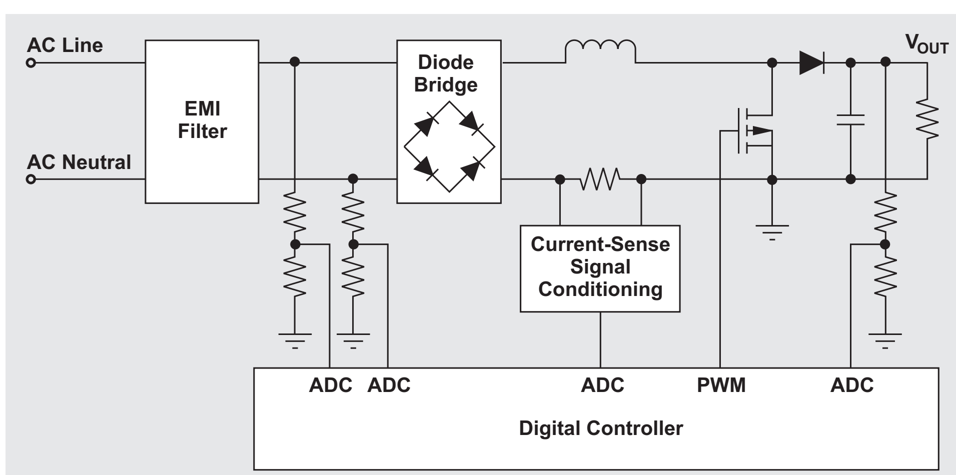
Introduction

Real-time measurement of energy consumption, including measurement of real input power and input RMS current for off-line power supplies, is becoming ever more important nowadays. These measurements can be used to adjust power delivery and optimize energy usage. More specifically, data centers, which contain many servers, are interested in submetering at the server level to implement low-cost data services and intelligently manage power processing during lower-power operation. The usual method of measuring input power and current uses a dedicated power-metering chip and an extra sensing circuit. While the power-metering chip provides acceptable results, it significantly increases the cost and design effort. This article provides a novel, low-cost but accurate solution for measuring input power and RMS current. It utilizes the existing digital power-factor-correction (PFC) control chip and hardware, with simple two-point calibration and optimized mathematical calculations. This provides excellent measurement accuracy and greatly reduces the cost and design effort, while having no impact on normal PFC control.

Measurement setup

Figure 1 shows a conventional PFC setup controlled by a digital controller for isolated power. The input line and neutral voltages are both sensed through an attenuation network and are subsequently sampled by two separate analog-to-digital-converter (ADC) inputs. The current signal is sensed by a current shunt and is amplified and filtered by a signal-conditioning circuit. It is then connected to an ADC for current-loop control. Since the input voltage and current measurements are already available, they can be used to measure the input power and RMS current as well. The same conventional PFC setup is used for these measurements. The traditional dedicated power-metering chip and extra sensing circuit are eliminated.

Figure 1. PFC setup for measuring input power and current



Current measurement and calibration

The current-sense signal-conditioning circuit (Figure 1) normally consists of an operational amplifier and a low-pass filter to amplify the small sensed signal and remove high-frequency noise. The signal is then measured by an ADC and reported in ADC counts. To get the real current value, the ADC counts need to be translated back to current in amperes. The relationship between ADC counts and amperes can be derived from the schematic; however, the component tolerances could make the measurement accuracy unacceptable. Therefore, a calibration is needed.

Given the circuit in Figure 1, at any moment the input current through the current shunt in milliamperes is

$$i = k_i C_i - m_i, \tag{1}$$

where k_i is the current-sense gain or slope, C_i is the ADC-conversion output (count), and m_i is the current-sense offset.

For constant direct-current (DC) input, the average value equals the instantaneous value, so Equation 1 is still valid:

$$I_{DC} = k_i C_i - m_i \tag{2}$$

Equation 2 indicates that a DC source can be used to calibrate the current-measurement circuit. A constant DC power is applied to the PFC input, and measurements are taken with a 25% load and then a 75% load. For comparison, a meter is used to provide benchmark measurements of actual input current for both load conditions. The count output of the ADC conversion is also read for both load conditions to determine the accuracy of the digital controller. The controller uses the following mathematical relationships. For a 25% load,

$$I_{DC1} = k_i C_{i1} - m_i. \tag{3}$$

For a 75% load,

$$I_{DC2} = k_i C_{i2} - m_i. \tag{4}$$

The current slope and offset can be calculated from Equations 3 and 4:

$$k_i = \frac{I_{DC2} - I_{DC1}}{C_{i2} - C_{i1}} \tag{5}$$

$$m_i = \frac{C_{i1} I_{DC2} - C_{i2} I_{DC1}}{C_{i2} - C_{i1}} \tag{6}$$

The calculated k_i and m_i are decimals and could be less than 1, while most of the digital controllers in PFC applications use a fixed point in mathematical calculation. To reduce the rounding errors and maintain enough accuracy in the calculations, the small decimal values are multiplied by 2^N and then rounded to the closest integer. For example, if the current-sense gain and offset for a PFC circuit are calculated as $k_i = 1.59$ and $m_i = 229.04$, then k_i will be multiplied by 2^8 and rounded to 407; and m_i will be multiplied by 2^0. The current slope and offset will respectively be

$$k_i = \text{iin\_slope} >> \text{iin\_slope\_shift}$$

and

$$m_i = \text{iin\_offset} >> \text{iin\_offset\_shift},$$

where iin_slope = 407, iin_slope_shift = 8, iin_offset = 229, and iin_offset_shift = 0.

When the input power and RMS current are calculated, if k_i and m_i are multipliers, then instead of using them directly, one can use iin_slope and iin_offset to do multiplication first. Then the result is right shifted by iin_slope_shift and iin_offset_shift. For example, instead of the calculation $y = k_i \times x + m_i \times z$, the following can be used:

$$y = [(\text{iin\_slope} \times x) >> \text{iin\_slope\_shift}] + [(\text{iin\_offset} \times z) >> \text{iin\_offset\_shift}]$$

Input-voltage measurement and calibration

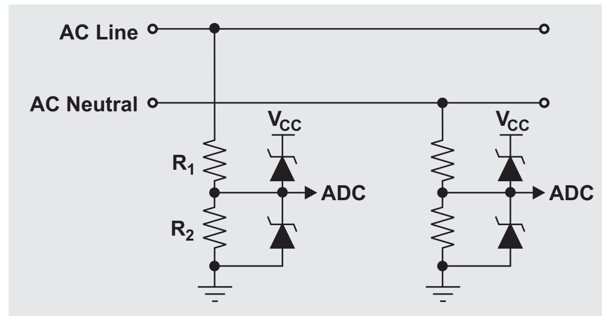
The voltage-sense circuit is quite simple and can be just a voltage divider, as shown in Figure 2. Usually there are clamp diodes to protect the ADC pins. Since the reverse leakage current of the diodes affects the ADC's measurement accuracy, diodes with low reverse leakage current should be chosen.

At any moment, the input voltage is

$$v = k_v C_v - m_v, \tag{7}$$

where k_v is the voltage-sense gain, C_v is the ADC-conversion output (count), and m_v is the voltage-sense offset. k_v and m_v can be calibrated in a way similar to calibrating the current-sense gain and offset. However, a much simpler way is to just calculate from the schematic. Since there is no calibration, the accuracy of the resistance

Figure 2. Voltage-sense circuit for AC input



used for the voltage divider affects measurement accuracy. Using low-tolerance resistors as the voltage divider is recommended—for example, 0.1% tolerance.

For a digital controller with a 12-bit ADC and referenced to 2.5 V, the input voltage is attenuated by the voltage divider to a magnitude of less than 2.5 V. Then the attenuated signal is converted to a digital signal by the ADC. Therefore,

$$C_v = \frac{vR_2}{2.5(R_1 + R_2)} \times 4096. \tag{8}$$

By rearranging Equation 8, the input voltage can be calculated as

$$v = \frac{2.5(R_1 + R_2)}{4096 R_2} \times C_v. \tag{9}$$

Therefore,

$$k_v = \frac{2.5(R_1 + R_2)}{4096 R_2}, \tag{10}$$

and

$$m_v = 0. \tag{11}$$

Similar to the input-current measurement, the voltage-sense gain and offset need to be manipulated to accommodate a fixed-point microprocessor and to reduce the calculation error.

V_{IN} and I_{IN} correlation

Real input power is defined as

$$P = \frac{1}{T}\int_0^T v(t)i(t)dt. \tag{12}$$

In discrete format, it is defined as

$$P = \frac{\sum[v(n)i(n)]}{N}, \tag{13}$$

where N is the total number of samples. Equation 13 indicates that V_{IN} and I_{IN} need to be sampled at the same time. However, V_{IN} and I_{IN} are sampled at different times by two different ADC channels. Even the small time discrepancy can contribute to a measurement error. In some digital controllers, such as the Texas Instruments UCD3138, a mechanism called *dual sample-and-hold* is provided that allows these two channels to be sampled simultaneously, eliminating this error.

Due to the low-pass filter used in the current-sense circuit, the measured current signal is delayed and out of phase with the actual current. This is shown in Figure 3, where Channel 2 is the actual current signal; and Channel 1 is the same signal amplified, which then comes out of the low-pass filter. The amplified signal has a phase delay of about 220 µs. This delay needs to be compensated for; otherwise it will affect the accuracy of the input-power measurement. A simple way to compensate is to delay the V_{IN}-sense signal by about 220 µs, then use the delayed V_{IN} signal to do an input-power calculation. So if V_{IN} is measured every 20 µs, it needs to be delayed by 220/20 = 11 times.

Calculating real input power

Combining Equations 1, 7, and 13 yields

$$P = \frac{k_v k_i \Sigma C_v(n) C_i(n)}{N} - \frac{k_v m_i \Sigma C_v(n)}{N} - \frac{k_i m_v \Sigma C_i(n)}{N} + m_v m_i. \quad \textbf{(14)}$$

V_{IN} and I_{IN} are measured by ADCs in the standard interrupt loop, which has a limited time period and is mainly used for PFC loop control. Therefore, to save CPU calculation time and prevent overflow in the standard interrupt loop, only $C_v(n)C_i(n)$ is calculated in this loop. Also, the terms

$$\frac{\Sigma C_v(n) C_i(n)}{N}, \ \frac{\Sigma C_v(n)}{N}, \text{ and } \frac{\Sigma C_i(n)}{N}$$

from Equation 14 are implemented with infinite impulse response (IIR) filters. The final calculation of real input power is done in the background loop.

Calculating input RMS current

The current measurement by the digital controller in Figure 1 does not represent the total input current, since the contribution of the capacitance in the electromagnetic-interference (EMI) filter is not included. At high line voltage and light load, this filter current is not negligible any more and must be included for accurate input-current reporting.

Figure 4 shows a simplified EMI filter where the inductors are removed and the total capacitance is replaced with a single capacitor (C). In this figure, I_{EMI} is the RMS reactive current of the EMI capacitor, $I_{Measure}$ is the input RMS current measured by the digital controller, and I_{IN} is the total input RMS current.

The reactive current produced by the EMI filter is

$$I_{EMI} = 2\pi f C V_{IN(RMS)}. \quad \textbf{(15)}$$

To calculate the reactive current of the EMI capacitor, the input-voltage frequency first needs to be determined. The AC line and neutral voltage are sensed by two ADC channels and then rectified by firmware. The zero crossing is found by comparing the two ADC results. Since the input voltage is sampled at a fixed rate, the AC frequency can be calculated by counting the number of samples between two consecutive zero-crossing points. Once the input-voltage frequency is known, the reactive current of the EMI capacitor is calculated as

$$I_{EMI} = 2\pi f C \sqrt{\frac{k_v^2 \Sigma C_v^2(n)}{N} - \frac{2k_v m_v \Sigma C_v(n)}{N} + m_v^2}. \quad \textbf{(16)}$$

As stated earlier, the voltage is measured in the standard interrupt loop; so, to save CPU calculation time and prevent overflow in this loop, only $C_v^2(n)$ is calculated in it. The terms

$$\frac{\Sigma C_v^2(n)}{N} \text{ and } \frac{\Sigma C_v(n)}{N}$$

from Equation 16 are implemented with IIR filters. The final EMI reactive current is calculated in the background loop.

The current measured by the ADC is defined as

$$I_{Measure(RMS)} = \sqrt{\frac{1}{T}\int_0^T i(t)^2 dt}. \quad \textbf{(17)}$$

Figure 3. Current-sense phase shift

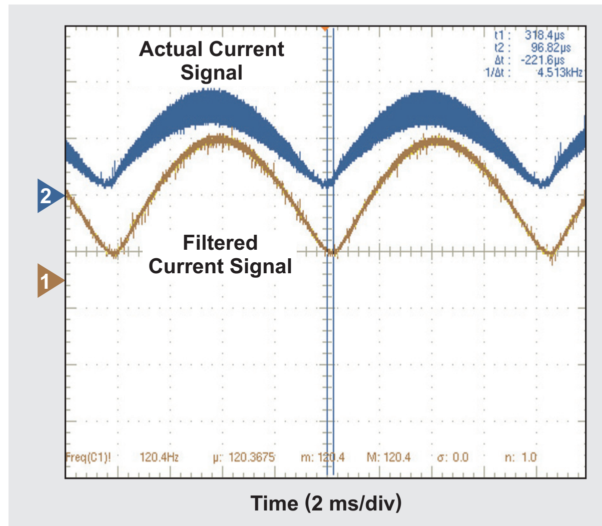
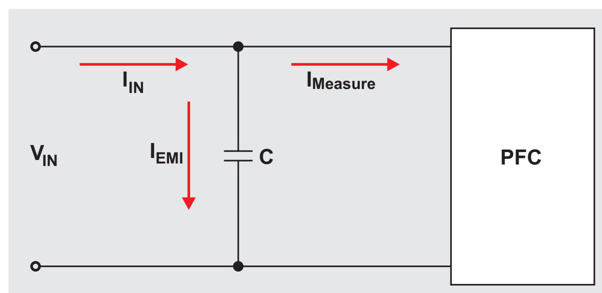


Figure 4. Current in simplified EMI filter



In discrete format, it is defined as

$$I_{Measure(RMS)} = \sqrt{\frac{\sum i_{IN}(n)^2}{N}}. \quad \mathbf{(18)}$$

Combining Equations 1 and 18 leads to

$$I_{Measure(RMS)} = \sqrt{\frac{k_i^2 \sum C_i^2(n)}{N} - \frac{2k_i m_i \sum C_i(n)}{N} + m_i^2}. \quad \mathbf{(19)}$$

As stated earlier, the current is measured in the standard interrupt loop; so only $C_i^2(n)$ is calculated in this loop. The terms

$$\frac{\sum C_i^2(n)}{N} \text{ and } \frac{\sum C_i(n)}{N}$$

from Equation 19 are implemented with IIR filters.

Finally, the EMI filter's reactive current (I_{EMI}) is added to $I_{Measure(RMS)}$ to get the total input current. I_{EMI} leads the measured current ($I_{Measure(RMS)}$) by 90º; therefore,

$$I_{IN(RMS)} = \sqrt{I_{EMI}^2 + I_{Measure(RMS)}^2}. \quad \mathbf{(20)}$$

The final input RMS current is calculated in the background loop.

Test results

This method of measuring input power and RMS current was tested on a 360-W PFC evaluation module. The results, shown in Table 1, demonstrate that this method provides excellent measurement accuracy.

Conclusion

A low-cost but accurate method of measuring input power and RMS current for off-line power supplies has been presented. This method uses the existing PFC controller chip and hardware, eliminating the traditional dedicated power-metering chip and extra sensing circuit, with no impact on normal PFC control. In addition, it provides the following features:

- Extremely low cost
- Simple two-point calibration
- Simultaneous sampling of V_{IN} and I_{IN} with dual sample-and-hold
- Firmware EMI-current compensation
- Firmware current-sense, phase-shift compensation
- Optimized mathematical calculations with little overhead in CPU usage

Reference

1. "Highly integrated digital controller for isolated power," UCD3138 Data Manual. Available: www.ti.com/slusap2-aaj

Related Web sites

Power Management:
www.ti.com/power-aaj

Subscribe to the AAJ:
www.ti.com/subscribe-aaj

Table 1. Test results of measuring input power and RMS current

OUTPUT LOAD (%)	P_{IN} (W) WITH METER	P_{IN} (W) WITH DIGITAL CONTROLLER	P_{IN} (W) DIFFERENCE	$I_{IN(RMS)}$ (mA) WITH METER	$I_{IN(RMS)}$ (mA) WITH DIGITAL CONTROLLER	$I_{IN(RMS)}$ (mA) DIFFERENCE
$V_{IN(RMS)}$ = 110 V						
2.50	11.5	10.3	1.2	112	101	11.0
5	18.8	17.9	0.9	180	170	10.0
10	35.4	34.3	1.1	328	317	11.0
20	72.7	71.7	1.0	665	659	6.0
30	107.7	107.2	0.5	989	985	4.0
40	143.5	143.1	0.4	1314	1315	–1.0
50	181.0	180.4	0.6	1656	1661	–5.0
60	216.3	215.4	0.9	1980	1987	–7.0
70	251.6	250.4	1.2	2305	2315	–10.0
80	287.0	285.3	1.7	2631	2643	–12.0
90	324.9	322.8	2.1	2981	2994	–13.0
100	360.6	357.9	2.7	3313	3325	–12.0
$V_{IN(RMS)}$ = 230 V						
2.50	11.0	9.1	1.9	88	87	1.0
5	19.0	16.8	2.2	111	105	6.0
10	36.5	34.5	2.0	177	168	9.0
20	71.1	69.1	2.0	320	311	9.0
30	107.7	106.0	1.7	477	469	8.0
40	144.9	143.1	1.8	637	631	6.0
50	179.4	177.6	1.8	786	782	4.0
60	216.1	214.6	1.5	945	942	3.0
70	253.1	251.6	1.5	1105	1106	–1.0
80	287.7	286.4	1.3	1256	1258	–2.0
90	324.5	322.9	1.6	1416	1419	–3.0
100	361.2	359.9	1.3	1576	1580	–4.0

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	Phone	+1(512) 434-1560
Brazil	Phone	0800-891-2616
Mexico	Phone	0800-670-7544
	Fax	+1(972) 927-6377
	Internet/Email	support.ti.com/sc/pic/americas.htm

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

Japan

Phone	Domestic	0120-92-3326
Fax	International	+81-3-3344-5317
	Domestic	0120-81-0036
Internet/Email	International	support.ti.com/sc/pic/japan.htm
	Domestic	www.tij.co.jp/pic

Asia

Phone

International	+91-80-41381665
Domestic	Toll-Free Number

Note: Toll-free numbers do not support mobile and IP phones.

Australia	1-800-999-084
China	800-820-8682
Hong Kong	800-96-5941
India	1-800-425-7888
Indonesia	001-803-8861-1006
Korea	080-551-2804
Malaysia	1-800-80-3973
New Zealand	0800-446-934
Philippines	1-800-765-7404
Singapore	800-886-1028
Taiwan	0800-006800
Thailand	001-800-886-0010

Fax	+8621-23073686
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.

A090712

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		**Applications**	
Audio	www.ti.com/audio	Automotive and Transportation	www.ti.com/automotive
Amplifiers	amplifier.ti.com	Communications and Telecom	www.ti.com/communications
Data Converters	dataconverter.ti.com	Computers and Peripherals	www.ti.com/computers
DLP® Products	www.dlp.com	Consumer Electronics	www.ti.com/consumer-apps
DSP	dsp.ti.com	Energy and Lighting	www.ti.com/energy
Clocks and Timers	www.ti.com/clocks	Industrial	www.ti.com/industrial
Interface	interface.ti.com	Medical	www.ti.com/medical
Logic	logic.ti.com	Security	www.ti.com/security
Power Mgmt	power.ti.com	Space, Avionics and Defense	www.ti.com/space-avionics-defense
Microcontrollers	microcontroller.ti.com	Video and Imaging	www.ti.com/video
RFID	www.ti-rfid.com		
OMAP Applications Processors	www.ti.com/omap	**TI E2E Community**	e2e.ti.com
Wireless Connectivity	www.ti.com/wirelessconnectivity		

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265
Copyright © 2013, Texas Instruments Incorporated