

Dimmable LED Driver with Precise Power Metering

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A dimmable light-emitting-diode (LED) driver with precise power metering is proposed in this paper. A buck-type power factor corrector (PFC) circuit with the merits of high power efficiency and high power factor (PF) is adapted in the LED driver. The input power of the LED driver can be evaluated precisely by calculating the sensed voltage and current on the output terminal of the PFC circuit. The slight reduction of the power efficiency during dimming can eliminate the error of the power evaluation. Therefore, the electrical sensors of the feedback circuit and the computation algorithm for power evaluation can be simplified to meet the requirements of high accuracy and cost-effectiveness. The detailed design topology, evaluation method, and verification results are provided. In experiments, dimmable LED drivers rated at 20 W exhibited an error of less than 2% when operating from 5 to 20 W and an error of less than 5% when operating from 2 to 5 W.

1. Introduction

The light-emitting-diode (LED) is now the world's most popular energy-efficient lighting source. With the increased popularity of LEDs in the lighting market, a significant impact on energy savings is anticipated. In recent years, LED lighting systems with smart LED drivers have become widely utilized in residential and commercial areas for cost-effective lighting with excellent quality. LED lighting systems with intelligent technologies and smart LED drivers with diverse functions have been vigorously implemented over the past decade as part of government policy to promote energy saving. Nowadays, the auxiliary functions of smart LED drivers, such as wireless control, communication, and lighting state monitoring, are attractive features for providing high LED lighting performances. In these auxiliary functions, the power used in the LED driver is the most important information for executing the energy-saving strategy by controlling and monitoring the LED lighting state. However, the more functions the LED driver features, the more electrical power is needed, making LED drivers very costly, especially if they feature power metering.

The conventional power metering methods, such as the use of analog front end (AFE) ICs and digital computation with a micro-controller unit (MCU),^(1–3) are too costly and complicated to be

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adopted in LED drivers. Costly digital power factor corrector (PFC) ICs featuring power metering,^(4–6) which are specifically designed for high-power applications, are also not appropriate for LED driver design. Therefore, to meet the demand from the LED lighting market, a cost-effective solution for precise power metering is necessary and critical for LED drivers in intelligent LED lighting systems.

This research focuses on the development of indoor LED lighting drivers. To guarantee the lighting quality, lifetime, and electrical performance of LED modules, the performance of LED drivers, such as power efficiency, power factor (PF), and total harmonic distortion (THD), must meet international standards and certification requirements.^(7–11) To comply with all these requirements, a novel power metering method and a circuit topology are proposed for a dimmable LED driver in this paper.

2. LED Driver Topology

The circuit topology of the proposed dimmable LED driver is simply constructed using a buck-type PFC and a linear LED current regulator as shown in Fig. 1. From Eq. (1), the active power of the LED driver, P_{in} , can be obtained by dividing the dc power output of the PFC circuit, P_{cv} , by its power conversion efficiency, η . The power losses on the rectifier and PFC circuit are included in the measured η . P_{cv} is calculated by multiplying the measured voltage, V_{cv} , and current, I_{cv} , on the PFC output terminal. The coefficient k is the reciprocal of η and is used for power evaluation [Eq. (2)].

$$P_{in} = \frac{P_{cv}}{\eta} = \frac{V_{cv} \times I_{cv}}{\eta} \quad (1)$$

$$k = \frac{1}{\eta} \quad (2)$$

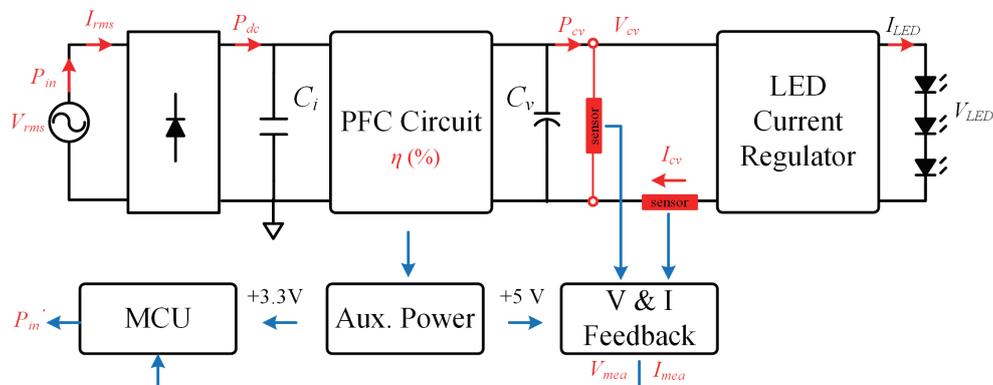


Fig. 1. (Color online) Proposed topology of LED driver with precise power metering.

The amplitudes of V_{cv} and I_{cv} are electrically sensed by a feedback circuit, which are represented as V_{mea} and I_{mea} in Fig. 1, respectively. Then the sensed values, V_{mea} and I_{mea} , are reverse derived to evaluate the PFC voltage and current, V_{eva} and I_{eva} , respectively, which are calculated using an MCU. Finally, the evaluated input power, P'_{in} , of the LED driver can be obtained as

$$P'_{in} = k \times (V_{eva} \times I_{eva}). \quad (3)$$

In the proposed driver, the auxiliary power for MCU operation and the feedback circuit power supply are coupled from the PFC circuit, and the LED current regulator for LED dimming is powered directly from the PFC output terminal. Therefore, P'_{in} is evaluated by including the power consumptions of the LED lighting driver, MCU, and feedback circuit. The error, ε , between P'_{in} and P_{in} is calculated as follows to evaluate the accuracy of power metering:

$$\varepsilon(\%) = \frac{100 \times (P'_{in} - P_{in})}{P_{in}}. \quad (4)$$

2.1 Circuit design

Because an indoor smart LED lighting driver is typically designed to operate at a low terminal voltage for an LED lamp, a non-isolated buck converter or an isolated flyback converter is usually utilized for a PFC. However, a traditional buck PFC is essentially characterized to have a poor PF and THD, and a flyback PFC has low power efficiency despite its excellent PF.^(12,13) In this study, as illustrated in Fig. 2, a buck-type PFC circuit is adopted to obtain the advantages of high power efficiency, excellent PF, and low THD in the dimming operation.^(14,15) The highly consistent and excellent electrical performance of the buck-type PFC circuit will decrease the evaluation error.

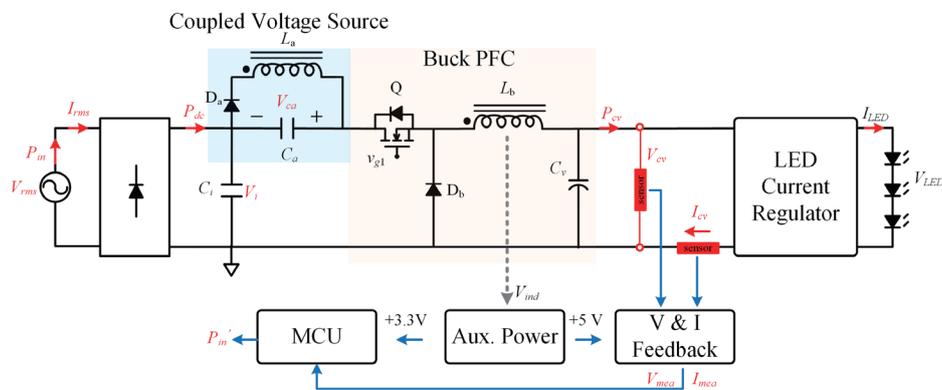


Fig. 2. (Color online) Proposed buck-type PFC circuit with high PF.

In the buck-type PFC circuit, a coupled voltage source is inserted in series with the rectified ac input source to sustain the continuity of the input current during the low-voltage interval. The coupled voltage source is realized by a coupling inductor L_a , blocking diode D_a , and series-connected capacitor C_a . The additional voltage on C_a can increase the input voltage of the conventional buck PFC circuit to decrease the dead zone of the input current. Therefore, an improved PF and low THD performance can be achieved during the lighting of the LED lamp even in the dimming operation.

The auxiliary power for supporting the feedback circuit and the MCU operation is coupled from the buck inductor L_b by drawing the energy via the auxiliary winding. When the power switch Q is in the off-state, the voltage on L_b is identical to V_{cv} , which can provide an induced voltage, V_{ind} , on the auxiliary winding with a designed turn ratio. Since V_{ind} is unregulated, the voltage sources of 5 and 3.3 V in the auxiliary power are regulated by low-dropout (LDO) regulators. Therefore, V_{ind} is designed to be slightly higher than 5 V, then the turn ratio is determined by the ratio of V_{cv} to V_{ind} ,

$$\frac{N_{Lb}}{N_{Aux}} = \frac{V_{cv}}{V_{ind}}, \quad (5)$$

where N_{Lb} and N_{Aux} are the numbers of winding turns of L_b and the auxiliary winding, respectively.

2.2 Power metering method

With the proposed circuit topology, an excellent PF can be maintained in the entire LED current operating range of the driver, and the power efficiency of the PFC circuit is slightly decreased when the LED lamp is dimmed. The voltage output of the buck-type PFC circuit is designed to be a constant low level close to the LED terminal voltage. Therefore, a linear current regulator can be utilized to regulate the LED current, which is identical to the PFC output current. In this circuit topology, as shown in Fig. 2, a low-voltage sensor and a low-side current sensor are cost-effectively adopted to feed back the voltage and current of the PFC circuit. The PFC output power, P_{cv} , is calculated by multiplying V_{eva} and I_{eva} in the MCU, then P'_{in} is obtained from Eq. (3). Furthermore, the status of the LED lamp is also monitored by the sensed current. The process of the input power evaluation is illustrated in Fig. 3.

2.3 Simulation results

The buck-type PFC is operated as a front-end constant-voltage source for the following LED current-regulating stage. The simulation results are shown in Fig. 4. The AC input voltage of 110 V_{ac} and the current are perfectly in phase with a PF of 0.98, as shown in Fig. 4(a).

The constant voltage of 60 V and the current of 300 mA on the PFC output terminal for a dimmable 20 W LED driver are shown in Fig. 4(b). Table 1 shows the simulation voltages, currents, and power efficiencies of the buck-type PFC circuit at 100, 50, 25, and 10% of the rated

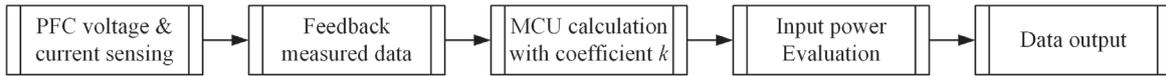


Fig. 3. Process of input power evaluation.

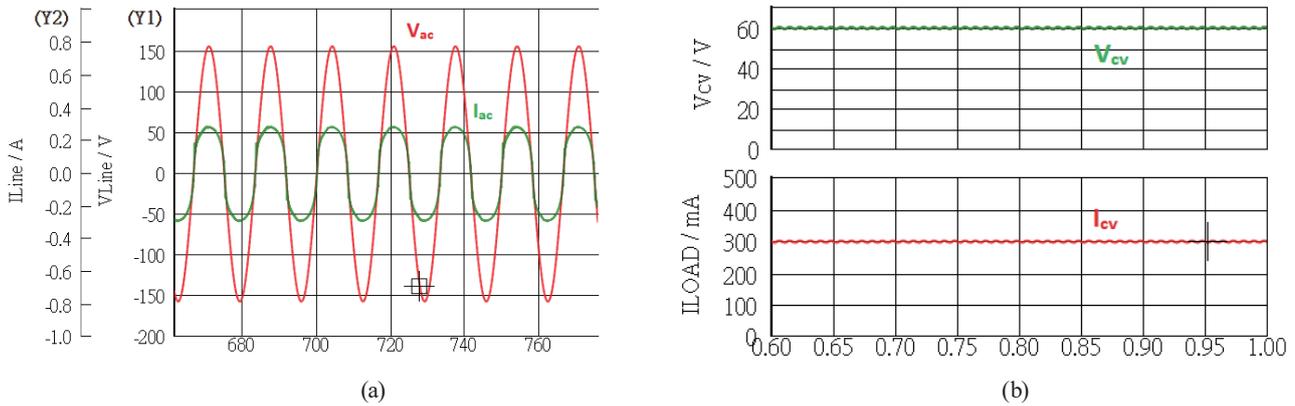


Fig. 4. (Color online) Simulation waveforms of (a) AC mains input and (b) PFC output terminal of the 20 W LED driver.

Table 1
Simulation results of the buck-type PFC circuit.

Input power (W)	Output voltage (V)	Output current (mA)	Power efficiency (%)	Evaluation error (%)
2	62.2	29.0	88.3	0.28
5	61.7	74.1	91.2	0.09
10	61.1	152.4	92.7	-0.05
20	60.7	302.6	91.6	0.03

power of 20 W, from which the error between P_{in} and P'_{in} can be calculated. As listed in Table 1, the power efficiency is over 91% at an input power of 5 W and above but decreases to 88.3% when the input power is reduced to 2 W, i.e., the LED is dimmed. Low efficiency is inevitable when the driver operates under a light load. Therefore, the coefficient k varies with the LED lighting state. In the entire operation power range during LED dimming, the buck-type PFC characterized with a high PF and high efficiency can minimize the variation of k .

3. Experimental Verification

A cost-effective and precise power metering feature is implemented in a dimmable LED driver rated at 20 W. The proposed power evaluation method has the advantages of low cost and high accuracy because of the following characteristics: 1. The PFC circuit has a constant and low output voltage, allowing voltage divider resistors without an extremely high resolution to be adopted as a voltage sensor; 2. the LED current is identical to the PFC output current, and a low-side current sensor is cost-effectively adopted to feed back the PFC current; 3. the PF and power

efficiency of the buck-type PFC circuit are high and consistent, and the value of k can be depicted as a curve with small variation during LED dimming.

In the verification experiment, the output voltage of the PFC, V_{cv} , is divided by 20 and is sensed as V_{mea} by the MCU. On the other hand, the output current of the PFC, I_{cv} , is magnified by 50 and is sensed as I_{mea} by the MCU. Therefore, the evaluated values of the PFC voltage and current, V_{eva} and I_{eva} , in the MCU are obtained using Eqs. (6) and (7), respectively. Finally, P'_{in} is evaluated with the corresponding k for different amounts of dimming of the LED current.

$$V_{eva} = 20 \times V_{mea} \quad (6)$$

$$I_{eva} = I_{mea} / 50 \quad (7)$$

3.1 k -curve

Figure 5 shows the k -curves of the buck-type PFC circuit operated at 110 and 220 V_{ac} . Small variations of k of 0.14 at 110 V_{ac} and 0.24 at 220 V_{ac} can be observed. Since the power efficiency gradually decreases with LED dimming, the k -curves are varied slightly, which can alleviate the calculation burden on the MCU. To realize the k -curves in the MCU, the averaged value of k at every 0.5 W is embedded in the MCU to evaluate the corresponding P'_{in} .

3.2 Demonstration of dimmable LED driver with precise power metering

As shown in Fig. 6, a laboratory circuit of the proposed LED driver is designed and tested at 110 and 220 V_{ac} with a line frequency of 60 Hz. In the experiments, the LED lamp is driven at 58 V and 300 mA with a total power efficiency of over 85%. The voltage and current waveforms of the AC mains input are shown in Fig. 7, and excellent PFs of 0.99 at 110 V_{ac} and 0.96 at 220 V_{ac} are obtained with the buck-type PFC circuit. The constant PFC output voltage at 64 V with a small voltage ripple of less than 5 V is shown in Fig. 8.

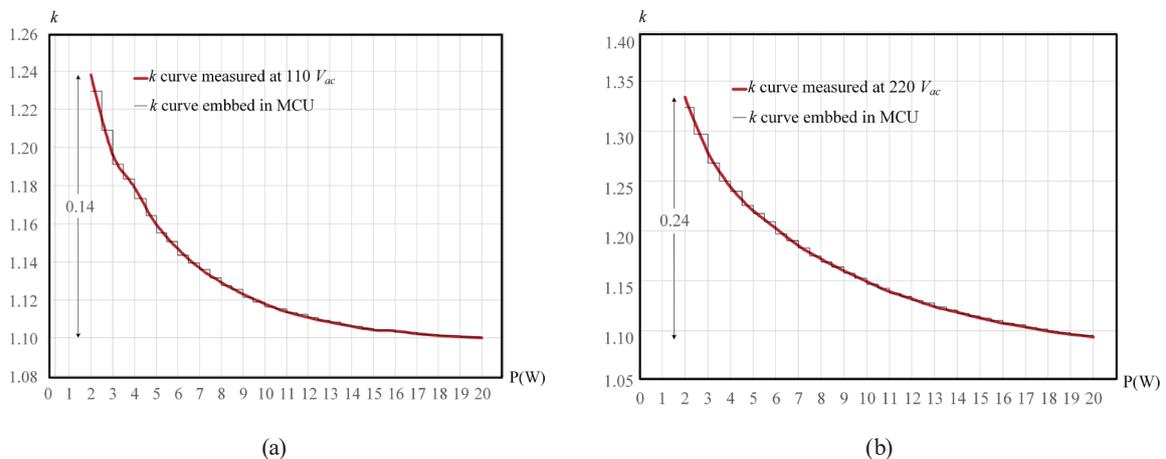


Fig. 5. (Color online) k -curves of the buck-type PFC circuit: (a) 110 V_{ac} input and (b) 220 V_{ac} input.

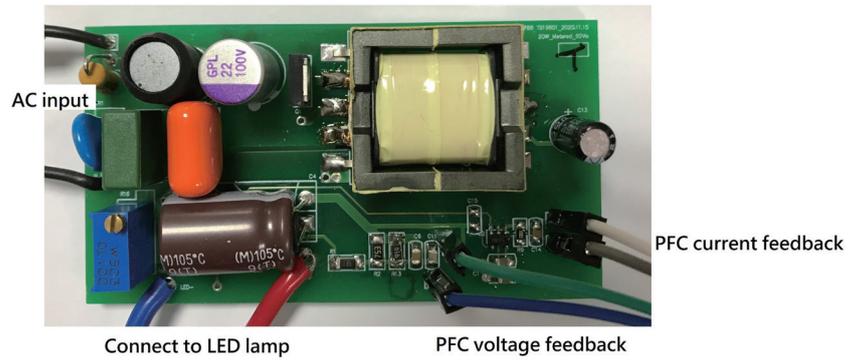


Fig. 6. (Color online) Proposed LED driver with precise power metering.

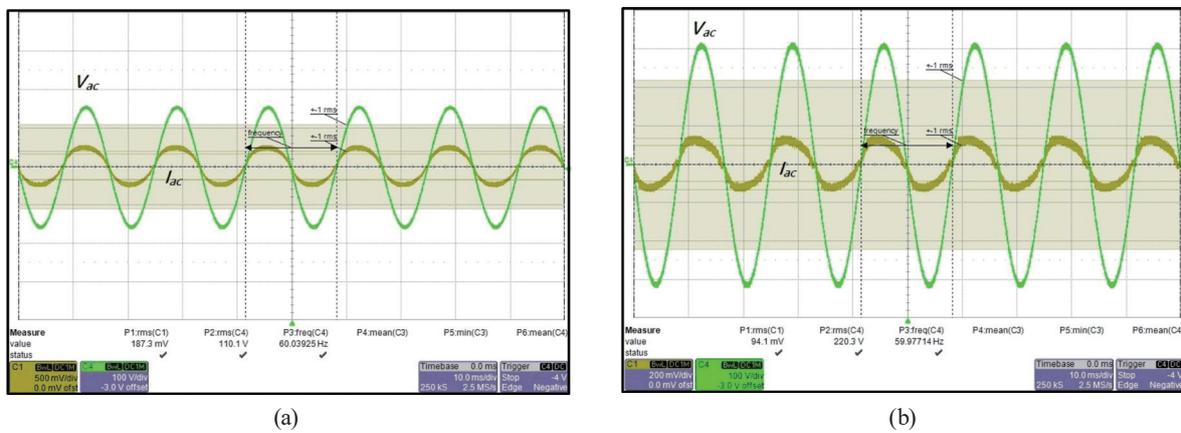


Fig. 7. (Color online) Waveforms of AC mains input: (a) 110 V_{ac} and (b) 220 V_{ac} .

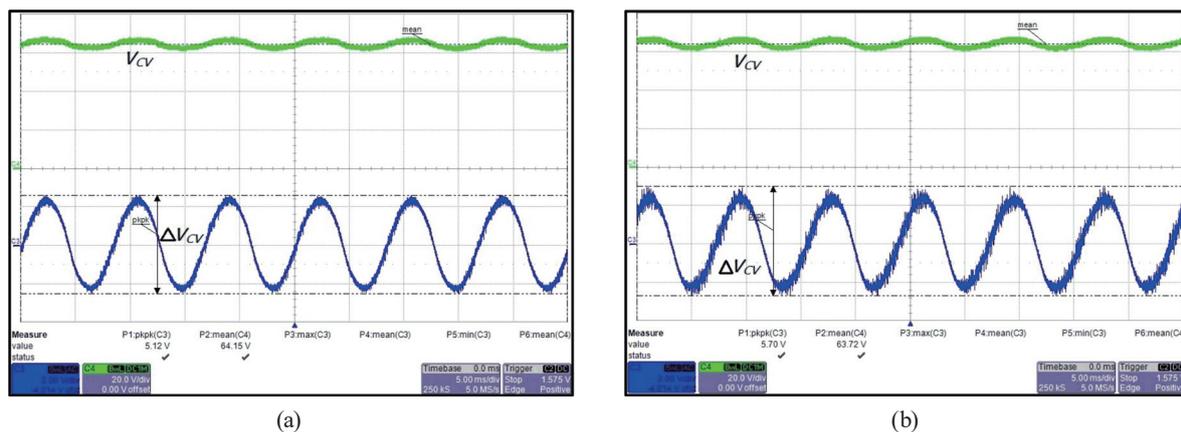


Fig. 8. (Color online) Waveforms of PFC circuit output: (a) 110 V_{ac} and (b) 220 V_{ac} .

To verify the reliability and feasibility of the proposed topology, we measure the percentage errors of the power metering in five individual LED drivers, which are illustrated in Fig. 9. The active power P_{in} of the LED drivers is measured with a YOKOGAWA WT1800 power analyzer.

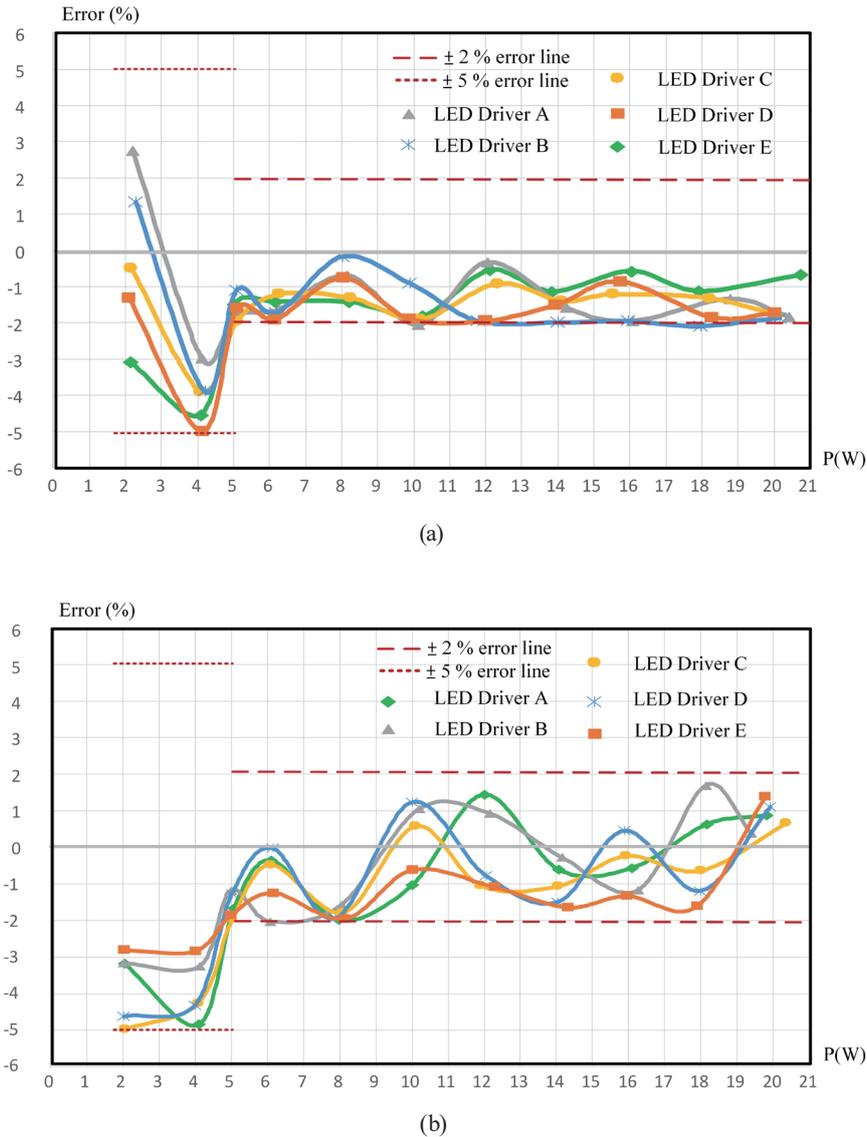


Fig. 9. (Color online) Evaluation errors of power metering of the dimmable LED drivers. (a) 110 V_{ac} and (b) 220 V_{ac} .

The power P'_m evaluated by power metering is transmitted to an Excel file for error calculation. As shown in Fig. 9, the trends of the error curves of the five LED drivers are similar. In operation at both 110 and 220 V_{ac} , the dimmable LED drivers rated at 20 W exhibit an error of less than 2% when operating from 5 to 20 W and an error of less than 5% when operating from 2 to 5 W.

4. Conclusions

A dimmable LED driver with precise power metering is proposed by adapting a buck-type PFC circuit. The consistent high PF and high efficiency of the PFC circuit during LED dimming

can improve the accuracy of input power evaluation. Furthermore, the electrical feedback circuit can be cost-effective and have high accuracy without requiring high-resolution sensors, making the proposed driver suitable for LED lighting applications.

In the experimental verification, a dimmable LED driver is designed for lighting an LED lamp at a rated current of 300 mA. Experimental results on a laboratory circuit have demonstrated high PFs of 0.99 and 0.96 for operation at 110 and 220 V_{ac} , respectively, with excellent efficiency of over 85%. Most importantly, the precise power metering feature in the dimmable LED driver is confirmed to have an error of less than 2% when operating from 5 to 20 W and an error of less than 5% when operating from 2 to 5 W.

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