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A high-precision broadband low-cost multiplier topology for electric energy measurement

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Abstract: The multiplier is an indispensable component of electronic energy meters, and is also the main source of energy metering errors. This paper quantitatively analyses the metering error of the conventional time-division multiplier in the presence of harmonics. The theoretical error expression is derived, which indicates that the error increases with the increase of harmonic order. To address the problem of inaccurate power metering under harmonic condition, this paper proposes a high-precision, wide-bandwidth, and low-cost multiplier topology. The accuracy of the multiplier in the presence of harmonics is successfully verified through theoretical derivation and simulation. Furthermore, an experimental prototype of the proposed high-precision broadband low-cost multiplier has been built to verify the simulation results, which supports the effectiveness of the proposed high-precision broadband low-cost multiplier in this paper.

Keywords: multiplier; harmonics; high-precision; wide-bandwidth; low-cost.

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1 Introduction

Electric energy measurement is fundamental to economic accounting in the power grid, and its accuracy is critical to the economic benefits of both power suppliers and consumers (Yue et al., 2020). At present, commonly used electric energy metering methods can be divided into three types (Li et al., 2008):

- 1 Electric energy metering: This method only measures the fundamental wave power consumed by the user.
- 2 Separate fundamental and harmonic electric energy metering: This method involves using separate meters to measure the fundamental power and harmonic power consumed by the customer.
- 3 Full-wave electric energy metering: This method takes into account both the fundamental power and the absorbed or emitted harmonic power to obtain the total electrical energy consumed by the user.

Therefore, full-wave electric energy metering requires wide frequency response for various orders of harmonics. The full-wave electric energy metering method is widely used in most countries. Currently, the solutions addressing the impact of harmonics on the metering performance of electric energy meters mainly focus on metering algorithms. Additionally, some scholars have conducted research on the internal hardware measurement circuits of electric energy meters, performing a quantitative analysis of the metering errors of the time-division multiplier within the meters under harmonic conditions. They believe that when the modulation frequency is relatively high, the metering errors of the time-division multiplier can be neglected. However, due to the increasing number of nonlinear loads connected to the power grid, there are now large numbers of harmonics, inter-harmonics and even DC components in the grid voltage and current. Some of these harmonics are generated by nonlinear loads and injected into the power grid, opposing the fundamental current. This harmonic current generates harmonic power that offsets part of the fundamental active power (Di Paolo, 2017). While, users of linear loads are impacted by harmonics, which result in the consumption of both fundamental and harmonic electric energy (Lo et al., 1999). Therefore, it is of great importance and practical value to study how to accurately and reasonably measure power when input voltage and current contain a large number of harmonic components.

The multiplier is a critical component for full-wave type of electric energy meter. Currently, time division multiplier (TDM) is the most commonly used multiplier in domestic electronic energy meters (Jovanović, 2016). The research in Yu et al. (2014) established a simulation model of the time-division multiplier. According to the operation principle of the time-division multiplier, the theoretical model of its metering error under harmonic conditions is established in Wang et al. (2014), which provides a theoretical

basis for quantitative analysis of the error of the metering system under harmonic conditions. Based on simulation and calculations analysis, it is concluded that high harmonic content can significantly affect the electronic energy meter's ability to accurately measure electric energy. By integrating high-frequency electric energy pulse output technology, interpolation re-sampling dot product and algorithm, as well as high-performance DSP, Xia et al. (2018) has successfully developed a novel digital reference energy meter.

Although previous research has addressed the issue of accurately measuring electric energy in the presence of harmonics, it has not fully deal with the challenges of simple de-sign, low cost and high accuracy. To overcome these challenges, this paper proposes a high-precision broad-band low-cost multiplier topology, which can accurately measure the electric power for the application of full-wave type electric energy meter when the input voltage and current contain high orders of harmonics. This structure reduces measurement errors, operates unaffected by frequency variations and also contributes to lowering manufacturing costs. This paper proposes and validates an improved power measurement model based on the time-division multiplier. This model significantly enhances measurement accuracy by integrating an active measurement correction module and adapting to the dynamic characteristics of distributed photovoltaics.

This paper is organised as follows: in Section 2, the current research status of electric energy measurement considering harmonics is mainly introduced. In Section 3, the traditional triangular voltage comparison TDM is analysed to quantify its measurement error; In Section 4, a novel multiplier topology is introduced, which boasts high accuracy, a wide bandwidth, and a low cost. Alongside, a mathematical model is presented to substantiate its effectiveness. Furthermore, simulation models are established to validate the metering error of the traditional TDM as well as the newly proposed multiplier; in Section 5, an experimental prototype of the pro-posed multiplier has been built to verify the simulation results.

2 Related works

To improve the accuracy of electric energy measurement in the presence of harmonics, a modified power metering model based on the time-division multiplier model is proposed in Dou et al. (2017). An active metering correction module is designed, and photovoltaic grid-connected signals are mathematically characterised to adapt to the dynamic characteristics of distributed photovoltaics. Specifically, measurement errors can be corrected in real-time, thus enhancing the accuracy and reliability of energy measurement. An improved meter using wavelet transform to calculate the energy of nonlinear loads is designed in Liu et al. (2016). Validation through examples shows that this algorithm is significantly more accurate than traditional ones. Complex electrical signals are effectively decomposed and analysed by the wavelet transform, accurately capturing energy variations caused by nonlinear loads, thereby improving energy measurement accuracy. How advanced metering infrastructure (AMI) in smart grids enhances energy efficiency and power quality through real-time monitoring and management is discussed in Das and Bera (2023). Energy usage data can be collected, analysed, and transmitted in real-time by AMI systems, enabling fine-grained management of the power system. Energy wastage is reduced, transparency in energy

usage is increased, and load management is optimised by this technology. In Costa et al. (2023), wavelet transform is used to analyse and improve power quality issues such as transients, flicker, and harmonics. Wavelet transform is a powerful signal processing tool that allows multi-scale decomposition and analysis of signals in both time and frequency domains, enabling accurate identification and classification of power quality issues. The understanding and handling of complex signals are enhanced by this method, thereby improving the stability and reliability of power systems.

A new power load monitoring method based on energy compensation is proposed in Gu et al. (2022a), the basic framework of high-power electrical load monitoring method is given. A new virtual instrument-power meter and power quality analyser is described in Arsov et al. (2014), the instrument enables complete monitoring of all the powers and power quality parameters, as well as simultaneous measurements of voltages and currents and application for motor current signature analysis (MCSA) and technical diagnostics. In recent years, research on electric energy measurement that takes into account harmonics has also been making continuous progress. The research in De Oro Arenas et al. (2021) designs an intelligent energy meter based on FPGA, which not only realises accurate power quantity definition, but also performs well in the three-phase four-wire system. It can effectively cope with the harmonic components caused by nonlinear loads and supply voltage, as well as the bidirectional power flow in distributed generation scenarios. The non-sinusoidal harmonic signal detection method based on pulse resonance principle proposed in Gu et al. (2022b) has significant advantages and potential in the field of energy metering. This method has good anti-interference ability for non-sinusoidal harmonic signals, and can accurately detect even in the presence of noise and interference. The data-driven harmonic contribution model in Yang et al. (2022), leveraging data selection and regression coefficient analysis, enables prompt detection and resolution of harmonic issues in dynamic customer environments, ensuring power system stability. The harmonic amplitude measurement method based on wavelet transform proposed in Costa et al. (2023) has demonstrated good performance in the presence of interharmonics. Mazumdar and Harley (2008) presents a pioneering method employing recurrent neural networks (RNNs) trained with the backpropagation through time (BPTT) algorithm. This approach aims to estimate harmonic currents generated by nonlinear loads more effectively than conventional methods. By harnessing the capabilities of RNNs and BPTT, the study advances the field by providing a robust framework capable of capturing the intricate dynamics and nonlinearities inherent in harmonic current estimation.

3 TDM electronic energy meter metering model

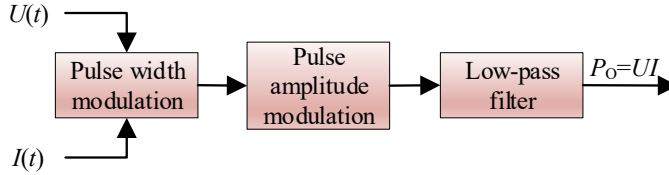
3.1 Basic principle

The block diagram of TDM is shown in Figure 1. It is mainly composed of three parts: the pulse width modulation circuit, the pulse amplitude modulation circuit controlled by the output signal of the width modulation circuit, and the low-pass filter circuit. The expression of its realisation principle is:

$$W = \int_0^T u i dt = \Delta t \lim_{m \rightarrow \infty} \sum_{k=1}^m u_k i_k \approx \Delta t \sum_{k=1}^m u_k i_k \quad (1)$$

where m is the number of samples in a cycle, W is the electric energy, and u and i are the voltage and current respectively. From equation (1), it can be further concluded that in a cycle, the load energy consumption is equal to the sum of m voltage and current products. The higher the m value is, the smaller the error can be achieved. Therefore, segmentation and multiplication are the basic ideas of the multiplier.

Figure 1 System structure diagram (see online version for colours)

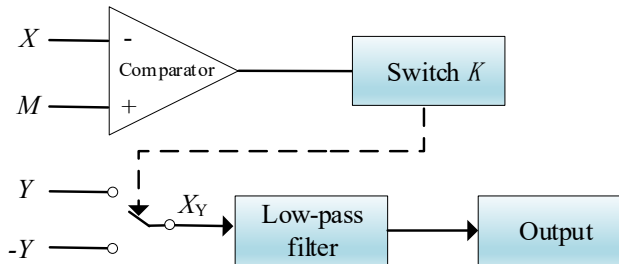


The process of division involves dividing a cycle into m equal parts with a time interval of Δt . When m approaches infinity, Δt approaches zero. In this case, the instantaneous values of voltage and current can be treated as constants, with a magnitude of U and I , respectively. The multiplier of TDM utilises U and I to modulate the pulse width and amplitude, and ensure the area of the pulse is proportional to their product. Thus, the resulting value is the average of the instantaneous product.

3.2 Working principle of triangular wave voltage comparison type TDM

The detailed block diagram of TDM based on triangular wave voltage comparison circuit is shown in Figure 2. The input signals are X and Y , and the modulation signal M is a triangular wave signal.

Figure 2 Circuit diagram of triangular wave voltage comparison type TDM (see online version for colours)

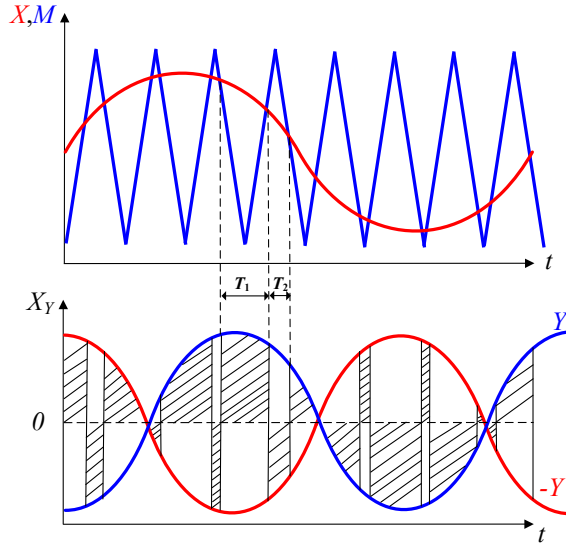


The circuit's operation principle is as follows: the input signal X is compared with the modulation signal M . If X is greater than M , the comparator outputs a high level, which controls the switch K to allow the input signal Y to pass through. If X is less than M , the comparator output is low, and control switch K to allow the inverted input signal $-Y$ to pass through. After the pulse width modulation, a sine envelope pulse width modulation

waveform XY is obtained, as shown in Figure 3. Finally, the waveform is filtered and output to obtain the multiplying product.

Taking a triangle wave period $T = T_1 + T_2$ shown in Figure 3 as an example, due to the much higher frequency of the triangle wave compared to the sine wave, both T_1 and T_2 are very small. Within a period T , the sine wave can be regarded as a straight line with a slope. The intersection coordinates of each cycle of the sine wave and the triangular wave can be determined based on the expressions of the sine wave and triangular wave, and the pulse width can be determined to obtain the measurement value of AC active power within a certain period of time. After comparison with the theoretical value, the error expression of the multiplier AC active power measurement can be obtained.

Figure 3 Operation waveform of triangular wave voltage comparison type TDM
(see online version for colours)



3.3 Working principle of triangular wave voltage comparison type TDM

Under the condition of harmonics, it is assumed that the voltage and current inputs of TDM consist of the h^{th} harmonics, where $u = \sqrt{2}U \sin(\omega_h t)$, $i = \sqrt{2}I \sin(\omega_h t + \varphi)$, and U and I are the effective values of voltage and current, respectively. $\omega_h = 2\pi hf$ is the angular frequency of input voltage, and f is the fundamental frequency, φ is the h^{th} harmonic phase difference. Let the frequency of the triangular wave modulation signal be F , it can be known from Figure 3 that one fundamental cycle is divided into $k_1 = F/f$ equal parts. Then, the h^{th} harmonics cycle is divided into $k_h = k_1/h$ equal parts.

The first step is to calculate the power of the fundamental wave condition, where $h = 1$, then for the n^{th} part, the input voltage U_n is derived:

$$U_n = \frac{k_1}{2\pi} \int_{\frac{2(n-1)\pi}{k_h}}^{\frac{2n\pi}{k_1}} u d(\omega_t) = \frac{k_1 U}{\sqrt{2}\pi} \left\{ \cos \left[\frac{2(n-1)\pi}{k_1} \right] - \cos \left(\frac{2n\pi}{k_1} \right) \right\} \quad (2)$$

the input current I_n is derived:

$$I_n = \frac{k_1}{2\pi} \int_{\frac{2(n-1)\pi}{k_1}}^{\frac{2n\pi}{k_1}} id(\omega_t) = \frac{k_1 I}{\sqrt{2\pi}} \left\{ \cos \left[\frac{2(n-1)\pi}{k_1} + \varphi \right] - \cos \left(\frac{2n\pi}{k_1} + \varphi \right) \right\} \quad (3)$$

The n th part of power is $P_n = U_n I_n$, then the average value $P_h = 1$ of instantaneous power in one cycle is:

$$\begin{aligned} P_{h=1} &= \frac{1}{k_1} \sum_{n=1}^{k_1} P_n = \frac{k_1 UI}{2\pi^2} \times \sum_{n=1}^{k_1} \left\{ \cos \left[\frac{2(n-1)\pi}{k_1} \right] - \cos \left(\frac{2n\pi}{k_1} \right) \right. \\ &\quad \times \cos \left[\frac{2(n-1)\pi}{k_1} + \varphi \right] - \cos \left(\frac{2n\pi}{k_1} + \varphi \right) \left. \right\} \\ &= \frac{k_1 UI \cos \varphi}{2\pi^2} \sum_{n=1}^{k_1} \left\{ \cos \left[\frac{2(n-1)\pi}{k_1} \right] - \cos \left(\frac{2n\pi}{k_1} \right) \right\}^2 \end{aligned} \quad (4)$$

The second step is to calculate the power of the h^{th} harmonics. Similarly, the average power of the h^{th} harmonic P_h at the same modulation frequency can be obtained as:

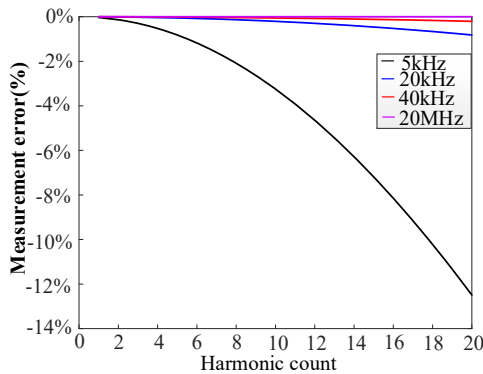
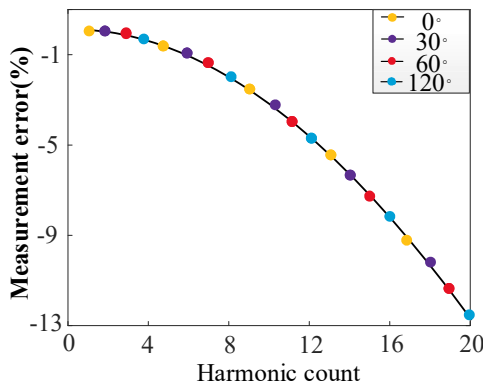
$$P_h = \frac{k_h UI \cos \varphi}{2\pi^2} \sum_{n=1}^{k_h} \left\{ \cos \left[\frac{2(n-1)\pi}{k_h} \right] - \cos \left(\frac{2n\pi}{k_h} \right) \right\}^2 \quad (5)$$

The third step is to calculate the metering error of the h^{th} harmonic power, $P_t = UI \cos \varphi$ is the theoretical value of the h^{th} harmonic power, thus, the measurement error e_{ph} is obtained:

$$e_{ph} = \frac{P - P_t}{P_t} \times 100\% \quad (6)$$

Then, according to equations (5) and (6), numerical calculations are carried out using MATLAB with a modulation frequency of $F_1 = 5$ kHz, $F_2 = 20$ kHz, $F_3 = 40$ kHz, and $F_4 = 20$ MHz. The relationship among the harmonic order, modulated signal frequency, and measurement error is plotted in Figure 4. The results show that the measurement error increases with an increase in the harmonic order, while it decreases with the increase of the modulation frequency. For the modulation frequency of 40 kHz, the measurement errors of harmonic order 1st to 20th can meet the accuracy requirement of 0.2%. When the modulation frequency reaches a certain level, such as 20 MHz, the error for each harmonic is negligible, demonstrating that the theoretical error of TDM is negligible in practical engineering applications. However, when the modulation frequency is too high, the cost of the multiplier chip becomes expensive. Additionally, at high frequencies, the time division multiplexing processing may cause signal distortion and increased noise, ultimately decreasing the accuracy and reliability of power metering systems.

When analysing the impact of input voltage and current at different phases on TDM error measurement, the modulation frequency F is maintained at a constant 5 kHz. The phase difference of the input signal Ψ_h is then varied as 0° , 30° , 60° , 90° and 120° , respectively. Figure 5 illustrates the measurement error curve of TDM based on equation (4).

Figure 4 The relationship among the harmonic order, modulated signal frequency and the measurement error (see online version for colours)**Figure 5** Measurement error curve of single harmonic with different phase differences (see online version for colours)

Based on Figure 5, it is evident that the measurement error remains consistent for all four phase differences across various harmonic frequencies. Consequently, the measurement error for an individual harmonic is unaffected by the phase difference between the two input signals. This finding validates the accuracy of the theoretical derivation.

4 High-precision broadband low-cost multiplier and simulation verification

4.1 High-precision broadband low-cost multiplier

In order to address the limitations of traditional TDM multipliers, this paper proposes a new multiplier topology with high accuracy, wide bandwidth, and low cost, as shown in Figure 6. Due to the AC input voltage and current having both positive and negative values, the paper employs absolute value circuit to deal with the input signals, as chips that can handle negative signals on the market are relatively expensive. The absolute value circuit utilises A_1 and A_3 operational amplifiers for inverse amplification, while A_2 and A_4 realises proportional amplification. Then A_5 and A_7 achieves logarithmic

amplification, while A_6 realises inverse logarithmic amplification. Thus, the principle of the proposed multiplier topology is derived as:

$$v_{be1} + v_{be2} = v_{be3} \quad (7)$$

The relationship between the base-emitter voltage v_{be} and the collector current i_c in the triode working in the amplification region is logarithmic, that is:

$$v_{be} = V_T \cdot \ln(i_c / I_s) \quad (8)$$

where V_T is the temperature voltage equivalent of the triode and I_s is its reverse saturation current.

Substituting equation (8) into equation (7) to obtain:

$$v_{T1} \cdot \ln(i_{c1} / I_{s1}) + v_{T2} \cdot \ln(i_{c2} / I_{s2}) = v_{T3} \cdot \ln(i_{c3} / I_{s3}) \quad (9)$$

If the three triodes are identical, then $V_{T1} = V_{T2} = V_{T3}$, $I_{s1} = I_{s2} = I_{s3}$, then equation (9) is simplified as:

$$i_{c1} \cdot i_{c2} = i_{c3} \quad (10)$$

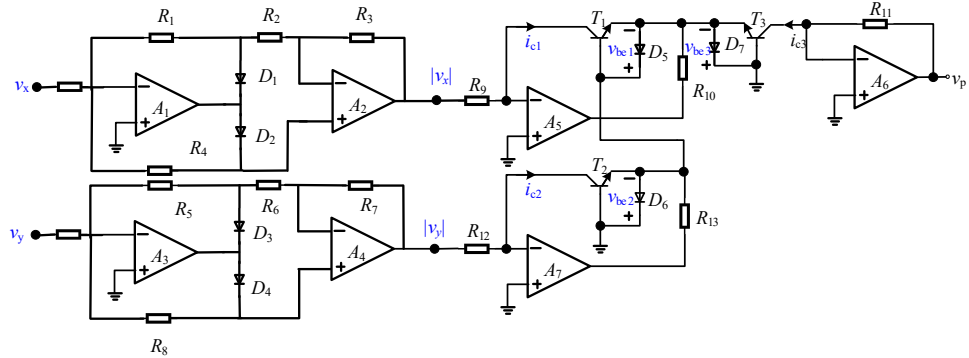
Combined with the virtual short characteristic of operational amplifier, then it can be deduced from equation (10):

$$(|v_x| / R_1) \cdot (|v_y| / R_2) = (v_p / R_3) \quad (11)$$

If $R_1 = R_2 = R_3$, the output voltage v_p of the analogue multiplier is:

$$v_p = |v_x| |v_y| \quad (12)$$

Figure 6 High-precision, broadband and low-cost multiplier topology (see online version for colours)



4.2 Simulation and verification of high precision, wide bandwidth and low-cost multiplier

4.2.1 Simulation and verification of proposed multiplier under varying input harmonic frequencies

Figure 11 shows the comparison results of the simulated power and theoretical power for the proposed multiplier, when the input voltage and current frequency is 50 Hz, and the modulation frequency is 5 kHz. The red curve represents the simulation value, and the blue curve represents the theoretical value. It is evident that the simulation curve is consistent with the theoretical curve, indicating that the multiplier proposed in this paper can achieves high calculation accuracy and precision when the input voltage and current do not contain harmonics.

Figure 7 Comparison between simulated power and theoretical power ($f = 50$ Hz)
(see online version for colours)

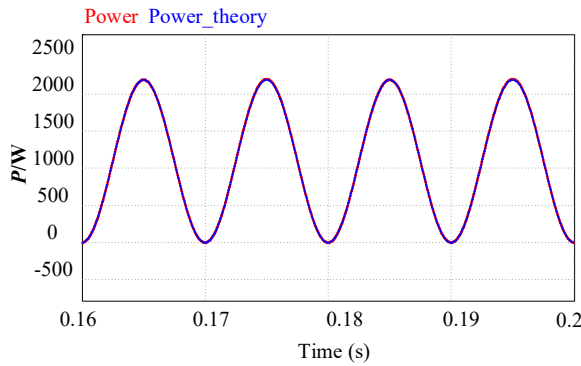


Figure 8 Comparison between simulated power and theoretical power ($f = 300$ Hz)
(see online version for colours)

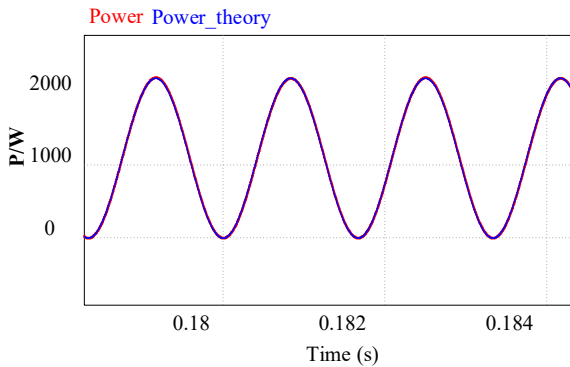
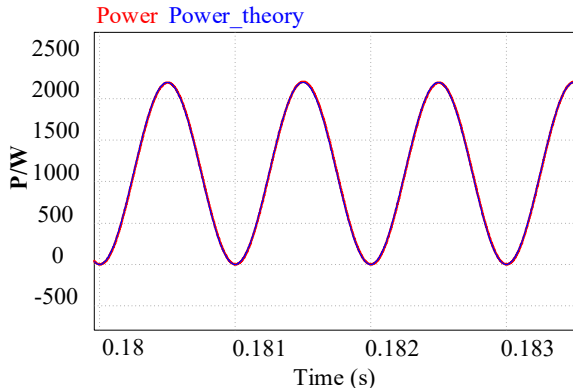


Figure 7 shows the comparison results of the simulated power and theoretical power when the input voltage and current frequency is 300 Hz, and the modulation frequency is 5 kHz. The red curve represents the simulation value, while the blue curve represents the theoretical value. It is evident that the simulation curve is also consistent with the theoretical curve. Therefore, when the input voltage and current contain higher

harmonics, the proposed multiplier can also achieve high calculation accuracy and precision.

To further explore the performance of the proposed multiplying topology, Figure 9 presents the comparison results of simulated power and theoretical power when the input voltage and current frequency is 500 Hz, and the modulation frequency is 5 kHz. Similarly, it is evident that the simulation curve is consistent with the theoretical curve.

Figure 9 Comparison between simulated power and theoretical power ($f = 500$ Hz)
(see online version for colours)



4.2.2 Simulation and verification of proposed multiplier under varying input phases

The comparison results of simulation power and theoretical power for the proposed multiplier are presented in Figure 10. The phase difference between the input voltage and current is varied as 0° , 30° , 60° , 90° , and 120° , while the frequency is set at 50 Hz. The modulation frequency remains constant at 5 kHz. The simulation values are represented by the red curve, while the theoretical values are shown by the blue curve. It is evident that the simulation and theoretical curves closely align, indicating good agreement between them. Therefore, the proposed multiplier demonstrates high calculation accuracy and precision, unaffected by the varying phase of the input voltage and current.

4.3 Simulation of traditional TDM

In order to verify the theoretical analysis on the measurement error of traditional TDM and the effectiveness of the proposed multiplying topology. A simulation model of traditional TDM, as well as the proposed multiplier is performed by PSIM in this Section.

4.3.1 Simulation of traditional TDM under varying input harmonic frequencies

The comparison results of the simulation power and theoretical power for traditional TDM are shown in Figure 11, when the input voltage and current frequency is 50 Hz, and the modulation frequency is 5 kHz. The red curve represents the simulation value, and the blue curve represents the theoretical value. It is clear that the simulation curve and

theoretical curve are in good agreement. Therefore, the TDM exhibits high calculation accuracy and precision when the input voltage and current do not contain harmonics.

Figure 10 Comparison between simulated power and theoretical power under different phases, (a) $\Psi_h = 30^\circ$ (b) $\Psi_h = 60^\circ$ (c) $\Psi_h = 90^\circ$ (d) $\Psi_h = 120^\circ$ (see online version for colours)

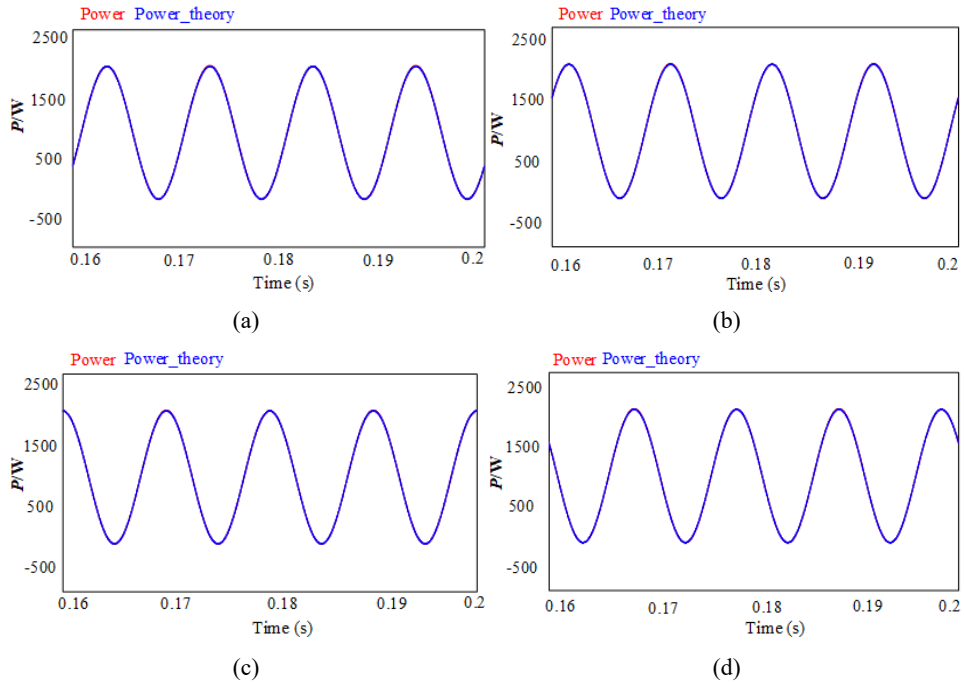


Figure 11 Comparison between simulated power and theoretical power ($f = 50$ Hz) (see online version for colours)

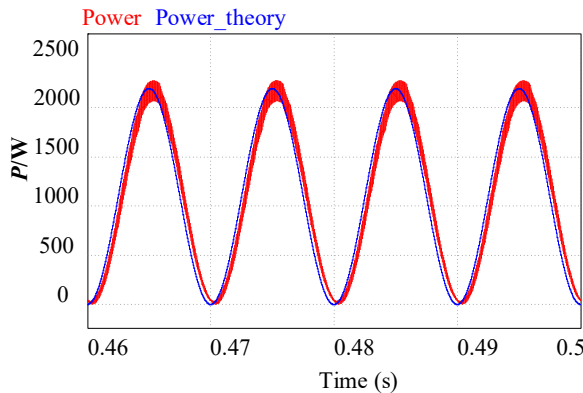
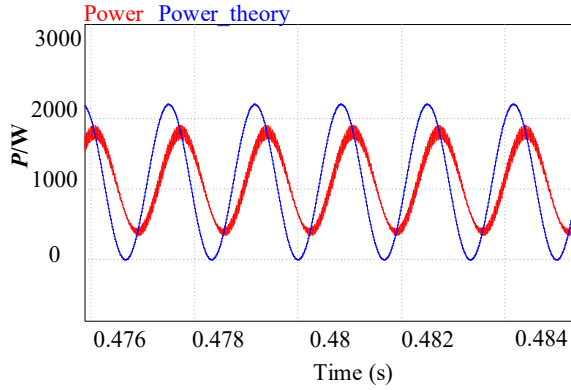


Figure 12 shows the comparison results of the simulated power and theoretical power for TDM, when the input voltage and current frequency is 300 Hz, and the modulation frequency is 5 kHz. The red curve represents the simulation value, and the blue curve represents the theoretical value. It is evident that there are significant amplitude and phase differences between the simulated power curve and theoretical power curve.

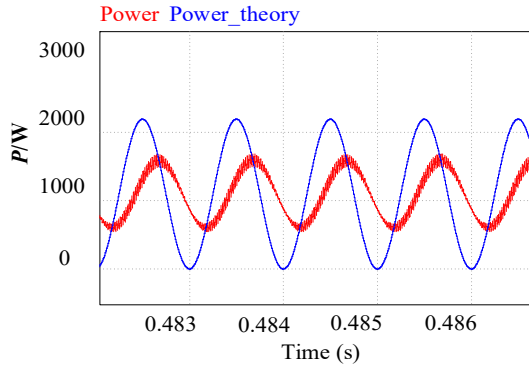
Consequently, when the input voltage and current contain higher harmonics, the calculation accuracy of the TDM is deteriorated.

Figure 12 Comparison between simulated power and theoretical power ($f = 300$ Hz)
(see online version for colours)



To further verify the performance of TDM, Figure 13 illustrates the comparison results of the simulated power and theoretical power, when the input voltage and current frequency increase to 500 Hz, and the modulation frequency is 5 kHz. It can be observed from Figure 13 that there are evident amplitude and phase differences between the simulated power and theoretical power.

Figure 13 Comparison between simulated power and theoretical power ($f = 500$ Hz)
(see online version for colours)

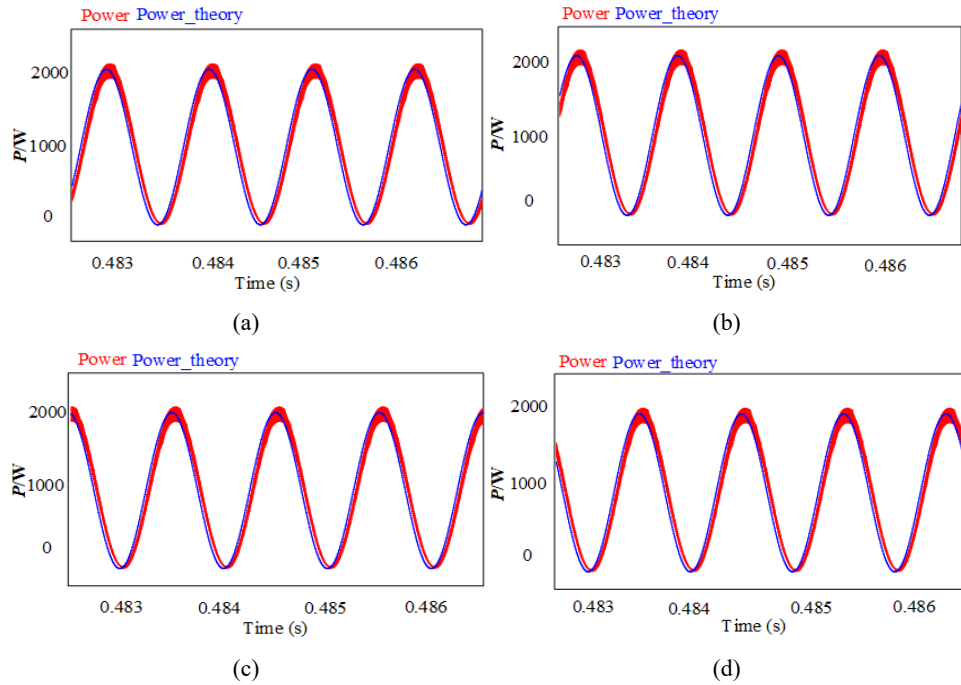


As a result, the traditional TDM multiplier exhibits high calculation accuracy when the input voltage and current do not contain harmonics. However, with the presence of higher order of harmonic, due to insufficient sampling frequency, nonlinear distortion, as well as sampling and computation delays, the calculation accuracy and precision of traditional TDM multipliers will decrease. Consequently, the error of the energy metering will be increased, leading to improper charge. In the design and use of time-division multiplexing multipliers, potential influencing factors such as temperature effects and signal amplitude distortion are considered and addressed.

4.3.2 Simulation of traditional TDM under varying input phases

The comparison results of simulation power and theoretical power for traditional TDM are presented in Figure 14. The phase difference between the input voltage and current is varied as 0° , 30° , 60° , 90° , and 120° , while the frequency is set at 50 Hz, and the modulation frequency remains constant at 5 kHz. The simulation values are represented by the red curve, while the theoretical values are shown by the blue curve. It is evident that the simulation and theoretical curves closely align, indicating good agreement between them. Therefore, the TDM demonstrates high calculation accuracy and precision, unaffected by the varying phase of the input voltage and current.

Figure 14 Comparison between simulated power and theoretical power under different phases, (a) $\Psi_h = 30^\circ$ (b) $\Psi_h = 60^\circ$ (c) $\Psi_h = 90^\circ$ (d) $\Psi_h = 120^\circ$ (see online version for colours)



As a result, the proposed high-precision broadband low-cost multiplier can accurately measure the electric power for full-wave type of energy metering when the input voltage and current contain high order of harmonics. In order to further prove the effectiveness of the proposed multiplier, Table 1 gives the comparison of measurement error between traditional TDM and the multiplier proposed in this paper under different harmonic orders. As is shown, the measurement error increases with the increase of harmonic order for traditional TDM, which is consistent to the theoretical error curve under modulation frequency of 5 kHz in Figure 4. While, compared to the traditional approach, the measurement error of the proposed multiplier is greatly reduced and keeps constant within the harmonic orders of 1st to 10th, which supports the effectiveness of the proposed multiplier in this paper.

Furthermore, both the traditional TDM and the proposed multiplier exhibit high calculation accuracy and precision, regardless of the varying phase of the input voltage

and current at a frequency of 50 Hz. To further investigate the impact of different input voltage and current phases, Table 2 provides a comparison of the measurement error between traditional TDM and the multiplier proposed in this paper. As is shown, the measurement error remains consistent for all five phase differences under an input voltage and current frequency of 50 Hz. Consequently, the measurement error for an individual harmonic is unaffected by the phase difference between the two input signals, which is consistent to the theoretical error curve in Figure 5.

Table 1 Comparison of measurement error between traditional TDM and the multiplier proposed in this article under different harmonic frequencies.

Harmonic count h	1	2	3	4	5	6	7	8	9	10
Proposed multiplier	0.20%	0.20%	0.20%	0.20%	0.20%	0.20%	0.20%	0.20%	0.20%	0.20%
Traditional TDM	-0.44%	-0.68%	-1.11%	-1.56%	-2.01%	-2.46%	-2.82%	-3.18%	-3.50%	-3.96%

Table 2 Comparison of measurement error between traditional TDM and the multiplier proposed in this article under different input phases

Input phases Ψ_h	0°	30°	60°	90°	120°
Proposed multiplier	0.20%	0.20%	0.20%	0.20%	0.20%
Traditional TDM	-0.44%	-0.44%	-0.44%	-0.44%	-0.44%

5 Experimental verification

To validate the effectiveness of the proposed multiplier topology, the theoretical analysis and simulation results were verified under different input voltage and current frequencies and phases. Therefore, an experimental prototype of the multiplier was built for validation. TI LM358 is utilised for A1~A4, and TI LM6142 is utilised for A5~A6.

The test system is shown in Figure 15. This system consists of a programmable three-phase AC power supply IT7625, a programmable three-phase AC electronic load IT8617, a test energy metering device, a four-channel oscilloscope Tek MDO3014, and an AC power meter IT9121. The programmable three-phase AC power supply IT7625 is used to simulate and generate high-order harmonic voltages. The AC electronic load is used to consume harmonic power. The test energy metering device samples the system voltage and current signals, performs real-time calculations, and meters real-time power and energy. The oscilloscope is used to record harmonic voltage and current signals as well as corresponding power measurement signals. The AC power meter is connected to the system in parallel and series as a standard instrument to measure real-time power and energy, comparing the metering accuracy of the test energy metering device.

Figures 16 to 21 depict the experimental waveforms of input voltage u , input current i , and power p at different input voltage and current frequencies. The blue curve represents the input current, the green curve represents the input voltage, and the purple curve represents the output power. As shown in the figure, at input voltage and current frequencies of 50 Hz, 100 Hz, 200 Hz, 300 Hz, 400 Hz, and 500 Hz, the power output consistently equals the product of the input voltage and current, which confirms the

correctness of the theoretical analysis. This indicates that the proposed multiplier effectively calculates power by multiplying the input voltage and current. The frequency range of 50 Hz to 500 Hz was chosen to cover typical operating scenarios and better match real-world application environments.

Figure 15 The structure of the test system (see online version for colours)

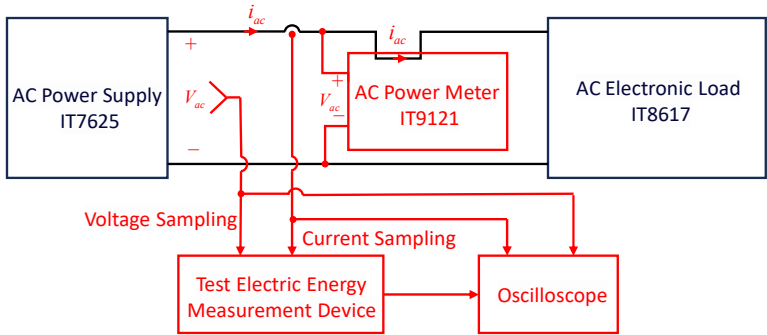


Figure 16 The output current, voltage and power waveform at 50 Hz (see online version for colours)

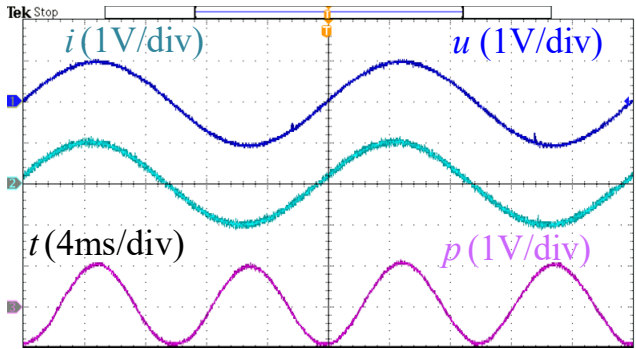


Figure 17 The output current, voltage and power waveform at 100 Hz (see online version for colours)

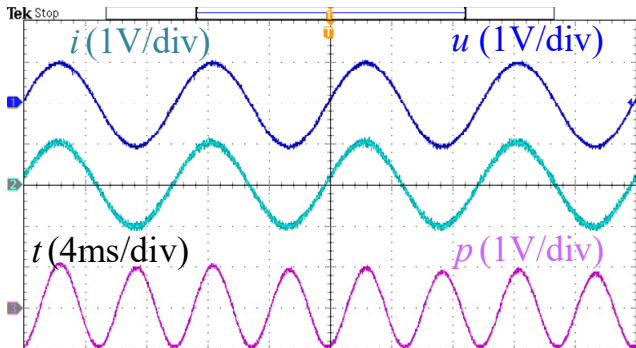


Figure 18 The output current, voltage and power waveform at 200 Hz (see online version for colours)

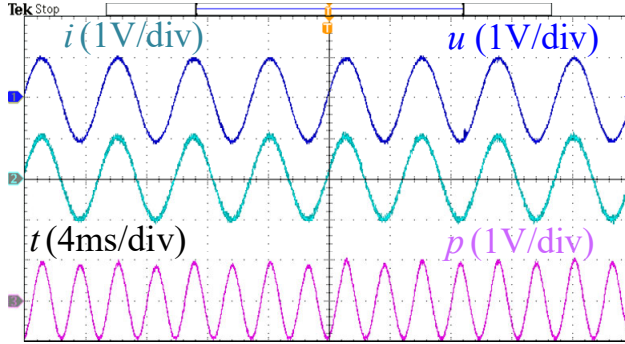


Figure 19 The output current, voltage and power waveform at 300 Hz (see online version for colours)

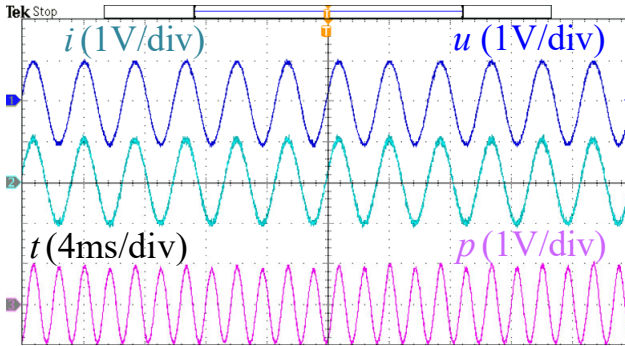
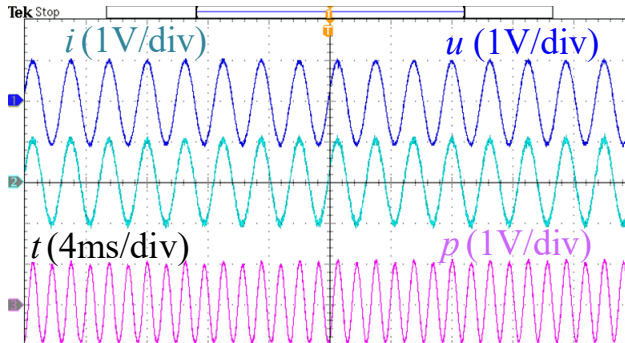


Figure 20 The output current, voltage and power waveform at 400 Hz (see online version for colours)



Similarly, Figures 22 to 25 depict the experimental waveforms of the input voltage u , input current i , and power p under different input phases when the frequency is set at 50 Hz. Some typical scenarios are chosen, including when the phase difference between current and voltage is 30° , 60° , 90° , and 120° . As shown in the figure, consistent with the

theoretical analysis, the measured power of individual harmonics is not affected by the phase difference between the two input signals. This also highlights the strong robustness of the proposed multiplier in accurately determining power regardless of phase differences. The experimental waveforms from the two application scenarios indicate that smooth sinusoidal curves are observed for both current, voltage, and power, which demonstrates the stable operation of the multiplier across a wide range of frequencies and various complex operating conditions.

Figure 21 The output current, voltage and power waveform at 500 Hz (see online version for colours)

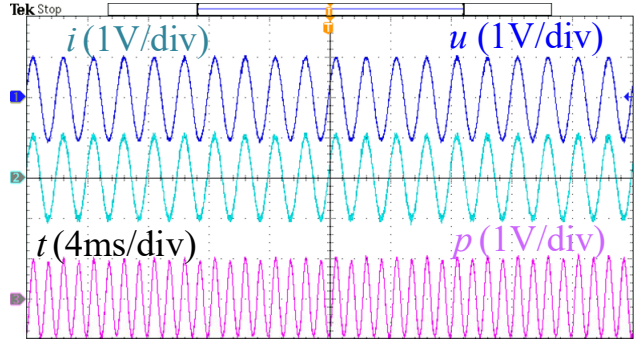


Figure 22 The output current, voltage and power waveform at 30° (see online version for colours)

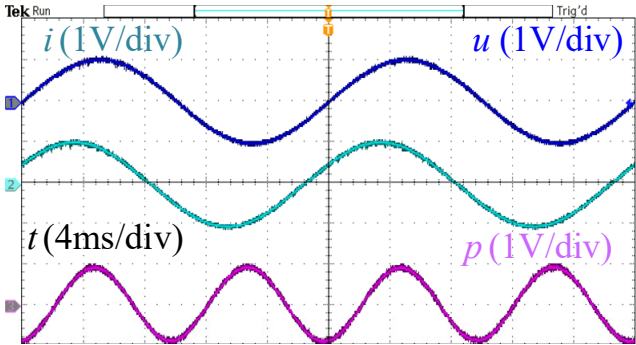


Figure 23 The output current, voltage and power waveform at 60° (see online version for colours)

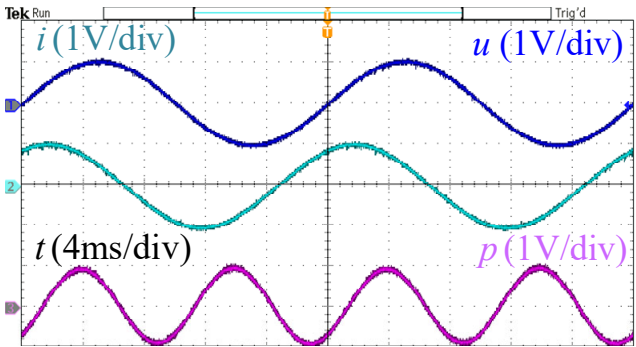
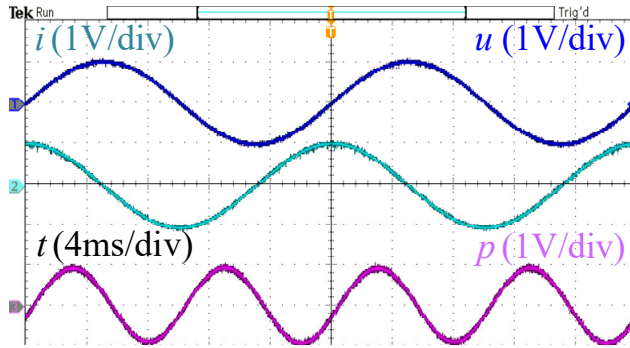
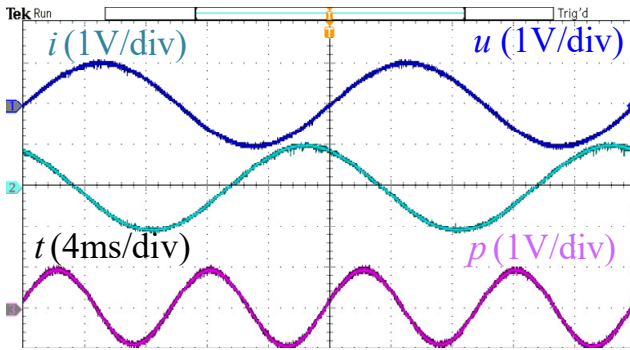


Figure 24 The output current, voltage and power waveform at 90° (see online version for colours)**Figure 25** The output current, voltage and power waveform at 120° (see online version for colours)

Through various experimental tests, the excellent performance of the multiplier under different frequency and phase conditions is clearly demonstrated. Regardless of how the frequency of the input voltage and current varies, the multiplier accurately calculates the power, validating its stability and reliability under varying frequency conditions. Furthermore, power measurement is not affected by phase differences, indicating that high-precision power calculation is maintained by the multiplier when handling input signals under different phase conditions. This is particularly important for practical applications in complex grid environments, where precise energy measurement and power analysis are required, especially in applications such as battery energy storage systems and vehicle-to-grid interactions.

6 Conclusions

The multiplier is an indispensable component of electronic energy meters and the main source of energy metering errors. This paper quantitatively studies and analyses the metering error of the conventional triangular wave voltage comparison type time-division multiplier in the presence of harmonics, derives its theoretical error expression, and verifies it through simulation. In order to solve the problem of inaccurate power metering in the harmonic condition, this paper proposes a high-precision, wide-bandwidth,

low-cost multiplier topology. The accuracy of the multiplier in the harmonic condition is successfully verified through theoretical derivation and simulation. Furthermore, an experimental prototype of the proposed high-precision broadband low-cost multiplier has been built to verify the simulation results, which supports the effectiveness of the proposed high-precision broadband low-cost multiplier in this paper.

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