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Design and Implementation of a Single-phase Inverter with Technology of Sinusoidal Pulse Width Modulation

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In this paper, a single-phase inverter with the technology of sinusoidal pulse width modulation (SPWM) is proposed. The single-phase inverter fabricated using low-cost components is designed and implemented to test on various AC loads, such as lamps, fans and chargers. In this study, the single-phase inverter is controlled by an SPWM controller to generate a pure sine wave with low total harmonic distortion (THD) and provide good load regulation. The single-phase inverter with an inductor–capacitor–inductor (LCL) filter can significantly reduce the THD of output voltage to less than 3%. Finally, to verify its feasibility, a prototype of the single-phase inverter is built. From the theoretical and experimental results, it can be confirmed that the proposed single-phase inverter is suitable for applications of resistive or inductive loads.

1. Introduction

Economic and technological growth results in the rapid consumption of fossil fuels. Renewable energies can replace fossil fuel energies to reduce air pollution. Most commercial electronic products are supplied with alternating current (AC) powers. Therefore, renewable energies converted into usable AC power are a research topic. An inverter is one of the few kinds of converter and is known as a direct current (DC)-to-AC converter, which generates AC voltages in a single phase or three phases from a DC source.(1–3) The inverter is widely used in uninterruptible power supply systems (UPSs), AC motor drives, induction heaters, and renewable energy source systems. The inverter consists of power electronics components and is based on the principles of sinusoidal pulse width modulation (SPWM) to control a full-bridge circuit and an inductor–capacitor–inductor (LCL) filter. Therefore, pure sinusoidal powers and good load regulation can be obtained from AC loads.

There are three output waveforms of a single-phase inverter. They are the square, modified square, and pure sine waves, as shown in Fig. 1.(3–5) The single-phase inverter with a square wave is the simplest and cheapest type among the three types of single-phase inverter. It is generally not used for commerce because of its low power quality and high harmonic output (about 45%).(6–8) The single-phase inverter with a modified square wave adjusts some dead

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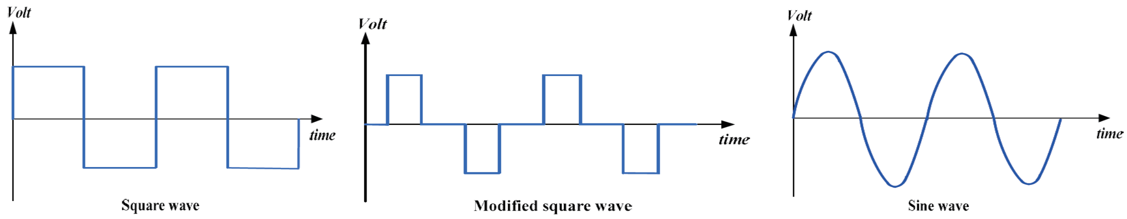


Fig. 1. (Color online) Inverter with three wave forms.

regions between its positive and negative half cycles. Therefore, a low harmonic distortion can be obtained from the single-phase inverter.(9–11) The inverter with a pure sine wave to produce AC sinusoidal output voltages has high power quality and low total harmonic distortion (THD), and it has been widely applied in renewable energy. For example, solar panels are connected to grids.

In this paper, a single-phase inverter with an LCL filter is designed and implemented to obtain AC sinusoidal output power, as shown in Fig. 2. An SPWM controller is applied to the single-phase inverter, controlling pure sinusoidal power and obtaining good load regulation. The SPWM switching technology and single-phase inverter system are described in Sect. 2. The operational principles of the single-phase inverter are analyzed in Sect. 3. The results of experiments conducted to verify the feasibility of the single-phase inverter are shown in Sect. 4. Finally, conclusions are given in Sect. 5.

2. Descriptions of Single-phase Inverter System and SPWM Switching Technology

Figure 2 shows the circuit flowchart of a single-phase inverter, which consists of a DC source via a DC boost converter to increase DC voltage from 48 to 400 V. The full-bridge switching circuit uses SPWM switching technology to convert DC 400 V_{DC} to AC 110 or 220 V_{rms} with an LCL filter. The driving signals of the full-bridge power switches are generated by the SPWM controller according to the SPWM control program.

SPWM technology can be divided into bipolar and unipolar SPWMs. Of these two, unipolar SPWM can obtain smaller current harmonics, as shown in Fig. 3. Therefore, it is widely used in various inverters. Its principle is to compare the triangular carrier wave of the triangular wave generator with the sine control wave of the sine wave generator. Therefore, the output of the comparator can obtain a set of SPWM waves, as shown in Fig. 4. By comparing the frequency of the triangular carrier wave with that of the sine control wave in Fig. 4, we find that the sine control wave is divided into numerous driving signals within one cycle. The following approximate equations are used to calculate the pulse width and carrier wave frequency of SPWM:

$$D = 2\left(\frac{V_{sin}}{V_{tri}}\right)\left(\frac{\pi}{N}\right)\sin\left(\frac{2\pi}{N}\right), \tag{1}$$

and

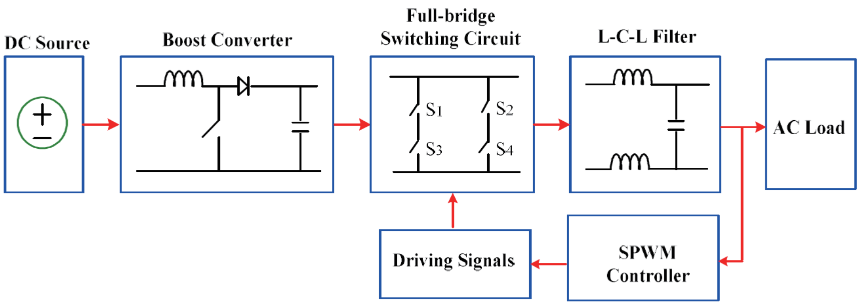


Fig. 2. (Color online) Circuit flowchart of single-phase inverter.

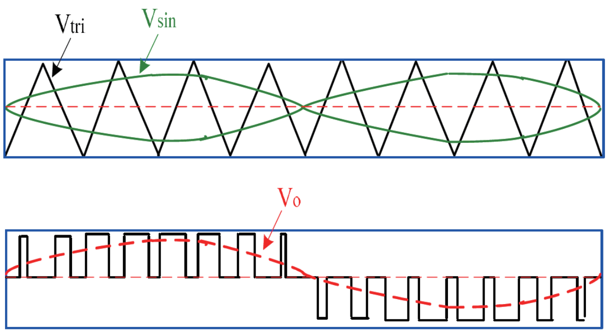


Fig. 3. (Color online) Wave analysis of unipolar SPWM technology.

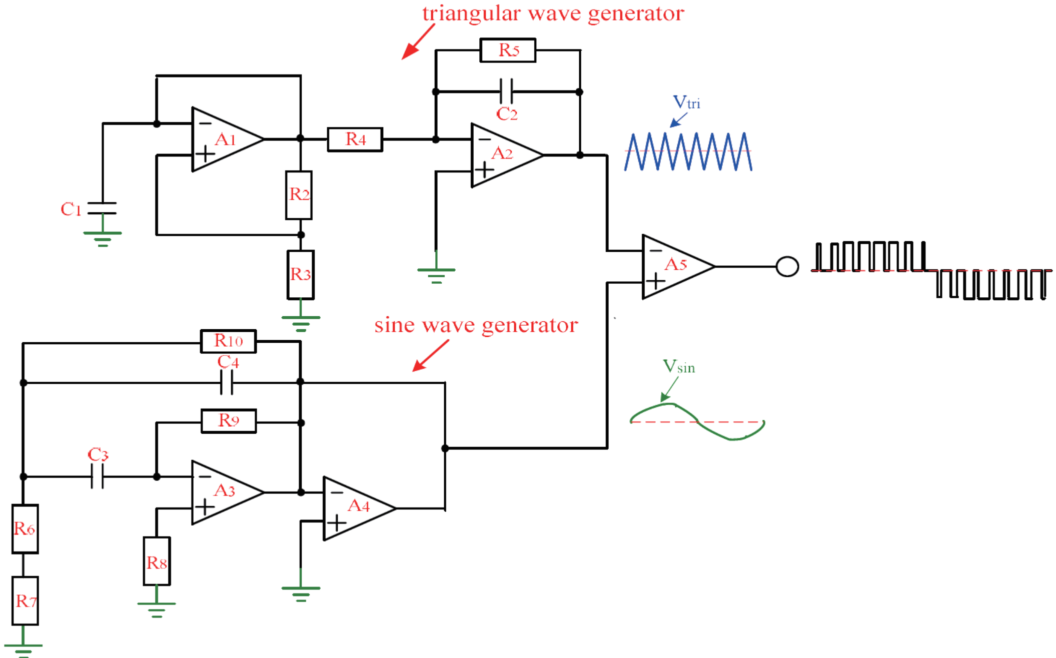


Fig. 4. (Color online) SPWM wave generator.

$$f_C = \frac{1}{2\pi\sqrt{(R_6 + R_7)R_9C_3C_4}}, \tag{2}$$

where D is the pulse width of SPWM, N is the carrier wave ratio, and f_c is the carrier wave frequency.

3. Operational Principles of Single-phase Inverter

Figure 5 shows the structure of the single-phase inverter. It consists of a full-bridge switching circuit and an LCL filter. The four switches of the full-bridge switching circuit can be divided into two pairs of switches, one is the switch pair (S_1 and S_4) and the other is the switch pair (S_2 and S_3). In the switching scheme, S_1 and S_3 are operated at a high frequency, and S_2 and S_4 are at a low frequency. The operational principles of the single-phase inverter are described below.

3.1 Positive half cycle of sine wave

(1) When S_1 and S_4 are turned on and S_2 and S_3 are turned off, the inductors L_1 and L_2 are operated at an energy charging interval. The current $i_1(t)$ flows through S_1 and S_4 in the clockwise direction, as shown in Fig. 6(a).

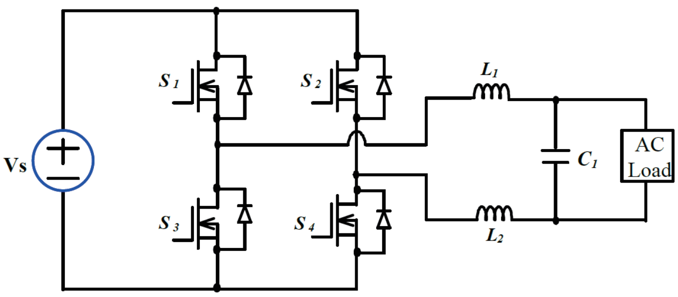


Fig. 5. (Color online) Structure of single-phase inverter.

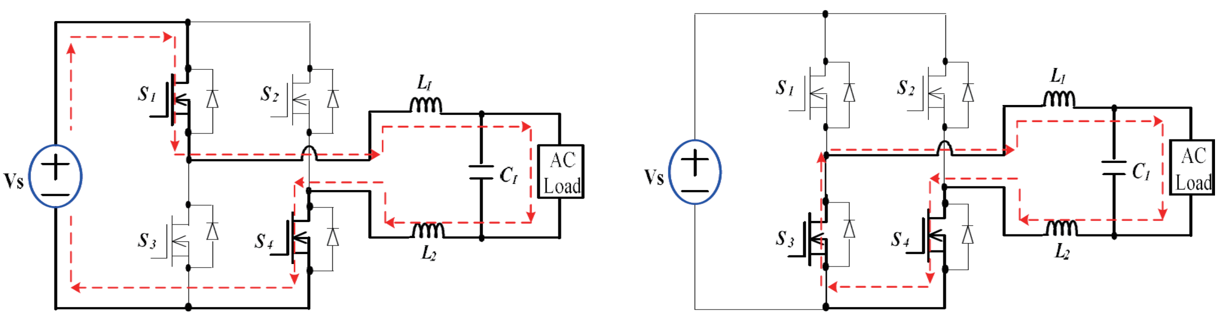


Fig. 6. (Color online) SPWM driving signal to control generation of pure sine wave in positive half cycle. (a) Energy charging interval of inductors L_1 and L_2. (b) Energy discharging interval of inductors L_1 and L_2.

(2) When S_3 and S_4 are turned on and S_1 and S_2 are turned off, the inductors L_1 and L_2 are operated at an energy discharging interval. The current $i_1(t)$ flows through S_3 and S_4 in the freewheeling direction, as shown in Fig. 6(b).

The driving signals of S_1, S_3, and S_4 as well as the energy charging waves of the inductors L_1 and L_2 are operated in the positive half cycle of the sine wave, as shown in Fig. 7.

3.2 Negative half cycle of sine wave

(1) When S_2 and S_3 are turned on and S_1 and S_4 are turned off, the inductors L_1 and L_2 are operated at an energy charging interval. The current $i_1(t)$ flows through S_2 and S_3 in the counterclockwise direction, as shown in Fig. 8(a).

(2) When S_1 and S_2 are turned on and S_3 and S_4 are turned off, the inductors L_1 and L_2 are operated at an energy discharging interval. The current i_1(t) flows through S_1 and S_2 in the freewheeling direction, as shown in Fig. 8(b).

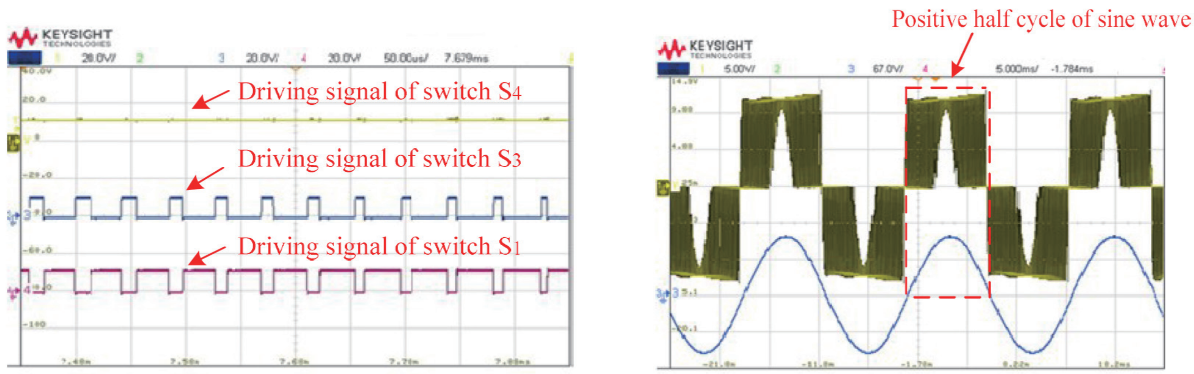
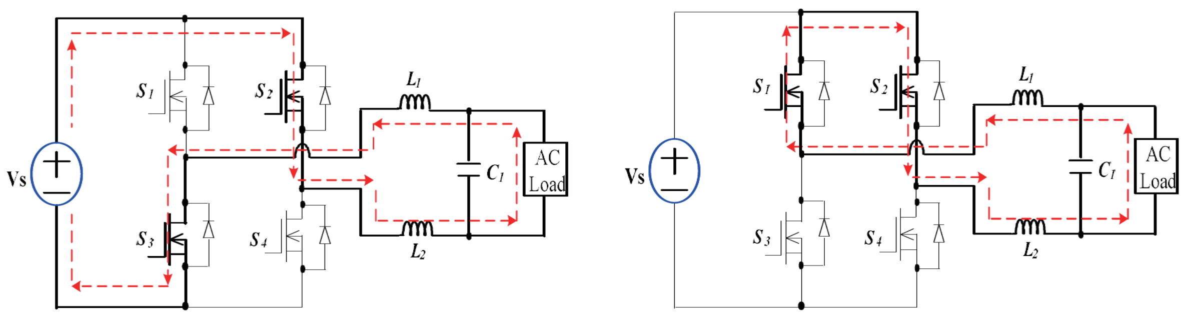


Fig. 7. (Color online) Driving signals of S_1, S_3, and S_4 and energy charging waves of inductors L_1 and L_2 operated in positive half cycle of sine wave.



(a) (b)

Fig. 8. (Color online) SPWM driving signal to control generation of pure sine wave in negative half cycle. (a) Energy charging interval of inductors L_1 and L_2. (b) Energy discharging interval of inductors L_1 and L_2.

The driving signals of S_1, S_3 and S_4 and the energy charging waves of the inductors L_1 and L_2 are operated in the positive half cycle of a sine wave, as shown in Fig. 9.

4. Sensing and Protecting Circuits of Single-phase Inverter

The signal of the output sinusoidal voltage is sensed through a filter and a full-bridge rectifier, as shown in Fig. 10. When output sinusoidal voltages are decreasing, an increased signal of power is generated by the SPWM controller to turn on S_1 and S_3. Therefore, a stable output power of the signal-phase inverter can be obtained.

The temperature, output current, and voltage of the single-phase inverter are monitored continuously. The single-phase inverter is operated at a high switching frequency in load changes, resulting in high temperatures, currents, and voltages. Therefore, the cooling and breakdown protection circuits must be designed. The cooling and protection circuits of the single-phase inverter are shown in Fig. 11.

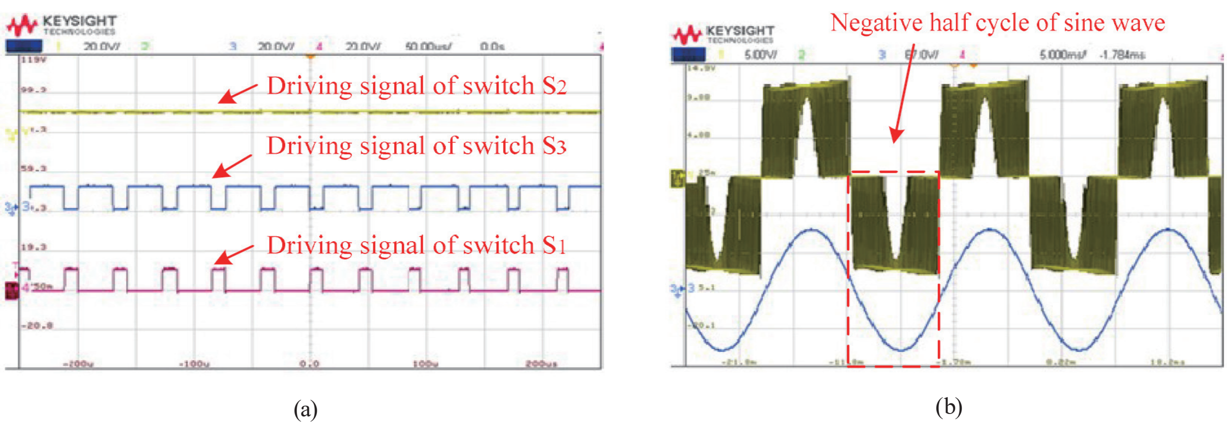


Fig. 9. (Color online) Driving signals of S_2, S_3 and S_1 and energy charging waves of inductors L_1 and L_2 operated in negative half cycle of sine wave.

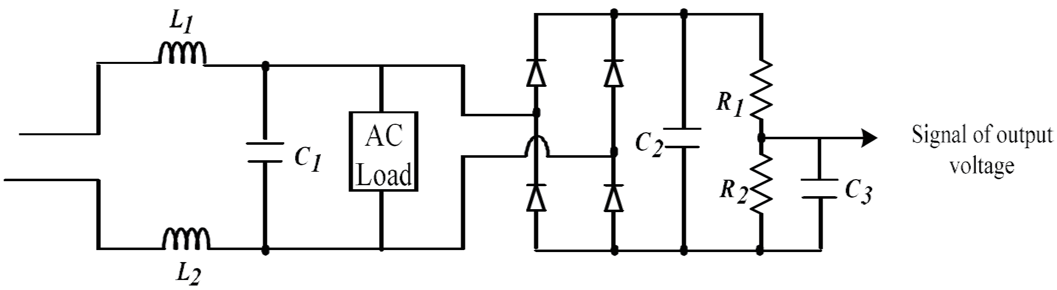


Fig. 10. Sensing circuit of output sinusoidal voltage.

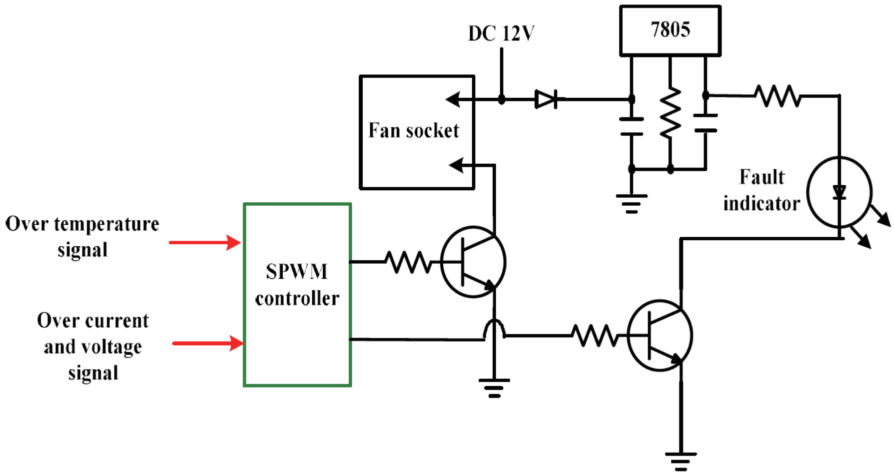


Fig. 11. (Color online) Cooling and protection circuits of single-phase inverter.

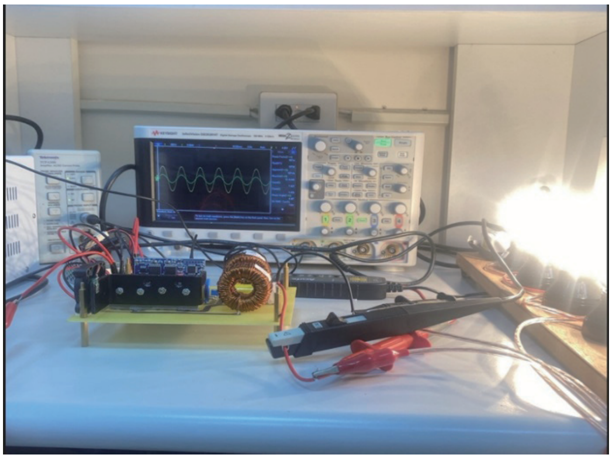


Fig. 12. (Color online) Test single-phase inverter with SPWM technology.

5. Experimental Results of Single-phase Inverter

We built a test single-phase inverter with an input voltage of 400 V_{DC}, an output AC voltage of 220 V_{rms} and a current of 5 A_{rms}, as well as an AC output power of 1.1 kVA to verify the feasibility of the inverter, as shown in Fig. 12.

Figure 13 shows the measured output voltage and current waveforms of the single-phase inverter with SPWM technology, from which it can be seen that the output voltage and current are in phase under the full-load condition. Figure 14 shows that the single-phase inverter with

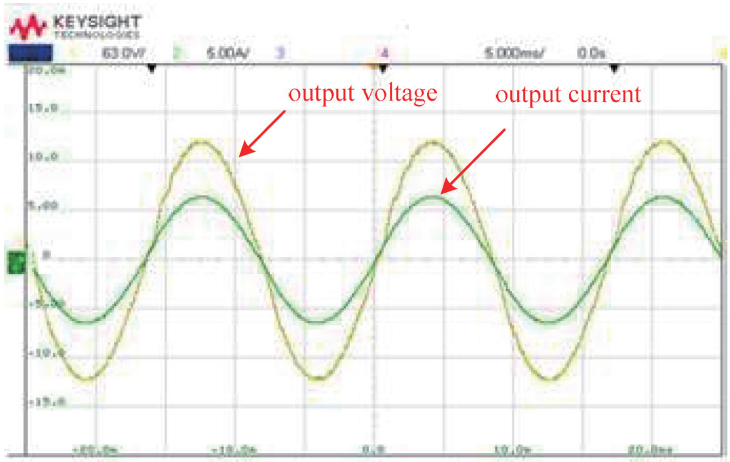


Fig. 13. (Color online) Measured output voltage and current waveforms of single-phase inverter.

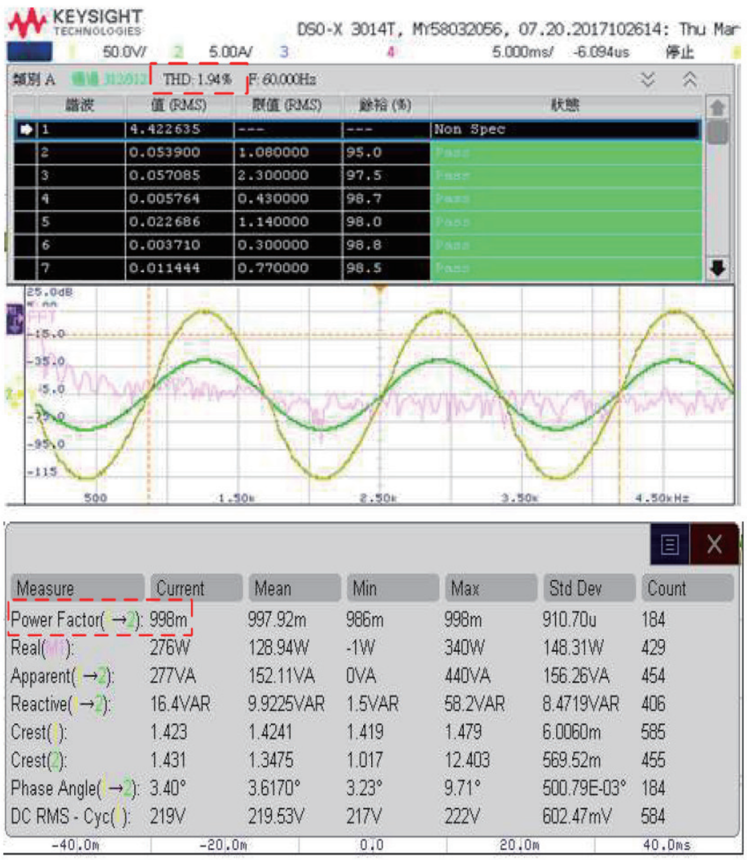


Fig. 14. (Color online) Measured THD and power factor of single-phase inverter.

SPWM technology can obtain low THD (1.94%) and high power factor (0.998). From the above measurement results, we verified that the single-phase inverter can obtain the best pure sinusoidal power with SPWM technology.

6. Conclusions

A single-phase inverter with SPWM technology was proposed, built, and implemented. It uses an LCL filter and an SPWM controller to generate pure sinusoidal power. From the experimental results of the single-phase inverter, it can be seen that the output voltage and current are in phase with low THD and high power factor. The produced optimal THD value was 1.94%, which meets the allowable standard of utility harmonic and is less than 3%. The SPWM technology is superior to other PWM technologies because it can improve the power quality of the output waveform. This will help improve power stability in the applications of standalone or grid-connected photovoltaic systems.

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Author Contributions

Cheng-Tao Tsai designed the circuit and wrote the paper. Chi-Yang Weng analyzed the experimental results.

Conflicts of Interests

The authors declare no conflicts of interest.

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