Published by :
http://www.ijert.org
International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 10, October-2016

Design and Tests of a Programmable Step-Up Converter for Collecting the Residual Electric Power in used Batteries

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***Abstract*—This research aims to design and test a programmable step-up converter for collecting the residual electric power in used batteries. Used batteries may have residual electric power. The residual electric power should be recovered in order for people to use it again. The input terminal of the developed programmable step-up converter connects to used batteries and the output terminal connects to normal rechargeable batteries. The developed programmable step-up converter was able to pump the residual electric power in used batteries into normal rechargeable batteries via a pulse width modulation technique even though the used batteries' voltages are lower than the normal rechargeable batteries. Therefore, the residual electric power collected by the developed programmable step-up converter can be utilized again by people. This research is effective in energy-saving and environment protection.**

Keywords*—*Step-up converter, residual electric power, used battery.

I. INTRODUCTION

A battery is an element for storing electric power. Currently people use various batteries to supply electricity to mobile phones, flashlights, remote controls, uninterruptible power supplies, vehicles, etc [1]. Because people use lots of batteries every day and thus create a large number of used batteries [2]. Although the used batteries are not used by people any longer, they may still have residual electric power. Perhaps the residual electric power in used batteries is not much, it deserves to be recovered due to the numbers of used batteries. If the residual electric power in used batteries can be recovered as much as possible, it will be benefit of environment protection and energy-saving [3,4].

The method for recovering the residual electric power in used batteries is to pump this electric power into normal rechargeable batteries. To achieve this purpose, the first requirement is that used batteries' voltages must be higher than normal rechargeable batteries' voltages. But used batteries' voltages are generally low. Their residual electric power can not be directly released to normal rechargeable batteries. Moreover, the used batteries' voltages will continue to fall and the normal rechargeable batteries' voltages will continue to rise during the process of pumping the residual electric power of used batteries into normal rechargeable batteries. In this situation, to recover the residual electric power is more difficult. In order to solve this problem, we developed a programmable step-up converter. The developed programmable step-up converter is able to pump the residual electric power of used batteries into normal rechargeable batteries as far as possible. In this paper, the topology and the function of the developed a programmable step-up converter are presented. The results of three tests are also presented and discussed in this paper.

II. DESIGN OF THE DEVELOPED CONVERTER

The developed step-up converter was based on a boost circuit. Fig. 1 depicts the function blocks of the developed step-up converter. The detail structure and functions of each component in the developed step-up converter is described as follows.

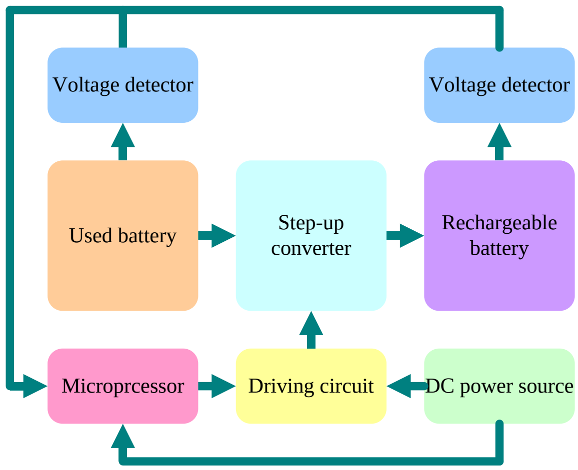

Fig. 1. Function blocks of the developed step-up converter.

A. The step-up converter

Fig. 2 depicts the structure of the developed step-up converter based on a non-isolated boost circuit. The developed step-up converter consisted of an inductor, an n-channel MOSFET, a fast recovery diode and a filter capacitor. The n-channel MOSFET Q is used as a switch and the inductor L is used as an energy-saving element. While the MOSFET Q conducts, the inductor L stores electric power from used batteries. Oppositely, while the MOSFET Q closes, the inductor L and the used batteries will be in series causing a higher voltage to charge the normal rechargeable batteries through the diode D. As a result, the normal rechargeable batteries can store the residual electric power in the used batteries.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
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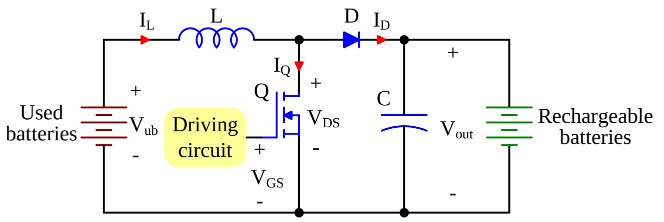

Fig. 2. The structure of the developed step-up converter.

The operating principle of the developed step-up is described bellow [5,6].

1) Mode 1:

When the MOSFET Q conducts at the time t=0, the current I_L provided by used batteries flows through the inductor L and MOSFET Q. During this time the diode D is closed due to a reverse voltage. Fig. 3 depicts the equivalet circuit of the developed step-up converter under mode 1. The voltage across the inductor L is

$$V_L = V_{ub} \qquad (1)$$

where V_{ub} is the voltage across the used batteries.

Because the voltage of the inductor L is induced from the current I_L, (1) can be represented as follows.

$$L\frac{dI_L}{dt} = V_{ub} \qquad (2)$$

Equation (2) can be rewritten as follows.

$$\frac{dI_L}{dt} = \frac{V_{ub}}{L} \qquad (3)$$

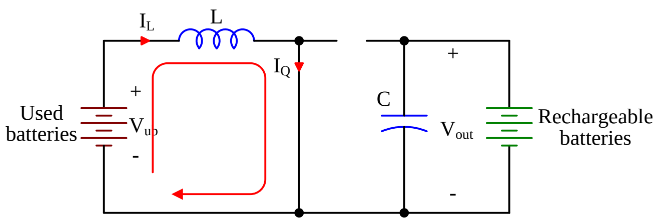

Fig. 3. The equivalet circuit of the developed step-up converter under mode 1.

In this duration, the current I_L is increasing gradually. The increase in current of the inductor L during the conduction of MOSFET Q is given by:

$$\Delta I_L^+ = \frac{V_{ub}}{L} \cdot t_{on} \qquad (4)$$

where t_{on} is the period while the MOSFET Q conducts.

2) Mode 2:

When the MOSFET Q closes at the time $t=t_{on}$, the voltage polarity of the inductor L will be reversed according to Lenz's law. In this duration, the current I_L flows through the diode D and the normal rechargeable batteries. Fig. 4 depicts the equivalet circuit of the developed step-up converter under mode 2. The voltage across the inductor L becomes

$$V_L = V_{out} - V_{ub} \qquad (5)$$

or

$$L\frac{dI_L}{dt} = V_{out} - V_{ub} \qquad (6) \qquad (1)$$

where V_{out} is the voltage across the normal rechargeable batteries.

In this duration, the current I_L is decreasing gradually. The decrease in current of the inductor L during the close of MOSFET Q is given by:

$$\Delta I_L^- = \frac{V_{out} - V_{ub}}{L} \cdot t_{off} \qquad (7)$$

where t_{on} is the period while the MOSFET Q closes.

Assuming that the inductor current is continuous during the whole period T= t_{on} + t_{off}, therefore the (4) is equal to (7).

(1)

$$\Delta I_L^+ = \Delta I_L^- \qquad (8)$$

That means

$$\frac{V_{ub}}{L} \cdot t_{on} = \frac{V_{out} - V_{ub}}{L} \cdot t_{off} \qquad (9)$$

The duty cycle is defined as follows.

(1)

$$D = \frac{t_{on}}{T} \qquad (10)$$

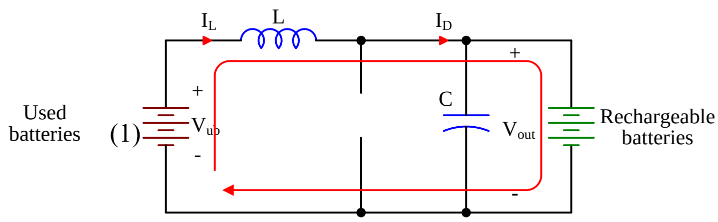

Fig. 4. The equivalet circuit of the developed step-up converter under mode 2.

Substituting (9) by (10) yields:

$$V_{ub} \cdot D \cdot T = (V_{out} - V_{ub})(1 - D)T \qquad (11)$$

This can be written as:

$$V_{out} = \frac{1}{1-D} \cdot V_{ub} \qquad (12)$$

Equation (12) represents the voltages of used batteries can be boosted via the developed step-up converter while the duty cycle(1)s higher than 0.5. If the duty cycle is higher, the voltages of used batteries are higher, too. When the voltages of used batteries are higher than the normal rechargeable batteries, the former can charge the latter.

B. The microprocessor

The microprocessor employed by this research was HT46R24 produced by Holtek Inc. HT46R24 is an 8-bit RSIC microprocessor. It has 28 pins and 4-channel 8-bit PWM outputs. Fig. 5 illustrates the planning of some pin's function of the HT46R24 employed by this research.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 10, October-2016

The pin 27 (PB7) was used to produce PWM signals. The maximum frequency of PWM signals was 32 kHz. The pins 9 and 10 (PB0 and PB1) were used to receive the terminal voltages of used batteries and normal rechargeable batteries, respectively. The maximum input voltage of HT46R24 is DC 5V. Two voltage detectors were used to detect the voltages across the used batteries and normal rechargeable batteries, respectively. The feedback voltages were all send to the A/D converter inside the microprocessor HT46R24. The pins 3~6, 12~14 and 23~25 were used to control the LCD displayer.

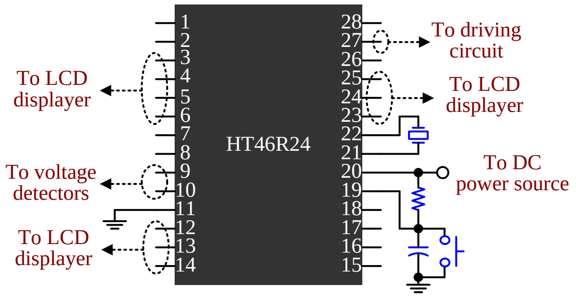

Fig. 5. The planning of some pin's function of the HT46R24.

C. The driving circuit

Fig. 6 depicts the structure of the driving circuit. In this research, an optical coupler 4N25 was used as a driving circuit. The driving circuit contains a light source (a LED) which converts the PWM signals from the microprocessor into light and an optotransistor, which detects incoming light and generates PWM signals with the same frequency but higher voltage level. The higher voltage level signals can drive the MOSFET Q easily.

D. The DC power source

The DC power source employed by this research contained an AC/DC rectifier, a filter capacitor and two voltage regulators, LM7805 and LM7812. Fig. 7 depicts the structure of the DC power source. The AC/DC rectifier was used to change an AC voltage at input terminal into a DC voltage. The filter capacitor was used to reduce the ripple rate of the DC output voltage of the AC/DC rectifier. The voltage regulator LM7805 was used to provide DC 5V for the microprocessor HT46R24 and the voltage regulator LM7812 was used to provide DC 12V for the driving circuit.

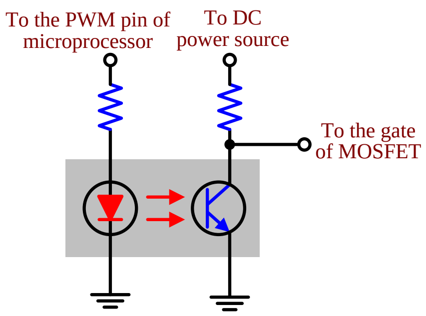

Fig. 6. The structure of the driving circuit.

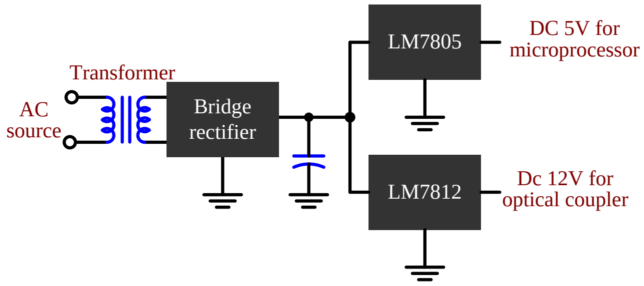

Fig. 7. The structure of the DC power source.

III. CONTROLLING STRATEGY FOR COLLECTING RESIDUAL ENERGY

The voltages of used batteries and normal rechargeable batteries vary at any time while the developed step-up converter pumps the residual electric power in used batteries into normal rechargeable batteries. In order to maximize the recovering benefit, a controlling strategy for the developed step-up converter was proposed and described as follows.

Firstly, both the voltages of normal rechargeable batteries and used batteries are detected simultaneously and sent to the microprocessor.

Secondly, if the used batteries' voltage is lower than the normal rechargeable batteries' voltage, the microprocessor produces PWM signals with a bigger duty cycle to the developed step-up converter. Then the developed step-up converter boosts the used batteries' voltage. If the output voltage of the developed step-up converter is still lower than the normal rechargeable batteries' voltage, the microprocessor increases PWM signals' duty cycle continuously until the output voltage of the developed step-up converter is higher than the normal rechargeable batteries' voltage.

Thirdly, if the normal rechargeable batteries' voltage has reached its upper limit, the microprocessor stops the developed step-up converter.

Finally, if the used batteries' voltage has reached its lower limit, the microprocessor stops the developed step-up converter as well.

IV. TEST RESUTS OF THE DEVELOPED CONVERTER

The development of a programmable step-up converter has been achieved. The entity of the developed step-up converter with a LCD displayer, a DC power source, a microprocessor, a driving circuit, two voltage detectors, a normal rechargeable battery and a used battery is shown in Fig. 8. The LCD displayer was used to display the discharging states of the used battery and the charging states of the normal rechargeable battery. Both the used battery and the normal rechargeable battery were lea-acid batteries in this research. Their rating voltages and capacities were all 6V and 4Ah.

International Journal of Engineering Research & Technology (IJERT)
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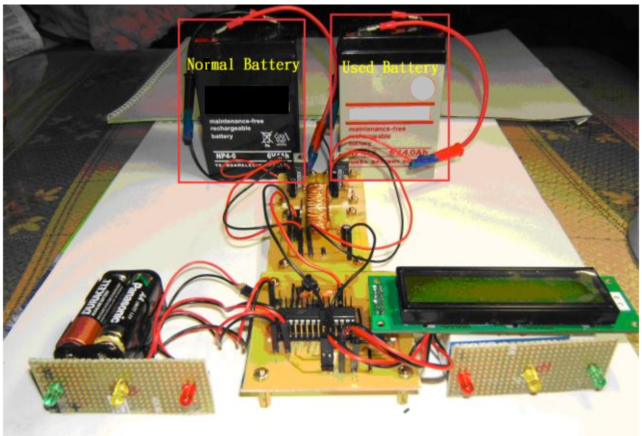

Fig. 8. The entity of the developed step-up converter.

There are three tests adopted in this research. The work of each test was defined as follows.

Test 1: To examine the original states of the used battery and the normal rechargeable battery.

Test 2: To pump the residual electric power of the used battery into the normal rechargeable battery and examine the charging/discharging states at any time.

Test 3: To examine the latest states of the used battery and the normal rechargeable battery after a charging/discharging process.

The three tests have been carried out. The results are presented and discussed below.

A. Test 1

In this test, the used battery was disconnected from the input terminal of the developed step-up converter and the normal rechargeable battery was disconnected from the output terminal of the developed step-up converter. The two voltage detectors detected the original terminal voltages of the used battery and the normal rechargeable battery. They were 5.0V and 5.2V, respectively. The discharging currents of the used battery and the charging current of the normal rechargeable battery were all 0mA. Fig. 9 and 10 show the original states of the used battery and the normal rechargeable battery, respectively.

Fig. 9. The original states of the used battery in test 1.

Fig. 10. The original states of the normal rechargeable battery in test 1.

B. Test 2

In this test, the used battery and the normal rechargeable battery were connected to the input terminal and the output terminal of the developed step-up converter, respectively. The developed step-up converter started a charging/discharging work. The duration of the test 2 was five hours. The residual electric power in used battery was pumped into the normal rechargeable battery. Results of the test 2 have been arranged and are shown in Fig. 11 to 14.

Fig. 11 illustrates the charging states of the normal rechargeable battery in test 2. The original terminal voltage of the normal rechargeable battery was 5.2V. In order to charge the normal rechargeable battery, the output voltage of the developed step-up converter was controlled at 5.6V. The terminal voltage of the normal rechargeable battery rose gradually from 5.6V to 6.4V during a five-hour charging process. The reason was that the developed step-up converter continually pumped the residual electric power in the used battery into the normal rechargeable battery. The charging current was held at 100mA because a constant current charging method was adopted in this test.

Fig. 12 illustrates the discharging states of the used battery in test 2. When the developed step-up converter started to pump the residual electric power in the used battery, the terminal voltage of the used battery dropped from 5.0V to 4.6V immediately. The discharging current of the used battery increased gradually from 135mA to 254mA. The reason is that the terminal voltage of the used battery dropped continuously and the charging current of the normal rechargeable battery was held at constant. In order to provide enough electric power with the normal rechargeable battery, the used battery was forced to provide increased current.

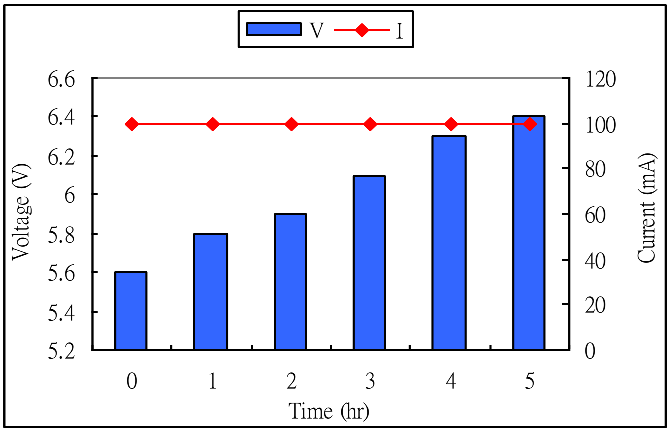

Fig. 11. Results of the normal rechargeable battery in test 2.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 10, October-2016

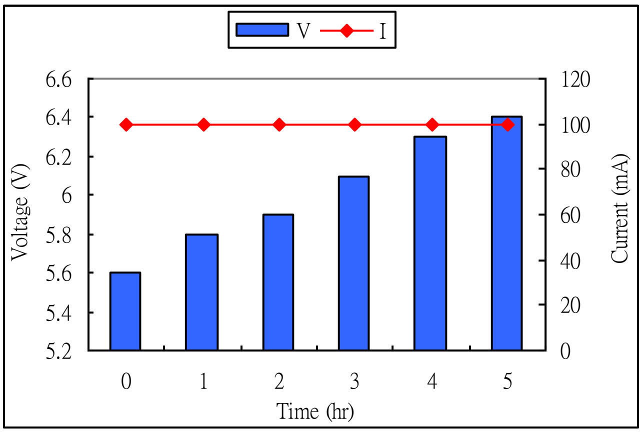

Fig. 12. Results of the used battery im test 2.

Figs. 13 and 14 show the comparisons between the terminal voltages and discharging/charging currents of the used battery and the normal rechargeable battery during a five-hour charging/discharging process. The terminal voltages of the used battery and the normal rechargeable battery dropped and rose continuously, respectively. Moreover, the discharging current of the used battery increased continuously and the charging current of the normal rechargeable battery was held at constant at all time. Therefore, the two figures can demonstrate that the developed step-up converter was able to collect the residual electric power from used batteries.

Fig. 15 shows the discharging/charging power of the used battery and the normal rechargeable battery during a five-hour charging/discharging process. This figure demonstrates that the residual electric power of the used battery was surely stored into the normal rechargeable battery. The power converting efficiencies of the developed step-up converter during a five-hour charging/discharging process are also presented in Fig. 15. The efficiency dropped from 90.2% to 84.0%. The major reason was that the discharging current of the used battery increased continuously during discharging process. The larger discharging current caused more power losses in developed step-up converter. The longer the discharging time, the lower the power converting efficiency of the developed step-up converter.

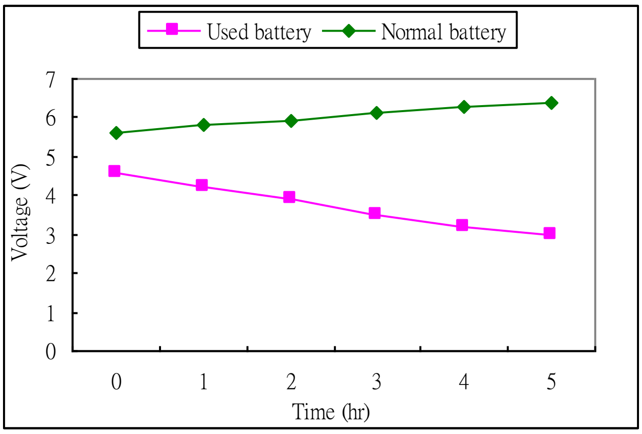

Fig. 13. A comparison between the terminal voltages of the used battery and the normal rechargeable battery in test 2.

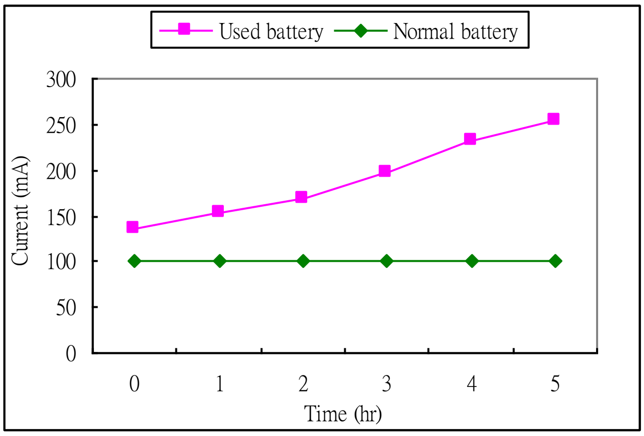

Fig. 14. A comparison between the discharging/charging currents of the used battery and the normal rechargeable battery in test 2.

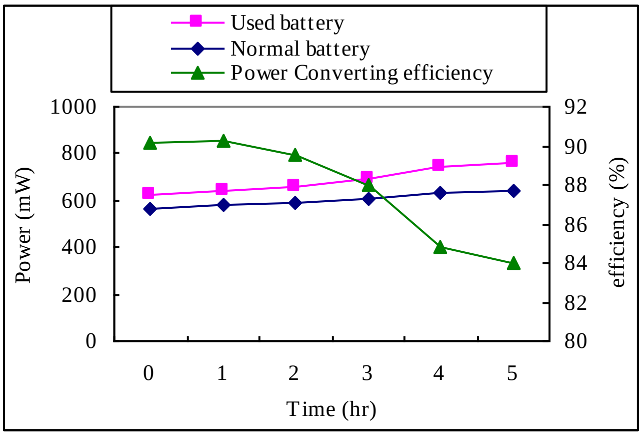

Fig. 15. The discharging/charging power of the used battery and the normal rechargeable battery in test 2.

C. Test 3

In this test, the used battery was disconnected from the input terminal of the developed step-up converter and the normal rechargeable battery was disconnected from the output terminal of the developed step-up converter again. The two voltage detectors detected the terminal voltages of the used battery and the normal rechargeable battery to get the latest states of the two batteries. They were 3.3V and 6.0V, respectively. Fig. 16 and 17 show the latest states of the used battery and the normal rechargeable battery, respectively. The terminal voltage of the used battery in test 3 was higher than the voltage at the 5^{th} hour in test 2. The reason was that the discharging current of the used battery in test 3 became 0mA. The voltage drop of the inner resistance in the used battery also became 0V. Therefore, the terminal voltage of the used battery increased 0.3V. Similarly, the charging current of the normal rechargeable battery in test 3 became 0mA after disconnecting from the output terminal of the developed step-up converter. The voltage drop of the inner resistance in the normal rechargeable battery also became 0V. Therefore, the terminal voltage of the normal rechargeable battery decreased 0.4V.

Fig. 16. The latest states of the used battery in test 3.

Fig. 17. The latest states of the normal rechargeable battery in test 3.

V. CONCLUSIONS

A programmable step-up converter for collecting the residual electric power of used batteries has been implemented by this research. The programmable step-up converter was developed based on a non-isolated boost circuit. Its output voltage magnitude could be adjusted according to the width of a PWM signal produced by a microprocessor. Therefore, the developed step-up converter could boost used batteries' voltages continuously to charge normal rechargeable batteries. Three tests have been carried out by this research. The results presented in this paper have demonstrated that the developed step-up converter has the ability to collect the residual electric power of used batteries.

Up to date, people use more and more batteries and then produce numerous used batteries every year. Used batteries may have residual electric power [7]. People should collect and reuse this residual electric power. The programmable step-up converter is developed for this purpose. It is benefit of environment protection and energy-saving.

ACKNOWLEDGMENT

This research was founded by a grant provided by the Ministry of Science and Technology, Taiwan, R.O.C., under the grant number: MOST 104-2221-E-149-003.

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