

## **Movable Solar Battery Charger Using Push-Pull Converter Based Switch-Mode Power Supply**

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**Abstract**— This article describes the design and construction of a push-pull converter-based switch-mode power supply (SMPS) to recharge a sealed lead-acid (SLA) battery that receives power from a photovoltaic (PV) module. The PV module is mounted on a wheeled construction, hence named the movable solar battery charger (MSBC). The fishermen will utilize the SLA battery to power the electric lights for night fishing. Since it employs the SMPS circuit, the battery is charged using the floating method, which is implemented by maintaining a constant voltage of 14.1 volts at the battery terminals. The MSBC power circuit utilizes two MOSFETs, while its control circuit employs the SG3524 PWM controller operating at a switching frequency of 25 kHz. Testing with a resistive load has shown that the MSBC can produce a stabilized output voltage of 14.1 volts with 5% regulation for up to 4.5 A loading. Testing by charging a 12V/24Ah SLA battery with an initial state of charge (SoC) of 40% resulted in the MSBC fully charging the battery in approximately 3.5 hours.

*Keywords: Movable Solar Battery Charger, SMPS, Push-Pull Converter, SG3524 PWM Controller, Light Fishing*

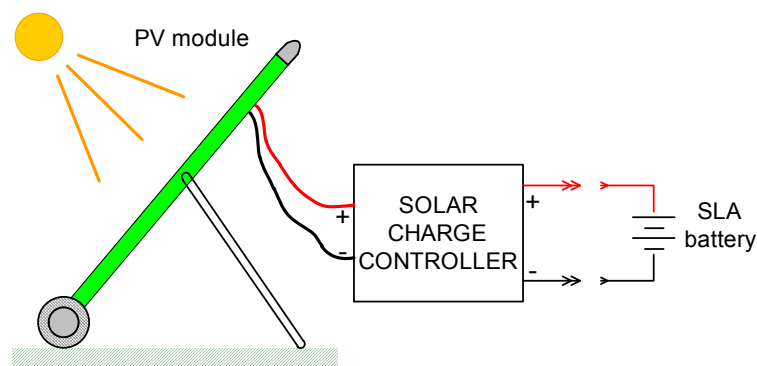


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### **INTRODUCTION**

A DC power supply is typically used to provide a fixed voltage up to a specific current value for operating an electronic circuit. In this study, however, it will be used for a different purpose: charging the battery. Based on its operating principle, there are two types of power supply circuits: linear-mode and switch-mode. A linear-mode power supply obtains a constant output voltage by controlling the voltage drop on the control element; this type of power supply generally uses a power transistor. In contrast, a switch-mode power supply (SMPS) obtains a constant output voltage by operating the control element (e.g., a power transistor, MOSFET, or IGBT) as a switch. SMPSs are superior to linear power supplies because they are more efficient, have a larger power capacity, and are smaller, lighter, and more compact [1]-[3]. Applying the SMPS circuit for battery charging has resulted in the consequence that the process must be conducted using the constant voltage (CV) method. In CV charging, once the battery is full, the charging voltage remains fixed at the float voltage. The float charging voltage varies depending on the type of battery. For lead-acid batteries, the float voltage is 2.3–2.4 V per cell. Thus, for a 12-V lead-acid battery (comprising six cells),

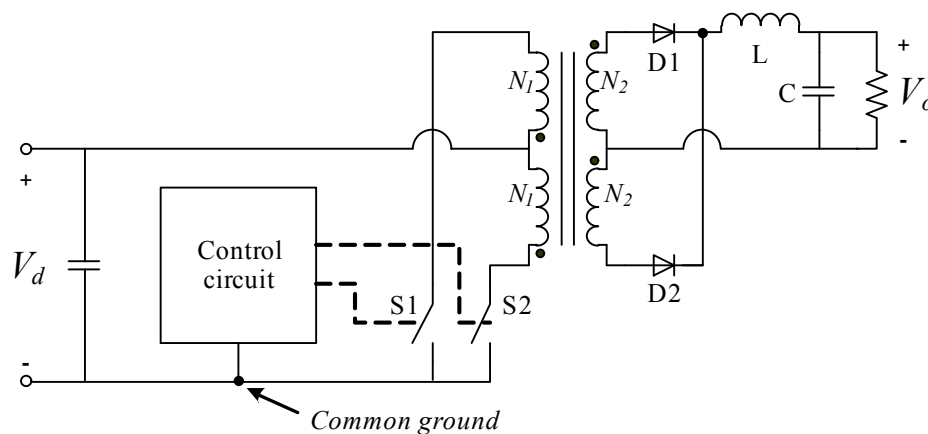
the float voltage ranges from 13.8 to 14.4 V [4]. We use a float charging voltage of 2.35 V per cell, so a 12-V lead-acid battery has a float charging voltage of 14.1 V. In this article, the SMPS receives input power from the solar panel. The battery charger that utilizes energy from solar panels is known as a solar battery charger (SBC). Anto *et al.* have made an SBC based on a linear-mode power supply system [5]. The SBC employs an LM338 voltage regulator IC with a charging current of up to 1.5 A. The SBC is mounted on a construction that can be moved, called a portable solar battery charger. The equipment was used to charge a 12V/7.5Ah sealed lead-acid (SLA) battery, which in turn powered the LED lamp used for lighting the business premises of mobile food merchants. The SBCs are actually needed by fishermen for fishing, where the battery is used to power electric lamps for light fishing. Light fishing techniques, or fishing with the help of artificial light, have been applied by fishermen around the world, both in developing and developed countries [6]-[8]. Large-scale fishermen use electric lights powered by the engine-generators, while small-scale fishermen generally use kerosene lanterns. The use of kerosene lanterns is currently facing availability constraints because the government, since 2008, has implemented a policy of converting the use of kerosene to liquefied petroleum gas (LPG). This policy has caused a scarcity of kerosene in the market, so the price has become expensive [9], [10]. Therefore, this research aims to make an SBC with a large charging current that can charge a large-capacity battery. Furthermore, the battery will power the electric lamps, replacing kerosene lanterns, which are high in operational costs and not environmentally friendly.



**Figure 1.** The concept of MSBC

Portable solar-powered battery charging equipment and mobile solar-powered electrical equipment have attracted the interest of many researchers. That interest is due to the fact that electrical energy from the sunlight is abundantly available for free. Rahman *et al.* have built a portable solar power supply for plasma generators [11]. The system they created utilizes two units of lithium-ion batteries, allowing it to be used at night or when sunlight is unavailable. Rehman *et al.* have developed a portable solar battery charger that can charge devices with varying working voltages [12]. The battery charger is equipped with Internet of Things (IoT) features, enabling users to remotely monitor the battery status in real time. Saputri *et al.* have developed a portable off-grid solar power generation system for supplying electricity to small-scale needs in remote areas or places where conventional power grids are unavailable [13]. They integrated a 120Wp PV module, a 10A solar charge controller, a 12V/100Ah SLA battery, and a 1200W power inverter to become an AC power source for small power appliances. Another type of solar battery charger for fisheries has been introduced by [14]. They have developed a solar battery charger for a 12V/5Ah SLA battery. The battery will then power a 2W LED lamp, replacing the kerosene lantern that fishermen previously used for light fishing. Their achievement has encouraged us to develop a portable solar battery charger for large-capacity batteries for light fishing. The SBC we developed consists of a PV module mounted on a wheeled construction, a charge controller, and a battery. Because it is equipped with wheels, the SBC can be easily moved to get maximum

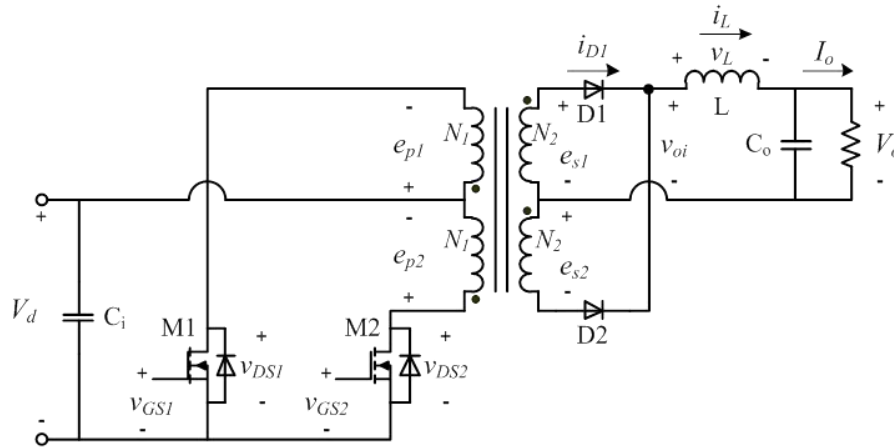
sunlight intensity. Therefore, the SBC is referred to as a movable solar battery charger (MSBC). The concept of the MSBC is shown in Figure 1. The PV module functions to generate electricity from sunlight, which is stored in the battery. The charge controller regulates the battery charging process to ensure it occurs safely for the battery. We have selected the SLA battery for this application because it requires no maintenance and is readily available at a significantly lower price than other types of batteries, such as lithium-ion batteries. Research related to the SBC for large-capacity batteries generally focuses on the development of switch-mode power converters used in the charge controller unit. This trend is because switch-mode power converters are more efficient and compact than linear-type power converters. Febriyandi *et al.* have made a full-bridge converter-based SBC to charge SLA batteries [15]. Rezzak *et al.* have made an SBC for SLA batteries using a non-inverting buck-boost converter [16]. Singh *et al.* have made a SEPIC converter-based SBC for a 24V/100Ah SLA battery used on light electric vehicles [17]. Martínez-Navarro *et al.* have made a buck converter-based SBC combined with a single-phase inverter for use as a mini electric scooter battery charging terminal [18].



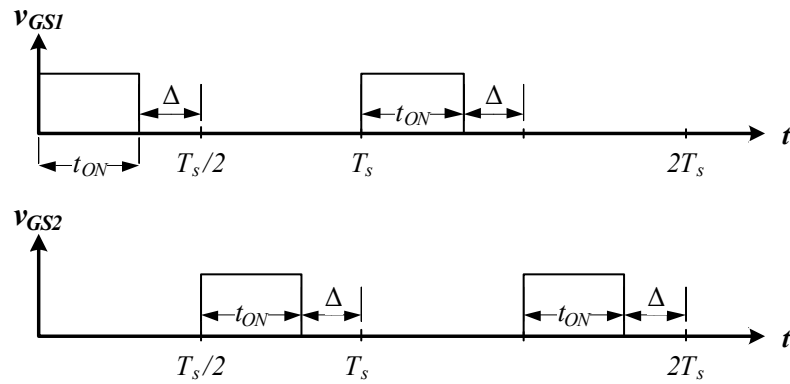
**Figure 2.** Circuit diagram of push-pull converter.

In this research, we have used a push-pull converter in the charge controller unit. This power converter utilizes two electronic switches (S1 and S2) and a transformer with center taps on both the primary and secondary windings, as illustrated in Figure 2. Although both have linear regulation characteristics, the push-pull converter has advantages over the full-bridge converter in that it utilizes fewer electronic switches, and the control circuit of the switches uses the same ground terminal as the power circuit, as shown in Figure 2. Therefore, the control circuit of this converter is simpler than other topologies that use more than one electronic switch. For large power applications, the push-pull converter is superior to topologies with a single electronic switch, such as the buck-boost, SEPIC, and buck converters, because the electric current to be transmitted to the load is shared equally by both electronic switches, resulting in reduced current stress on the electronic switch. The SBC that we made uses a push-pull converter as the basic structure of the solar charge controller. The push-pull converter is a DC-DC converter that provides galvanic isolation between the input and output circuits. The power circuit diagram of the push-pull DC-DC converter is shown in Figure 3. The electronic switches S1 and S2 in Figure 2 are replaced with MOSFETs M1 and M2. It can also be seen that each MOSFET is equipped with a body diode. MOSFETs M1 and M2 are controlled using signals derived from a pulse-width-modulation (PWM) controller. The shape of the control voltage signals is shown in Figure 4. In Figure 3,  $V_d$  is the converter's input voltage, and  $V_o$  is its output voltage.  $I_o$  is the converter's output current.  $e_{p1}$  and  $e_{p2}$  are the induced voltages in the transformer's primary windings, while  $e_{s1}$  and  $e_{s2}$  are the induced voltages in the secondary windings of the transformer, respectively. The transformer used is a transformer with a center tap on the

primary and secondary sides and uses a ferrite core without an air gap.  $i_{D1}$  is the current in diode D1.  $v_L$  and  $i_L$  are the voltage and current of inductor L, respectively. The inductor used is an inductor with a ferrite core.



**Figure 3.** Power circuit diagram of push-pull converter.



**Figure 4.** Time diagram of control signals for MOSFETs M1 and M2

In Figure 4,  $v_{GS1}$  is the MOSFET M1 control voltage signal, and  $v_{GS2}$  is the MOSFET M2 control voltage signal. A voltage signal with a high level causes the affected MOSFET to close (ON), while a voltage signal with a low level causes the MOSFET to open (OFF).  $t_{ON}$  is the duration of MOSFET M1 or MOSFET M2 in the ON state, while  $\Delta$  is the duration of both MOSFETs in the OFF state.  $T_s$  is the period of the control voltage signals M1 and M2. Also, in Figure 4, the control signal of MOSFET M2 is made half-period later than that of M1. The control signals  $v_{GS1}$  and  $v_{GS2}$  in Figure 4 can be generated by a PWM controller such as the SG3524 integrated circuit [19].

There exists a term, duty cycle  $D$ , which is defined as follows,

$$D = \frac{t_{ON}}{T_s} \quad (1)$$

The operation of the push-pull converter in steady state is explained using the four states of M1 and M2 switches with reference to the time diagram of the control voltage signals of the two switches, as shown in Figure 4. Note that MOSFETs M1 and M2 are considered as ideal switches, and the capacitance of  $C_o$  in the output circuit is very large.

State 1 ( $0 \leq t < t_{ON}$ ).

In State 1, MOSFET M1 is ON, while M2 is OFF, so the following equations are obtained,

$$e_{p1} = V_d \quad (2)$$

$$v_{DS1} = 0 \quad (3)$$

$$v_{DS2} = e_{p2} + V_d = 2V_d \quad (4)$$

The induced voltage on the secondary windings of the transformer causes the diode D1 ON, while the D2 OFF, so the following equations are obtained,

$$v_{oi} = e_{s1} = \frac{N_2}{N_1} \times e_{p1} = \frac{N_2}{N_1} V_d \quad (5)$$

$$v_L = v_{oi} - V_o = \frac{N_2}{N_1} V_d - V_o \quad (6)$$

State 2 ( $t_{ON} \leq t < T_s / 2$ ).

In State 2, MOSFET M1 is OFF, and M2 is OFF, so the induced voltage on the primary windings is zero, so the following equation is obtained,

$$v_{DS1} = V_d \quad (7)$$

The induced voltage in the secondary windings is also zero, so the following equations are obtained,

$$v_{oi} = 0 \quad (8)$$

$$v_L = v_{oi} - V_o = -V_o \quad (9)$$

However, in this condition, the inductor will function as a voltage source that flows inductive current, causing diode D1 ON and diode D2 ON. The inductor current is divided into 2 paths, each of which passes through diode D1 and diode D2.

State 3 ( $T_s / 2 \leq t < T_s / 2 + t_{ON}$ ).

In State 3, MOSFET M1 is OFF, while M2 is ON, so the following equations are obtained,

$$e_{p2} = -V_d \quad (10)$$

$$e_{p1} = e_{p2} = -V_d \quad (11)$$

$$v_{DS1} = -e_{p1} + V_d = 2V_d \quad (12)$$

The induced voltage on the secondary windings causes diode D1 OFF and diode D2 ON, so the following equations are obtained,

$$v_{oi} = -e_{s2} = -\frac{N_2}{N_1} \times e_{p2} = \frac{N_2}{N_1} V_d \quad (13)$$

$$v_L = v_{oi} - V_o = \frac{N_2}{N_1} V_d - V_o \quad (14)$$

State 4 ( $T_s / 2 + t_{ON} \leq t < T_s$ ).

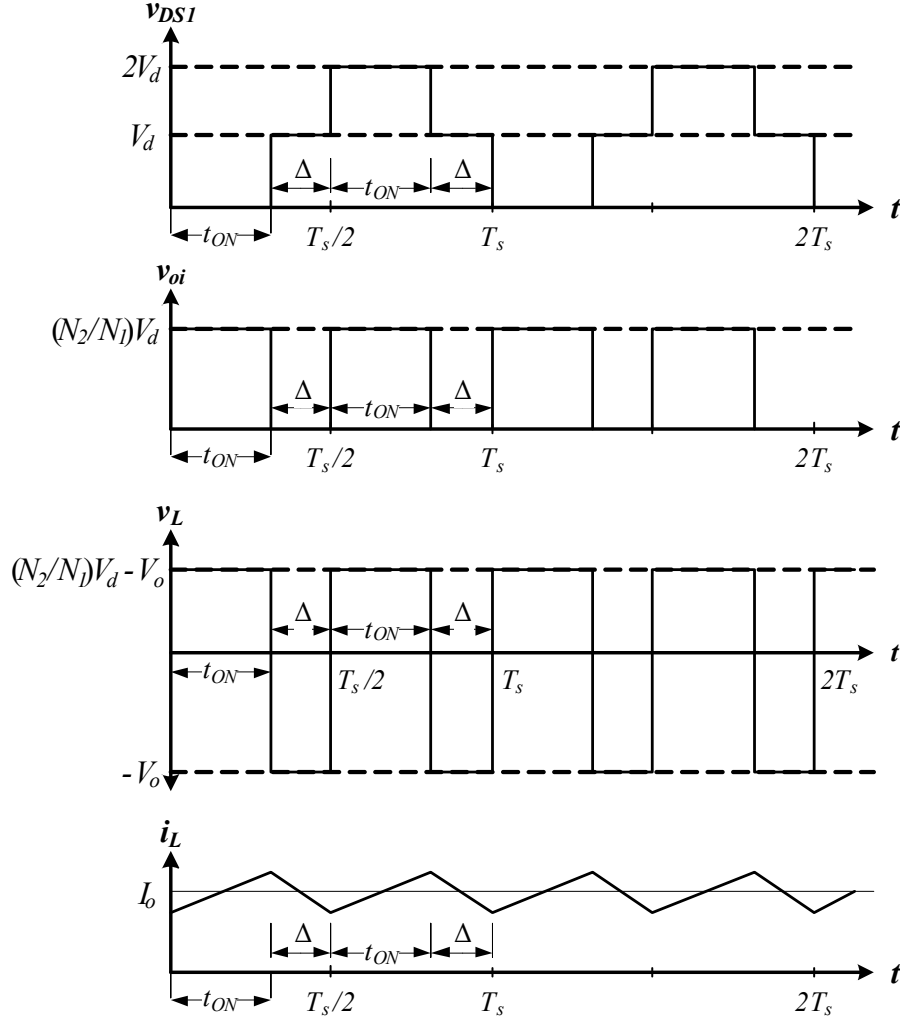
In state 4, M1 OFF and M2 OFF. The induced voltage in the primary windings is equal to zero, so also the induced voltage in the secondary windings is also zero, so the following equations are obtained,

$$v_{DS1} = V_d \quad (15)$$

$$v_{oi} = 0 \quad (16)$$

$$v_L = v_{oi} - V_o = -V_o \quad (17)$$

However, in this condition, the inductor will function as a voltage source that flows inductive current, causing diode D1 ON and diode D2 ON. The inductor current is divided into 2 paths, each of which passes through diode D1 and diode D2.



**Figure 5.** The waveforms of  $v_{DS1}$ ,  $v_{oi}$ , inductor voltage  $v_L$ , and inductor current  $i_L$ .

Based on the above explanation, the waveforms of  $v_{DS1}$ ,  $v_{oi}$ ,  $v_L$ , and  $i_L$  are constructed, and they are all illustrated in Figure 5. The converter output voltage equation  $V_o$  can be derived from the inductor voltage  $v_L$  based on the principle that the average value of  $v_L$  is equal to zero, so the following equation is obtained,

$$\left( \frac{N_2}{N_1} V_d - V_o \right) \times t_{ON} = V_o \times \Delta = V_o \times \left( \frac{T_s}{2} - t_{ON} \right) \quad (18)$$

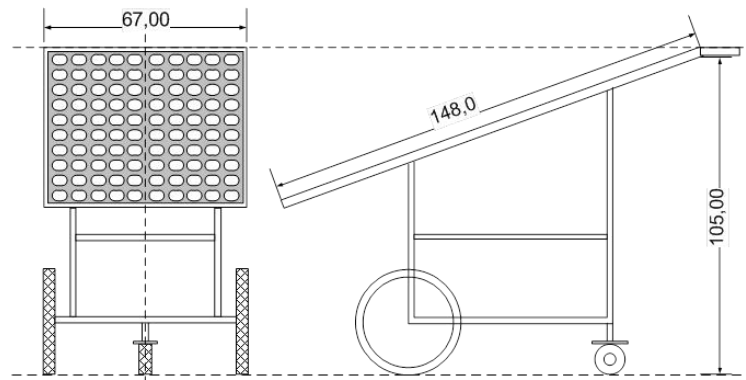
Substitution (1) into (18) results equation as follows,

$$V_o = 2 \times \frac{N_2}{N_1} \times D \times V_d \quad (19)$$

The Equation (19) shows that the relationship between the output voltage and the input voltage of the push-pull converter is linear with the control parameter  $D$ , which is the duty cycle of the MOSFET M1 and M2 control signals. Equation (19) also implies that by adjusting the value of  $D$ , the voltage  $V_o$  can be kept constant under changing  $V_d$  conditions.

## METHOD

The research begins by determining the size of the SLA battery required to power the LED lamp that replaces the kerosene lantern during its use time. Then, determine the solar panel size needed to charge the SLA battery within 1 day of fully charging. Then, the solar panel is mounted on a mechanical construction and equipped with wheels to move it. The design of the mechanical construction supporting the solar panel is shown in Figure 6. The next step is to determine the specifications of the push-pull converter and then proceed with designing the push-pull converter according to the predetermined specifications. After the design process, proceed with manufacturing a push-pull converter-based charge controller circuit. After that, proceed with installing the charge controller on the mechanical construction that supports the solar panel. The MSBC was then functionally tested by charging the SLA battery, which had a state-of-charge (SoC) of 40%. During the test time, the voltage generated by the solar panel and the battery voltage and charging current were measured and recorded. The battery charging voltage must be below the float charging voltage (14.1 volts) despite the fluctuating voltage generated by the solar panel.



**Figure 6.** Design of movable mechanical construction supporting the PV module

### A. Battery Sizing

Research conducted by Mills *et al.* on the characteristics of several kerosene lamp constructions has concluded that a pressurized kerosene lantern produces 1300 lumens of light [20]. Currently, LED lamps can theoretically have an efficacy of 160 lm/W, so to produce 1300 lumens of light, a 9-W LED lamp can be used [21]. A 14.5 W LED lamp with white light by Philips can produce 1700 lumens of light [22]. Thus, one kerosene lantern is equivalent to one 14.5 W LED lamp.

The battery capacity  $Q$  with a nominal voltage of  $E$  volts to supply a load of  $W$  watts for  $t$  hours can be calculated with the following equation,

$$Q = \frac{W \times t}{0.6 \times E} \quad (20)$$

Number 0.6 in (20) expresses the maximum depth of discharge (DoD) allowed for lead acid batteries to extend their lifespan [23]. If each fisherman uses a 14.5 W LED lamp for 11 hours, then based on (20), the minimum capacity of an SLA battery with a nominal voltage of

12 volts is 22.2 Ah. The SLA battery capacity greater than this value and available in the market is 24 Ah, so the MSBC must be able to charge SLA batteries with a capacity of 24 Ah.

## **B. PV Module Sizing**

The power size of the PV module ( $P$ ) required to charge a lead-acid battery is calculated using the following equation [24],

$$P = \frac{Q \times E}{h} \times 1.25 \quad (21)$$

In (20),  $Q$  is the capacity of the lead-acid battery in Ah,  $E$  is the nominal voltage of the battery in volts, and  $h$  is the peak-sun hour (PSH), which is the duration of solar radiation of 1000 W/m<sup>2</sup> in one day. The value of  $h$  is determined by the geographical position of a region, obtained from statistical data, and is the lowest average value in one year. We have used  $h = 3.18$  hours based on Solargis application [25]. Using the values of  $Q = 24$  Ah,  $E = 12$  V, and  $h = 3.18$  hours in (20),  $P = 113.2$  W is obtained. Furthermore, a solar panel with a peak power output of 150 W is selected.

## **C. Determine Push-Pull Converter Specification**

The push-pull converter-based SMPS is designed to charge a 12V/24Ah SLA battery. Since the battery is charged using the floating method, the SMPS must produce an output voltage of 14.1 volts. The current with this charging method can reach 0.3Q, where  $Q$  is the battery capacity [4]. For a 24-Ah battery, the charging current can reach 7.2 amperes. Based on the description above, the output voltage of the push-pull converter is 14.1 volts, and the maximum output current is 7.2 amperes.

The push-pull converter input power comes from a 150-Wp PV module. The PV module has specifications: the output voltage at no-load conditions is 21.67 volts, the maximum output power is 150 watts, the voltage at maximum power is 17.5 volts, and the current at maximum power is 9.41 amperes. The output voltage of the PV module depends on the solar radiation that hits it. In this study, the lowest PV module output voltage is assumed to be 15.0 volts. Based on the description above, the specifications of the push-pull converter to be made are shown in Table 1.

**Table 1.** Push-Pull Converter Specifications

| Parameter                              | Value          |
|----------------------------------------|----------------|
| Input voltage ( $V_d$ )                | 15.0 – 21.67 V |
| Output voltage ( $V_o$ )               | 14.1 V         |
| Output voltage ripple factor ( $r_v$ ) | 0.01           |
| Maximum output current ( $I_o$ )       | 7.2 A          |
| Switching frequency ( $f_s$ )          | 25 kHz         |

The works related to the design of the push-pull converter include designing the transformer, determining the inductance value of the inductor and the capacitance value of the output capacitor, determining the specifications of MOSFETs and power diodes, and designing the push-pull converter control circuit and its power supply.

## **D. Design of Transformer for Push-Pull Converter**

Designing the transformer is based on the specifications of the push-pull converter, as listed in Table 1. The design of the transformer aims to determine the dimensions of the transformer core, calculate the number of turns for the primary winding and the secondary winding, and select the conductor wire size for the transformer windings. The design of the push-pull converter transformer is carried out using the Area-Product method [26][27]. The

transformer design procedure is described as follows,

- (1) Calculate the transformer's output power ( $P_o$ ) using the equation as follows,

$$P_o = (V_o + V_{rl} + V_D) \times I_o \quad (22)$$

$V_o$  is push-pull converter's output voltage.  $V_{rl}$  is the voltage drop at transformer windings and is usually taken as 10% of  $V_o$ .  $V_D$  is the diode forward voltage, usually 1.5 volts.  $I_o$  is maximum output current of push-pull converter.

- (2) Calculate the Area-Product ( $A_p$ ) using the equation as follows,

$$A_p = A_c \times A_w = \frac{\sqrt{2} P_o \left( 1 + \frac{1}{\eta} \right)}{4 k_w J B_m f_s} \quad (23)$$

$A_c$  is the transformer's core cross section.  $A_w$  is the transformer's window area.  $\eta$  is the efficiency of the transformer.  $k_w$  is the transformer's window utilization factor.  $J$  is the current density of winding conductors.  $B_m$  is the maximum flux density of the transformer's core.  $f_s$  is the switching frequency.

- (3) Selecting the appropriate ferrite core size based on the  $A_p$  value calculated using (23). The selected core size is the one with an  $A_p$  value greater than that calculated using (23). The ferrite core sizes and their area-product values are shown in Table 2 [26].

**Table 2.** Ferrite Core Sizes and Their Parameters.

| Core's Size | MLT (mm) | $I_m$ (mm) | $A_c$ (x100 mm <sup>2</sup> ) | $A_w$ (x100 mm <sup>2</sup> ) | $A_p$ (x10 <sup>4</sup> mm <sup>4</sup> ) |
|-------------|----------|------------|-------------------------------|-------------------------------|-------------------------------------------|
| E20/10/5    | 38       | 42.8       | 0.31                          | 0.478                         | 0.149                                     |
| E25/9/6     | 51.2     | 48.8       | 0.40                          | 0.78                          | 0.312                                     |
| E25/13/7    | 52       | 57.5       | 0.55                          | 0.87                          | 0.478                                     |
| E30/15/7    | 56       | 66.9       | 0.597                         | 1.19                          | 0.71                                      |
| E36/18/11   | 70.6     | 78.0       | 1.31                          | 1.41                          | 1.847                                     |
| E42/21/9    | 77.6     | 108.5      | 1.07                          | 2.56                          | 2.739                                     |
| E42/21/15   | 93       | 97.2       | 1.82                          | 2.56                          | 4.659                                     |
| E42/21/20   | 99       | 98.0       | 2.35                          | 2.56                          | 6.016                                     |
| ETD49/25/16 | 86       | 114        | 2.11                          | 2.69                          | 5.684                                     |
| E65/32/13   | 150      | 146.3      | 2.66                          | 5.37                          | 14.284                                    |

From Table 2,  $MLT$  is the mean length per turn of the transformer's winding.  $I_m$  is the mean magnetic path of the transformer's core.

- (4) Compute the number of turns of the transformer's primary winding ( $N_1$ )

$$N_1 = \frac{V_{d\max}}{4 A_c B_m f_s} \quad (24)$$

$V_{d\max}$  is the maximum value of the converter's input voltage.

- (5) Compute the turn ratio of primary to secondary windings ( $n$ ).

$$n = \frac{N_2}{N_1} = \frac{V_o + V_{rl} + V_D}{2 \times D_{\max} \times V_{d \min}} \quad (25)$$

$D_{\max}$  is the maximum value of the duty cycle of the PWM signal generated by the PWM controller.  $V_{d \min}$  is the minimum value of the converter's input voltage.

- (6) Compute the number of turns of the transformer's secondary winding ( $N_2$ ).

$$N_2 = n \times N_1 \quad (26)$$

- (7) Compute the RMS value of the transformer's secondary current ( $I_2$ ).

$$I_2 = I_o \sqrt{D_{\max}} \quad (27)$$

- (8) Compute the RMS value of the transformer's primary current ( $I_1$ ).

$$I_1 = n \times I_2 \quad (28)$$

- (9) Compute the required cross sections of the primary winding conductor ( $a_1$ ) and the secondary winding conductor ( $a_2$ ).

$$a_1 = \frac{I_1}{J} \quad (29)$$

$$a_2 = \frac{I_2}{J} \quad (30)$$

#### E. Design of L-C Filter of Push-Pull Converter

The L-C filter functions to flatten the output voltage and output current of the push-pull converter. The inductance of output inductor ( $L_o$ ) is calculated using the following equation,

$$L_o = \frac{(V_o + V_{rl} + V_D)(1 - 2D_{\max})}{2 \times \Delta i_L \times f_s} \quad (31)$$

In (28),  $\Delta i_L$  is the inductor current ripple at nominal output current ( $I_o$ ), its value ranges from  $0.1 - 0.4 \times I_o$ .

The capacitance of output capacitor ( $C_o$ ) is computed using equation as follows,

$$C_o = \frac{1}{32} \frac{(1 - 2D_{\max})}{r_v \times L_o \times f_s^2} \quad (32)$$

In (29),  $r_v$  is the converter's output voltage ripple factor, and it is defined as follows,

$$r_v = \frac{\Delta V_o}{V_o} \quad (33)$$

#### F. Choosing MOSFET for Push-Pull Converter

The type of MOSFET is selected based on several considerations: 1) the maximum voltage at the MOSFET's power terminals ( $v_{DS}$ ) when it is at the OFF state; 2) the maximum current passing through the MOSFET; and 3) the average value of the current passing through the MOSFET. Based on the  $v_{DS}$  waveform in Figure 5, the maximum voltage between the MOSFET's drain and source terminals is  $2V_d$ . The maximum current passing through the MOSFET ( $I_{Qmax}$ ) is calculated using the following equation,

$$I_{Q\max} = n \times \left( I_o + \frac{1}{2} \Delta i_L \right) \quad (34)$$

The average value of the current passing through the MOSFET ( $I_{Qavg}$ ) is calculated as follows,

$$I_{Qavg} = n \times D_{\max} \times I_o \quad (35)$$

### G. Choosing Power Diode for Push-Pull Converter

Similar to the MOSFET, the selection of the type of power diode connected to the push-pull converter output circuit is based on considerations: 1) the repetitive peak reverse voltage, 2) the repetitive peak forward current, and 3) the average forward current. The maximum value of the diode reverse voltage ( $V_{RRM}$ ) is equal to twice the maximum value of the transformer secondary voltage, so the following equation is obtained.

$$V_{RRM} = 2 \times (V_o + V_{rI} + V_D) \quad (36)$$

The maximum current passing through the diode repetitively ( $I_{RFM}$ ) is equal to the maximum inductor current, so the following equation is obtained.

$$I_{RFM} = I_o + \frac{1}{2} \Delta i_L \quad (37)$$

The average value of the current passing through the diode ( $I_{F(AV)}$ ) is computed using the following equation,

$$I_{F(AV)} = D_{\max} \times I_o \quad (38)$$

### H. Design of Control Circuit of Push-Pull Converter

The push-pull converter control circuit is based on the PWM controller integrated circuit. This circuit controls the push-pull converter's operation by varying the PWM signal's duty cycle to obtain the desired output voltage. The converter control circuit employs the SG3524 PWM controller. The SG3525 is a PWM controller that works with a fixed frequency. It generates two PWM signals at its output terminals, which differ in phase by 180 degrees.

### I. Power Supply for Push-Pull Converter's Control Circuit

The power supply circuit provides a constant voltage to supply the SG3524. This circuit utilizes the LM7812 linear voltage regulator to produce a stable 12-volt output. The LM7812 has been chosen because it has a 1 amp output current capacity with an input voltage range of 14.5-35.0 volts [28], so it can be directly connected to the 150-Wp PV module.

## RESULT AND DISCUSSION

### A. Results

The MSBC, equipped with a push-pull converter-based SMPS, is used to recharge a 12V/24Ah SLA battery utilizing a float charging method, which involves maintaining the voltage at the battery terminals at 14.1 volts. Thus, the push-pull converter will produce an output voltage of 14.1 volts and a maximum output current of 7.2 A. Note that this current is the maximum charging current of a 12V/24Ah SLA battery charged by the float-charging method. The transformer design for the push-pull converter is performed using (22) through (30). The parameters for designing the transformer of push-pull converter are shown in Table 3. Using the data  $V_o = 14.1$  volts,  $V_{rI} = 1.41$  volts,  $V_D = 1.5$  volts, and  $I_o = 7.2$  amps into (22), we obtain  $P_o = 122.47$  watts. Entering the data  $\eta = 0.8$ ;  $K_w = 0.4$ ;  $J = 3 \times 10^6$  A/m<sup>2</sup>;  $B_m = 0.2$  T, and  $f_s = 25$  kHz into (23),  $A_p = 16.237 \times 10^{-9}$  m<sup>4</sup> =  $1.624 \times 10^4$  mm<sup>4</sup> is obtained. Based on Table 2, the E36/18/11 core was selected. Due to availability reasons, we have used the

ETD49/25/16 core. The ETD49/25/16 has parameters:  $MLT=86$  mm;  $l_m=114.0$  mm;  $A_c=211$  mm<sup>2</sup>;  $A_w = 269.4$  mm<sup>2</sup>;  $A_p = 5.684 \times 10^4$  mm<sup>4</sup>. Entering the data  $V_{dmax} = 21.67$  volts and  $A_c = 211$  mm<sup>2</sup> into (24), we obtain  $N_1 = 5.1$  turns, rounded to 5 turns. Using  $D_{max} = 0.4$  and  $V_{dmin} = 15.0$  volts in (25), we obtain  $n = 1.42$ . Then using (26), we obtain  $N_2 = 7.1$  turns, rounded to 7 turns.

**Table 3.** Parameters for Push-Pull Converter Transformer Design.

| Parameter                               | Symbol   | Value                            | Remarks          |
|-----------------------------------------|----------|----------------------------------|------------------|
| Output voltage                          | $V_o$    | 14.1 V                           |                  |
| Voltage drops at transformer windings   | $V_{rl}$ | 1.41 V                           | $0.1 \times V_o$ |
| Voltage drops at power diode            | $V_D$    | 1.5 V                            |                  |
| Output current                          | $I_o$    | 7.2 A                            |                  |
| Maximum magnetic flux density           | $B_m$    | 0.2 T                            |                  |
| Current density                         | $J$      | $3 \times 10^6$ A/m <sup>2</sup> |                  |
| Transformer's window utilization factor | $k_w$    | 0.4                              |                  |
| Switching frequency                     | $f_s$    | 25 kHz                           |                  |
| Transformer's efficiency                | $\eta$   | 0.8                              |                  |

From (27), the RMS value of the secondary coil current is  $I_2 = 4.55$  A, and from (28), the RMS value of the primary coil current is  $I_1 = 6.46$  A. By using the value of  $J = 3$  A/mm<sup>2</sup> in (29) and (30), the primary wire cross-sectional area  $a_1 = 2.15$  mm<sup>2</sup> and the secondary wire cross-sectional area  $a_2 = 1.52$  mm<sup>2</sup> are obtained. The transformer design data is presented in Table 4.

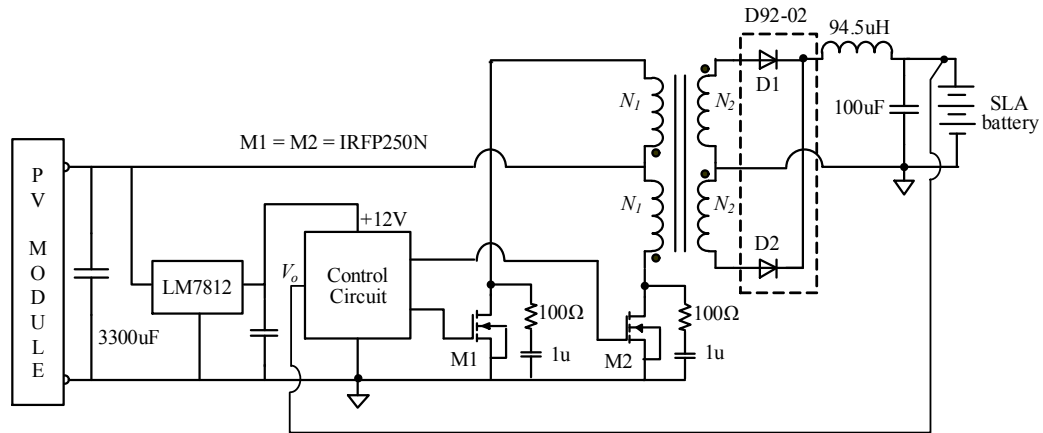
**Table 4.** Transformer Design Data

| Parameter                         | Symbol | Value                 |
|-----------------------------------|--------|-----------------------|
| Type of ferrite core              |        | ETD49/25/16 un-gapped |
| Primary winding turns             | $N_1$  | 5 turns               |
| Secondary winding turns           | $N_2$  | 7 turns               |
| Primary conductor cross section   | $a_1$  | 2.15 mm <sup>2</sup>  |
| Secondary conductor cross section | $a_2$  | 1.52 mm <sup>2</sup>  |

The inductance and capacitance of the L-C filter are determined using (31) and (32). Entering  $\Delta i_L = 0.1 I_o = 0.72$  A into (31),  $L_o = 94.5$   $\mu$ H is obtained. Furthermore, from (32), using  $r_v = 0.01$ ,  $C_o = 10.58$   $\mu$ F is obtained. We have used a 100- $\mu$ F 50-V electrolytic capacitor for the L-C filter. Based on the MOSFET selection criteria, the minimum specifications for the MOSFET are as follows: Drain-Source Voltage ( $V_{DS}$ ) is 43.34 volts, Pulsed Drain Current ( $I_{DM}$ ) is 10.74 A, and Continuous Drain Current ( $I_D$ ) is 4.09 A. Considering the availability of electronic components, we used the IRFP250N MOSFET, which has a  $V_{DS}$  rating of 200 V, an  $I_{DM}$  rating of 120 A, and an  $I_D$  rating of 20 A. Based on the power diode selection criteria, the minimum specifications for the power diode are as follows: Repetitive Peak Reverse Voltage ( $V_{RMM}$ ) is 34.02 V, Repetitive Peak Forward Current ( $I_{RFM}$ ) is 7.56 A, and Average Forward Current ( $I_{F(AV)}$ ) is 2.88 A. Considering the availability of electronic components, we used the D92-02 ultrafast recovery diode, which has a  $V_{RMM}$  rating of 200 V, an  $I_{RFM}$  rating of 40 A, and an  $I_{F(AV)}$  rating of 20 A.

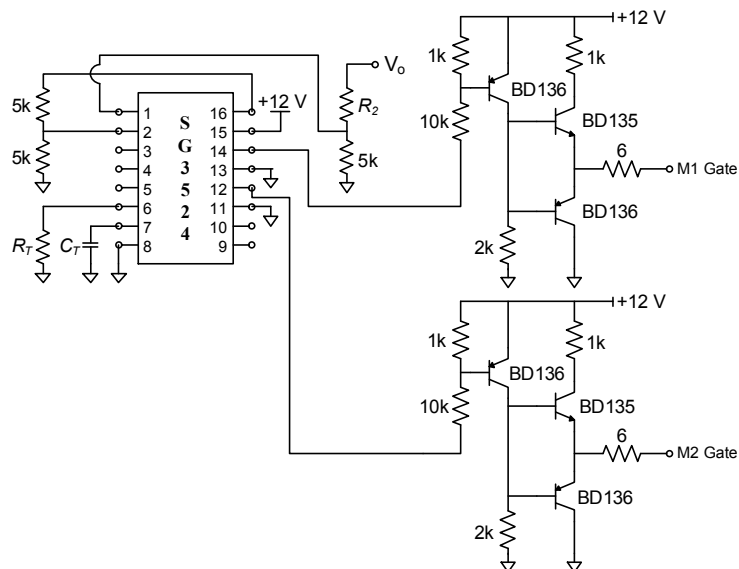
The schematic diagram of the push-pull converter power circuit is shown in Figure 7. There is a 3300  $\mu$ F electrolytic capacitor at the input terminal of the push-pull converter. The LM7812 linear voltage regulator, which receives power from the PV module, provides a constant 12-V voltage to the push-pull converter control circuit. Each MOSFET is equipped with an RC snubber circuit, consisting of a 100-ohm resistor in series with a 1- $\mu$ F capacitor, to protect the MOSFET from overvoltage caused by the switching process. The D92-02 power diode is a package composed of two identical ultra-fast diodes. The L-C filter is composed of a 94.5  $\mu$ H ferrite inductor and a 100  $\mu$ F electrolytic capacitor. It can also be observed that the negative

terminal of the control circuit's power supply is connected to the negative terminal of both the primary side power circuit and the output circuit. Additionally, there is a feedback line connecting the converter's output terminal to the feedback input of the converter's control circuit.



**Figure 7.** Power circuit of push-pull converter based SBC

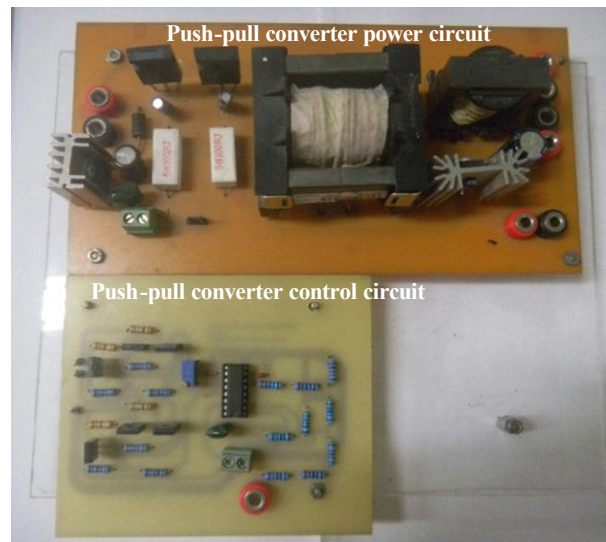
The schematic diagram of the push-pull converter control circuit is shown in Figure 8. This circuit utilizes the SG3524 PWM controller, which generates PWM signals with a frequency of 25 kHz on both output channels, pins 12 and 14. The outputs of SG3524 on pins 12 and 14 are connected to the Gate terminal of the MOSFET through a driver circuit built using BD135 and BD136 transistors arranged in a totem-pole structure. The SG3524 has been configured to control the push-pull converter in closed-loop mode, so it is equipped with a feedback circuit that compares the output voltage of the push-pull converter with a reference voltage, thereby maintaining a constant output voltage.



**Figure 8.** Schematic diagram of push-pull converter control circuit.

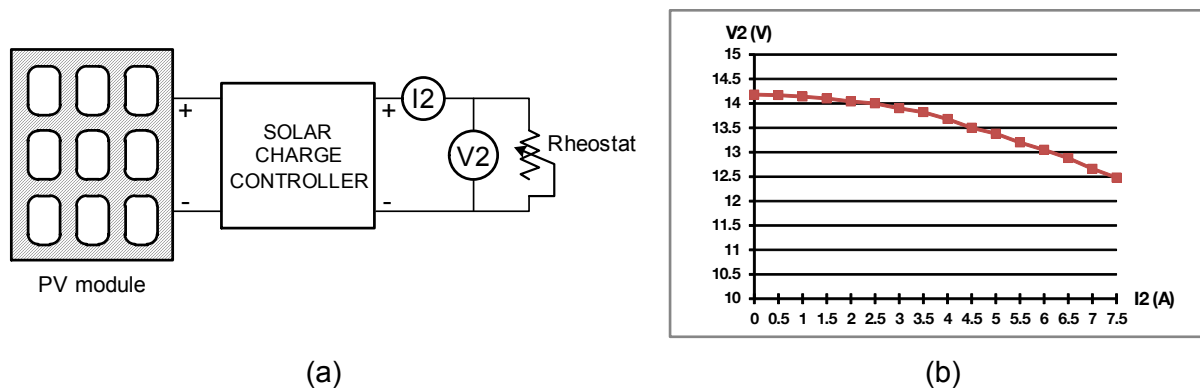
The solar charge controller that we developed is shown in Figure 9. It is built from two separate circuit boards: a power circuit board and a control circuit board. Both boards are equipped with terminals for making connections between them using cables. We then performed functional testing on the charge controller. The testing was conducted in 2 conditions. In condition 1, the output of the charge controller circuit was connected to a resistive load in the form of a rheostat, whose resistance can be varied. The purpose of this

test is to obtain the output characteristics of the charge controller, namely the relationship between the output current and the output voltage of the charge controller.



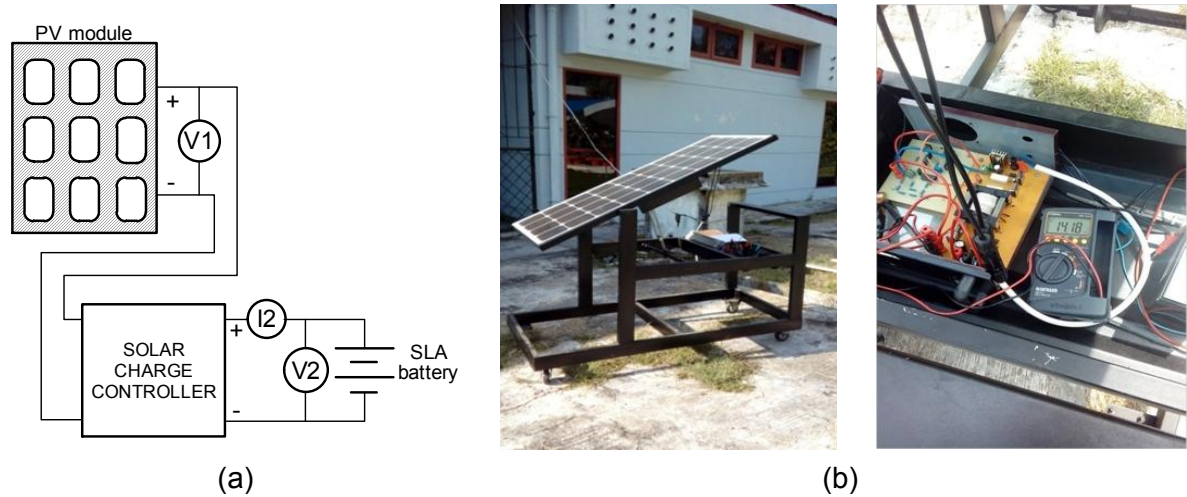
**Figure 9.** Push-pull converter based solar charge controller

The test circuit diagram is shown in Figure 10a. The input terminals of the charge controller are connected to the PV module, and its output terminals are connected to the rheostat. During the test, the output current ( $I_2$  amp meter) of the charge controller is gradually increased and recorded for each increment, along with the corresponding output voltage ( $V_2$  voltmeter). The test results are presented in the graph shown in Figure 10b.

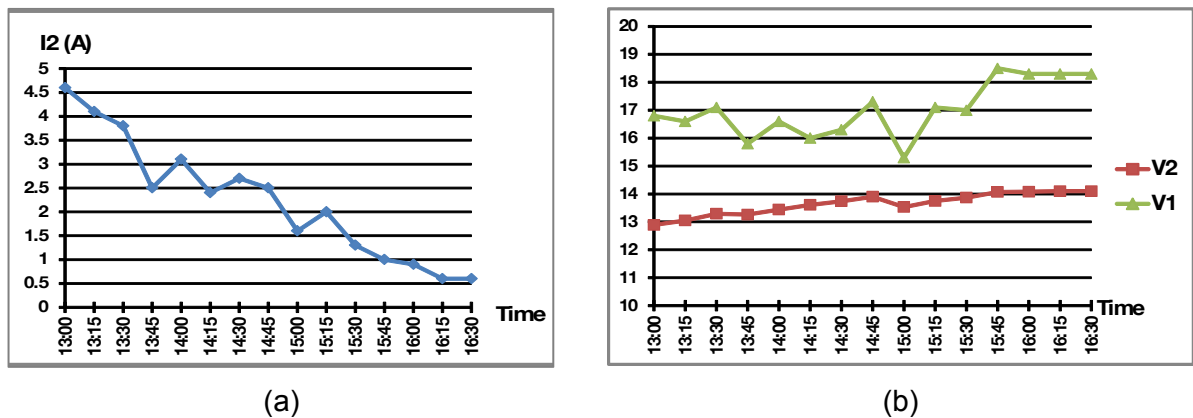


**Figure 10.** (a) Wiring diagram of SBC resistive loading test, (b) Output V-I characteristics

The functional test condition 2 involves testing the MSBC to charge a 12V/24Ah SLA battery from its initial state to a fully charged state. The test circuit diagram is shown in Figure 11a. The input terminals of the charge controller are connected to the PV module, and its output terminals are connected to the battery under test. Before conducting the test, the battery was discharged to the initial condition of 40% State of Charge (SoC). The testing is conducted in clear weather. During the test period, the battery charging voltage ( $V_2$  voltmeter) and current ( $I_2$  amp meter) are recorded, along with the output voltage of the PV module ( $V_1$  voltmeter). The documentations of functional testing condition two are shown in Figure 11b. SBC testing under condition two was conducted during the day from 1:00 pm to 4:30 pm in clear weather. During the test, the battery charging voltage and current were recorded every 15 minutes, along with the PV module's output voltage. The test results are presented in graphical form shown in Figure 12a and Figure 12b.



**Figure 11.** (a) Wiring diagram of testing the SBC charge the battery, (b) Documentations



**Figure 12.** (a) Profile of SBC charging current, (b) SBC's output - input voltages

## B. Discussion

From the graph in Figure 10b, it can be seen that at the no-load condition, the output voltage of the charge controller is 14.18 V. This value remains stable until the load current reaches 3 A, after which it continues to drop to 12.48 V at 7.5 A loading. Note that the charge controller output voltage at a load current of 7.2 A is 12.56 V. Additionally, from the graph, it is evident that the greater the output current of the charge controller, the lower the output voltage tends to be. Ideally, the charge controller's output voltage remains constant until the output current reaches 7.2 A. The voltage drop from the no-load condition to the 7.2 A loading is 1.62 V or 11.42%. This figure is quite large for a DC power supply circuit, as power supplies for general applications typically have a maximum voltage regulation of 5%. From Figure 10b, if we use the 5% voltage regulation requirement, this solar charge controller only works well for supplying current up to 4.5 A. Thus, for a power supply circuit, this push-pull converter-based SMPS has a maximum output current of 4.5 A. The considerable voltage drop of 11.42%, from the no-load condition to the full-load condition, is due to the approach we used, which involved separating the power circuit board and control circuit board of the push-pull converter. The connection between these two circuit boards is made using cables that are not permanently attached to the terminals of both circuit boards. The poor connection and length of the cables increase the values of circuit parameters, such as resistance, inductance, and capacitance. Although these values are small, because this electronic circuit operates at a high frequency (25 kHz), the increase in these values worsens the performance of the push-pull converter circuit. Therefore, in future research, we will unite the power circuit and

control circuit to become a compact circuit board, so as to obtain better push-pull converter performance. The poor performance can also be attributed to the fact that we have connected the negative terminal of the converter's output circuit with the negative terminal of the converter's input circuit, even though these two circuits are naturally isolated by the use of a transformer. We did this so that the control circuit could gather the converter's output voltage for feedback purposes, thus forming a closed-loop control circuit. We can actually reach a closed-loop control system while maintaining the isolation between the input and the output circuit of the converter, by using a voltage sensor circuit equipped with an optocoupler device. Therefore, to improve the performance of the push-pull converter, in addition to unifying the circuit board of the power circuit with the control circuit, we will also separate the output circuit from the input circuit of the push-pull converter using a voltage sensor circuit equipped with optocoupler device.

In Figure 12a, it can be seen that the initial charging current of the battery is 4.6 A, and the current tends to decrease as the state of charge (SoC) of the battery increases, as characterized by an increase in battery voltage, as shown in Figure 12b. Between 4:15 pm and 4:30 pm, the battery voltage reached 14.1 volts and remained stable, indicating that the battery was fully charged. Based on this data, we conclude that it takes 3.5 hours for the MSBC to charge the battery fully. The data presented in Figure 12b shows that, although in its role as a power supply, the performance of this push-pull converter is suboptimal, however, when utilized as a battery charger, this push-pull converter exhibits satisfactory performance. This is because, in the float charging process, the increase in battery voltage is followed by a decrease in battery charging current. Consequently, the push-pull converter is not really forever working at full-load condition. From Figure 12b, it can be seen that the battery charging voltage was kept below 14.1 volts despite the fluctuating output voltage of the PV module. With this condition, the battery charging process has been done safely for the battery.

## CONCLUSION

In this research, we have designed and constructed a movable solar charge controller based on a push-pull converter SMPS that produces a constant voltage of 14.1 volts for charging the SLA battery under the float charging method. The push-pull converter circuit operates at a switching frequency of 25 kHz, utilizing two IRFP250N MOSFETs as electronic switches and an SG3524 integrated circuit as a PWM controller. Charging tests on a 12V/24Ah SLA battery with an initial state of charge (SoC) of 40% have shown that the solar charge controller can fully charge the battery within 3.5 hours. The battery charging voltage is kept below 14.1 volts, even though the output voltage of the PV module fluctuates, providing a safe charging condition for the SLA battery. In its role as a power supply, the charge controller we made operates effectively up to 4.5 A, falling short of the target of 7.2 A. Therefore, some improvements are still needed, specifically unifying the power and control circuit boards to become a compact circuit board, enhancing the circuit board to minimize circuit interference and reduce the inductance of the circuit path, and utilizing an optocoupler device in the voltage sensing circuit of the push-pull converter control circuit to maintain the galvanic isolation between the input and output circuit of the push-pull converter. While this study has not yet yielded an SBC with optimal performance, it has made a substantial contribution to the use of push-pull converters for charging large-capacity SLA batteries. These batteries are essential for fishermen, providing a reliable source of electricity for light fishing needs. Furthermore, in future research, taking advantage of the linear regulation characteristic exhibited by the push-pull converter, the MPPT techniques might be implemented in the push-pull converter control circuit, to achieve the SLA battery charging process occurs in conditions where the PV module generates the maximum electrical power. It is imperative to acknowledge that this novel SLA battery charging process will diverge significantly from the float charging method.

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