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Wireless Photovoltaic Power Transfer Based on DC-DC Converter for the Application of Battery Charger System

Muhammad Irwanto[1,2,*], Nor Hanisah Baharudin[2], Yoga Tri Nugraha[1], Indra Nisja[3], Togar Timoteus Gultom[1]

[1] Department of Electrical Engineering, Universitas Prima Indonesia (UNPRI), Kota Medan, Sumatera Utara 20118, Indonesia
[2] Fellow of Center of Excellence for Renewable Energy, Universiti Malaysia Perlis (UniMAP), Kuala Perlis, 02600 Arau, Perlis, Malaysia
[3] Department of Electrical Engineering, Universitas Bung Hatta (UBH), Padang City, West Sumatra, Indonesia

ABSTRACT

Typically, a wire is used to convey electrical energy from the sending terminal to the receiving terminal. Higher electrical energy demands larger cable sizes, which raises costs and has less-than-exciting technical implications. Additionally, a wired electrical system is unsuitable in a small space. So, in the needed region, a wireless photovoltaic power transfer (WPVPT) system is implemented. In this paper, a WPVPT system based on a DC-DC boost converter for a battery charger system application using MATLAB SIMULINK is presented. In order to attain a longer distance and greater power, the distance between the transmitting and receiving coils as well as the AC voltage on the transmission are taken into consideration using mathematical modelling. According to the simulation results, 35 PV modules connected in series are needed to keep the DC-DC converter's output voltage at 14.81 V and its output power at 50.77 W while it is charging a 12 V, 1. 2 Ah battery. The battery will require 1000 s to reach its completely charged condition if it begins the charging process with a state of charge (SOC) of 25%.

Keywords:

Photovoltaic; WPVPT system; DC-DC converter; Battery charger

1. Introduction

An electrical device known as a photovoltaic (PV) module transforms solar energy into electrical energy [1]. The solar energy entering the PV module's surface can be observed, and it also contains heat that will produce photon energy in the PV module's substance. If it is connected to DC loads, it causes the electrons to migrate and current to flow from the positive terminal to the negative terminal [2-4].

When deciding whether or not to apply PV power generation in a particular place, the research of solar energy is crucial. Solar energy research was carried out by [5] in relation to the electrical installation of PV modules on the campus of Universiti Utara Malaysia. The application of PV modules in the building system has been applied widely. A development of greenhouse based on

* *Corresponding author.*
E-mail address: muhammadirwanto@unprimdn.ac.id

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the PV module is developed by [6] to energies the electrical utilization of green house. An organic PV module integrated building system is constructed and analysed by [7], it is applied in various type of building. One on them is pyramid building and obtained that its building efficiency is increased. The PV module has seen extensive use in applications for DC loads. [7,8] have tested the use of a PV module in a DC water pump. In Ghardaia, Algeria [7] has implemented a water pump system with optimal PV module sizing. The size of the PV module and its predicted electrical output are proportional to the tank's water capacity. Additionally, [8] uses a Brushless Direct Current (BLDC) motor in a DC water pump system. The PV module powers the BLDC motor, using a radial basis function neural network, the maximum power tracking of a PV module is observed. Based on the PV module's current ripple, voltage ripple, and power loss, the proposed method's effectiveness is observed.

The PV module is used in battery charging systems as well. [9] studies a lithium battery management system with a PV module attached. Due to an overcharging scenario, the battery is charged and managed to prevent a battery explosion. For a 3.7 V, 3.2 Ah lithium battery with a 10% state of charge (SOC), it is modelled using MATLAB software. The results indicate that the battery charges completely in 5400 seconds. The battery as one part of energy storage is studied by [10,11] that have undertaken research on the correlation between SOC and battery charger time. The condition of SOC is altered from 20% to 70%, and the relationship is modelled using MATLAB software. The outcome demonstrates that a battery needs less time to reach full charge the higher its SOC.

The battery charger system requires a DC-DC converter, whose input voltage can originate from a DC voltage source that has been rectified from an AC voltage source or a DC voltage source from a PV module. In a battery charger system, a DC-DC converter's goal is to maintain the needed output voltage, which serves as the battery charger's input voltage. In the battery charger system, [12-14] a boost converter and buck converter integrated by PV module are used. In mathematical modelling, the electrical parameters (inductance, capacitance, and resistance) are modelled and calculated to give the necessary values for the appropriate design. The main objective of this system is to capture the maximum poser of PV module using perturb and observe (P&O) algorithm. This algorithm creates a decision to the multiplication of input voltage and current of PV module as its input power to obtain a maximum power point of PV module. In MATLAB, the circuits are modelled and simulated. The findings demonstrate that the circuits are appropriate for use in battery charger systems. Voltage ripple, current ripple, and power ripple are present initially, but they will disappear over time and their levels will stabilize.

The employment of PV modules in wireless photovoltaic power transfer (WPVPT) systems with integrated DC-DC converters for battery charger systems is discussed in this paper. Using MATLAB SIMULINK, models of the PV module, WPVPT system, DC-DC converter, and battery are created. To determine the mutual inductance of the distance between the transmitting and receiving coils in the WPVPT system, a mathematical model is used. The WPVPT system's PV module serves as the DC voltage source, and an inverter circuit converts it to AC voltage. The DC-DC converter boosts the AC voltage on the receiving coil to produce the necessary DC voltage and power for the battery charger system.

2. Methodology

The WPVPT system, which uses a DC-DC boost converter to apply a battery charger, is described in this section. This section describes the electrical specifications of the PV module, the WPVPT system idea, the necessary requirements for the DC-DC boost converter, and the battery specifications. To implement the entire system, MATLAB SIMULINK is used to model each component.

A flowchart of the research technique is shown in Figure 1. When modelling the PV module with MATLAB SIMULINK, the electrical parameters must be entered. Finding the inductance values of the transmitting and receiving coils is necessary for the WPVPT system in order to establish a matching frequency between the coils. A DC-DC converter specification is created for use in the battery charging system.

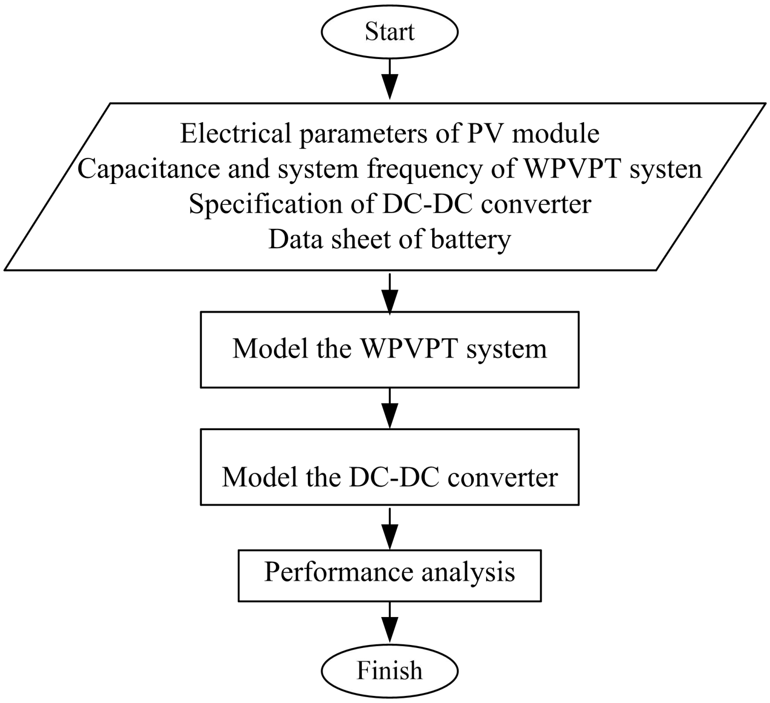


Fig. 1. Flowchart for the research process

2.1 Modelling of WPVPT System

The four basic parts of the WPVPT system are the PV module's DC voltage source, the inverter circuit, the transmitting circuit, and the receiving circuit. The PV module is used as a DC voltage source and has electrical characteristics that are listed in Table 1; this DC voltage source is then converted to an AC voltage source on the transmitting coil by the inverter circuit. According to designs by [15] and [16], the transmitting and receiving circuits each have a solenoid coil with the necessary number of turns to produce the desired inductance and frequency.

Table 1
PV module electrical specifications

Parameters	Value
Pmax, or maximum power, in watts	250
Amperes of short circuit current, I_{sc}	8.75
Voltage of an open circuit, V_{oc} in volt	38
Maximum power point voltage, V_{mp} in volt	30.3
Maximum power point current, I_{mp} in ampere	8.26
Temperature coefficient of V_{oc} in %/deg.C	-0.31
Temperature coefficient of I_{sc} in %/deg.C	0.05
Cell per module	60

According to Eq. (1) [15], the WPVPT system is made to transmit AC power over a distance, d_{tr}, from the transmitting coil to the receiving coil. It is made to achieve the needed output voltage level of a DC-DC converter across a distance of about 10 m. In order to produce the desired voltage, 35 PV modules are connected in series.

$$M_{tr} = \frac{\pi\mu_0 {N_t}^2 r_t^2 r_r^2 k}{\sqrt{\left(d_{tr}^2 + r_r^2\right)^3}} \tag{1}$$

The mutual inductance between the transmitting and receiving coils, M_{tr}, is influenced by the distance between the transmitting and receiving coils, d_{tr}, according to Eq. (1). It is also influenced by the coil's N_t turn count, r_t transmit coil radius, and r_r receive coil radius. The air permeability in this instance is 4 x 10-7 H.m^{-1}, and the constant value of k ranges from 0.0004 to 0.001.

The ability of magnetic flux creation to reach the receiving coil is impacted by the AC voltage, e_t produced by the transmitting coil. Eq. (2) demonstrates the relationship between the magnetic flux and the peak value of AC voltage.

$$\Phi_t = \frac{1}{Nt}\int e_t dt$$
(2)

2.2 Modelling of DC-DC Converter

Because it will be used in a battery charger system, the WPVPT system's receiving coil's AC voltage needs to be converted back to a DC voltage source via a rectifier circuit. It is suggested that the system charge a 12 V battery. To boost and stabilize the battery's DC input voltage, a DC-DC converter is therefore required.

The output voltage of the rectifier is 9.6 V (resulting from rectified AC voltage on the receiving coil), which is increased by the DC-DC converter to 14. 7 V (appropriate for battery charger systems operating at 12 V) [17]. This indicates that the DC-DC converter is built with a 50 W output power and input and output voltages of 9.6 V and 14. 7 V, respectively. Following the formulation in [17], the DC-DC converter is created for the frequency of 25 kHz and its suitable inductance and capacitance values.

2.3 Modelling of WPVPT System Based on DC-DC Converter

The WPVPT system is modelled in Figure 2 using a DC-DC converter to charge the battery. The WPVPT system, rectifier, DC-DC converter, and battery make up the entire system. The primary purpose of the WPVPT system is to communicate the AC voltage created by the PV module's DC voltage conversion to the receiving coil. The rectifier circuit should convert the AC voltage into a DC voltage source, and the DC-DC converter should increase it to the necessary DC voltage level to charge a 12 V battery system.

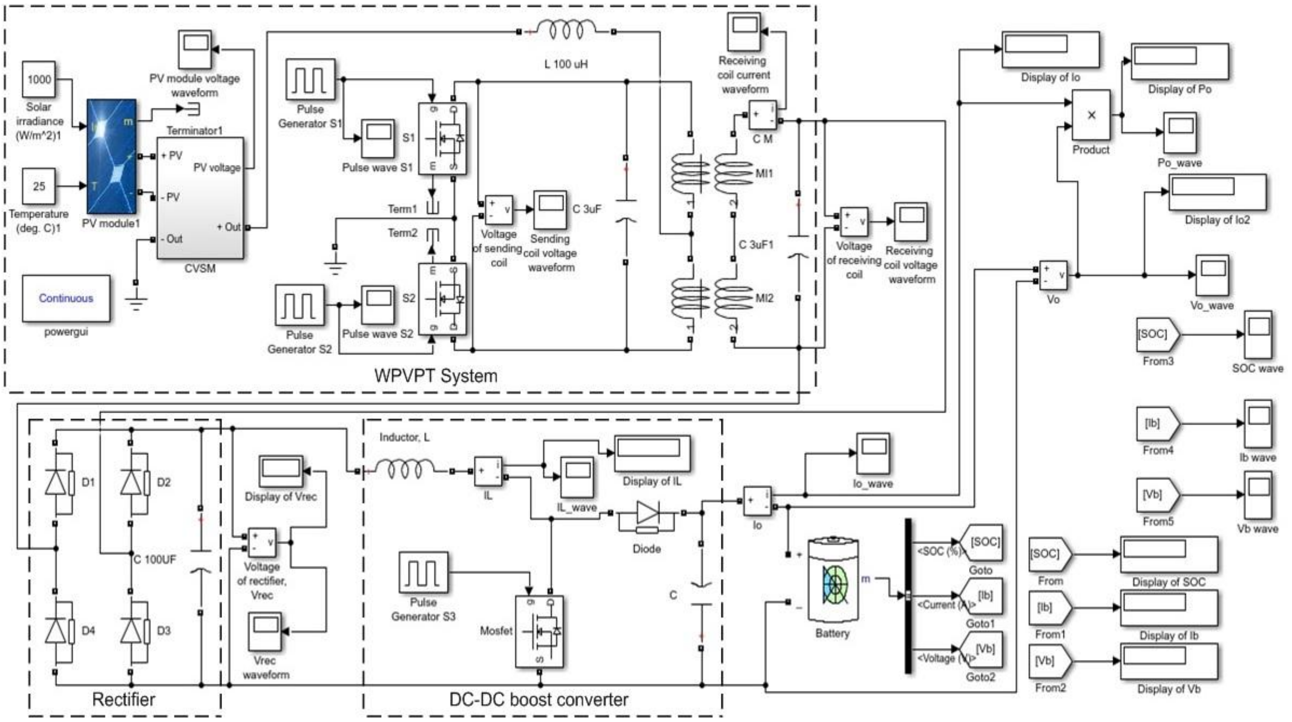


Fig. 2. DC-DC converter-based WPVPT system for use with a battery charger system

3. Results

The findings from the simulation of a WPVPT system based on a DC-DC converter for charging the battery using MATLAB SIMULINK are covered in this section. For 1 and 35 PV modules, the DC voltages of the PV module and the AC voltage waveform on the transmitting and receiving coil are addressed. When a DC-DC converter is connected to a battery, its input voltage, output voltage, output current, and output power are all addressed along with how well it performs. In this section, the battery's charging voltage, current, and state of charge are also discussed.

3.1 Performance of WPVPT System

Upon standard test (for solar irradiance of 1000 W/m2 and surface temperature of 25 ^{o}C), the WPVPT system is supplied by DC voltage of PV module with its open circuit voltage of 38 V. This voltage serves as the transmitting coil's input voltage. Its positive terminal is connected to the coil's centre tap, and its negative terminal is connected to the inverter circuit's ground. The primary goal of the connection is to use a half bridge inverter circuit, as shown in Figure 2, to transform the DC voltage of the PV module into an AC voltage waveform on the transmitting coil.

According to Figure 3(a), the voltage drop from the open circuit voltage of 38 V (38 V to 37.54 V) is 0.46 V, or -1.2 percent of the open circuit voltage (the negative sign is indicated as a decreasing of voltage). Voltage drop percentages are still categorized according to a minimum requirement of 5% [18]. The WPVPT system can be operated with a stable DC input voltage of 37.54 V.

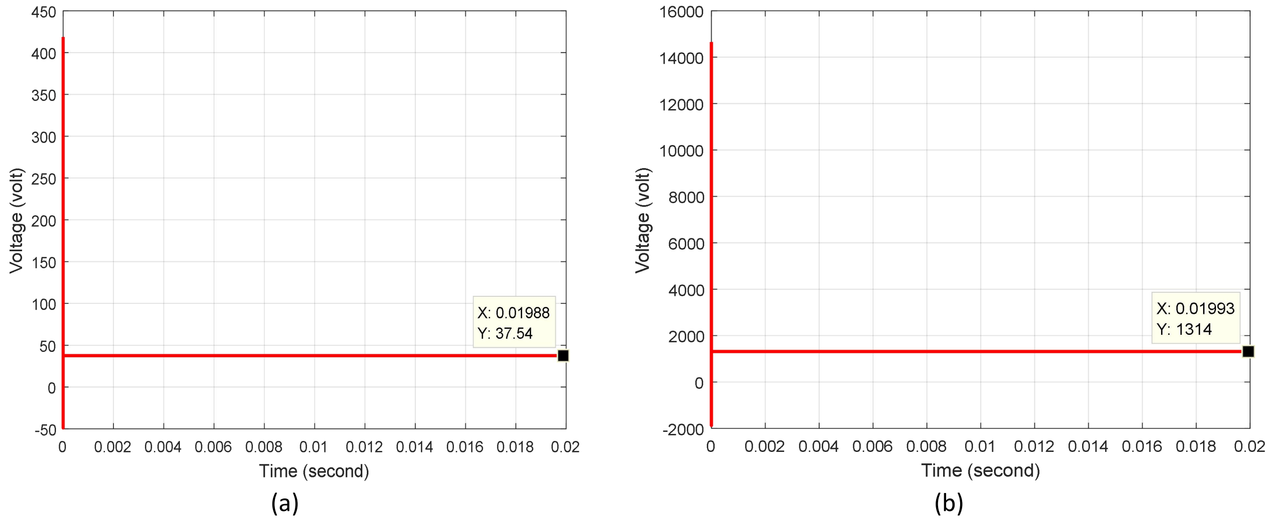


Fig. 3. Output voltage of PV module (a) 1 PV module (b) 35 PV modules in series connection

Despite being steady enough to power the WPVPT system, the output voltage of 37.54 V is still insufficient to power the DC-DC converter. Due to the fact that the receiving coil's AC voltage is lower than the transmitting coil's, the DC voltage of the PV module will be converted to AC on the transmitting coil and transferred there. Additionally, the receiving coil's active power, in particular, is lower than the transmitting coil's in terms of AC power. In order to boost the DC output voltage of the PV module, 35 PV modules should be connected in series.

The DC output voltage of 35 PV modules connected in series is shown in Figure 3(b). The WPVPT system's DC input voltage is 1314 V; precisely, it will be transformed to AC voltage on its transmitting coil with a magnitude that is nearly identical to the DC voltage. The primary goal of raising the DC and AC voltage is to also raise the magnetic flux produced on the coil. As a result, it can generate the required level of AC voltage on the receiving coil and then return to be converted to DC voltage by a rectifier as the DC input of a DC-DC converter to achieve its required level of DC output voltage as requirement of DC voltage level for charging a 12 V battery.

Figure 4 shows the AC voltage waveform for one PV module on the WPVPT system's transmitting and receiving coil (its output DC voltage of 37.54 V). The transmitting coil converts the DC output voltage to AC voltage, having a peak voltage of 24.62 V. The reason there is a difference in voltage between the output DC voltage and peak voltage value is because, as illustrated in Figure 2, an inverter circuit switching operation takes place at a system frequency of 5 kHz. Indicating a voltage drop on the switching component during the switching operation is another thing it shows.

Figure 4 shows the voltage waveform on the transmitting coil for one period or cycle at a time between 0.008301 s and 0.008501 s, which corresponds to the system frequency of 5 kHz. It implies that the system frequency of 5 kHz corresponds to the period of 0.0002 s. The AC voltage waveform on the transmitting coil and the AC voltage waveform on the receiving coil have the same system frequency of 5 kHz. It might happen because a frequency matching is created by connecting each connection of a coil's inductance and a capacitor's capacitance in parallel.

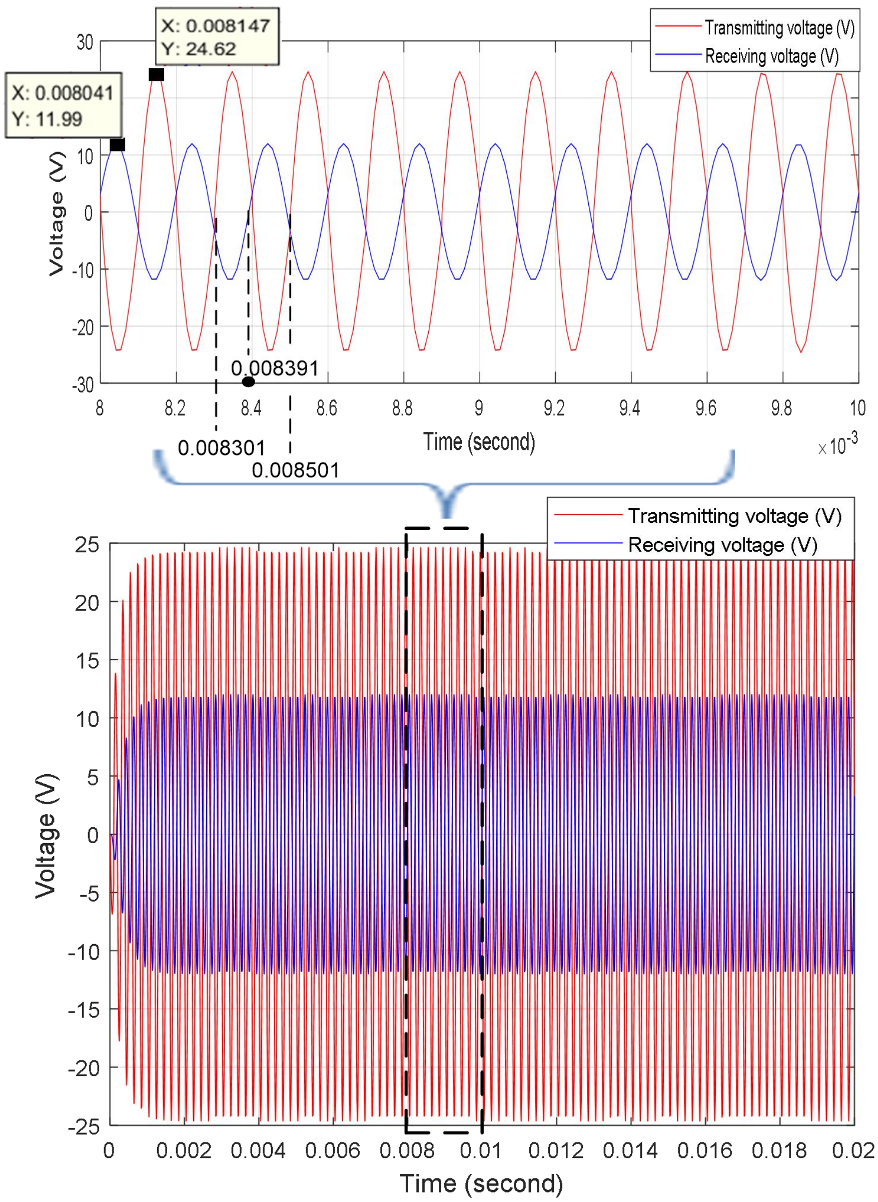


Fig. 4. Waveform of the transmitting and receiving coil's AC voltage

The transmitting coil's peak voltage of 24.62 V has an impact on the creation of magnetic flux according to Eq. (2). When it reaches the receiving coil, which is 10 m away from the transmitting coil, an AC voltage with a peak value of 11.99 V will be produced on the coil, as illustrated in Figure 4. Because air (and not a wire) serves as the transmission medium between the transmitting and receiving coils, the peak voltage value on the receiving coil is lower than the peak voltage value on the receiving coil. As a result, the peak voltage value on the receiving coil entirely depends on the capacity of magnetic flux produced on the transmitting coil.

One cycle of the two voltage waveforms is attained in 0.0002 seconds, or 360^{o}. Based on the timing of voltage waveforms in Figure 4 for the AC voltage waveform on the transmitting coil reaching a positive value at 0.008301 s and the AC voltage waveform on the receiving coil reaching a positive value at 0.008391 s. The time difference between the transmitting and receiving coils' AC voltage waveforms reaching a positive value is approximately 0.00009 seconds. It shows that the AC voltage waveform on the transmitting and receiving coils are 162^{o} out of phase with one another.

Additionally, it can be said that the transmitting coil's AC voltage waveform lags the receiving coil's by 162^o.

As shown in Figure 5, the transmitting coil is connected to the capacitor in parallel while an AC voltage of 24.62 V is generated on the coil. As a result, an AC current of 1.664 A flows through the coil. The AC voltage waveform on the sending coil is obtained at the time of 0.008301 s, while the AC current waveform flows through the transmitting coil at the time of 0.008347 s, with a time difference of about 0.000046 s. This observation can be used to determine the phase difference (there is phase difference of 82.8^o). It indicates that the AC voltage waveform leads the AC current waveform by 82.8^o. The transmitting coil produces 2.57 W of active power, 20.32 VAR of reactive power, and 20.48 VA of apparent power as a result. Compared to the DC power of a PV module, it has a very low power.

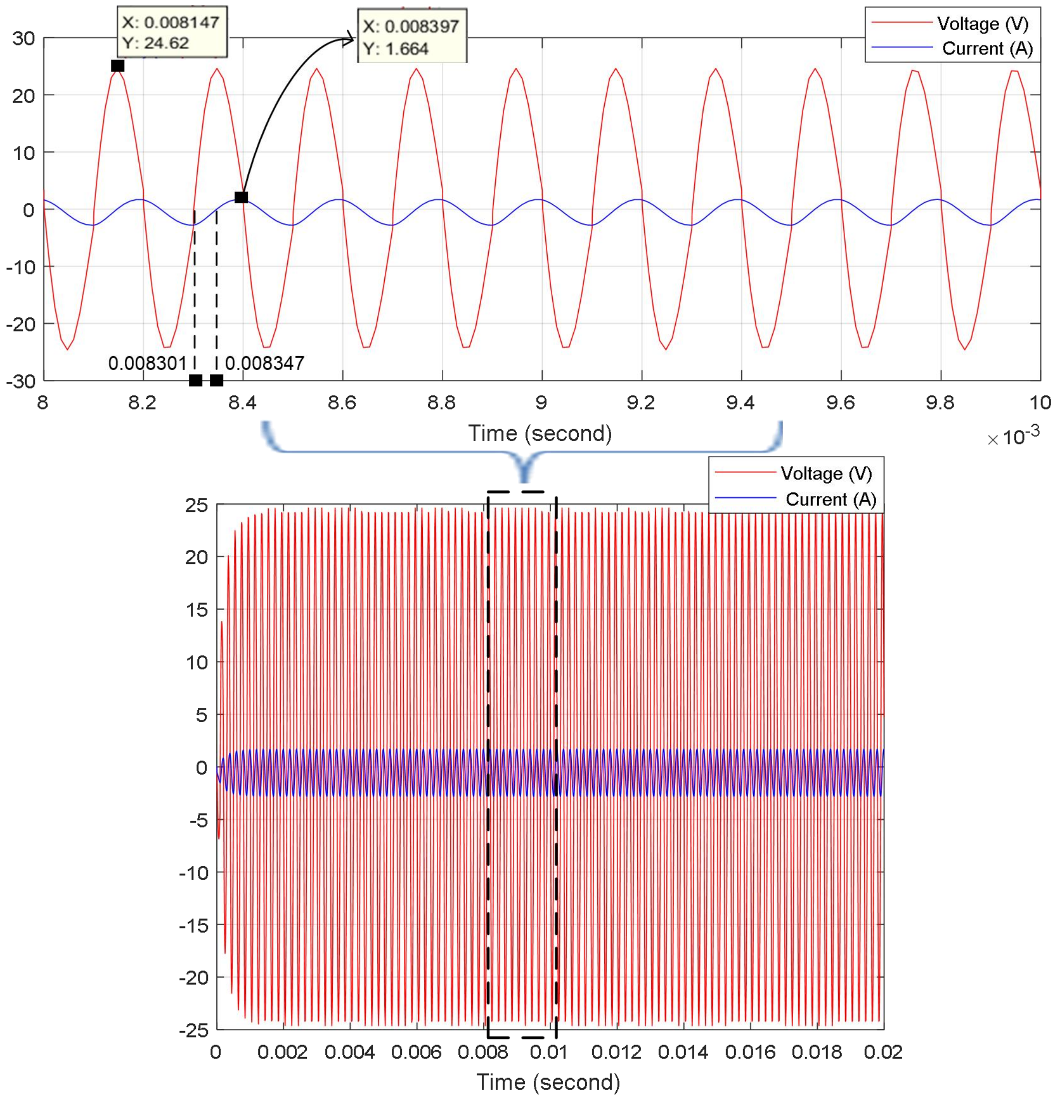


Fig. 5. Waveforms of AC voltage and current on the transmitting coil

Based on Figure 6, it can be deduced that there is a phase difference between the AC voltage and current waveforms as well. If the receiving coil's AC voltage waveform reaches a positive value at 0.008191 seconds and the receiving coil's AC current waveform reaches a positive value at 0.008347 seconds, there is a time discrepancy of about 0.000156 seconds (there is phase difference of 280.8^o). It shows that the AC voltage waveform is 280.8^o leads the AC current waveform.

The receiving coil serves as a power storage device that holds both active and reactive as well as apparent power. It is possible to analyse that the active, reactive, and apparent power are 1.24 W, 6.51 VAR, and 6.63 VA, respectively, based on Figure 6 and the phase difference of 280.8°. The WPVPT system has a 48.25% efficiency when the active powers on the transmitting and receiving coils are compared.

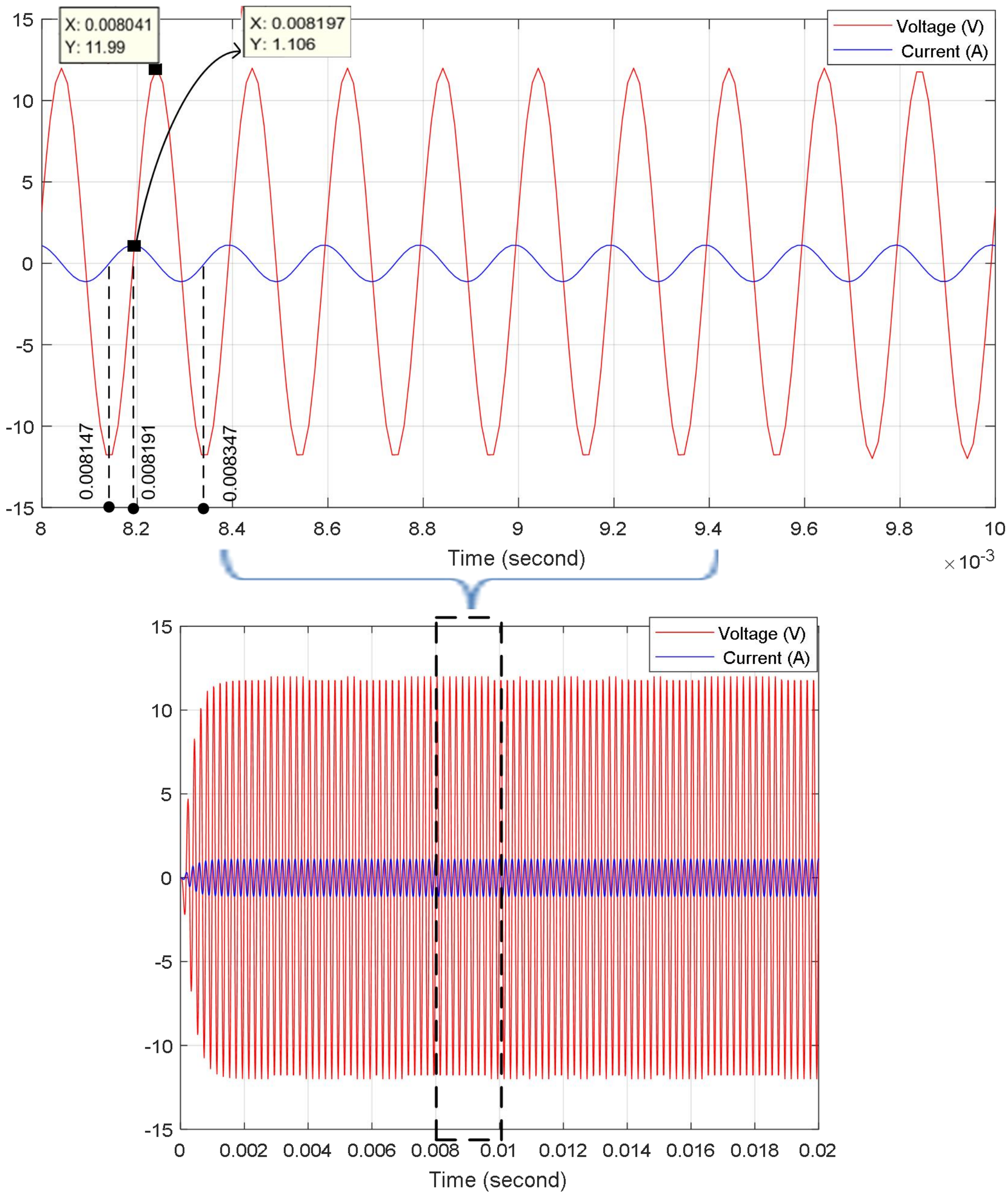
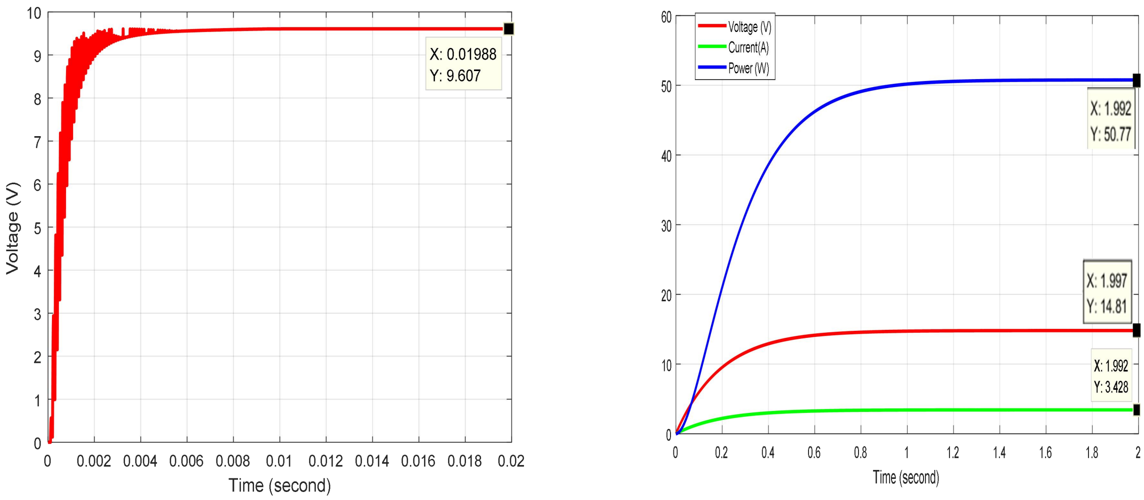


Fig. 6. AC voltage and current waveform on the receiving coil

3.2 Performance of DC-DC Converter and Battery Charger System

The WPVPT system's primary function is to recharge the battery. Therefore, a rectifier circuit should be used to correct the AC voltage on the receiving coil. The AC voltage on the receiving coil was rectified, resulting in the rectifier's output voltage of 9.607 V as illustrated in Figure 7(a). Because it serves as the input voltage for a DC-DC converter that must be increased to 14.7 V, it is always at a constant value of roughly 9.607 V for charging the battery (this voltage is suitable for charging 12 V battery system). The DC-DC converter is also built to have a 50 W output power.

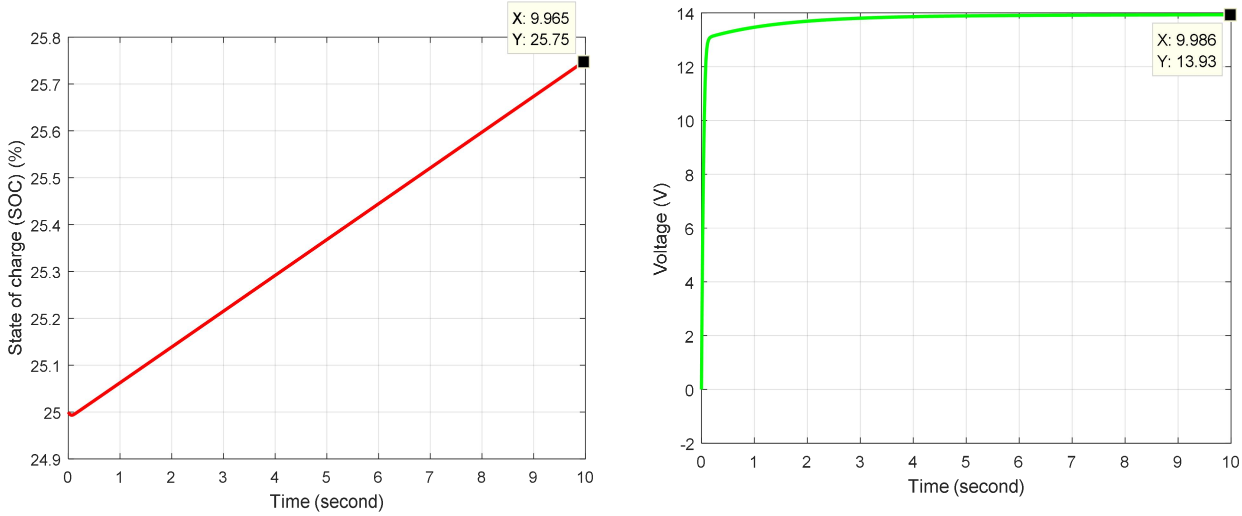


(a) (b)

Fig. 7. Performance of DC-DC converter (a) Output voltage of rectifier (b) Output voltage, current and power of DC-DC converter

To meet the demands of the DC-DC converter design, the inductor, capacitor, and load resistor values are 4.48×10^{-4} H, 4.76×10^{-2} F, and 4.32 Ω. The DC-DC converter's output voltage is 14.81 V, according to the simulation findings displayed in Figure 7(b). Although it exceeds the required output voltage of 14.7 V, its error percentage of 0.75% still falls within a tolerable range [19]. Figure 7 illustrates how the output power is 50.77 W when 14.81 A of current flows through the load resistor (b). Additionally, the output power exceeds the required power design, although its error percentage of 1.54% is still within acceptable bounds.

The 12 V, 1.2 Ah battery is charged by a DC-DC converter. Referring to Figure 8(a), the battery voltage is 13.93 V, and the initial charging condition of the battery, or state of charge (SOC) (percentage of entirely depleted battery), is 25% (11.85 V) of the fully charging condition of 13.06 V [17] (refer Figure 8 (b)). The battery receives a 10 second charge, reaching its SOC of 25.75%. According to this, a SOC of 0.75% is required in 10 seconds, and a SOC of 1% is required in 13.33 seconds. To attain the fully charged condition, it takes 1000 seconds and a SOC range of 75% (SOC of 25% to 100%).



(a) (b)

Fig. 8. Performance of battery (a) State of charge (SOC) (b) Battery voltage

4. Conclusions

In a DC-DC converter, the WPVPT system is used to implement a battery charger system. The WPVPT system is made up of an inverter circuit, a PV module operating as a source of DC voltage, and transmitting and receiving circuits. The DC-DC converter is intended to charge a 12 V, 1.2 Ah battery with an output voltage of 14.7 V and an input voltage of 9.607 V.

For a distance of 10 m from the transmitting coil, the active power on the receiving coil of the WPVPT system is 1.24 W. 35 PV modules to be connected together in series to generate the required output power of a DC-DC converter, which is just a low active power of 50 W.

The DC-DC converter's output voltage of 14.81 V and output power of 50.77 W are suitable for use with the battery charging system. The battery system's performance demonstrates that it can be charged for a full 1000 seconds when in the fully charged state.

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