Efficiency improvement of 50 Hz wireless photovoltaic power transfer using magnetic relay

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ABSTRACT

A photovoltaic direct current (DC) power can be changed into AC power using an inverter. The inverter must be connected to an alternating current (AC) load using wire, which has drawbacks in terms of air space, wire cost, and an unattractive view of the sky. It is appropriate to suggest a wireless power transfer (WPT) system concept to replace the use of wires in the transfer of electrical power. The WPT system has been conducted by the previous researchers, but it is still in the frequency system of hundred, kilo, mega or gigahertz, thus it can only be applied on DC load after rectifying it, but cannot be applied for a normal AC load, also its distance is relative near. The modelling of wireless photovoltaic power transfer (WPVPT) with a 50 Hz system frequency is presented in this work. The four modelling components that create the WPVPT system are models of the PV module, the transmitter circuit, the magnetic relay, and the receiver circuit. The findings indicate that the efficiency of the proposed WPVPT system is 71.27% without a magnetic relay and 72.82% with a magnetic relay. It suggests that the use of magnetic relay can improve the WPVPT system's efficiency.

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1. INTRODUCTION

The use of renewable energy, particularly photovoltaic (PV) modules, it has a significant impact on the global use of electrical energy. The inability of conventional energy sources to meet the demand for electricity is to blame that it should be solved. Therefore, it is crucial to treat the photovoltaic module as a direct current (DC) electrical power source [1]. In terms of the quantity of necessary solar irradiation, it is tied to a geographic area. It is caused by the fact that different parts of the world receive varying amounts of solar radiation [2]. It also depends on the angle formed by a point's latitude and longitude on the earth's surface.

Based on the photovoltaic effect, which is the voltage produced by the semiconductor materials in the anode and cathode when sunlight strikes their surfaces, a PV module is a semiconductor device that transforms solar energy into electrical energy [3], [4]. Amorphous silicon (a-Si), silicon (Si), or germanium

(Ge) can all be used as semiconductor materials. The semiconductor material, which possesses photon energy to transport the electron from its atomic structure, observes the sunlight as it approaches the surface. A semiconductor's n-type and p-type regions, respectively, are those containing free electrons and holes. The semiconductor material's n-type and p-type junction serves as the new location for the electron. It makes the PV module's n-type and p-type terminals the negative and positive terminals. If a load is connected to both terminals, current will flow from the positive terminal of the PV module to the negative terminal [5].

The direct current (DC) and alternating current (AC) electrical power have both been used with the PV module. Using a solar charger, a battery may store the DC electrical energy of a PV module throughout the day so that it can be used to power DC loads. Massaq *et al.* [6] discusses a mathematical model of a PV module that powers a DC pump. The model introduces the idea of maximum power point tracking so that the PV module can capture the most solar irradiation and produce the most power. To regulate the speed of the DC pump, a fuzzy logic controller integrates modelling. The modelling helps enhance the DC pump system's transient response.

A PV module's DC power must be converted to AC power using an inverter to provide AC loads. [7]–[10] introduces the use of a PV module to power the inverter. It is a single-phase multi-level inverter that requires a PV module to produce a voltage waveform with multiple levels. To create the waveform, a cascaded full bridge inverter circuit is used. To connect the output inverter to the AC loads, wire is still required. Additionally, inverters are used in wireless power transfer (WPT), which eliminates the need for wires when transmitting power from the transmitter coil to the receiver coil.

Based on the fundamental idea of electromagnetic induction, the WPT system uses two coils separated by the necessary amount of space and an air gap to work. The transmitter coil will generate an electromagnetic field because the first coil is connected to an AC voltage source; the strength of this field relies on the amount of current flowing through the transmitter coil. They are inversely proportional, therefore if a lot of current passes through the transmitter coil, a lot of electromagnetic energy will likewise be generated on the transmitter coil. The electromagnetic flux that arrives at the receiving coil can travel a distance depending on the electromagnetic field's strength. Due to the electromagnetic flux connecting the receiving coil, a voltage will be induced on the receiving coil. The distance between the two coils will affect the mutual inductance, M, that is created between them [11]. Based on the following explanation of the electric energy generating concept, the WPT system may be divided into two categories [12], [13]. They are magnetic resonant coupling wireless power transfer (MRC-WPT), which operates on the principle that a high frequency power supply generates the output of high frequency alternating current through a transmitter coil, and electromagnetic induced wireless power transfer (EI-WPT), which is based on the idea that when current flows through a transmitter coil, a magnetic field is generated by the transmitter coil and it induces an electromotive force or an induced voltage [14], [15].

Batteries or renewable energy sources (fuel cell, wind power or photovoltaic) can serve as the DC voltage source for WPT. Temperature and solar radiation both affect photovoltaic performance. The performance of photovoltaic systems increases along with an increase in solar radiation, but this relationship is inversely correlated with temperature (a rise in temperature will result in a fall in photovoltaic performance) [16], [17]. To determine whether a location is suitable for developing a photovoltaic system or not, it is crucial to study the solar radiation requirements (250 W/m^2 or 3000 Wh/m^2 above) [18].

Okoyeigbo *et al.* [19] reviews WPT system in term of its operation principle and application. The concept of inductive coupling and resonant coupling with a frequency of 5.8 GHz which it is applied in the electrical vehicle. A method of multi-input multi-output (MIMO) is applied to increase the power of WPT system. The system is still in near far and low efficiency. The development of spiral coil of WPT system using genetic algorithm (GA) is applied by Konghirun *et al.* [20] to reduce the length of coil and improve the efficiency for the system frequency of 85 kHz. The transmitter and receiver coil are positioned in the distance of 80 mm.

A technique of hexagonal coil on the WPT system is applied in the electrical vehicle [21], [22] to increase its efficiency for misalignment conditions. It uses a 555 timer to generate the pulse wave and to drive the switching component on the inverter of WPT system. It is due to that it is constructed by coils with diameter of 15 cm, thus this WPT system has a near distance to transmit the electrical energy from the transmitter and receiver coils, also it can only increase its efficiency of 10%.

The previous research of WPT system is still in the frequency system of hundred, kilo, mega or gigahertz, thus it can only be applied on DC load after rectifying it, but cannot be applied for a normal AC load. Also, its efficiency is low and has a near transferring distance. In order to directly operate 50 Hz AC loads, a wireless photovoltaic power transfer (WPVPT) with a system frequency of 50 Hz is presented in this paper. MATLAB Simulink is used for its design and simulation. A magnetic relay model for the WPVPT system is suggested in order to increase the AC power on the receiving coil and increase its efficiency.

2. METHOD

This section explains a way for comparing a WPVPT system with and without a magnetic relay for coil distances that are the same. Utilizing MATLAB Simulink and a mathematical formulation, the WPVPT is modelled. The PV module, transmitter circuit, magnetic relay, and receiver circuit are the four models that create this system. To determine the power efficiency that is transferred from one part to the other, each component of the modelling is examined in terms of each power.

2.1. Modeling of the WPVPT system's PV module, transmitter, and receiver circuit without a magnetic relay

In this case, the PV module with its data sheet in Table 1 is modelled to produce 240 V of DC output voltage. The center taps of the transmitter coil and the half bridge circuit, respectively, are linked to the positive and negative terminals of the PV module. The simulation results and the PV module data sheet verify the PV module's performance in terms of the current versus voltage curve and the power versus voltage curve. The validation is carried out at a solar irradiation of 1000 W/m^2 and a temperature of 25 °C, and it is based on an error percentage, where the simulation result is legitimate if the error percentage is in the range of 10% [23].

Table 1. Data sheet for PV module

Parameter	Value
Maximum power in watt (W)	75.08
Open circuit voltage in volt (V)	21.5
Voltage at maximum power in volt (V)	17.5
Short circuit in ampere (A)	4.91
Current at maximum power in ampere (A)	4.29

The WPVPT system proposes a system frequency of 50 Hz; therefore, a frequency matching that is formed on the transmitter coil should be taken into consideration. The capacitance of the capacitor, *C*, is coupled with the inductance of the transmitter, magnetic relay, and receiver coils, *L*. According to the following equation, the system frequency, *f*, the capacitance of the capacitor, *C*, and the inductance of the transmitter, magnetic relay, and receiver coil, *L*, are all related (1). Since the capacitance of the capacitor, *C*, is chosen first in this instance, the value of the inductance, *L*, may be calculated by utilizing (1).

$$L = \frac{1}{4\pi^2 f^2 C} \tag{1}$$

Figure 1 shows a proposed circuit and modelling of WPVPT system without a magnetic relay. Figure 1(a) depicts the transmitter and receiver circuit. A half bridge circuit and a pulse driver circuit make up the transmitter circuit. Two high power switching components, S1 and S2, are used to build the half bridge circuit on MATLAB Simulink as shown in Figure 1(b). These components have a high capacity to apply DC voltage from the PV module voltage. Pulse waves with a system frequency of 50 Hz are generated by the pulse driver circuit or pulse generator on MATLAB Simulink and are used to drive the two high power switching components. A receiver coil and capacitor make up the receiver circuit. The capacitance of the capacitor, *C*, and the inductance of the receiver coil, *L*, should be set at values that correspond to the 50 Hz system frequency.

Figure 1 depicts the overall modelling of the WPVPT system without a magnetic relay. It includes measurements of the voltage and current of the PV modules, the voltage and current of the transmitter coil, and the voltage and current of the receiver coil for the purpose of displaying their root mean square (rms) values and waveforms. The inductance values for the transmitter and reception coils are provided by (2) and (3), respectively.

$$L_{t1} = L_{t2} = 0.5\, L \tag{2}$$

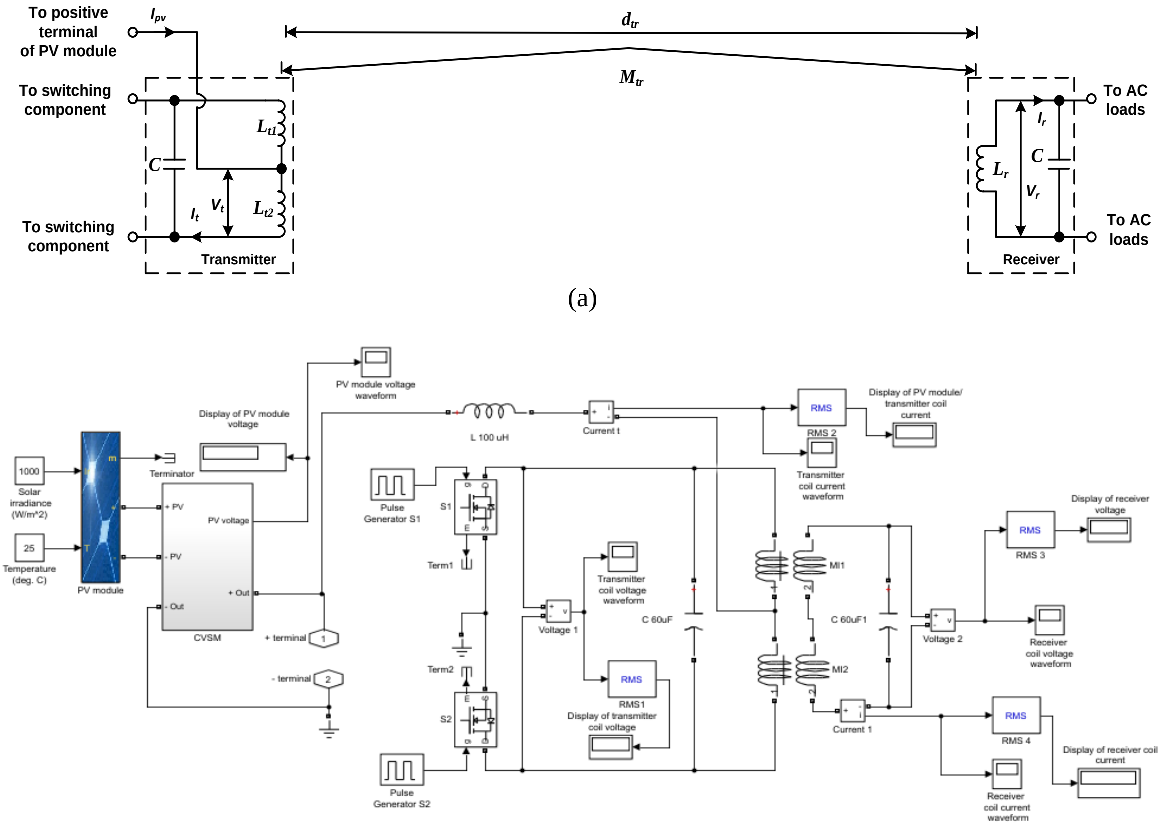
where L_{t1} = inductance of transmitter coil for part 1 and L_{t2} = inductance of transmitter coil for part 2.

The inductance of receiver coil, L_r is given by (3).

$$L_r = L \tag{3}$$

The distance, d_{tr}, between the transmitter and receiver coils produces a mutual inductance, M_{tr}. If the transmitter and receiver coils are separated by air with a permeability of $\mu_0 = 4\times10^{-7}$ H.m^{-1} and the turn number of the transmitter coil, N_t, the turn number of the receiver coil, N_r, the radius of the transmitter coil, r_t, and the radius of the receiver coil, r_r, the mutual inductance, M_{tr}, is given by (4). The mutual inductance value depends on and is inversely proportional to the distance between the transmitter and receiver coils since the values of turn number and radius of the transmitter and receiver coils are fixed.

$$M_{tr} = \frac{\pi\mu_0 N_t N_r r_t^2 r_r^2 x10^{-2}}{\sqrt{(d_{tr}^2+r_r^2)^3}} \quad (4)$$



(a)

(b)

Figure 1. Overall proposed modelling of WPVPT system without a magnetic relay (a) proposed circuit and (b) MATLAB Simulink

2.2. Proposed modelling of magnetic relay

A proposed circuit and modelling of WPVPT system with a magnetic relay is shown in Figure 2(a) and 2(b). The inductance, L, of the transmitter, magnetic relay, and receiver coil is the same. The center tap of the division between the two identical halves of the transmitter coil serves as the division terminal point, and it is connected to the positive terminal of the PV module. On the right and left sides of the capacitor, C, the inductance, L, are divided into equal halves. It holds true for every coil of a magnetic relay.

The physical characteristics of the transmitter, magnetic relay, and receiver coil are identical. The N_t, N_m, and N_r turns for the transmitter, magnetic relay, and receiver coils, respectively, are all the same. Each coil's radius, r_t, r_m, and r_r, stands for transmitter, magnetic relay, and receiver, respectively. Only the distance between the two coils affects their mutual inductance. The mutual inductance, M_{tm}, between the transmitter and magnetic relay coil is determined by the distance, d_{tm}, between the two coils and given by (5). Given the distance between the magnetic relay and receiver coil, d_{mr}, the mutual inductance between the two coils is M_{mr} and given by (6).

$$M_{tm} = \frac{\pi\mu_0 \, N_t \, N_m \; r_t^2 \, r_m^2}{8\sqrt{(d_{tm}^2+r_{tm}^2)^3}} \quad (5)$$

$$M_{mr} = \frac{\pi\mu_0 \, N_r \, N_m \, r_r^2 r_m^2}{8\sqrt{(d_{tm}^2+r_{tm}^2)^3}} \tag{6}$$

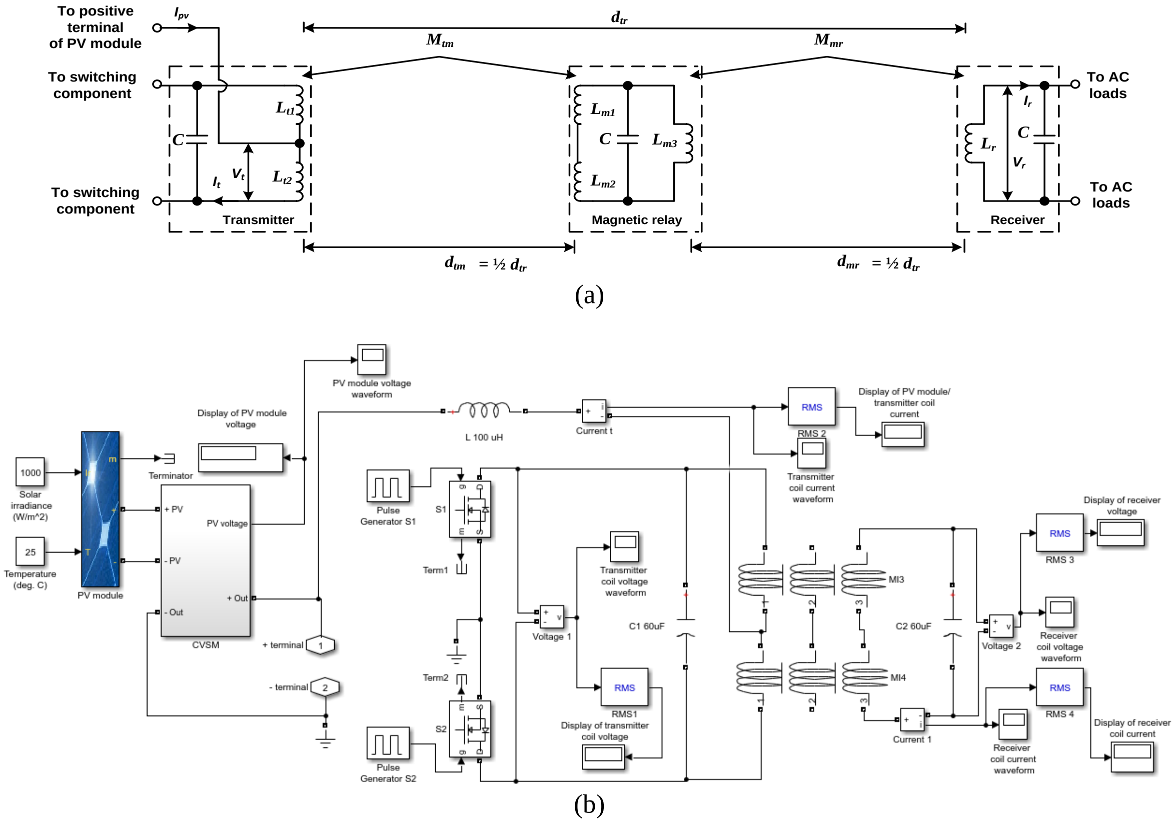


Figure 2. Overall proposed modelling of WPVPT system with a magnetic relay (a) proposed circuit and (b) MATLAB Simulink

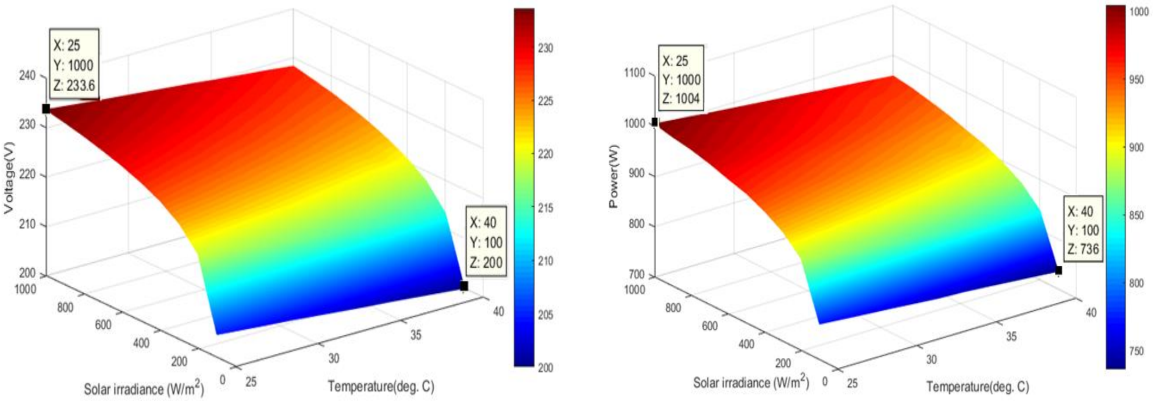
3. RESULT AND DISCUSSION

On the transmitter, magnetic relay, and receiver coil, a 50 Hz frequency matching is produced. To achieve the system frequency of 50 Hz, the capacitor capacitance of 60 µF is coupled to each transmitter, magnetic relay, and receiver coil with each coil inductance of 0.17 H (see to (1)). To achieve the required system frequency of 50 Hz, the capacitor capacitance of 60 µF and the coil inductance of 0.17 H for the transmitter, magnetic relay, and receiver coil are utilized. On the WPVPT system's transmitter, magnetic relay, and receiver coil, a 50 Hz AC voltage waveform is produced. It is the end result of the inverter circuit converting the DC voltage waveform of the PV module to an AC voltage waveform.

3.1. Performance of PV module

The PV module is simulated for a 1000 W/m^2 solar irradiance and 25 °C temperature (these values are from the standard test condition (STC) provided by the PV module's factory fabrication for listing the data sheet in Table 1). The PV module voltage, current, and power are influenced by the temperature in °C and the solar irradiation in W/m^2 [24], [25]. With rising solar irradiation and constant temperature, as illustrated in Figure 3, the PV module voltage rises. The PV module voltage will fall in the opposite direction with rising temperatures and constant solar irradiation. The solar irradiation of 1000 W/m^2 and temperature of 25 °C result in the highest PV module voltage of 233.6 V, as illustrated in Figure 3(a). The solar irradiation of 100 W/m^2 and temperature of 40 °C result in the lowest PV module voltage of 200 V, as illustrated in Figure 3(a).

In addition to increasing the power produced by the PV module as shown in Figure 3(b), a greater PV module voltage also increases the AC power produced by the WPVPT system's transmitter and receiver coils. A lower PV module voltage, on the other hand, will result in a lower PV module power, as well as a lower AC power on the transmitter and receiver coils of the WPVPT system. It is because the inverter circuit directly converts the voltage level of the PV module into the AC voltage level on the transmitter coil, and the PV module current flows via the transmitter coil and they have a proportional relationship. Additionally, it results from the fact that the electromagnetic field produced by the transmitter coil increases according to the amount of current flowing through it [26]. For the fixed distance between the transmitter and receiver coils of the WPVPT system, a higher electromagnetic field will result in a longer range of the electromagnetic field. As a result, a greater number of electromagnetic field flux will be captured by the receiver coil and it will produce a higher induced voltage, current, and power on the receiver coil. The solar irradiation of 1000 W/m^2 and a temperature of 25 °C provide the maximum PV module power of 1004 W, as indicated in Figure 3 (b), and the minimum PV module power of 736 W, as shown in Figure 3(b), at a solar irradiance of 100 W/m^2 and a temperature of 40 °C.



(a) (b)

Figure 3. PV module voltage and power as function of solar irradiance and temperature (a) voltage and (b) power

3.2. WPVPT system's power and efficiency without a magnetic relay

For a distance between the transmitter and receiver coil of 10 meters, the AC power on the transmitter coil is transmitted to the receiving coil. Figure 4(a) displays the AC power on the receiver coil for a range of solar irradiances from 100 to 1000 W/m^2 and a range of temperatures from 25 °C to 40 °C. The receiver coil's maximum AC power is 596.8 W, which happens at a solar irradiation of 1000 W/m^2 and a temperature of 25 °C. A solar irradiation of 400 W/m^2 and a temperature of 25 °C result in a minimum AC power of 434.7 W on the transmitter coil. There is proportional relationship between the AC power on the transmitter and receiver coil, it is that the increasing of AC power on the transmitter coil causes the increasing of AC power on the receiver coil, inversely the decreasing of AC power on the transmitter coil causes the decreasing of AC power on the receiver coil.

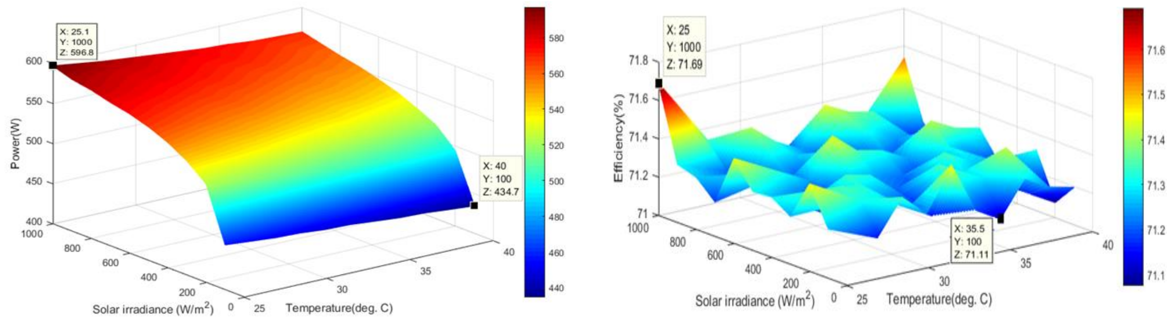
The transmitter coil transfers AC power, however there are power losses on the air material along the entire $d_{tr} = 10$ m distance between the transmitter and receiver coil. As a result, the AC power that reaches the receiver coil is less than that reaches the transmitter coil. The WPVPT system's capacity to transfer power is its electromagnetic range capability, which depends on the AC power produced by the transmitter coil. Figure 4 (b) illustrates the efficiency of the WPVPT system as a comparison of the power of the receiver and transmitter coil for a range of solar irradiation from 100 to 1000 W/m^2 and a range of temperature from 25 °C to 40 °C. The highest efficiency is 71.69% when the temperature is 25 °C and the solar irradiance is 1000 W/m^2, and the minimum efficiency is 71.11% when the temperature is 40 °C and the solar irradiance is 100 W/m^2. It demonstrates that, when comparing the power of the receiver and transmitter coils, the efficiency of the WPVPT system tends to range between 71.11% and 71.69%, or its average efficiency is 71.27%. The WPVPT system's efficiencies demonstrate that a strong electromagnetic field that is arriving at the receiver coil caused a voltage to be induced across it at a distance of 10 meters between the transmitter and reception coil.

3.3. Power and efficiency improvement of WPVPT system using a magnetic relay

The magnetic relay is positioned in the middle of the transmitter and receiver coils affects the power as shown in Figure 5(a), which also depicts the AC power on the receiver coil of the WPVPT system. Simulated conditions include solar irradiation ranging from 100 to 1000 W/m^2, temperature ranging from

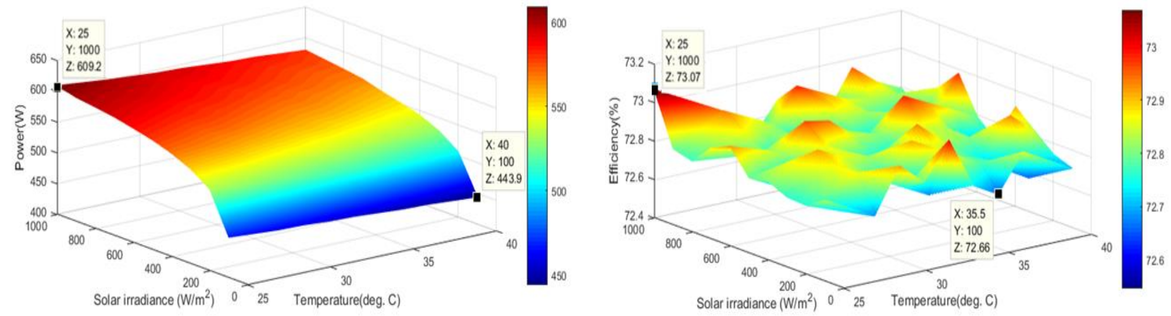
25 °C to 40 °C, and a distance between the transmitter and receiver coil of 10 m. The receiver coil with magnetic relay may generate up to 609.2 W of AC power at a solar irradiance of 1000 W/m^2 and a temperature of 25 °C, and it can generate as little as 443.9 W of AC power with a solar irradiance of 100 W/m^2 and a temperature of 40 °C. Figure 5(a) shows the maximum and minimum AC power on the receiver coil with a magnetic relay; these values are larger than those in Figure 4(a) for the receiver coil without a magnetic relay. It suggests that the magnetic relay situated in the middle of the transmitter and receiver coil can increase the quantity of electromagnetic fields reaching the receiver coil, leading to a higher induced voltage produced by the receiver coil as well as a higher current flow through the coil and, finally, a higher AC power produced by the coil.

The WPVPT system is affected by the generating AC power on the receiver coil. Figure 5(b) compares the AC power of the receiver and transmitter coils for a range of solar irradiation from 100 to 1000 W/m^2 and a range of temperature from 25 °C to 40 °C with a distance between the transmitter and receiver coils of 10 m. The WPVPT system with a magnetic relay has a maximum efficiency of 73.07%, which occurs at solar irradiances of 1000 W/m^2 and temperatures of 25 °C, and a minimum efficiency of 72.66%, which occurs at solar irradiances of 100 W/m^2 and temperatures of 35.5 °C. It is possible to state that the efficiency of a WPVPT system with a magnetic relay tends to be between 72.66% and 73.07%, or that its average efficiency is 72.82%, for solar irradiances ranging from 100 to 1000 W/m^2 and temperatures ranging from 25 °C to 40 °C with a distance between the transmitter and receiver coil of 10 m. As demonstrated in Figure 5(b), the efficiency of the WPVPT system with a magnetic relay is greater than the efficiency of the WPVPT system without a magnetic relay as indicated in Figure 4(b).



(a) (b)

Figure 4. AC power on the receiver coil and efficiency of WPVPT system for the distance between the transmitter and receiver coil, $d_{tr} = 10$ m without a magnetic relay (a) AC power and (b) efficiency

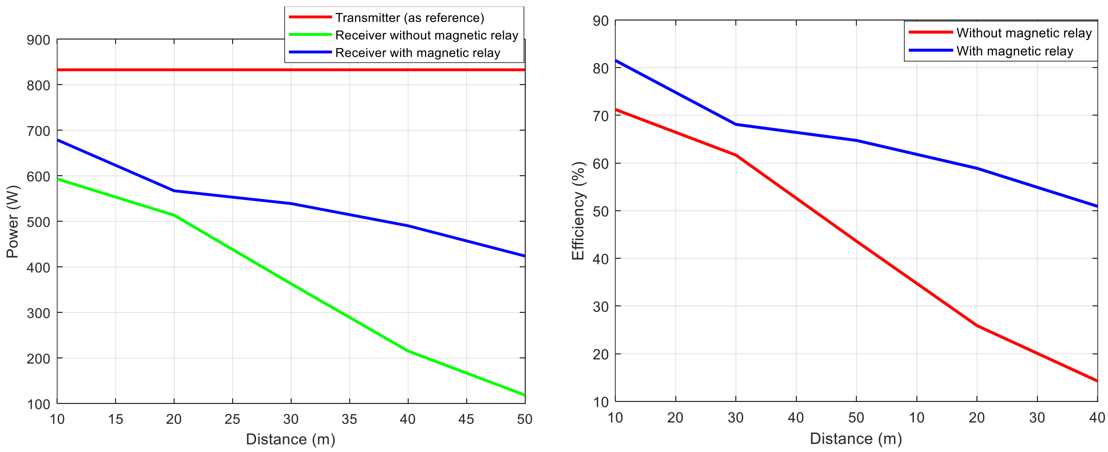


(a) (b)

Figure 5. AC power on the receiver coil and efficiency of WPVPT system with magnetic relay (a) AC power and (b) efficiency

The AC power of the transmitter and receiver coil at various distances between 10 and 50 meters is shown in Figure 6(a). Because it is powered by the same DC power of a PV module with the same solar irradiation of 1000 W/m^2 and the same temperature of 25 °C, the transmitter coil generates an AC power of 832.9 W over varying distances of 10 to 50 m. The receiver coil receives the 832.9 W of AC power from the transmitter coil. Figure 6(a) demonstrates that in a WPVPT system without a magnetic relay, a longer distance between the transmitter and receiver coil results in a lower AC power being received by the receiver coil. This is because the longer distance between the transmitter and receiver coil also results in a lower mutual inductance and a lower electromagnetic field reaching the receiver coil. However, it is demonstrated that the AC power on the receiving coil may be enhanced at each distance by placing the magnetic relay in the middle of the transmitter and receiver coil.

When comparing the AC power on the receiver and transmitter coils, the distance between the transmitter and receiver coils has an impact on the WPVPT system's efficiency. Figure 6(b) compares the efficiency of the WPVPT system with AC power on the receiver and transmitter coils at various transmitter and receiver distances between 10 and 50 m. The WPVPT system has a poorer efficiency over a longer distance as a result of the reduced AC power on the receiver coil. Additionally, it suggests that bigger power losses occur on air-based materials over longer distances. However, placing the magnetic relay in the middle of the transmitter and receiver coil demonstrates that the WPVPT system's efficiency may be increased and that it has a substantial impact over a longer distance, as illustrated in Figure 6(b).



(a) (b)

Figure 6. Power and efficiency of WPVPT system with various distance between the transmitter and receiver coil

4. CONCLUSION

It is suggested that the 50 Hz WPVPT system use a magnetic relay that is placed in the middle of the transmitter and receiver coils to increase its efficiency. The modelling of the WPVPT system comprises of modelling the PV module, the transmitter circuit, the magnetic relay, and the receiver circuit, all of which are based on mathematical formulations. The performance of PV module, WPVPT system with and without magnetic relay are discussed to prove that the efficiency of WPVPT system with magnetic relay is higher than the efficiency of WPVPT system without magnetic relay. Some conclusions can be justified as follows.

The WPVPT system uses the PV module as its primary DC voltage source, which is then converted to AC power on the transmitter coil and delivered to the receiver coil. The simulation results of the curves of current versus voltage and power versus voltage of PV modules are validated to the data sheet of the PV module under standard test conditions (STC), which are 25 °C and 1000 W/m^2 of solar radiation. Based on the percentage error, the short circuit current, open circuit voltage, and maximum power of the PV module are correct. They suggest that the WPVPT system may effectively use the PV module modelling.

With a 10 m distance between the transmitter and receiver coils, the powers and efficiencies of a WPVPT system with and without a magnetic relay are examined for solar irradiances ranging from 100 W/m^2 to 1000 W/m^2 and temperatures ranging from 25 °C to 40 °C. By using the magnetic relay, the AC power on the receiver coil is increased, which also increases its efficiency. Without a magnetic relay, their efficiency is 71.27%, and with one, they are 72.82%.

This study explored a comprehensive efficiency improvement of WPVPT system with and without a magnetic relay. The efficiency of WPVPT system with a magnetic relay is higher than that of WPVPT system without a magnetic relay. However, further and in-depth studies may be needed to confirm its power transferring, especially regarding the mutual inductance between the transmitter and receiver coil that has a proportional value to the magnetic field arriving on the receiver coil.

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