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Research Article

Effect of Reverse Polarisation of an Electromagnetic Field on the Performance of a Silicon PV Cell

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This paper investigated, by one-dimensional modelling, the effects of reverse polarisation of an electromagnetic field, generated by an amplitude modulation radio antenna, on the efficiency of a silicon PV cell. Through a simulation, the effects of both the incidence angle and the electromagnetic field magnitude on the power output of the PV cell are analyzed. The power output curves against the junction dynamic velocity are used to find the junction dynamic velocity at the equilibrium, the maximum power output, and the efficiency of the PV cell. The results have shown that the presence of important electromagnetic fields in the neighborhood of a silicon PV cell decreases its performance.

1. Introduction

The implementation side by side of photovoltaic systems and telecommunication antennas or high-voltage (HV) power transmission lines, causing interaction between the PV cells or modules and electromagnetic waves, emitted by these antennas or HV power transmission lines, has been investigated by many researchers.

Some researchers have investigated the reaction of PV cells and modules to external electromagnetic fields, essentially radio waves.

Yamaguchi et al. [1] investigated the reflection and absorption characteristics of electromagnetic waves (TV waves) for PV modules by simulation and experiment. The authors showed that a PV module is able to attenuate electromagnetic wave depending on its combination. Thus, the attenuation was, respectively, 6 dB in one PV module and 12 dB in multiple PV modules. The authors also concluded that a PV module can be considered as a receiving antenna of TV by changing the structure of the PV module. Following the previous work, Tada et al. [2] developed a novel PV module, which absorbs the electromagnetic wave in the UHF band (TV waves) by rearranging solar cells. The authors designed, by rearranging solar cells, a loop antenna which operates as a receiving antenna in the UHF band. The analytical results showed that the cell loop antenna has the receiving potential in the UHF band and also in broad band, while experimentally the absorbing characteristic of the cell loop module has been confirmed. As for Drapalik et al. [3], they studied crystalline PV cells as both receivers and emitters of electromagnetic waves. As receivers, they concluded that the reception of electromagnetic radiation depends linearly on the cell area, at least at low frequencies (below 10 MHz). The authors also concluded that, following the reciprocity theorem, a solar cell array may also emit significant amounts of undesired electromagnetic radiation if it is excited by unfiltered noise in the power electronics, light fluctuations, or vibrations. In a similar vein, Costia et al. [4] described, through experimental tests, a PV cell-like receiver for electromagnetic waves in VHF-UHF bands and the application of a PV cell in planar antenna structures. This is done by replacing the radiating patch element of a planar antenna by a PV cell, and so the PV cell is able to receive and transmit electromagnetic waves. The results showed that PV cells can be used to design planar antennas and PV plants integrated in buildings can also be used at the same time as broadcasting antennas. At last, the authors concluded that the use of appropriate low-pass filters prevents the energy production to be disturbed by received signals.

Other researchers have investigated the effect of electromagnetic waves on the efficiency of PV cells and modules.

Fathabadi [5], with theoretical analysis and experimental verifications, studied the impact of the electromagnetic (EM) wave produced by 400 kV high-voltage (HV) power transmission line on the power production of a PV module located near the power transmission line. The results showed that the electric field of the EM wave produced by a HV power transmission line has no effect on the output power of a PV module located near the power transmission line, while the magnetic field of the EM wave has a huge negative impact on the output power. The study also showed that the negative impact of the magnetic field of the EM wave increases when the current of the power transmission line becomes larger to respond load demand and declines by increasing the distance between the PV module and the conductors of the power transmission line. Finally, from experimental verifications, the author recommended a minimum distance of 200 m between PV panels and HV power transmission lines to avoid the negative impact of the EM wave. Following the previous work, Raza et al. [6] studied the influence of the EM wave produced by 500 kV HV power transmission line (TL) on the power generation of the PV module situated nearby the HV power transmission line. The authors arrived at the same results than Fathabadi [5].

Zerbo et al. [7–9] conducted theoretical modelling of the effect of AM and FM radio waves on the efficiency of PV cells. The studies were conducted considering a given orientation of the electromagnetic field and varying the distance between the PV cells and the radio antenna.

The studies showed that the magnetic field of the EM wave has negligible effect on the efficiency of PV cells, while the electric field of the EM wave has a positive effect on it.

In a previous work [10], we investigated the effects of direct polarisation of an electromagnetic field on the efficiency of a silicon PV cell. We have shown that the incidence angle and also the magnitude of the electromagnetic field have negative influence on the efficiency of the PV cell.

This study aimed to investigate the effects of reverse polarisation of an electromagnetic field on the PV cell's efficiency. The effects of incidence angle which varies from $\pi/2$ to π rad and the electromagnetic field magnitude are studied on the electric power. Curves of power output according to junction dynamic velocity are used to find the junction dynamic velocity at the equilibrium, the maximum power output, and the efficiency.

It is well known that the reverse current of a p-n diode saturates to a value called reverse saturation current. This value is quite small so that the diode is considered essentially nonconducting [11]. Contrary to a p-n diode under reverse bias, the novelty of this study is that, under a reverse polarisation of electromagnetic fields, a PV cell behaves either like no generator of power output or like generator of power output. Thus, the behavior of the PV cell under reverse polarisation of an electromagnetic field depends on a particular value Sf_{eq} of the operating point.

2. Theoretical Background

The base region of the polycrystalline PV cell in Figure 1 is studied with the same assumptions of the previous work [10].

The expression of the PV cell's power output is [10]

$$P(Sf,\theta) = V_T \ln\left(N_B \frac{\delta(x=0,Sf,\theta)}{n_i^2} + 1\right) \cdot q\left[Sf + \mu_n^* E_0 \cos(\theta)\right]\delta(x=0,Sf,\theta). \quad (1)$$

V_T is the thermal voltage, N_B is the density of dopants in the base, and n_i is the density of intrinsic carriers at thermodynamic equilibrium.

μ_n^* is the electron mobility in the magnetic field, E_0 is the magnitude of the electric field, and Sf is the rate of carriers collected at the junction called junction dynamic velocity, and it defines the working point of the PV cell.

The efficiency of the PV cell in Air Mass 1.5 standard conditions is calculated using the following equation [10]:

$$\eta(\theta) = \frac{P(Sf,\theta)_{max}}{100 mW\cdot cm^{-2}}. \quad (2)$$

3. Results and Discussion

As in the previous study [10], the simulation of incidence angle's effect is made with the following assumptions:

(i) The AM radio antenna radiates in the free space at a power of 2 MW

(ii) The PV cell and the radio antenna are separated by a distance $r = 50$ m

(iii) The electromagnetic field magnitude is $E_0 = 154.9$ V/m and $B_0 = 5.162 \times 10^{-7}$ T

The incidence angle $\theta = \pi$ rad is used for the simulation of the influence of the electromagnetic field magnitude.

Simulations are conducted using a base thickness $H = 300\,\mu$m and the following parameters of electrons (excess minority carriers): $L_n = 0.02$ cm; $D_n = 26$ cm^2/s; and $\mu_n = 1000$ cm^2/V.s.

In Table 1, the intensities of the electric and magnetic fields in the radio wave versus the distance between the solar cell and the radio antenna are given [10].

3.1. Effect of Electromagnetic Field's Incidence Angle on the Output Power.

Figure 2 plots the power output's curves according to junction dynamic velocity for different values of the incidence angle.

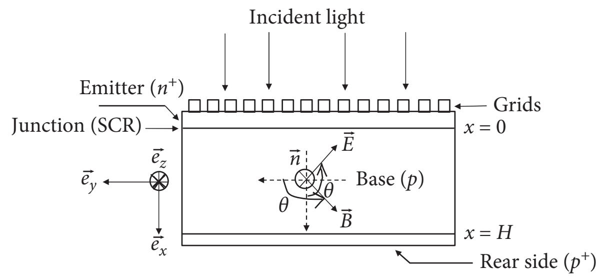

FIGURE 1: Illuminated silicon PV cell under reverse polarisation of an electromagnetic field.

TABLE 1: Intensity of the electric and magnetic fields for different distances separating the PV cell and the antenna.

Distance r (m)	50	100	500	1000	Absence of radio wave
E_0 (V/m)	154.9	77.4	15.5	7.7	0
B_0 (T)	5.162×10^{-7}	2.581×10^{-7}	5.162×10^{-8}	2.581×10^{-8}	0

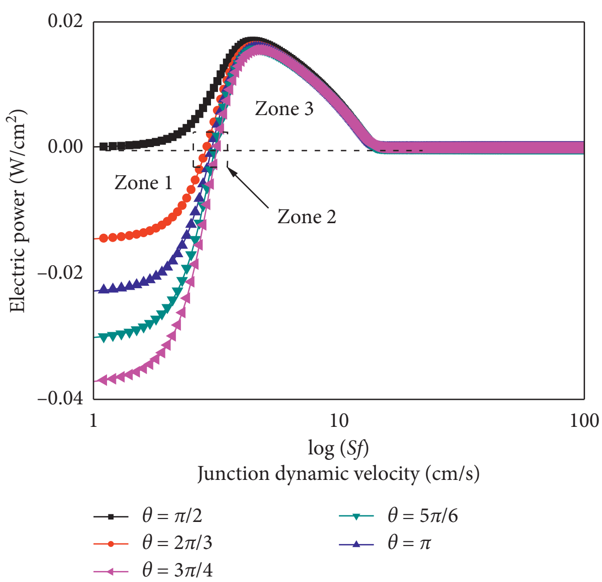

FIGURE 2: Power output as function of junction dynamic velocity for different incidence angles.

Except the curve of $\theta = \pi/2$ rad, which is similar to the traditional curve of electric power [12–16] because the electromagnetic field is null (absence of radio wave) and does not impact it, the other curves present four zones but three very significant. The three very significant zones of the curves are marked in Figure 2. In the first zone, near the open circuit, the electric power is negative, and it is not provided to an external load. The electric power is null in the second zone which is a point for each curve, and it is positive in the third zone. At last, the electric power is null in the fourth zone corresponding to the short circuit.

In the second zone of each curve, the electric power is null and that allows us to find the solutions of the following equation:

$$P(Sf,\theta) = V_T \ln\left(N_B \frac{\delta(x=0,Sf,\theta)}{n_i^2} + 1\right) \cdot q\left[Sf + \mu_n^* E_0 \cos(\theta)\right]\delta(x=0,Sf,\theta) = 0. \quad (3)$$

Equation (3) has two solutions:

$$\mathrm{Vph}(Sf,\theta) = V_T \ln\left(N_B \frac{\delta(x=0,Sf,\theta)}{n_i^2} + 1\right) = 0,$$

$$\text{or } \mathrm{Jph}(Sf,\theta) = q \cdot \left[Sf + \mu_n^* E_0 \cos(\theta)\right] \cdot \delta(x=0,Sf,\theta) = 0. \quad (4)$$

One must reject the first solution because it corresponds to the solar cell operating in the short circuit, so the solution of equation (3) is

$$\mathrm{Jph}(Sf,\theta) = q \cdot \left[Sf + \mu_n^* E_0 \cos(\theta)\right] \cdot \delta(x=0,Sf,\theta) = 0. \quad (5)$$

In the expression of the photocurrent density given in equation (5), $\mathrm{Jph}_{\mathrm{diffusion}} = q \cdot Sf \cdot \delta(x=0,Sf,\theta)$ and $\mathrm{Jph}_{\mathrm{drift}} = q \cdot \mu_n^* \cdot E_0 \cdot \cos(\theta) \cdot \delta(x=0,Sf,\theta)$ are, respectively, the diffusion current density and the drift current density.

The solution of equation (5) is $Sf_{\mathrm{eq}} = -\mu_n^* E_0 \cos(\theta)$. This junction dynamic velocity for which the diffusion current density is equal to the drift current density and therefore the photocurrent density is null is called junction dynamic velocity at the equilibrium.

Using the solution of equation (5), the drift current density and the photocurrent density can be rewritten, respectively:

$$\begin{aligned} \mathrm{Jph}_{\mathrm{drift}} &= -qSf_{\mathrm{eq}}\delta(x=0,Sf,\theta), \\ \mathrm{Jph}(Sf,\theta) &= q \cdot \left(Sf - Sf_{\mathrm{eq}}\right) \cdot \delta(x=0,Sf,\theta). \end{aligned} \quad (6)$$

Equation (6) shows that the density of the drift current is negative ($\mathrm{Jph}_{\mathrm{drift}} < 0$) and that means that the electrons migrate towards the rear side of the PV cell. On the contrary, the diffusion current density is positive ($\mathrm{Jph}_{\mathrm{diffusion}} > 0$) and that means that the electrons diffuse towards the junction of the PV cell.

The expression of the PV cell's power output can also be rewritten:

TABLE 2: Junction dynamic velocity at the equilibrium and efficiency for various incidence angles.

θ (rad)	$\pi/2$	$2\pi/3$	$3\pi/4$	$5\pi/6$	π
Sf_{eq} (cm/s)	0	776.247	1.096×10^3	1.349×10^3	1.549×10^3
P_{max} (mW/cm^2)	17	16.268	15.977	15.759	15.578
Efficiency η (%)	17	16.268	15.977	15.759	15.578

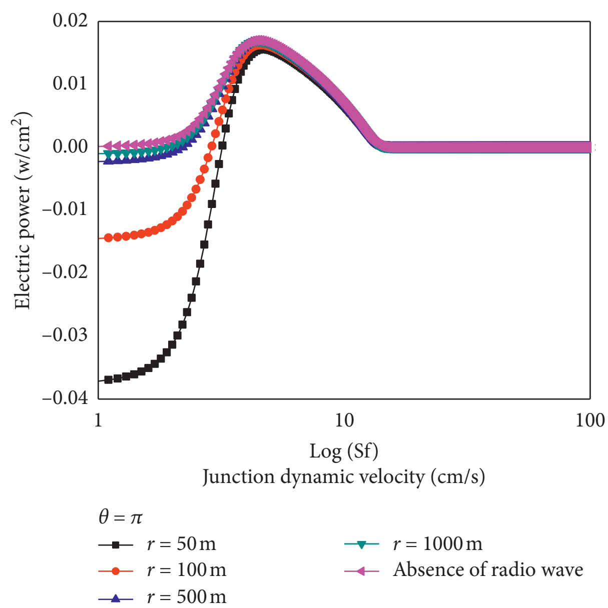

FIGURE 3: Power output as function of junction dynamic velocity for various distances.

$$P(Sf,\theta) = V_T \ln\left(N_B \frac{\delta(x=0,Sf,\theta)}{n_i^2}+1\right) \cdot q\left(Sf - Sf_{eq}\right)\delta(x=0,Sf,\theta). \quad (7)$$

As the photovoltage of a PV cell is always positive, the sign of the power output in equation (7) depends on one of the photocurrent densities.

For $Sf = Sf_{eq}$, the solar cell is blocked because the photocurrent density is null, and consequently, the electric power is also null.

In the first zone, $Sf < Sf_{eq}$, $|Jph_{diffusion}| < |Jph_{drift}|$, resulting in a negative value of the density of photocurrent and the power output. Thus, the electrons instead of crossing the junction as in the case of a solar cell under direct polarisation of an electromagnetic field [10] to produce a leakage photocurrent density, they migrate towards the rear side of the PV cell. The migration of the electrons towards the rear side of the PV cell produces a negative photocurrent density and a negative electric power which are not provided to an external load. Consequently, the PV cell is blocked, and it cannot supply a power output to a load.

In the third zone, $Sf > Sf_{eq}$, $|Jph_{diffusion}| > |Jph_{drift}|$, the diffusion current density is positive, and it is higher than the drift current density; so, the density of photocurrent and the power output are positive, and they are provided to an external load.

The values of the junction dynamic velocity at the equilibrium and the efficiency according to the incidence angle are given in Table 2.

Results in Table 2 show a decrease of the maximum power output and the efficiency when the incidence angle varies from $\pi/2$ rad to π rad (increase of electromagnetic field's effect). On the contrary, the junction dynamic velocity at the equilibrium increases resulting in a working state of the solar cell where it is blocked.

3.2. Effect of Electromagnetic Field's Intensity on the Power Output. Curves of power output against the junction dynamic velocity for different distances are shown in Figure 3.

The shapes of curves in Figure 3 are in concord with those in Figure 2, and the negative power output disappears with the increase of the distance (decrease of electromagnetic field's intensity).

Values of junction dynamic velocity at the equilibrium and efficiency according to the distance are summarized in Table 3.

The maximum power output and the efficiency increase when the radio antenna is far from the solar cell, while the junction dynamic velocity at the equilibrium decreases. The decrease of the junction dynamic velocity at the equilibrium leads to a situation where the solar cell passes from the working state where it is blocked to the one where it provides an electric power to an external circuit.

Table 3: Junction dynamic velocity at the equilibrium and efficiency for various distances.

r (m)	50	100	500	1000	Absence of radio wave
Sf_{eq} (cm/s)	1.549×10^3	776.247	154.882	77.625	0
P_{max} (mW/cm^2)	15.578	16.268	16.844	16.917	17.00
Efficiency η (%)	15.578	16.268	16.844	16.917	17.00

4. Conclusions

The effects of reverse polarisation of an electromagnetic field have been investigated on the performance of a PV cell.

The one-dimensional study pointed out that, for an incidence angle such as $\theta \in]\pi/2, \pi]\cos(\theta) < 0$, the density of the drift current is negative so that there is a competition between the density of diffusion current and the density of drift current. For a particular value of the junction dynamic velocity called junction dynamic velocity at the equilibrium, the density of photocurrent and the power output are null. For this operating point, the solar cell is blocked. Thus, near the open circuit ($Sf < Sf_{eq}$), the photocurrent density and the electric power are negative, and they are not delivered to an external circuit. Therefore, for $Sf \leq Sf_{eq}$, the solar cell is blocked, and the density of photocurrent and the power output provided to an external load are null. Conversely, for $Sf > Sf_{eq}$, the diffusion current density is positive, and it is higher than the drift current density; so, the density of the photocurrent and the power output are positive, and they are provided to an external load. For a given electromagnetic field's intensity, when the electromagnetic field's incidence angle increases, the conversion efficiency decreases, while the junction dynamic velocity at the equilibrium increases resulting in a blockage of the solar cell.

This work also pointed out that, for an incidence angle $\theta = \pi$ rad, the electric power is firstly negative ($Sf < Sf_{eq}$) so that the solar cell is blocked. Then, the electric power is null ($Sf = Sf_{eq}$), and the solar cell is still blocked. At last, the electric power is positive ($Sf > Sf_{eq}$), and the solar cell operates normally. The efficiency increases with the increase of the distance, while the junction dynamic velocity at the equilibrium decreases.

The presence of relatively important electromagnetic fields, generated by radio antennas, in the neighborhood of a silicon solar cell decreases its performance.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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