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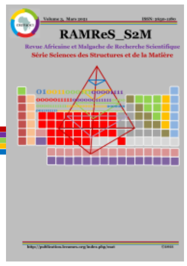

Determination of the optimal operating distance of a solar PV module under the influence of the electromagnetic field

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***Abstract*:**

The effect of an electromagnetic field (EMF) on the various electrical parameters of a photovoltaic (PV) solar cell or PV module is not uniform. A high intensity or proximity to an electromagnetic field increases the photoelectric current, while the photovoltage has the opposite effect. Thus, for certain electrical parameters, the EMF can be considered as an external constraint for the operation of a PV solar cell or module. The aim of this work is to determine the optimum operating distance of a PV module exposed to an electromagnetic field. This distance separates the PV solar cell from the source emitting the EMF. The curves and values of the various electrical parameters are analyzed as a function of distance before applying the optimal distance method. A theoretical method is proposed for determining the optimum operating distance of a PV module under an Amplitude Modulation (AM) radio wave field. This method combines the analysis of electrical parameters extracted and calculated from the current-voltage characteristic of the PV module subjected to an EMF, with the use of a color code associated with coefficients. The results show that the optimum operating distance for a polycrystalline silicon PV module subjected to an AM radio wave is 325 m. This value is consistent with that reported in the literature. The proposed method can be used with other external factors affecting PV cell operation.

***Keywords*:** Photovoltaic module ; Electromagnetic field ; Optimal distance ; AM radio wave.

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1. Introduction

The present work concerns the determination of the optimal operating distance of a polysilicon photovoltaic module. Such a distance should provide a better operating compromise between the main electrical parameters of the PV module when subjected to a source emitting an electromagnetic field. Indeed, the operation of a photovoltaic module can be disrupted by environmental factors and other external constraints. These can include magnetic and electromagnetic fields produced by antennas and telecommunication sources, high-voltage (HV) transmission lines, transformers, electrical machines, etc. [1, 2]. In the energy sector, climate change has led to technological innovations over the last few decades to ensure the energy transition [3] and meet two-thirds of the world's energy needs from renewable energies [4]. Among these renewable energies, solar energy remains the most abundant [5]. It is mainly accessible through its two components, solar thermal energy and solar photovoltaic (PV) energy; the latter converts solar radiation directly into electrical energy using a photovoltaic solar cell.

Advances in PV technology in recent years have facilitated its use and deployment in a variety of environments. In some of these environments, certain factors can hinder the operation of PV modules. External environmental factors that can influence the electrical parameters of solar PV modules include magnetic and electromagnetic fields produced by antennas and telecommunication sources, HV transmission lines, transformers, electrical machines, etc. The impact of these external constraints can, for example, increase or decrease conversion efficiency on the one hand, and reduce the lifetime of photovoltaic modules on the other.

Numerous experimental and theoretical studies have therefore been carried out to investigate the impact of some of these various external factors on module operation. One group of researchers studied the magnetic and/or electric field in static, quasi-static, transient and/or frequency-dynamic regimes on solar cells [6–9]. Another group then focused on the effect of electromagnetic waves, on the one hand to characterize recombination parameters [10], and on the other to study the influence of the electromagnetic field on the performance of photovoltaic cells and/or modules [11–16]. The work carried out by the second group demonstrated that the proximity or high intensity of EMFs affects or diminishes the performance of photovoltaic cells or modules, with a negative impact on their lifespan. One reason for this is that, at the junction, the photovoltaic solar cell or module strongly absorbs the electromagnetic field [2, 15], which can affect junction quality over time. Fathabadi [13], for his part, has demonstrated that the magnetic component of the electromagnetic field has a negative impact on the operation of photovoltaic modules. He also recommended a distance of at least 200 m between the photovoltaic module and the HV transmission line that generates this electromagnetic field, without proposing a method for determining this distance. The same is true of other previous studies, which have not addressed the question of determining an optimum operating distance for the photovoltaic module in the presence of an EMF source. This theoretical study therefore proposes a method for determining this distance, which offers the best compromise between the main electrical parameters of a PV module subjected to an electromagnetic field. At this distance, the module can achieve good electrical performance while maintaining its lifetime. This method combines the analysis of electrical parameters based on the intensity of the electromagnetic field, represented by the distance separating the emitting source from the photovoltaic module, and a statistical approach based on a code of colors assigned coefficients.

2. Theoretical study

The solar photovoltaic module used in this study is a multi-grain polycrystalline silicon module. Each grain is assumed to have the same electrical properties as the polysilicon photovoltaic module. This section presents the theoretical background to this work. A parallelepiped polysilicon grain illuminated by multispectral light identical to that in [2] is considered. The electromagnetic field is generated by an AM radio antenna. The wavelength, corresponding to AM radio waves with a maximum frequency of 30 MHz, varies from 10 m to 10 km; this means that the maximum energy carried by these radio waves has a value of 1.25 eV. The radio wave is therefore not ionizing for silicon, as its initial ionization energy is 8.151 eV [17]. However, this energy carried by radio waves has the potential to cause an avalanche in the semiconductor material of the photovoltaic module.

In this work, the electromagnetic field emitted by a 2 MW AM radio antenna with a plane-wave structure is considered. The geometrical characteristics of the AM radio antenna are not considered, only its electromagnetic structure.

This study proposes a theoretical approach to determining the optimum distance of the polycrystalline silicon photovoltaic module in the presence of an external constraint, in this case the electromagnetic field. This will not be an ideal distance, free from any influence of electromagnetic waves, but rather a distance where the various electrical parameters of the solar photovoltaic module can be well balanced. What's more, this method makes it possible to determine which parameters should be favored over others for each distance. The electrical parameters of the photovoltaic module subjected to the electromagnetic field were simulated using Mathcad software.

Figure 1 shows the polysilicon grain under the influence of the electromagnetic field.

In this work, the following assumptions concerning the junction dynamic velocity S_f:

- For $S_f < 10^3$ cm/s; corresponds to the open circuit situation;
- For 10^3 cm/s $< S_f < 10^6$ cm/s, corresponds to intermediate operation;
- For $S_f > 10^6$ cm/s, corresponds to the short-circuit situation.

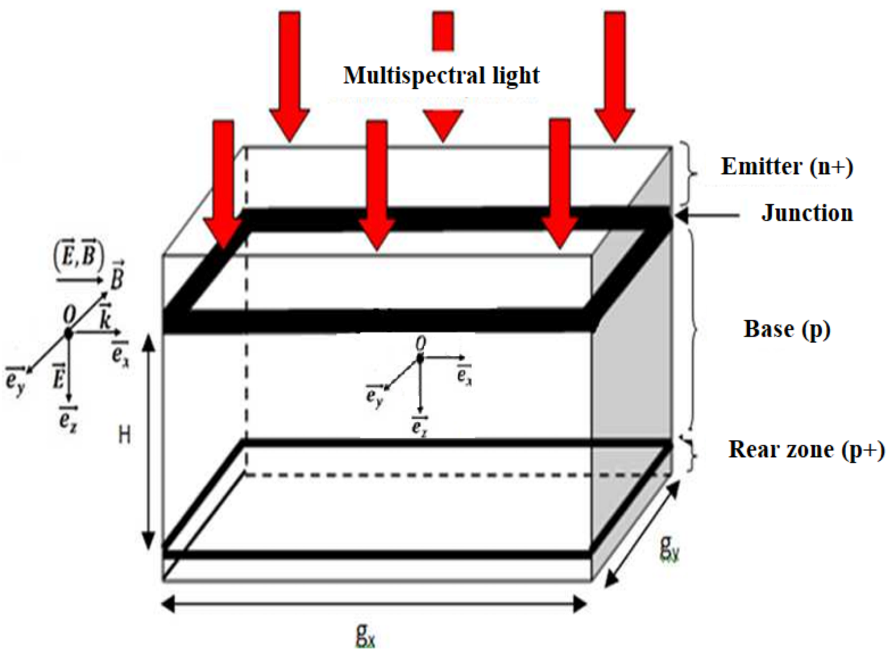

Fig. 1. Illuminated polysilicon grain subjected to AM radio wave.

Dynamic junction speed is characterized by the flow of carriers through the junction. The higher the S_f value, the more the photovoltaic cell or module operates in a short-circuit situation. A lower value means open-circuit operation. However, normal operation should be neither short-circuited nor open-circuited, but intermediate.

Bokoyo *et al.* [11] have solved the transport equation governing this type of grain. The expressions for photocurrent density (J_{ph}), photovoltage (V_{ph}), electrical power (P_{ph}), conversion efficiency (η), fill factor (FF), shunt resistance (R_{sh}) and series resistance (R_s) are given by equations (1) to (7), respectively.

$$J_{ph}(S_f, E, B) = \frac{e}{g_x g_y \sqrt{1+\mu_n B^2}} \sum_j \sum_k R_{j,k} \left[D_n^* \left(\beta A_{j,k} + \alpha B_{j,k} - \sum_{i=1}^{3} K_i b_i \right) \right] \tag{1}$$

With:

$$R_{j,k} = \frac{4\sin\left(C_{jx}\frac{g_x}{2}\right)\sin\left(C_{ky}\frac{g_y}{2}\right)}{C_{jx}\,C_{ky}}, \quad D_n^* = \frac{D_n}{1+\mu_n^2 B^2}, \quad K_i = \frac{-a_i}{D_{j,k}\left(b_i^2 - L_E b_i - \frac{1}{L_{j,k}^2}\right)},$$

$$A_{j,k} = \sum_{i=1}^{3} K_i \frac{-D_n^*\alpha(D_n^* b_i - S_b)\exp[-H(\beta+b_i)] + \left(D_n^* b_i + S_f\right)[(D_n^*\beta + S_b)\sinh(\alpha H) + D_n^*\alpha\cosh(\alpha H)]}{\left(D_n^*\beta - S_f\right)[(D_n^*\beta+S_b)\sinh(\alpha H) + D_n^*\alpha\cosh(\alpha H)] - D_n^*\alpha[(D_n^*\beta+S_b)\cosh(\alpha H) + D_n^*\alpha\sinh(\alpha H)]},$$

$$B_{j,k} = \sum_{i=1}^{3} K_i \frac{(D_n^* b_i - S_b)\left(D_n^*\beta - S_f\right)\exp[-H(\beta+b_i)] - \left(D_n^* b_i + S_f\right)[(D_n^*\beta + S_b)\cosh(\alpha H) + D_n^*\alpha\sinh(\alpha H)]}{\left(D_n^*\beta - S_f\right)[(D_n^*\beta+S_b)\sinh(\alpha H) + D_n^*\alpha\cosh(\alpha H)] - D_n^*\alpha[(D_n^*\beta+S_b)\cosh(\alpha H) + D_n^*\alpha\sinh(\alpha H)]}.$$

a_i and b_i are obtained from the tabulated values of solar radiation and the dependence of the absorption coefficient of silicon.

$$V_{ph}(S_f, E, B) = V_T \ln\left(1 + \frac{N_B}{n_i^2}\sum_j \sum_k R_{jk}\left[A_{jk} + \sum_{i=1}^{3} K_i\right]\right) \tag{2}$$

where, V_T is the thermal voltage, N_B is the impurity doping concentration in the base and n_i is the intrinsic carrier concentration.

$$P_{ph}(S_f, E, B) = J_{ph}(S_f, E, B) \times V_{ph}(S_f, E, B) \tag{3}$$

$$\eta(E, B) = \frac{V_{max}(E, B) \times J_{max}(E, B)}{P_i} = \frac{P_{max}(E, B)}{P_i} \tag{4}$$

J_{max} and V_{max} are the photocurrent density and the photovoltage at the maximum electrical power P_{max}, respectively.

$$FF(E, B) = \frac{V_{max}(E, B) \times J_{max}(E, B)}{V_{oc}(E, B) \times J_{sc}(E, B)} \tag{5}$$

$$R_{sh}(E, B) = \frac{V_{max}(E, B)}{J_{sc}(E, B) - J_{max}(E, B)} \tag{6}$$

J_{sc} is the photocurrent density at the short-circuit.

$$R_s(E, B) = \frac{V_{oc}(E, B)}{J_{sc}(E, B)} - \frac{V_{max}(E, B)}{J_{max}(E, B)} \tag{7}$$

V_{oc} is the open circuit photovoltage.

The quality of a solar cell depends not only on the values of its electronic parameters, but also on those of its electrical parameters (photocurrent, photovoltage, shunt resistance, series resistance, etc.). The latter parameters are expressed as a function of the electromagnetic field. The presence of the electromagnetic field should generally increase the movement of charge carriers across the junction, leading to an increase in photocurrent and a decrease in photovoltage. This would also have a different impact on other electrical parameters.

Figure 2 illustrates some cases of PV modules operating in the vicinity of EMF-emitting sources.

The electrical parameters of the photovoltaic module subjected to the electromagnetic field were simulated to obtain the results of the study.

3. Results and discussion

3.1. Study of photocurrent density

Figure 3 shows the curves of photocurrent versus junction dynamic velocity in the presence and absence of EMF.

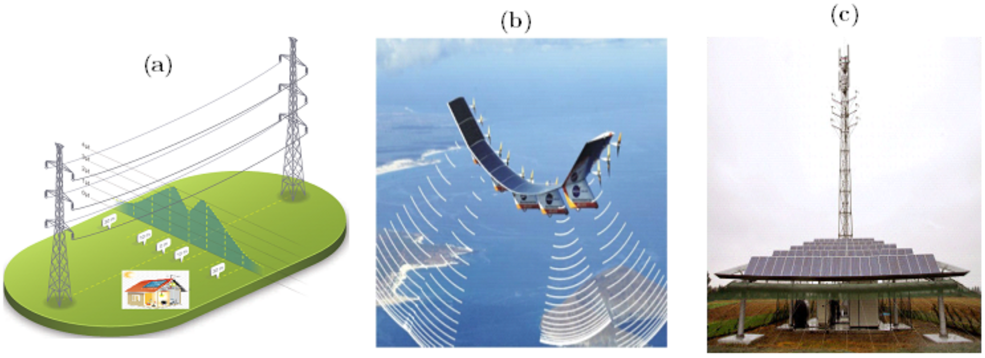

Fig. 2. Illustrative images of PV modules subjected to electromagnetic fields: (a) house near a high-voltage line, (b) aircraft and (c) telecommunications antenna.

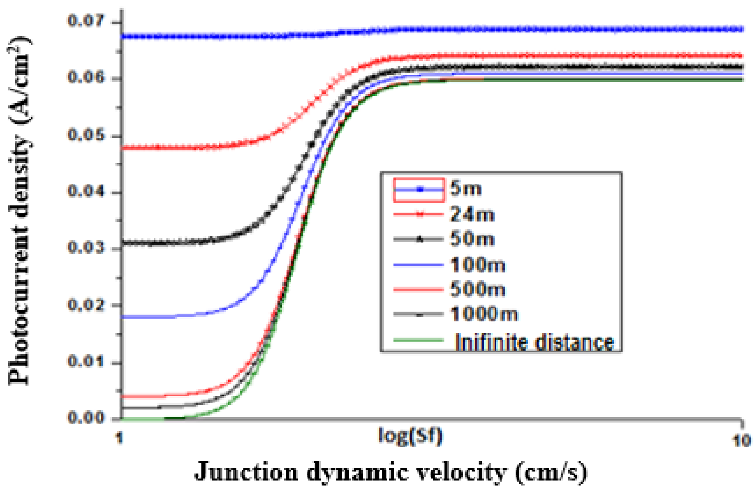

Fig. 3. Photocurrent density versus junction dynamic velocity.

Figure 3 shows the photocurrent density as a function of the junction dynamic velocity. For high values of junction dynamic velocity ($S_f \geq 10^6$ cm/s) and low values of dynamic velocity ($S_f \leq 10^2$ cm/s), the curves do not vary as a function of junction dynamic velocity (horizontal parts); there is then a short circuit and an open circuit, with the corresponding currents being the short-circuit and open-circuit currents respectively. It can be seen that, in the absence of an electromagnetic field, the photoelectric current density is zero for low values of the dynamic speed of the junction in open-circuit operation; however, the open-circuit photoelectric current density is non-zero in the presence of an electromagnetic field. Moreover, for high values of electromagnetic field strength, this open-circuit current is proportional to the electromagnetic field strength and tends towards the short-circuit current.

Figure 4 presents the variation of photocurrent versus distance in open-circuit, intermediate operation and short-circuit.

All three curves in Figure 4 have the same shape. The short-circuit current increases slightly in relation to the open-circuit and intermediate-circuit curves, from the absence of an electromagnetic field to the presence of one. So, for a given curve, when the slope of the curve is constant or increases very slightly, this implies that the electromagnetic field strength is also constant or almost constant. Consequently, the electromagnetic field does not have a sufficient impact on the photovoltaic cell at infinity, so the open-circuit photocurrent is zero, and the disappearance of the electromagnetic field at a certain distance has an influence.

The change in the slope of the curve with the decreasing distance, attests to an increase in the effect of radio waves on the solar cell.

At higher electromagnetic field intensities, corresponding to shorter distances, the curves in Figure 4 become tighter, demonstrating a strong dependence of currents on the field.

3.2. Study of photovoltage

Figure 5 shows the photovoltage versus junction dynamic velocity in the presence and absence of EMF.

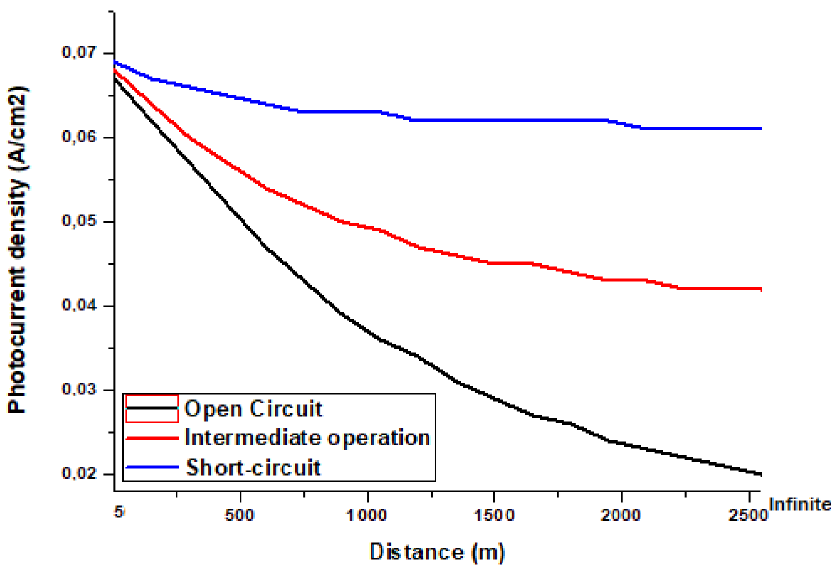

Fig. 4. Photocurrent density versus distance in short-circuit ($S_f = 7.10^7$ cm s^{-1}), intermediate operation ($S_f = 3.10^3$ cm s^{-1}) and open circuit ($S_f = 10^1$ cm s^{-1}).

For low values of junction dynamic velocity ($S_f < 10^3$ cm/s) and for a given value of electromagnetic field, each curve remains constant; this is the vicinity of the open circuit. However, it can be observed that as the electromagnetic field increases, the open-circuit photovoltage decreases. This result is consistent with the results of Erel's experiment [18]. Also, it can be emphasized that the intermediate mode is used, whatever the value of the electromagnetic field, all the curves overlap, with the exception of the one corresponding to 24 m. They all decrease linearly as the electromagnetic field increases. They all decrease linearly as the junction dynamic velocity increases, until reaching zero at the short circuit ($S_f > 10^9$ cm/s).

Figure 6 presents the variation of photovoltage versus distance in open-circuit and intermediate operation.

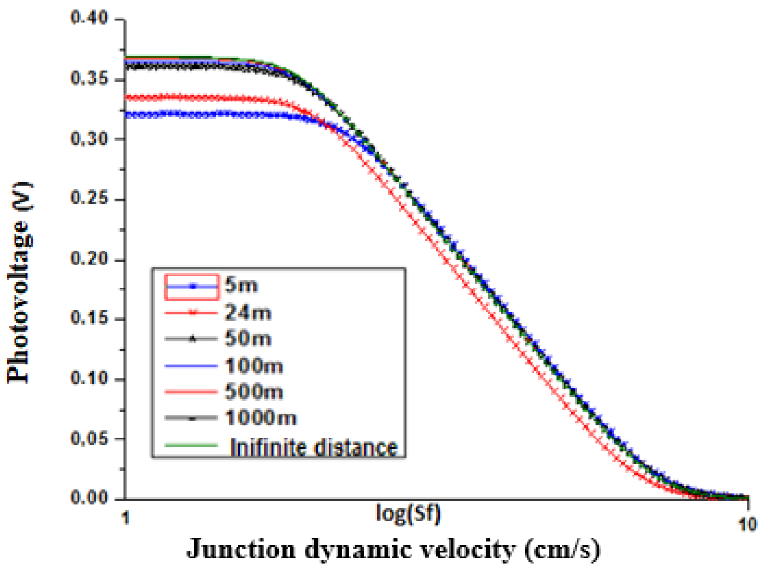

Fig. 5. Photovoltage versus junction dynamic velocity.

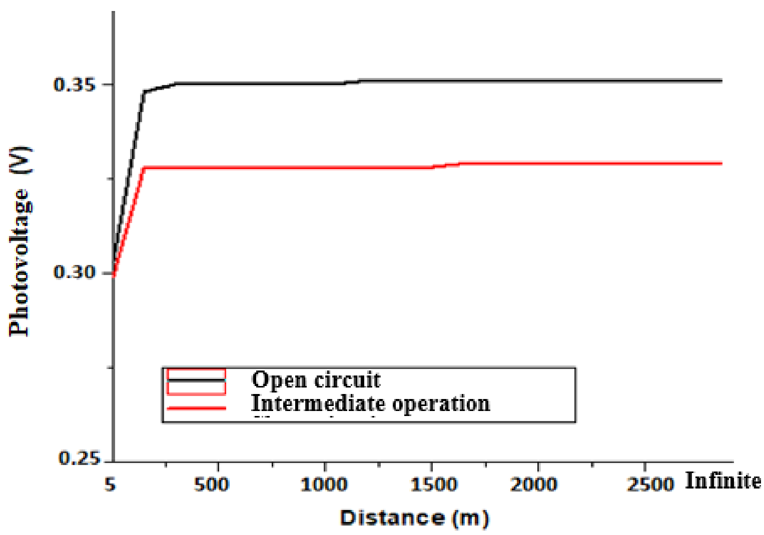

Fig. 6. Photovoltage versus distance in open-circuit ($S_f = 10^1$ cm.s^{-1}) and intermediate operation ($S_f = 3.10^3$ cm.s^{-1}).

The two curves in Figure 6 have the same shape. They stabilize from the absence of an electromagnetic field up to around 300 m before decreasing linearly. The open-circuit voltage decreases slightly between 300 and 100 m, then both curves decrease between 100 and 5 m. This means that the electromagnetic field only significantly affects open-circuit and intermediate-operation photovoltage when its intensity is high. This corresponds to a distance of less than 100 m.

3.3. Power study

Figure 7 shows electrical power as a function of distance in open circuit and intermediate operation. The curves show that from the absence of electromagnetic fields to the presence of EMFs, the power increases and then crosses between 500 and 250 m. Growth continues until a maximum value is reached at around 100 m, before decreasing. Figures 3 to 7 show the influence of the electromagnetic field on current, voltage and power output.

3.4. Determination of the values of the other parameters from the J-V/P-V characteristics

Figure 8 depicts the combined J-V/PV curves. They provide the values for the calculation of the various electrical parameters given by Eq.(3) to (7) to be derived. Table 1 shows the calculated values of these parameters.

It was observed that maximum power and conversion efficiency increased from the absence of field to 24 m; while shunt resistance, series resistance and fill factor decreased from the absence of field to 5 m.

Thus, the electromagnetic field can be beneficial for some parameters (P_{max}, efficiency, R_s, photocurrent), but unfavorable for others (R_{sh}, FF, voltage).

3.5. Determination of the optimal distance

In this section, the method for determining the optimum distance was used. This is the distance at which the photovoltaic module can operate optimally. For this purpose, the seven distances used in the simulations are required, assuming that each electrical parameter has equal importance. With seven distances, it is also necessary to choose a seven-color code. Each color is assigned increasing coefficients from 1 to 7. The number of colors chosen is equal to the number of distances used in the simulation.

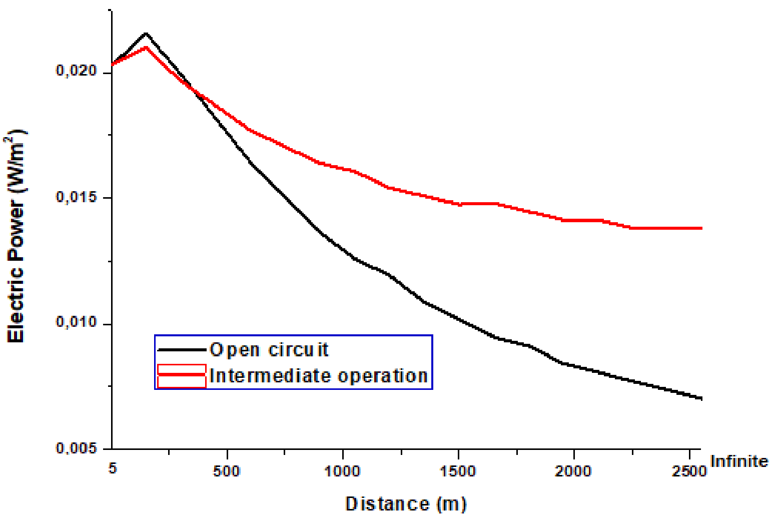

Fig. 7. Electric power versus distance in open circuit ($S_f = 10^1$ cm.s^{-1}) and intermediate operation ($S_f = 3.10^3$ cm.s^{-1}).

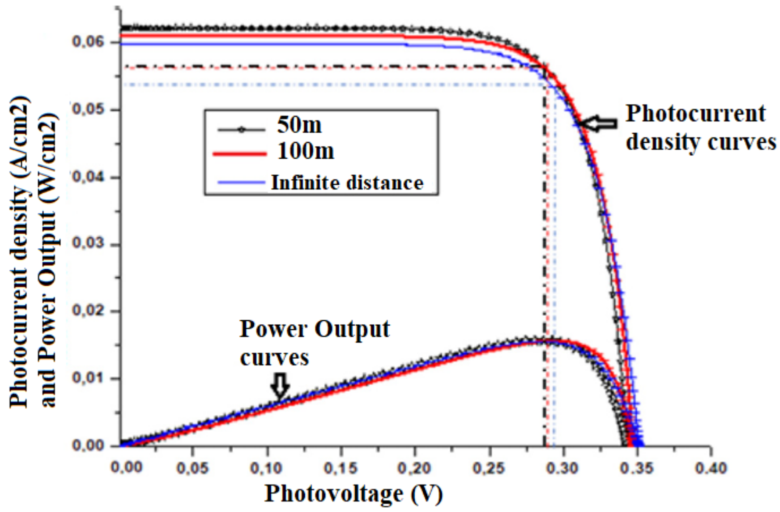

Fig. 8. J-V and P-V characteristics for various distances [11].

Table 1
Summary of solar cell electrical parameters based on J–V / P–V characteristics.

d (m)	$P_{\max}$ (mW/cm^2)	$V_{\text{ph,max}}$ (mV)	$J_{\text{ph,max}}$ (mA/cm^2)	$V_{\text{ph,co}}$ (mV)	$J_{\text{ph,cc}}$ (mA/cm^2)	η (%)	FF (%)	R_s (Ωcm^2)	R_{sh} (Ωcm^2)
5	15.060	243	61.900	303	68.800	15.060	72.200	0.479	35.500
24	15.900	269	57.900	332	64.700	15.900	73.870	0.494	39.140
50	15.860	281	56.500	343	62.200	15.860	74.400	0.551	49.700
100	15.790	281	56.500	343	62.100	15.790	74.500	0.556	50.020
500	15.720	287	54.900	350	60.100	15.720	74.700	0.607	55.100
1000	15.710	287	54.800	351	59.900	15.710	74.800	0.623	56.100
∞	15.700	287	54.800	351	59.800	15.700	75.000	0.639	57.100

For a given parameter, the distance that improves its value is given the value 1. The second distance receives the value 2, and so on up to the last value 7. The same operation is repeated until all the parameters considered have been exhausted. High parameter values indicate a negative influence of the electromagnetic field. Low values indicate a positive impact. Ultimately, the distance with the lowest total, excluding distances where the influence of the electromagnetic field would be negligible, would constitute the optimum distance. It would therefore enable operation with a better compromise of the main electrical parameters of the photovoltaic cell or module in the presence of the electromagnetic field. On the other hand, the highest point total represents the situation where the impact of electromagnetic waves is extremely negative. This method is tedious because it involves analyzing the curves of the various electrical parameters of the PV module and it requires numerous calculations. Indeed, the values of each of these parameters must be calculated for each distance considered. An error in the calculation cannot lead to the right result.

Furthermore, it does not calculate the error in the optimum distance values found because this method is both analytical and statistical.

The color code used is shown in Table 2. This color code has been applied to certain simulated distances that are not very far away, up to 1000 m from the solar photovoltaic cell.

Table 3 shows the calculated values for the various electrical parameters.

Analysis of Table 3 reveals that the lowest point total is 15. This corresponds to distances of 24, 50, 100, 500, 1000 m and infinity. At 24 m, the PV module is always in the Rayleigh zone [11]. At 1000 m or infinite distance, the electromagnetic field has little or no influence. The infinite distance and 1000 m can therefore be eliminated from the search for optimum operation.

In addition, Figures 4, 6 and 7 show the variations in the shape of the curves for the various parameters studied between 100 m and 500 m. In this way, the search for the optimum operating point can be restricted to the 100 to 500 m range. The same colors are used. The distance interval between 100 m and 500 m is then divided into seven 75 m segments to use the same color code.

Table 4 shows the calculated values for the various electrical parameters in reduced interval.

Analysis of Table 4 shows that the optimum distance is 325 m. At this distance, the shunt resistance, series resistance, fill factor and efficiency of the photovoltaic cells present the best compromise in the presence of the electromagnetic field.

This distance lies within the Fraunhofer zone, where the electromagnetic field structure of the AM radio antenna is flat. It corresponds to Fathabadi's experimental recommendation [13], with a difference of 125 m from his reference value. This, in turn, is closer to the 175 m distance shown in Table 4 with the second lowest point total.

Table 2
Color weighting.

Blue	**Green**	**Yellow**	**Orange**	**Brown**	**Pink**	**Red**
1	2	3	4	5	6	7

Table 3
Summary of solar cell electrical parameters based on J-V/P-V characteristics.

Distance (m)	5	24	50	100	500	1000	∞
R_{sh}	35.500	39.140	49.670	50.020	55.100	56.100	57.100
R_s	0.479	0.494	0.551	0.556	0.607	0.623	0.639
FF	72.200	73.870	74.400	74.500	74.700	74.800	75.000
η	15.060	15.900	15.860	15.790	15.720	15.710	15.700
Total	22	15	15	15	15	15	15

Table 4
Summary of electrical parameters for reduced distance 100-500 m.

Distance (m)	100	175	250	325	400	475	500
R_{sh}	50	51.500	53.100	54	54.600	55	55.100
R_s	0.556	0.546	0.574	0.589	0.598	0.605	0.607
FF	74.500%	74.647%	74.697%	74.722%	74.737%	74.747%	74.749%
η	15.790%	15.753%	15.739%	15.731%	15.726%	15.722%	15.721%
Total	17	15	16	12	16	16	16

4. Conclusion

In this study, an approach was proposed to determine the optimal operating distance of a photovoltaic module exposed to an electromagnetic field.

The effect of EMF can be positive or negative, depending on the electrical parameters of a photovoltaic module. This can have a long-term impact on its service life.

Analysis of current and electrical parameters, combined with the use of color-coded coefficients, has enabled us to find the optimum operating distance. It is 325 m for a photovoltaic module exposed to the EMF generated by an AM radio antenna.

This distance lies within the Fraunhofer zone of the electromagnetic field generated by a 2 MW AM radio antenna, and seems to match the piction of Fathabadi [13], who used an electromagnetic field generated by a HV transmission line.

In the future, it may be possible to apply this method to other external factors that can have various impacts on the different electrical parameters of photovoltaic modules.

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