**The Impact of External Magnetic Field on The Output Electrical Characteristics of Polycrystalline Photovoltaic Modules**

**ABSTRACT**

The performance and efficiency of photovoltaic (PV) modules are affected by various environmental factors, including solar radiation, temperature, humidity, and magnetic fields. In this study, one PV module was installed with an applied magnetic field, while another module, installed without the magnetic field, served as the control. Both modules were mounted on a platform 4 meters above sea level in a horizontal position facing the sun. The solar power level at the surface of the PV modules was measured using a digital solar power meter. The cell temperature and relative humidity at the surface of the PV modules were measured using a digital infrared thermometer and a hygrometer, respectively. An intelligent maximum power point tracker was utilized to determine the output electrical parameters of the PV modules under specific real-time atmospheric conditions. The short circuit current was measured using a digital multimeter. The results indicate that the magnetic field has little effect on the open circuit voltage. However, the control module outperformed the module subjected to the magnetic field in terms of maximum voltage, short circuit current, and maximum current production. This led to the control module generating more electrical power and achieving higher efficiency. Notably, both photovoltaic modules exhibited the same efficiency below a solar power level of 170 W/m². Moreover, the findings demonstrate that the magnetic field significantly reduces the output power of the PV module. At a constant solar power of 1000 W/m² and a humidity level of 50%, the difference in output power between the two PV modules was 10.6 W at a temperature of 49 °C and 9.9 W at 51 °C. This corresponds to a power drop of 20.4% and 20%, respectively. Additionally, at these temperatures (49 °C and 51 °C), the magnetic field decreased the module's efficiency by 13% and 12%, respectively, highlighting the detrimental effect of the magnetic field on PV module performance. The magnetic field enhances the electron-hole recombination rate in the silicon crystal, reducing the charge carrier lifetime and lowering the output voltage and current.

**Keywords:** Polycrystalline, Magnetic field configuration, magnetoresistance, junction recombination velocity, dynamic efficiency.

1. **INTRODUCTION**

As humans evolve and become more sophisticated, energy has become a crucial part of their lives daily; therefore, its supply should be constant, sustainable, and safe [1]. Energy supply is a critical component in the growth of any society and has now become the leading pillar for any country aspiring to increase its socio-economic and technical-industrial development [2]. This is why the world's electrical energy consumption has kept surging for the last decade [3].

Electricity generated via sunlight using a photovoltaic cell is a direct current (DC) energy. In addition to being able to convert solar radiation to DC, the cell is also required to have high energy conversion efficiency for optimum power generation [4]. Moreover, the highest known efficiency recorded for monocrystalline silicon photovoltaic cells is relatively low, ranging between 15-20% [5]. Therefore, several research is geared towards the enhancement of photovoltaic cell efficiency [6], which can be categorised into three common approaches. Firstly, through the use of new, improved or modified cell materials and structures, earth-abundant absorbers, and innovative devices. This approach can enable more effective charge collection and advance the absorption of the solar spectrum than that built inside the solar cells. Secondly, employing suitable peripheral elements or devices to improve the solar cell efficiency [7-8]. Thirdly, employing environmental factor enhancement to improve efficiency, e.g., ensuring that the cell’s surface is free from hard shade (dust and dirt) [9], reducing the temperature on the cell’s surface [10-11]. However, controlling environmental parameters such as wind, dust, and dirt can make the system more complex and consume the power generated by the system [12-13].

When a solar photovoltaic module is fully in operation (in the process of converting solar radiation into electrical energy), a couple of internal factors are at play. These factors include (but are not limited to) the magnetoresistance, junction recombination velocity, surface recombination velocity, junction dynamic velocity and the solar cell dynamic efficiency.

Magnetoresistance (MR) is the change in the electrical resistance of a material when it is exposed to a magnetic field [14]. This phenomenon occurs in semiconductors, conductors and insulators that exhibit a significant change in their resistivity when exposed to a magnetic field [15].

When materials that respond to magnetic fields are subjected to a magnetic field, the trajectory of the charge carriers (electrons or holes) is altered, inevitably leading to a change in the material's resistance [16]. The magnetic field can cause the charge carriers to scatter (leading to increased resistance) or to align the spins of the charge carriers (reducing scattering and decreasing resistance) [17].

The solar cell junction recombination velocity (JRV) is a crucial parameter that determines how efficiently charge carriers (electrons and holes) are collected at the p-n junction of a solar cell. It refers to the rate at which charge carriers recombine at the junction interface between the p-type and n-type semiconductors, which influences the overall efficiency of the solar cell [18].

At the p-n junction, electron-hole pairs can recombine before being collected. This recombination enhances the plummet in the photogenerated current and the power output of the solar cell. This recombination velocity also represents the effective speed at which carriers are lost due to recombination at the junction [19]. Higher recombination velocities indicate higher losses in charge carriers, inevitably lowering the cell efficiency [20].

Surface recombination velocity **(SRV)** is a critical parameter in the analysis and design of semiconductor devices, including solar cells [21]. It quantifies the rate at which charge carriers (electrons and holes) recombine at a surface or interface of a semiconductor material, typically due to the presence of surface states or defects [21]. These recombination events occur without contributing to the device's electrical output, negatively impacting performance [22].

In solar cells, SRV is more pronounced at the front surface, which is directly exposed to sunlight, where light-generated carriers are abundant, and at the rear surface in thin film cells, where carriers diffuse to the rear and encounter surface states [23]. The recombination at these surfaces impacts the short-circuit current **(**due to loss of photogenerated carriers) and the open-circuit voltageby increased recombination and decreases the overall performance of the solar cell due to non-radiative losses [23]. High recombination rates at the top surface have a particularly detrimental impact on the short-circuit current since the top surface also corresponds to the highest generation region of carriers in the solar cell [24]. In the presence of a magnetic field, the recombination rates are significantly influenced either at the junction interface or at points of defects [25]. In some cases, magnetic fields can cause a modulation in the carrier lifetimes or generation rates, further affecting the current-voltage (I−V) characteristics [26].

The junction dynamic velocity of a solar cell refers to the speed or real-time rate at which photogenerated charge carriers (electrons and holes) are transported across the solar cell junction before recombining under varying illumination or operational conditions [27]. In the presence of a magnetic field, the dynamic velocity of the solar cell will be significantly altered depending on whether the magnetic field slows down or enables the photogenerated charge carriers to move faster. Low dynamic velocity will inevitably lead to higher recombination rates and vice versa [27].

The dynamic efficiency of a solar cell is the real-time ability of a solar cell to convert incident light into electrical energy. It refers to the time-dependent or situation-specific efficiency of a solar cell under fluctuating conditions, such as fluctuations in solar flux (illumination), solar power (solar irradiance), spectral composition, cell temperature, humidity or electrical load [28]. In contrast with the standard efficiency of a solar cell, which is typically measured under steady-state conditions (standard test conditions), dynamic efficiency refers to the ability of a solar cell to convert sunlight into electricity under transient effects, operational or atmospheric conditions that vary with time [29]. In the presence of a magnetic field, the dynamic efficiency of the solar cell will be significantly influenced depending on whether the magnetic field causes the charge carriers to align or scatter or if the magnetic field will increase or decrease the junction recombination rate.

Various studies have been embarked on in the past to unravel how the magnetic field influences the output electrical characteristics of photovoltaic modules. Sourabie et al. [30] investigated the effect of the incidence angle of a magnetic field on the performance of a polycrystalline silicon solar cell under multispectral illumination. The investigation was theoretical based, and the magnetic field intensity used was 7.5 mT. Expression of the density of excess minority carriers and other related electrical parameters, such as the photocurrent density, the photovoltage and the electric power, was solved using the magneto-transport and continuity equations of excess minority charge carriers. The investigation reveals that the magnetic field causes a degradation in the electrical parameters of the solar cell. However, the investigation also reveals that increasing the angle of incidence of the magnetic field from 0 rad to π/2 rad can reduce the degradation of the solar cell performance.

Zerbo and his team in 2015 [31], studied the effect of an external magnetic field on a bifacial silicon solar cell's electric power and conversion efficiency. The study was a one-dimensional modelling study, and the magneto-transport and continuity equations for excess minority charge carriers were deciphered to determine the solar cell's electric power along with its photovoltage and photocurrent density. Reports from the study reveal an increase in the cell's magnetoresistance, which resulted in a drop in the cell’s photocurrent.

In 2017, a team of researchers led by Combari embarked on a theoretical modelling study to unravel the impact of magnetic fields on the performance of silicon PV modules [32]. The study aimed to examine how voltage transformers and telecommunication antennas affect PV installations since they generate a significant level of magnetic fields. The authors reported a decrease in maximum electric power and conversion efficiency as the magnetic field intensity increases, coupled with an increase in the fill factor and resistance at the maximum power point. In 2018, Combari and his team conducted another study to evaluate the performance of a silicon crystalline PV module under the influence of a magnetic field [33]. The study was experimental and employed a 5W monocrystalline PV module. The magnetic field ranging between 0 to 50 mT was generated via a U-shaped inductance coil connected to an autotransformer. The inductance coil was placed around the solar module but kept 1 cm away. They also reported that the efficiency of the PV module plummeted with increasing magnetic field intensity, decreasing the maximum power output and conversion efficiency. Zoungrana et al. [34] theoretically studied the effect of a magnetic field on the efficiency of a silicon PV cell under an intense light concentration. Electric power curves versus junction dynamic velocity were used to ascertain the PV cell's maximum electric power, and the conversion efficiency was calculated under varying magnetic fields. The authors demonstrated that the maximum electric power decreases with increasing magnetic field strength, which triggered a drop in the junction dynamic velocity. The magnetic field caused carrier storage near the cells' junction, which led to an increase in the fill factor and open-circuit voltage. In a previous study by Zoungrana et al. [35], a 3D modelling of magnetic field and light concentration effects on a bifacial silicon solar cell illuminated by its rear side was conducted. Numerical computations were done using the Mathcad software. The results of the computation reveal that the carrier diffusion length and its coefficient decrease as the magnetic field strength increases. The results also revealed that photocurrent and photovoltage decreased as the magnetic field strength increased. In 2018, Fathabadi studied the effect of external AC electric and magnetic fields on the power production of a silicon solar cell [36]. Their influence on photocurrent density, open-circuit voltage, and power output was evaluated via theoretical analysis and experimental methods. The study demonstrated that increasing electric field strength is related to decreased power output, while magnetic field effects led to reduced power output with higher magnetic field strengths. In 2019, Fathabadi conducted a comparative study on the effect of magnetic field on the photocurrent density of organic, dye-sensitized and silicon solar cells [37]. Each cell type was exposed to a controlled magnetic field with varying strengths, while the durations in which each cell was exposed to the magnetic field were considered to evaluate their impact on photocurrent density. The findings of the study disclosed that organic solar cells display an increase in photocurrent density when exposed to a magnetic field intensity of 15 mT. Contrariwise, dye-sensitized and silicon solar cells show a decrease in photocurrent density with increasing magnetic field intensity. Dieng et al. [38] conducted a comprehensive theoretical 3D study on the magnetic field effect on the electrical parameters of a polycrystalline silicon solar cell. They reported that the series resistance, parallel resistance, and space charge region capacitance increase with increasing magnetic field strength due to solar cell magnetoresistance. Furthermore, their report indicated that the conversion efficiency of the solar cell was dependent on the applied magnetic field. A theoretical 3D modelling study in 2012 on the influence of magnetic field on electrical model and electrical parameters of a PV cell under intense multispectral illumination was conducted by Toure et al. [49]. The study also extends its focus to the electric field at the base of the PV cell due to intense light intensity. Also, new analytical formulations of the continuity equation were developed, which gave insights into the carrier density within the cell's base. The results of the study show that magnetic fields cause charges to accumulate at the junction and increase the junction recombination velocity and open-circuit voltage while simultaneously decreasing the short-circuit current density.

Various studies exist on how magnetic field influences the functionality and performance of photovoltaics, but a huge part of the information available is theoretical. The experimental information focuses more on other photovoltaic technologies that are not made of silicon. The little information that is available for silicon polycrystalline technologies employs mini-PV modules that can only be used to charge small batteries and power torchlights. Generally, there is little information on the impact of magnetic field on the output electrical characteristics of polycrystalline PV technology in specific locations, especially in Nigeria, that can be effectively utilized for the design and sizing of photovoltaic modules.

The novelty of this study lies in the thorough experimental investigation of the impact of magnetic field on the output electrical characteristics of polycrystalline PV technology in Nigeria. While the study is centred on experimentally investigating how magnetic field impacts the output electrical characteristics of polycrystalline PV modules, the size of the module used is large enough to power home appliances. The objectives of the study deal with revealing the behavioural pattern of the PV module under fluctuating and transient environmental conditions. In achieving its objectives, the study used N52-grade neodymium magnets for the creation of the magnetic field. This study provides information that may trigger users to thoroughly examine the site of installation for PV modules for magnetic materials.

1. **MATERIALS AND METHODS**

This section discusses the materials used in this study, how they were set up, and the procedures followed in the course of measurement/data acquisition.

* 1. **Materials Used in This Study**

Two identical 80 W polycrystalline PV modules produced by Taiyo Solar with the same output electrical characteristics were used for this study (Table 1 reveals the output electrical characteristics). One PV module was subjected to the magnetic field while the other served as control. Aluminium stands (1 m high) were utilized for mounting the PV modules. A high-precision intelligent digital photovoltaic panel maximum power point (MPP) tracker was used to track and determine the maximum values of power, voltage, and current, as well as the open circuit voltage (VOC) generated by the PV modules. A precision digital multimeter was deployed to track the maximum short circuit current (ISC). A digital solar power meter and a digital hygrometer were deployed for the smooth tracking of the solar power and relative humidity, respectively, at the surface of the PV modules. With the aid of a digital non-contact infrared gun thermometer, the module's surface temperature was easily determined. N52 grade Neodymium magnets (as shown in Fig. 1a and 1b) were used for the creation of the magnetic field. The magnetic field intensity on each of the N52 grade Neodymium magnets was tested and measured using the digital auto range Tesla/Gauss meter. The range and accuracy of all the measuring instruments deployed for this study are displayed in Table 2.

**TABLE 1: PV module output electrical characteristics**

|  |  |
| --- | --- |
| **Electrical Specification** | **Value** |
| Peak Power | 80W |
| Current at Maximum Power (Imp) | 4.55A |
| Voltage at Maximum Power (Vmp) | 17.6V |
| Short Circuit Current (Isc) | 5.1A |
| Open-circuit Voltage (Voc) | 21.8V |
| Nominal Operating Cell Temperature (NOCT) | 47+2 0C |
| Operating Temperature | -40 0C to +85 0C |
| Production Tolerance  Maximum System Voltage  Maximum Series Fuse | ± 5%  1000 VDC  15A |
| Module dimension | 1200mm\*535mm\*35mm |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Table 2. Description of instrument** | | | | |
| **Instrument** | **Company** | **Model** | **Accuracy** | **Range** |
| MPP tracker | Elejoy | WS400A | ± 0.1 Watt | 0-400 W |
|  |  |  | ± 0.1 Volt | 0-60 V |
|  |  |  | ± 0.1 Amps | 0-20 A |
| Solar power meter | RZ | SM206 | 0.1 W/m2 | 0.1-1999.9 W/m2 |
|  |  |  | 0.1 Btu | 0.1-1999.9 Btu |
| Hygrometer | KT | KT-908 | ± 5% RH | 0-100% |
|  |  |  | ± 1% 0C | -50.0-70.0 0C |
| Non-contact infrared gun thermometer | Aneng | GM320 | ± 1.5 0C | -50.0 -400.0 0C |
| Tesla/Gauss meter | Meterk | ZMST-5 | ± 1% | 0-2000 mT |

|  |  |
| --- | --- |
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(a) Magnets Top View (b) Magnets Side View

Fig.1. Neodymium magnets used in the creation of the magnetic field

* 1. **Experimental Setup**

The research was carried out in an outdoor environment of the University of Cross River State (UNICROSS) Calabar, with a coordinate of 4.9313°N, 8.3295°E. The two 80 W polycrystalline photovoltaic modules were mounted on aluminium frames 1 m high, on a platform of 4 m above sea level, as displayed in Fig. 2a. After the mounting of the photovoltaic modules, the neodymium magnets were configured on one of the polycrystalline modules to create the magnetic field. The magnets were placed on every cell (36 cells in total) of the PV module with even spacing to create the desired magnetic field, as displayed in Fig. 2b. The MPP tracker was connected to the output of the PV module via probes and crocodile clips.

The PV module without the magnet served as the control. Connecting cables were connected from its output into a two-way switch. One output of the two-way switch was connected to the input of the intelligent MPP tracker, from which its maximum power points were precisely tracked and determined, while the other output was connected to the digital multimeter for determination of the module’s short circuit current. The PV module under study (installed with the magnetic field) also has the same setup as the one serving as the control, as shown in Fig. 3.

* 1. **Creation of the magnetic field**

The magnetic field on the PV module under study was achieved using N52 grade neodymium magnets (shown in Fig. 1a and 1b), each with a field strength of approximately 250 mT, as shown in Fig. 4. In creating the magnetic field, the North pole of the magnets (as evident in the Tesla/Gauss meter displayed in Fig. 4) was placed on each cell beneath the PV module under study.

* 1. **Measurement Procedure**

Data was obtained from the PV modules at 30-minute intervals, from 8.00 am to 5.00 pm, for a duration of 8 months. During measurements, the solar power reaching the surface of the PV modules was measured with the solar power meter, while the cell/panel temperature was determined with the infrared gun thermometer. The readings were taken simultaneously from both modules, and the data were recorded. During the time of data collection, the values of the meteorological parameters, such as relative humidity and ambient temperature, and all the output electrical parameters of the PV modules were taken in real time simultaneously. With the aid of an intelligent MPP tracker, the maximum power PMP at maximum power points, the instantaneous current IMP and voltage VMP at maximum power, and the open circuit voltage VOC under real-time atmospheric conditions were measured. The short circuit current ISC from both modules was simultaneously determined via the digital multimeter.

|  |  |
| --- | --- |
|  |  |

1. PV modules mounted 4 m above sea level (b) magnets placed on each cell of the PV module

Fig.2. PV modules mounted 4 m above sea level and magnets placed on each cell of the PV module.

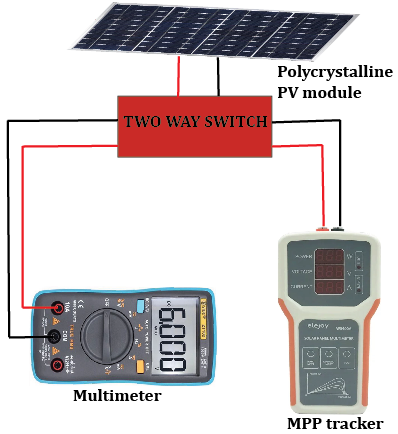


Fig.3. Experimental setup



Fig.4. Tesla/Gauss meter showing the strength of the neodymium magnet

* 1. **Data Processing**

This research was conducted in actual outdoor conditions with fluctuating environmental parameters. The efficiency of a PV module is dependent on the voltage and current it produces, which is affected by maintenance and environmental parameters. The short circuit current ISC is hugely influenced by the solar power (H) reaching the surface of the PV module, which can be ascertained by (1) as revealed by [40]. The IMP is significantly influenced by temperature (T) and can be confirmed via (2), which is also revealed by [40].

**Short Circuit Current:**

(1)

**Load Current:**

(2)

Where IPH is the photogenerated current, which is the short circuit current ISC. b is a constant that is determined by the junction properties of the semiconductor, and H is the incident solar power reaching the PV module. I0 is the diode reverse saturated current, KB is the Boltzmann constant, T is the absolute temperature, q is the electronic charge, V is the voltage at the terminals of the PV module, and *℮* is the exponential symbol.

**Load Voltage:**

The load voltage VMP is also influenced by temperature (T) and can be confirmed via (13), which is also revealed by [40] after resolving equation (2). (3) to (12) reveals the transformation of (2) to arrive at (13).

(3)

(4)

(5)

(6)

(7)

(8)

Multiplying through by 1

(9)

(10)

Rearranging the left-hand side

(11)

Taking the natural log of both sides

(12)

(13)

Where I is the load current.

**Open-Circuit Voltage:**

According to [40], the open-circuit voltage VOC as shown in (17) is also influenced by temperature (T), and can be obtained by resolving (13). At VOC,the load current . (14) to (16) reveals the transformation of (13) to arrive at (17).

(14)

(15)

(16)

According to [41], (16) can be approximated and reduced to (17)

(17)

In contrast, from the data obtained, the dynamic efficiency of the PV modules was computed with (18) while the solar panel efficiency at STC was confirmed via (19) as shown by [42-43].

**Dynamic Efficiency:**

(18)

Where PMEA and PMAX are the measured power and the maximum power of the PV module at STC respectively.

**Module Efficiency at STC:**

(19)

The external magnetic field B can influence the output electrical characteristics of the cell in terms of photocurrent density (J) as expressed by the equations of transportation phenomenon in (20)-(22) as revealed by [44].

(20)

) (21)

(22)

Where Is the electron’s intrinsic diffusion coefficient, is the excess minority carrier density in the base of the PV module, is the electric field originating from the carrier concentration gradient along the base of the PV module, T is the absolute temperature, is the mass of the electron, is the charge carrier lifetime, and is the electric field originating from the carrier concentration gradient along the base of the PV module.

**2.6 Study Area**

Our study location is Calabar (latitude of 4°57’06” N and longitude of 8°19'19'' E), 32 meters above sea level. Calabar serves as the capital of Cross River State in southern Nigeria. The region is characterized by a unique tropical monsoon climate, which brings rainfall for most of the year. However, there are two brief dry seasons, typically between January and March and again from October to December [45] in Calabar. Calabar experiences significant rainfall most of the year, with the brief dry season having minimal impact. The climate remains hot and humid year-round, with the wet season characterized by overcast skies, while the dry season is generally cloudy. Temperatures typically range from 64°F (17.78°C) to 92°F (33.33°C), rarely exceeding 96°F (35.56°C) or dropping below 58°F (14.44°C) [45]. The proportion of the sky covered by clouds fluctuates throughout the year. The clearest period begins around November 25 and continues until February 15, with December typically experiencing the clearest skies. Conversely, the cloudiest period spans from February 15 to November 25, peaking in April, when the sky is overcast about 89% of the time [45]. In Calabar, the duration of daylight remains relatively stable throughout the year, varying by no more than 24 minutes from a 12-hour average. The longest day occurs on June 21, lasting 12 hours and 25 minutes, while the shortest is on December 21, with only 11 hours and 50 minutes of daylight [45].

Calabar experiences seasonal variations in average hourly wind speed. The windy season extends from May 23 to October 15, lasting approximately 4.7 months, during which average wind speeds exceed 5.8 miles per hour. August is the windiest month, with an average hourly speed of 7.5 miles per hour. Conversely, the calmer season spans from October 15 to May 23, covering about 7.3 months, where average wind speeds drop below 5.8 miles per hour. December is the calmest month, recording an average hourly wind speed of 4.2 miles per hour [45]. January is the hottest month in Calabar, with an average high of 95.4°F (35.2°C) and an average low of 74.8°F (23.8°C). In contrast, August is the coldest month, with an average high temperature of 82.9°F (28.3°C). The highest recorded temperature to date is 102°F (38.9°C) in January, while the lowest, 66°F (18.9°C), was recorded in April [60]. January is the least humid month, with an average relative humidity of 69%, while the highest humidity levels occur between July and September, averaging 87%. Regarding rainfall, December experiences the fewest rainy days (13.5), whereas July sees the most, with 29.9 days [46]. When it comes to sunshine hours, December receives the most sunlight, averaging 9.5 hours per day, while August has the least, with only 4 hours of sunshine daily [46].

1. **RESULTS AND DISCUSSION**

This section presents data obtained from experimental measurements and analysis, structured into two parts. The first part examines the effect of the magnetic field on the electrical output parameters of the PV module under varying solar power, as illustrated in Fig. 5. The second part provides an analysis of the results, focusing on the influence of the magnetic field on the PV module's output power and efficiency at different temperatures, as shown in Fig. 6.

Table 3 displays the descriptive analysis of the amount of solar power reaching the PV module surfaces, while Tables 4 and 5 show the descriptive analysis of the output electrical parameters from both PV modules.

It is pertinent to note that the output electrical parameters (VMP, VOC, IMP, ISC, PMP, and ) used in the analysis of the results are the maximum voltage, current, power, and efficiency respectively that the modules produce instantly under a particular atmospheric condition.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Table 3. Descriptive analysis of solar power (W/m2) reaching the PV modules surface** | | | | | | | |
| **Statistics** | | | | **Solar Power (W/m2)** | | | |
| Minimum | | | | 18.27 | | | |
| Maximum | | | | 1168.55 | | | |
| Range | | | | 1150.28 | | | |
| Mean | | | | 544.26 | | | |
| Median | | | | 503.15 | | | |
| Variance | | | | 113313.33 | | | |
| Standard deviation | | | | 336.62 | | | |
| Standard error | | | | 52.57 | | | |
| **Table 4. Descriptive analysis of output electrical parameters from control module** | | | | | | | | |
| **Statistics** | **VOC (V)** | **VMP (V)** | **ISC (A)** | | **IMP (A)** | **PMP (W)** | **(%)** | |
| Minimum | 16.47 | 13.17 | 0.067 | | 0.04 | 0.52 | 1 | |
| Maximum | 20.23 | 16.57 | 3.98 | | 3.73 | 54 | 68 | |
| Range | 3.77 | 3.404 | 3.913 | | 3.69 | 53.48 | 67 | |
| Mean | 19.71 | 15.24 | 1.95 | | 1.76 | 28.01 | 35 | |
| Median | 19.97 | 15.375 | 1.98 | | 1.854 | 29.48 | 37 | |
| Variance | 0.49 | 1.195 | 1.34 | | 1.14 | 273.86 | 4 | |
| Standard deviation | 0.699 | 1.09 | 1.157 | | 1.07 | 16.55 | 21 | |
| Standard error | 0.112 | 0.33 | 0.183 | | 0.173 | 2.62 | 3 | |
| **Table 5. Descriptive analysis of output electrical parameters from the module with the magnetic field** | | | | | | | | |
| **Statistics** | **VOC (V)** | **VMP (V)** | **ISC (A)** | | **IMP (A)** | **PMP (W)** | **(%)** | |
| Minimum | 15.54 | 11.27 | 0.06 | | 0.03 | 0.34 | 0 | |
| Maximum | 20.3 | 16.012 | 3.75 | | 3.35 | 45.9 | 57 | |
| Range | 4.77 | 4.75 | 3.69 | | 3.32 | 45.56 | 57 | |
| Mean | 19.7 | 14.632 | 1.71 | | 1.45 | 21.92 | 27 | |
| Median | 19.92 | 15.2 | 1.68 | | 1.266 | 23.19 | 29 | |
| Variance | 0.743 | 2.15 | 1.06 | | 0.92 | 162.86 | 3 | |
| Standard deviation | 0.862 | 1.465 | 1.03 | | 0.957 | 12.76 | 16 | |
| Standard error | 0.135 | 0.488 | 0.157 | | 0.155 | 1.99 | 2 | |

* 1. **Influence of Solar Power on the Electrical Parameters of PV Modules in the presence and absence of an external magnetic field**

Figure 5a shows the influence of the magnetic field (north pole) on the module open circuit voltage with fluctuating solar power. From the figure, it can be seen that the open circuit voltage from both modules first increased from 0 to about 200 W/m2 of solar power before attaining stability. Furthermore, the figure shows that both modules deliver the same open circuit voltage, which shows that the magnetic field has very little effect on the open circuit voltage.

Figure 5b depicts the influence of the magnetic field (north pole) on the module voltage with varying solar power. The figure reveals that the photovoltaic module serving as the control performs better in voltage production than the module with the magnetic field, which aligns with studies by [30] and [33] that reported that the magnetic field causes a degradation in the electrical parameters of the solar cell. The figure further reveals some interesting trends as it shows an increase in voltage between 0 to 200 W/m2 of solar power before attaining fair stability close to the voltage at STC, which agrees with earlier studies by [13]. Still, in Figure 5b, a slight decreasing trend is visible as solar power increases. This decreasing trend as solar power increases is due to the increase in panel temperature with increasing solar power, which conforms to earlier studies by [4], which reveal that about 0.5 V is lost for every degree rise in temperature. Furthermore, the figure reveals that both modules generate the same voltage when the solar power exceeds 1000 W/m2.

The open circuit condition is an operation of the photovoltaic module which corresponds to the maximum output voltage when the output current from the module is almost zero. An important parameter that sets this open circuit operating condition is the junction recombination velocity of the minority carriers across the junction. This open circuit condition corresponds to the lowest junction recombination velocity rate of the minority charge carriers across the junction. So, the magnetic field setup aids in increasing the junction recombination velocity, which resulted in a lower maximum voltage from the solar module under study.

Figure 5c portrays the impact of the magnetic field (north pole) on the module short circuit current with fluctuating solar power. For both photovoltaic modules, a linear positive trend is observed as solar power increases, which confirms that a linear relationship exists between solar power and current, which also agrees with earlier work by [13]. Furthermore, the figure interestingly reveals that the magnetic field hinders the production of short-circuit current, which agrees with earlier studies by [35], which observed a decrease in photocurrent and photovoltage as magnetic field strength increases.

Figure 5d portrays the impact of the magnetic field (north pole) on the modules' maximum current with varying solar power. For both photovoltaic modules, a linear positive trend is observed as solar power increases, confirming that a linear relationship exists between solar power and current, which also agrees with earlier work by [13]. Furthermore, the figure interestingly reveals that the magnetic field hinders the production of current from PV modules, which agrees with the reports of earlier studies by [31], which disclosed that the magnetic field led to an increase in the cell's magnetoresistance, which resulted in a drop in the cell’s photocurrent.

The short circuit condition is a unique operation of the photovoltaic module, which corresponds to the maximum output current when the output voltage from the module is almost zero. The junction recombination velocity of the minority carriers across the junction plays a vital role in determining the short circuit condition. This short circuit condition corresponds to the highest or maximum junction recombination velocity rate of the minority charge carriers across the junction. So, what the result of figures 5c and 5d portrays is that the magnetic field setup aids in further increasing the junction recombination velocity, which resulted in the annihilation of charge carriers, thereby resulting in lower short circuit current and maximum current from the PV module under study.

Figure 5e depicts how the magnetic field (north pole) influences the module output power as solar power fluctuates. For both photovoltaic modules, a linear positive trend is observed as solar power increases, which is still in alignment with studies by [13]. However, a closer look at the figure shows that the same amount of power is generated between 0 to 170 W/m2. Above 170 W/m2, the photovoltaic module, under the influence of the magnetic field, generated lower power, which shows that the magnetic field hurts the power output for solar power levels above 170 W/m2.

Figure 5f unravels how efficient the photovoltaic module is under the influence of the magnetic field (north pole) as solar power varies. The figure reveals that both photovoltaic modules have equal efficiency for solar power below 170 W/m2. Above 170 W/m2, the effect of the magnetic field sets in, which hinders the module's efficiency. The results from Figure 5e and Figure 5f are in alignment with earlier work by [32], which reported a decrease in maximum electric power and conversion efficiency as the magnetic field intensity increases.



Fig.5. Impact of magnetic field on the PV module output electrical parameters under varying solar power

* 1. **influence of magnetic field on the PV module's output power and efficiency at different temperatures**

Figure 6a reveals the impact of the magnetic field on the module output power concerning temperature at constant solar power (1000 W/m2) and humidity (50%). Firstly, the figure shows a gradual loss in power with temperature, which conforms to earlier works by [4]. Secondly, the figure shows that the magnetic field decreases the output power of the photovoltaic module. At 49 0C and 51 0C, the difference in the output power between the two PV modules is 10.6 W and 9.9 W, respectively, corresponding to a 20.4% and 20% drop in power respectively, which highlights the negative impact of the magnetic field and conforms with reports by [32].

Figure 6b reveals the impact of the magnetic field on the efficiency of the module concerning temperature at constant solar power (1000 W/m2) and humidity (50%). Firstly, the figure shows a decline in dynamic efficiency with temperature, which agrees with works by [4]. Also, the magnetic field triggers a plummet in the dynamic efficiency of the photovoltaic module. At 49 0C and 51 0C, the magnetic field decreases the module efficiency by 13% and 12%, respectively, which demonstrates the negative impact of the magnetic field on PV module efficiency, which aligns with reports of [33].

Figure 6c further reveals the negative impact of the magnetic field on the module output power concerning temperature at a slightly elevated solar power (1100 W/m2) and humidity (50%). It shows a huge difference of 17.7 W and 15.4 W in the output power between the two PV modules for temperature corresponding to 47.5 0C and 52.6 0C, which corresponds to a 29.8% and 28.3% drop in power, respectively. This result further highlights the negative impact of the magnetic field and is also in agreement with studies by [32].

Figure 6d further demonstrates the impact of the magnetic field on the module efficiency concerning temperature at a slightly raised solar power (1100 W/m2) and humidity (50%). At this level of solar power, at 47.5 0C and 52.6 0C, the magnetic field causes the dynamic efficiency of the module to drop by 22% and 19%, respectively, which further highlights the negative impact of the magnetic field and agrees with the preceding research conducted by [33].

From Figure 5f, Figure 6b, and Figure 6d, it is evident that the magnetic field negatively impacts the dynamic efficiency of the PV module. This indicates that the fill factor of the PV module has severely deteriorated because of the magnetic field. For the fill factor to deteriorate, it implies that the junction recombination velocity and the magnetoresistance have been increased while simultaneously worsening the module dynamic velocity.



Fig.6. Impact of magnetic field on the PV module output power and efficiency at distinct temperature

**CONCLUSION**

The performance and efficiency of PV modules are influenced by surrounding environmental factors, such as solar radiation, temperature, humidity, and magnetic fields. The PV modules were installed on a platform 4 m above sea level, horizontally flat, facing the sun. One solar panel was installed with the magnetic field, while the other was installed without the magnetic field and served as the control. The solar power level, the cell temperature, and relative humidity at the surface of the modules were measured via a digital solar power meter, digital infrared gun thermometer and hygrometer, respectively. The open circuit voltage, maximum voltage, maximum current, and power the panels could generate under specific real-time atmospheric conditions were ascertained via an intelligent maximum power point tracker. The short circuit current was tracked and determined via a digital multimeter. The results reveal that the magnetic field has very little effect on the open circuit voltage. However, the result further discloses that the module serving as the control showed better electrical output performance above the module under the influence of the magnetic field. The control module produced greater voltage and current, allowing it to generate more electrical power and achieve higher dynamic efficiency. Also, the results show that below 170 W/m2, both PV modules attained the same level of dynamic efficiency. Moreover, the results show that the magnetic field triggers a plummet in the output power of the PV module. At a constant solar power of 1000 W/m2 and humidity of 50%, at 49 0C and 51 0C, the difference in the output power between the two PV modules is 10.6 W and 9.9 W, respectively, corresponding to a 20.4% and 20% drop in power respectively. Additionally, at 49 0C and 51 0C, the magnetic field decreases the module efficiency by 13% and 12%, respectively. The magnetic field negatively impacts the dynamic efficiency of the PV module, indicating that the fill factor of the PV module has severely deteriorated because of the magnetic field. For the fill factor to deteriorate, it implies that the junction recombination velocity and the magnetoresistance have increased while simultaneously worsening the module dynamic velocity.

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1.

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