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Research Article

Performance Investigation of a Silicon Photovoltaic Module under the Influence of a Magnetic Field

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Aside from the terrestrial magnetic field that is generated from the earth core, power transmission, and distribution lines, transformers and other equipment do produce a certain amount of magnetic field that could interfere with the performance of photovoltaic modules. This study conducted an experiment and investigated the performance of a silicon photovoltaic module subjected to a magnetic field. The current-voltage and power-voltage characteristics were plotted in the same axis system and allowed us to find, as a function of the magnetic field, the electrical parameters of the photovoltaic module such as maximum electric power, fill factor, conversion efficiency, and charge resistance at the maximum power point. These electrical parameters were then used to calculate the series and shunt resistances of the equivalent circuit of the photovoltaic module. The results have shown that the efficiency of a solar module is affected by the presence of magnetic fields. However, the magnitude of ambient magnetic field generated by power transmissions lines and other equipment is extremely low (in the order of 10^{-2} mT or less) as compared to the values of the magnetic field used in this study. That made it difficult to conclude as to the impact of such field on solar photovoltaic installations.

1. Introduction

The performance of a photovoltaic module (PV module) depends on climatic and seasonal parameters but may also depend on the presence of some external factors such as electric field, magnetic field, and electromagnetic field.

Various researchers have used theoretical and experimental methods to investigate the effect of climatic and seasonal conditions on photovoltaic modules and arrived at different results.

Emetere et al. [1] examined, through experimental tests, the effects of solar radiation irregularities due to climate change on the electrical performance of photovoltaic modules. Koffi et al. [2] experimentally investigated the seasonal variation of the operating temperature of silicon solar modules under tropical atmospheric conditions, including high turbidity (Harmattan dust particles). Their results confirmed that monocrystalline modules have lower temperature coefficient than polycrystalline and amorphous solar modules. Dia et al. [3] studied the degradation of photovoltaic modules under tropical weather conditions. The degradation of the photovoltaic modules, due to exposure to UV radiation, temperature, humidity, and aerosols in a Sahelian environment was investigated. The study showed that the degradation of the photovoltaic modules is more affected by temperature as well as solar irradiation. In the same vain, Kazem et al. [4] investigated the effect of dust on the performance of photovoltaic modules. The authors conducted an experiment to identify the effect of deposition of different pollutants (red soil, ash, sand, calcium carbonate, and silica) on the voltage and power output of photovoltaic modules. The results showed a drop of the voltage and the power output

Figure 1: Photography of experimental setup.

of the photovoltaic module when dust particles are deposited on the photovoltaic module. This drop was noted to be strongly dependent on the type of pollutant and on the level of deposition. The study also noted that ash pollutant affects the most the voltage of photovoltaic modules as compared to the other pollutants.

Other researchers used experimental methods to study the effect of magnetic field on the performances of solar cells. Betser et al. [5] used an experimental method to measure the mobility of minority carriers in the base of InP/GaInAs heterojunction bipolar transistor under constant magnetic field. The magnetic field was applied perpendicular to the direction of the current flow. The standard magnetotransport theory was used to establish a relation between the base current with no magnetic field, the change in the base current induced by the magnetic field, the mobility of the electrons, and the intensity of the applied magnetic field. The authors obtained the electron mobility in the base of an NPN InP/GaInAs HBT by measuring the base current as a function of the intensity of applied magnetic field. The result was in agreement with the value of the mobility measured by the zero field time of flight technique. Vardanyan et al. [6] proposed a method for measuring all recombination parameters (diffusion length, diffusion coefficient, carriers mobility, back surface recombination velocity) in the base region of bifacial solar cell illuminated by its rear side and under constant magnetic field applied parallel to the surface of the p-n junction. The bifacial solar cell was illuminated with a monochromatic light and the expression of electron photocurrent and the associated parameters were obtained by solving the continuity equation. By measuring the short circuit photocurrents for two different wavelengths without magnetic field and under applied magnetic field, the authors obtained the recombination parameters of the solar cell. Erel [7] conducted an experiment and studied the effect of electric and magnetic fields on the response of three different types of solar cells (monocrystal, polycrystal, and amorphous Si solar cells). The cells were first illuminated with LEDs of different color and secondly by a lamp, with tungsten filament, of different flux intensity. Erel concluded that the short circuit current and the open circuit voltage decreased in the presence of magnetic the field from red LED to the blue one. For an increasing light flux intensity produced by the lamp with tungsten filament, the short circuit current and the open circuit voltage decreased in the presence of the magnetic field.

In a previous work [8] we have shown, by simulation, that within the limits of the study, magnetic fields affect the performance of a photovoltaic module made up of ideal solar cells.

The aim of this work was to investigate potential negative impact of magnetic fields on the performance of a commercial silicon photovoltaic module. From experimental measurements of I-V and P-V characteristics of the photovoltaic module, we found the maximum electric power, the fill factor, the conversion efficiency, and the charge resistance at the maximum power point. Then, we calculated the series and shunt resistances of the equivalent circuit of the photovoltaic module.

2. Materials and Methods

2.1. Experimental Setup. The material used for the experimental study (Figures 1 and 2) was as follows:

(i) a monocrystalline silicon photovoltaic module whose characteristics are as follows:

(a) maximum electric power $P_{max} = 5W$

(b) voltage at maximum power point: $V_{max} = 17.50V$

(c) current at maximum power point: $I_{max} = 0.29A$

(d) open circuit voltage: $V_{OC} = 22.05V$

(e) short circuit current: $I_{SC} = 0.32A$

(f) surface of the photovoltaic module: $S_{mod} = 270\,cm^2$

(ii) an inductance in U form used for the creation of the magnetic field

(iii) a device used for the measurement of the intensity of the magnetic field, made up of a probe and a millivoltmeter

(iv) two DC generators: 31.5 V - 2.5 A

(v) three rheostats:3300Ω-0.25A, 1000 Ω -0.5A, and 100Ω- 1.5A

(vi) a magnetoelectric amperemeter and a magnetoelectric voltmeter

(vii) a ferromagnetic voltmeter and a ferromagnetic amperemeter

(viii) a ferromagnetic millivoltmeter

(ix) an autotransformer: 400 V-13A

(x) a pyranometer, Standard ST-1307 to measure the solar irradiance

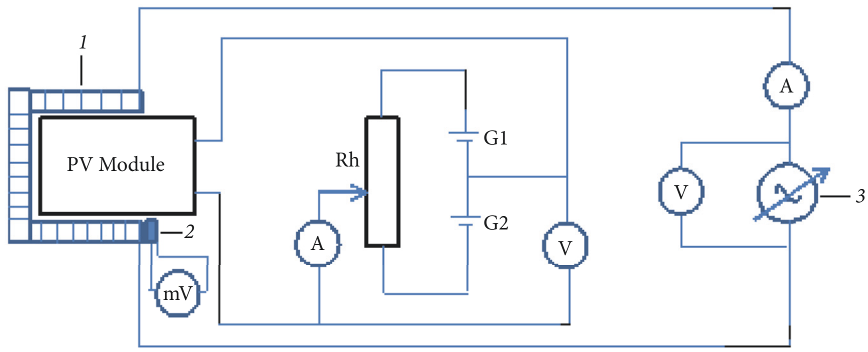

FIGURE 2: Experimental setup ((1) inductance in U form; (2) probe; (3) autotransformer.).

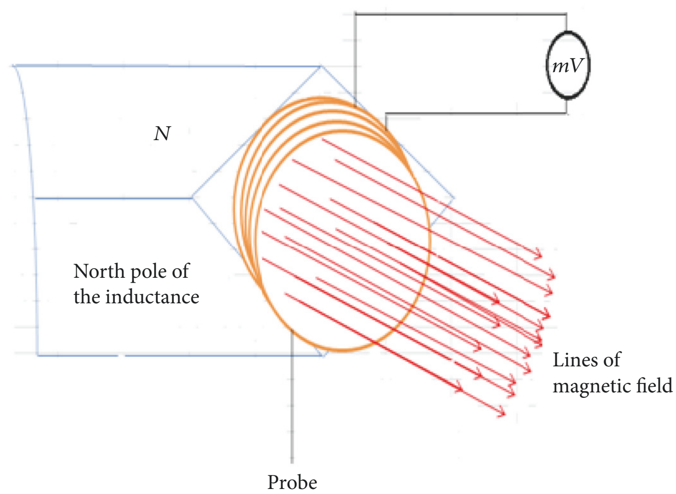

FIGURE 3: Device (probe) used for the measurement of the magnetic field.

(xi) a Midi Logger GL 200A to measure the temperature T_1 at the front side of the photovoltaic module, the temperature T_2 at the back side of the photovoltaic module, and the ambient temperature T_3

The autotransformer was used to vary the intensity of the current through the U inductance located at 1 cm from the photovoltaic module, by varying its supply voltage. Consequently, the intensity of the created magnetic field varied. The variation of the current supplied by the photovoltaic module was obtained by the variation of the charge resistance Rh.

It is worth noting that the test was conducted in Ouagadougou located at latitude 12.37°N and longitude 1.52°W.

2.2. Magnetic Field Measurement

2.2.1. Device for the Magnetic Field Measurement. The probe used for the measurement of the magnetic field intensity was a coil; this is illustrated by Figure 3. This coil is a toroidal inductor whose diameter is 450 mm and it is made up of 10 loops. The loops are made with copper of 1 mm^2 of section and protected with an insulator. This probe is positioned at the section of the magnetic circuit of the inductance that creates the magnetic field. The probe is connected to a ferromagnetic millivoltmeter of class 0.5 (Figure 3).

The method used for the measurement of the magnetic field is the principle of the electromagnetic induction.

2.2.2. Determination of the Teslametric Constant. We suppose that the inductance is not saturated; therefore, it generates a sinusoidal magnetic field whose instantaneous value is given by

$$b(t) = B_m \sin(\omega t) \tag{1}$$

B_m is the amplitude of the magnetic field.

The sinusoidal magnetic field generated by the inductance in U form produces a magnetic flux through the coil of the probe. The instantaneous value of this magnetic flux is given by

$$\phi(t) = NSB_m \sin(\omega t) \tag{2}$$

N is the number of loops of the probe and S is the section of the coil.

Table 1: Effective values of the magnetic field.

E (mV)	0	49.93	74.89	149.76	349.63	499.25	748.88
ΔE (mV)	0	1.00	1.00	2.00	2.00	0.50	5.50
B (mT)	0	10	15	30	50	100	150
ΔB (mT)	0	0.20	0.20	0.40	0.40	0.10	1.10

An electromotive force is induced in the coil and its effective value is measured with a millivoltmeter. The instantaneous value of the electromotive force induced in the coil is expressed in the following:

$$e(t) = -\frac{d\phi(t)}{dt} = \omega NSB_m \cos(\omega t + \pi) \tag{3}$$

$$e(t) = \omega NSB\sqrt{2}\cos(\omega t + \pi) \tag{4}$$

The expression of the amplitude of the electromotive force is given by

$$E_m = \omega NSB\sqrt{2} \tag{5}$$

Thus, we deduced the relation between the effective value of the magnetic field and the one of the electromotive force given by

$$B = \frac{1}{\omega NS}E = K_T E \tag{6}$$

where B is effective value of the magnetic field, E is effective value of the electromotive force induced in the coil, and K_T is teslametric constant.

In this study, the value of the teslametric constant is $K_T = 0.2003\ (TV^{-1})$.

Knowing the value of the teslametric constant, we deduced the effective value of the magnetic field from the measured effective value of the electromotive force.

The effective values of the magnetic field are given in Table 1.

Figure 4 is a plot of the effective value of the magnetic field as against the effective value of the electromotive force.

We used Figure 4, which is a straight line passing by the origin of the axis, for the determination of the effective value of the magnetic field.

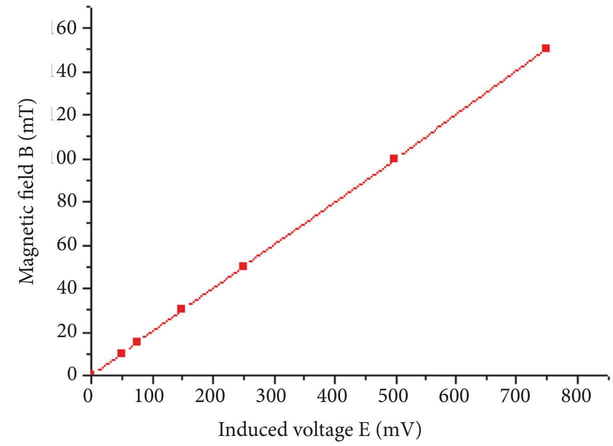

Figure 4: Effective value of magnetic field versus effective value of electromotive force.

3. Results and Discussion

3.1. Experimental I-V Characteristics. The experimental setup of Figure 1 allowed us to measure the intensity provided by the photovoltaic module to a variable charge resistance and its voltage for four constant values of magnetic field intensity. The results of the measurement are presented in Table 2.

The results in Table 2 show that, from short circuit to open circuit, the intensity of the electric current decreases when the intensity of the applied magnetic field increases.

We noticed that the ambient temperatures T_3 are higher than the temperatures T_1 measured at the front side of the photovoltaic module. The temperatures T_1 are also higher than the temperatures T_2 measured at the back side of the photovoltaic module.

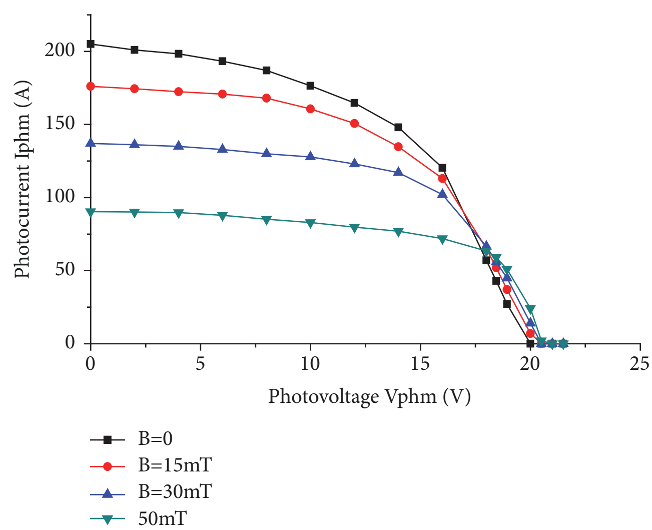

Figure 5: Experimental I-V characteristics at different intensity of the magnetic field.

Figure 5 is a plot of the experimental I-V curves of the photovoltaic module for different values of the magnetic field.

The experimental I-V curves have the same shape as the theoretical I-V curves obtained through modelling in a previous study by Combari et al. [8]. As the intensity of the magnetic field in milliTesla (mT) was varied from 0 to 15, 0 to 30, and 0 to 50, the short circuit current decreased by 14%, 22%, and 34%, respectively, while the open circuit voltage slightly increased by 5%, 5%, and 8%, respectively.

Table 2: Values of current and voltage of the photovoltaic module against the intensity of the magnetic field and for a solar irradiance of 600 W/m^2.

	B (mT)						
	0	15	30	50	Temperature at front side	Temperature at back side	Ambient temperature
V_{mod} (V)	I_{mod1}(mA)	I_{mod2}(mA)	I_{mod3}(mA)	I_{mod4}(mA)	T_1 (°C)	T_2 (°C)	T_3 (°C)
0	205	176.12	137	90.4	38.9	37.7	52.6
2	201	174.49	136.2	90.16	43.9	41.3	54.5
4	198.35	172.38	135	89.7	43.7	41.5	53.5
6	193.25	170.79	132.85	87.8	42	41.6	54.7
8	187	168	130	85.2	43	41.4	54.6
10	176.42	160.65	127.75	82.9	43.6	41.2	53.6
12	164.69	150.62	123	79.7	44.2	41	52.8
14	148.03	134.79	117	77	44.3	41.2	52.9
16	120.29	113	102	71.88	44	41.3	52.8
18	57	65.05	66.67	63.44	43.4	41	52.7
18.45	42.96	52	55.83	59	43.8	41.4	54
18.94	27	37	44.88	51	43.8	41	55.5
20	0	7	14	24.2	41.6	40.3	54.4
20.91	0	0	0	2	41.4	40.8	55
21.5	0	0	0	0	42.1	41.4	54.6

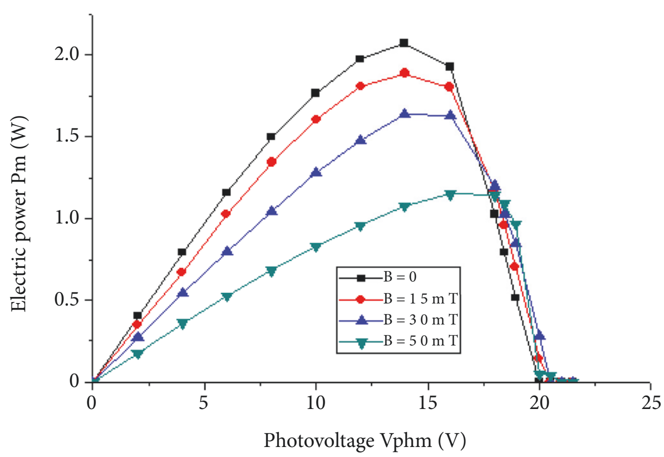

Figure 6: Experimental power versus voltage at different intensity of the magnetic field.

3.2. Experimental Power-Voltage Characteristics. The experimental values in Table 2 allowed us to compute the electric power that the photovoltaic module can provide to an external charge. The results are in Table 3.

The results show that the electric power decreases with an increase of the magnetic field, except for points close to the open circuit voltage. The decrease of the electric power means that, as the magnetic field increases, the decrease in current is much more important than the increase in voltage.

Figure 6 is a plot of the electric power versus the voltage at different intensity of the magnetic field.

Figure 6 is also in accordance with the theoretical power-voltage characteristics which were obtained through modelling in a previous study by Combari et al. [8]. It can be observed that, as the intensity of the magnetic field increases, the electric power at the maximum power point decreases. Also, as intensity of the magnetic field increases, the curves get less steep and shift to the right towards the open circuit voltage region. Consequently, the maximum power point moves towards large values of the voltage but lower values of the current, hence decreasing the electric power. In fact, as the intensity of the magnetic field in milliTesla (mT) was varied from 0 to 15, 0 to 30, and 0 to 50, the electric power at the maximum power point decreased by about 9%, 21%, and 48%, respectively.

3.3. Characteristic Values of the Photovoltaic Module. We present in this section the characteristics of the photovoltaic module under the influence of the magnetic field. The characteristics include current, voltage, and charge resistance

Table 3: Electric power and voltage of the photovoltaic module against the intensity of the magnetic field for a solar irradiance of 600 W/m^2.

	B (mT)						
	0	15	30	50	Temperature at front side	Temperature at back side	Ambient temperature
V_{mod} (V)	P_{mod1}(W)	P_{mod2} (W)	P_{mod3} (W)	P_{mod4} (W)	T_1 (°C)	T_2 (°C)	T_3 (°C)
0	0	0	0	0	38.9	37.7	52.6
2	0.402	0.349	0.272	0.18	43.9	41.3	54.5
4	0.793	0.67	0.54	0.359	43.7	41.5	53.5
6	1.16	1.025	0.797	0.527	42	41.6	54.7
8	1.496	1.344	1.04	0.682	43	41.4	54.6
10	1.764	1.607	1.278	0.829	43.6	41.2	53.6
12	1.976	1.807	1.476	0.956	44.2	41	52.8
14	2.072	1.887	1.638	1.078	44.3	41.2	52.9
16	1.925	1.802	1.632	1.152	44	41.3	52.8
18	1.026	1.171	1.2	1.142	43.4	41	52.7
18.45	0.793	0.96	1.03	1.089	43.8	41.4	54
18.94	0.511	0.701	0.85	0.966	43.8	41	55.5
20	0	0.14	0.28	0.048	41.6	40.3	54.4
20.91	0	0	0	0.042	41.4	40.8	55
21.5	0	0	0	0	42.1	41.4	54.6

Table 4: Electrical parameters of the photovoltaic module against the intensity of the magnetic field and for a solar irradiance of 600 W/m^2.

B(mT)	P_{max}(W)	V_{max}(V)	I_{max}(A)	V_{oc}(V)	I_{sc}(A)	R_{MPP}(Ω)	FF (%)	η (%)
0	2.075	13.65	0.152	20.00	0,205	89.80	50.61	12.81
15	1.931	14.41	0.134	20.50	0,176	107.54	53.49	11.91
30	1.694	15.40	0.11	20.91	0.137	140.00	59.13	10.46
50	1.152	16.00	0.072	21.50	0.090	222.22	59.59	7.12

at the maximum power point (MPP), series and shunt resistances, maximum electric power, fill factor, and conversion efficiency.

3.3.1. Electrical Parameters of the Photovoltaic Module. The electrical parameters (current and voltage at maximum power point, maximum electric power, fill factor, conversion efficiency, and charge resistance at the maximum power point) of the photovoltaic module under magnetic field are found using the method proposed in previous works [8, 10].

During the test, while measuring the characteristics I-V and P-V, the solar irradiance was also simultaneously measured alongside. The retained values were those corresponding to a measured solar irradiance of 600 W. The incident irradiance falling on the photovoltaic module was calculated through the formula $P_{inc}\ S_{mod}$ and found to be 16.20 W; S_{mod} is the surface of the photovoltaic module, as defined in Section 2.1. The above calculated incident irradiance was used for the calculation of the conversion efficiency.

The results are presented in Table 4.

On one hand, these results show that the maximum electric power and the related conversion efficiency decrease with an increase of the magnetic field; on the other hand the fill factor and the resistance at the maximum power point increase with an increase of the magnetic field. These experimental results are in agreement with the findings of the studies conducted on a silicon solar cell [10, 11] and on a silicon photovoltaic module [8, 11].

Within the limits of this study, it is clear that the efficiency of a solar module is affected by the presence of a magnetic field. However, the magnitude of ambient magnetic field generated by power transmissions lines and other equipment is extremely low (in the order of 10^{-2} mT or less as illustrated in Table 5) as compared to the values of the magnetic field used in this study. That makes it difficult to conclude as to the impact of such field on solar photovoltaic installations.

3.3.2. Series and Shunt Resistances of the Equivalent Circuit of the Photovoltaic Module. The experimental values of the series and shunt resistances of the equivalent circuit of the photovoltaic module were calculated using equations suggested by Combari et al. [8].

Table 6 gives the series and shunt resistances of the equivalent circuit of the photovoltaic module.

The values of the series and shunt resistances of the equivalent circuit of the photovoltaic module increase with the intensity of the magnetic field. This is in line with the results achieved by the theoretical study [8].

Table 5: Magnetic field from high voltage power transmission lines [9].

Voltage (kV)	Magnitude of the magnetic field from high voltage power transmission lines according to distance to the source (mT)		
	0 m	30 m	100 m
400	0.03	0.012	0.001
225	0.02	0.003	0.0003
90	0.01	0.001	0.0001

Table 6: Series and shunt resistance of the equivalent circuit of the photovoltaic module as a function of the magnetic field and for a solar irradiance of 600 W/m^2.

B(mT)	0	15	30	50
R_s (Ω)	7.76	9.90	12.20	17.70
R_{sh} (Ω)	257.547	363.430	562.590	888.889

4. Conclusions

This experimental study shows that the maximum electric power output of a photovoltaic module, hence its conversion efficiency, decreases when the intensity of the magnetic field increases. On the contrary, the fill factor and the resistance at the maximum power point do increase with the intensity of the magnetic field. The increase of the experimental values of the series and shunt resistances of the equivalent circuit of the photovoltaic module under magnetic field confirm its resistive behaviour called magnetoresistance.

Thus, the maximum electric power and the conversion efficiency are two electrical parameters extremely dependent on the intensity of the applied magnetic field. Consequently, the presence of relatively important magnetic fields in the neighborhood of a photovoltaic module decreases its performance.

However, it is difficult to conclude as to whether ambient magnetic field generated by power transmissions lines and other equipment have noticeable impact on solar photovoltaic installations, since the magnitude of such field is extremely lower compared to the values of the magnetic field used in this study.

The authors then recommend further studies that will narrow into magnetic fields in the order of those generated by power transmissions lines, transformers, and other equipment.

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 article.

Acknowledgments

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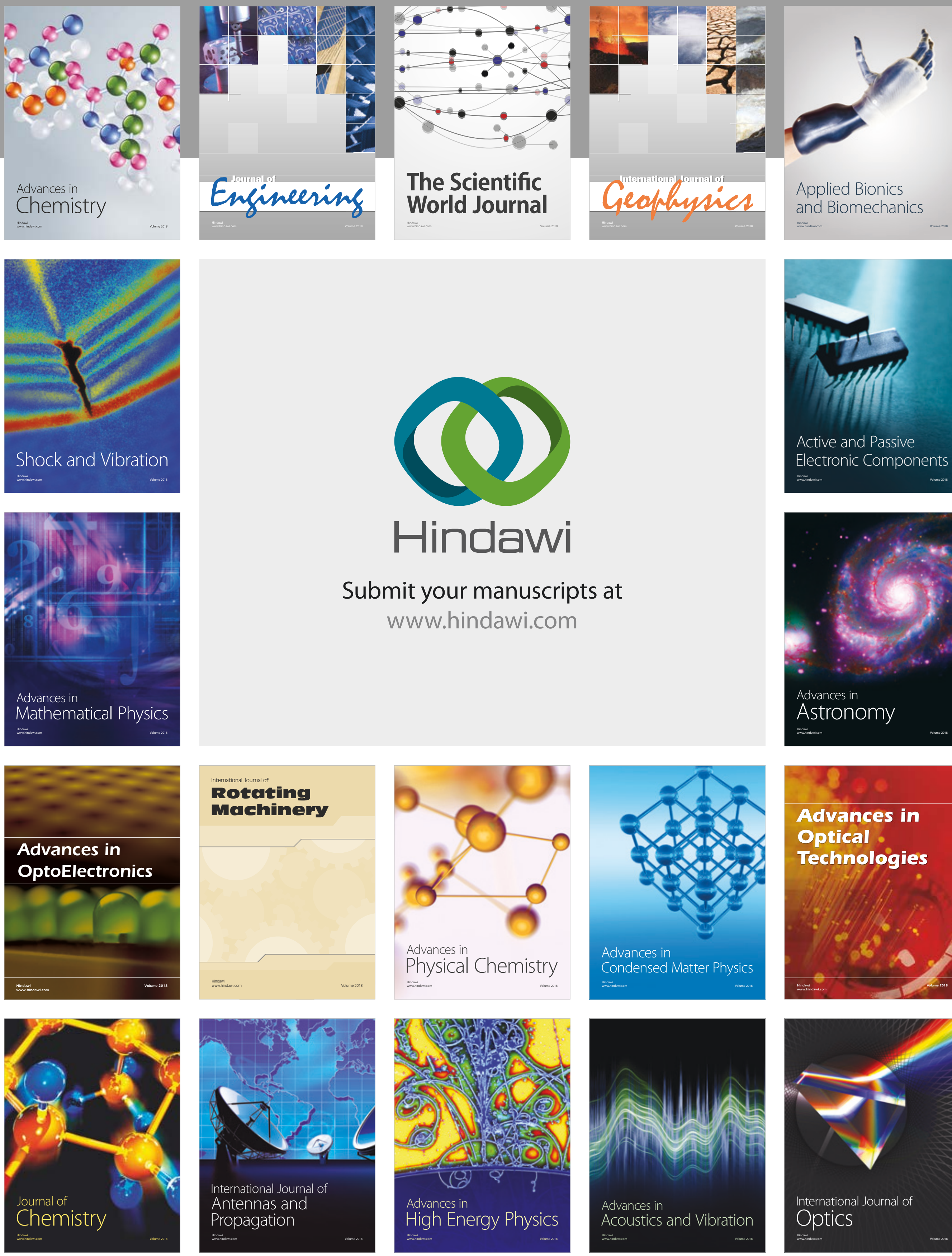
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