**Sudan University of Science and Technology**

**College of Graduate Studies**

**Department of Physics**

# The Effects of Partial Shading and Dust on the Performance of solar cells

**آثار التظليل الجزئى والغبار على أداء الخلايا الشمسية**

**A** thesis Submitted in Partial Fulfillment for the Requirement for the Degree of Master of Physics

By:

**Walaa Abdelmajeed Ebrahim**

Supervised by:

**Prof. Mohammed Osman Sid-Ahmed**

**October 2016**

بسم الله الرحمن الرحيم

Sudan University of Science & Technology

College of Graduate Studies

جامعة السودان للعلوم والتكنولوجيا

كلية الدراسات العليا

كلية الدراسات العليا

# Approval Page

Name of Candidate: Walaa Abdelmajeed Ebrahim

Thesis title: The Effects of Partial Shading and Dust on the Performance of Photovoltaic System

Approved by:

**1. External Examiner**

Name: Hassan Wardi Hassan

Signature: ............ Date: 13/10/2016

**2. Internal Examiner**

Name: Ahmed Elhassan Elfaki

Signature: ............ Date: 13/10/2016

**3. Supervisor**

Name: Mohamed Osman Sid-Ahmed

Signature: M.O. ............ Date: 13/10/2016

# الاية

اعوذ بالله من الشيطان الرجيم

**قال تعالى:**

(قَل رَبِّ اشْرَحْ لِي صَدْرِي (25) وَيَسِّرْ لِي أَمْرِي (26) وَاحْلُلْ عُقْدَةً مِنْ لِسَانِي (27) يَفْقَهُوا قَوْلِي (28)

صدق الله العظيم

سورة طه (25-28)

# DEDICATION

To my great mother.

To my great father.

To my sister and my brothers.

To all who helped me.

This simple effort with my love & best wishes.

# Acknowledgements

Sincere gratitude to Prof. Mohammed Osman Sid-Ahmed for his supervision throughout this work; his contributions in stimulating suggestions and encouragement has helped me to improve my thesis.

## Abstract

In this work the effects of partial shading and dust on the performance of single, series and parallel-connected solar cells has been studied. The measurements have been taken in the Energy Researches Council, Soba, Khartoum. The current and voltage of the two solar cells have been measured from each cell and also, when the cells are connected in series and in parallel. From the results it is concluded that both shading and dust reduce the current. It appears that when a solar cell is partially shaded or covered with dust, it becomes equivalent to a resistor which consumes the energy generated by its neighboring cell. The loss of power could justify the application of self-cleaning coating.

# ملخص البحث

في هذا البحث  تم دراسة آثار التظليل الجزئي و الغبار على أداء خلية شمسية واحدة ثم خليتين شمسيتين متصلتين على التوالي والتوازي . أجريت التجربة داخل معهد أبحاث الطاقة- سوبا. تم قياس فرق الجهد و التيار الكهربي لكل خلية شمسية على حدة ثم قياسهما لخليتين شمسيتين تم توصيلهما علي التوالي و التوازي.من ملاحظة النتائج تم التوصل إلى أن التظليل الجزئي و الغبار يقللان قيمة التيار. من الواضح أنه عندما تكون الخلية الشمسية تحت تأثير التظليل الجزئي أو الأوساخ  فإنها تصبح مثل المقاومة التي تستهلك الطاقة المنتجة بواسطة الخلية المجاورة .فقدان الطاقة قد يبرر إستخدام تقنية التنظيف الذاتي .

## List of Contents


الاية ........................................................................................ii
DEDICATION ........................................................................................ii
Acknowledgements ........................................................................................ iii
Abstract ........................................................................................iv
ملخص البحث ........................................................................................v
List of Contents ........................................................................................vi
List of Figures ........................................................................................ viii
List of tables ........................................................................................ix
Chapter one ........................................................................................1
1.1 Introduction: ........................................................................................1
1.2 Solar energy in Sudan: ........................................................................................1
1.3 Future plan of solar energy in Sudan: ........................................................................................5
1.4 Lay out of the thesis ........................................................................................7
Chapter Two ........................................................................................8
Effects of partial shading and dust ........................................................................................8
2.1 Introduction ........................................................................................8
2.2 Effect of partial shading ........................................................................................8
2.3 Photovoltaic array configurations: ........................................................................................8
2.3.1 Series-parallel (SP) configuration: ........................................................................................8
2.3.2 Bridge- linked(BL): ........................................................................................9
2 .3.3 Total-cross-tied (TCT): ........................................................................................9
2. 3.4 Honey-comp(HC): ........................................................................................9
2.4 Effect of dusts: ........................................................................................11
2.5 Cleaning methods: ........................................................................................12
2.5.1 Mechanical removal of dusts: ........................................................................................12
2.5.2 Electrostatic removal of dusts: ........................................................................................12
2.5.3 Self-cleaning nano-film: ........................................................................................12

Chapter Three ........................................................................................ 14
Instrumentation and method ........................................................................ 14
3.1 Instrumentation ...................................................................................... 14
3.2 Experimental procedure .......................................................................... 15
3.3 The effect of partial shading .................................................................. 16
3.4 The effect of dust ................................................................................... 16
Chapter Four ........................................................................................... 17
Results and discussion .............................................................................. 17
4.1 Effect of partial shading .......................................................................... 17
Chapter Five ............................................................................................ 23
Conclusion and recommendations ............................................................... 23
5.1 Conclusion ............................................................................................. 23
5.2 Recommendations ................................................................................... 23
References ............................................................................................... 24

# List of Figures


Fig 1.1. Electricity generation……………………………………... 2

Fig 1.2. Solar irradiation map in Sudan ………………………… 3

Fig 1.3. Renewable energy -targets 2031……………………….. 6

Fig 2.1 Solar array configurations………………………………. 10

Fig 3.1. Solar cell ………………………………………………. 14

Fig 3.2. AVO-meter…………………………………………….. 15

Fig 3.3. Rheostat ……………………………………………... 15

Fig 3.4. Circuit diagram for measuring the IV characteristic of solar cell……………………………………………………… 16

Fig 4.1. IV characteristics of two solar cells, one of them was partially shaded…………………………………………………….. 17

Fig 4.2. IV characteristics of two solar cells, connected in series. One of them was partially shaded……………………………….. 18

Fig 4.3. IV characteristics of two solar cells, connected in parallel. One of them was partially shaded……………………… 19

Fig 4.4. IV characteristics of two solar cells, one of them was partially covered with dust……………………………………… 20

Fig 4.5. IV characteristics of two solar cells, connected in series. One of them was partially covered with dust…………………… 21

Fig 4.6. IV characteristics of two solar cells, connected in parallel. One of them was partially covered with dust………….. 22

## List of tables

Table 1.1. Total solar irradiation (MegaJ$m^{-2}$\year) for 7stations, averaged Table over 30 years )……………………………………………………………4

# CHAPTER ONE

# INTRODUCTION

# Chapter one

## 1.1 Introduction:

The demand for the provision of energy is increasing rapidly and the trend is likely to continue in future worldwide. In 2005 [1], the worldwide electricity generation was 17450 TW h out of which 16% originated from hydro, 40% from coal, 20% from gas,16% from nuclear, 7% from oil and only 2% from renewable sources (small hydro, wind, geothermal, etc.) . At present, renewable energy resources contributes 13.5% of the global energy demand [1].

A typical PV module is made up of around 36 or 72 cells connected in series, encapsulated in a structure made of aluminum, depending on the application and type of cell technology being used. The increasing demand of electricity peak load has activated the utilization of renewable energy for different kinds of applications area such as heating, ventilation and air- conditioning.

## 1.2 Solar energy in Sudan:

The Sudan has largely untapped – renewable energy resources. Solar energy, averaging 6.1 $kWh/m^2$ [2], is particularly significant, and is considered one of the best solar resources globally. Moreover, it is well distributed throughout the country, facilitating the provision of energy services to rural settlements that are unlikely to be reached by modern energy infrastructure (electric grid and pipelines) in the foreseeable future, Fig.1.2 and Table 1.1. This renewable energy potential is increasingly recognized by the Government.

Presently, electricity generation is mainly by hydro (51%). The contribution of solar energy is not significant, Fig.1.1.

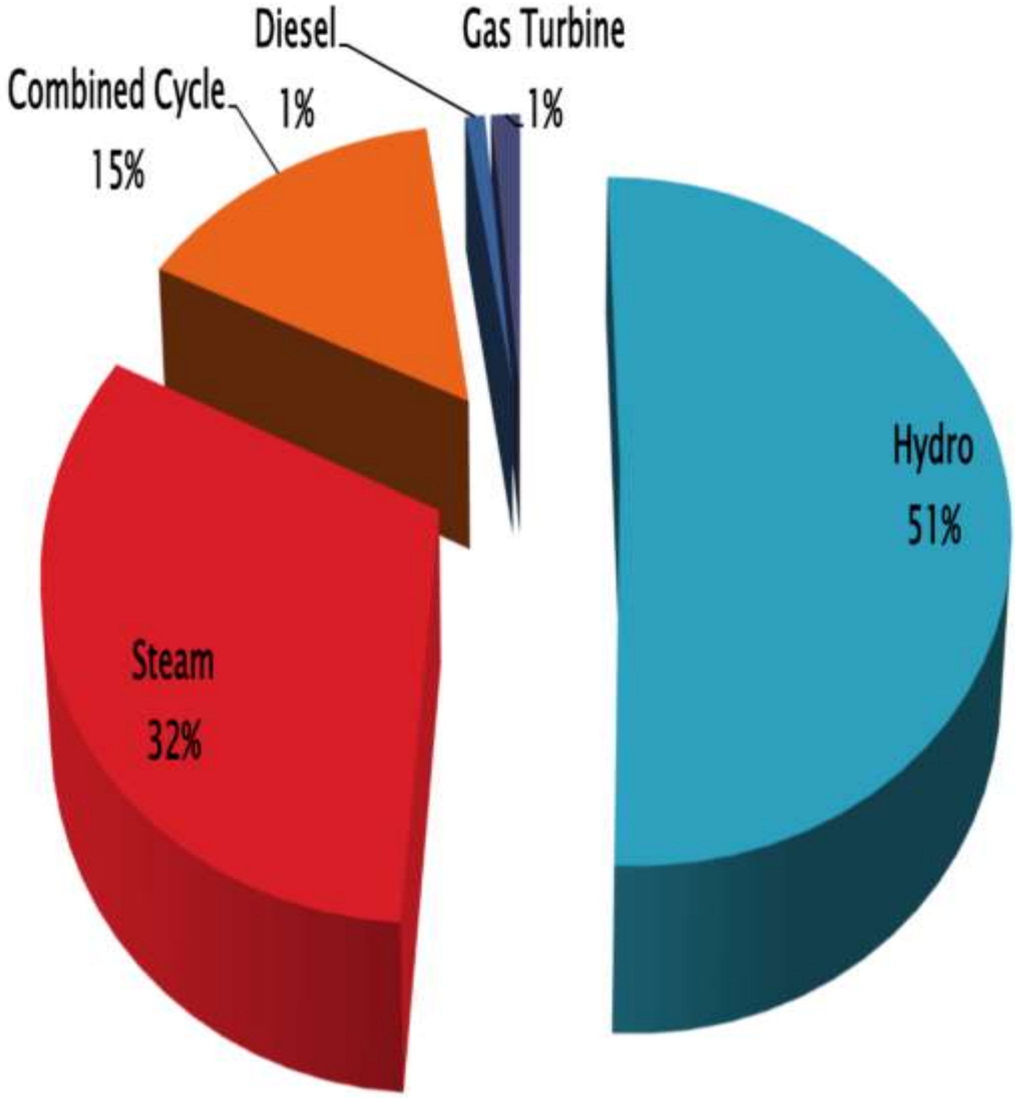


**Fig 1.1. Electricity generation [2].**

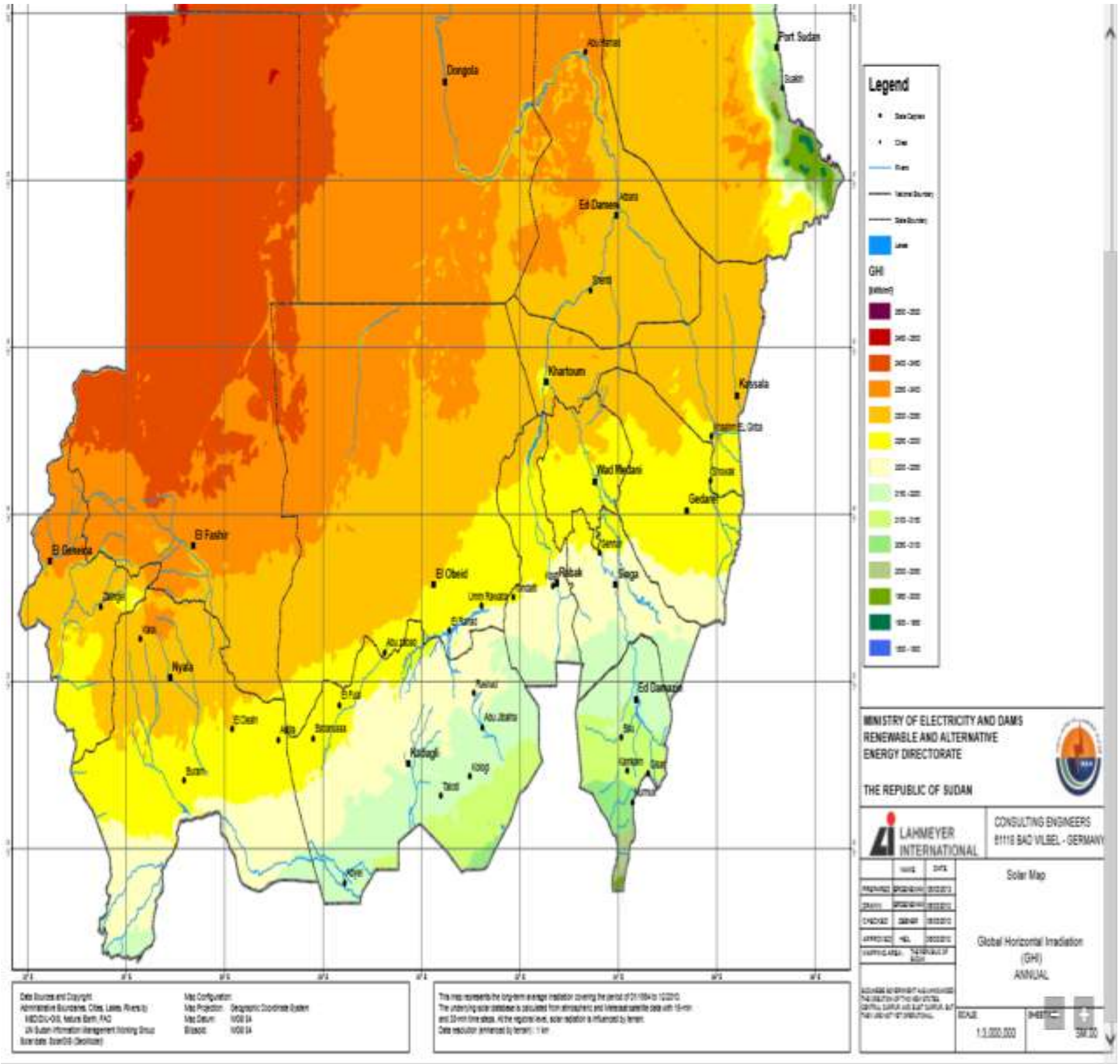


**Fig1.2. Solar irradiation map in Sudan[2].**

**Table 1.1: Total solar irradiation (MegaJ m$^{-2}$\year) for 7stations, averaged over 30 years )[3].**

| | Kadogle11° 00´N, 29° 43´E | Alfasher 13° 38´N, 25° 20´E | Abonaama 12° 44´N 34° 08´E | Madani 14° 23´N, 33° 29´E | Port sudan 19° 35´N, 37° 13´E | ˡDongola 19° 10´N, 30° 29´E | Gazala Jawazet 11° 28´N, 26° 27´E |
|---|---|---|---|---|---|---|---|
| January | 21.23 | 20.71 | 21.76 | 21.39 | 15.33 | 19.23 | 20.52 |
| February | 22.83 | 23.46 | 24.8 | 23.46 | 19.42 | 21.09 | 22.48 |
| March | 23.13 | 24.7 | 26.55 | 24.94 | 32.48 | 24.98 | 23.36 |
| April | 23.97 | 25.43 | 26.07 | 26.03 | 25.96 | 25.81 | 23.57 |
| May | 21.25 | 25.10 | 26.02 | 26.44 | 25.38 | 25.88 | 23.53 |
| June | 19.23 | 23.92 | 23.83 | 24.05 | 26.08 | 25.68 | 21.65 |
| July | 20.01 | 22.45 | 22.12 | 22.76 | 22.69 | 24.54 | 20.47 |
| August | 18.15 | 23.3 | 22.6 | 23.48 | 22.76 | 23.74 | 21.23 |
| September | 18.57 | 23.3 | 23.84 | 23.48 | 22.61 | 22.92 | 21.31 |
| October | 20.13 | 22.76 | 22.47 | 22.67 | 2.53 | 22.04 | 21.39 |
| November | 21.77 | 21.88 | 22.01 | 21.63 | 16.92 | 19.84 | 21.23 |
| December | 22.66 | 20.58 | 20.67 | 20.72 | 15.14 | 18.41 | 20.35 |
| Average\Year\Day | 21.8 | 23.03 | 23.32 | 23.37 | 21.36 | 22.85 | 21.60 |

### 1.3 Future plan of solar energy in Sudan:

Presently , there are four solar energy generation projects with a total capacity of 20 MW:

- 10MW Khartoum photovoltaic power plant.
- 5MW Nyala photovoltaic power plant.
- 3MW Alfashir photovoltaic power plant.
- 2MW Algenina photovoltaic power plant.

The Ministry of Water Resources and Electricity (WRE) has a Renewable Energy Master Plan (REMP), Fig.1.3,for power generation from the renewable energy resources in Sudan. In 2031, renewable energy (RE) will represent 29.3% of the installed capacity[2].

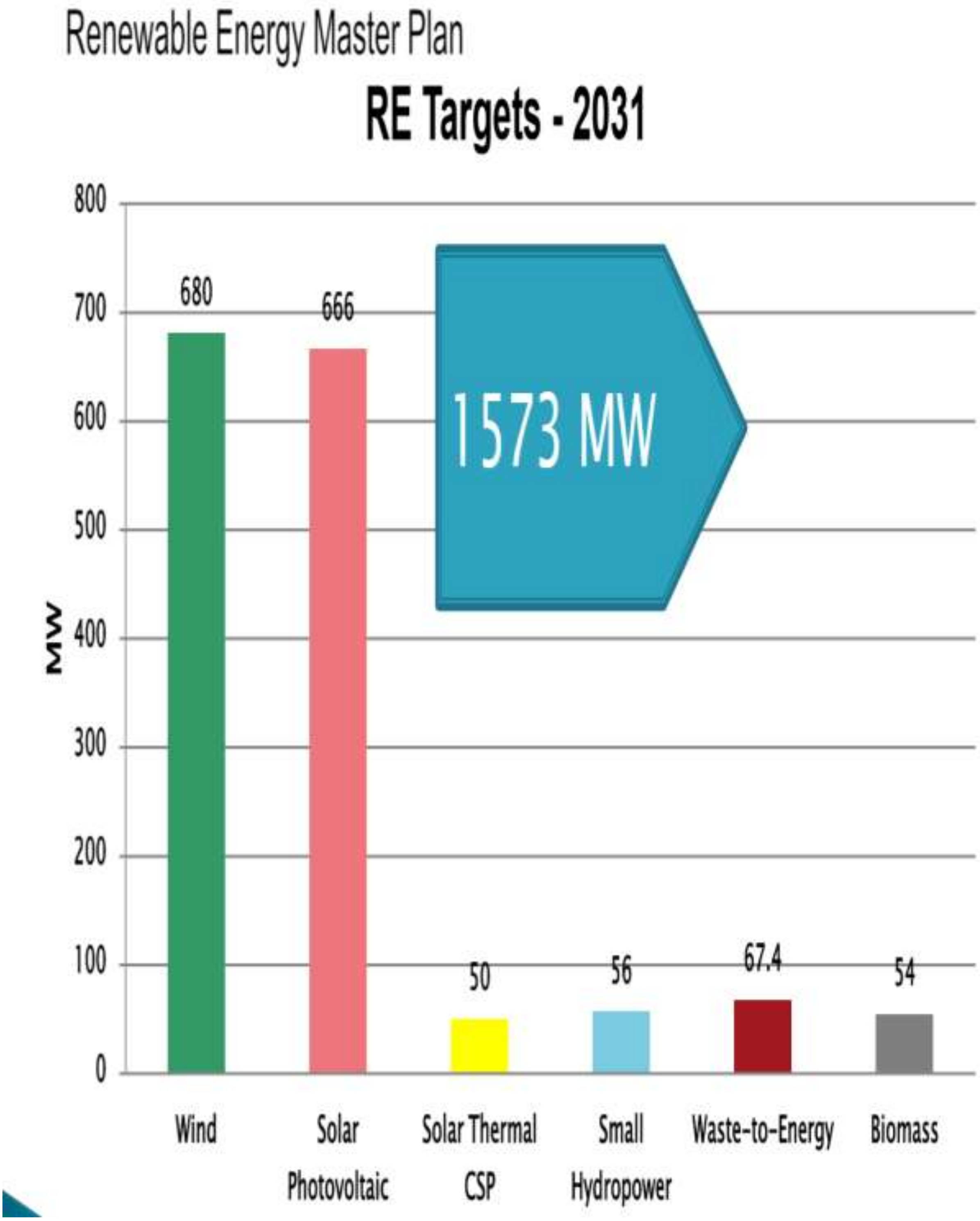


**Fig 1.3. RE targets - 2031 [2].**

## 1.4 Lay out of the thesis

This thesis contains five chapters. Chapter one is about introduction and sources of energy in Sudan and chapter two discuss the effects of partial shading and dust on the performance of solar cells. Chapter three contains the instrumentation and method and chapter four is about results and discussion. Chapter five contains the conclusion and recommendations.

# CHAPTER TWO

# EFFECTS OF PARTIAL SHADING AND DUST

# Chapter Two
# Effects of partial shading and dust

## 2.1 Introduction

Photovoltaic (PV) is a method of generating electrical power by converting solar radiation into direct current electricity using semiconductors that exhibit the photovoltaic effect. Photovoltaic power generation employs solar panels composed of a number of cells containing a photovoltaic material. Since the panels cover a large area, some of the panels could be partially shaded by buildings, dust or other light blocking objects. This could cause reverse-biasing [4].

## 2.2 Effect of partial shading

If solar panels cover a vast area, it is so much probable that some parts of the cells become shaded by any reason like trees' shadow, birds nesting on solar panels, passing clouds and neighboring tall buildings. In this situations, the shaded cells may act reversely and deplete power from other turned-on cells which reduces solar cells output power [5] .

## 2.3 Photovoltaic array configurations:

Solar arrays of photovoltaic systems use various configurations to achieve desired voltage and currents .These are; parallel (P), series(S), series-parallel(SP), total-cross-tied(TCT), bridge-linked(BL) and honey- comp(HC).

### 2.3.1 Series-parallel (SP) configuration:

In SP configuration, the modules are connected in series to each other to reach the required voltage and then these series connections are connected in parallel to each other, Fig.2.1(a).

### 2.3.2 Bridge- linked(BL):

In BL configuration, every four modules are connected to each other in the form of a rectifier bridge in which at first two modules are connected in series and then in parallel to each other, Fig.2.1(b).

### 2 .3.3 Total-cross-tied (TCT):

TCT configuration is formed by connecting all nodes of rows in SP configuration. In TCT configuration, the voltages of all nodes and also the sum of currents in different junctions are equal, Fig .2.1(c).

### 2. 3.4 Honey-comp(HC):

By modification of BL configuration, a new configuration named as HC is formed.

The advantages of BL and TCT configurations are combined in HC configuration, Fig.2.1(d).

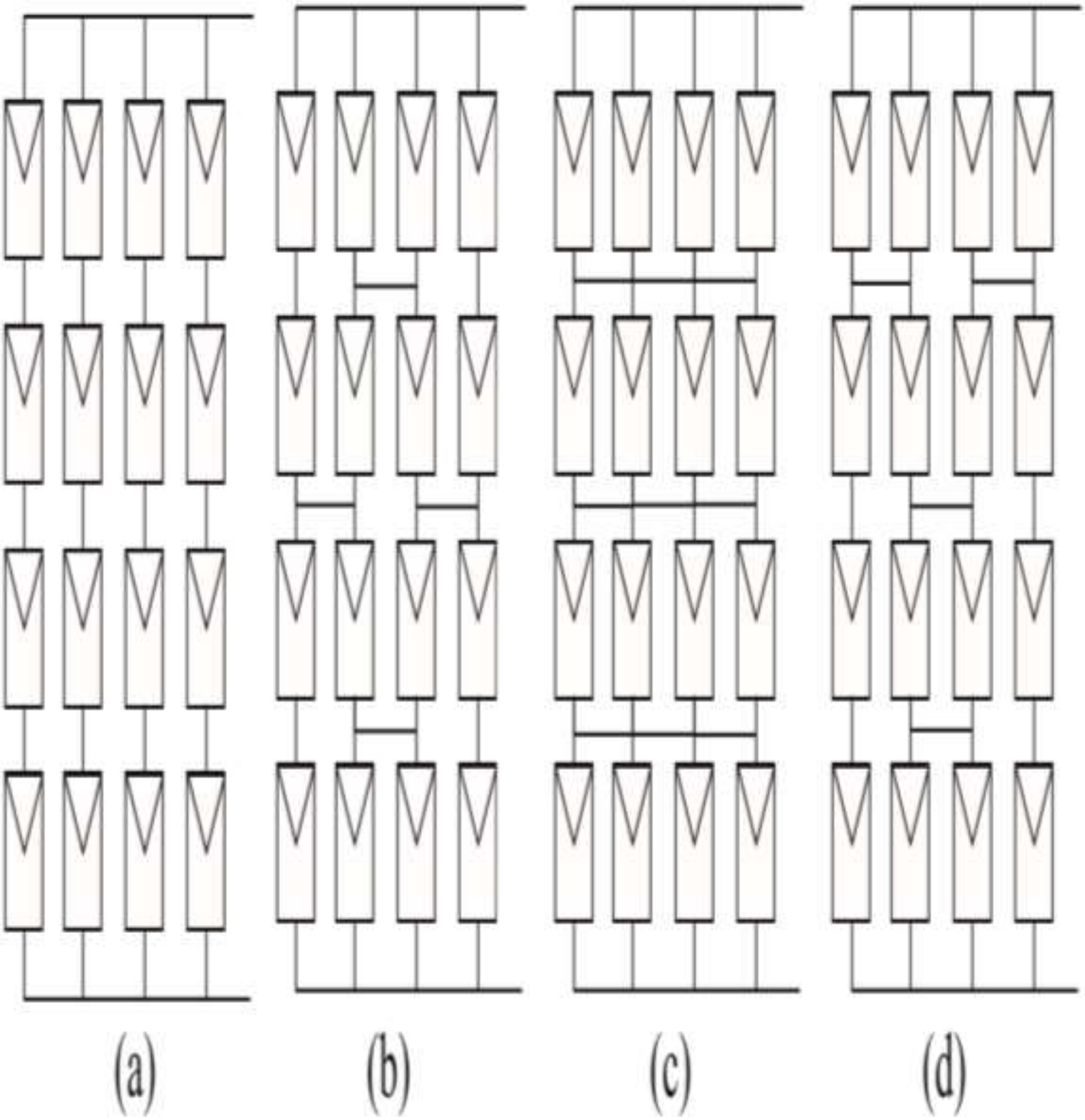


**Fig 2.1Soalr array configurations (a) SP, (b) BL, (c) TCT, (d) HC.**

There have been many studies conducted on comparison between different solar array configurations (SP, HC, BL and TCT) under partial shading conditions. Mohammadnejad [5], analysed theTCT configuration, under partial shading conditions, using Matlab simulation. The results showed the superiority of the performance of TCT compared to other configurations. Similarly, Belhachat [6], found that the TCT configuration presents the best performance, concerning the highest maximum power and hence the lowest relative power losses when one or two columns are completely and unevenly shaded.

**2.4 Effect of dusts:**

Large-scale solar installations usually are located in sun-drenched desert areas where winds sweep dust into the air and deposit it onto the surface of solar panel. That dust reduces the amount of light that can enter the solar panel, decreasing the amount of electricity produced. The motion of dust particles during wind erosion causes charging of the particles and it is particle size dependent .The electrostatic charge of the dust particles can significantly affect the PV system output especially in the tropical/desert region/industrial area applications[7].Dust accumulation on a surface mainly depends on dust particle's size, electrostatic charge, and the presence or absence of an adsorbed moisture layer, the electrical resistivity of the dust, etc.

After a dust storm, smaller particles are predominantly charged positive and larger particles are predominantly charged negative. Clouds of uncharged particles such as sand or volcanic ash become charged by some undetermined mechanism and experiments now show that nearby electric

fields could be responsible.

## 2.5 Cleaning methods:

### 2.5.1 Mechanical removal of dusts:

The mechanical methods remove the dusts by brushing, blowing, vibrating and ultrasonic driving . The brushing methods clean the solar cell with something like the broom or brush driven by a machine. It is designed just like a windscreen-wiper. This method is not very attractive because it requires a source of external power.

### 2.5.2 Electrostatic removal of dusts:

The most popular the electro dust removal technology is based on the electric curtain. The electric curtains consist of a series of parallel electrodes embedded in a dielectric surface, across which are transmitted oscillations in the electrode potentials. When the electrodes connect to a multi-phase AC voltage, a traveling-wave electric curtain be excited .Under the right frequency and amplitude conditions, the charged particles will not be allowed to deposit, but will be entrained to move along the surface following the electric field. In this way, the surface will stay clean of particle deposition .

### 2.5.3 Self-cleaning nano-film:

The self-cleaning nano-film is made of super-hydrophilicity material or super-hydrophobic material.

#### 2.5.3.1 Super-hydrophopic film:

Super-hydrophobic surfaces such as the leaves of the lotus plant show high hydrophobicity and extremely low wettability. Various studies have been conducted to realize superhydrophobic surfaces by forming microstructures or nanostructures. The nanostructures of this surface can enhance the contact angle (CA) to higher than 150, so the Water droplets that hit the surface would quickly roll off, carrying dust and other particles with them [8].

### 2.5.3.2 Super-hydrophilicity:

The popular super hydrophilcity film is $TiO_2$.The thin-film must be activated to be operational. The activation occurs by virtue of UV radiation, where the $TiO_2$ reacts with the oxygen and water molecules in the air and produces free radicals leading to oxidative species .This process needs some daylight exposure, usually about one week, to ensure full activation. When dirt, dust and other deposits later may fasten to the surface as a result of natural weathering, the UV radiation causes oxidative species that results in photogenerated electrons and holes. Electrons will then reduce oxygen to water (vapor) and holes will oxidize the organic matter, and there of deteriorating the dirt and dust [9].

Y.Xu and J.Liao[10], prepared a highly –reflective thin film consisting of $TiO_2$ -$SiO_2$-Ag by magnetron sputtering for solar front reflectors .The thin film showed a highest reflectivity of a -bout 0.9601 which was identical with the simulated results based on the designed model. Xiande Lu [11], developed a transparent coating with thermal insulation and self-cleaning properties using fluorocarbon emulsion doped with proper ATO and anatase $TiO_2$ nanoparticles. ATO and $TiO_2$ co-doped fluorocarbon coating exhibit excellent thermal insulation properties, good self-cleaning performance, as well as being highly transparent for visible light.

C.Thompson[12], has demonstrated a simple silica nanoparticle film that exhibits excellent self-cleaning and antifogging properties due to the super-hydrophilicity of the coating. The coated surface was found to remove twice the amount of contaminant particles than bare glass under light wetting conditions. This results in a 4.3% increase of the solar transmittance between 350and 1100 nm.

# CHAPTER THREE

# INSTRUMENTATION AND METHOD

# Chapter Three

## Instrumentation and method

### 3.1 Instrumentation

1- Solar cells, Fig 3.1.

2- Two AVO-meters, one for measuring current through rheostat and the other for measuring the voltage, Fig 3.2.

3- Rheostat, Fig3.3.

4- Connection wires.

Fig 3.1. Solar cell.

Fig 3.2.  AVO-meter.

Fig 3.3. Rheostat.

**3.2 Experimental procedure**

The measurements were taken in the Energy Researches Council, Soba. The current and voltage of the two solar cells were measured for each cell and then when the cells were connected in series and in parallel, Fig 3.4.

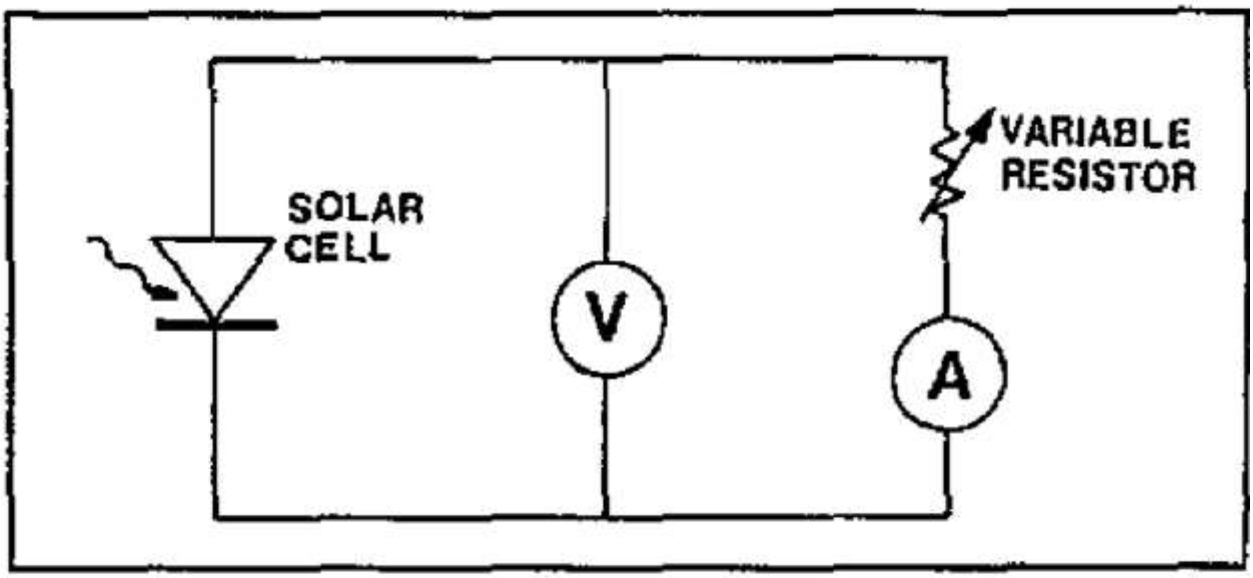


Fig 3.4. Circuit diagram for measuring the IV characteristic of solar cell.

### 3.3 The effect of partial shading

One of the cells has been partially shaded. The measurements were taken as described in Fig 3.4.

### 3.4 The effect of dust

One of the cells has been partially covered with dust. The measurements were taken as described in Fig 3.4.

# CHAPTER FOUR

# RESULTS AND DISCUSSION

## Chapter Four

## Results and discussion

### 4.1 Effect of partial shading

Fig.4.1 shows the IV characteristics of separated and identical cells with one of them was partially shaded. The shading decreased the current from 3.5 to 2.9 A.

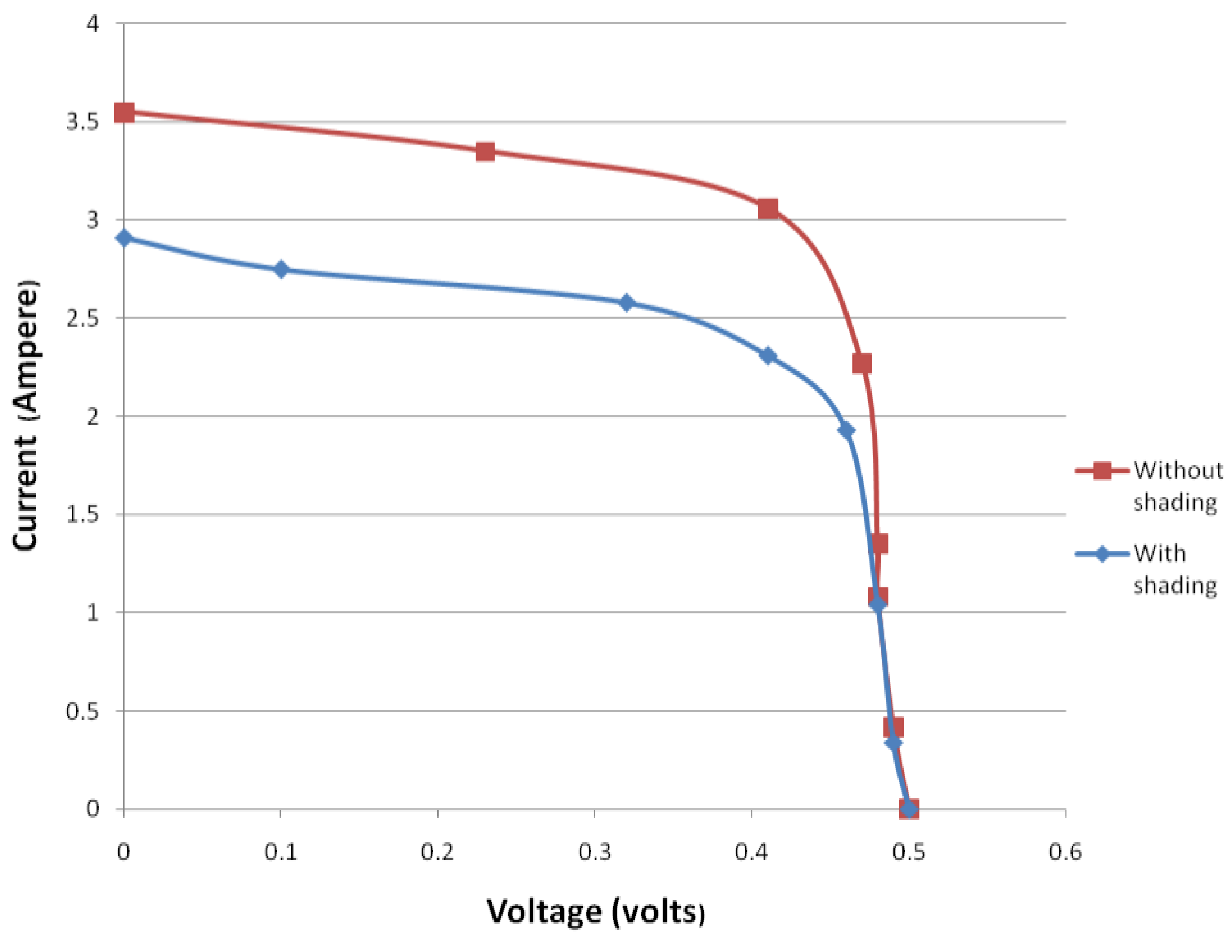


Fig 4.1. IV characteristics of identical solar cells, one of them is partially shaded.

Fig 4.2 shows the IV characteristics of two solar cells, connected in series. One of the cells was partially shaded. There is no effect on the voltage, but the current decreased from 3.56 to 3.17 A.

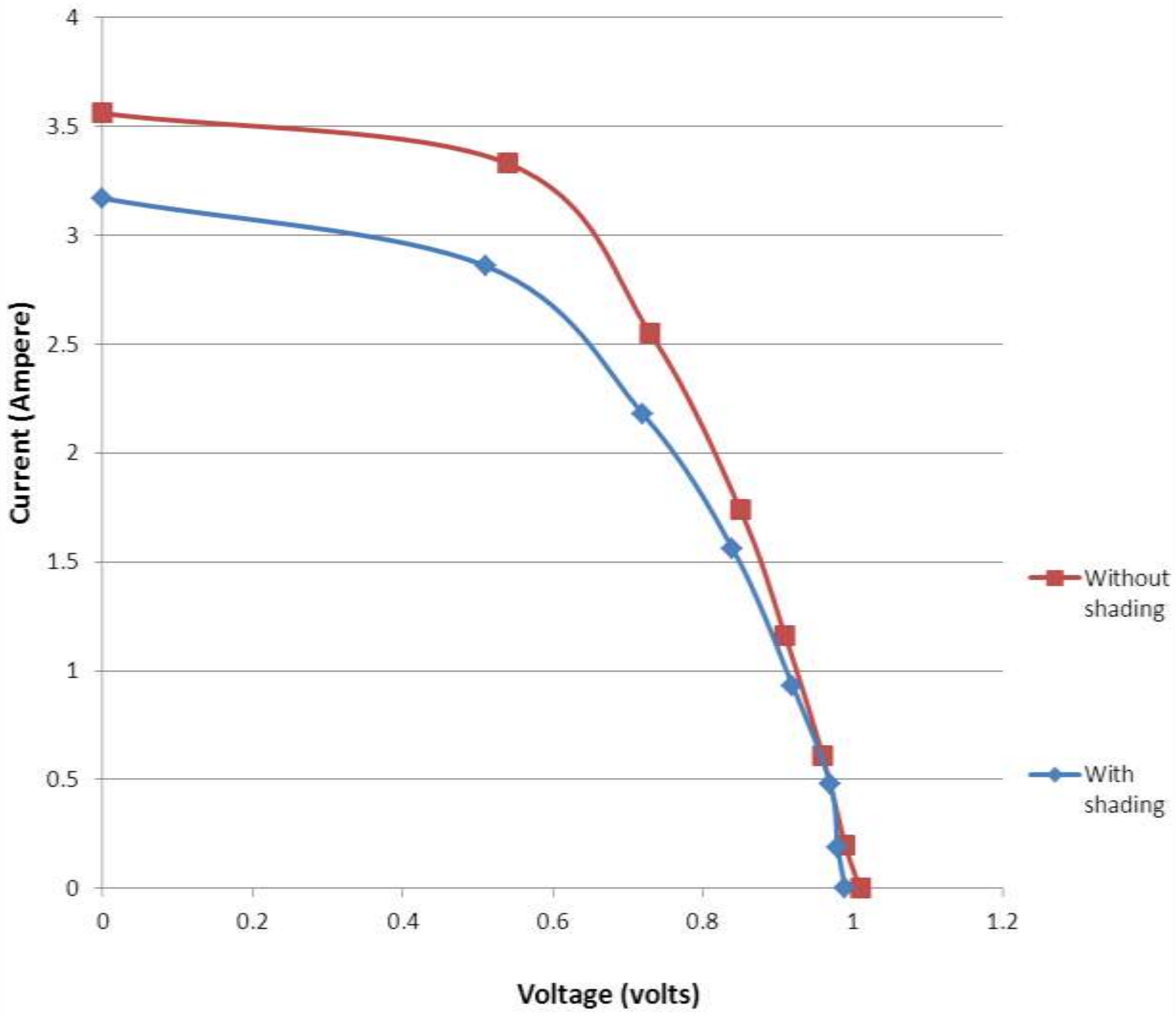


**Fig 4.2. IV characteristics of two solar cells, connected in series.One of them was partially shaded.**

Fig 4.3 shows the IV characteristics of two solar cells, connected in parallel. One of the cells was partially shaded. The shading decreased the current from 6.92 to 5.7A.

It appears that when a solar cell is shaded, it became equivalent to a resistor which consumes the energy generated by its neighboring cell. Partial shading has serious consequences like hot spots. Hot spots lead to distractive affects that include flawing the glass or the cell, melting soldered parts and dismantling solar cells [7].

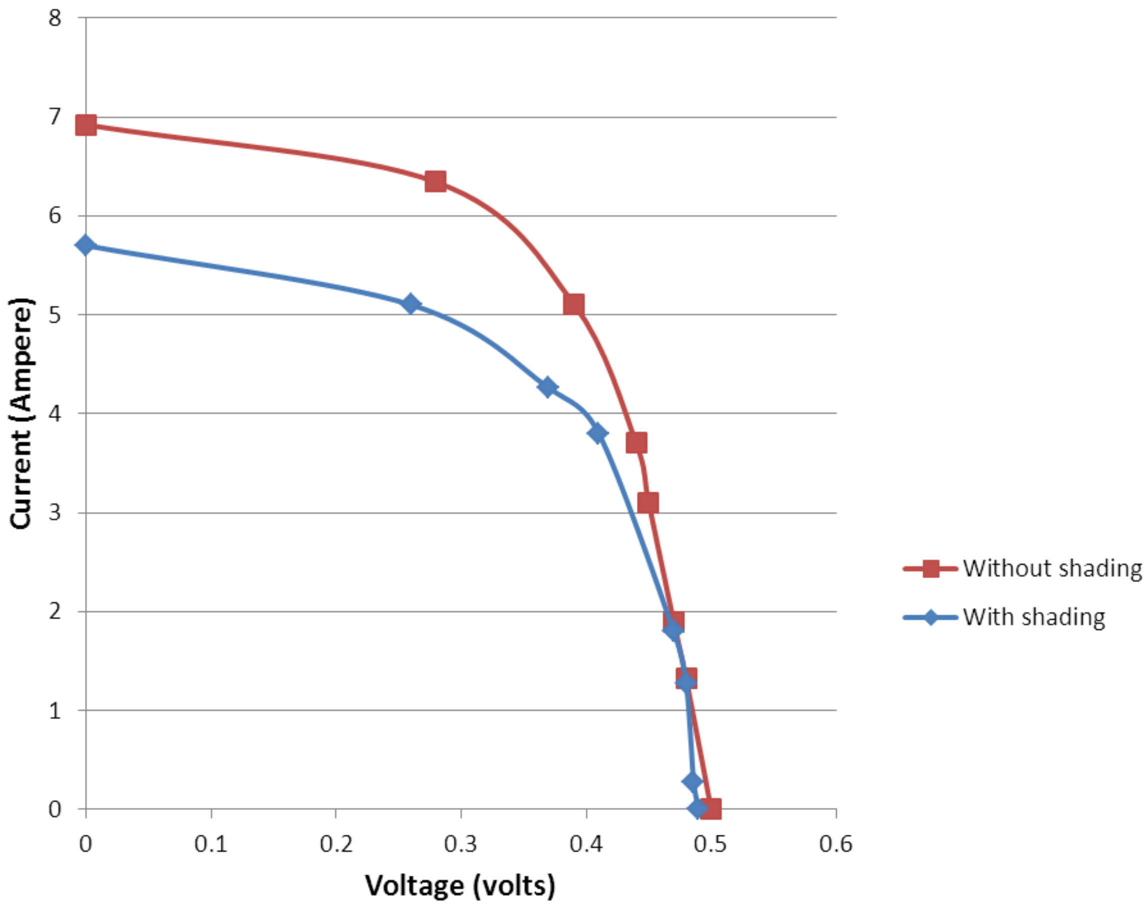


**Fig 4.3. IV characteristics of two solar cells, connected in parallel. One of them was partially shaded .**

## 4.2 Effects of dust

Fig 4.4 shows the IV characteristics of separated and identical cells, one of the cells was partially covered with dust. The dust decreased the current from 3.52 to 2.87 A.

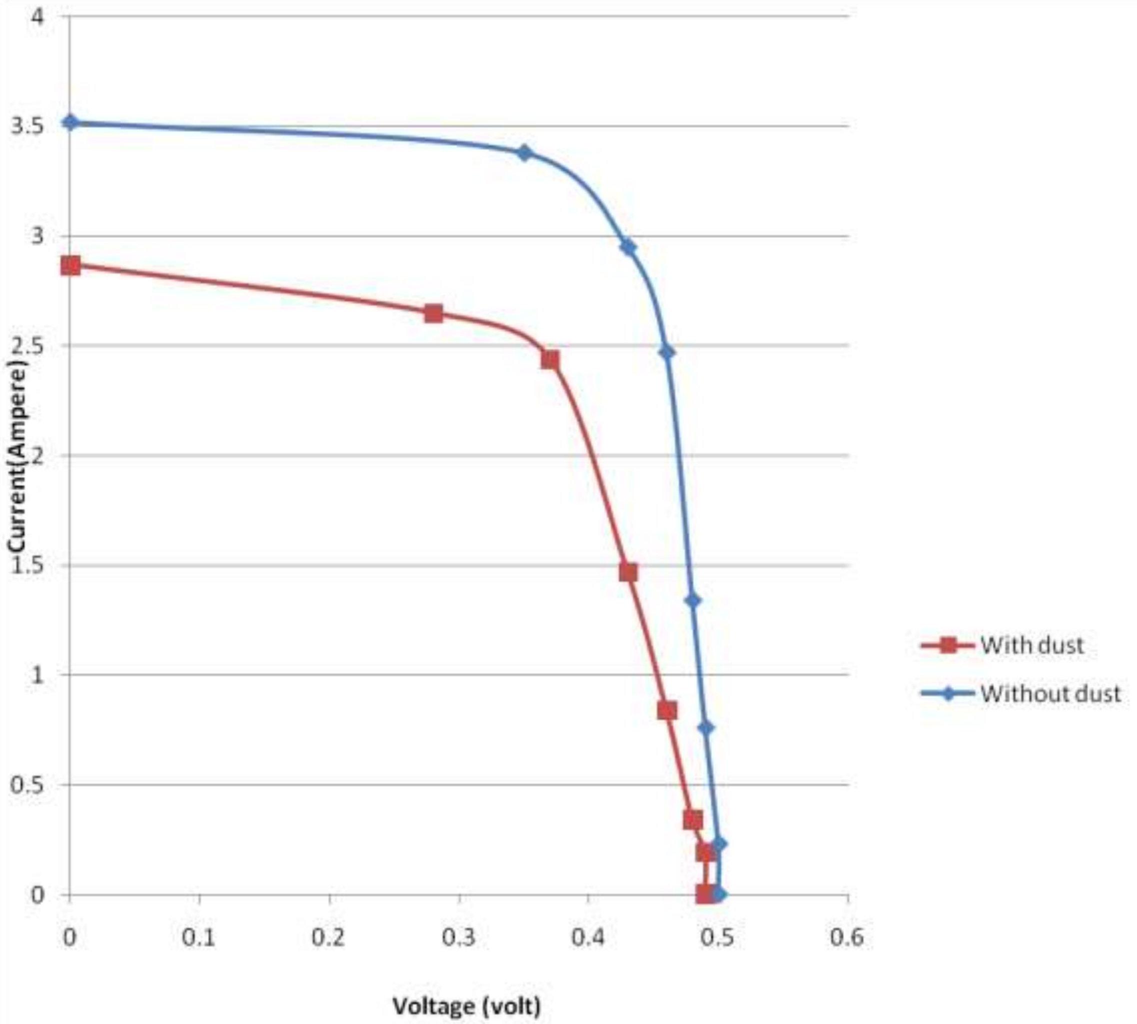


**Fig 4.4. IV characteristics of identical solar cells. One of them is partially covered with dust.**

Fig 4.5 shows the IV characteristics of two solar cells, connected in series. One of the cells was partially covered with dust. The dust decreased the current from 3.56 to 3.06 A.

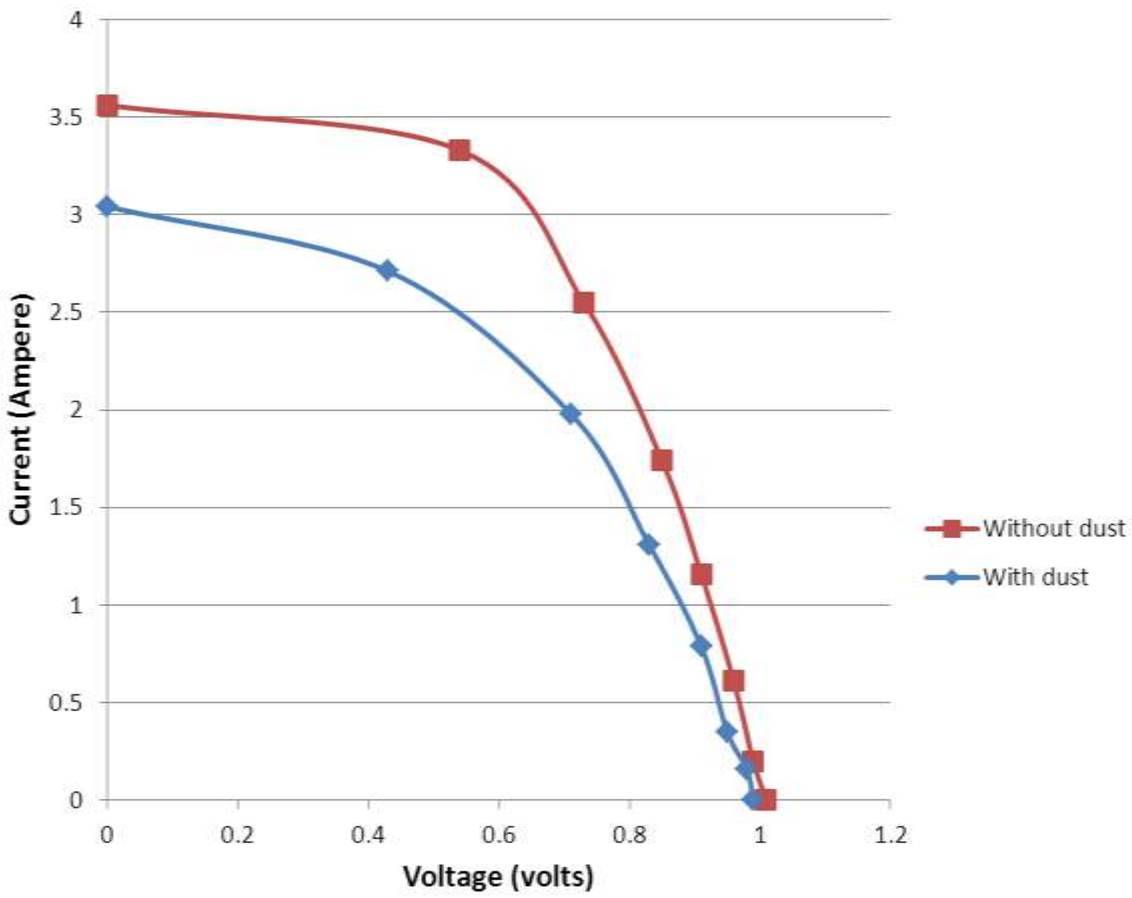


**Fig 4.5. IV characteristics of two solar cells, connected in series. One of them was partially covered with dust.**

Fig 4.6 shows the IV characteristics of two solar cells, connected in parallel. One of the cells was partially covered with dust. The dust decreased the current from 6.9 to 5.49A.The dust deposition reduces the amount of radiation which is falling on the cell and creates shadow effect. The effect of dust is typical to that of shading.

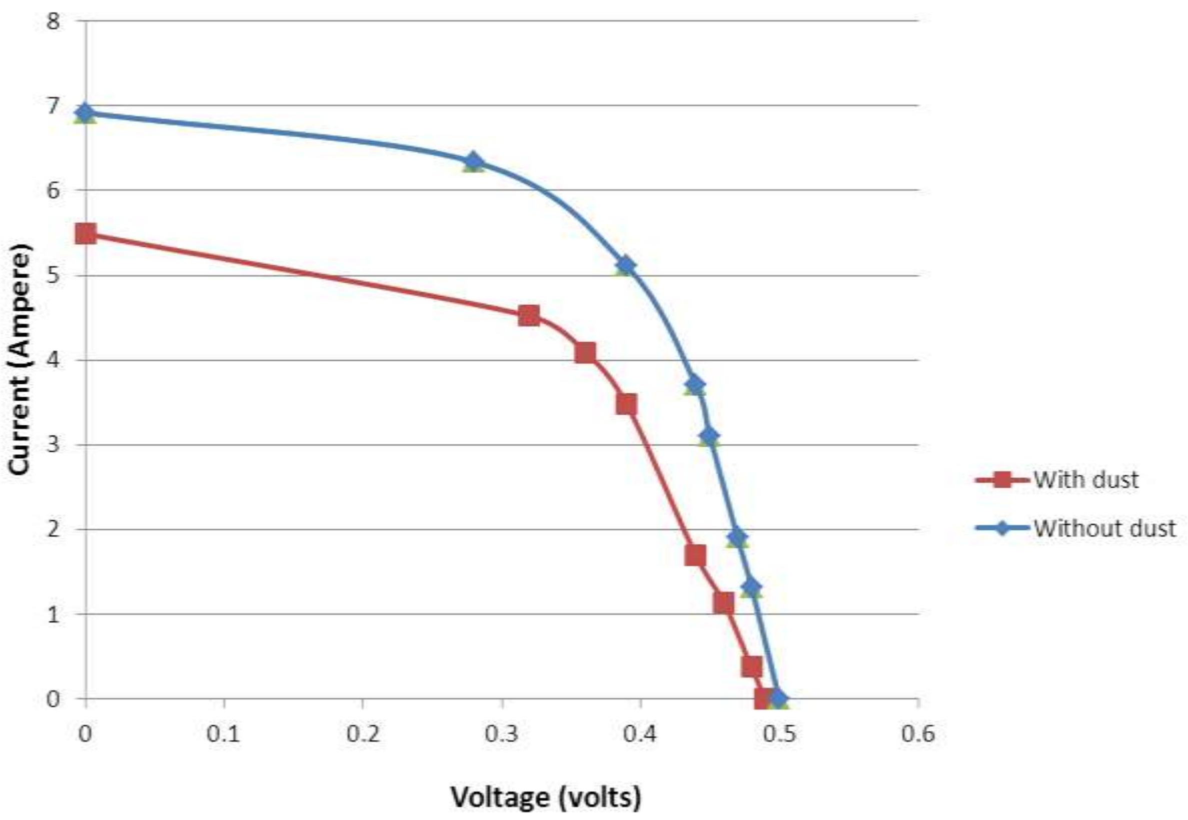


**Fig 4.6. IV characteristics of two solar cells, connected in parallel. One of them was partially covered with dust.**

# CHAPTER FIVE

# CONCLUSION AND RECOMMENDATIONS

# Chapter Five
# Conclusion and recommendations

## 5.1 Conclusion

In this work, the effect of partial shading and dust on the performance of single, series and parallel- connected solar cells was studied. It was found that both shading and dust reduced the current. When a solar cell was shaded, or covered with dust, it became equivalent to a resistor which consumes the energy generated by its neighboring cell. The dust deposition reduces the amount of radiation which is falling on the cell, so the power generation is reduced.

## 5.2 Recommendations

1. The problem of dust can be solved by using self-cleaning technology. The power loss could justify the additional cost of self-cleaning.

2. The effects of partial shading and dust can be reduced by using total-cross-tied configuration [5,6].

## References

[1] Sarat Kumar Sahoo, Solar photovoltaic energy progress in India:Areview, Renewable andSustainable Energy Reviews 59 (2016) 927-939 .

[2] Yassir Saied,The future of energy in Sudan. Ministry of Water Resources and Electricity, Sudan 2015.

[3] Sudanese petroleum corporation, General Directorate for Energy Affairs.

[4] I.Geisemyer,F.Fertig et al.,Prediction of silicon PV module temperature for hot spots and worst case partial shading situation using spatially resolved lock-in thermography. Solar Energy Materials &Solar Cells 120 (2014) 259-269.

[5] Shahram Mohammad Nejad et al.,Mathematical Analysis of total-cross -tied photovoltaic array under partial shading condition and its comparison with other configurations.Solar Energy 133 (2016) 501-511.

[6] F.Belhachat, C,Larbes, et al. Modeling, Analysis and comparison of solar photovoltaic array configurations under partial shading conditions. Solar Energy 120 (2015) 399-418.

[7] K.Dastoori, G.Shabaan, et al., Impact of accumulated dust particles charge on the photovoltaic module performance. Journal of Electrostatics 79 (2016) 20-24.

[8] Gaofa He, Chunde Zhou, et al., Review of seif-cleaning method for solar cell array. Procedia Engineering 16 (2011) 640-645.

[9] Krister M iatdal, Bjon Petter, Self- cleaning glazing products: A state- of-the-art review and future research pathways, Solar Energy Materials & Solar cells 109 (2013) 126-141.

[10]Y.Xu, J.X.Liao, et al. Preparation of highly- reflective $Tio_2$\$Sio_2$ \Ag thin film with self-cleaning properties bymagnetron sputtering for solar front reflectors, Solar Energy Materials & Solar Cells 113 (2013) 7-12.

[11] Xiande Lu, Gang Yu, et al., Preparation and characterization of transparent fluoro carbon emulsion doped with antimony tin oxide and $Tio_2$ asthermal-insulating and self-cleaning coating. J. Coat. Technol. Res., 11 (4) 567–574, 2014 .

[12] C.S.Thomson, R.Fleming M.Zou, et al.,Transparent self-cleaning and antifogging silica nano particle films, Solar Energy Materials & Solar Cells 115 (2013) 108-113.