



**AIR-COOLING TECHNIQUE USING THERMOREGULATED CROSS-FLOW FAN FOR
RETROFITTED ROOFTOP PHOTOVOLTAIC SYSTEM**

By

ROZITA BINTI MUSTAFA

**Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia,
in Fulfilment of the Requirements for the Degree of Doctor of Philosophy**

January 2025

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January 2025

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Photovoltaic (PV) technology is a fast-growing source of renewable energy, notably on residential rooftops. Raising the temperature of the PV module results in a reduction in power generation, which is dependent on the module's temperature coefficient. One of the biggest problems with rooftop PV systems was the air trapped between the PV array and the roof, which made the PV module work at higher temperatures. To maximize the efficiency of a rooftop PV system, it is critical to reduce the temperature of the PV module, T_{cell} . Implementing a cooling system can effectively control the T_{cell} 's rise. This research developed air-cooling system using thermoregulated cross-flow fan to supply a uniform and wide airflow system, which is well-suited for effectively cooling wide-width regions. The thermoregulated air-cooling for retrofitted PV system conserves energy by working within a temperature range. The air-cooling system's design considered the space between the PV system and the rooftop, the area surrounding, ease of installation, and lighter weight without modifying the existing PV system. The experiment was run continuously for 12 hours, starting at 7:00 a.m. and

ending at 7:00 p.m at existing PV system in the German Malaysian Institute in Kajang, Selangor, Malaysia. Irradiance, T_{cell} , and electrical characteristics were recorded at 3s intervals, providing a daily total of at least twelve thousand results for further investigation.

A black-box technique in the System Identification toolbox, Matlab were used to create thermoregulated air-cooling for retrofitted PV system model to accurately predict PV module and air-cooling PV system performance, and ensuring that the proposed system can handle varying solar irradiance without hot weather experiments or field risks. The Ziegler-Nichols method was employed to set the PID controller's starting parameters and simulated under various solar irradiance levels using Simulink, Matlab.

The validation findings indicate that the mean output voltage increases by 11.77%, 21.51%, and 18.86% for high, moderate, and low levels of irradiance, respectively. A notable rise in the average output voltage has proven the effectiveness of an air-cooling system. Specifically, the system with PID shows a 3.95%, 3.45%, and 3.35% gain in voltage compared to the system without PID.

Keywords: Retrofitted PV system, Air-cooling PV system, Air-cooling PV system modeling, PID controller design

SDG: GOAL 4: Quality Education, GOAL 7: Affordable and Clean Energy

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

**TEKNIK PENYEJUKAN UDARA MENGGUNAKAN KIPAS ALIRAN
LINTANG TERMOREGULASI UNTUK SISTEM FOTOVOLTA
BERBUMBUNG**

Oleh

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Teknologi fotovoltan merupakan salah satu sumber tenaga boleh diperbaharui yang semakin meningkat penggunaannya terutamanya yang melibatkan pemasangan di atas bumbung. Peningkatan suhu operasi modul fotovoltan, T_{sel} akan menyebabkan penurunan penghasilan voltan dan kuasa bergantung kepada pekali suhu modul fotovoltan tersebut. Bagi sistem fotovoltan berbumbung, kenaikan T_{sel} yang disebabkan oleh udara yang terperangkap dalam jurang udara antara tatasusila fotovoltan dan juga bumbung perlu diatasi. Bagi kecekapan sistem fotovoltan berbumbung yang maksima, penurunan nilai T_{sel} terutama pada ketika menerima kekuatan sinaran suria yang tinggi adalah kritikal. Penggunaan sistem penyejukan, berkesan dalam mengawal kenaikan T_{sel} . Dalam penyelidikan ini, inovasi bagi kaedah penyejukan sistem fotovoltan telah dibangunkan menggunakan kipas aliran silang termoregulasi yang mewujudkan sistem aliran udara yang seragam dengan capaian luas yang besar yang sesuai untuk penyejukan kawasan yang lebar berdasarkan perubahan suhu. Sistem termoregulasi melalui kawalan suhu membolehkan ia beroperasi secara automatik dan

meningkatkan penjimatan tenaga. Rekabentuknya mempertimbangkan kawasan sedia ada di antara sistem fotovolta dan bumbung, ringan, serta pemasangan yang mudah, tanpa perlu mengubahsuai sistem fotovolta sedia ada. Eksperiment telah dijalankan 12 jam tanpa henti bermula 7.00 am sehingga 7.00 pm di German Malaysian Institut, Kajang, Selangor, Malaysia. Bacaan kekuatan sinar suria, T_{sel} dan parameter elektrik dicatat dalam setiap sela masa 3 saat, menghasilkan dua belas ribu bacaan sehari untuk dianalisis.

Model sistem penyejukan udara menggunakan kipas silang termoregulasi dibangunkan menggunakan Sistem Identifikasi dengan pendekatan kotak-hitam bagi meramal keluaran modul fotovolta dan juga prestasi sistem penyejukan yang dibangunkan. Kaedah Ziegler-Nichols digunakan bagi mensetkan parameter model sistem kawalan PID dan telah disimulasi dengan pelbagai aras kekuatan suria menggunakan Simulink yang terdapat di dalam perisian Matlab.

Pengesahan penemuan membuktikan kenaikan voltan sebanyak 11.77%, 21.51%, dan 18.86% bagi aras tinggi, pertengahan dan rendah sinar suria. Peningkatan ketara dalam purata voltan keluaran telah membuktikan keberkesanan sistem penyejukan udara. Secara khusus, sistem penyejukan udara menggunakan kipas silang termoregulasi yang diertai pengawal PID menunjukkan peningkatan voltan sebanyak 3.95%, 3.45%, dan 3.35% bagi kekuatan sinar suria tinggi, pertengahan dan rendah.

Kata Kunci: Sistem PV berbumbung, Sistem penyejukan sistem PV, Model sistem penyejukan sistem PV, Reka bentuk pengawal PID

SDG: MATLAMAT 4: Pendidikan Berkualiti, MATLAMAT 7: Tenaga Berpatutan dan Bersih

ACKNOWLEDGEMENTS

In the Name of Allah, Most Gracious, Most Merciful, all praise and thanks are due to Allah, and peace and blessings be upon. I am first and foremost grateful to The Almighty Allah (SWT) for preserving my life until this moment and granting me the opportunity to conduct this exceptional research.

I am deeply grateful to Prof. Dr. Mohd Amran Mohd Radzi, my supervisor and chairman of my supervisory committee, for his priceless advice and encouragement during the course of my studies. I am extremely appreciative of his assistance, availability, encouragement, time, and suggestions for providing valuable feedback on this project. I also like to thank my dedicated co-supervisors, Assoc Prof. Dr. Hashim Hizam and Dr. Azura Che Soh, for their great suggestions. I am happy of you both as co-supervisors who scrutinized this excellent study to make it what it is now.

I appreciate my mother, brothers, and sisters' unwavering support. Finally, I thank my loving spouse Najmi for his patience, moral support, encouragement, love, and prayers. The same goes for my children Adam, Anis, Aryan, Arfan, and Arslan. I appreciate your patience, understanding, and prayers. Thank you to all my friends who encouraged me, especially Noor Hafizah, who was with me throughout. I'd like to thank my Advanced Lightning, Power and Energy Research (ALPER) lab mates for their support and helpful advice.

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF SYMBOLS

a	Diode Ideality Constant
AM	Air Mass Solar Irradiance
$^{\circ}\text{C}$	Degree Celsius
f_{temp}	Temperature Factor
GW	Giga Watt
G	Solar Irradiance
G_{amb}	Irradiance at T_{amb}
G_{array_plane}	Solar Irradiance in Array Plane
h	Hour
H	Solar Irradiation
I	Current
I_D	Diode Current
I_L	Incident Light Current
I_{mp}	Current at Maximum Power
I_O	Saturation Current of Diode
I_P	Shunt Resistor Current
I_{ph}	PV Current
K	Boltzan Constant
Kd	Derivative Parameter
Ki	Integration Parameter
Kp	Proportional Parameter
Ku	Ultimate Gain
kW	Kilo Watt

kW/m^2	Kilo Watt per Square Metre,
kWh/m^2	Kilo Watt Hour per Square Metre
lx	Lux
mV	Milli Volt
MHz	Mega Hertz
MPP	Maximum Power Point
MW	Mega Watt
n	Cells Connected in Series
P_{max}	Maximum Power Output
P_{mp}	Maximum Power Output
P_{mp_stc}	Maximum Power PV Module at STC
P_{mp_roc}	Maximum PV Module Power at Real Operating Condition
P_{mp_calc}	Calculated Power at Maximum Power
P_{mp_exp}	Maximum Power During Experiment
$P_{mp_roc_calc}$	Calculated Maximum PV Module Power at Real Operating Condition
P_{pv_exp}	PV Module Power During Experiment
P_{pv_x}	PV Module Power at x Condition
$P_{pv_cool_calc}$	Calculated PV Module Power After Applying Air-Cooling System

$P_{pvuncool_calc}$	Calculated PV Module Power Before Applying Air-Cooling System
P_{x_stc}	Power for x Condition at STC
q	Electron Charge
$R_{Addition}$	Addition Resistor
R_p	Parallel Resistor
R_s	Series Resistor
R_x	Resistor for x
s	Second
t	Time
T_{amb}	Ambient Temperature
$T_{amb_pv_operation}$	PV Ambient Average Maximum Temperature During Operation
T_{cell}	Operation Temperature of PV Module
$T_{cell_minimum}$	Minimum Temperatures of PV Module
$T_{cell_maximum}$	Maximum Temperatures of PV Module
$u(t)$	Control Variable
V_{cell}	Cell Voltage
V_{mp}	Voltage at Maximum Power
V_{mp_exp}	Voltage at Maximum Power During Experiment
V_{mp_roc}	Maximum Power Voltage at Real Operating Condition

$V_{mp_roc_calc}$	Calculated Maximum PV Module Voltage at Real Operating Condition
$V_{mp_roc_exp}$	Maximum PV Module Voltage at Real Operating Condition During Experiment
V_{mp_stc}	Maximum Power Voltage at STC
V_{mp_calc}	Calculated Voltage at Maximum Power
V_{oc}	Open-Circuit Voltage
V_{Out}	Output Voltage
V_{pv_x}	PV Module Voltage at x condition
V_{pvexp}	PV Module Voltage During Experiment
V_{pvexp_cool}	PV Module Voltage After Applying Air-Cooling System During Experiment
V_{pvexp_uncool}	PV Module Voltage Before Applying Air-Cooling System During Experiment
V_{pvcool_calc}	Calculated PV Module Voltage After Applying Air-Cooling System
$V_{pvuncool_calc}$	Calculated PV Module Voltage Before Applying Air-Cooling System
V_{pvset}	Setpoint PV Module Voltage
V_{pvref}	Reference PV Module Voltage
V_{x_stc}	PV Module Voltage for x condition at STC
W	Watt
W/m^2	Watt per Square Metre,
Wh/m^2	Watt Hour per Square Metre
γ	Temperature Coefficient
$\gamma_{P_{mp}}$	Maximum Power Temperature Coefficient

γ_{P_x}	Power Temperature Coefficient at x Condition
$\gamma_{V_{mp}}$	Maximum Power Voltage Temperature Coefficient
γ_{V_x}	Voltage Temperature Coefficient at x condition



LIST OF ABBREVIATIONS

AC	Alternating Current
ADDR	Address
BIPV	Building-Integrated Photovoltaic
BOS	Balance of System
BWHE	Buried Water Heat Exchanger
CPU	Central Processing Unit
DC	Direct Current
EAHE	Earth-to-Air Heat Exchanger
EC	Energy Commission
GCPV	Grid-Connected Photovoltaic
GEP	Generated Electrical Power
GHI	Global Horizontal Radiation
GMI	German Malaysian Institute
IA	Implementing Agency
IEA	The International Energy Agency
I2C	Inter-integrated Circuit
ICSP	In-circuit Serial Programming
I-V	Current-Voltage
I/O	Input / Output
KCL	Kirchhoff's Current Law
KeTSA	Ministry of Energy and Natural Resources
LCD	Liquid Crystal Display
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
NAPIC	National Property Information Center

NEM 3.0	Net Energy Metering 3.0
NOCT	Nominal Operating Cell Temperature,
PCM	Phase Change Materials
PID	Proportional, Integral and Derivative
PSF	Peak Sun Factor
PSH	Peak Sun Hour
PV	Photovoltaic
P-V	Power-Voltage
PVT	Photovoltaic Thermal
PWM	Pulse Width Modulation
RTC	Real Time Clock
ROC	Real Operating Condition
ROI	Return on Investment
SAPV	Stand-Alone Photovoltaic
SD	Secure Digital
SEDA	Sustainable Energy Development Authority of Malaysian
Si	Silicon
SDA	Serial Data
SI	System Identification
SLA	Seal Lead Acid
SLC	Serial Clock
STC	Standard Test Conditions

TF	Transfer Function
TSI	Total Solar Irradiance
UV	Ultraviolet Light
USB	Universal Serial Bus





CHAPTER 1

INTRODUCTION

1.1 Background

The most serious difficulty for emerging countries is energy scarcity, and Malaysia is one of them. Malaysia is determined to grow its renewable energy capacity mix share to 31% by 2025 and 40% by 2035 [1]. As a tropical country, Malaysia can be categorized as a country with high peak sun hour (PSH) per day. Photovoltaic (PV) modules harness the Sun to give sustainable energy to the world [2]. Solar energy's lack of noise and pollution, renewable nature, and independence as an energy source directly obtained from solar irradiance have received attention in recent decades. PV modules transform solar energy into electrical power for the load.

A rooftop PV system harvests solar irradiance on a building's roof. Residential or business roofs typically host most PV systems, which generate inexpensive, long-term electricity and conserve land. Retrofit mounting is an installation in which PV modules are affixed to roof-mounted brackets. This PV system can assist buildings in generating electricity, yet, it possesses some characteristics that may diminish power production. [3]. The quantity of electricity produced by this PV system is contingent upon several parameters, including the mounting structure, design, configuration and alignment of the PV modules, and weather conditions [3].

Most of the solar energy are lost as heat through convection and radiation. Restricted ventilation causes some of this heat to be retained underneath the PV module, leading

to heat accumulation behind the PV array, which is a major concern for retrofitting mounting. Operating temperature of PV module, T_{cell} rises due to this heat-trapping air, and PV module's output falls as a result of heat. The performance of PV modules degrades drastically as their T_{cell} increases. It is vital to limit as many factors as possible that contribute to the rising of the T_{cell} such as reducing the amount of hot air trapped within the rear of the PV module and the roof.

Managing the T_{cell} is the primary challenge of a rooftop PV system in a tropical region with high ambient temperatures, T_{amb} . Heat is produced by the PV array's mounting arrangement and the air gap beneath it. Aside from insufficient ventilation, the roofing material's temperature might also impair the T_{cell} [4]. One of the most important parts of solar energy conversion is the T_{cell} . A PV module's power output and electrical efficiency are defined by its T_{cell} and temperature coefficient [5], [6]. For every degree over 25 °C, there is an average decrease in efficiency of around 0.45% [7]. Considering Standard Test Conditions (STC) help assess PV module's performance [8].

The PV module converts approximately 50–60% of the total solar energy into heat, resulting in an elevated T_{cell} throughout its operation, necessitating cooling to enhance the efficiency of photovoltaic modules [9], [10]. Dissipating heat energy is necessary to minimise the T_{cell} . Consequently, the T_{cell} can be maintained near the T_{amb} while minimizing the temperature differential [11]. Cooling PV modules and eliminating excess heat is critical for obtaining efficient energy output from a PV system. This heat may be removed by circulating water or air beneath the PV module via thermal collectors, commonly referred to as PV thermal (PVT) collectors [12].

Previous research has suggested a variety of approaches for reducing the T_{cell} [13]. An essential step in enhancing the performance of PV systems is implementing an integrated cooling system for use during operation [14]. Research has demonstrated that a cooling system may significantly increase power output [15]. Cooling solutions for heat applications were presented early in PV deployment [16]. There is active cooling, which involves the use of energy-consuming devices like pumps and fans, and passive cooling, which relies on natural convection and conduction to remove heat. The majority of cooling techniques use air or water. Passive cooling solutions struggle to cool PV cells due to excessive heat extraction via restricted no cost heat transfer by convection and radiation [14].

Because of its better thermal qualities, water-cooled PV systems outperform their air-cooled counterparts. This is especially true in hot climates where air is less effective. On the other hand, air-cooled PV systems are still highly respected since they are inexpensive to build and run [16]. It would be great if a cooling system could handle the changes in T_{cell} without interfering with or changing the existing PV system. This is to ensure cost savings and not to complicate maintenance tasks. The temperature control system must be capable of operating independently, hence enhancing its energy saving.

1.2 Problem Statement

Previous research studies have tried many cooling techniques, and it is proven to improve PV module performance; however, the cooling system examined is manually operated [17], [18], using time intervals [19], and some are turned on all the time

during the experiment [14], [20] that need someone to monitor system start-up. For active cooling systems, especially for rooftop PV systems, the cooling system must consume less electricity than it generates [21], [22] to ensure the investment is worthwhile and the return on investment (ROI) is accelerated. It is a waste if the cooling system works when the temperature of the PV module/system is not high or when it rains. Thus, the active air-cooling PV system should use energy-saving ideas like temperature sensitivity to minimize power consumption and boost production. Furthermore, enhancing the performance of photovoltaic modules might indirectly enhance the energy efficiency of the used system.

A model that clearly understands the significant inputs and outputs is a must-have to provide convenience and cost advantages over other means of obtaining the necessary information on reality more quickly and accurately [23], [24]. Several research studies have examined models for PV modules [25], [26], however, most have not concentrated on thermoregulated air-cooling for retrofitted PV system model. A model is required for engineering evaluations [27] incorporating PV module and thermoregulated air-cooling systems. Algorithms for thermoregulated air-cooling PV systems offer significant cost savings by simulating and evaluating the cooling system before to actual construction. A black box system identification model using experimental data as both input and output is necessary for any existing thermoregulated air-cooling for retrofitted PV system. The input data's quality determines the model's quality [28], which is gathered through experimental approaches. This model analyses the system's influence and aids research on enhancing the thermoregulated air-cooling system and PV module under various irradiance levels, removing the need for extra devices and cutting costs. The model

accurately predicts PV module and system performance, reducing the need for field testing in hot weather or risky fieldwork, such as climbing on a tall building.

There are various control approaches used in thermoregulated air-cooling PV systems to optimize PV module performance. To expedite the ROI and make the investment worthwhile, the cooling system's control operation is a must have. Adding control capabilities to the controller makes the cooling PV system more efficient. Model-based control algorithms are useful for air-cooling PV systems because they allow for cost optimization through simulation and assessment before the physical fabrication of the controller. The most usual kind of controller used in industrial are PID controllers, which stand for proportional, integral, and derivative [28]. According to Aboelhassan, etc. [29] and Zhang, etc. [30], PID procedures are the most exact and highly recommended. Because of its simplicity and great control performance, PID controllers are an excellent choice for regulating a wide range of modern industrial processes [31].

1.3 Aim and Objectives

The aim of this work is to develop a new technique of thermoregulated active cooling system for a retrofitted rooftop PV system that requires considerable space between PV system and rooftop, easier installation to existing system and lighter. In order to achieve this aim, the specific objectives are listed below:

- i. To develop air-cooling for a rooftop photovoltaic system integrated with a thermoregulated controller and speed regulation for PV module performance improvement

- ii. To design an air-cooling photovoltaic system identification model using black box approach and real experiment data for forecasting the performance of PV module under several level of solar irradiance
- iii. To design PID controller for air-cooling PV system aimed at enhancing the efficiency and performance of the cooling system

1.4 Scopes and Limitations

The scopes and limitations of this work are as follows:

- i. The experiment was conducted continuously from 7:00 a.m. to 7:00 p.m. The study's data collection was restricted to a three-second interval for each device and meter employed.
- ii. The experiment was conducted by device and meter programmed using the ATmega328P microcontroller each, based on the state of the study, namely thermo regulated fan controlling device, irradiance meter, and energy meter.
- iii. The study area is at Complex Technology 5, German Malaysian Institute (GMI), with GPS Coordinates: N2 56.004 E101 47.917. The PV system, which became the study area, was installed in 2016. Based on the 1 percent per year factor of aging, 6 percent of aging factors should be accounted for in the studies conducted.
- iv. The study was limited to the existing 3kW polycrystalline grid-connected PV system. However, the study was conducted on one of the PV modules installed on the system and not on the entire PV array for the system. This is because the study was conducted using a single fan, and the results were easier to analyze with only the PV module involved. Even though only one of the PV modules from the PV array was tested, studies still are being conducted on the existing system.

- v. The existing PV system has been installed on a zinc-type roof. Thus, the scope of the study was limited to the air conduction at the space occupied by the cooling system technique between the bottom of the solar array and the zinc roof type. There is a 50 mm to 60 mm gap between them, and they comply with MS2240:2012.
- vi. Due to the uncontrollable nature of weather conditions, such as rain, heat, solar radiation, ultraviolet light (UV), and wind, the experimental conditions were restricted. Conditions for the study can only be imposed on the equipment, devices, and meters used to collect data.
- vii. This cooling system technique is investigated with limited use of only one DC cross-flow fan 1055 mm long by 62 mm tall. The fan is positioned at the end of the solar array's upper diagonal, which measures 9828 mm in length and 3958 mm in width. Since the study was only conducted on approximately 3.75% of the solar array's total area, the experiment's effectiveness should also consider the total area of the affected area.
- viii. Only PV module ambient average maximum temperature during operation $T_{amb_pv_operation}$ and solar irradiance were examined as essential meteorological indicators in this research due to the low wind speed in the experiment location [32].
- ix. The data was collected one month prior to the installation of the thermoregulated air-cooling system and one and a half months subsequent, with each data point categorized based on daily irradiance levels: high solar irradiance, moderate solar irradiance, and low irradiance.
- x. The study was done based on the solar irradiance received each day, which influenced the T_{cell} and was not dependent on the number of days of solar irradiance received.

1.5 Contribution of Research

Knowing the large amounts of solar irradiance and humidity in tropical regions, it is crucial to comprehend the influence of humidity on temperature. The elevated T_{cell} reduces the PV module's efficiency, resulting in lower power production than expected. Therefore, a technique is required to reduce T_{cell} due to excessive solar irradiance. This knowledge is necessary to optimise solar energy conversion into voltage and power.

This study adds a simple, dependable, cost-effective installation method for an air-cooling system with thermo regulated variable fan speed to the cooling PV system. By avoiding constant rotation, it saves energy. The system's innovative technique and concept align with the existing rooftop PV system, allowing for easy integration of the cooling system without extensive modifications to the current PV system, which can potentially result in roof leaks and incur significant re-installation expenses. This work is significant as it tackles the problem of decreased output performance in PV systems caused by voltage and power drops resulting from the rise of T_{cell} due to increasing solar irradiance.

This work also aided in developing air-cooling PV system models, an area previously unexplored in research. The model was constructed utilizing a substantial volume of data from experiments done by skilled individuals and systems that adhere to the Sustainable Energy Development Authority of Malaysian (SEDA) standard. The model is realistic and closely matches real-world cooling system performance. This model helps forecast PV system performance and cooling PV system effectiveness

under varying solar irradiation levels. The PV module and cooling system performance must be improved without high costs or having to endure hot weather to study the created cooling system

This research demonstrates how a control system model improves the cooling of PV systems. This approach minimises the necessity for new prototypes and PV system development to evaluate the system. Control models derived from the current cooling system model may be utilised.

1.6 Thesis Organization

The reminder of this thesis is organized as such:

Chapter 2 describes an overview of PV, PV module characteristics, main part of PV systems, including grid-connected and stand-alone, different types of mounting configurations of PV systems, and factors that affecting PV output. After that, a review of solar radiation and different techniques for cooling PV modules primarily be relates to improving PV module performance. Finally, system identification modeling and PID controller are explained.

Chapter 3 addresses the methodology, which consists of two primary parts: the hardware design for the equipment used and the cross-flow fan air-cooling PV system, which operates using the Atmel328 microcontroller for hardware implementation, as well as modelling in Matlab for both the air-cooling PV system and the controller. At first, the hardware, including cross-flow fan, sensors, microcontroller, and their circuits, were illustrated and described. After that, the experimental work using an

air-cooling PV system at the site was explained. Next, the implementation of the designed modeling for air-cooling PV system using the Matlab-System Identification (SI) approach and application to an PID controller in Matlab-Simulink were presented.

Chapter 4, firstly, experimental results present solar irradiance, $T_{amb_pv_operation}$, and temperature of PV module on the existing PV system at the site, and also the performance of PV module under changing solar irradiance and temperature of PV module for both with and without proposed air-cooling PV system. Comparison of experimental and calculation results before and after installing the proposed air-cooling PV system are given. Secondly, simulation results containing both PV modules with proposed air-cooling modeling and PID controller are present and comparison without PID under rapidly and slowly changing solar irradiance.

Chapter 5 contains the conclusion and recommendations for future work. The references and appendices are attached at the end of the thesis.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The photovoltaic (PV) system should be able to efficiently convert the maximum amount of solar irradiance that the PV module can capture into electricity. When solar irradiance reaches the surface of a PV module, a fraction of its energy is converted into heat, leading to an increase in the operating temperature of the PV module, T_{cell} . The elevated T_{cell} caused by this heat can significantly diminish the efficiency of the PV modules, hence impacting overall performance. Lowering the T_{cell} can greatly enhance PV module's efficiency. Thus, this chapter covers the PV system and critically reviews and analyses prior efforts on cooling PV modules.

2.2 Photovoltaic

Photovoltaic is derived from the Greek word for light, "photo," as well as electrical pioneer Alessandro Volta's coined term, "volt." Henri Becquerel invented light-to-electricity in 1839. PV technology is eco-friendly and sustainable. It has no fuel or moving components, making it a sustainable energy source. Nowadays, PV technology has advanced significantly and is used in a variety of applications. PV technology minimizes climate change by emitting significantly less carbon dioxide.

2.2.1 Photovoltaic Cell

PV cells directly transform solar irradiance into electricity. A PV cell consists of a p-n junction formed by semiconducting materials [13]. A p-n junction is formed when a semiconductor like silicon is doped with n-dopant impurities such as phosphorous for negative doping and boron for positive doping. These materials absorb sunlight, which separates electrons from their atoms, allowing current to flow and generate power.

This conversion of light to electricity is called the PV effect. The crystalline element silicon (Si) is employed in several PV technologies. A popular Si technology assembly types include monocrystalline and polycrystalline cells. In addition, non-crystalline amorphous silicon (Amorphous -Si), also known as thin-film, is also available. Amorphous denotes the absence of a crystalline lattice structure. PV cells may be joined to make a module, also known as a PV module.

2.2.1.1 Electrical Equivalent Circuit of Photovoltaic Cell

A PV cell is actually a reverse-biased, illuminated p-n junction connected to a resistive load and can be represented by a p-n junction equivalent circuit diagram [33]. A photovoltaic cell generally has a p-n junction that produces electron-hole pairs when exposed to light. When a photon hits the PV cell, it excites semiconductor electrons, creating electron-hole pairs. The built-in electric field of the p-n junction separates these charge carriers and produces an electric field when p-type (positive) and n-type (negative) materials touch. This field naturally pulls electrons towards the n-side and

holes towards the p-side, generating a built-in potential that depletes the area of free charge carriers.

To allow current flow, diodes are forward-biased. PV cell p-n junctions are reverse-biased. The electric field of the built-in potential stops current from flowing without light (or outside power), and it also pushes photogenerated charge carriers (electrons and holes) apart and in different directions. A resistive load across the cell creates a current by transferring photogenerated electrons from the n-type to the p-type regions.

The reverse bias keeps these carriers in the proper direction, preventing the diode from conducting a significant reverse current while permitting a modest current from the photocurrent created by light. A photovoltaic cell's reverse bias does not come from an outside voltage applied to the p-n junction. Instead, it comes from the p-n junction itself creating an electric field inside the cell that helps current flow when the cell is exposed to light. Figure 2.1 shows an ideal PV cell as an anti-parallel current source with a diode [34].

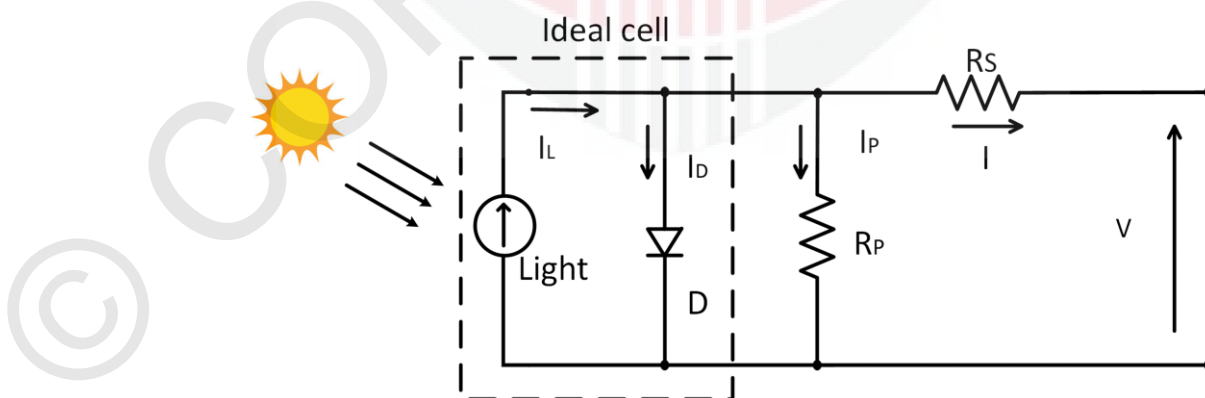


Figure 2.1: Equivalent circuit of a PV cell [34]

By use Kirchhoff's current law (KCL) to analyze Figure 2.1, the output current for the PV cell can be described as follows [35]:

$$I = I_L - I_D - I_p \quad (2.1)$$

where:

I_L = current generated by the incident light, directly proportional to the solar irradiance

I_D = diode current

I_p = current through the shunt resistor

When each term in equation (2.1) is replaced by its value, the output current of PV cell [26]:

$$I = I_L - I_o \cdot \left(e^{\frac{q(V+IR_s)}{aKT_{cell}}} - 1 \right) - \frac{(V+IR_s)}{R_p} \quad (2.2)$$

where:

I_o = saturation current of the diode (A)

V = cell voltage (V)

q = the charge of an electron, 1.6×10^{-19} (C)

a = the diode ideality constant

K = the Boltzman's constant, 1.38×10^{-23} ($\frac{J}{K}$)

T_{cell} = cell temperature

Equation (2.2) is modified to account for realistic arrays that have numerous linked PV cells [36]:

$$I = I_L - I_0 \left[\exp \left(\frac{q}{nKT} (V + R_s I) \right) \right] - \frac{V + R_s I}{R_p} \quad (2.3)$$

where:

I = photovoltaic currents (A)

I_0 = saturation currents (A)

n = cells connected in series

R_s = series resistor

R_p = parallel resistor

2.2.2 Photovoltaic Module

PV modules are groups of PV cells. A PV array is made up of several PV modules that are linked together to get the power and current that are needed. PV modules can be interconnected in parallel or series to deliver the requisite voltage and current for a specific system. When integrated with a substantial PV module, significant quantities of renewable energy can be produced [37].

2.2.2.1 Characteristic of Photovoltaic Module

Current-voltage characteristics, also known as I-V characteristic curve, are one of the most important electro physical properties of a PV module. The I-V characteristic curve illustrates the current and voltage combinations at which the PV module may

operate under the assumption of constant irradiance and cell temperature. The evaluation of PV module performance and the design of PV systems must be based on the electrical characteristics such as the current-voltage relationships of the PV module subjected to varying levels of irradiance and temperature [38]. Figure 2.2 shows I-V Characteristic of PV module.

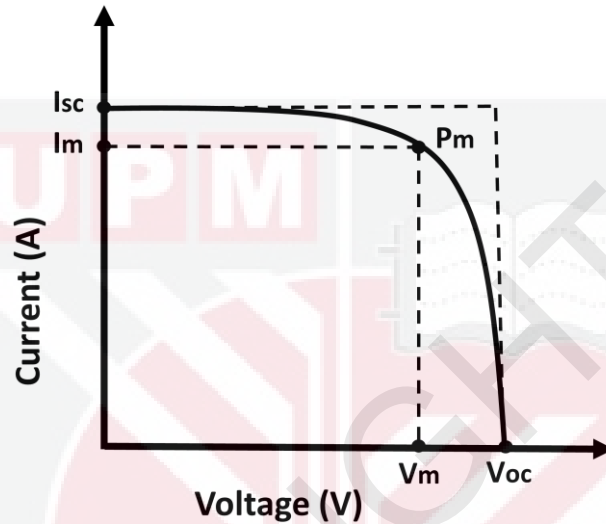


Figure 2.2: I-V characteristic of PV module [39]

From Figure 2.2, the important parameters for calculating power conversion are:

- i. The short-circuit current, I_{sc} where the I-V curve crosses the x-axis at 0 V. This is the current output from the PV module when the resistance is zero.
- ii. The open-circuit voltage, V_{oc} is the voltage across the output terminals of a PV module operating in open circuit (that is, an incomplete electrical circuit in which no current flows, $I = 0$).

- iii. The maximum power output, P_{mp} or P_{max} refers to the voltage and current levels at which the PV module generates the most power. The point on an I-V curve is commonly based on the maximum power point (MPP).
- iv. The current at maximum power, I_{mp} is the module's current level at P_{mp}
- v. The voltage at maximum power, V_{mp} is the module's voltage level at P_{mp}

Figure 2.3 shows the power and voltage curve [40]. The analysis of I-V and P-V curves of a solar module is great significance as it helps to evaluate different techniques and algorithms [41].

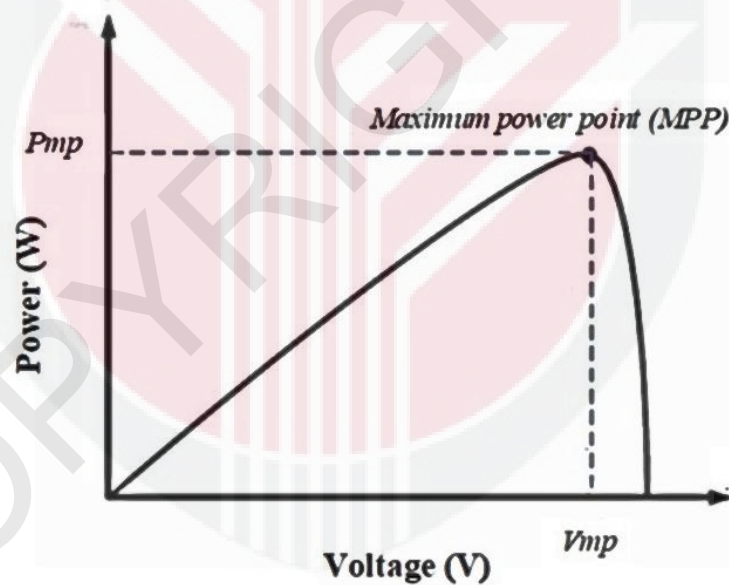


Figure 2.3: P-V characteristic of PV module [40]

Figure 2.4 illustrates an I-V characteristic curve plotted with power output of PV module. Noticed in Figure 2. that the curve has a knee. The *MPP* exists at the knee. The whole area beneath the IV curve signifies the effective total power produced by the PV module, calculable as follows:

$$P_{mp} = I_{mp} \times V_{mp} \quad (2.4)$$

In practical operating conditions, the power output of a PV module depends on fluctuations in temperature and the intensity of solar irradiance.

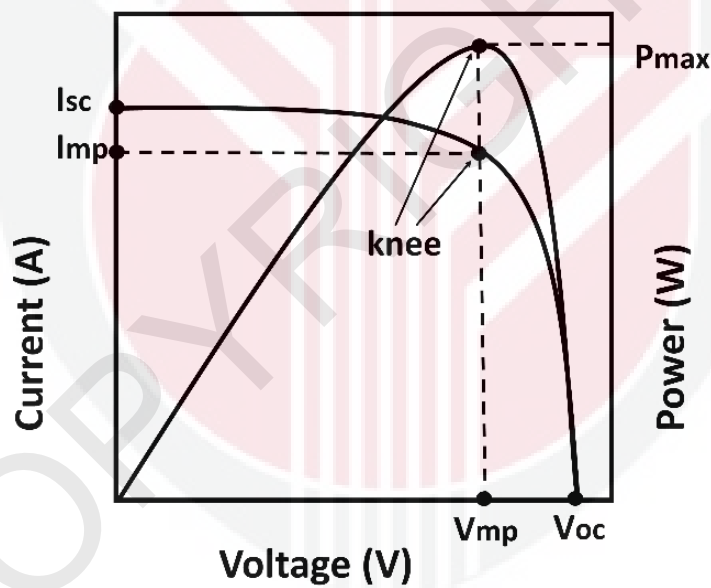


Figure 2.4: An I-V characteristic curve plotted with power output of PV module
[40]

2.2.3 Photovoltaic System

A fully functional PV system consists of two primary components: PV array and balance of system (BOS) [42]. A PV array is made up of PV modules that are linked in a series-parallel arrangement, while the BOS comprises all other components that allow the system to produce the desired output. Typical BOS components required for a PV system may include inverters, cables, breakers, protection device, fuses, mounting structure, battery, etc. PV systems are growing rapidly and supply over 20% of the world's power by 2050. [43].

The widespread acceptance of PV systems is because of its enormous capacity to generate clean energy [44]. The use of PV technology for harvesting solar energy has been the subject of extensive research [45]. Since 2010, the PV capacity of the installed system has increased from 20 *GW* to about 120 *GW* in 2019 [46]. The PV power generation capacity has grown annually [47], [48].

2.2.3.1 Categorization of PV System

PV system can be categorized into grid-connected PV (GCPV) and stand-alone PV (SAPV) system. GCPV system was connected to a national utility grid compared to stand-alone not connect to utility grid but direct to load or with battery. Figure 2.5 shows schematic diagram for a typical configuration of GCPV [49].

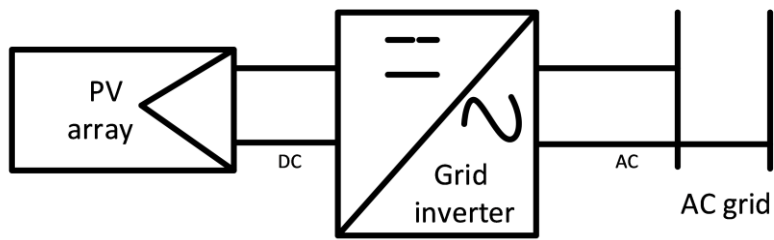


Figure 2.5: A typical configuration of GCPV

The hybrid PV system can be configured as PV direct, PV and battery, and PV, battery, and auxiliary generator. PV direct utilized direct current (DC), such as PV connected directly to a DC load, whereas PV and battery were used for DC and/or alternating current (AC) loads. The following figures illustrate the fundamental schematic diagram of a SAPV system. Figure 2.6 shows a typical configuration of a direct DC SAPV system for DC loads while Figure 2.7 represents a typical SAPV battery configuration for DC and AC loads [50].

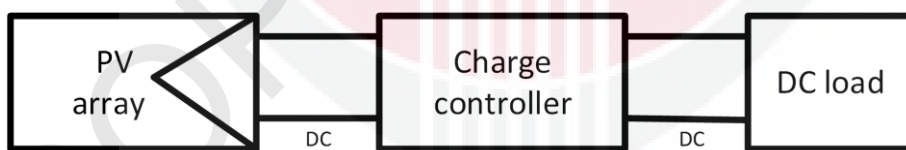


Figure 2.6: A typical configuration of a direct DC SAPV system for DC loads

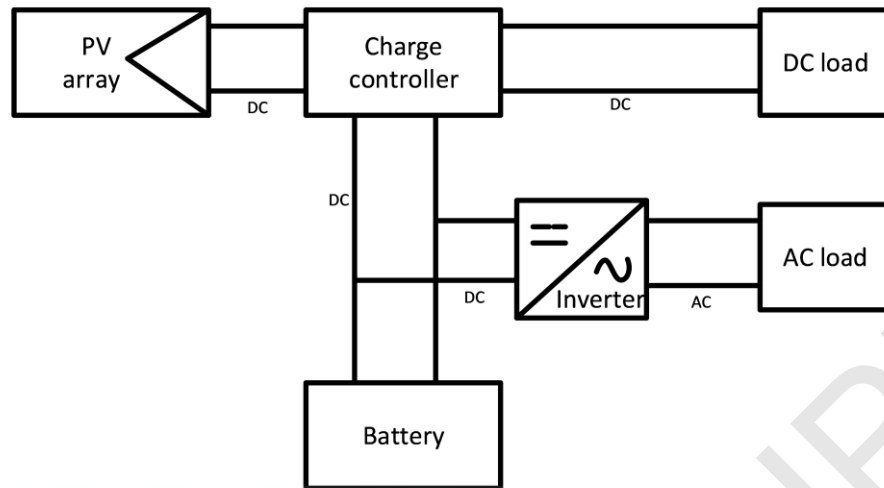


Figure 2.7: A typical configuration of a direct DC SAPV system for DC and AC loads

2.2.3.2 Types of PV System Configuration

Three typical mounting types for PV system installation on rooftops were building-integrated photovoltaic (BIPV), free-standing, and retrofitting systems [51], [52]. Due to the greater airflow under the PV array, the best configuration is considered being freestanding. Installing PV modules on top of preexisting roof tiles using brackets to raise them off the roof is known as retrofitted mounting [53]. Airflow through the module may be limited if there is a small space between it and the surface of the roof.

Integrating PV modules into a structure is known as BIPV mounting [54]. Rooftop BIPV mounting may have the leakage issues. Retrofit mounting is gaining popularity as an alternative to reduce leakage [55] because it also saves the cost due to the use of existing roof [56].

2.2.3.3 Rooftop Photovoltaic System

A rooftop PV system is a PV system mounted on the rooftop of a residential or commercial building or structure [57]. A PV system is an electrical installation that uses solar energy to generate electricity and distributes that electricity to either power the building's own appliances or, in some situations, return excess power to the grid [58]. Building size, energy use, and available funds are the three primary factors that determine the optimal rooftop PV system [57]. The normal capacity of rooftop PV systems on residential buildings ranges from 5 kW to 20 kW, whereas commercial buildings frequently have systems with capacities of 100 kW or higher [59].

The main components for rooftop PV system was PV array and balance of system (BOS). PV arrays have series or parallel PV modules depending on system size. BOS includes mounting framework, wires, array junction box, surge protection device, inverter, and meter. Rooftop PV systems provide clean energy well [57]. The Malaysian government has promoted PV project investment extensively [60]. This was discovered by [61] from their surveyed which is 47.1% of Malaysian respondents intend to install PV panel systems for their landed property homes when they receive some returns as electricity through money back schemes.

Residential, commercial, and institutional rooftop solar expanded by an average of more than 50% per year between 2008 and 2014 [62]. Due to technology advances and economies of scale, rooftop PV systems are cheaper, making them more popular [63]. Rooftop PV system are growing cheaper for households, businesses, and communities. Between 2010 and 2014, United States home PV system prices dropped

45% due to lower technology prices, creative financing, and increased networking of PV installers and financial partners. [62].

Research studies by Kurpaska, etc. [41] and Paidipate, etc. [57] extrapolate total rooftop area from total floor area using data provided in their study and found out that 22% to 27% of residential rooftop space and 60% to 65% of commercial rooftop space are suitable for PV system. In Egypt January 2015, 69 bidders with solar PV projects above 20 MW, 13 for PV less than 20 MW including 300 MW for rooftop solar projects proven the volume of bids described critical oversubscription [65]. Cities use 75% of transformed energy and emit 50–60% of greenhouse gases [66], despite housing 54.5% of the world's population [67]. Further research is required as energy production, industrial, and agricultural land are insufficient to meet the demands of contemporary city residents, prompting cities to outsource energy, materials, water, and food [68].

Table 2.1: Property supply in Malaysia for year 2020

Type	Existing Stock (Units)	Incoming Supply (Units)	Planned Supply (Units)
Residential	5,845,580	434,807	429,985
Shops	540,699	32,033	33,034
Serviced Apartment	282,992	132,818	168,028
SOHO	47,878	32,003	14,201
Industry	118,301	4,354	6,828

Table 2.1 displays National Property Information Center (NAPIC) data regarding property supply in Malaysia for the year 2020 by type, existing stock, incoming supply, and planned supply [69]. From Table 2.1, it shows Malaysia has a relatively

large number of roofed buildings that can be used in addressing energy issue. In December 2020, Ministry of Energy and Natural Resources (KeTSA) announced Net Energy Metering 3.0 (NEM 3.0) to allow power users to install PV system on their rooftops to reduce their electricity cost [70].

Through NEM, excessive PV power may be "one-on-one" offset with grid electricity. This system provides credit for any excess solar energy generated and then used to offset the next electricity bill in order to save money and protect against future increases in the cost of electricity. Under the supervision of the Energy Commission (EC), the Sustainable Energy Development Authority (SEDA) of Malaysia served as the Implementing Agency (IA) for the NEM scheme, which was carried out by the Ministry of Energy and Natural Resources (KeTSA). In their evaluation of Lethbridge, Canada's rooftop photovoltaics, Kouhestani and colleagues [71] found that the system could provide 36% of the city's annual energy demand.

The weather in Malaysia is consistently tropical rain forest due to the country's equatorial location. Due to the greater solar altitudes during the day, houses in tropical climates experience significant radiant heat gains at the rooftops [72]. Rooftop photovoltaic correlates positively with building energy consumption, particularly with load driven by air conditioning [73], [74]. From 1990 to 2016, the proportion of building energy consumption attributable to cooling increased from 2.5% to 6%, according to the International Energy Agency (IEA) [75].

In tropical nations such as Malaysia, space cooling accounted for 11% of residential electricity consumption in 2016 [76]. Roof form angle, and direction, and the

building's possible shade, were considered while determining the optimal area for PV system installation [77]. Installing PV modules on the roof requires a suitable mounting structure to ensure airflow between the array and the roof [78]. Conversely, it generally elevates the thermal output of the solar cells, increases the T_{cell} , and diminishes the the generated energy production and effectiveness of the PV system.

2.3 Factors Affecting Photovoltaic Module Output

A PV module's electrical output is affected by a number of factors that can be grouped into three groups [79]:

- i. Heat effect - because of the solar irradiance, air gap beneath the PV array and the type of mounting arrangement
- ii. Light input - because of the site's shade and the strength of the solar irradiance
- iii. Other factors - dirt accumulates on the PV surface and aging

Temperature and irradiance are the two most crucial ambient parameters for the PV material [49]. The effect of irradiation on the highest point of power is clear: the greatest point of power increases with increasing radiation [80]. Archana's team from their study found that incident light would produce a constant current, although it would slightly increase as the voltage changes while voltage and energy are reduced as a result of the temperature increase as shown in Figure 2.8 [81]. Figure 2.8 illustrates the influenced temperature IV and PV simulation outcomes under the same conditions, respectively to show that voltage and energy are reduced as a result of the temperature spike.

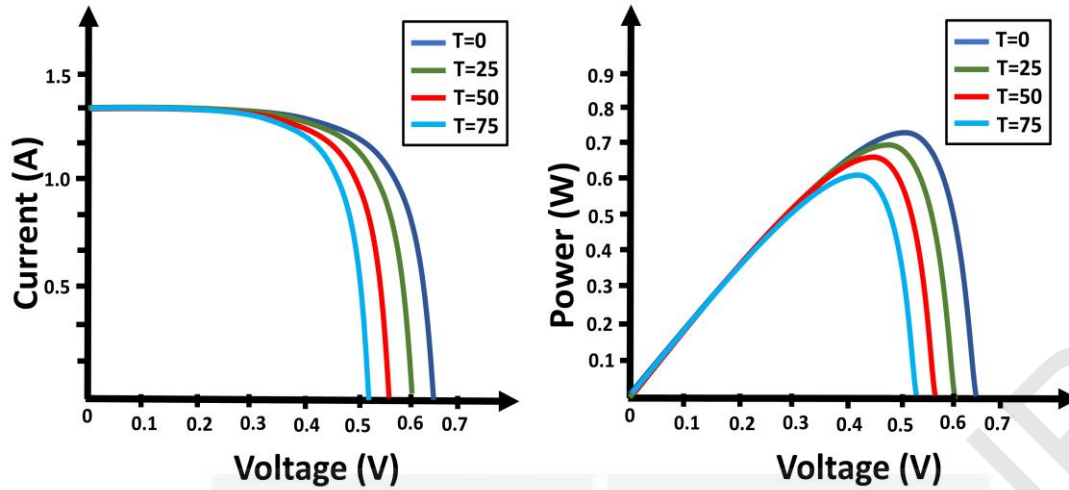


Figure 2.8: IV and PV outcome by influence of temperature [81]

2.3.1 Photovoltaic Module Temperature

There are several elements that directly impact the generation of electrical output, one of which is the T_{cell} . Figure 2.8 illustrates the ideal P-V properties of a PV module for a temperature range of $0^{\circ}C$ to $75^{\circ}C$ [81]. Every $1^{\circ}C$ increase in T_{cell} reduces electricity efficiency by 0.5% [82]. Zeyad et al. [7] discovered that PV module performance declines with T_{cell} due to the temperature-sensitive materials used for PV cells, notably crystalline silicone [83]. The performance of thin film photovoltaic cells (Amorphous-Si, CIGS, and CdTe) is less influenced by temperature increases; decreases by around 0.25% to 0.38% for each $1^{\circ}C$ increase in cell temperature [84].

Module efficiency decreased with increasing temperature due to an increase in carrier concentrations at the p-n junction [85] and a closer band gap inside the semiconductor material, which increased some non-noticeable current and decreased voltage by 2.2 mV per $^{\circ}C$ [86], [87]. As T_{cell} rises, fill factor and open circuit voltage fall, reducing

electrical efficiency [32]. Experiment confirms that when $T_{amb_pv_operation}$ increases from 25°C to 75°C, the open circuit voltage drops, leading to a drop in electrical efficiency, and the maximum output power of the PV module drops from 227 W to 196 W under 1000 W/m² irradiation [88].

Kurpaska et.al have done experiment in proven efficiency conversion of solar radiation and found from their tested ambient conditions that the average efficiency of radiation conversion ranged between 0.076 and 0.114. Their investigations have indicated that a doubling of radiation intensity and T_{amb} causes a rise in module temperature from 23.9% to nearly 40%, a temperature increase from 0°C to 50°C in the tested range, and a decrease in silicon panel efficiency of 20.1% [43]. About 20% of solar irradiance hitting the PV module surface is converted to electricity, while the rest is transformed to absorbed heat [14]. The residual solar energy converted to heat, elevating the T_{cell} by up to 40 °C above ambient [89], [90].

According to the spectral mechanism, photons possessing energy exceeding the band-gap of PV cells have the potential to generate electricity [91], whereas those with energy below the band-gap are transmitted and ultimately converted into detrimental heat within the substrate of the PV cells [92], [93]. In warmer climes, most incoming solar irradiance is absorbed as heat on the PV module, which reduces its performance. Since there is an immediate effect of temperature on the PV modules, it is useful to incorporate a temperature factor, f_{temp} and may be expressed as [94]:

$$f_{temp_x} = 1 + \left[\left(\frac{\gamma_x}{100} \right) (T_{cell} - T_{stc}) \right] \quad (2.5)$$

where

x could be $I_{sc}, V_{oc}, I_{mp}, V_{mp}, P_{mp}$

f_{temp_x} is temperature correction factor of parameter x for the module

γ_x is temperature coefficient of x (% per temperature change)

T_{cell} is necessary as per equation (2.5). The following criteria provide a formula for estimating T_{cell} during operation:

If the nominal operating cell temperature, (NOCT) value is unavailable, utilize [94]:

$$T_{cell} = T_{amb_pv_operation} + 25 \quad (2.6)$$

where

$T_{amb_pv_operation}$ is PV ambient average maximum temperature during operation ($^{\circ}\text{C}$)

In this study, $T_{amb_pv_operation}$ denotes the temperature between the PV module's backside and the rooftop. If both the NOCT and irradiance numbers are provided, utilize the following [94]:

$$T_{amb_pv_operation} = T_{cell} - \left(\frac{NOCT - 20}{800} \right) G_{amb} \quad (2.7)$$

where

NOCT is nominal operating cell temperature ($^{\circ}\text{C}$)

G_{amb} is irradiance at that T_{amb} (W/m^2)

2.3.2 Effect by Solar Irradiance

The amount of solar irradiance directly affects the current generated by a PV module [49]. As the solar irradiance increases, the current generated by the PV module also rises, leading to higher energy output. However, as Figure 2.9 shows, the voltage output of a CS6P-250P Canadian Solar PV module remains pretty constant around open circuit voltage and only slightly increases.

This stability in voltage output, despite variations in solar irradiance, indicates that while the energy production capacity of a PV module can change significantly with light levels, its operational voltage remains relatively unaffected. To summarize, the effect of irradiance on the PV module may be characterized as follows: It has a roughly proportional influence on the current and has a little effect on the voltage.

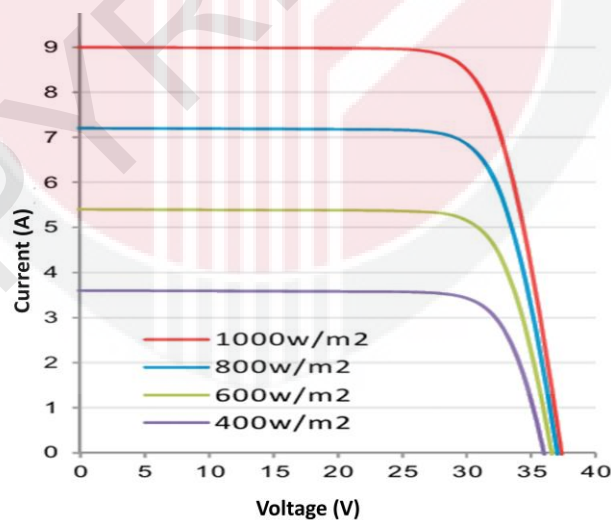


Figure 2.9: Irradiance effect on IV curve of CS6P 250P Canadian Solar PV module [Appendix A.10]

2.4 Solar Radiation

Using a variety of technologies, solar radiation is one of the renewable energy sources, or simply sunlight, that can be converted into heat and electricity [43], [95]. According to Zervos et.al. [96], The yearly global energy consumption is 1,800 times smaller than the entire quantity of solar radiation that reaches Earth's surface.

2.4.1 Solar Irradiance

Solar irradiance is the quantity of solar energy per unit area that is directed at a surface at a specific angle. It is quantified in watts per square metre W/m^2 or kilowatts per square metre kW/m^2 , where $1000W$ is equivalent to $1kW$ [97]. The irradiance values at the Earth's surface are significantly less than the solar constant. Depending on the regional climate, sunlight is scattered and reflected as it passes through the atmosphere, reducing the amount of energy that reaches the earth's surface. Solar irradiance data is utilized in the design, cost analysis, and performance evaluation of all types of PV projects [98].

2.4.2 Solar Irradiation

Solar irradiation is the amount of energy that hits a surface as a function of area, calculated by integrating the irradiance over a certain time period (hour per day) [99].

Solar irradiation value is in Wh/m^2 or kWh/m^2 and can be defined as the solar energy intensity at an observation point. All measurements and design calculations for solar-based energy technologies involve the implementation of power intensities over

time to determine solar energy intensity. This energy intensity can be reported as daily, monthly, or annual values [49].

2.4.3 Peak Sun Hour

The average daily solar irradiation is sometimes referred to peak sun hours (PSH). It denotes the quantity of solar irradiation that a certain area would get if the sun emits peak intensity for a designated number of hours [100]. PSH corresponds to 1000 Wm^{-2} of sunlight for one hour. Since the peak solar radiation is 1 kWm^{-2} the number of PSH and the average daily solar irradiation are numerically identical. For instance, a location that receives 8 kWh/m^2 per day receives 8 hours of sunlight per day at 1 kW . PV modules typically have an STC of 1000 Wm^{-2} therefore, the ability to calculate peak sun hours is useful. Frequently, when sizing PV systems, it is more practical to employ the concept of PSH. Consider the bell-shaped curve in the following plot of solar irradiance intensity in Wm^{-2} versus time (hours) in Figure 2.10 [50].

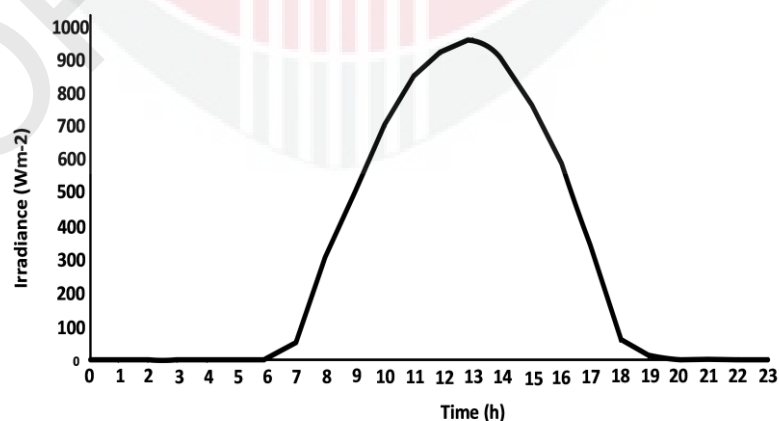


Figure 2.10: Plot of solar irradiance versus time

Calculated solar irradiation is equal to the area under the curve [50].

$$H = \int_0^{23} G dt \quad (2.8)$$

where:

H is solar irradiation (Whm^{-2})

G is solar irradiance (Wm^{-2})

t is time (hour)

The preceding equation can be numerically calculated as (2.6) [50]:

$$H = \sum_0^{23} G_n \Delta t \quad (2.9)$$

The total solar energy (irradiation) received in a day is equal to the total area under the solar irradiance curve. Curiously, the shape of the curve can be transformed into a rectangle or square by setting the height of the rectangle (or square) to $1,000 W/m^2$ while maintaining the same area Figure 2.11 illustrates the effect.

The magnitude of the area under the curve in Figure 2.11 is preserved, but the shape of the curve has been transformed into a rectangle (shown by the shaded region). This figure represents the entire area under the solar irradiance curve, leading to the idea of PSH. This PSH concept greatly simplifies all solar radiation-based application designs employing PV technology [50]. Daily irradiation is also commonly referred to as PSH.

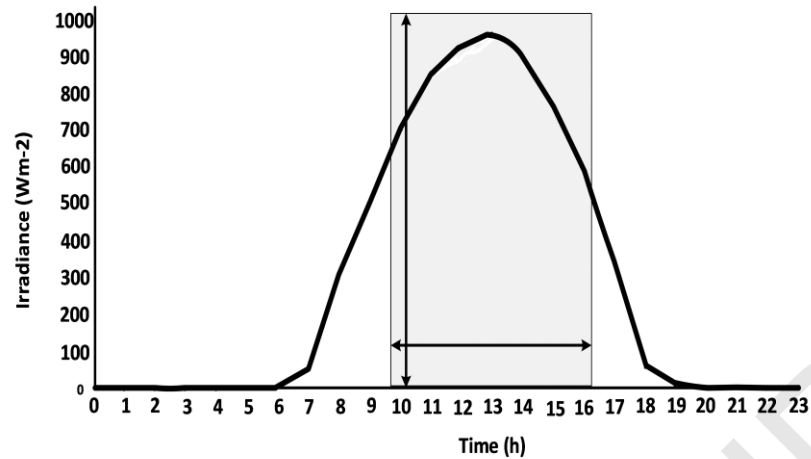


Figure 2.11: Relationship between solar irradiance, irradiation and Peak Sun Hour

2.5 Cooling the Photovoltaic System

Previous research has investigated several methods to reduce T_{cell} , particularly by employing a cooling technique for PV modules. These include evaporation cooling, thermoelectric cooling, transparent coating, natural air, forced air, and phase change materials (PCM) [7]. The enhanced electrical efficiency in photovoltaic thermal (PVT) systems can diminish the investment payback period and extend the system's lifespan, thereby augmenting the economic viability of implementing this system and promoting electricity generation from this source [101], [102].

A converging heat exchanger-cooled photovoltaic module reduced cell temperature to 45.1°C and increased power output by 35.5 %, according to Baloch et al. [103]. A variety of cooling methods have been tested and validated; nevertheless, the enhancement in electrical efficiency is contingent upon the cooling method, module type and dimensions, geographical location, and seasonal variations [86].

As a tropical country, Malaysia can be categorized as a country that has high PSH per day. The main problem with rooftop PV system in a tropical country where the T_{amb} is quite hot and have to deal with the T_{cell} . PV modules experiences overheating as a result of intense solar radiation and elevated T_{amb} [104]. Increasing temperature of roof due to over exposed to solar irradiation affects the rising of T_{cell} and led to the less efficiency of PV system. Overheat reduces the efficiency of the modules dramatically [105].

Dwivedi et al. [10] has reported that every 1 °C rise in T_{cell} , decreases effectiveness by 0.5%. Zeyad et al. [7] found that PV modules receive solar irradiation and give electrical energy to the load, but part of the solar energy is transformed into heat and lost by radiation and convection. The heat is released into the environment via the air gap at both the back and front surfaces [106]. PV module' s performance notably declines as their T_{cell} , rises [7].

Cooling is necessary to improve PV module performance and reduce heat waste as only 13%–15% of solar radiation is converted into electricity [107], [108]. To reduce T_{cell} , heat energy must be dispersed. The T_{cell} can be maintained near to T_{amb} while reducing temperature differential [109]. To maximise PV power generation, PV modules must be cooled by draining excess heat. PVT collectors or thermal collectors can capture this heat by moving water/air beneath the PV module [110].

Improving the PV module output power efficiency is a critical task for the solar industry and applications. Elevated temperatures have a detrimental effect on performing photovoltaic systems. To achieve conversion efficiency, excess

overheating must be dissipated. The operation of an integrated PV cooling system is crucial for enhancing the performance of PV systems [14]. Research indicates that implementing such a cooling system can yield a significant power increase, potentially reaching up to 5 % [111]. Cooling systems reduce PV cell costs, improve module life, promote solar industries, and maximise module output power [112].

2.5.1 Classification of Cooling System

Early proposals for cooling techniques emerged during the exploitation of PV systems [113]. Figure 2.12 shows that there are numerous methods to cool a PV module. Some of these approaches include using water, air, and PCM [114]. Each of these approaches, together with their respective kinds, are designed to maintain PV modules at the optimal T_{cell} , so enhancing PV module's performance, extending lifespan, and facilitating the advancement of renewable energy. The techniques may be classified into passive and active cooling methods [20], [115].

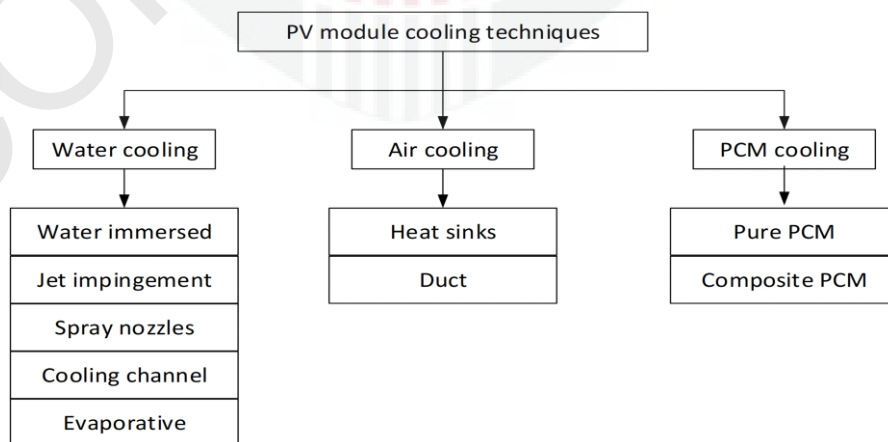


Figure 2.12: Categorization of primary cooling techniques

Passive cooling uses natural water flow and eliminates the pump demand to cool PV modules [108]. However, it can only chill water to a certain point before the water becomes too hot to handle. As a result of buoyancy, hot and cold gases exchange heat in a process known as natural convection [114]. As a PV module increases in temperature, it elevates the temperature of the surrounding air, resulting in a decrease in air density. This facilitates the ascent of heated air, so generating a natural convection circulation. Active cooling, on the other hand, uses pumps to manage T_{cell} by altering the pace of the water flow [116].

Nevertheless, an increased flow rate necessitates greater pumping power, leading to elevated energy consumption. Forced convection, however, depends on airflow across the front and rear of modules to maintain consistent temperatures, requiring a significant amount of fan power [13]. The PV module's power output decreases due to the fan or pump's power consumption [117]. Figure 2.13 illustrates that this technique could be divided into two main groups: forced water cooling and forced air cooling [114]. The majority of these techniques rely on cooling with either air or water [115].

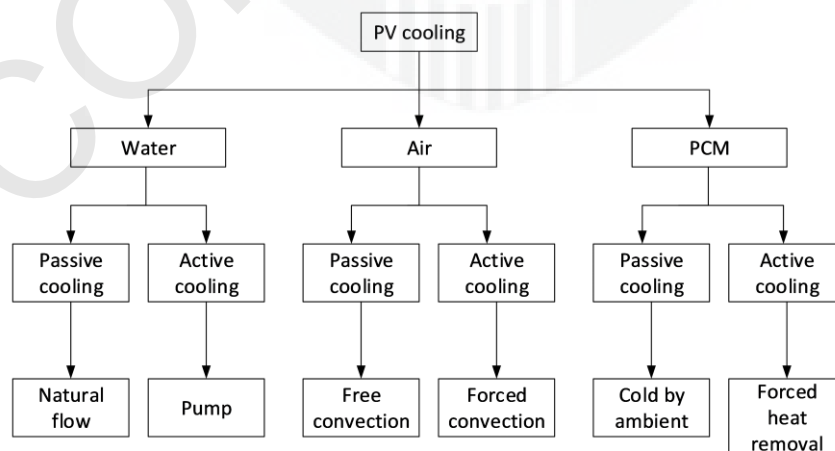


Figure 2.13: Classification of active and passive cooling techniques

Passive cooling is simple and inexpensive, but it has a poor heat transfer rate and does not significantly improve PV module efficiency [13]. Active cooling is an effective way to improve PV module performance, however it requires an extra power source, which subtracts from the PV module's power and lowers its net output power.

2.5.2 Water Cooling Photovoltaic System

Water cooling is a specific approach that considerably improves PV system performance due to water's outstanding heat absorption characteristics. This method helps to enhance T_{cell} management and the whole effectiveness of PV systems by effectively dispersing surplus heat. It may be used in either passive or active cooling, offering flexible solutions to meet specific needs. Zubeer and Ali [118] placed two reflectors side by side and utilised a 45 W AC water pump to transport water from a tank to a pipe on the module's front side, improving its electrical performance by 17.7 %. By spraying water in front of the PV module and placing fins on the rear, Gomaa et al. [119] employed active and passive cooling. They showed 10.2 % daily energy harvesting growth.

Dida et al. [120] studied passive cooling using water evaporation and a hessian cloth connected to the module's back. Effective, this method increased electrical efficiency by 14.75 % They suggest studying this technique's cooling performance in relation to wind speed, water temperature, and water flow rate. Elminshawy et al. [121] proposed passive water cooling with a buried water heat exchanger (BWHE). The suggested cooling system enhanced peak produced electrical power (GEP) by 18.6% and relative leveled cost of energy by 12.20%.

All of the above water-cooling techniques were evaluated on a prototype *PV* system module. Castanheira et al. [122] evaluated their prototype's active cooling method on a 5 *kW* (25 panels) solar power plant string. Sprinkle low-pressure water around *PV* modules to achieve equal distribution and decrease leakage. The proposed method raised yearly energy output by 2% and maximum power by 17%. Joseph et al. [86] employed the same notion of coolant preservation and allowed the heated coolant to be used in product manufacture in their simulation-based research study for active *PV* cooling. Their double-sided cooling technique increased performance and efficiency by 7.7 %.

When utilising water to cool an installed *PV* system, the rooftop water supply position must be carefully considered. Suppose the *PV* system is near the water source. In that instance, solar irradiation heats the water storage, making it unsuitable for chilling. Hence, it is imperative to find a viable solution that ensures a consistently low water temperature to facilitate the cooling process of the *PV* system. If the water source is in a shaded area, it should be placed at a considerable distance from the current *PV* system because the *PV* system operates based on solar irradiation and is located in an area that is highly exposed to it. To do this, a technique must be developed to transport water from the source to the region of the *PV* system. It should consider factors such as water pressure, selecting appropriate materials to prevent excessive heat absorption, and determining the energy needed for this process.

Water management throughout the cooling process must be emphasized as a key priority. The discharged water allowed to flow onto the roof, and the potential long-term consequences of subjecting the roof to high humidity and moisture should be

considered. Roof leaks or the gutter channel designed for draining water may necessitate changes to the existing PV system and incur additional costs.

2.5.3 Air-Cooling Photovoltaic System

Cooling PV systems is critical, particularly when it comes to air cooling type. This method efficiently utilizes the thermal characteristics of air to remove heat from the PV module, resulting in better T_{cell} management and PV system performance. Heat can be dissipated by a variety of convection techniques, either natural or forced. Air cools less efficiently than liquids, but it uses less material and costs less [123].

Kaewchoothong et al. [83] built numerous cooling modules with rear-mounted rib turbulators to uniformly cool and increase PV module performance. Their aggressive air-cooling system boosted average output power by 13.97%. By inducing air circulation on the PV module's backside and pouring water on the front, Lebbi et al. [17] increased electrical efficiency. They employ active cooling with self-cleaning and Bi-Fluid coolants and propose improving solar pumping irrigation for big applications with their hybrid technology. Kabeel et al. [20] use reflector-based forced-air and water-cooling systems. The result showed net electricity output growth. Elminshawy et al. [14] precooled ambient air via an earth-to-air heat exchanger (EAHE) to cool the PV panel back. In average, PV module output power and electrical efficiency increased 18.90% and 22.98%, respectively.

Previous study used DC fans on the back of PV modules to collect heat and cool them [124] by covered rear of PV module with zinc sheet [18], [125] to install the DC fan.

This involves adjustments to the solar module and is quite challenging for the existing PV system. It adds weight and is difficult to install on an existing PV system. Installation of heatsink and DC fan to every PV module used, resulting in high operating costs and energy consumption.

Both fan and heatsink installations require considerable space from the rooftop to ensure airflow is not affected by the roof heat. The problem arises if the stability of the solar system, as the mounting structure with high altitude on a rooftop, is more susceptible to wind factors. The higher altitude, the less stable the PV system becomes. Axial fans have a high airflow, but using one as a DC fan on the back of a PV module only covers a small area, resulting in winds that are uneven and concentrated in certain areas. If we desire an even wind, an enormous fan and hamper-sized fan equal to the size of the PV module or a substantial number of fans for one back-side PV module may produce superior results.

A research study also proposed using a centrifugal fan and steel plater under the PV module to create an air channel underneath it, with a duct linked to cool the PV module [19]. The duct design is unsuitable for wide-width cooling since it must consider the centrifugal fan's design. Heat pipe cooling was used to remove the high heat [126], [127] and reject the heat to ambient. The heat pipe size must be considered for the cooling PV system.

Ensuring a consistent airflow and selecting the suitable air source for the compact area beneath the PV array are crucial factors when using air for cooling the PV system. Selecting a fan that can effectively channel the increased wind flow is important to

optimize the airflow between the PV module and the rooftop. It may be achieved by using a wider blade fan to generate more wind.

Past research on cooling solutions has consistently shown that the performance of PV modules may be improved by lowering the T_{cell} . However, the majority of earlier studies were done on prototypes that were built on a small scale. Conducting research tests on the current PV system is recommended to assess and determine all components and constraints that arise when implementing the cooling system on the actual PV system, particularly when it is installed on a rooftop.

2.6 System Identification Modeling

Most analytical techniques in engineering were based on a model. Models can be built using theoretical methods based on physical principles or experimental methods based on system data [128], [129]. System identification (SI) is the process of developing models based on empirical data [130], and numerical modeling may be improved by including an extra experimental-based method [131]. Identification experiments seek to discover a process's dynamic properties.

One advantage of employing models is that the step test used is extensive, making it easy and inexpensive to implement. Step testing is frequently performed on a system once the process has been identified or stabilized. SI modeling is a systematic approach for acquiring, organizing, analyzing, and identifying black-box models produced from raw data from real-world systems.

Modeling in process control is of the highest relevance because a successful control system is dependent on the availability of a well-constructed model that exactly portrays the dynamics of the process [132]. Modelling helps optimise air-cooling PV system efficiency, both in PV module performance and air-cooling mechanism efficiency.

SI is the process of developing mathematical representations of dynamic systems using statistical techniques on acquired data. SI research involved creating experiments to successfully collect data from the system in order to construct models and reduce model complexity. SI uses stimulus and response samples to model a dynamic system mathematically. The current focus is on identifying parameters and properties of dynamic systems through the use of specialist identification methods [133]. SI creates a mathematical description of the system using measurable input and output data in order to build an accurate model [134]. These systems are defined using input and output vectors, but because the bulk of physical systems are nonlinear, analytical linearization is challenging [135]. As a result, creating models that match analytical criteria may necessitate nonlinear engineering models. The model correctly predicts the effects and reactions of the created model [136].

SI consists of numerous critical components, including experiment design, experiment implementation, data pre-processing, model structure selection, model fitting to data, and model validation [137], as seen in Figure 2.14. These components are critical for accurately recognizing and comprehending the many characteristics of a particular system. Continuous time transfer functions can be used to describe physical models in general.

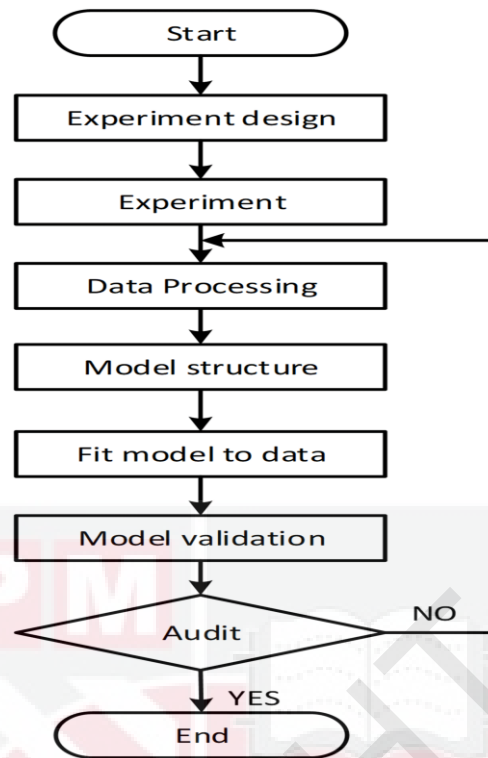


Figure 2.14: Flow chart for system identification

In Matlab, the SI toolbox is a collection of techniques for identifying and analyzing various system components, including their structure, characteristics, and experiment data from the time domain [138], as well as simplifying SI using experimental data. The SI tool integrates the functions of transfer function (TF) or process models, making it easier to employ different identification methodologies.

A dynamical model describes a system or process's time- or frequency-dependent behaviour [139]. The program provides a reliable, near-accurate model foundation. We evaluated and simulated the proposed model to confirm its efficacy and reliability. This method may also be used to estimate the model for an air-cooled PV system. Intelligent, linear, and nonlinear models are some of the modeling strategies that may be used.

2.7 Proportional Integral Derivative Controller

Adding a controller to the system can improve its reliability and subsequently increase its performance. The controller was used to explore how controller parameters affect system behavior [15] by using a controller input tuned based on the response [140]. With advancements in control technology, a controller may enhance outcomes and lower failure rates, resulting in a drop in failure rates [141].

Optimising system performance requires a good controller. Control system development and investigation are necessary to increase return on investment and make the investment profitable. The primary enhancement involves endowing the controller with control capabilities to enhance system efficiency. Many physical systems are complicated, making it difficult to represent them accurately for control strategy development [142].

The ability to test and evaluate model-based control algorithms prior to controller construction is a key advantage of these algorithms. The identification of control-oriented models has been on the rise in recent years. The most frequent controllers used in businesses are proportional-integral-derivative (PID) controllers [28]. PID techniques are considered to be the most precise and highly recommended, as stated by [29], [143]. PID controllers are an ideal alternative for regulating many modern industrial processes due to their simplicity and great control performance. Their digital design execution causes this [144]. Digital PID controllers use auto tuning, fuzzy fine-tuning, anti-windup mechanisms, and adaptive algorithms to enhance efficiency while still adjusting parameters [145].

The PID controller parameters K_p , K_i and K_d may be adjusted to improve system performance such rising time, overshoot, settling time, and error steady state. This is because each component serves a different purpose. P mode, or proportional action, adjusts controller output according to error magnitude. Current system behaviour determines it. The integral action, or I mode, eliminates steady state offsets using prior knowledge. However, the derivative action, or D mode, predicts control error levels to forecast trends and accelerate reaction time.

These three actions are merged to create a robust feedback controller and supply the control output at the correct setpoint to maximise each control mode's benefits. The PID controller remains the most often used controller in industry [146] because to its ease of operation and robustness. PID control utilizes modelling of a problem, particularly a process loop, to govern a system without the need to develop a system model.

It is unnecessary to implement intelligent control strategies that need extra devices for assessment when selecting the optimal control solution using a PID controller. For air-cooling PV systems, model-based control algorithms are advantageous because they enable cost minimization through simulation and evaluation prior to the physical construction of a controller. This approach predicted air-cooling PV system performance under different irradiance levels and provided an adjustment vector that minimises the cost function while meeting limitations.

PID control uses the difference between a process variable's desired and actual value. Its precision, stability, and low offset error make it desirable for academic and

industrial use [147]. In addition, the PID controller has proven its capacity to improve the effectiveness of traditional control systems, especially when it comes to nonlinear control [148] and unstable systems [149]. The PID controller is recognized for its ability to fulfil performance metrics, computational capacity limits, and resource accessibility. Furthermore, it offers advantages in terms of flexibility, precision, and resilience, particularly when used in conjunction with other control systems [134], [150].

2.8 Gaps and Challenges in Cooling Photovoltaic System

The dimensions and mass of the cooling system are critical factors for the rooftop PV system. This type of cooling on retrofitted rooftop PV systems is questionable; hence it overcomes the mass of PV systems on rooftops and cannot easily be compared with large-scale PV systems on the landed area. Excessive overload on the roof could bend the roof.

Due to its high static pressure and highly focused air flow, the centrifugal fan could condition the flow in a precise direction and increase pressure. Spot cooling is suitable for centrifugal fans, but the area between the back side of the PV module and the roof is too great for spot cooling. It would be preferable if we generate a uniform, wide airflow suitable for width cooling beneath the PV module. A temperature-dependent air-cooling mechanism with adjustable fan velocity to enhance the effectiveness of PV modules by reducing the T_{cell} is must have for energy savings by preventing continuous rotation, hence lowering energy consumption.

The lack of development in the prior air-cooling PV system model necessitated the development of the new model, which is a significant innovation. The air-cooling PV system model allows for accurate prediction of the performance of PV modules and the air-cooling PV system under different levels of irradiance without the need for conducting experiments in hot weather or exposing oneself to risks in the field, such as standing on the roof of a high-rise building.

The investigation on suitable controller operation of the air-cooling PV system can provide a controller with control capabilities to increase the efficiency of the air-cooling PV system in order to accelerate the return on investment (*ROI*) and make the investment beneficial.

2.9 Summary

This chapter provides an overview of the basic principles of PV cells, including their characteristics and the factors that influence PV module's performance. It also discusses the different types of PV systems, their configurations, and classifications. Additionally, it includes a review of important parameters such as irradiance, irradiation, peak sun hour, and operating temperature of PV modules. Subsequently, the notion of cooling a PV system was examined through a thorough evaluation and discerning examination of prior research. The application of both passive and active cooling techniques is thoroughly considered.

This study provides a more comprehensive explanation of cooling techniques, specifically water- and air-based cooling methods. The resolution of traditional limitations in active cooling of PV modules is being examined. The suggested air-cooling PV system may use the cooling approach and address the disadvantages of the current retrofitting rooftop PV system.

An investigation was conducted to analyze the air-cooling PV system to determine the optimal air convection for the cooling system and research purposes. The air-cooling approach is selected to decrease the T_{cell} and thus enhance the output efficiency of the PV module. Black-box modeling is selected to create an input/output model for air-cooling PV modules in TF forms using SI. This model aims to forecast the efficiency of air-cooling PV systems and improve the output performance of the PV modules. The model is applicable in a PID control-based system.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter has two main sections: experimental work and simulation work, illustrated in Figure 3.1. Experimental work focuses on system design and testing for a thermoregulated air-cooling retrofitted photovoltaic (PV) system. Experimental work outlined the idea and functioning, including finding out the cross-flow fan as a suitable design, size, and weight of the fan for a compact area between the rear of the PV array and the rooftop. All relevant equipment and materials are designed and were developed for experimental purposes. A thermoregulated air-cooling system's operating temperature range is determined by an experiment that analyses all relevant variables. The experiment has been done from 7:00 *a.m.* to 7:00 *p.m.*, and T_{cell} , solar irradiance, output voltage and power, were recorded before and after implementing the air-cooling system. Simulation work focuses on modelling the cooling solution with a proportional-integral-derivative (PID) controller as a control mechanism. All experiment's data were used as both input and output in system identification (SI) with a black box approach to create a model of the PV module and thermoregulated air-cooling retrofitted PV system. The development model is used to develop a control-based model using a PID controller in Simulink. The PID controller was designed using the Ziegler-Nichols method. All simulations were done before and after applying an air-cooling and under various solar irradiance levels.

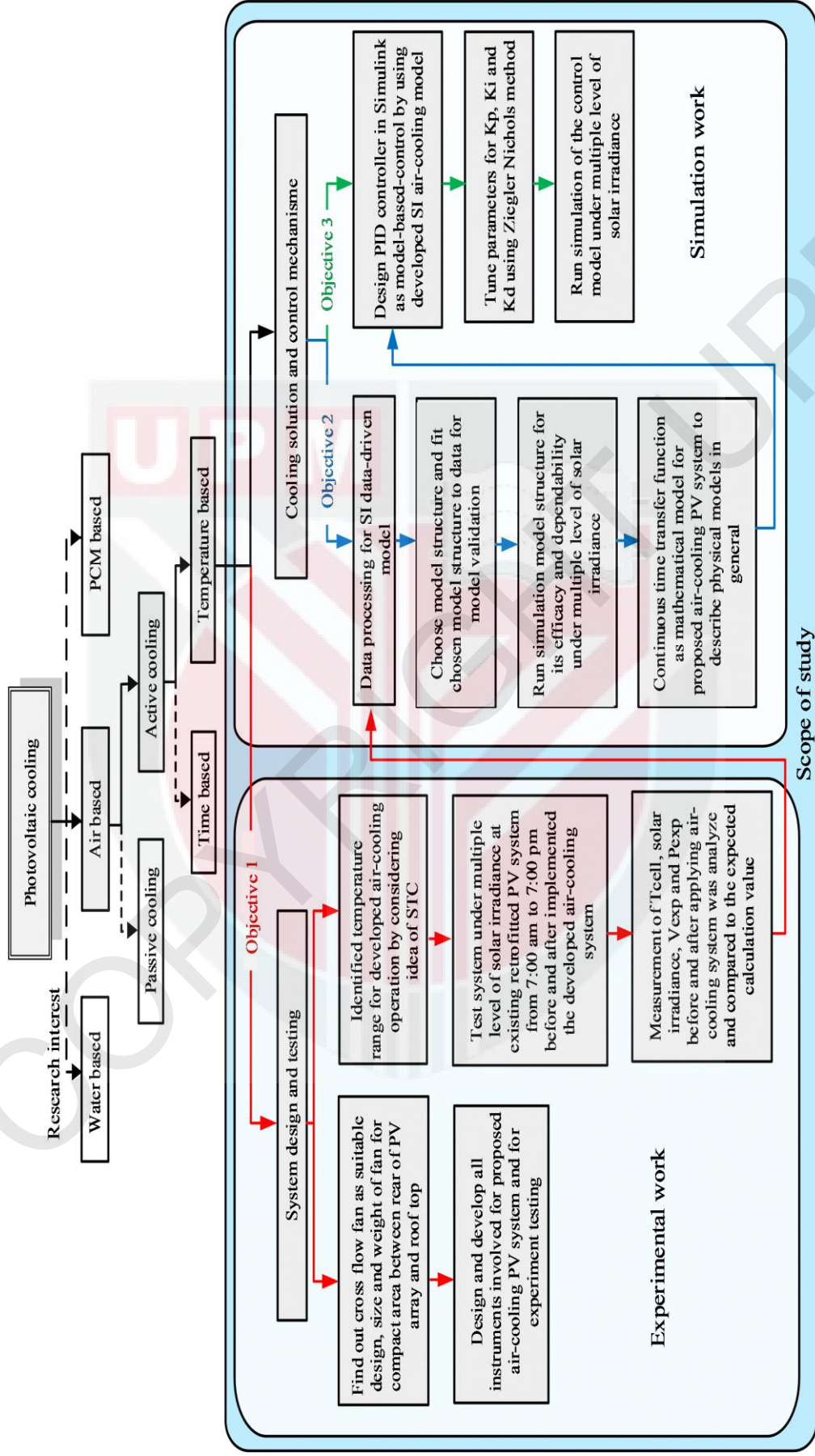


Figure 3.1: The overall procedure for suggested methodology for thermoregulated air-cooling retrofitted PV system

3.2 Experimental Work for Thermoregulated Air-Cooling Retrofitted Photovoltaic System

This section focuses on thermoregulated cross-flow air-cooling for retrofitted PV system concept and hardware design and development. To lower the operation temperature of the PV module, T_{cell} attach a cross-flow fan below it to provide uniform air conduction. Cold air flow was assured by eliminating the trapping of hot air below the PV module.

The suggested air-cooling system is designed to operate within a specific temperature range, hence functioning as a thermo regulated cooling system. Irradiance meter, direct current (DC) energy meter, and fan controller device are essential components of the instrument used in the experimental testing of the proposed air-cooling system. These devices were designed and developed specifically for this purpose. Experiment was conducted on a pre-existing retrofitted PV system.

Since Malaysia has a tropical climate with rain and heat all year, and the research region does not suffer extreme weather such as rain or heat for a limited time, recording the variability in environmental conditions over a longer period is unnecessary. Furthermore, the studies conducted relied on data before and after the installation of the cooling system. Therefore, each comparison done requires two days with almost the same solar irradiance reception and does not require data for a long period.

3.2.1 Thermoregulated Air-Cooling Retrofitted Photovoltaic System Concept

Thermoregulated air-cooling retrofitted PV system consists of a DC motor for a cross-flow fan, temperature sensor and controller box act as fan controller device. The temperature sensor was attached to the back of solar module to detect temperature changes on the T_{cell} . The specified temperature range for the proposed air-cooling system is defined by $T_{cell_minimum}$ and $T_{cell_maximum}$, which represent the minimum and maximum temperatures for T_{cell} . Figure 3.2 illustrates the proposed thermoregulated air-cooling retrofitted PV system control strategy concept for this study.

When the temperature sensor detects T_{cell} below $T_{cell_minimum}$, the cooling fan is turned off. Nevertheless, if the T_{cell} is between $T_{cell_minimum}$ and $T_{cell_maximum}$, the microcontroller sends a signal in the form of voltage to the metal oxide semiconductor field effect transistor (MOSFET) gate to turn on the fan according to the pulse with modulation (PWM) setting in microcontroller. The fan operates at a speed according to the temperature within the designated range.

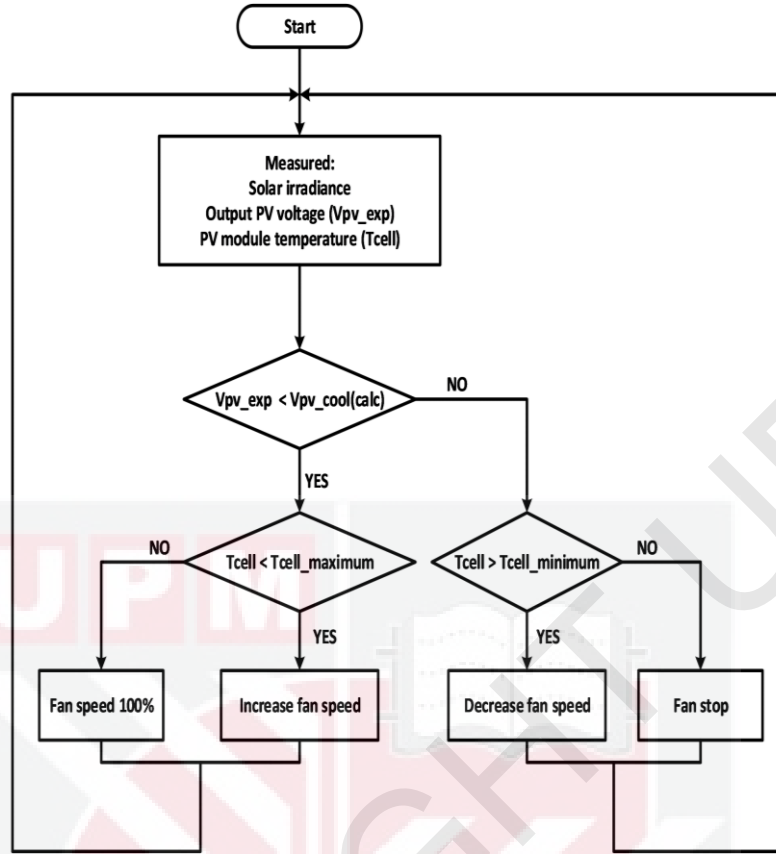


Figure 3.2: Proposed thermoregulated air-cooling retrofitted PV system control strategy

When the T_{cell} exceeds $T_{cell_maximum}$, the fan operates at its highest speed. As the temperature drops, the fan's speed decreases until it eventually stops. Here, we assume that the solar irradiance metre functions perfectly and the output voltage of PV module at real operating condition (ROC), V_{mp_roc} also known as voltage output of PV module during experiment, V_{pv_exp} can reach the set point or expected output voltage of PV module after applying the thermoregulated air-cooling system, $V_{pv_cool_calc}$ within a short time. The output voltage of PV module can be calculated as below:

$$V_{pv_x} = V_{x_stc} \times \left[1 + \left(\frac{\gamma_{V_x}}{100} \right) (T_{cell} - T_{stc}) \right] \quad (3.1)$$

where

V_{pv_x} is voltage for PV module at x condition

V_{x_stc} is voltage for x condition at STC (Volt)

γ_{V_x} is temperature coefficient for voltage at x condition

From equation (3.1), the expected output voltage for maximum power point voltage before applying thermoregulated air-cooling system, $V_{pv_uncool_calc}$ was calculated as follows:

$$V_{pv_uncool_calc} = V_{mp_stc} \times [1 + (\frac{\gamma_{V_{mp}}}{100})(T_{cell} - T_{stc})] \quad (3.2)$$

where

V_{mp_stc} is voltage at maximum power point at STC (Volt)

$\gamma_{V_{mp}}$ is temperature coefficient for voltage at maximum power point

The expected output voltage for maximum power point voltage after applying thermoregulated air-cooling system, $V_{pv_cool_calc}$ was calculated using same equation (3.2). The study examined the impact of installing an air-cooling system on the T_{cell} , both before and after implementation. Solar irradiance, T_{cell} , and output voltage of the PV module were monitored simultaneously to establish the correlation between these parameters. The experiment compares the PV module's output voltage, V_{pv_exp} to the predicted output voltage, $V_{pv_uncool_calc}$ and $V_{pv_cool_calc}$ both before and after the implementation thermoregulated air-cooling retrofitted PV system.

3.2.2 Design and Development of Thermoregulated Air-Cooling Retrofitted Photovoltaic System

A hardware prototype that was developed and implemented in the experiment has been showcased, as shown in Figure 3.3. The hardware unit comprises an irradiance metre, a DC energy metre, and a controller box. This sub-section provides a detailed description of all the equipment utilized in the design and development of the thermoregulated air-cooling for retrofitted PV system. The study incorporated the necessary equipment for measuring the pertinent parameters.

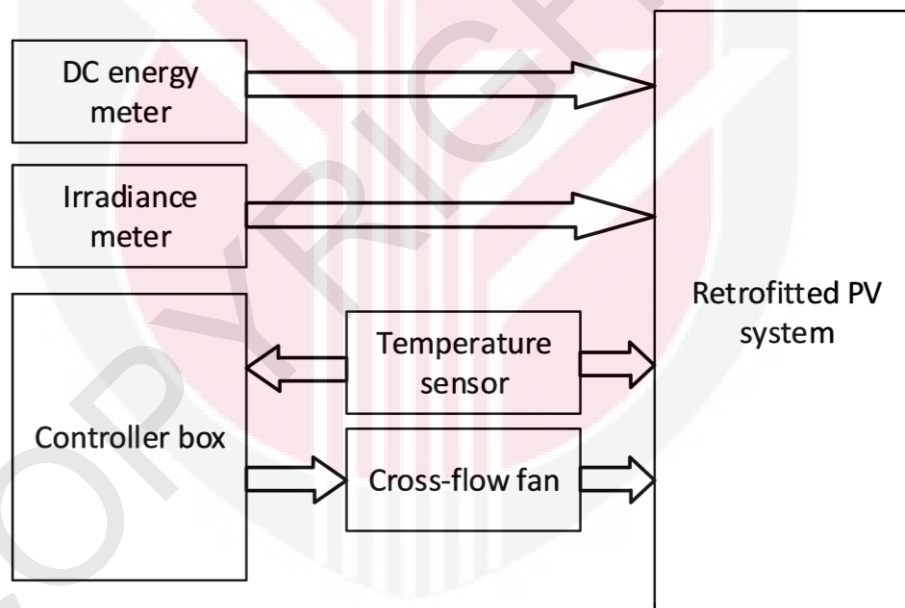


Figure 3.3: Simplified block diagram for a typical thermoregulated air-cooling retrofitted PV system

3.2.2.1 Arduino UNO

A microcontroller is a small, integrated circuit that is specifically intended to regulate a particular activity within an embedded system. A standard microcontroller has a CPU, memory, and input/output (I/O) peripherals on one chip. Most of the investigation's equipment controlled a device function with the ATmega 328P microcontroller. The central processor interpreted the data it received from its input/output peripherals. ATmega328P is the microcontroller on which the Arduino UNO is based on it.

Arduino UNO contains 14 digital I/O pins (six of which are PWM outputs), 6 analogue inputs, a 16 MHz ceramic resonator, a USB connector, a power jack, an ICSP header, and a reset button. Everything for microcontroller support is included. The Arduino UNO board's ATmega328 microprocessor is easily accessible and easy to use. Timers, PWM pins, external or internal interrupts, and sleep modes are also on the board. The research built an irradiance meter, DC energy meter, and controller box with Arduino UNO board. The technical specification for this Arduino UNO can be found in Appendix A1.

3.2.2.2 Datalogger Shield

Datalogger shield is an expansion board made up of three major components: the secure digital (SD) card module, the real time clock (RTC) module, and the prototype board. The SD card and RTC modules are essential for data logging, while the prototype board can be used to connect sensor terminals or make any other wiring

modifications. The datalogger shield may be used immediately after being placed on the Arduino UNO. Unlike SD card and RTC modules purchased separately, no additional cabling is needed.

This work uses Datalogger shield to properly capture Arduino UNO data in SD card. LCD Display shield and datalogger shield are typically placed together. In this study, the datalogger shield was employed to create an irradiance meter, DC energy meter, and controller box. The data specification for this data logger shield can be found in Appendix A2.

3.2.2.3 Liquid Crystal Display Shield

Without wiring, a 16X2 LCD Display Shield may be mounted on the Arduino UNO board. This LCD display shield is usually used with the datalogger shield. LCD display shield displays current value while datalogger shield captures data. The datalogger shield placed between the LCD display shield and Arduino UNO board. The LCD display shield was used in the creation of the irradiance meter, DC energy meter, and controller box.

3.2.2.4 Irradiance Meter

There are no readily accessible sensors for measuring solar irradiance levels. Solar irradiance can be difficult to measure due to the Sun's extensive range of wavelengths. Numerous studies [151], [152] have examined the spectral irradiance of the sun in order to develop a standard model of solar irradiance. Typically, the pyranometer,

which is a very expensive instrument, is used to measure solar irradiance. Goswami et.al. in his book stated solar irradiance value is in watts per square metre, W/m^2 [153], while light illuminance is in lux, lx [154].

Light meters measure brightness in lumens, lm per metre squared or lux, lx . They are cheaper and more sensitive in low light. Michael et al. found a conversion factor between W/m^2 and lx that lets light metres evaluate photovoltaic performance in low solar irradiation [139]. They study solar irradiance and illuminance and create a theoretical and laboratory conversion guide.

This research would be aided by an irradiance metre to measures low solar irradiance in a straightforward and economical manner applying an engineering rule of thumb which is $120\ lx$ equals to $1\ W/m^2$, or $1\ Sun$ equals $120000\ lx$ found by [155]. Figure 3.4 illustrates block diagram for irradiance meter developed in this study. BH1750 light metre was used as a photodiode sensor, while the Arduino UNO as a microcontroller. Datalogger shield used to store the data, and a 16 X 2 LCD to display the irradiance measurement. Figure 3.5 illustrates a schematic circuit for interfacing Arduino UNO and BH 1750 in this work. The output of the BH1750 is displayed on a 16 X 2 LCD that is interfaced with Arduino UNO.

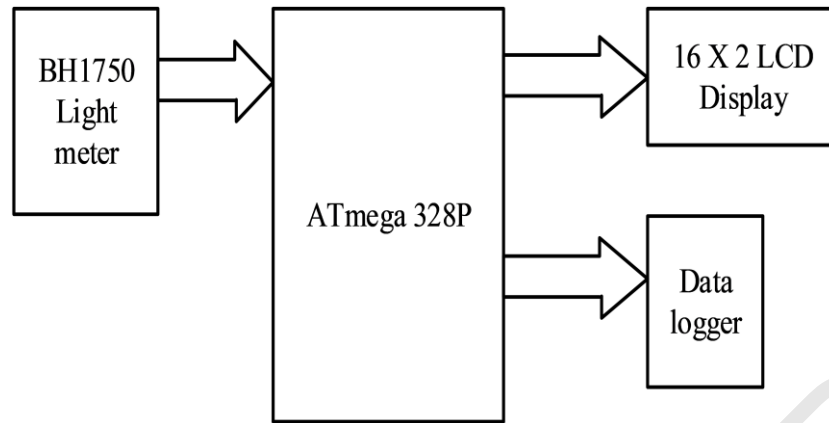


Figure 3.4: Block diagram for irradiance meter used for experimental work

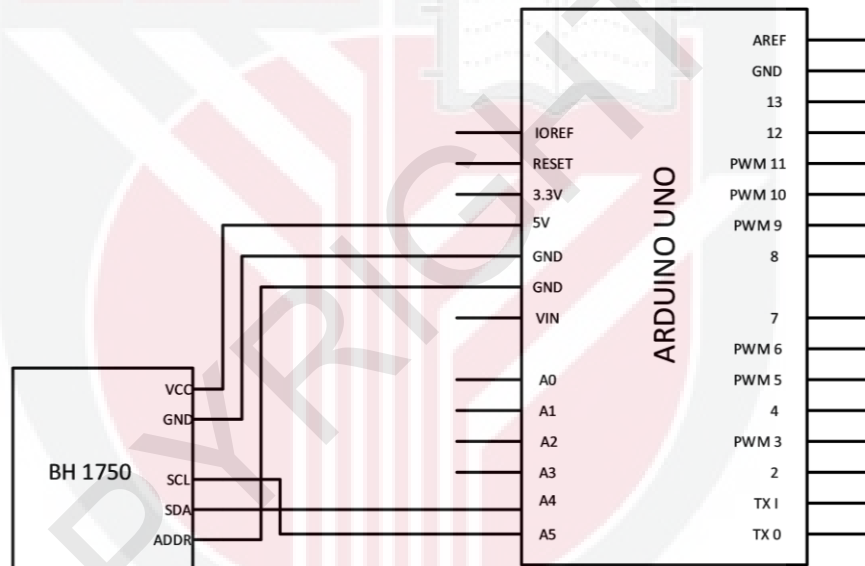


Figure 3.5: Schematic circuit interfacing Arduino UNO and BH 1750

3.2.2.4.1 Light Meter

This study acknowledges the light sensor's relevance. Many sensors detect flux, including light-dependent resistors [156], but imprecisely. For this, a widely available, cost-effective solution is needed. It supports 65,535, lx units max. This is half the

brightest sunshine. Table 3.1 displays a maximum value or value range for a variety of brightest conditions.

Table 3.1: A maximum value or value range for a variety of brightest conditions

Case	Illuminance (lx)
Brightest Sunlight	120000
Bright Sunlight	100000-110000
Shaded Clear sky	20000

Under a clear sky, BH1750 sensor might offer ambient light range that could be translated to standard irradiance for typical applications. Technically, it may give a certain irradiance range. With a wider ambient light spectrum, the complete spectrum may be attained. BH1750, a 3.3V digital ambient light sensor, connects with microcontrollers via inter-integrated-circuit (I2C). The ADDR pin is for I2C device address, whereas SCL and SDA are for clock and data. The dimension and full technical specification for BH1750 light sensor can be found in Appendix A3.

3.2.2.5 Direct Current Energy Meter

A DC energy meter measures DC voltage, DC current, instantaneous power, and cumulative energy consumption. DC energy generation or DC load systems like PV module use this device. As said, this study requires two sensors: a DC voltage sensor and a DC current sensor to provide four characteristics. Arduino UNO module analogue input pins measure DC voltage and current. Each measurement requires one of six analogue input pins. Datalogger shield Analogue Pins A4 and A5 are used for

I2C connection with the real time clock module, whereas LCD display shield Analogue Pin A0 is used for button function. Analogue Pins A1 to A3 were left for DC current and voltage.

A1 configures to measure DC Voltage, while A2 measures the current of the module. DC voltage sensor (via module) and HSTS016L Hall effect current were sensor used in this designed DC energy meter for measuring voltage and current. The block diagram for DC energy meter developed in this study is illustrated Figure 3.6. LCD display shield and datalogger shield were stacked together to Arduino UNO board in this project. A schematic circuit for interfacing between DC Voltage sensor, HSTS016L current sensor and Arduino UNO used in this study is shown in Figure 3.7.

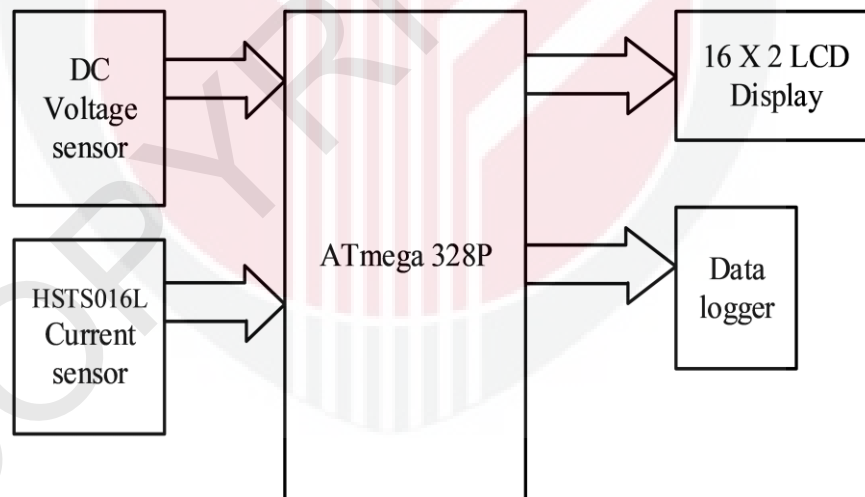


Figure 3.6: DC energy block meter block diagram developed for the experiment work

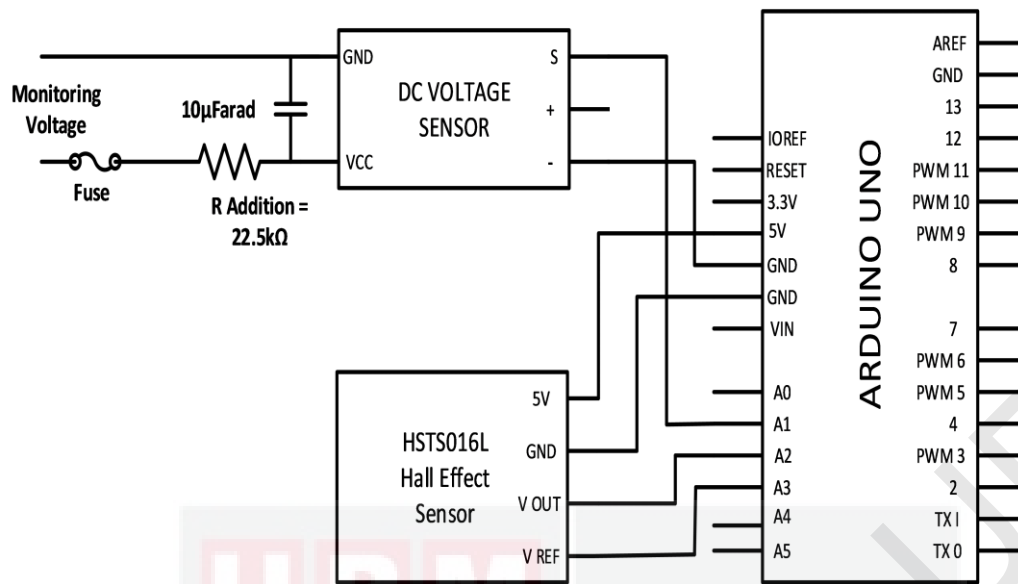


Figure 3.7: A schematic circuit interfaced between DC voltage sensor, HSTS016L hall effect sensor and Arduino UNO for the energy meter

3.2.2.5.1 Voltage Divider for Direct Current Voltage Sensor Module

We can measure DC voltage value directly on the analogue pin without any modification if it is less than or equal to 5.0V. To measure input voltages greater than that, we employ the voltage divider method, a very simple circuit consisting of two resistors. This decreases the voltage and increases the input impedance, preventing the measuring instrument from overloading the circuit. It is measuring and skewing the reading.

A modification involving the addition of a resistor and a capacitor to the DC voltage sensor module (0-25V) was utilized in this study in order to measure voltages up to 40V. These inexpensive devices utilize precision resistors to provide accurate readings. It is comprised of a 7.5k and a 30k resistor. Figure 3.8 shows a schematic divider circuit for DC voltage sensor module that was used in this project.

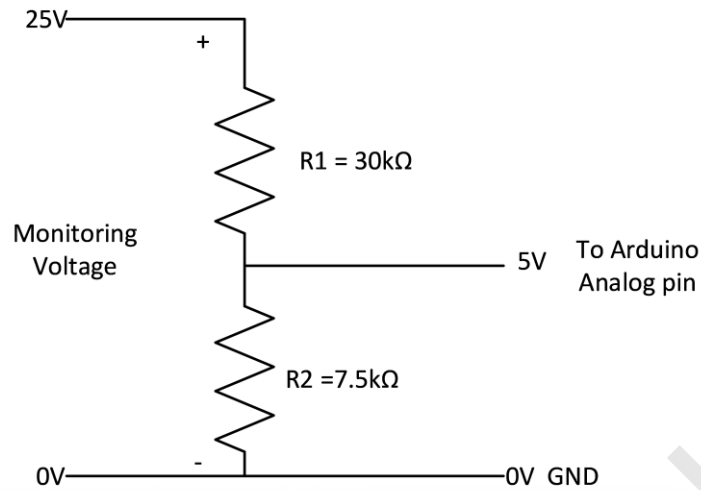


Figure 3.8: A voltage divider circuit for DC voltage sensor module

The module circuit must be modified so that it can be used to measure voltages up to 40V. We need to add some series resistor to R_1 based on the calculations below. From schematic circuit in Figure 3.8, let:

$$R_X = R_{Addition} + R_1 \quad (3.3)$$

and

$$V_{Out} = \frac{R_2 \times V_{In}}{R_X + R_2} \quad (3.4)$$

Replace $V_{Out} = 5V$, $R_2 = 7500\Omega$ and $V_{in} = 40V$ into (3.4):

$$5R_X + 37500 = 300000$$

$$R_X = 52500$$

Replace $R_x = 52500$ into (3.3):

$$R_{Addition} = 52500 - 30000$$

$$R_{Addition} = 22500\Omega$$

From calculation above, $22.5\text{ k}\Omega$ resistor needs to be added in series to R_1 , for the energy meter can read up to 40V . Figure 3.9 illustrates a schematic circuit for interfacing the DC voltage sensor module to Arduino UNO with modification input. The technical specification for this DC voltage sensor can be found in Appendix A4.

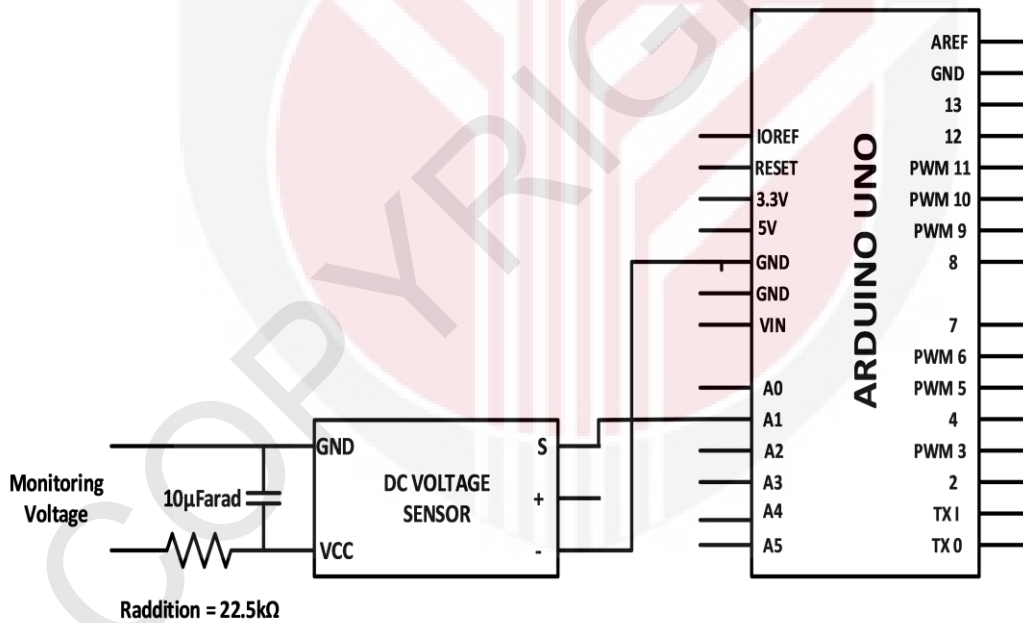


Figure 3.9: Schematic circuit interfacing DC voltage sensor module to Arduino UNO with modification input

3.2.2.5.2 Hall Effect Current Transformer Sensor for Current Measurement

The widely utilised Arduino UNO current sensor uses the hall-effect phenomena to create voltage via current flow in a magnetic field. Since the hall effect voltage is exactly proportional to the applied current, the voltage may be used to determine the current. This study used HSTS016L hall-effect sensors with split-core, which can measure up to 20A. Existing systems need no adjustment using split-core current sensors. The experiment uses HSTS016L hall-effect sensors with split-core transformers since it uses a deployed grid-connected PV system. Use split-core current sensors in existing PV systems without modification. The HSTS016L merely needs to be clamped to a cable utilized in the experiment. The technical specification for this HSTS016L sensor can be found in Appendix A5.

3.2.2.6 Controller Box

In this study, a controller box was designed to regulate the activation and deactivation of the fan, as well as adjust its speed. This control is achieved by defining a range of temperatures. The controller box, works together with digital temperature sensor, cross-flow fan and sealed lead acid battery as fan controller devices. The controller box employed a metal oxide semiconductor field effect transistor (MOSFET) to operate the fan's motor. It used an Arduino UNO as a microcontroller, a datalogger shield to store data, and a 16 X 2 LCD to show the T_{cell} measurement, as seen in Figure 3.10. The controller box connects to the digital temperature sensor for measuring the current T_{cell} and to the fan for regulating it based on the T_{cell} value. Figure 3.11 shows the thermoregulated cross-flow fan controller circuit.

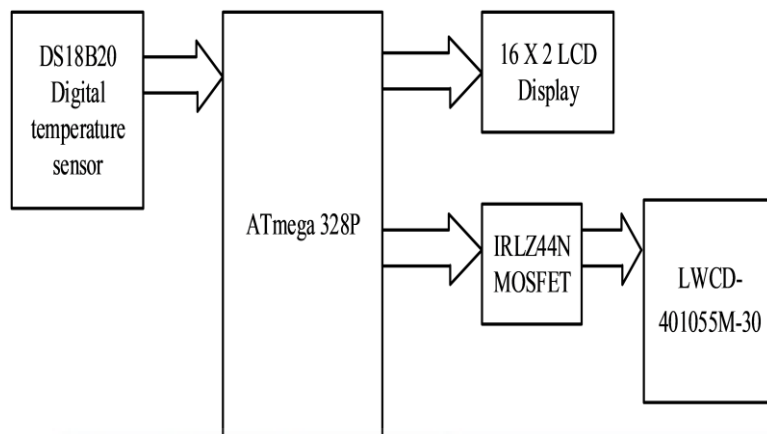


Figure 3.10: Thermoregulated cross-flow fan controller box

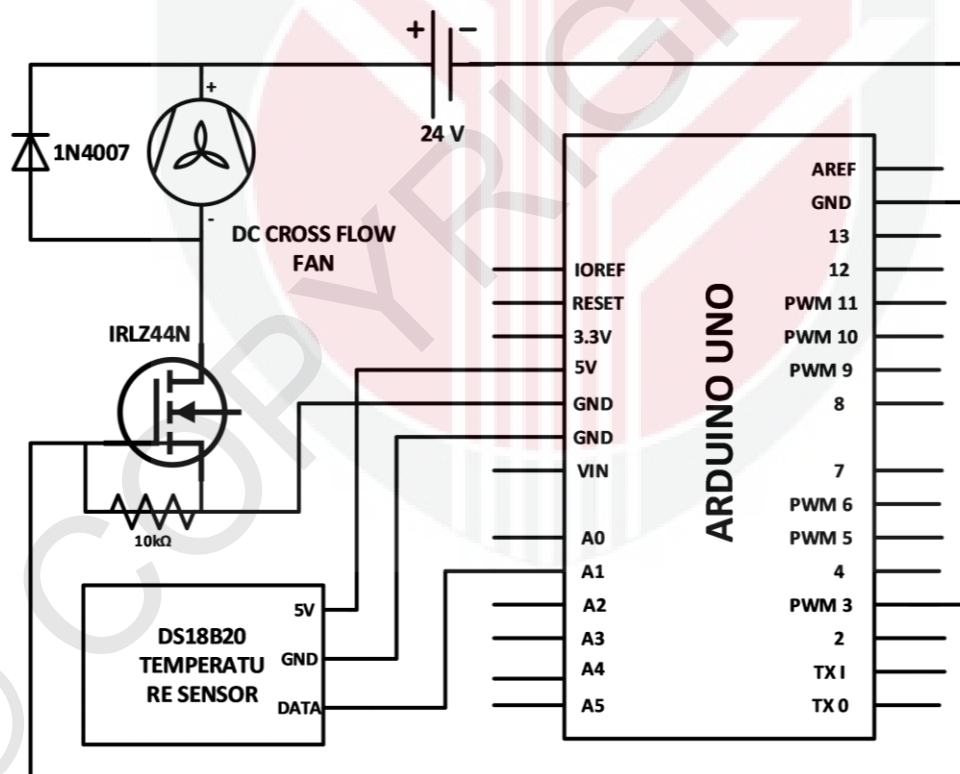


Figure 3.11: A thermoregulated cross-flow fan controller circuit

3.2.2.6.1 Digital Temperature sensor

The waterproof version of the DS18B20 digital temperature sensor was used in this work. It is useful for measuring distant objects or in wet conditions. While the sensor can withstand temperatures up to 125°C, the cable is PVC-coated and should be kept below 100°C. Because it is digital, we do not get any signal degradation even over long distances.

The DS18B20 provides temperature readings over a one-wire interface, so only one wire (and ground) must be connected from an Arduino UNO microcontroller in this application. The DS18B20 is compatible with 3.0 to 5.5V systems. The full dimension and technical specification for this digital temperature sensor DS18B20 can be found in Appendix A6.

3.2.2.6.2 Metal Oxide Semiconductor Field Effect Transistor

Arduino cannot drive high voltage device directly. Metal oxide semiconductor field effect transistor (MOSFET) was used to drive the 24V DC fan motor in this study work. IRLZ44N was selected, N-channel logic level MOSFET. As the power dissipation of the MOSFET is below the maximum limit, a heat sink is not required for this circuit analysis. Given that the power dissipation during MOSFET operation is lower than the maximum power dissipation without employing a heat sink, it is permissible to operate the circuit without a heat sink. The technical specification for this IRLZ44N MOSFET can be found in Appendix A7.

3.2.2.6.3 Cross-Flow Fan

In selecting a fan or wind source for this research, the first factor to consider is the fan's design and its compatibility with the available space between the PV module and the roof. The selected design also considers the dimensions and mass of the fan. The suitability of the selected fan as a wind source for cooling the PV system being designed depends on the sort of wind it generates. The fan's power consumption must be examined to ensure that it does not exceed the power generated by the PV module. After evaluating all the previously listed factors, the cross-flow fan better fulfils the intended requirements. A cross-flow fan is designed to generate broad and consistent airflow across a vast area.

In this study, a DC cross flow fan model LWCD-401055M-30 was used to generate a consistent airflow in a confined space beneath a retrofitted PV system. The fan was selected to ensure uniform airflow and was depicted in Figure 3.12. This fan uses DC brushless external rotor motor and was housing in an aluminum alloy material. The blade is also composed of aluminum alloy. Pulse width modulation (PWM) control was used to regulate the fan speed. The dimensions and full specification for this cross-flow fan can be found in Appendix A8.



Figure 3.12: DC cross-flow fan LWCD-401055M-30

3.2.2.6.4 Sealed Lead Acid Battery

Rechargeable seal Lead Acid (SLA) battery was used in this work. It is inexpensive, robust, and requires less maintenance. Among the features owned by this SLA battery were rechargeable, recyclable, no memory effect and able to use for most of the 12V controllers, motors or any other appliances. Full specification can be found in Appendix A9. Any standard DC power supply can be used to charge SLA batteries as long as it provides the correct voltage. Since the fan used in this work operates at a voltage of 24 V, then two batteries have been used.

3.2.3 Experiment Testing for Thermoregulated Cross-Flow Air-Cooling Retrofitted Photovoltaic System

The experiment was done using a single Canadian Solar CS6P-250P module from a 3 kW polycrystalline PV system, as the pre-existing system was a polycrystalline system. This experiment was done using polycrystalline because This polycrystalline PV system was mounted on the zinc-type roof using an appropriate mounting framework. The installation adhered to the regulations set by the Sustainable Energy Development Authority (SEDA) Malaysia, which included leaving a space of 40-50 mm beneath the PV array. Experiments was conducted at different levels of solar irradiance to guarantee that the produced cooling system can adjust to varying levels of irradiance and create a system that is resilient to weather fluctuations.

3.2.3.1 Temperature Range for Air-Cooling Operation

PV modules are composed of silicon material. When the solar irradiance reaches the surface of the PV module, the PV module converts the energy carried by the solar irradiance into electrical energy. A portion of this energy has been transformed into thermal energy, resulting in the T_{cell} being elevated compared to the ambient temperature, $T_{amb_pv_operation}$. This has been demonstrated by equation (2.5) and equation (2.6) in section 2.3.1. Consider NOCT is unavailable, and equation (2.5) was used in this study to determine the $T_{cell_minimum}$ and $T_{cell_maximum}$ as temperature ranges for the proposed air-cooling, which operates as described in Section 3.2.1.

This study examines the functioning of a thermoregulated cross-flow fan based on T_{cell} . Reducing the T_{amb} , is a crucial component in improving the accuracy of power output estimation for PV modules [157]. The intent of this study is to reduce the $T_{amb_pv_operation}$ by activating the suggested air-cooling system when the $T_{cell_minimum}$ reaches $30^{\circ}C$. This allows the air-cooling system to remove the hot air underneath the PV module when the $T_{amb_pv_operation}$ start reaches $5^{\circ}C$ and above.

While the $T_{amb_pv_operation}$ is quite low, it is important to note that the T_{cell} is calculated by adding the $T_{amb_pv_operation}$ to the STC temperature, as shown in equation (2.5). As mentioned in section 2.3.1, every $1^{\circ}C$ rise in T_{cell} results in a decrease up to 0.5% in electrical efficiency [36] and in order to determine the performance of a PV module, it is necessary to consider the idea of STC [8], where the STC was $25^{\circ}C$. By considered T_{cell} increased $5^{\circ}C$ from STC, it means considering up to 2.5% decreasing in electrical efficiency.

Thus, it is advisable to avoid setting the T_{cell} too high while initiating the cooling process with the suggested cooling system, since this significantly increases the possibility of PV module output performance deterioration. By supplying wind at a lower T_{amb} , it is possible to decelerate the increase in T_{cell} . This hypothesis is substantiated by the experimental findings obtained from the implementation of the suggested air-cooling method, as shown in the results and discussion section.

As elucidated in section 3.2.1, this temperature range not only governs the activation and deactivation of the fan's rotation, but also regulates the velocity of the fan's motor. The fan begins to rotate once T_{cell} reaches $T_{cell_minimum}$, and it continues to rotate at an increased pace when T_{cell} increases beyond the $T_{cell_maximum}$. The $T_{cell_maximum}$ is set to $55^{\circ}C$. Once T_{cell} reaches $T_{cell_maximum}$, the fan continues to rotate at its full speed. The existence of a wind source that repels the heat trapped as T_{amb} underneath the PV module impedes the increase in T_{cell} . This enables the reduction of T_{amb} , hence decreasing the value of T_{cell} . When there is a constant breeze by considering the T_{amb} , the fan motor may conserve electricity by adjusting its rotation speed to optimum energy efficiency.

3.2.3.2 Location of Experiment

Studies were carried out at the German Malaysian Institute (GMI), which is located at coordinates $2^{\circ}55'59.2"N$ and $101^{\circ}47'50.6"E$ in Kajang, Selangor, Malaysia. Typically, GMI experiences tropical weather with high humidity and temperatures. The area has extremely hot weather, particularly between 11:00 a.m. and 3:30 p.m.

(which varies depending on the path of the sun throughout the day). The efficiency of PV systems is significantly hampered by these high temperatures.

With a 3kW capacity, the PV system at GMi was linked to the grid for electricity. It included 12 pieces of 250W polycrystalline Canadian Solar CS6P-250P modules. One string of 12 modules was installed. This system's performance was monitored by the sunny sensor box via www.sunnyportal.com. Sunny sensor box has solar radiation and external module temperature sensors. It compares irradiance levels and PV power by measuring solar irradiance (W/m^2) with the inbuilt sensor and records PV system power daily with a 15-minute interval.

Table 3.2: Technical specifications for Canadian Solar CS6P-250P polycrystalline PV module under STC ($T_a = 25^\circ C, G = 1000 W/m^2$)

Parameter	Specification
Manufacturer	Canadian Solar
Model	CS6P-250P
Technology	Polycrystalline
Maximum power (W)	250
Maximum voltage (V)	30.1
Maximum current (A)	8.3
Open circuit voltage (V)	37.2
Short circuit current (A)	8.87
Number of cells	60 (6 X 10)
Dimension	1638 x 982 x 40 mm
Weight (kg)	18.5kg

This study utilizes the monitored data and graphs obtained from this portal for a typical day to verify that the observed solar irradiance and T_{cell} of the constructed devices are suitable for use in the next solar system air-cooling experiment, by giving a comparison benchmark. The electrical specification under STC for the PV module is

given in Table 3.2. The dimensions and full specification for Canadian Solar CS6P-250P can be found in Appendix A10.

3.2.3.3 Implementation of Thermoregulated Cross-Flow Air-Cooling Retrofitted Photovoltaic System

The tilt angle for an existing PV system is at a 25° roof tilt angle. The cross-flow fan is placed at the upper side of the PV array to protect the fan from stagnant water in the fan due to the rain. Small boxes are attached at both ends of the cross-flow fan with the aim of elevating the fan from touching the hot surface of the roof as depicted in Figure 3.13. This is done to ensure that the temperature of the fan is not affected by the surface temperature of the roof, and consequently that the wind produced by the fan is not affected by the temperature of the roof. Daily, from sunrise to sunset, the PV system was shade-free.

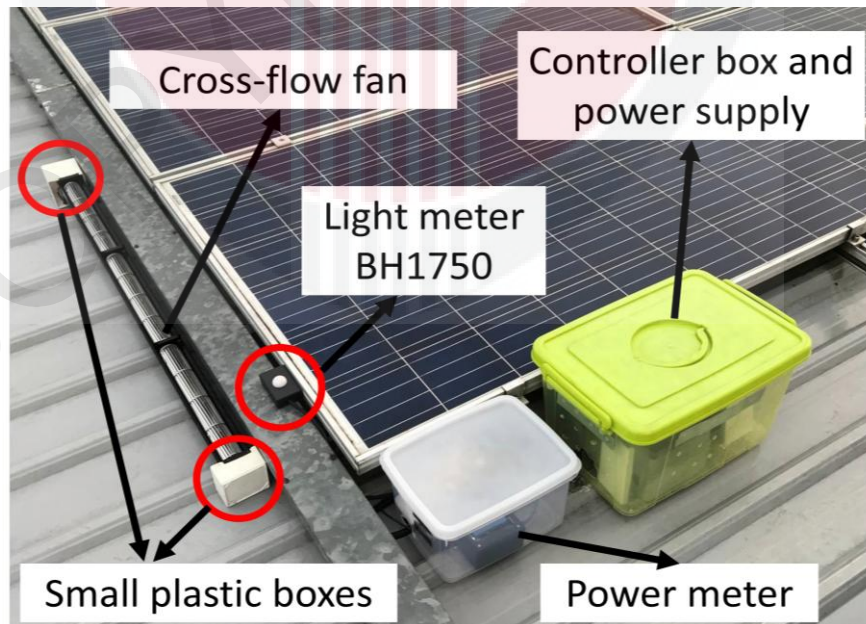


Figure 3.13: A prototype of thermoregulated cross-flow air-cooling setup at Canadian Solar CS6P-250P polycrystalline PV module of a 3kW retrofitted PV system

Table 3.3: Temperature characteristics for the CS6P-250P Canadian Solar PV module

Specification	Data
Temperature coefficient Pmax	-0.43%/C
Temperature coefficient Voc	-0.34%/C
Temperature coefficient Isc	0.065%/C
Nominal operating cell temperature (NOCT)	45+-2C

Table 3.3 displays temperature characteristic for PV module performance under standard test condition (STC) (radiation $AM\ 1.5\ 1000\ W/m^2$, temperature $25^{\circ}C$).

Power is roughly proportional to solar irradiance but affected by T_{cell} . Table 3. shows that PV module power reduces by $-0.43\%/^{\circ}C$ increasing temperature. Here, we assume that the solar irradiance and energy metre functions perfectly and the output power of PV during experiment, $P_{pv_{exp}}$ can reach the expected output power of PV module after applying air-cooling system, $P_{pv_{cool_{calc}}}$. The output power of PV module can be calculated as below:

$$P_{pv_x} = P_{x_{stc}} \times \left[1 + \left(\frac{\gamma_{P_x}}{100} \right) (T_{cell} - T_{stc}) \right] \quad (3.5)$$

where

P_{pv_x} is power for PV module at x condition

$P_{x_{stc}}$ is power for x condition at STC (Watt)

γ_{P_x} is temperature coefficient for power at x condition

From equation (3.5), the expected output power at maximum power point before applying air-cooling system, $P_{pv_{uncool_{calc}}}$ was calculated as follows:

$$P_{pv_{uncool_calc}} = P_{mp_stc} \times \left[1 + \left(\frac{\gamma_{P_{mp}}}{100} \right) (T_{cell} - T_{stc}) \right] \quad (3.6)$$

where

P_{mp_stc} is power at maximum power point at STC (Wwatt)

$\gamma_{P_{mp}}$ is temperature coefficient for voltage at maximum power point

The expected output power at maximum power point after applying air-cooling system, $P_{pv_{cool_calc}}$ was calculated using same equation (3.6). The experiment assesses the PV module's output power, $P_{pv_{exp}}$ in relation to the expected output power, $P_{pv_{uncool_calc}}$ and $P_{pv_{cool_calc}}$ both before to and following the installation of the air-cooling system.

Since the cross-flow fan used in this study work is limited to one cross-flow fan only, then the cross-flow fan is placed at the upper end of the side of the PV array and the first end module of poly-crystalline PV was chosen as shown in Figure 3.13. Experiments were done for only one module. Figure 3 illustrates the placement of the BH1750 light meter in proximity to the designated area, ensuring that the irradiance measurements obtained for analysis are accurate.

The waterproof variant of the digital temperature sensor DS18B20 was mounted on the rear side of the solar module, to keep track of the T_{cell} variations, with subsequent adjustments made to the fan speed as necessary. This 12-hour experiment took place on location from 7:00 a.m. to 7:00 p.m. Numerous days of experimentation have occurred before to and subsequent to the installation of the air-cooling system.

The controller box, energy metre, and irradiance metre have been placed in a sealed box as predicted in Figure 3.13 to protect them from rain and heat, as all equipment and metres must be placed on the site continuously for 12 hours each time the experiment is conducted. Data on *PV* module temperature, fan speed, current irradiance value, voltage, current and power measurements are stored on the 32 GB SDS2 memory card that is inserted into each metre. The microcontroller has been programmed with a three-second interval for the time between each data collection. In this research study, the data were collected from *April 26, 2022* to *June 26, 2022*.

3.2.3.4 Peak Sun Factor

The concept of expected instantaneous output [11] where how much output of *PV* module per peak sun factor (PSF) at 1000W/m^2 was implemented in this study. The PSF quantity influencing the peak sun hour (PSH) per day in a location was considered for comparison between the days before and after implementing cooling system, with similar or closest PSF or PSH amounts. The expected output for voltage and power at maximum power point for real operating condition, V_{mp_roc} and P_{mp_roc} can be calculated from equation (3.4) and equation (3.6) by multiplying it with PSF for current time. The $V_{mp_roc_calc}$ for a current time was calculated as follow:

$$V_{mp_roc_calc} = V_{mp_stc} \times \left[1 + \left(\frac{V_{mp}}{100} \right) (T_{cell} - T_{stc}) \right] \times PSF \quad (3.7)$$

While the $P_{mp_roc_calc}$ for a current time was calculated as follow:

$$P_{mp_roc_calc} = P_{mp_stc} \times \left[1 + \left(\frac{V_{mp}}{100} \right) (T_{cell} - T_{stc}) \right] \times PSF \quad (3.8)$$

The predicted values of $V_{mp_roc_calc}$ and $P_{mp_roc_calc}$ were determined using the identical T_{cell} and PSF throughout the experiment, making them representative of the real operating conditions, but these values were obtained by calculations. The experimental value is obtained via measurements and known as $V_{mp_roc_exp}$ and $P_{mp_roc_exp}$. The $V_{mp_roc_exp}$ and $P_{mp_roc_exp}$ was compared to the $V_{mp_roc_calc}$ and $P_{mp_roc_calc}$ in result and discussion.

3.2.3.5 Solar Irradiance Level

An estimation of solar irradiance magnitude using total solar irradiance (TSI) was used in order to differentiate between levels of solar irradiance received [158], [159]. In this study, total PSF or PSH in a day was used as TSI to classify level of solar irradiance received per day. Solar irradiance levels are classified as high when the number of PSF or PSH exceeds 5.5, moderate when the range is between 3.5 and 5.4, and low when the level is below 3.5.

The irradiance metre was strategically placed near the PV module area to ensure the accuracy of the irradiance from experiment for analysis. The solar irradiance data was collected at the site for 12 consecutive hours, from 7:00 a.m. to 7:00 p.m. for several days. All data for solar irradiance, are trended at 3-second intervals. Wind effect is not significant for low wind speed geographical location [32] and since Malaysia is situated in a low wind speed region [160], only solar irradiance and T_{cell} have been considered for the present study.

3.3 Simulation Work for Thermoregulated Air-Cooling Retrofitted Photovoltaic System with PID Controller

This section focuses on the modelling of thermoregulated air-cooling retrofitted PV system using SI in Matlab and the creation of a PID controller in Simulink, Matlab. The black-box model was constructed using actual experimental data. The created model is subsequently employed in a control-based model to optimize the efficiency of the air-cooling PV system operation and improve the output performance of the PV module. The controller is specifically intended to regulate the functioning of an air-cooling PV system. The Ziegler-Nichols approach is employed to fine-tune the PID parameter.

3.3.1 Modeling of Thermoregulated Air-Cooling Retrofitted Photovoltaic System

In this study, SI toolbox in Matlab was used as approach for the data-based model development. The research in this study includes the collecting and processing of all essential data, the selection and creation of the model structure, the estimation of model parameters, and the validation of the model. Data used in this study was collected from experiment work. All collected data was divided into training and testing sets. Since solar irradiance and T_{cell} determine a PV module's actual output, it is crucial to create an accurate model that captures its dynamic behaviour. This work develops a basic transfer function with varying time delays and orders, but more realistic model structures for air-cooling PV systems using the system identification black box methods. To validate the results, the performance of each model structure is compared using data from experimental investigations.

The black box approach is a method that can convert a potentially complex system into a set of relationships between inputs and outputs without any other information about the system. Various models are investigated to determine the best structure yielding satisfactory accuracy based on the fit percentage. The selected model was tested using high, medium and low level of solar irradiance generated data in a day from experiment for optimization, evaluation and validation for most optimal model.

3.3.1.1 Data Collection and Pre-Processing

As mentioned in section 3.3.3, the experiments were performed on the site for 12 continuous hours before and after installing the air-cooling system. The experiment involved measuring and recording the output voltage of the PV module $V_{pv_{exp}}$, solar irradiance, and T_{cell} before and after implementing the air-cooling system. The provided data used to construct a model using SI. The generated models heavily depend on data. Experiments acquired 14,400 data points between 7:00 a.m. and 7:00 p.m., at a sampling rate of one data point every 3s. The given dataset facilitated the evaluation of a nonlinear model for the output of a PV module, comprising voltage, solar irradiance, and T_{cell} .

This project involved the development of two black-box models: (1) a model for predicting the output of PV module and (2) a model for simulating the performance of an air-cooling PV system. This model represents a PV system that utilizes an air-cooling mechanism for the PV module. The methods of SI can utilize either all obtained data as both input and output data, or just the output data. Figure 3.14 illustrates that the input for the PV module model is solar irradiance, while the output

is the PV's voltage before the implementation of an air-cooling system. The PV data's output voltage serves as an input for the air-cooling PV system model, while the output voltage after incorporating the cooling system data is the final output for the air-cooling PV system model. During the development of the data-based model, the following assumptions were considered.

- i. The close proximity of the PV module to the roof and the limited natural heat transfer prevent wind from impacting the temperature of the T_{cell} .
- ii. Solar irradiance and T_{cell} were assessed as the key factors influencing the output of PV modules.

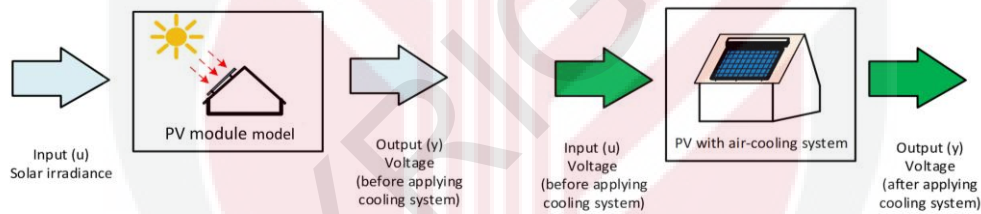


Figure 3.14: Input and output for PV module and thermoregulated air-cooling retrofitted PV system model

3.3.1.2 Selection and Creation of Structure Model

Before conducting simulation, the input and output signal processing is analyzed, and the transfer function (TF) of the system is computed using Matlab's SI Toolbox. When trying to identify anything, parametric models come in handy. These include building a black-box model using actual data [161], [162]. The model must have the capacity to measure and express the output of the system. To enhance the efficiency of the

transfer function estimation system and obtain accurate results [163] for the air-cooling PV system, it is crucial to construct the system's Pole and Zero in a way that maximizes the alignment with the graph. Several models were discovered in order to ascertain the most optimal answer. To determine the optimal model, the transfer function was utilized in these systems, allowing for manipulation of the order of the polynomial functions in the numerator $Nu_i(s)$ and denominator $De_j(s)$:

$$G(S) = \frac{Nu_i(s)}{De_j(s)} \quad (3.9)$$

3.3.1.3 Model Estimation, Optimization and Validation

The identification approach involves a step-by-step process of selecting model structures, finding the best model within each structure, and evaluating the characteristics of this model to decide if they are suitable. The models that exhibited the most superior performance were selected for validation based on the utilized assessment measure. Upon the successful completion of the model validation process, the acceptability of the model may be ascertained by comparing the measurement output with the model's simulation output, resulting in the generation of the model's outcome curve.

The optimal structure that produces a suitable level of accuracy is determined based on the fit percentage. The chosen model underwent testing utilizing data collected from experiments with high, medium, and low levels of solar irradiance. This was done to optimize, assess, and validate the model for best performance. The obtained models were employed in Simulink to validate their performance.

3.3.2 Development of PID controller

This study advocated the use of the conventional control PID in order to ensure system dependability. A PID control method was utilized to control ON/OFF air-cooling PV system with variable speed of fan in order to reduce the T_{cell} . The suggested approach would produce a dynamic fan speed based on the $V_{pv_{exp}}$ and $V_{pv_{cool_calc}}$ at each control time step. According to the theoretical study, the suggested control is crucial for a feedforward feedback control, which enables the air-cooling PV system to reliably modify the cooling fan's speed and operation based on its understanding of how the temperature of the PV module influences the output PV voltage.

In Simulink, the developed thermoregulated air-cooling retrofitting PV system model in SI using black-box approach was employed as a plant process to simulate the control-based model using a PID controller. Simulink verified and control theory examined the suggested approach, while the simulation provides quantitative data to demonstrate the superiority of the proposed control strategy, the theoretical analysis explains the mechanism of the suggested approach.

3.3.2.1 Thermoregulated Air-Cooling Retrofitted Photovoltaic System Control Strategy

The output voltage for the cooled PV module, $V_{pv_{exp}}$, can be adjusted based on the correlation between the solar irradiance and the output of the PV module for each control time step. In this study, a variable-speed fan is used to increase energy efficiency by decreasing power usage. Regarding the control strategy, there is an expectation that the T_{cell} can be controlled by changing expected PV output voltage

after implementing air-cooling system, $V_{pv_{cool_calc}}(t)$ as set point to follow the variations of solar irradiance.

3.3.2.2 PID Controller on Thermoregulated Air-Cooling Retrofitted Photovoltaic System

Prior to construction of the air-cooling PV system, the model technique utilized real data experiment. It is crucial to obtain $V_{pv_{exp}}$ based on the solar irradiance similar to expected PV module's output voltage $V_{pv_{cool_calc}}$ because of the temperature influences. Figure 3.15 shows a closed loop air-cooling PV system control unit that is operated by a PID controller. The set-point, $V_{pv_{cool_calc}}(t)$, is defined as the desired value for the controlled variable.

The controller system has three sub-units: proportional, integral, and derivative. Its purpose is to minimize the error ($Error(t)$) and ensure that the output from experiment $V_{pv_{exp}}(t)$ closely matches the preset value $V_{pv_{cool_calc}}(t)$. The exit of the loop is an output of PV module on the same variable. A PID controller method continually calculates an error value by subtracting the intended setpoint $V_{pv_{cool_calc}}(t)$ from the observed process variable $V_{pv_{exp}}(t)$, the process plant feedback signal. The algorithm then creates a combined response or controlled output signal $U(t)$ to regulate plant components. In the actual system, the process plant is the PV with air-cooling system. The $error(t)$ can be calculated as:

$$error(t) = V_{pv_{cool_calc}}(t) - V_{pv_{exp}}(t) \quad (3.10)$$

where $V_{pv_{exp}}(t)$ is the output from actual system or process

The most important output of the PID is the control variable $u(t)$, which is obtained from the following equation.

$$u(t) = K_p \times Error(t) + K_i \int_0^t Error(\tau) d\tau + K_d \frac{d}{dt}[Error(t)] \quad (3.11)$$

Defining $K_i = \frac{K_p}{T_i}$ and $K_d = K_p T_d$, we have:

$$u(t) = K_p (Error(t) + \frac{1}{T_i} \int_0^t Error(\tau) d\tau + T_d \frac{d}{dt}[Error(t)]) \quad (3.12)$$

The air-cooling PV system has been adjusted to reduce the time it takes to obtain a stable signal, while also minimize the overshoot of the desired temperature [164]. The PID regulator relies solely on changes in the $V_{pv_{cool_calc}}$, $V_{pv_{exp}}$, and T_{cell} . The controller's reaction can be characterized by the discrepancy between the calculated $V_{pv_{cool_calc}}$ and the expected $V_{pv_{exp}}$. The feedback control loop is meant to manage the airflow for cooling the PV module by adjusting the operation and speed of the fan, hence reducing the T_{cell} .

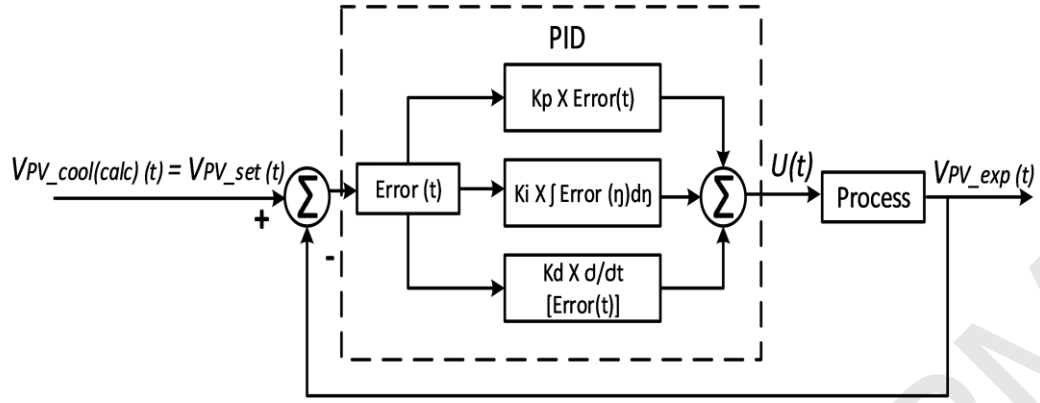


Figure 3.15: PID control function for thermoregulated air-cooling retrofitted PV system

In this system, PID controller plays a crucial role to accurately identify the connected solar irradiance and output PV voltage from cooling experiment $V_{pv_{exp}}$. The PID controller is responsible for identifying the load connected on $V_{pv_{exp}}$ and $V_{pv_{cool_calc}}$. The PID controller then uses this information to determine the target setpoint voltage $V_{pv_{set}}$ required for optimizing the operation of air-cooling PV system through adjusting the speed of the fan to maintain the T_{cell} and reach the desired $V_{pv_{set}}$. In this study, $V_{pv_{cool_calc}}$ was used as $V_{pv_{set}}$.

By combining the solar irradiance and output PV voltage identification to the PID controller for constant dynamic output PV voltage, the system adapts to variation of solar irradiance with varying $V_{pv_{exp}}$ requirements. This control mechanism ensures that the air-cooling system can cater to a range of T_{cell} with different solar irradiance, providing an efficient and accurate cooling process to each specific load.

There are various methods available to obtain the gains or adjustment parameters of the PID. Obtaining the PID parameters using the trial and error method is time-consuming. The Ziegler-Nichols method, a heuristic method [165] for defining PID controller weighting parameters, was used in this study by setting parameters I and D to 0 and adjusting parameter P until it reached Ku , the ultimate gain at which output oscillations are constant. System stability must be considered. Increasing this term minimises the error between $V_{pv_{exp}}$ and the $V_{pv_{ref}}$ or $V_{pv_{set}}$.

3.4 Summary

This chapter presents the work methodology, which covers the development of an air-cooling PV system integrated with a temperature controller and speed regulation using a cross-flow fan. Also, it provides the designs of black-box modelling for an air-cooling PV system from actual experiment data using SI, Matlab. This proposed method's design allows for the use of all obtained data, either as input and output data or just as input data alone. Furthermore, this chapter also covers the design and development of PID controllers for air-cooling PV systems, particularly their response to various levels of solar irradiance.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The development and modelling of an air-cooling photovoltaic (PV) system with a proportional-integral-derivative (PID) controller for a retrofitted PV system are covered in this chapter. Experimental and modelling findings for the proposed air-cooling PV system are presented. This chapter consists of three main sections. The first section entails the hardware validation used in this research to develop and test the proposed air-cooling PV system. The second section reports the experiment's results, which evaluated the air-cooling PV system's performance before and after installation. This section emphasises all experiments. Third section covers simulation findings, an air-cooling PV system model's performance, and a controller to compare real outputs with simulation results and analyze dynamic controller reaction. The suggested modelling system was constructed utilizing system identification (SI) with a PID controller and tested in several irradiance schemes to compare with PV module output.

4.2 Thermoregulated Air-Cooling Retrofitted Photovoltaic System Verification

This section presents the experimental setup for the proposed thermoregulated air-cooling system for retrofitted rooftop PV system. All the designed and produced equipment was used to experimentally validate the performance of the air-cooling

system. Furthermore, all the constructed instruments had been verified to ensure their suitability for the experiment.

4.2.1 Meter and Devices

Figure 4.1 depicts the entirety of the equipment that was created and utilized in this research. The system consists of an irradiance metre, an energy metre, a thermo regulated fan control device, a power supply box, and a cross-flow fan. While the energy metre monitors PV module voltage and power, the irradiance meter regularly measures solar irradiance. All equipment was protected in a case for durability and simplicity of use. A comparison has been conducted between data from the Sunny Portal website and experimental data. The distinction among these data was demonstrated in Table 4.1. Table 4.1 displays the specifications of the instruments designed for use in the experiment.



Figure 4.1: Meter and devices used in the thermoregulated air-cooling retrofitted PV system experiment

Table 4.1: Specifications of the developed measuring instruments in comparison to monitoring system at GMi from Sunny Portal's web data

Parameter	Range	Accuracy
Solar irradiation	0 – 1500 Wm^{-2}	+ – 1.28 %
Temperature	–55 ⁰ C - 125 ⁰ CC	+ – 0.5 C
DC voltage	0.1 – 330 V	+ – 0.1 %
DC current	0.1 – 20 A	+ – 0.4 – 0.9 %

4.2.2 Sunny Portal System Monitoring

On *April 14, 2021*, a reference measurement was taken from the German Malaysian Institute (GMI) system monitoring Sunny Portal for an average day. Appendix B1 depicts the daily 15 *min* interval recording of the irradiance meter and T_{cell} without a cooling system from Sunny Box readings between 12:15 a.m. and 11:45 p.m. At 1:00 p.m., the figure shows a maximum T_{cell} temperature of 73.69⁰C and solar irradiance of 801.1W/m². Morning temperatures range from 26⁰C up to 63⁰C, while noon temperatures can surpass exceed 73⁰C.

Figure 4.2 depicts experimental data collected for solar irradiance and T_{cell} at the GMI's PV system on *April 14, 2022* before implementing an air-cooling system at 3 s intervals. At 1:08 pm, the chart shows a maximum T_{cell} of 72.88⁰C and an average solar irradiance of 738.64W/m². Morning temperatures ranged from 24⁰C up to 65⁰C, while noontime temperatures can exceed 72⁰C. During the day, solar irradiance reached a maximum of 1098.29W/m². Thus, the maximum T_{cell} value did not always align with the highest solar irradiation. The maximum sun irradiance likely happened in a brief interval, insufficient to affect the T_{cell} value.

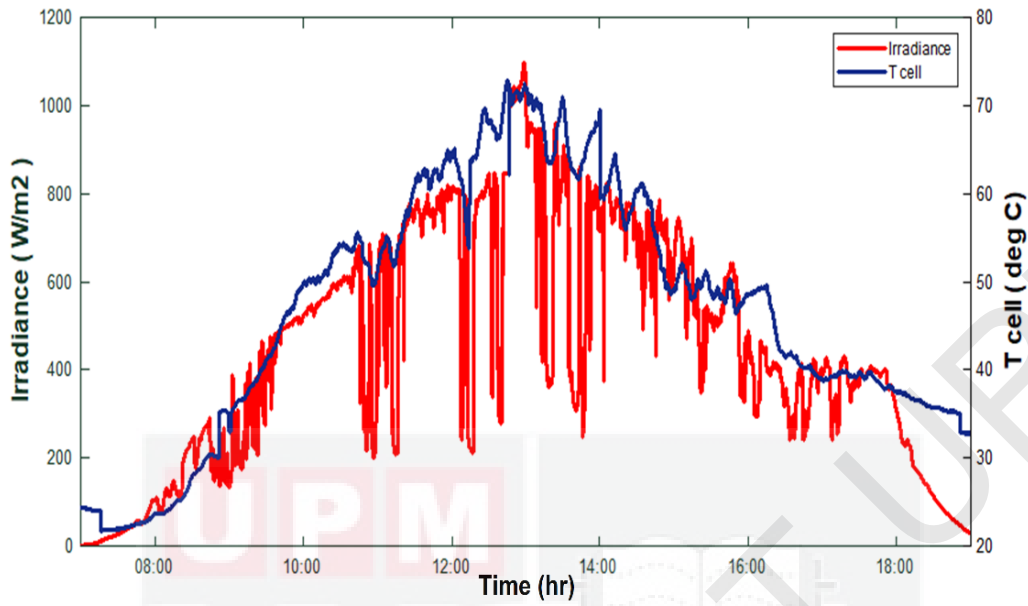


Figure 4.2: Solar irradiance and T_{cell} from experiment before applying thermoregulated air-cooling retrofitted PV system on April 14, 2022 at GMi

The experiment data in Figure 4. is applicable since the percentage difference between data from the PV system GMi monitoring is very small, at about 0.8 %. This slight discrepancy is explained by the data on the daily intra-variability of the global horizontal radiation (GHI) that can be obtained by characterising the solar irradiance at the study site, as per the research by Al-Kayiem et al. [166]. This includes the daily clearness coefficient, taking different cloud cover into account [167], and the sun's path, which is especially important in tropical climate regions.

The graph form of the experimental data in Figure 4.2 as a whole demonstrates a shape approaching from GMi's system monitoring. As the sun rises in the morning, both graphs show that solar irradiance is low. Until noon, solar irradiance increases as the intensity of the sun rises, but with modest decreases. When solar irradiance reaches its height, it fluctuates, but as the sun sets, the radiation gradually declines. The developed

instruments for measuring irradiance are therefore applicable and the specification for the employed measuring instruments is as shown in Table 4.1.

4.2.3 Level of Solar Irradiance

As proved in section 4.2.2 above, the developed instruments for measuring irradiance are applicable for implementing in the experiment. All data for solar irradiance from secure digital (SD) card that are trended at 3s intervals was plotted into graph. Figure 4. shows a graph for high, moderate and low-level data of solar irradiance used in this study to develop the desired models.

In Figure 4.3, the high level of solar irradiance received more than 5.5 number of PSH per day, while moderate level received solar irradiance between 3.5 and 5.4 of PSH. For low level of solar irradiance, the solar irradiance received below 3.5 of PSH per day. This estimation differentiated between level of solar irradiance received as researched by Egrova et al. [4] and Seleznyor et al. [5].

From the graph in Figure 4.3, the high solar irradiance level received the highest irradiance at 1138.05 Wm^{-2} between 12.00 to 1.00 pm. It received irradiance above 1000 Wm^{-2} from 11.00 am to 3.00 pm. The extended duration required for the reception of a significant quantity of solar irradiance classifies the total solar irradiance received on a given day as high level. The moderate and low solar irradiances received the highest solar irradiance at 846.49 Wm^{-2} and 710.73 Wm^{-2} respectively.

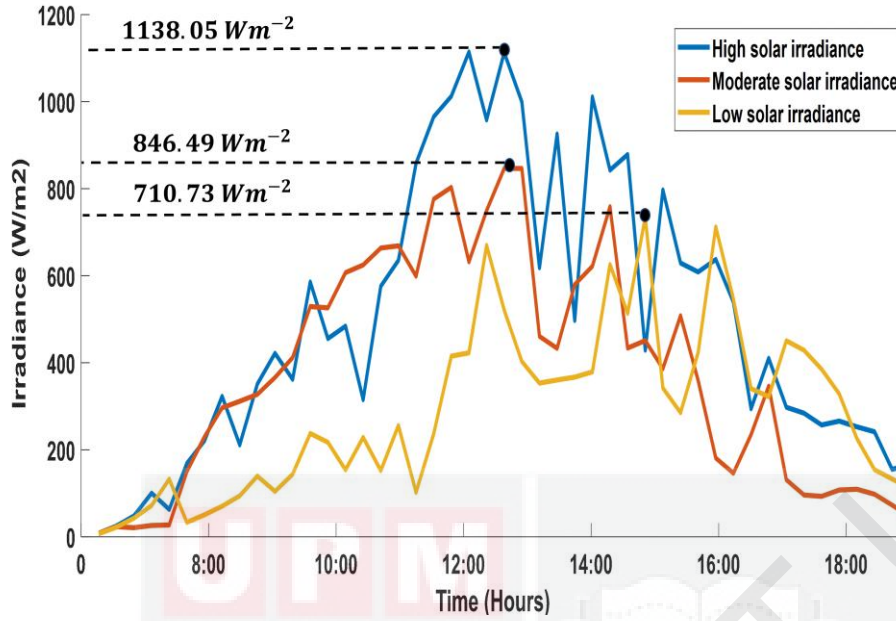


Figure 4.3: High, moderate and low level of solar irradiance received in a day

4.3 Experimental Results

In this section, experimental results for the proposed air-cooling PV system for both before and after implementing the air-cooling system are presented to experimentally validate performance of the PV module performance. Furthermore, experimental results for the performance of PV module are depicted for comparison to the expected output of PV module.

4.3.1 Performance Before Implementation Thermoregulated Air-Cooling Retrofitted Photovoltaic System

The temperature between the backside of the PV module and rooftop, known as the PV ambient average maximum temperature during operation, $T_{amb_pv_operation}$ grows with an increase in solar irradiance. The T_{cell} raises as shown in equation (2.6)

for both the front and rear PV modules. The PV module's surface temperature rises as a result of increased exposure to solar radiation. Heat is transferred from hotter to colder substances. Heats therefore move from the PV module's surface to its back, producing a backside T_{cell} that is greater than the $T_{amb_pv_operation}$.

Figure 4.4 presented an experimental data shows T_{cell} is higher than $T_{amb_pv_operation}$. The highest T_{cell} (line A) was $74.3^{\circ}C$ while the highest $T_{amb_pv_operation}$ (line B) was $60.5^{\circ}C$. It is essential to ensure that the backside of the PV module is cooled to reduce the T_{cell} . Figure 4.4 clearly shows that the level and time duration of irradiance influences the variation in T_{cell} value.

The highest T_{cell} (line A) does not occur precisely at the moment of maximum solar irradiance (C line), but rather in proximity to and when the PV module is subjected to elevated solar irradiance for the longest duration. The greatest amount of solar irradiance, exceeding 1000 W/m^2 , occurred briefly, lasting barely 1s to 3s and happening merely two to three times. Specifically, T_{cell} rises with an increase in irradiance, and conversely, it declines when the irradiance value drops.

This is also clearly illustrated in Figure 4.2 in section 4.2.2. This study used T_{cell} as a benchmark to evaluate the generated voltages, given the close correlation between the rise in T_{cell} and the level of irradiation. The goal of this study is to improve PV module output efficiency by decreasing the T_{cell} .

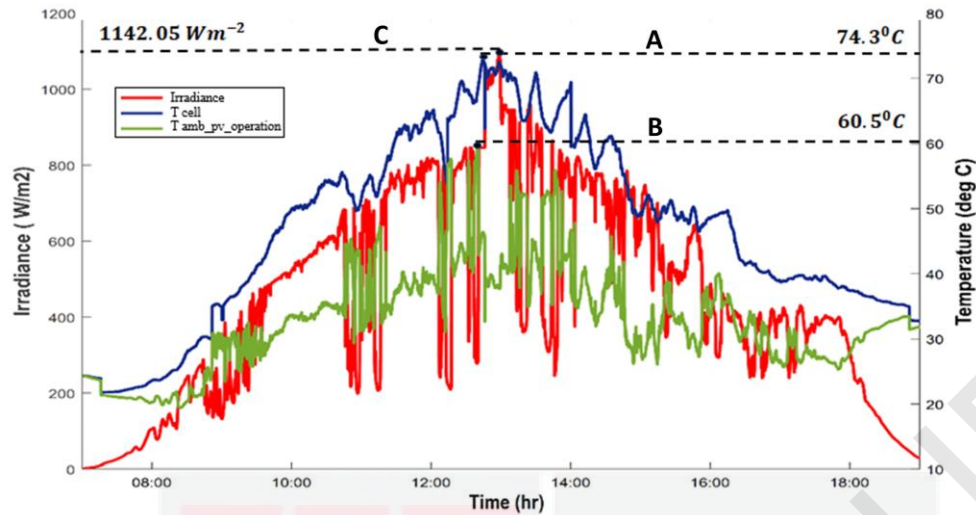


Figure 4.4: Solar irradiance, T_{cell} and T_{amb} from experiment before applying thermoregulated air-cooling retrofitted PV system on April 14, 2022 at GMi

As already observed in Figure 4.2 and Figure 4.4, T_{cell} increases as solar irradiance increases. This principle is equally applicable to the current situation. Figure 4.5 illustrates the relationship between current and irradiance, indicating that an increase in irradiance corresponds to an increase in current. Regardless of an increase in the T_{cell} value, the current continues to rise alongside an increase in the irradiance value.

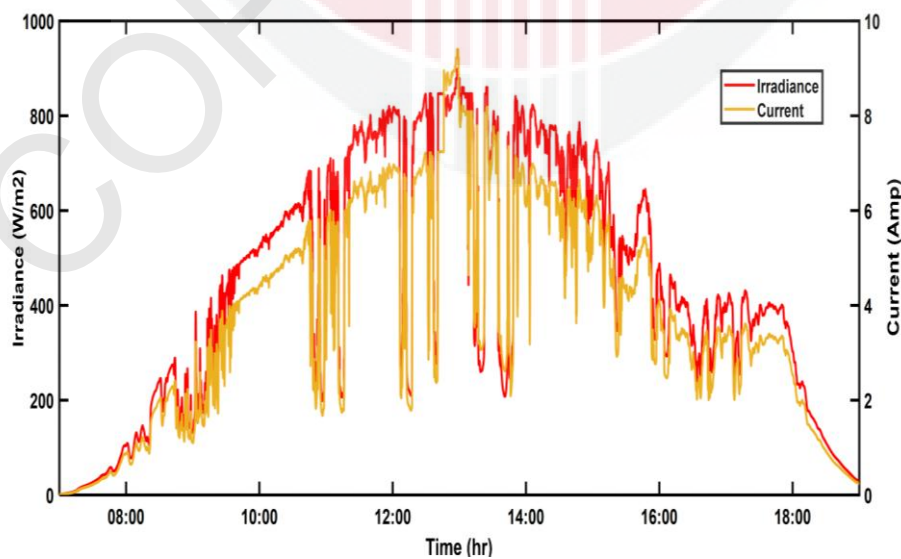


Figure 4.5: Increasing of current as irradiance increases

Figure 4.6 satisfy equation (3.1), which states that the voltage decreases when the T_{cell} exceeds the standard test condition (STC) temperature, $25^{\circ}C$. This happened because of thermal effect to the PV module due to negative value of temperature coefficient for voltage and power, γ as given in Table 3.3. Temperature characteristics for the CS6P-250P Canadian Solar PV module in Table 3.3 shows that the open circuit voltage, V_{oc} drops by the temperature at $-0.34\%/^{\circ}C$ based on the manufacturer's temperature characteristic while power at maximum power point, P_{mp} or P_{max} drops by the temperature at $-0.43\%/^{\circ}C$. Figure 4.6 shows a graph depicting the relationship between solar irradiance, T_{cell} and output voltage of the PV module.

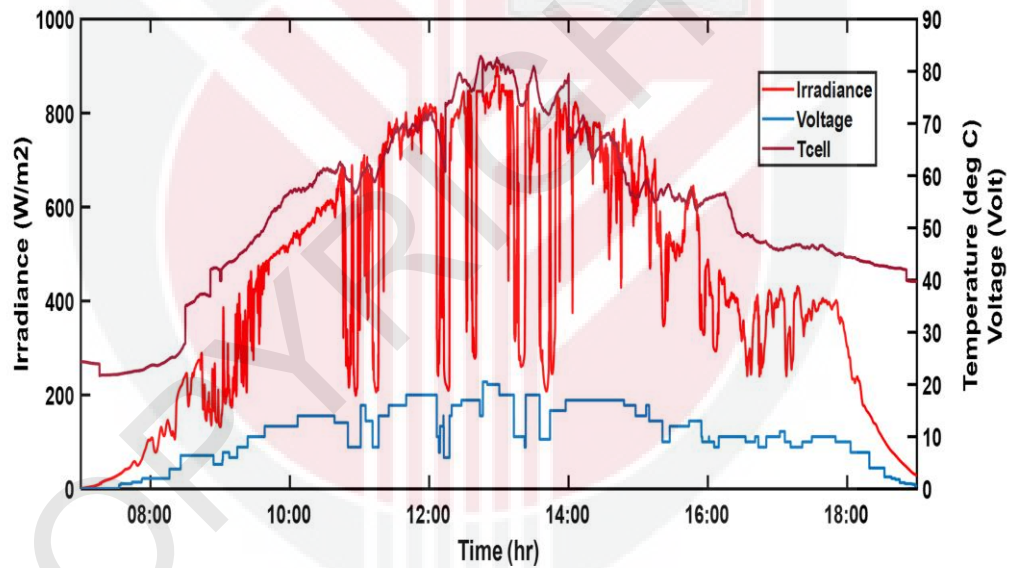


Figure 4.6: The relationship between solar irradiance, T_{cell} and output voltage for PV module

Table 4.2: The data for variation of voltage and power in average at real operating condition and calculation for one typical day before applying thermoregulated air-cooling retrofitted PV system.

Time	Average of PSF	Maximum Irradiance (W/m^2)	Maximum T_{cell} ($^{\circ}C$)	Average V_{mp_exp} (V)	Average V_{mp_calc} (V)	Average P_{mp_exp} (W)	Average P_{mp_calc} (W)
7 am	0.03	104.41	24.37	1.01	1.01	8.42	8.42
8 am	0.17	288.82	35.37	5.07	5.16	42.11	42.89
9 am	0.38	524.03	49.94	10.19	10.53	84.64	87.50
10 am	0.53	688.51	55.63	13.56	14.04	112.60	116.58
11 am	0.68	819.82	65.00	16.86	17.48	140.03	145.17
12 pm	0.74	1098.29	72.88	17.23	18.13	143.12	150.61
1 pm	0.68	978.51	71.88	15.82	16.70	131.42	138.71
2 pm	0.72	822.83	69.44	17.88	18.53	148.47	153.87
3 pm	0.55	748.39	52.13	14.36	14.86	119.26	123.41
4 pm	0.36	487.75	49.75	9.76	10.09	81.07	83.82
5 pm	0.37	431.08	39.81	10.22	10.56	84.86	87.67
6 pm	0.13	302.92	37.44	3.50	3.61	29.04	29.98
7 pm	0.03	28.43	32.69	0.80	0.83	6.66	6.87
5.38						1131.70	1175.50

Table 4.2 displays the data in average for voltage, V_{pv_exp} and power, P_{pv_exp} variation under real operating condition (ROC) during experiment and expected voltage, $V_{pv_uncool_calc}$ and power, $P_{pv_uncool_calc}$ prior to the installation of an air-cooling PV system. The notion of peak sun factor (PSF) was utilized, as described in section 3.3.4, to get the continuous current, voltage and power.

This allowed for the enabling a comparison between experiment value and calculated predicted value. These expected values for voltage, V_{mp_calc} and power, P_{mp_calc} also known as corrected values were calculated using equation (3.2) and equation (3.6). These corrected values were influenced by the temperature factor, f_{temp} and PSF on ROC as stated in equation (3.7) and equation (3.8).

As explained before, temperature coefficient at maximum power point, $\gamma_{x_{mp}}$ relates to the effect of voltage and power on the thermal expansion of the PV module. From a comparison of the experimental data for a maximum power point voltage, V_{mp_exp} and maximum power, P_{mp_exp} to the calculation data in Table 4., it was determined that the V_{mp_exp} and P_{mp_exp} were less than the calculation, particularly when the T_{cell} value was above $50^{\circ}C$, which occurred between 10:00 a.m. and 3:00 p.m. This means the addition of T_{cell} still contributed to the performance of V_{mp_exp} , even though the current T_{cell} and instantaneous PSF along with temperature coefficient, γ were accounted for. Based on the experiment results before applying the air-cooling PV system, an increase of T_{cell} caused the voltage and power values to decrease 3.75% and 3.73% respectively even though solar irradiance increased. The extended duration of voltage drops resulted in a significant power loss that requires attention.

Figure 4.7 depicts the graph for V_{mp_exp} and P_{mp_exp} influenced by f_{temp} and PSF on ROC, compared to the calculated data, before installing air-cooling PV system. The region labelled area A on the graph corresponds to the time interval from 7:00 am to 11:00 am. In region A, an initial rise in irradiance led to an increase in the V_{mp_exp} . However, based on the experimental data depicted in the graph, the V_{mp_exp} started to lower than the V_{mp_calc} . Due to the rising temperature in area B, resulted in a significant decrease in V_{mp_exp} compared to V_{mp_calc} . The values of V_{mp_exp} and V_{mp_calc} decrease as the T_{cell} continues to increase from 12:00 pm to 1:00 pm. Nevertheless, the value of V_{mp_exp} remains lower than the calculated value of V_{mp_calc} . From 1:00 pm to 2:00 pm, both V_{mp_exp} and V_{mp_calc} exhibit an upward trend, whereas T_{cell} experiences a decline.

Entering area C, the decline in V_{mp_exp} and V_{mp_calc} persists despite the decrease in T_{cell} . This is caused by a decrease in irradiance at this particular time. Consequently, the decline in T_{cell} no longer results in a rise in V_{mp_exp} and V_{mp_calc} at this juncture as a result of the diminishing irradiance. Same goes to power generated as seen in Figure 4.7 (b). The average peak sun hour (PSH) where the PV module received $1000W/m^2$ for the day was 5.38, as shown in Table 4.2 and average power output per $1000W/m^2$ of solar irradiation was $210.35 W$.

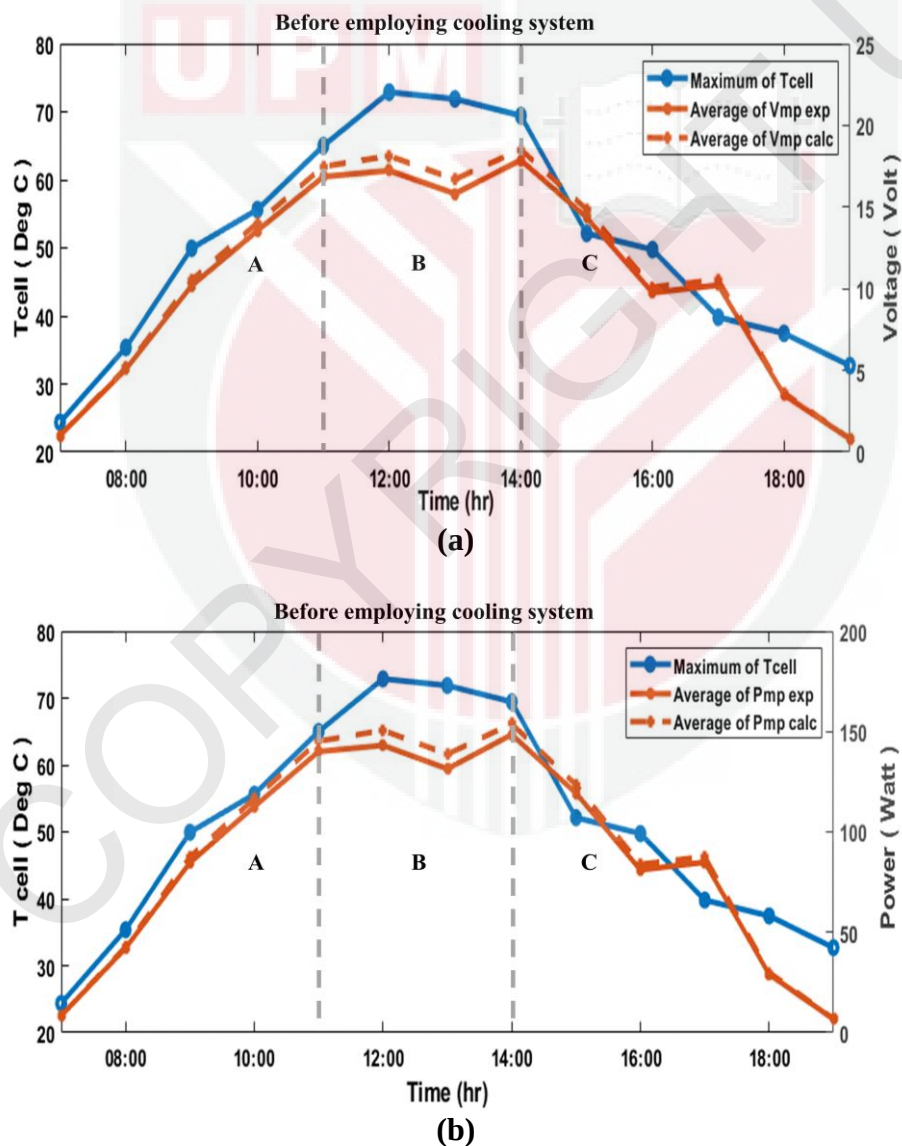


Figure 4.7: Measurement under real operating condition during experiment and expected values before applying an air-cooling PV system: (a) voltage and (b) power

4.3.2 Performance After Implementation Thermoregulated Air-Cooling Retrofitted Photovoltaic System

This research makes sure that cold air flows by making sure that the air conduction below the PV module is consistent, so that hot air does not get trapped underneath. After applying suggested innovative air-cooling to the PV module, effects can be considerate on the T_{cell} , and effect on voltage and power is influenced by T_{cell} and PSF.

4.3.2.1 Cooling Effect on T_{cell}

The findings were recorded continuously from 7:00 *am* to 7:00 *pm* as part of an experiment that involved connecting an air-cooling system to the existing PV system at GMi. Figure 4. depicts the T_{cell} , and speed percentage of the installed fan. When the temperature of the T_{cell} surpassed $T_{cell_minimum}$ of $30^{\circ}C$, the fan initiated rotation at a rate of 4% according to the PWM setting in microcontroller and response to fluctuations in the T_{cell} , as seen in Figure 4.8. The fan rotates at its highest speed of 100% when it surpasses the predetermined $T_{cell_maximum}$ value. The $T_{cell_maximum}$ set is $55^{\circ}C$.

Figure 4.8 depicts the irradiance, T_{cell} , and speed percentage of the installed fan. As solar irradiance increased, so did the T_{cell} , as shown in Figure 4.9. Figure 4.9 shows that the system with an air-cooling system had a slower temperature rise after $30^{\circ}C$ compared to the system without a cooling system in Figure 4.4.

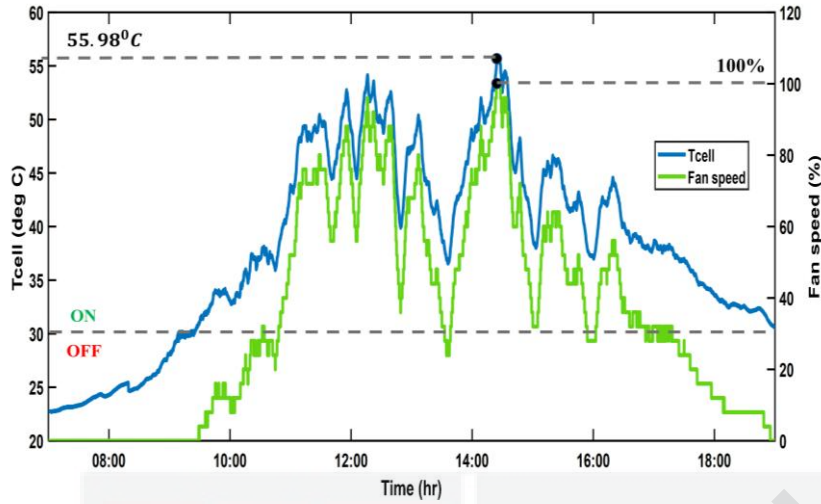


Figure 4.8: Fan speed changes depending on T_{cell} change

After the cooling system was installed, when T_{cell} surpassed $T_{cell_minimum}$, the fan began to revolve at 4% and changed dramatically with T_{cell} variations, as shown in Figure 4.9. The system retains its maximum rotational velocity after exceeding $T_{cell_maximum}$. Thus, T_{cell} grew slower although solar irradiance increased. The T_{cell} rose slower than without a cooling system. According to the graph in Figure 4.10 at point A, it appears that the maximum T_{cell} value does not coincide with the highest irradiance value which is 1046.49 W/m^2 . This is due to the intermittent nature of both the peak irradiance and the prior peak irradiance values.

The continuous rotation of the fan in the prior stage of moderately high irradiance, along with the occurrence of high irradiance within a short time frame, also contributes to preventing the T_{cell} value from increasing much. However, it should be mentioned that a crucial factor is the ratio of the amount of solar irradiance to the length of time a PV module receives it.

The T_{cell} grows more quickly when the solar irradiance received is high and comparatively protracted in both amount and duration. On the other hand, the T_{cell} change still happens if there is a great amount of solar radiation received over a short period of time, but it takes longer and the rate of T_{cell} rise is slower. This is because the hot air trapped beneath the PV module and potentially raising the T_{cell} has been forced out by the air conduction factor created by the fitted cooling system. The highest T_{cell} levels do not coincide with the greatest irradiance, which occurs at 1006.23 W/m^2 and results in T_{cell} attaining of 55.98°C , as can see in point B for Figure 4.9.

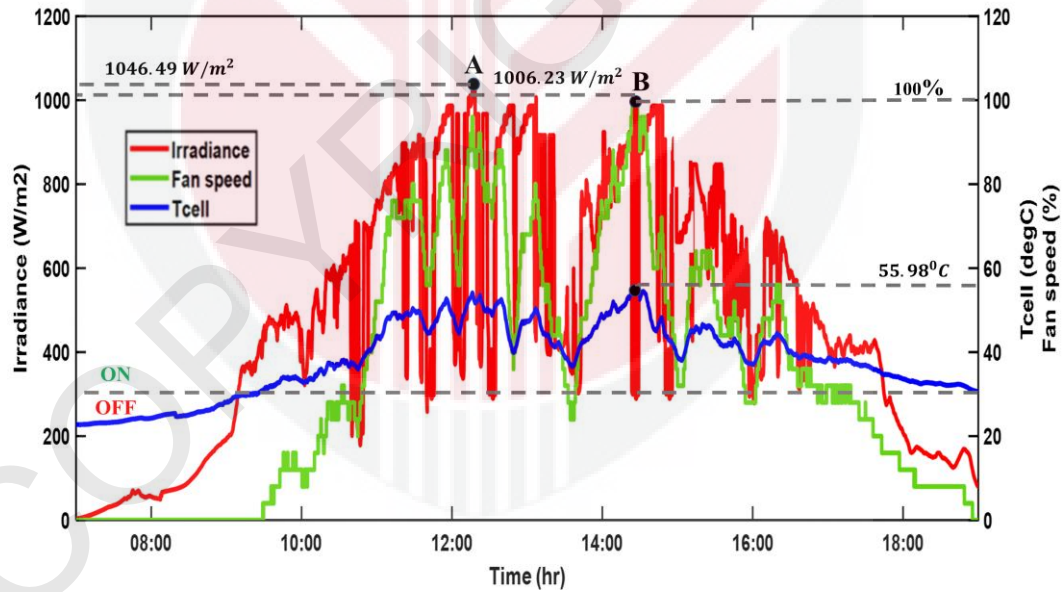


Figure 4.9: Irradiance, T_{cell} , and speed percentage of the installed fan after applying thermoregulated air-cooling retrofitted PV system on April 15, 2022

Table 4.3: The data for variation of voltage and power in average at real operating condition and calculation for one typical day after applying thermoregulated air-cooling retrofitted PV system

Time	Average of PSF	Max of Irradiance (W/m^2)	Max T_{cell} ($^{\circ}C$)	Average of Energy consumed by fan (Wh)	Average V_{mp_exp} (V)	Average V_{mp_calc} (V)	Average P_{mp_exp} (W)	Average P_{mp_calc} (W)	Max of Theory calculation P_{mp_roc} (W)
7 am	0.04	70.27	24.37	0.00	1.08	1.08	8.96	8.96	17.64
8 am	0.11	193.54	28.12	0.00	3.21	3.21	26.70	26.70	47.75
9 am	0.40	511.45	34.19	2.52	11.92	11.66	99.03	96.82	123.02
10 am	0.53	802.01	43.81	5.18	15.55	15.04	129.18	124.91	184.36
11 am	0.75	948.13	52.75	5.95	21.92	20.28	182.08	168.44	214.86
12 pm	0.60	852.39	54.13	5.98	17.84	16.27	148.15	135.17	193.88
1 pm	0.56	1046.49	55.98	6.02	17.00	15.54	141.17	129.06	233.78
2 pm	0.70	946.49	50.75	5.63	20.71	18.90	171.98	156.95	213.16
3 pm	0.61	852.32	46.63	5.55	17.90	16.88	148.64	140.16	199.62
4 pm	0.51	719.01	44.56	5.41	15.11	14.25	125.47	118.38	166.42
5 pm	0.37	439.76	38.69	5.15	11.12	10.50	92.33	87.20	103.82
6 pm	0.15	208.01	33.63	4.51	4.68	4.44	38.90	36.84	50.07
7 pm	0.08	80.77	30.56	0.00	2.43	2.37	20.14	19.71	19.71
5.40				51.89	160.46	150.42	1332.74	1249.30	233.78

Table 4.3 displays the data for voltage and power variation in average under actual operating conditions and calculations after the air-cooling PV system was installed. The average PSH where the PV module received $1000\text{W}/\text{m}^2$ for the day was 5.40. From Table 4.3, the maximum T_{cell} was 55.98°C between 2:00 to 3:00 p.m., while the maximum solar irradiance was $1046.49\text{ W}/\text{m}^2$ between 12:00 to 1:00 p.m. While the midday temperature stayed below 55.98°C , the morning temperature ranged up to 54.13°C . The average maximum T_{cell} for an average frequently solar irradiance of $800\text{ W}/\text{m}^2$ was 70°C before to the installation of an air-cooling PV system, and 49.5°C following the application of an air-cooling PV system.

It should be noted that weather circumstances are unpredictable and that the comparison is based on the two nearest days, both with and without an air-cooling PV system, when conditions were somewhat comparable. In this investigation, two days with PSH values of 5.38 and 5.4, respectively, were compared. To ensure that the data analysis is more accurate and helpful, the comparison days must be carefully chosen. According to Table 4.3, the voltage improvements range from 0.5 V to 1.81V , while the power gains range from 0.43 W to 15.03 W . The whole average voltage and power were 10.05 V and 83.44 W , above the calculated value, which demonstrated an energy efficiency of 6.68%. The percentages ranged from 2.16% to 8.76% for voltage and from 2.2% to 9.6% for power.

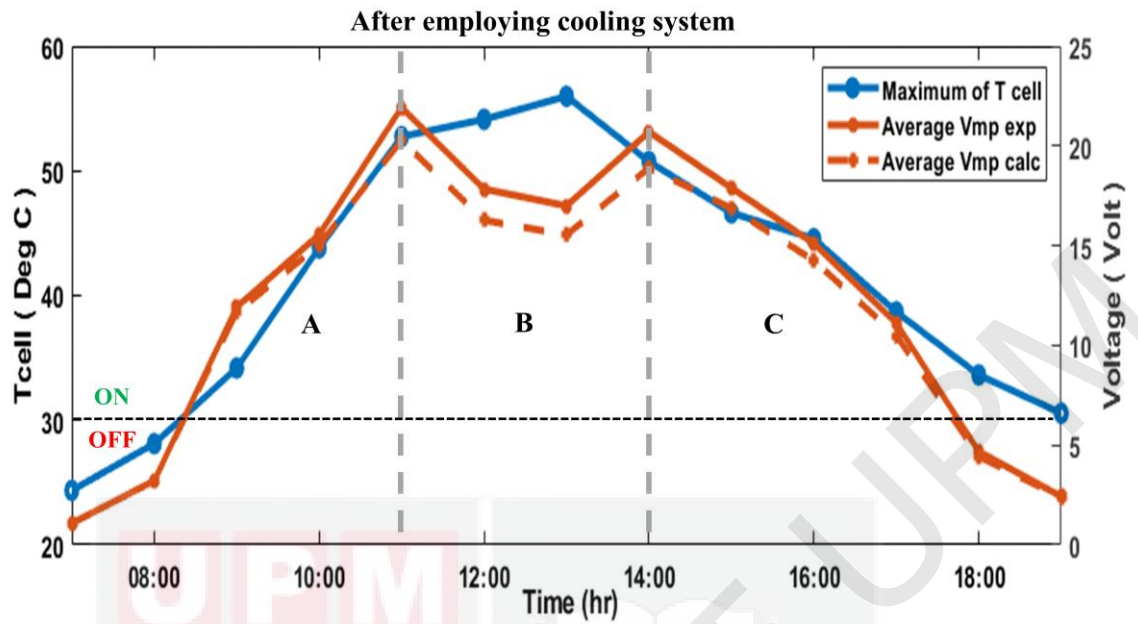
4.3.2.2 Cooling Effect on Output Voltage and Power

Installing an air-cooling PV system may effectively prolong the time it takes for a T_{cell} to increase while also managing the voltage loss that happens when the

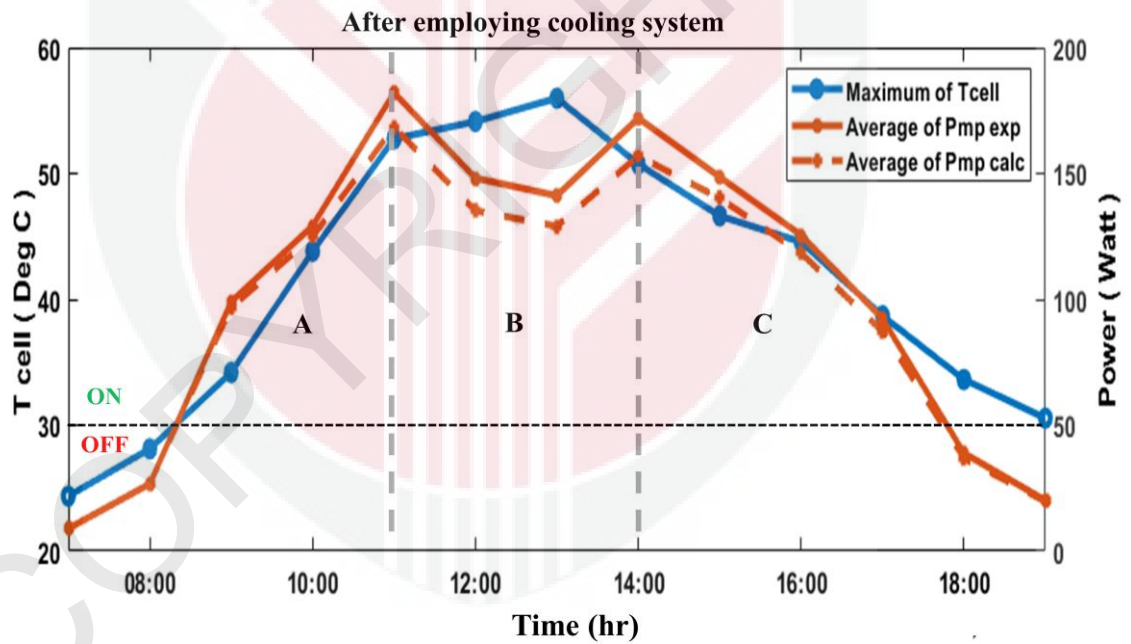
temperature reaches absurdly high levels. Given that voltage and power are directly proportional, it is important to note that a decrease in voltage results in a decrease in power.

Figure 4.10 is a graph that shows how f_{temp} and PSF change ROC on V_{mp_exp} and P_{mp_exp} , compared to the data of V_{mp_calc} and P_{mp_calc} after an air-cooling PV system was put in place. The diagram illustrates that the rotational speed of the cooling system's fan, which is dependent on temperature, begin when the T_{cell} exceeds $30^{\circ}C$. The region labelled area A on the graph corresponds to the time interval from 7:00 am to 11:00 am. Figure 4.10 in area A clearly illustrates the rise in the V_{mp_exp} and P_{mp_exp} , compared to V_{mp_calc} and P_{mp_calc} , commencing at around 9 a.m. and over, after the implementation of the air-cooling system.

In region B, as the T_{cell} increased, an increase in irradiance initially caused the V_{mp_exp} and P_{mp_exp} to rise, but as the T_{amb} continued to rise, an increase in irradiance caused the V_{mp_exp} and P_{mp_exp} to fall especially when T_{cell} achieve $50^{\circ}C$ and over. V_{mp_exp} and P_{mp_exp} continued to rise as the increase in irradiance, which occurred between 11:00 a.m. and 1:00 p.m., remained higher than the calculated value. T_{cell} began to decrease and the V_{mp_exp} and P_{mp_exp} started to increase with an increasing irradiance around 1:00 p.m. and over. This occurred when the T_{cell} exceeded the $T_{cell_maximum}$ threshold of $55^{\circ}C$. After 5:00 p.m. in region C, T_{cell} started a decline below $30^{\circ}C$, while V_{mp_exp} and P_{mp_exp} neared calculated values as irradiance diminished, accompanied by cloudier and windier afternoon conditions in the experimental area.



(a)



(b)

Figure 4.10: Measurement and expected value after installing thermoregulated air-cooling retrofitted PV system for (a) voltage and (b) power

Table 4.4: Comparison of past studies including current investigation and findings

No.	References	Analysis type and System Design	Type of Cooling	Method	PV Specification	Finding	Rating Power of Cooling System (fan/pump)	Operational time & Rating Power per Module	Energy consumption for 8 hrs
1	Lebbi, 2021	Experimental/ Model	Active cooling	Forced air circulation backside of PV module while its front flowing water	90 W 1200 x 550 x 30 mm	Average electrical efficiency of 3.7% for hybrid system	4.6 W	8 hrs 5.1%	46 W/h
2	A.E. Kabeel, 2019	Experimental/ Model	Active cooling	Forced air technologies together in the presence of reflectors Force air underneath PV module using helical fan attached to air duct covering the entire back surface of the PV module	130 W 1482 x 676 x 35 mm 140 W 1041 x 991 x 35 mm	Average 22.42% net output power Gain 0.19% output power and 5% per year	15 W 3.6 W	10 hrs 11.5% 12 hrs 2.6%	150 W/h 36 W/h
3	Arcuri 2014	Experimental/ Model and simulation	Active cooling						
4	Mazón-Hernández, 2013	Experimental/ Model	Active cooling	Force air underneath PV module using centrifugal fan attached to air duct	240 W 1956 x 992 x 50 mm	Gain 7.5% output power	NA	8 hrs	NA

Table 4.4: Continued

No.	References	Analysis type and System Design	Type of Cooling	Method	PV Specification	Finding	Rating Power of Cooling System (fan/pump)	Operational time & Rating Power per Module	Energy consumption for 8 hrs
5	Kidegho, 2021	Experimental/ Model and simulation	Passive cooling	Thermal interface materials (TIM) under air environments with aluminium honeycomb cooling panels as the cooling contact medium	325 × 325 × 20 mm 13 W	PV module power output increased by 1.8%	NA	5 hrs	NA
6	Proposed system	Experimental/ Existing PV system on steel rooftop	Active cooling	Force air using cross flow fan attached top between PV module and roof top	1638 x 982 x 40 mm 250 W	Gain 15.18% average net output power	6.48 W	12 hrs 2.6%	51.89 Wh

The findings of Lebbi et al.[17], A.E. Kabeel et al.[20], Arcuri et al.[168], Mazón-Hernández et al.[19], and Kidegho et al.[169] were compared with those of the proposed air-cooling PV system, as indicated in Table 4.4. Based on the percentage of power performance that each PV module ran under, all of them were compared. When cooling solutions were used, PV module output power and efficiency rose. Nevertheless, the literature does not provide comprehensive comparisons of the power rating for each module utilized in the study system.

The suggested system in the current study had a 6.48 *W* power rating and used a 250 *W* PV module with 1638 $\times$ 980 $\times$ 40 *mm* in size. The average net gain in output power was 12.9%, which is over 9% more than what Lebbi et al. [17] were able to achieve. With a module power rating of 2.6%, this suggested system has one of the two lowest ratings. Arcuri et al. [168] discovered another lowest, again with 2.6%. The Arcuri et al. system [168] employed a 140 *Wp* photovoltaic module measuring 1041 $\times$ 989 $\times$ 35 *mm* and had a power rating of 3.6 *W*.

The power of the PV module employed cannot match the power of the suggested system, which is significantly larger and only provided a gain in power of 0.19% compared to 12.9% net for the proposed one, even though the Arcuri et al.[168] power rating system is much lower than the proposed system. Although A.E. Kabeel et al.[20] used a 130 *Wp* PV module and a smaller dimension of 1482 $\times$ 672 $\times$ 35 *mm* than the one recommended, they were able to achieve the largest net gain in output power while still obtaining the maximum power rating of 15 *W*. With a percentage power rating of 111.5%. per module, the by A.E. Kabeel et al. technique [20] obtained the highest rating.

The suggested air-cooling PV system surpasses both Arcuri et al.[168] and A.E. Kabeel et al.[20] in terms of power rating per system and per PV module. This is because the PV module's peak power and size were substantially higher than those of Arcuri et al. [168]. Figure 4. clearly shows the advantages of the suggested air-cooling PV system over Lebbi et al.[17], Mazón-Hernández et al. [19], and Kidegho et al.[169]. Kidegho et al.'s [169] passive cooling method had no power rating and was used on 13 *Wp* PV modules measuring $325 \times 325 \times 20 \text{ mm}$, resulting in a 1.8% PV power generation. The smallest PV module as shown in Table 4. was used for the experiment, which resulted in a decreased output power but no power consumption. Adopting a system that is more power-efficient like the one in the proposed system, which has a low power rating per module and can provide a comparatively large power output is preferable to the suggested air-cooling PV system.

Thus, it is critical to keep in mind that reducing energy waste is greatly aided by the cooling temperature range. Avoiding using more energy for air-cooling systems than can be produced is a smart idea. In order for the ideal temperature to lessen or eliminate voltage drops, it is crucial to maintain the proper temperature ranges. It is not feasible to reach the STC for the rooftop PV system or to get a temperature that is too low because of the relatively considerable heat transfer that takes place in the roof area as a result of unpredictable external variables.

4.3.2.3 Cooling Effect on Output Voltage and Power Based on Peak Sun Factor

Experiments were carried out on the same system on several days, both with and without the air-cooling system. Given the uncontrollable nature of outside variables such as weather and solar irradiance, it is crucial to compare the output before and after the installation of the air-cooling system using a single variable.

Estimating the PV module or array's instantaneous outputs under actual operating circumstances may be necessary in many situations. Temperature and solar irradiance are instantaneous variables in ROC scenarios that instantly affect the outputs of PV modules. In addition, solar irradiance varies quickly, and the PV module's output varies along with solar irradiance. As a result, the predicted instantaneous output was ascertained using the following method, which is called the PSF:

$$PSF = \frac{G_{array_plane}}{1,000 \text{ Wm}^{-2}} \quad (4.1)$$

where:

PSF is Peak Sun Faktor (dimensionless)

G_{array_plane} is solar irradiance in array plane (Wm^{-2})

Table 4. displays the average PSF and power output produced by the PV module prior to the installation of an air-cooling PV system. The total average PSF achieved on the day of the experiment was 5375 equal to 5.38 for PSH, while total daily power output was 1131.70 W. At actual operating conditions, the average instantaneous power

output of PV modules without air-cooling PV system installation was 210.35 W per PSF at 1000 W/m^2 of solar irradiation.

According to Table 4., the day the air-cooling PV system was used, the total average PSF reached was 5402, or 5.40 for PSH. The PV module produced 1332.74 W of electricity in total, with an average output power per PSF of 246.80 W at 1000 W/m^2 of solar irradiation. In comparison to the pre- and post-implementation periods of the investigated air-cooling photovoltaic system, the projected instantaneous average power output of the PV modules rose by 17.3%, or 36.45W. While a great deal of study has been done to determine the effectiveness of PV cooling systems, much of it has been done via simulations.

As shown in Table 4., six earlier experiment-based research studies with reliable results were selected to be further validated against the suggested air-cooling PV system. The suggested air-cooling photovoltaic system used a little percentage of the electricity during the day, but it produced a significant net gain in power on average. The findings of testing the suggested air-cooling PV system at an already existing rooftop PV system was still better than those of previous experiment-based studies conducted on a single PV module.

The results demonstrate that, when compared to the prior study system, the suggested air-cooling PV system with an inventive cross-flow fan may greatly increase the efficiency of PV modules. Although there is no power loss when employing the passive cooling technique, the PV module's increased power output is insufficient and may be equalled by the active cooling method. Since more energy was generated than

was used for cooling, this demonstrates the efficacy and capacity of the suggested air-cooling PV system.

4.4 Simulation Results

This section concentrates on simulation results of the proposed black-box air-cooling PV system model using SI in Matlab. In addition, simulation results for PID controller in Simulink, Matlab are included as well. At the first step the created model is subsequently employed in a control-based model to show the performance of the method in high, moderate and low solar irradiance levels. At the second step, a performance comparison is provided after the controller is specifically intended to regulate the functioning of an air-cooling PV system. Simulation results are presented to validate performance of the PV module under low, medium and high level of solar irradiance. The values of the parameters K_p , K_i and K_d for the developed PID controller were presented in this section as well.

4.4.1 Black-Box Models Development

There are two black-box models developed in this study in form of transfer function (TF) in SI Matlab. The models were a model for predicting the output of PV module and a model for simulating the performance of an air-cooling PV system. Both models utilize all obtained real experiment data as both input and output data as mentioned in section 3.3.1.1.

4.4.1.1 Photovoltaic Module Model

The data from the experimental procedure have been used as input/output for developing PV module models using black-box approach in SI, Matlab. From Figure 3.25, the input for the PV module model was solar irradiance, while the output was PV's voltage before the implementation of an air-cooling system, $V_{pv_{exp_uncool}}$. The time-domain input/output signals of solar irradiance and output voltage of PV module data to find the transfer function for PV module model are shown in Figure 4.11. The data was separated into two sections for model estimation. The initial section of data is used to determine the system's model, while the other part is used to validate the model.

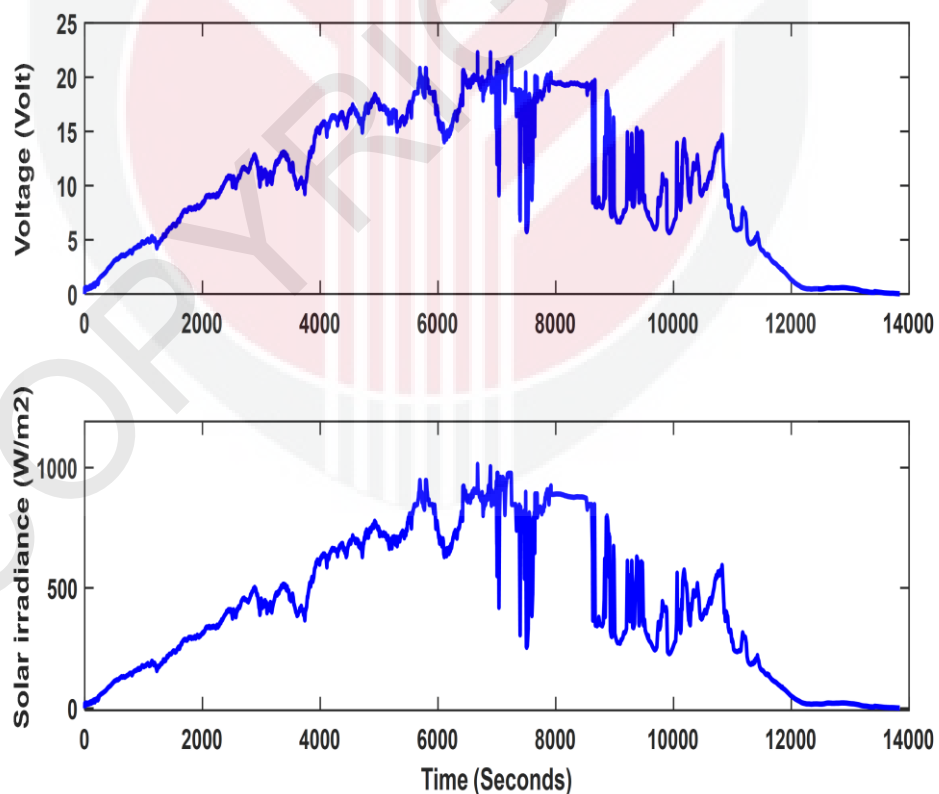


Figure 4.11: Input and output signals for identification of PV module model

The response must be taken into consideration while selecting the TF for identification. It is necessary to evaluate the chosen transfer function calculation's accuracy with the experiment data that is sent into Matlab. Additionally, Matlab may provide graphic results in the form of an output response based on the transfer function, as seen in Figure 4.12. As a general rule, models can be accepted when the percentage of fit is at least 90%. The output models' curves reveal that the percentage of fit is 94.25% for the PV module model. Figure 4. demonstrates the output voltage for PV module before implementing air-cooling system.

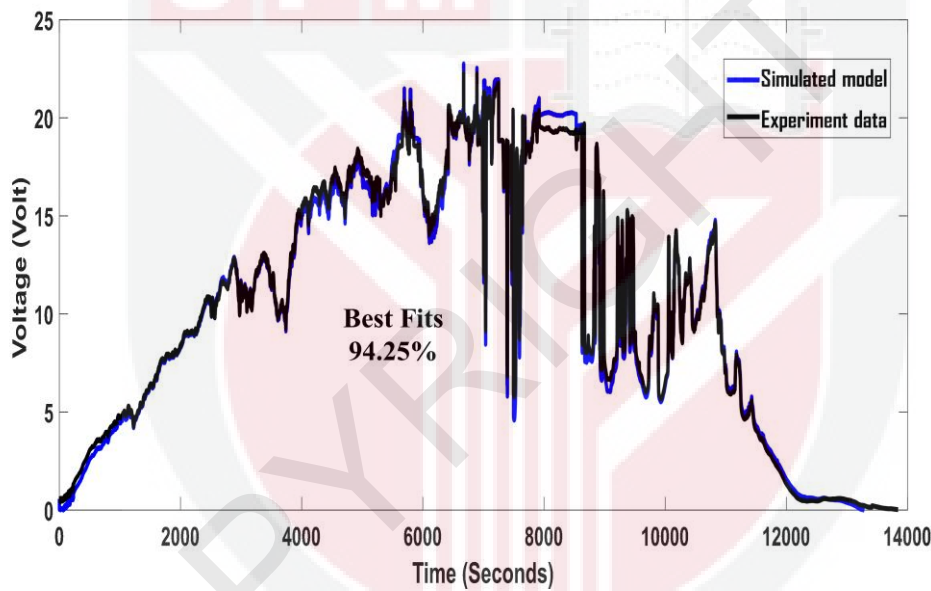


Figure 4.12: Experiment and simulated output of a PV module model during identification

The model after estimation is represented by the TF in the continuous-time domain as in equation (4.2):

$$G(S) = \frac{0.02717s^3 + 1.234 \times 10^{-5}s^2 + 3.516 \times 10^{-8}s + 1.448 \times 10^{-11}}{s^4 + 1.609s^3 + 0.0006364s^2 + 2.177 \times 10^{-6}s + 8.591 \times 10^{-10}} \quad (4.2)$$

The TF model of $G(S)$ is characterized by four poles and three zeros. The data from experiment at the GMI's system is correctly represented, with a high level of accuracy reaching up to 94.25%. The transfer function derived from the fourth-order differential equation results in a linear model. The resultant model is further simulated for development of PID controller for air-cooling PV system.

4.4.1.2 Thermoregulated Air-Cooling Retrofitted Photovoltaic System Model

The PV module's output voltage in Figure 4.11 serves as an input for the air-cooling PV system model identification in Figure 4.13, while the output voltage after incorporating the cooling system data is the final output for the air-cooling PV system model. The input and output signals for air-cooling PV system model identification are shown in Figure 4.13. The input was the output voltage of the PV module without air-cooling system, $V_{pv_{exp_uncool}}$ while the output signal was output voltage of the PV module with air-cooling system, $V_{pv_{exp_cool}}$. The data was separated into two sections for model estimation as well. The initial section of data is used to determine the system's model, while the other part is used to validate the model. SI toolbox in Matlab was utilized to perform all estimation processes.

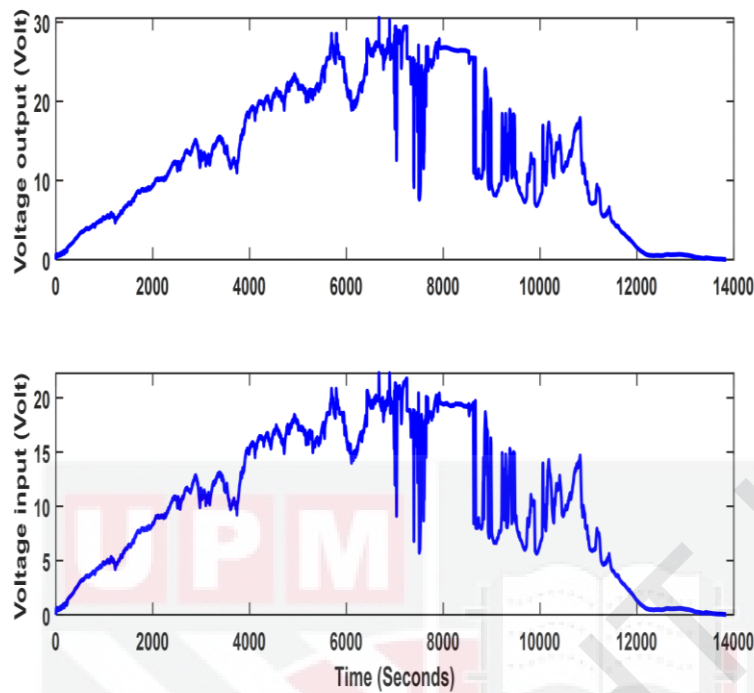


Figure 4.13: Input and output signals for identification of thermoregulated air-cooling retrofitted PV system model

The cross-validation process is used to get the validated model [170]. Data sets from the PV module's output are examined and contrasted in that process. The input and historical output data from the experiment are compared, followed by an output model simulation. Similar to the PV module model, which accepts models with a fit percentage of at least 90%, the models are chosen according to their final prediction error, percentage of fitness, and cost function. Figure 4.14 displays the output that has been verified. The air-cooling PV system model has the highest fitness, as shown by the TF model, at 96.42%. Figure 4.14 demonstrates the output voltage for PV module after implementing air-cooling system.

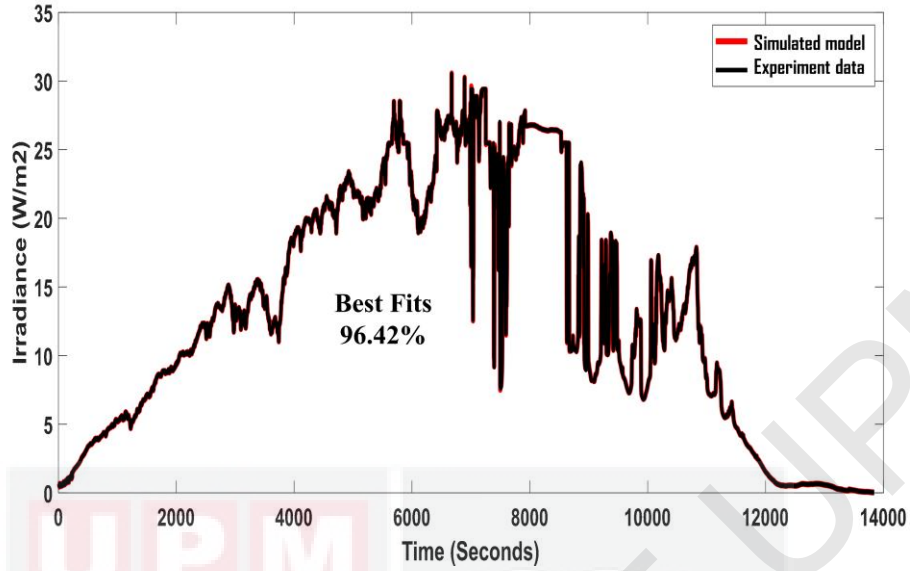


Figure 4.14: Experiment and simulated output of thermoregulated air-cooling retrofitted PV system model during identification

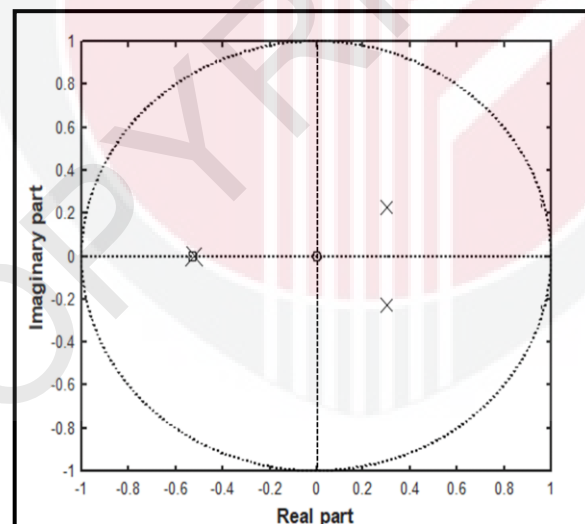
The Simulink model of the air-cooling PV system is designed to represent the changes in parameters over time based on solar irradiance. The models were developed as transfer function model. The TF is performed in the continuous-time domain as equation (4.3):

$$G(S) = \frac{484.7s^2 + 0.0809s + 0.0002572}{s^3 + 375.5s^2 + 0.06245s + 0.0001988} \quad (4.3)$$

The transfer function model $G(s)$ contains three poles and two zeros. It accurately represents the data from the German Malaysian Institute's system, with a fit of up to 96.42%. The transfer function associated with the third-order differential equation yields a linear model. Additionally, the controllability and observability of the developed black-box models were evaluated. For every model, the pole and zero were plotted and watched in order to refine the model. When all of the poles and zeros of

an ideal model are found inside the unit circle, the model shows stability. A model is deemed optimal when all of its zeros and poles fall inside the unit circle, signifying stability.

Figure 4.15 illustrates that each of the zeros and poles are located inside the unit circle. This is referred to as a minimal phase model. This model specifically focuses on the principles of causality and stability. Its purpose is to be applied to comprehensive research and to build a connection between input and output variables. The linearity and TF description of the model used to calculate the output of a PV module with an air-cooling system make it impressive. It also has a connection to a differential equation of third order. Because the model ensured stability, its controllability and observability could be further investigated.



Poles (x) and Zeros (o)

Figure 4.15: Pole zero plot for the air-cooling PV system model

4.4.1.2 Performance Under High, Moderate and Low Level of Solar Irradiance

These black-box models were used to achieve the highest output of PV module when receiving a solar irradiance by decreasing the influence of T_{cell} . Model for PV module and air-cooling system was performed using a generic SI approach that included data analysis, model structure selection, parameter estimation, and model validation [171]. Data evaluation is done to acquire a decent data. To determine the model we wish to generate, the model structure is chosen. It may take linear, nonlinear, or intelligent model form.

Validation serves the objective of comparing the predicted output of the model with the observed outcome of the experiments. If the model validation satisfies the required percentage of fit and other criteria, it might be deemed acceptable [171]. In contrast to traditional approaches, this identification technique exhibits enhanced speed and accuracy. To ascertain the transfer function that most accurately reflects the accuracy of the estimation output model with respect to the input data, the highest percentage of fit was utilized to determine its selection. It is necessary to compare the accuracy of the selected transfer function computation with the input data provided to Matlab. Furthermore, Matlab has the capability to generate graphical representations such as output response, impulse response, and Bode diagrams based on the transfer function.

In Simulink implementation, the obtained models were used for observing the output performance of PV module before and after implementing the proposed air-cooling system using different level of solar irradiance data. This step is very important to ensure that the developed models are compatible with multiple levels of solar

irradiance. Figure 4.16 shows the simulation block diagram in Simulink used for air-cooling PV system observation.

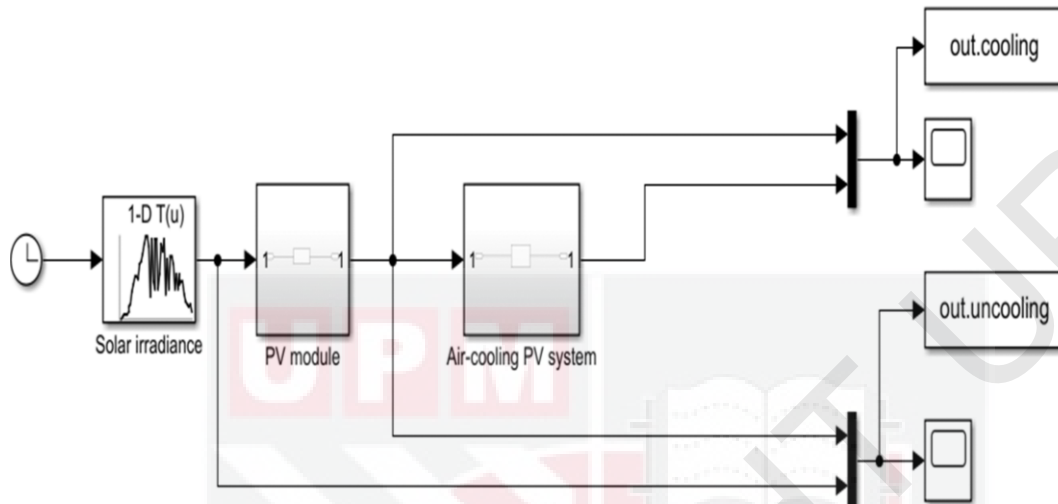


Figure 4.16: Simulation block diagram for air-cooling *PV* system

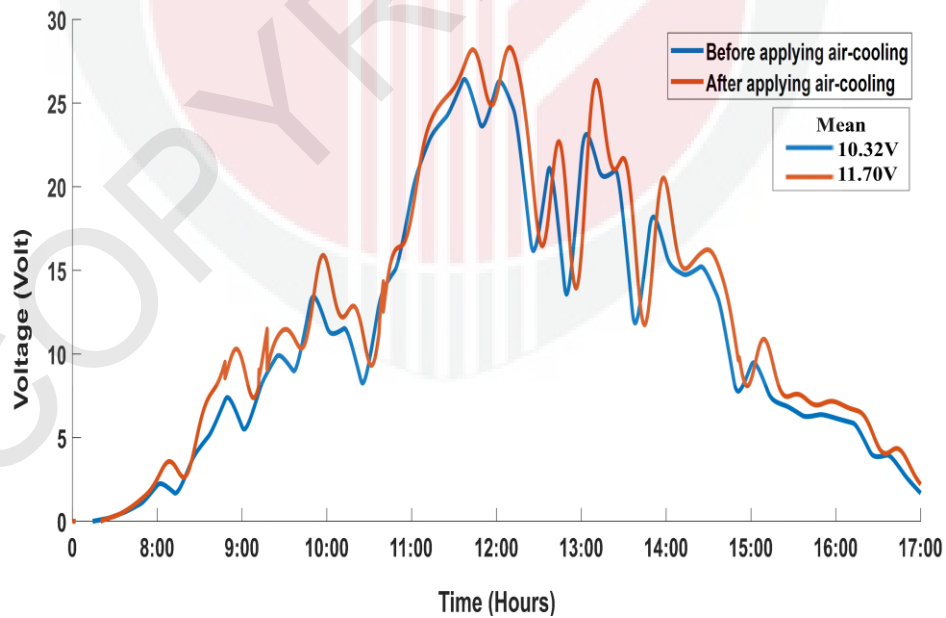
Table 4.5: Percentage of validation of simulated model to experiment data under high, moderate and low level of solar irradiance

Model	High solar irradiance	Moderate solar irradiance	Low solar irradiance
PV module	92.30%	94.65%	93.14%
Air-cooling PV system	93.71%	94.23%	94.17%

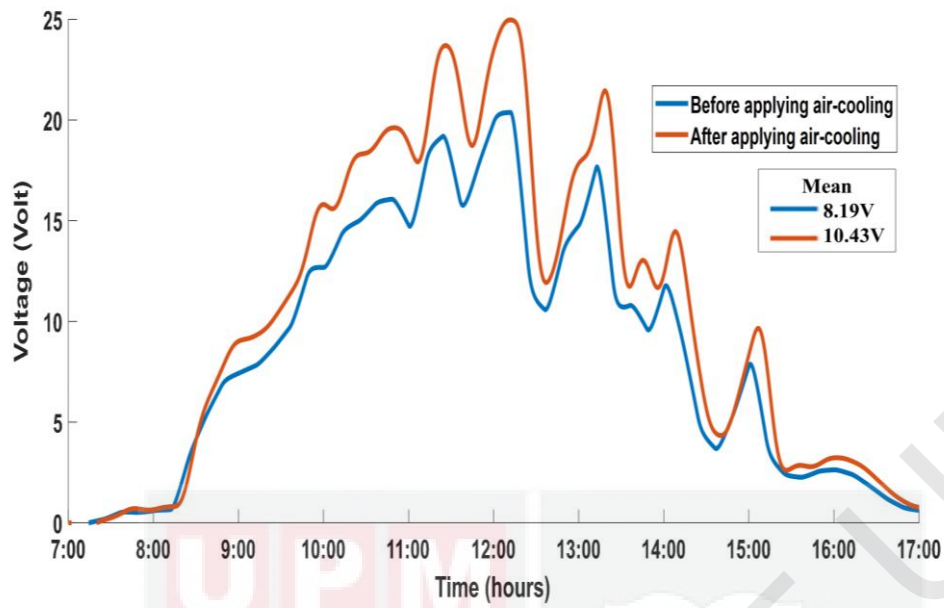
The simulated result under multiple level of solar irradiance obtained from the model than compared to experiment data in Appendix B. Table 4. shows percentage achieved for the validation models. From the table, the percentage of validation for high, moderate and low are above 90%. This means that the developed models are capable of anticipating a voltage output almost as accurate as the value when the experiment was carried out. The model's failure rate in predicting inequality is less than 10%. The

results shown in Table 4. demonstrate the effectiveness of the generated models in handling different levels of solar irradiation.

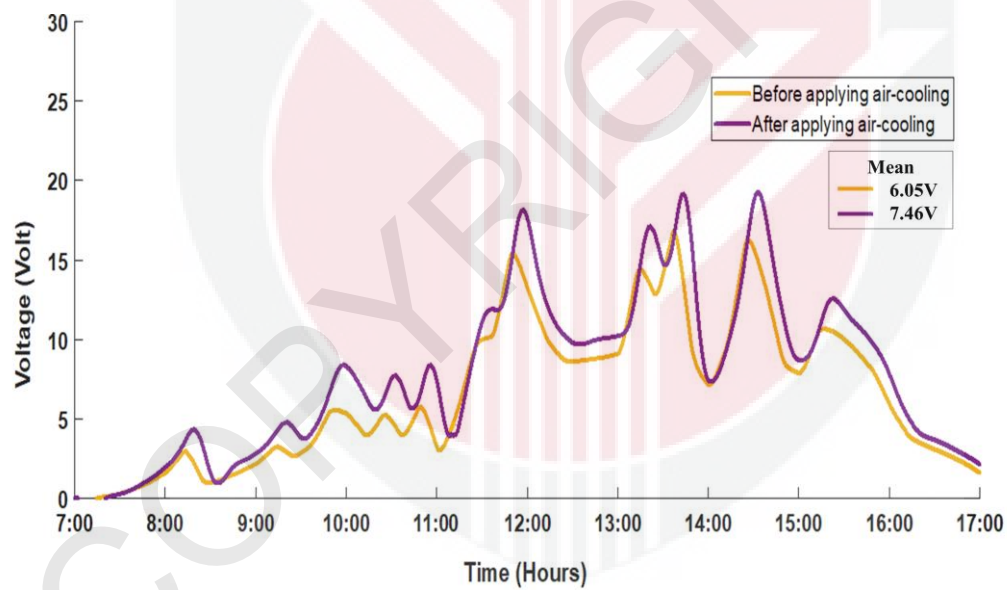
Strong evidence of air-cooling PV system to successfully boost the output performance of PV module was found when the output voltage after implementing air-cooling PV system, $V_{pv_{exp_cool}}$ was higher than before implementing the cooling system, $V_{pv_{exp_uncool}}$. Using multiple level of solar irradiance as an input to the model-based control developed as in Table 4., Figure 4.17 shows the output voltage, $V_{pv_{exp}}$ before and after applying air-cooling PV system for high, moderate and low level of irradiance. The results obtained from Figure 4.17, indicate that there is 11.79% gain in mean output voltage after implementing the proposed air-cooling PV system for high level solar irradiance, 21.51% for moderate level and 18.86% for low level.



(a)



(b)



(c)

Figure 4.17: Output voltage of PV module before and after applying an air-cooling system using SI model for (a) high level irradiance, (b) moderate level irradiance and (c) low level irradiance

Since the PV module has the largest T_{cell} , it has the lowest percentage increase in output voltage under high solar irradiance. While it is probable that the fan in the cooling system has reached its maximum rotational speed, further time is required to decrease T_{cell} because at the same time, the higher solar irradiance can keep T_{cell} high. Hence, while the PV module experiences a significant amount of solar irradiance at any one moment, the prolonged time of solar irradiance receipt also contributes the time to decrease the T_{cell} .

In instances of moderate solar irradiance, the T_{cell} exhibits a lower magnitude compared to instances of high solar irradiance. PV modules that receive moderate solar irradiance have a shorter time of high solar irradiance acceptance, resulting in a quicker temperature reduction compared to modules that receive high solar irradiance. This phenomenon results in a greater magnitude of voltage production in comparison to both high and low levels of solar irradiance. While the T_{cell} experiences a decrease when exposed to low solar irradiance, the percentage output voltage rise is rather small compared to the moderate solar irradiance it receives. Despite the low temperature, it is important to acknowledge that a decrease in solar irradiation results in a corresponding decrease in output voltage.

It is quite beneficial for PV modules to receive high levels of solar radiation during cold climates. This indicates how important and necessary cooling is to the recovery of the PV performance, and the recommended air-cooling system can do this task well. The aforementioned simulation findings show how well the produced models adapt to different levels of solar irradiance, suggesting that more research on them is essential.

4.4.2. PID Controller for Thermoregulated Air-Cooling Retrofitted Photovoltaic System

Modifying the derivative term's value results in less overshoot, increased gain, and maintained stability, rendering the system very vulnerable to noise. The latter parameter is generally employed in systems requiring improved precision and control to manage sudden and rapid fluctuations in external variables. Model-based control in Simulink integrates the designed PID controller. Figure 4.18 illustrates the simulation block diagram of the PID controller employed as model-based control in this research.

Figure 4.18 illustrates the simulation block diagram of the PID controller, which serves as a model-based control in this study. This proposed PID consists of PID 1 and PID 2. V_1 is the output before applying the air-cooling system, $V_{pv_{exp_uncool}}$. according to the block diagram. This V_1 serves as the feedback signal from the air-cooling process and needs to be ensured that the output closely matches the pre-set value to PID 1, V_2 which is $V_{pv_{cool_calc}}$. V_2 also be the pre-set value for PID 2. V_4 is the output after applying the air-cooling system, $V_{pv_{exp_cool}}$; it serves as the feedback signal from the air-cooling process for PID 2 and needs to be ensured that this $V_{pv_{exp_cool}}$ closely matches the preset value to PID 2, $V_{pv_{cool_calc}}$.

The PID controller algorithm constantly computes an error value by subtracting the desired setpoint, $V_{pv_{cool_calc}}$ from the process variable, $V_{pv_{exp_cool}}$ which serves as the feedback signal from the air-cooling process. The algorithm then generates a combined response, V_3 and V_5 , from PID 1 and PID 2, to control the air-cooling devices.

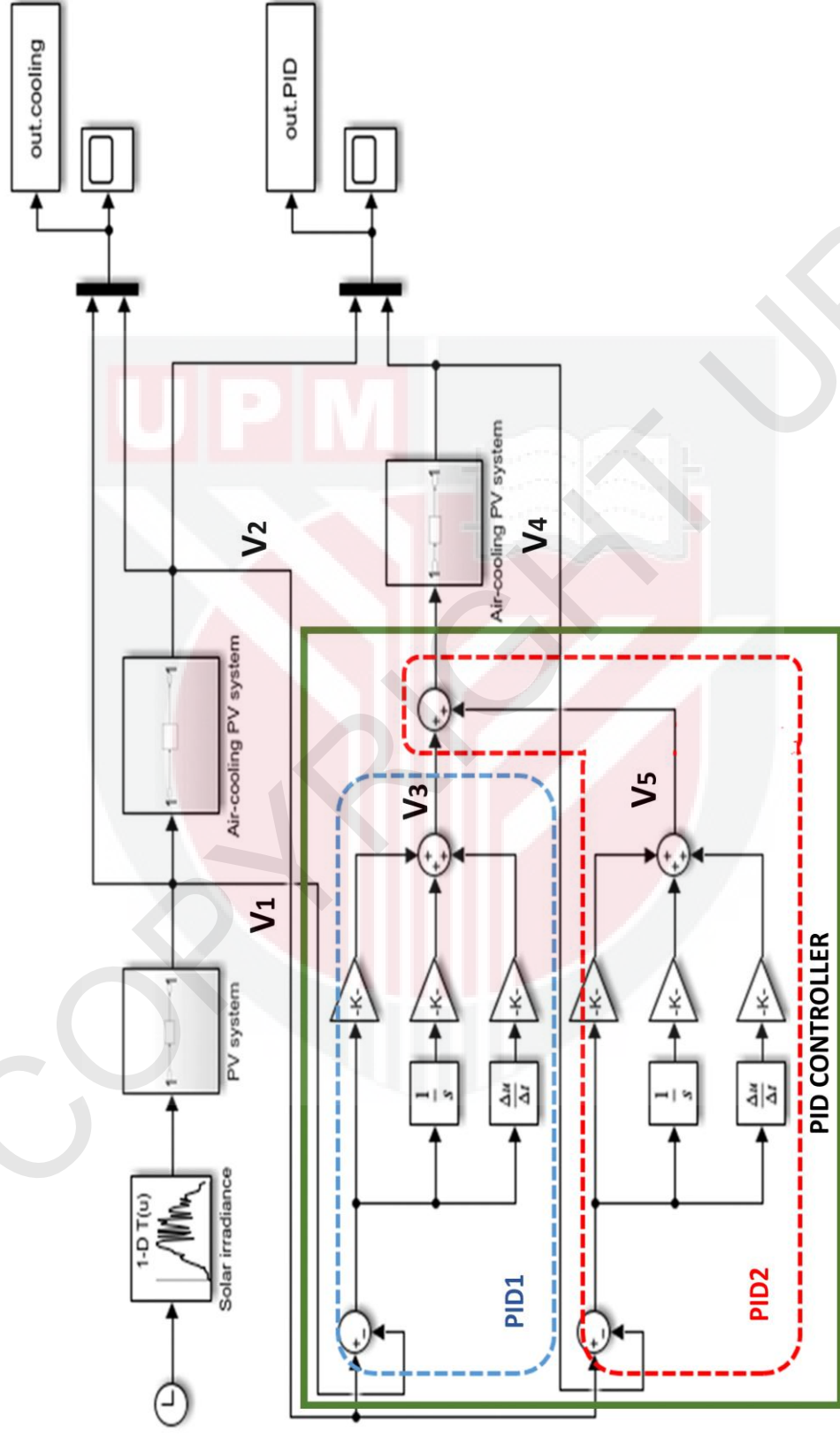


Figure 4.18: Simulation block diagram of PID controller for thermoregulated air-cooling retrofitted PV system

4.4.2.1 K_p , K_i and K_d Parameter Using Ziegler-Nichols

An error in the proposed air-cooling process was reduced by using a PID controller. The error was determined using equation (3.5). The PID controller presented in this work comprises of two components, PID 1 and PID 2, as seen in Figure 4.18. The primary objective of PID 1 was to decrease the error and guarantee that the output $V_{pv_{exp}}$ closely aligns with the preset value $V_{pv_{cool_calc}}$. The primary function of the PID 2 controller is to continuously calculate the error value by subtracting the desired setpoint $V_{pv_{cool_calc}}$ from the process variable $V_{pv_{exp}}$.

Table 4.6: K_p , K_i and K_d parameters using Ziegler–Nichols method

Control Type	K_p	K_i	K_d
PID ₁	$0.33Ku = 0.396$	$2K_p / Tu = 0.825$	$K_pTu / 3 = 0.384$
PID ₂	$0.33Ku = 1.260$	$2K_p / Tu = 2.6250$	$K_pTu / 3 = 0.1512$

The process variable is obtained from the feedback signal of the air-cooling PV system, which is used to optimise its operation. The procedure for this process was elucidated in section 3.3.2.2. Once the parameters I and D were set to zero, and the parameter P was adjusted until it reached the ultimate gain value, denoted as Ku , at the oscillation period (Tu), the values of the parameters K_p , K_i and K_d for the developed PID controller were calculated and are presented in Table 4.

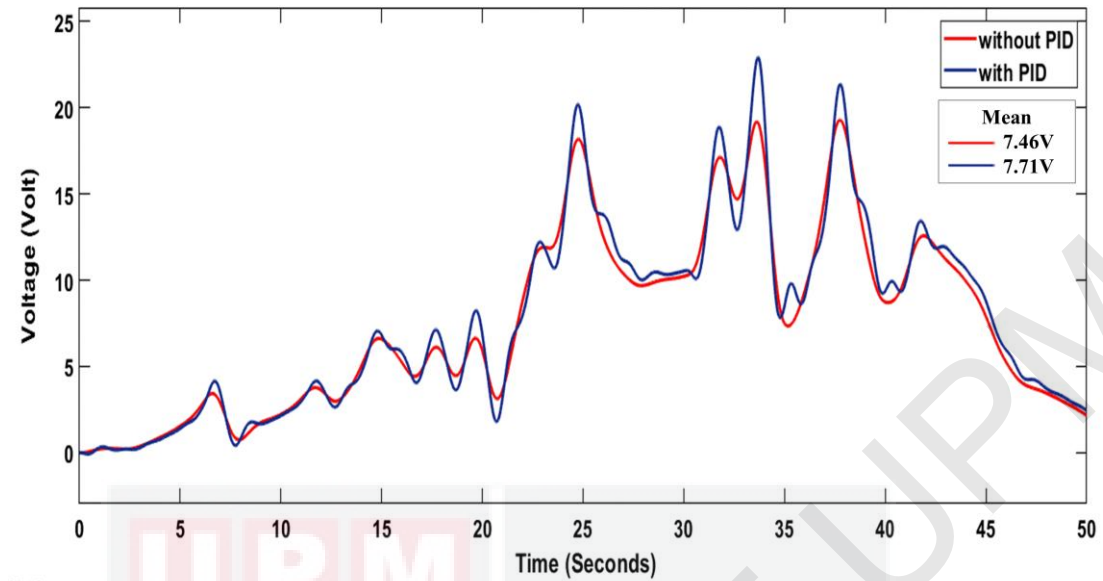
4.4.2.2 Performance Under High, Moderate and Low Level of Solar Irradiance

Strong evidence of air-cooling PV system to successfully boost the output performance of PV module was found when the output voltage after implementing air-cooling PV

system, $V_{pv_{exp_cool}}$ was higher than before implementing the cooling system, $V_{pv_{exp_uncool}}$. In Simulink, signal statistics such as the mean, median, variance, and other statistical measures are computed to gain insights into the properties of a signal or to assess the effectiveness of a system. This is achieved through the utilization of specialized blocks and tools that enable the computation of these statistics on simulated signals over a period of time. Rise time pertains to the duration required for a signal to undergo a transition from a certain low value to a predetermined high value.

The rise time of a voltage signal derived from a simulation of a PV module output serves as an indicator of the rate at which the voltage increases from a lower magnitude to a greater magnitude. The rise time is a critical factor in comprehending the dynamic behavior of the PV system, particularly in scenarios when swift voltage fluctuations are significant, such as during initialization or in reaction to varying external circumstances.

Within the framework of a simulation graph, the rise time is commonly denoted as the temporal length required for the voltage signal to undergo a transition from a certain low voltage level to a predetermined high voltage level. The visualization of this phenomenon may be achieved by quantifying the duration between the instances in which the voltage surpasses certain thresholds. Figure 4.19 display the simulation results for both with and without PID controllers for multiple level of solar irradiance.



(c)

Figure 4.19: Simulation result for air cooling PV system with PID controller and without PID controller for (a) high irradiance, (b) moderate irradiance and (c) low irradiance

Table 4.7: Mean rated output voltage of PV module after implementing the proposed thermoregulated air-cooling retrofitted PV system in the Simulink model-based control under varying levels of solar irradiance

	Percentage increasing		
	High	Moderate	Low
Rated output voltage	11.77%	21.51%	18.86%

The implementation of the suggested air-cooling PV system for high, moderate, and low solar irradiances, utilising a transfer function data-based model in the model-based control in Simulink, has resulted in an increase in the mean rated output voltage as shown in Table 4.. The findings derived from Table 4. demonstrate that the implementation of the proposed air-cooling PV system leads to an increase in mean output voltage of PV module by 11.77% for high solar irradiance, 21.51% for moderate solar irradiance, and 18.86% for low solar irradiance.

Table 4.8: Comparison of response for air cooling *PV* system with *PID* controller and without *PID* controller for high, moderate and low solar irradiances

		Without PID controller	With PID controller
Rise time (seconds)	High	9.658	NA
	Moderate	8.657	6.411
	Low	NA	NA
Mean	High	11.7	12.12
	Moderate	10.43	10.79
	Low	7.46	7.71
Median	High	10.2	10.45
	Moderate	9.76	10.07
	Low	6.41	6.39
Overshoot	High	35.74%	31.33%
	Moderate	21.32%	17.15%
	Low	NA	NA

According to Table 4., high irradiance causes a higher in rise time and there is no correlation between low irradiance and the rise time without PID controller. The rising time for high irradiance input becomes inapplicable after implementing a PID controller to the cooling system. The rising time decreases from 8.657s to 6.411 s for moderate irradiance. This result reflects that the system without PID was more aggressive which may lead to system instability and overshoot if not properly damped as apparent from the Table 4. where the overshoot achieved 35.74% and 21.32% for high and moderate irradiances respectively.

The concept of overshoot pertains to the temporary deviation of voltage from its eventual steady-state value, often observed during quick changes or transient events, such as abrupt alterations in ambient conditions or load. Overshoot in the simulation graph is commonly represented as a percentage relative to the ultimate steady-state

value. The overshoot decreases to 31.33% and 17.15% after implementing PID controller to the air-cooling system for high and moderate irradiances. Minima overshoot signifies that the air-cooling system promptly and smoothly stabilizes. Stability is essential for ensuring the reliability of control systems and the accuracy of simulations, as it ensures that the fan promptly responds to any temperature adjustments made within the setting range.

The calculation of the mean rated output voltage provides valuable insights into the normal performance of a PV module in different scenarios, such as fluctuations in irradiance or T_{cell} . The voltage signal generated by the PV module over time during a simulation is typically recorded, and then mathematical methods available in either Matlab or Simulink are used to calculate the mean voltage value.

The utilization of this mean value might be advantageous in the context of system design, optimization, or performance analysis. For instance, it can assist in determining the expected mean output from the PV module during experimentation. The mean output voltage scores for air-cooling PV system using PID controller were 3.59%, 3.45% and 3.35% higher compared without using PID controller for high, moderate and low irradiances respectively.

Based on the collected findings, it can be deduced that the implemented PID controller enhanced the efficiency of the air-cooling PV system while simultaneously improving the performance of the PV module across various levels of irradiance as input. The PID control system that has been created exhibits robustness across all levels of solar irradiance. The execution of microcontroller in the work was in the first stage. PID was

aimed to be implemented only in simulation, after the model was developed which is based on the system operated with microcontroller.

The median voltage value is a statistical measure that quantifies the voltage level at which the higher and lower voltage values are evenly divided for each half. The median is resilient to outliers and offers a more accurate depiction of the central trend of the data, particularly in situations where the dataset may exhibit skewness. In order to analyse the signal data acquired during the simulation, it is possible to compute the median voltage value using Simulink. The median value is valuable for comprehending the average voltage level produced by the PV module in various circumstances and can guide design choices or system enhancements. A median value in close proximity to the rated voltage suggests that the PV module routinely operates in close proximity to its anticipated output. The findings presented in Table 4. indicate that the implementation of the PID controller resulted in a higher median value.

The purpose of the controller for the air-cooling PV system is to automatically control the fan speed to accomplish the $V_{pv_{cool_calc}}$ for improved performance. Consequently, the proposed air-cooling PV system can be utilized effectively for any specific cooling application, as well as for energy efficiency. In addition, this air-cooling PV system can resolve the intermittent availability of solar as a renewable energy source for electricity generation. Fortunately, the temperature response in air-cooling PV systems occurs gradually over several seconds. This allowed to modify the PID controller's parameters in real time and with relative ease. By attaining $V_{pv_{cool_calc}}$, the dynamic response of the air-cooling system using a PID controller is enhanced. Using dynamic fan speed, the air-cooling PV system is able to reduce T_{cell} for energy efficiency.

4.5 Cost Analysis

Combining temperature effect, f_{temp} and PSH on the module output at ROC in the field, the output power per day becomes:

$$P_{mp_roc_calc} = P_{mp_stc} \times f_{temp_ROC} \times PSH \quad (4.4)$$

The expected output power of the module for one day was 980 *Wh* and 357.7 *kWh* annually, based on 4 of PSH. The experimental average output power was 3.73% lower than the predicted value. The module's output power is 344.36 *kWh* annually. Utilising a tariff rate of RM 0.218 per *kWh*, the module may earn around RM 75.07 prior to the implementation of an air-cooling system. After implementing the proposed air-cooling system, there was a 15.18% increase in average net output power. A total gain of 18.91% in power has been achieved by addressing the power reduction prior to the implementation of the air-cooling system, below the estimated value. The expected output power of the module is 1.17 *kWh* per day and 425.34 *kWh* per year. The module may produce around RM 92.72 with the implementation of an air-cooling system. The implementation of the suggested thermoregulated air-cooling retrofitted PV system yields annual savings of RM 17.65.

Table 4.9: Cost for the proposed thermoregulated air-cooling retrofitted PV system prototype

Item	Unit	Cost (RM)
Cross flow fan	1	30
Arduino UNO	1	95
SLA Battery	2	118
Digital temperature sensor	1	8
MOSFET	1	3.50
TOTAL		254.50

Table 4.9 presents the costing for the proposed air-cooling photovoltaic system prototype. Prototyping enables the evaluation of the technical feasibility of new concepts and improves the precision of cost estimations [172]. In engineering philosophy, product development during the conceptual design phase can minimize costs, resulting in estimated production expenses that are lower than those of the prototype [173]. A structured prototype framework can enhance cost efficiency by continually accounting for the unpredictability in market, product, and process characteristics [174]. The ROI can be rapid when manufacturing costs are reduced, as seen by the total savings per year derived from the total costing in Table 4.9. By figuring out the benefit-to-effort ratio of cooling needs for PV modules, tasks are put in order of importance because they lead to better performance for the modules.

4.6 Summary

Different roofing materials and the distance between the PV module and the roof influence the T_{cell} and result in a decline in photovoltaic performance. Guimarães et al. [175] discovered that galvanized steel roofs or zinc-type materials required sufficient separations at increased distances, since the T_{cell} consistently exceeded those of other roofing materials, such as ceramic and tiles, which are often utilized. Since the suggested air-cooling PV system shows better performance when tested on a zinc-type rooftop, it is for sure able to give better performance for a non-zinc rooftop PV system. The optimal arrangement is deemed to be freestanding such as ground-mounted system due to enhanced airflow beneath the PV array [51], [52]. Agro-Photovoltaic systems are superior for this sort of PV system, as the substantial area between the PV array and the ground may be employed for cultivating vegetables [176].

In this chapter, experimental and simulation results of the proposed innovative air-cooling for retrofitted PV system have been presented. A novel air-cooling system has been designed to simplify the installation of cooling system for retrofitted PV system. An experimental setup has also been presented utilizing developed air-cooling system at existing PV system in GMi. The provided findings demonstrate an enhancement in the output performance of the PV module following the implementation of the recommended air-cooling system, as compared to its performance prior to the system's implementation. A black-box model for air-cooling PV systems has been constructed using SI Matlab and presented as well.

A PID controller was constructed and included into the present air-cooling model. The simulations were conducted in the Simulink Matlab environment to analyze the reaction of the proposed air-cooling PV system model and controller under various solar irradiance levels. The results have been compared to the data obtained prior to the implementation of the air-cooling system. Effectiveness of the proposed air-cooling PV system, air-cooling PV system model and PID controller (in performing PV module's output) has successfully been verified and validated. According to all the experimental and simulation results obtained, it can be confirmed that the suggested innovative air-cooling PV system is able to enhance the performance of PV module's output.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusions

This thesis offers a comprehensive analysis of an innovative air-cooling photovoltaic (PV) design aimed at improving the performance output of retrofitted PV system in tropical regions such as Malaysia. The system effectively removes the accumulated heat from the back side of the PV modules by using a cross-flow fan with speed control capabilities, leading to a reduction in the module's temperature, T_{cell} . The experiment yielded results from 12 consecutive hours of testing. The maximum temperature recorded for T_{cell} was $72.88^{\circ}C$ without the air-cooling system and $55.75^{\circ}C$ with the air-cooling system. The average powers per peak sun factor (PSF) were $210.22\ W$ and $246.67\ W$, respectively. The system's energy efficiency was shown to have improved by up to 6.68%. The system's power rating was $6.48\ W$, equivalent to 2.6% per PV module.

Moreover, this study developed and assessed black-box system identification (SI) model to represent the output performance of the PV module. The analysis showed that the model had an accuracy of 94.25% before installing the air-cooling system, compared to 96.42% after implementing the suggested air-cooling system. The validation findings for the air-cooling model were 93.71%, 94.23%, and 94.17% for high, moderate, and low levels of irradiance, respectively. The average output voltage increases by 11.77%, 21.51%, and 18.86%. Combining the suggested air-cooling

with the designed PID controller resulted in average output voltages that were 3.59%, 3.45%, and 3.35% higher than the system without PID at high, moderate, and low levels of irradiance, respectively. The results indicate that the PID controller design exhibited robustness in the face of different intensities of sun irradiation. Furthermore, it improved the efficiency of the air-cooling system, resulting in increased PV module output.

5.1 Recommendations for Future Work

Additional research might focus on optimizing the positioning of fans and improving airflow. Further optimization analysis may be performed by specifying the engineering requirements of fans, determining the number of fans, and defining the air pocket between the PV panels and roof.

This study was conducted on a single PV module. Therefore, future research should be conducted on the full PV array. Future research aims to expand the air-cooling system to encompass the entire PV arrays, rather than individual modules. By implementing the cooling mechanism on a full-scale rooftop building, it can be feasible to evaluate the system's performance, the primary air streams, and the efficiency of the cooling mechanism.

Future research might focus on developing and implementing effective monitoring systems that provide ongoing control over cooling systems. This could involve the use of strategic algorithms to adjust the cooling system's operation based on real-time climate conditions. These systems have the ability to efficiently cool while minimizing

energy use, hence enhancing the efficacy of the PV system.

Investigating the impact of the cooling system on the lifespan of PV modules might be a valuable study area to examine. Low-temperature cooling systems may potentially increase the lifespan of PV modules. However, these hypotheses need to be further investigated through detailed surveys and assessments of module degradation rates over time.

If these recommendations are followed, future research improves the outcome of this study, potentially leading to the development of efficient, long-lasting, and marketable cooling technologies for rooftop photovoltaic systems. This, in turn, increases the commercial appeal of rooftop photovoltaic deployment, particularly in tropical regions.

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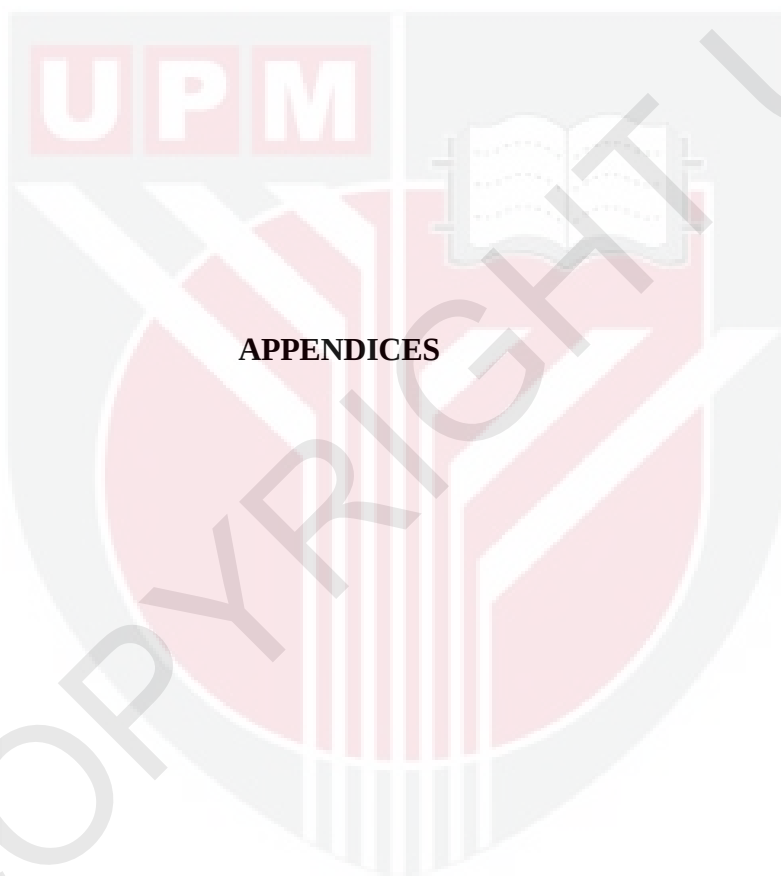
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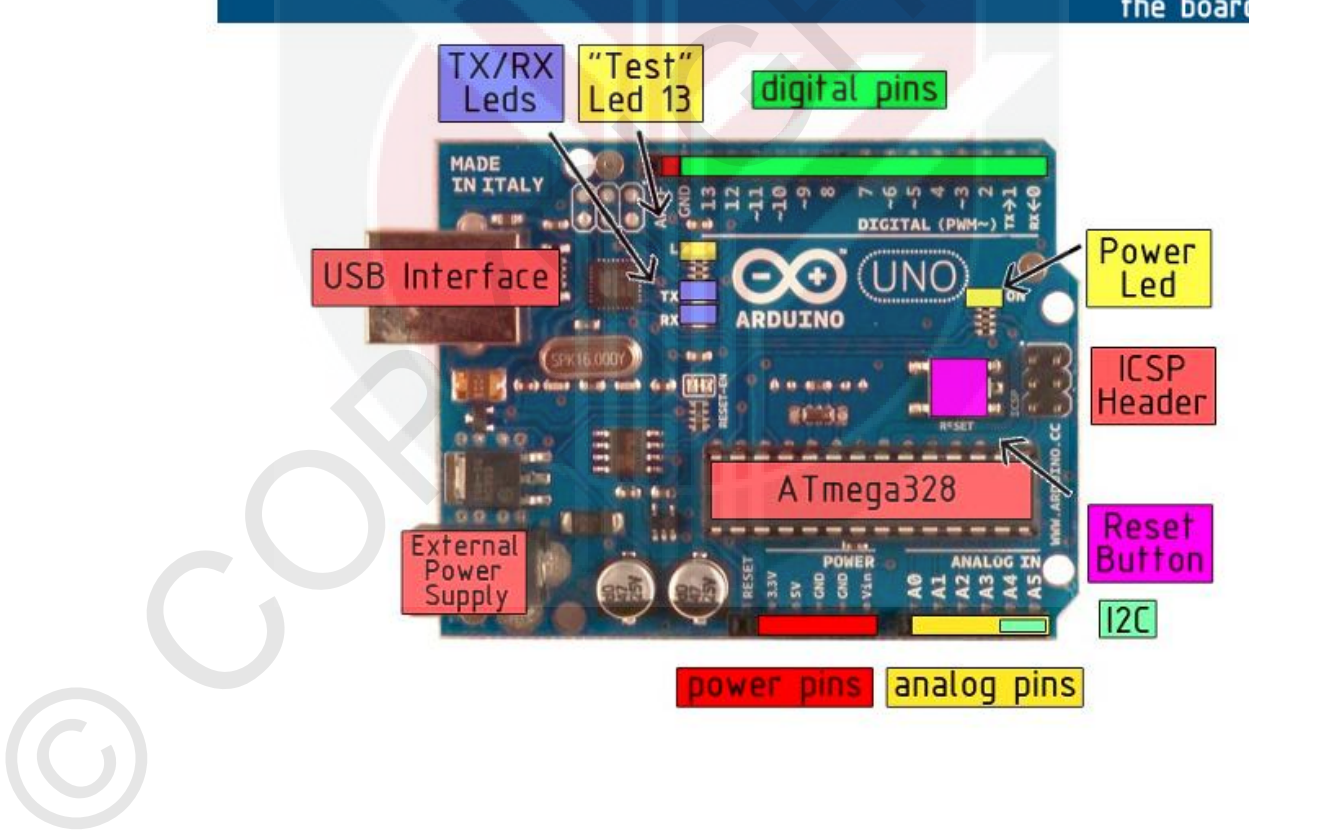
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APPENDICES

Summar

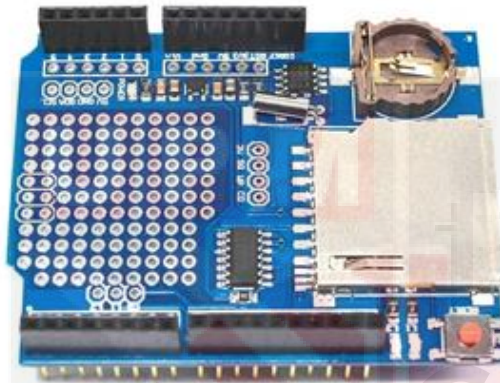
the board

Appendix A

A.2. Data logger RTC shield specification

XD-204 Data Logger+RTC Shield

Arduino Data Logger plus Real-Time-Clock (RTC) Shield which is designed to use with Arduino UNO, Duemilanove, Diecimila, Leonardo, ADK or Mega R3. Easy to implement with library for Arduino IDE.



SKU: MDU1114

Brief Data:

- SD card interface works with FAT16 or FAT32 formatted cards.
- 3.3v level shifter circuitry prevents damage to SD card.
- DS1307 Real time clock (RTC) with battery backup.
- Prototyping area for soldering connectors, circuitry or sensors.
- Onboard 3.3v regulator.

Mechanical Dimension:

Unit: mm



Appendix A

A.3. Ambient light BH1750 specification



Technical Note

Ambient Light Sensor IC Series

Digital 16bit Serial Output Type Ambient Light Sensor IC

BH1750FVI



No.11046EDT01

●Descriptions

BH1750FVI is a digital Ambient Light Sensor IC for I²C bus interface. This IC is the most suitable to obtain the ambient light data for adjusting LCD and Keypad backlight power of Mobile phone. It is possible to detect wide range at High resolution. (1 - 65535 lx).

●Features

- 1) I²C bus Interface (f / s Mode Support)
- 2) Spectral responsibility is approximately human eye response
- 3) Illuminance to Digital Converter
- 4) Wide range and High resolution. (1 - 65535 lx)
- 5) Low Current by power down function
- 6) 50Hz / 60Hz Light noise reject-function
- 7) 1.8V Logic input interface
- 8) No need any external parts
- 9) Light source dependency is little. (ex. Incandescent Lamp. Fluorescent Lamp. Halogen Lamp. White LED. Sun Light)
- 10) It is possible to select 2 type of I²C slave-address.
- 11) Adjustable measurement result for influence of optical window
(It is possible to detect min. 0.11 lx, max. 100000 lx by using this function.)
- 12) Small measurement variation (+/- 20%)
- 13) The influence of infrared is very small.

●Applications

Mobile phone, LCD TV, NOTE PC, Portable game machine, Digital camera, Digital video camera, PDA, LCD display

●Absolute Maximum Ratings

Parameter	Symbol	Ratings	Units
Supply Voltage	V _{max}	4.5	V
Operating Temperature	T _{opr}	-40~85	°C
Storage Temperature	T _{stg}	-40~100	°C
SDA Sink Current	I _{max}	7	mA
Power Dissipation	P _d	260 [※]	mW

※ 70mm × 70mm × 1.6mm glass epoxy board. Derating in done at 3.47mW/°C for operating above Ta=25°C.

●Operating Conditions

Parameter	Symbol	Ratings			Units
		Min.	Typ.	Max.	
V _{cc} Voltage	V _{cc}	2.4	3.0	3.6	V
I ² C Reference Voltage	V _{bvi}	1.65	-	V _{cc}	V

Appendix A

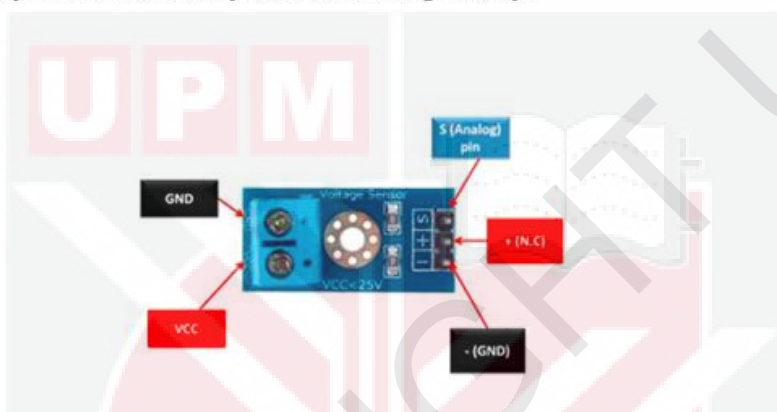
A.4. Voltage sensor module specification

25V Voltage Sensor Module

Features

- Output Interface: “+” Connected 5/3.3V, “-” Connected GND, “s” Connected Arduino AD pins
- DC Input interface: red terminal positive with VCC, negative with GND
- You Can Also Use the IICLCD1602 LCD to Display Voltage.
- By 3P Connector, connect this Module with the Expansion of Board Arduino, which not only makes it easier for you to detect voltage battery.

Pinout



Pin Name	Description
VCC	The positive terminal of the External voltage source (0-25V)
GND	The negative terminal of the External voltage source
S	Analog pin connected to Analog pin of Arduino
+	Not Connected
-	Ground Pin connected to GND of Arduino

Specifications

Dimensions	28 x 14 x 13 mm(LxWxH).
Weight	4 gm.
Input Voltage range	DC0 to 25 V
Voltage detection range	DC 0.02445 V to 25 V
Analog Voltage resolution	0.00489 V

Appendix A

A.5. HSTS016L hall effect current with split-core transformer sensor specification

HSTS016L

YHDC®

Detect DC, AC and pulse current, high insulation between primary side and the vice side circuit.

Product picture printing is for reference only, subject to the actual product

Product application

- Metallurgy
- Welding machine
- Robot
- Inverter power
- Inverter speed controller
- UPS uninterruptible power supply

Product features

- Light weight
- Low power consumption
- No insertion loss
- Fast response time
- Small size and beautiful appearance
- Suspended mounting and easy to use



Electrical parameters: the following parameters are typical values, the actual values shall be subject to the actual measurement of the product

Rated input	±10A	±20A	±30A	±50A	±100A	±150A	±200A
Input measurement range	±15A	±30A	±45A	±75A	±150A	±200A	±200A
Rated output	1.65V±0.625V						
Accuracy	1%						
Linearity	1%						
Supply voltage	+3.3V±5%						
Current consumption	≤12mA						
Load impedance	≥10KΩ						
Zero offset voltage	≤±15mV						
Response time	≤5μs						
Weight	86g						
Operation temperature	-10℃~+70℃						
Storage temperature	-25℃~+70℃						
Band width	DC~25KHz						
Dielectric strength	2.5KV 50Hz 1min						

Calculation formula : $1.65V \pm 0.625V$

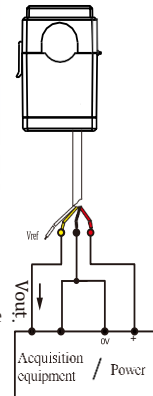
Forward direction : $1.65 + (I/I_{PN}) * 0.625$

Reverse direction : $1.65 - (I/I) * 0.625$

I: Actual measured current

I_{PN} : Rated input current

Wiring diagram :



Cable definition:

Red : V+

Black : 0V

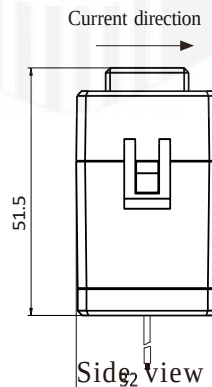
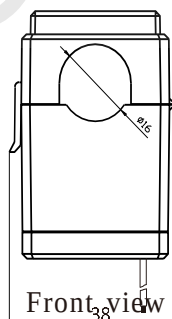
Yellow : Vout White :

Vref

Factory commissioning :

1. Debug with 0V as the reference point (acquiescence)
2. Debug with Vref as the reference point (optional)

Dimensions (in mm±0.5) :



Cable specification : 0.2mm² four-core shielding wire
Four core colors: red, black, yellow, white
Cable length: 50cm (50cm~55cm)

Appendix A

A.6. DS18B20 digital temperature sensor specification



DS18B20 Programmable Resolution 1-Wire Digital Thermometer

DESCRIPTION

The DS18B20 digital thermometer provides 9-bit to 12-bit Celsius temperature measurements and has an alarm function with nonvolatile user-programmable upper and lower trigger points. The DS18B20 communicates over a 1-Wire bus that by definition requires only one data line (and ground) for communication with a central microprocessor. It has an operating temperature range of -55°C to $+125^{\circ}\text{C}$ and is accurate to $\pm 0.5^{\circ}\text{C}$ over the range of -10°C to $+85^{\circ}\text{C}$. In addition, the DS18B20 can derive power directly from the data line ("parasite power"), eliminating the need for an external power supply.

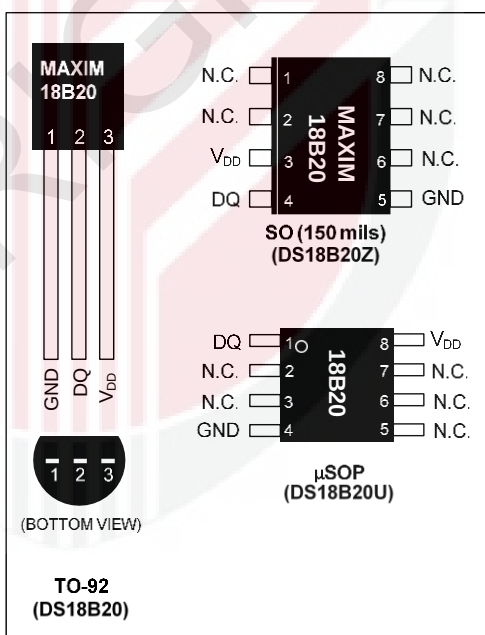
Each DS18B20 has a unique 64-bit serial code, which allows multiple DS18B20s to function on the same 1-Wire bus. Thus, it is simple to use one microprocessor to control many DS18B20s distributed over a large area. Applications that can benefit from this feature include HVAC environmental controls, temperature monitoring systems inside buildings, equipment, or machinery, and process monitoring and control systems.

FEATURES

- Unique 1-Wire® Interface Requires Only One Port Pin for Communication
- Each Device has a Unique 64-Bit Serial Code Stored in an On-Board ROM
- Multidrop Capability Simplifies Distributed Temperature-Sensing Applications
- Requires No External Components
- Can Be Powered from Data Line; Power Supply Range is 3.0V to 5.5V
- Measures Temperatures from -55°C to $+125^{\circ}\text{C}$ (-67°F to $+257^{\circ}\text{F}$)
- $\pm 0.5^{\circ}\text{C}$ Accuracy from -10°C to $+85^{\circ}\text{C}$
- Thermometer Resolution is User Selectable from 9 to 12 Bits
- Converts Temperature to 12-Bit Digital Word in 750ms (Max)

- User-Definable Nonvolatile (NV) Alarm Settings
- Alarm Search Command Identifies and Addresses Devices Whose Temperature is Outside Programmed Limits (Temperature Alarm Condition)
- Available in 8-Pin SO (150 mils), 8-Pin μSOP , and 3-Pin TO-92 Packages
- Software Compatible with the DS1822
- Applications Include Thermostatic Controls, Industrial Systems, Consumer Products, Thermometers, or Any Thermally Sensitive System

PIN CONFIGURATIONS



1-Wire is a registered trademark of Maxim Integrated Products, Inc.

For pricing, delivery, and ordering information, please contact Maxim Direct at 1-888-629-4642, or visit Maxim's website at www.maximintegrated.com.

REV: 042208

Appendix A

A.7. IRLZ44N metal oxide semiconductor field effect transistor specification

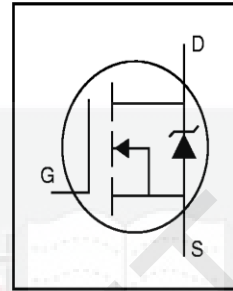
International
IR Rectifier

PD - 9.1346B

IRLZ44N

HEXFET® Power MOSFET

- Logic-Level Gate Drive
- Advanced Process Technology
- Dynamic dv/dt Rating
- 175°C Operating Temperature
- Fast Switching
- Fully Avalanche Rated



$$V_{DS} = 55V$$

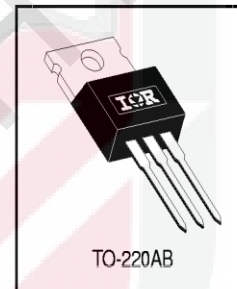
$$R_{DS(on)} = 0.022\Omega$$

$$I_D = 47A$$

Description

Fifth Generation HEXFETs from International Rectifier utilize advanced processing techniques to achieve the lowest possible on-resistance per silicon area. This benefit, combined with the fast switching speed and ruggedized device design that HEXFET Power MOSFETs are well known for, provides the designer with an extremely efficient device for use in a wide variety of applications.

The TO-220 package is universally preferred for all commercial-industrial applications at power dissipation levels to approximately 50 watts. The low thermal resistance and low package cost of the TO-220 contribute to its wide acceptance throughout the industry.



TO-220AB

Absolute Maximum Ratings

	Parameter	Max.	Units
$I_D @ T_C = 25^\circ C$	Continuous Drain Current, $V_{GS} @ 10V$	47	A
$I_D @ T_C = 100^\circ C$	Continuous Drain Current, $V_{GS} @ 10V$	33	
I_{DM}	Pulsed Drain Current ①	160	
$P_D @ T_C = 25^\circ C$	Power Dissipation	110	W
	Linear Derating Factor	0.71	W/°C
V_{GS}	Gate-to-Source Voltage	± 16	V
E_{AS}	Single Pulse Avalanche Energy ②	210	mJ
I_{AR}	Avalanche Current ①	25	A
E_{AR}	Repetitive Avalanche Energy ①	11	mJ
dv/dt	Peak Diode Recovery dv/dt ③	5.0	V/ns
T_J	Operating Junction and	-55 to + 175	°C
T_{STG}	Storage Temperature Range		
	Soldering Temperature, for 10 seconds	300 (1.6mm from case)	
	Mounting torque, 6-32 or M3 screw.	10 lbf•in (1.1N•m)	

Thermal Resistance

	Parameter	Min.	Typ.	Max.	Units
$R_{\theta JC}$	Junction-to-Case	—	—	1.4	°C/W
$R_{\theta CS}$	Case-to-Sink, Flat, Greased Surface	—	0.50	—	
$R_{\theta JA}$	Junction-to-Ambient	—	—	62	

8/25/97

Appendix A

A.8. LWCD-401055M-30 DC cross flow fan specification

CROSS FLOW FAN
DC

LWCD-030

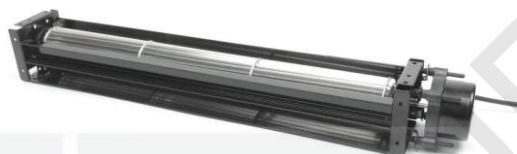
Motor Type : DC Brushless External Rotor Motor
Housing Material : Aluminum alloy Blade
Material : Aluminum Alloy Insulation Class :
B/F/H
Bearing Type: Ball bearing / Sleeve Bearing Speed
Control : 0~10V / PWM control Operation
Temperature : - 25 °C ~ +60 °C

TELL : 0086 574 6218 9863

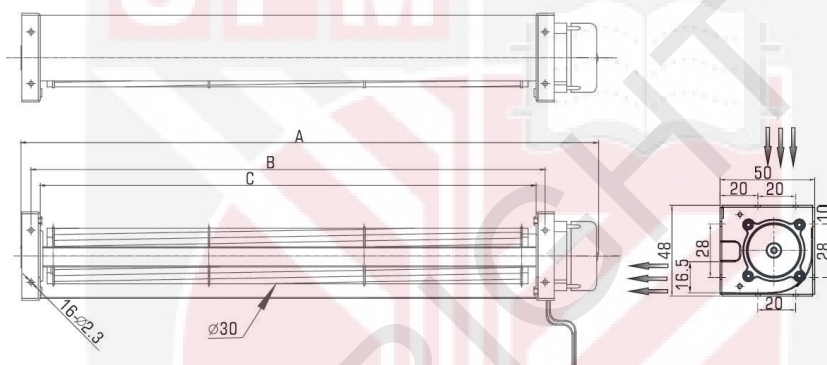
FAX : 0086 574 6218 9863

Email : sales@zjlongwell.com

Website : www.zjlongwell.com



■ Technical Specification



Model	Dimension(mm)			Voltage	Current	Speed	Pressure	Airflow	Noise
	A	B	C	V	A	rpm	Pa	m³/h	dB(A)
LWCD-3090L-10	152	108	98	12	0.1	3000	17	35	29
LWCD-3090M-10				24	0.05	3000	17	35	29
LWCD-30120L-10	214	170	160	12	0.12	2800	15	42	30
LWCD-30120M-10				24	0.07	2800	15	42	30
LWCD-30190L-10	252	208	198	12	0.14	2700	14	52	31
LWCD-30190M-10				24	0.08	2700	14	52	31
LWCD-30250L-10	302	258	248	12	0.16	2600	14	65	32
LWCD-30250M-10				24	0.09	2600	14	65	32
LWCD-30290L-10	354	310	300	12	0.18	2500	13	72	33
LWCD-30290M-10				24	0.09	2500	13	72	33
LWCD-30350L-10	406	362	352	12	0.2	2400	12	84	35
LWCD-30350M-10				24	0.1	2400	13	84	35

NINGBO LONGWELL ELECTRIC TECHNOLOGY CO.,LTD.

Tell: 0086 574 6218 9863 FAX: 0086 574 6218 9863 www.zjlongwell.com sales@zjlongwell.com



Appendix A

A.9. Rechargeable 12 V lead acid battery specification



ENGLISH

Datasheet: 537-7305

RS Pro Rechargeable 12V Lead Acid Battery, 12 Ah



From RS Pro, this is a highly efficient, all purpose, sealed rechargeable lead acid battery. This battery is valve regulated and utilises recombination technology to ensure that it remains maintenance free. The battery casing is constructed from ABS resin, which offers high impact strength, good resistance to chemicals and excellent temperature performance.

Storage:

This lead acid battery can be stored at +25 °C for more than 6 months with a self-discharge ratio of 3 %. It has an excellent standby life of five years. This lead acid battery features a high quality AGM separator which extends the cycle life and prevents micro short circuits.

Features:

- Valve regulated
- Suitable for float or standby use
- Low gas emission
- The resin case features fire resistance to UL94-HB
- Silver coated fast-on F1 terminals improve conductivity

Benefits:

- Maintenance free
- Leak proof
- Excellent recovery from deep discharge
- Five years standby life
- Road transport suitable as per UN2800
- Air transport suitable to Special Provision A67, IATA and ICAO
- Can be used in several orientations, but must not be used inverted

Appendix A

A.10. Canadian Solar CS6P-250P module specification



ELECTRICAL DATA | STC

Electrical Data	CS6P-250P	CS6P-255P
Nominal Maximum Power (Pmax)	250W	255W
Optimum Operating Voltage (Vmp)	30.1V	30.2V
Optimum Operating Current (Imp)	8.30A	8.43A
Open Circuit Voltage (Voc)	37.2V	37.4V
Short Circuit Current (Isc)	8.87A	9.00A
Module Efficiency	15.54%	15.85%
Operating Temperature	-40°C~+85°C	
Maximum System Voltage	1000V (IEC) / 1000V (UL) / 600V (UL)	
Maximum Series Fuse Rating	15A	
Application Classification	Class A	
Power Tolerance	0 ~ +5W	

*Under Standard Test Conditions (STC) of irradiance of 1000W/m², spectrum AM 1.5 and cell temperature of 25°C.

ELECTRICAL DATA | NOCT

Electrical Data	CS6P-250P	CS6P-255P
Nominal Maximum Power (Pmax)	181W	185W
Optimum Operating Voltage (Vmp)	27.5V	27.5V
Optimum Operating Current (Imp)	6.60A	6.71A
Open Circuit Voltage (Voc)	34.2V	34.4V
Short Circuit Current (Isc)	7.19A	7.29A

*Under Nominal Operating Cell Temperature (NOCT), irradiance of 800 W/m², spectrum AM 1.5, ambient temperature 20°C, wind speed 1 m/s.

MODULE | MECHANICAL DATA

Specification	Data
Cell Type	Poly-crystalline, 6inch
Cell Arrangement	60 (6 x 10)
Dimensions	1638 x 982 x 40mm (64.5 x 38.7 x 1.57in)
Weight	18.5kg (40.8 lbs)
Front Cover	3.2mm tempered glass
Frame Material	Anodized aluminium alloy
J-BOX	IP67, 3 diodes
Cable	4mm ² (IEC)/4mm ² & 12AWG 1000V (UL1000V)/12AWG (UL600V), 1000mm
Connectors	MC4 or MC4 comparable
Standard Packaging	24pcs, 504kg (quantity and weight per pallet)
Module Pieces Per Container	672pcs (40'HQ)

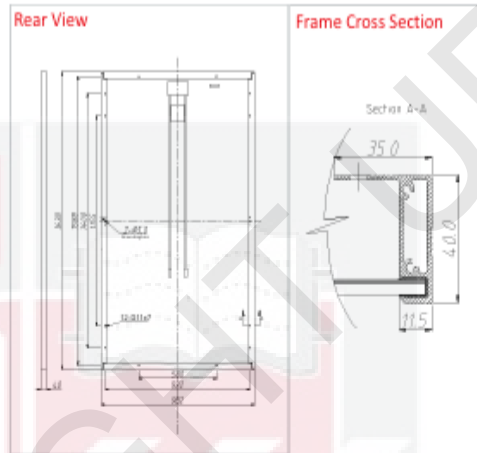
TEMPERATURE CHARACTERISTICS

Specification	Data
Temperature Coefficient (Pmax)	-0.43%/°C
Temperature Coefficient (Voc)	-0.34%/°C
Temperature Coefficient (Isc)	0.065%/°C
Nominal Operating Cell Temperature	45±2°C

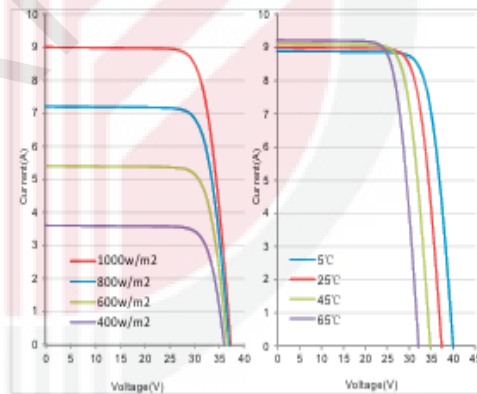
PERFORMANCE AT LOW IRRADIANCE

Industry leading performance at low irradiation environment, +96.5% module efficiency from an irradiance of 1000w/m² to 200w/m² (AM 1.5, 25 °C)

MODULE | ENGINEERING DRAWING



CS6P-255P | I-V CURVES

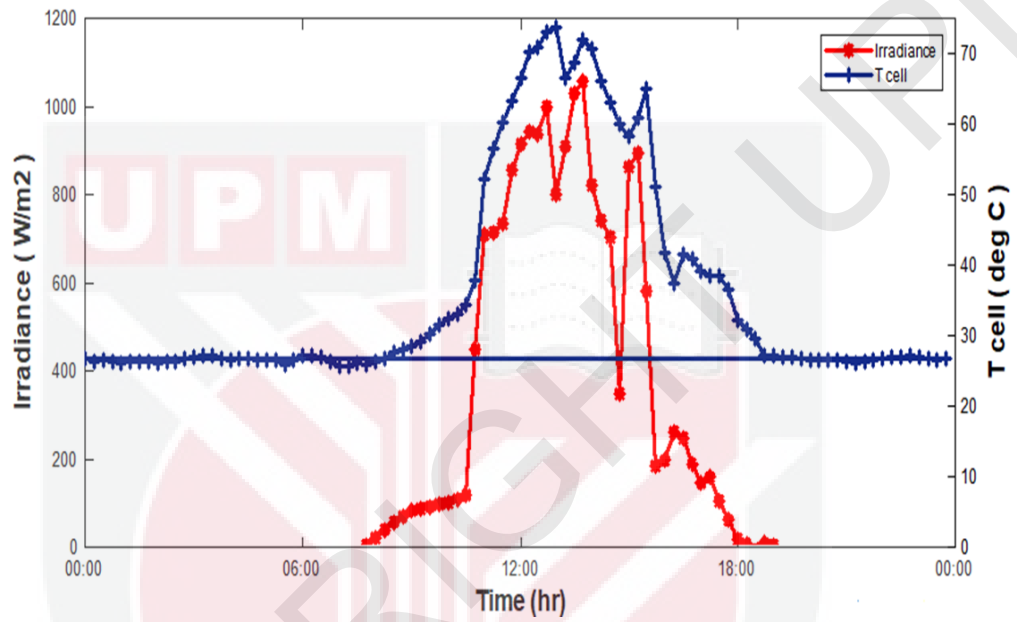


Partner Section

*The specifications made herein may deviate slightly and are not guaranteed. Due to ongoing innovation, research and product enhancement we reserve the right to make any adjustments to the information contained herein at any time without notice. Please always obtain the most recent revision of datasheet which shall be duly incorporated into the binding contract made by the parties governing all transactions related to the purchase and sale of the products described herein.

Appendix B

Figure B.1. Solar irradiance and T_{cell} for a typical day from Sunny Web portal for GMi PV system monitoring on *April 14, 2021*



BIODATA OF STUDENT

The student was born on 3th of February 1981 in Labis, Johor. She received his primary education at Sekolah Rendah Kebangsaan Sri Labis, Johor from 1988 to 1993. She then continued his secondary studies at Sekolah Menengah Kebangsaan Munshi Ibrahim Labis, Johor from 1994 until 1996 and at Mara Junior Science College from 1997 until 1998. She completed her Matrix studies at Matriculation College of Seremban, Negeri Sembilan in 1999. In 2004, she was awarded by Universiti Kebangsaan Malaysia (UKM) the Bachelor of Engineering in Microelectronics with honours.

After completing her Bachelor degree, she is employed as a lecturer at the Sultan Mizan Zainal Abidin Polytechnic in Dungun and the Sultan Idris Shah Polytechnic in Sabak Bernam, Selangor. She pursues her Master degree in 2008 and awarded by Universiti Tenaga Nasional (UNITEN) the Master of Electrical Engineering in 2010. Throughout her Master study, she was awarded Science Fund scholarship under Ministry of Science, Technology and Innovation. She was a lecturer at Malaysian Science University (MSU) from 2010 until 2011. She has been serving as a technical instructor at the German Malaysian Institute (GMi) since 2011. She pursues his Doctor of Philosophy (Ph.D.) in Electrical Engineering at UPM.

She was a qualified Sustainable Energy Development Authority (SEDA) Malaysia grid-connected photovoltaic system (GCPV) designer who was also appointed as a trainer for GCPV system installation and maintenance. She possesses teaching experience in the field of education, with a focus on subjects such as Digital, Electrical Principal, Elecronics, Photovoltaic Principal and System Design, Hydro and

Sustainable Engineering. She played a key role in the development of the Sustainable Energy & Power Distribution program at GMI, which included creating the curriculum and modules. Utilising her knowledge in Outcome Based Education (OBE), she ensures that the developed programs align with the necessary outcomes for both current and future industries in renewable energy engineering. Her current research interests include cooling photovoltaic system, and modeling system photovoltaic.



LIST OF PUBLICATIONS

Conference Proceeding:

Mustafa, R., Radzi, M. M., Hizam, H., & Soh, A. C. (2023, December). Solar insolation and PV module temperature impact on the actual grid connected solar photovoltaic system in German Malaysian Institute. In *IOP Conference Series: Earth and Environmental Science* (Vol. 1261, No. 1, p. 012001). IOP Publishing.

Journal Articles:

Mustafa, R., Radzi, M. A. B. M., Hizam, H. B., & Soh, A. C. (2024). An innovative air-cooling system for efficiency improvement of retrofitted rooftop photovoltaic module using cross-flow fan. *International Journal of Renewable Energy Development*, 13(2), 223-234.

Mustafa, R., Radzi, M. A. B. M., Hizam, H. B., & Soh, A. C. (2024). Air-Cooling Photovoltaic System Modeling Using System Identification. *Pertanika Journal of Science and Technology* (accepted)