AN IMPROVEMENT OF THERMAL ENERGY HARVESTING OUTPUT FOR HIGHER LEVEL USAGE

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This report is submitted in partial fulfilment of the requirements for the degree of Bachelor of Electronic Engineering with Honors

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DECLARATION

I declare that this report entitled “An Improvement of thermal energy harvesting output for higher level usage” is the result of my own work except for quotes as cited in the references.

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APPROVAL

I hereby declare that I have read this thesis and this thesis is sufficient in terms of scope and quality for the award of Bachelor of Electronic Engineering with Honours.

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DEDICATION

This study is dedicated to my beloved families, who have always been my source of motivation, guide and give me strength especially when I thought to giving up, who continually provide their spiritual, moral emotional, and financial support. I would like to thank particularly my supervisor Dr Norihan Binti Abdul Hamid for her sincere assistance during the preparation of this project, constantly guiding and teaching me to make this study better. I also dedicate this dissertation to my numerous friends who helped and encouraged me along the way. I will always be grateful for everything they did to support me in honing my technological skill and always encourage me with the motivational quote to make sure this thesis can be a success. Without their assistance, this research would not have been made possible.

ABSTRACT

Nowadays, many industries use a machine and the machine generate waste heat. This waste heat can be transformed into electricity by using thermal energy harvesting method. Here this research paper addresses the way to improve the thermal energy harvesting for higher level usage. This research uses the Thermoelectric generator (TEG). A thermoelectric generator (TEG) is a device that can generate electrical power from a temperature difference across its two sides. The working principle of a TEG is based on the Seebeck effect, a phenomenon where a temperature difference across a material generates a voltage difference. However, the thermoelectric generator (TEG)produces a small output current, and it is not enough to power up electronic. Therefore, additional component such as MPPT circuit and boost converter circuit was implemented in this study. As a result, the use of algorithm P&O for the MPPT and boost converter module increase the overall performance and efficiency of the TEG system. in conclusion, this research provides valuable insight into the thermal energy harvesting method for higher level usage and it contribute to the renewable energy as it environmentally friendly.

ABSTRAK

Pada zaman ini, banyak industri menggunakan mesin yang menghasilkan haba terbuang. Haba terbuang ini boleh diubahsuai menjadi tenaga elektrik dengan menggunakan kaedah penuaian tenaga terma. Kertas penyelidikan ini membincangkan cara untuk meningkatkan penuaian tenaga terma untuk kegunaan peringkat yang lebih tinggi. Penyelidikan ini menggunakan penjana Termoelektrik (TEG). Penjana Termoelektrik (TEG) ialah peranti yang boleh menghasilkan kuasa elektrik secara langsung dari perbezaan suhu di dua sisi peranti tersebut. Prinsip kerja TEG adalah berdasarkan kesan Seebeck, iaitu fenomena di mana perbezaan suhu merentangkan perbezaan voltan di sepanjang bahan. Walaubagaimanapun, penjana tenaga termoelektrik (TEG) menghasilkan arus keluaran yang kecil, dan ini tidak mencukupi untuk memberi daya kepada peranti elektronik. Oleh itu, komponen tambahan seperti litar MPPT dan litar penukar pacu diterapkan dalam kajian ini. Hasilnya, penggunaan algoritma P&O untuk MPPT dan modul penukar pacu meningkatkan prestasi dan kecekapan keseluruhan sistem TEG. Kesimpulannya, penyelidikan ini memberikan pandangan berharga tentang kaedah penuaian tenaga terma untuk kegunaan peringkat yang lebih tinggi dan memberikan sumbangan kepada tenaga boleh diperbaharui kerana ia mesra alam.

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First, I want to thank and praise Allah S.W.T, for all the blessing that is given to me. It is through His guidance, protection, power of consciousness, and the gift of good health that enabled me to complete this final year project. I'm grateful for every joyful moment in my life. I feel lucky to have had the opportunity to experience my university journey without regrets. This final year project has been the most valuable lesson for me.

As my time at university draws to a close, there are two people I want to express my deepest gratitude which is my dearest beloved parents. They have always been my source of motivation and gave me strength when I contemplated giving up, who continually provide their moral, spiritual, emotional, and financial support. They are angels of my life that lead me to the right path.

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LIST OF SYMBOLS AND ABBREVIATIONS

ANN	:	Artificial Neural Network
ESC	:	Extremum Seeking Control
INC	:	Incremental Conductance
IOT	:	Internet of Things
KCL	:	Kirchoff Current Law
KVL	:	Kirchoff Voltage Law
MPPT	:	Maximum Power Point Tracking
P&O	:	Perturbation and Observation
OCV	;	Open Circuit Voltage
SOC	:	State of Charge
TEG	:	Thermoelectric Generator
TEC	:	Temperature Control
WSN	:	Wireless Sensor Network

CHAPTER 1

INTRODUCTION

1.1 Background Study/ General Overview

Traditional energy sources, such as fossil fuels, are no longer suitable for energy demands due to the rapid expansion of the industrial economy and world population. Wind, light, vibration, heat, wave, rotation, and other renewable/sustainable energy sources have emerged as an effective and suggesting solution to the global energy crisis [1][2]. Numerous studies and efforts have been focused on environmental energy harvesting techniques throughout the past decade.

This thesis aims to enhance the output of thermal energy harvesting for higher-level applications. Thermal energy harvesting is a technique to capture and convert wasted heat into useful energy. In many processes and systems, heat is produced as a byproduct and usually just goes to waste. However, thermal energy harvesting gives a good advantage especially in converting that heat and transforming it into electricity or other forms of usable energy. For example, the car engine gets hot after running for a while. This heat has been generated because of the engine operation, but the heat energy is not used for anything[3][4]. By implementing the thermal energy harvesting concept, the heat can be captured and converted to electricity for used to power the other parts of the car such as charge its battery[5].

In addition, this thermal energy harvesting concept is no longer limited to the automobile sector only. Many industrial operations, structures generated waste heat include our own bodies. By implemented thermal energy harvesting concept, this heat can be captured and converted to energy for multipurpose of used. This technology can also be used in a small electronic gadget, especially in powering up them without needing to constantly recharge their batteries. It also can be used in larger systems like heating and cooling systems in the building. By applying this concept, the energy efficiency can be increase, cost effective and make it more environmentally friendly [6]. Thermal energy harvesting is a great approach to convert the heat that would be wasted into something valuable such as electric energy. Thus, by reducing waste it can save energy and contribute to a more sustainable future.

Moreover, thermal energy efficiency performance is defined as the efficiency with which thermal energy is transformed into useful energy. It calculates how well a system converts thermal energy into an output like electricity while minimizing energy losses. Determining how much energy may be produced from a given amount of heat input. Because of the better thermal energy efficiency, less energy is lost as heat loss is decreased and a larger percentage of the input heat is transformed into useful output energy. So, thermal energy harvesting is a renewable energy source, However, an improvement is required for higher usage application, particularly in terms of raising its efficiency.

A thermoelectric generator (TEG) is a device that uses the "Seebeck effect" to convert heat into electrical energy. According to this theory, an electric voltage will result from a temperature differential between two different types of materials. Electricity is essentially formed when a hot and cold side interact with specific materials[7][8]. Multiple semiconductor elements made of different materials with different electrical characteristics make up thermoelectric generators (TEGs). A voltage is produced across the TEG when one side is exposed to heat from sources like flames or hot surfaces while the other side stays cool[9]. A thermoelectric generator (TEG) can be used to restore batteries or power up small electronic devices. It is very helpful in situations when there is a temperature difference, like when recovering waste heat from industrial processes or car exhaust systems. TEG is a device that exploits heat to generate energy. The special materials on the TEG properties generate an electric charge in response to temperature changes to produce power.

Nevertheless, the output current of the thermoelectric generator (TEG) is slightly low[10][11]. An electrical device like a cell phone cannot be powered by this output current. The temperature differential across a thermoelectric generator (TEG), the number and size of thermoelectric components used, and the properties of the materials used in the TEG are some of the factors that affect the output current of any given TEG. Typical real-world uses of TEGs produce low voltages and currents. So, the TEG requires an additional electronic circuit to improve its performance. This has been proved by referring the journal “Complete implementation of the combined

TEG-TEC temperature control and energy harvesting system" written by Trevor Hocksun Kwan, Xiaofeng Wu and Qinghe Yao, it has said that the TEG-TEC control technique can be improve greatly by integrating device that assure the TEG output power can be resumed to the power source. There are two additional components that are connected to the TEG power circuit. TEG power circuit is employed with the two cascaded boost converter, with the maximum power point tracking (MPPT) and providing additional constant voltage gain to increase circuit compatibility [12]. Thus, to increase the TEG Output performance, additional circuits such boost converter[13]-[15] and as maximum power point tracking (MPPT) circuit need to be employed to TEG circuit[16][17].

Maximum Power Point Tracking (MPPT) technique in the method to maximize the efficiency of power generation systems such as thermoelectric generators (TEGs). MPPT continuously modifies the electrical load attached to a TEG to maximize its power output. Using the temperature differential across the TEG as a basis, the MPPT technique is applied to TEG systems to maximize the electrical energy production [18][19]. One side of the TEG is hotter, and the other is colder while it functions, creating a temperature gradient. When there is a temperature differential, the MPPT controller continuously measures it and modifies the electrical load to locate the ideal position at which the TEG produces the highest power [20].

Furthermore, to step up or raise the voltage level from an input to a higher output voltage, a boost converter is an example of a DC-to-DC power converter. It belongs to the family of switched-mode power supplies, which are widely utilized in a wide range of power systems and electronic equipment. An inductor, a switch (usually a transistor), a diode, and a capacitor are used in a boost converter's fundamental operation to transfer energy from an input voltage source to a higher output voltage.

Therefore, this project is focusing on designing and constructing the circuit that can increase the performance of the TEG by increase the output current and voltage. So, this output can be used for higher usage applications such as power up electronic devices such as mobile phones. The boost converter and maximum power point tracking (MPPT) circuit will be used to be employed with TEG circuit to raise the output current and voltage in this project[21].

The purpose of this project is to design and construct a circuit that can increase the TEG's output voltage and current to enhance its functionality. Thus, higher usage applications can benefit from this output such as turning on electronic devices like cell phones. To increase the output current and voltage in this project, the boost converter and maximum power point tracking (MPPT) circuit will be utilized together with the TEG circuit [21]. To make sure this project succeeds, the MATLAB, Simulink, OrCAD Cadence, and Multisim simulation will be used to run the circuit's performance to analyze the output such as the voltage and current output performance and ensure that it is stable for use before implementing it in the hardware. At the end of this project, the output performance is at least 1 to 2A at 12Vdc could be achieved by the improvement circuit of TEG. So, it can be used by high-power electronic equipment.

1.2 Problem Statement

The low output current generated by thermoelectric generators (TEGs) poses a significant challenge in achieving higher efficiency for energy harvesting applications. Current TEG systems exhibit conversion efficiencies typically in the range of 5-10%, limiting the overall power generation potential. Improving the TEG output current to a higher percentage value is essential to enhance the efficiency of energy harvesting systems and maximize power generation from available heat sources.

The inadequate power output of thermoelectric generators (TEGs) without additional electronic devices presents a challenge especially in achieving higher efficiency in energy harvesting. TEGs usually operate below their maximum power capacity, resulting in an efficiency below the targeted percentage. Enhancing the power generation of TEGs to approach or reach their full power potential is vital for optimizing energy harvesting systems and achieving higher overall efficiency in power generation.

1.3 Objectives/ Aim of Study

There are two main objectives of this project work enlisted as follows:

I. To design and simulate the performance of the Maximum Power Point (MPPT) circuit integration to increase the output performance of the TEG system.

II. To apply the Maximum Power Point Tracking (MPPT) circuit in TEG system hardware.

1.4 Scope of the Project

This project aims to design, simulate, and implement a boost converter circuit with Maximum Power Point Tracking (MPPT) circuit for a Thermoelectric Generator (TEG) system. Firstly, the point-to-point tacking circuit for TEG module will be investigated to know the detail about its performance. Secondly, the MPPT circuit will be compared with solar power generation to identify its difference and similarities. Next, a specialized circuit will be designed to track and optimize the power output of the TEG. Furthermore, the performance of the circuit will be simulated using MATLAB and Simulink, considering different conditions to ensure maximum power extraction from the TEG. Finally, the designed circuit will be physically implemented and integrated into the TEG system for practical testing. The target of the current output power for this project should be between 1A and 2A at 12Vdc.The project will adhere to safety standards, comprehensive documentation will be produced, and an efficient and compact design will be pursued. Deliverables will include a detailed design report, simulation results, and a functional prototype of the implemented circuit.

1.5 Thesis Outline

The development of cascade converter additional together with MPPT circuit to increase the output and efficiency of the TEG is done in this project whereby the progress and the results is obtained throughout the eight months effort is documented in this thesis. All the details about this thesis project are structured as follows:

Chapter I: Introduction

This chapter presents a brief idea of thermal energy harvesting especially for the TEG system and its advantage in converting the waste energy into a useful electric energy for higher application usage. The problem statement is done based on the TEG limitation output performance. In addition, objectives and problem statements of this project are discussed as well as to give a brief and essential idea on this project.

Chapter II: Background Study

This chapter includes the similar work done by other people that is related to TEG and boost converter circuit with MPPT circuit design in increasing the output and percentage of efficiency for TEG system. With the ultimate purpose of gaining knowledge and reference in designing the best additional circuit (MPPT) for TEG system, different journals and articles are reviewed.

Chapter III: Methodology

This chapter presents the process flow and the method used in designing suitable additional circuits which are boost converter and MPPT for TEG system with step-by-step explanation which includes all the parameters selection. This chapter covered the whole process for this project, and its experiment setup. A total of two major steps are discussed which are for the simulation and prototype test. The step or method covered about the TEG configuration, MPPT circuit with its simulation using the MATLAB and Simulink Software, the design of the boost converter circuit using OrCAD and Multisim, the employment of the boost converter and MPPT circuit in TEG system, and lastly measurement and testing of the Full TEG system.

Chapter IV: Results and Discussion

This chapter presents the results obtained that have been achieved throughout the semester. The result starts from the simulation outcome, hardware outcome and measurement testing of the full TEG system. The process for each part will be explained in detail.

Chapter V: Conclusion and Future Works

This chapter outlines the conclusion of the previous four chapters and outlines the results and functionality of the entire project. Guideline and recommendation for further improvement is done by research to help the future candidates that would like to continue the research and development of additional circuit for better output performance of the TEG system in energy harvesting applications.

CHAPTER 2

BACKGROUND STUDY

2.1 General Overview

This chapter demonstrates the journals and research papers related to thermal energy harvesting application and the way to implemented it concept. There are numerous of study done about the topic include the method to increase the TEGs efficiency performance by using the MPPT circuit. Each of the journals has their own unique research value. The journals enable the student to view the project from a whole new perspective, which is generally beyond the university academic syllabus. Through literature review, latest news and development of thermal energy harvesting by using TEGs circuit will be reviewed while the new design solutions are learned to solve specific problem for this investigation. Sources to obtain the journals are widely available on the internet and online platforms such as IEEE, IET Digital Library, and Science Direct.

2.2 Literature Review

In this chapter, the literature review is divided into six sub-chapter which are Thermoelectric Generator (TEGs), Maximum Power Point Tracking (MPPT), Point-To-Point Tracking Circuit for TEG Module Performance, Boost Converter, Solar Power Generation, Difference and Similarities of MPPT Circuit with Solar Power Generation. All the sub-chapters are supported with several journals and articles reviewed for better understanding for improvement of thermal energy harvesting by using MPPT circuit in TEGs system.

2.2.1 Thermoelectric Generator (TEGs)

Thermoelectric generators, or TEGs, are devices that transform thermal energy directly into electrical energy without the use of external fuel or moving parts. The Seebeck effect, which states that an electric current can be produced by a temperature differential across some materials, is the basis for TEG technology. The hot side and the cold side are two separate zones found in a TEG. An imbalance in the flow of electrons within the material results from a temperature differential between these two sides. Electric potential difference or voltage was produced by these results[8]. Batteries can then be charged, or electrical equipment can be powered by this voltage. A collection of thermoelectric modules consisting of semiconducting materials, such as bismuth, telluride, or antimony, make up the TEG. The effective conversion of heat into electricity is a criterion for selecting these materials[22][23].

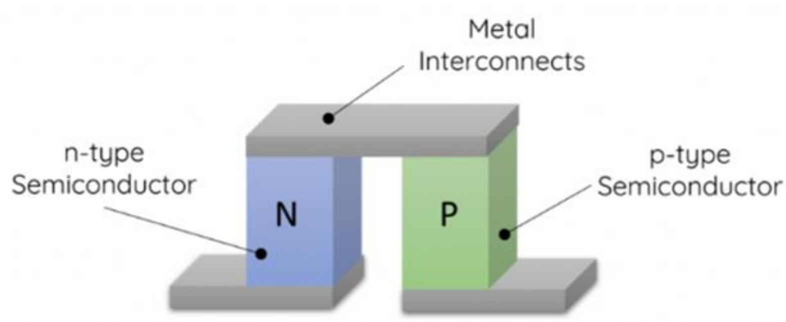


Figure 2.1: TEG Material

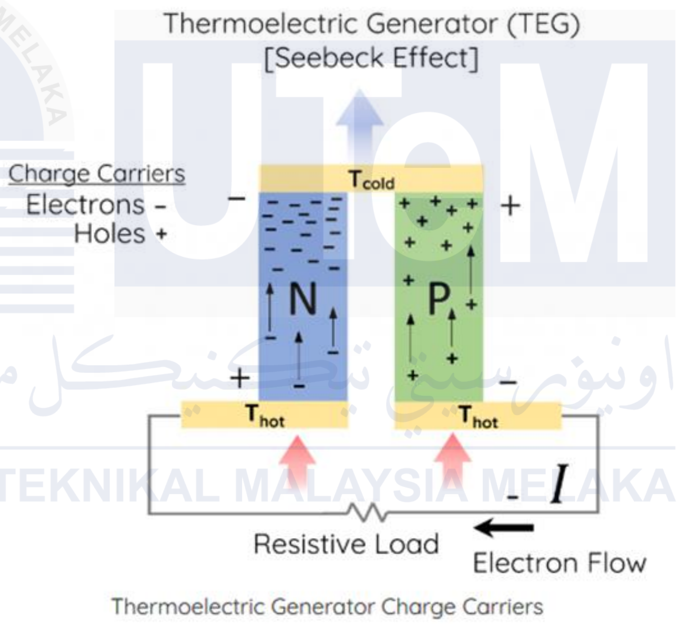


Figure 2.2: Thermoelectric generator charge carrier

Figure 2.1: TEG Material shows the TEG material which is constructed from the P-type and N-type semiconductor material. This material is interconnected with each other by a metal. **Figure 2.2: Thermoelectric generator charge carrier** illustrates the TEG functionality concept which is known as Seebeck effect. The TEG's hot side absorbs heat while the cold side maintains a lower temperature when it is exposed to a heat source, such as the differential in temperature between the human body and its surroundings or waste heat from industrial operations. The electrons go from the hot

side to the cold side due to this temperature differential. It generated an electric current. This TEG can be used for various applications ranging from powering small electronic devices to waste heat recovery in industries. TEGs can be used in wearable devices, remote sensors, or even in spacecraft, where they convert the excess heat generated by electronic components into usable electricity. One of the advantages of TEGs is their reliability and simplicity. They have no moving parts, making them durable and low maintenance. However, their efficiency is currently limited, and they are most effective in situations where there is a significant temperature difference [8][22][23].

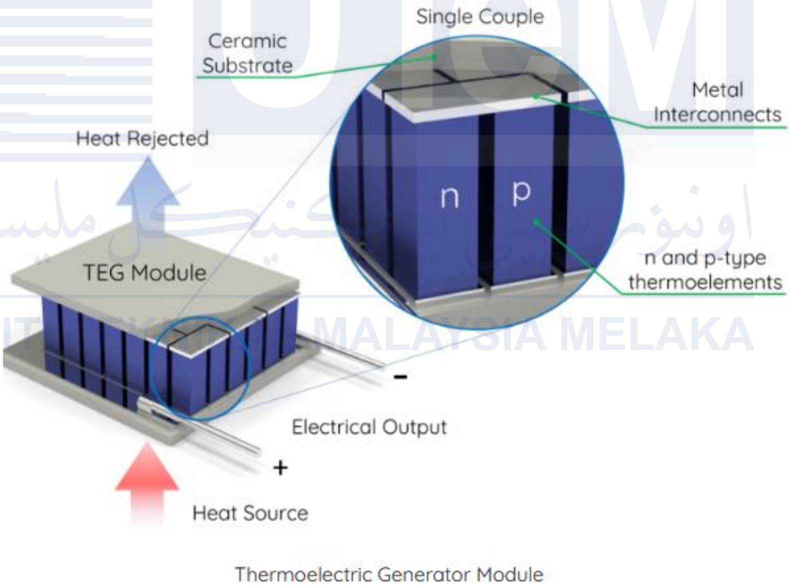


Figure 2.3: Thermoelectric Generator Module

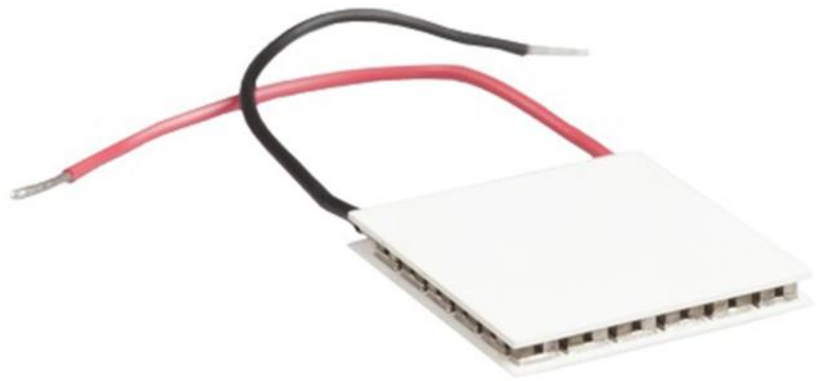


Figure 2.4: TEG module (Peltier Module)

Figure **2.3**: Thermoelectric Generator Module illustrates the full TEG module and its material. TEG modules have several N and P-type semiconductor connections. Figure **2.4**: TEG module (Peltier Module)shows the last product of the TEG module.

Based on the essay "A comprehensive review of Thermoelectric Generators: Technologies and common applications"[22], the author is optimistic about the use of TEGs. Global warming, rising electricity prices, and environmental degradation are among the challenges being tackled now. To reduce these effects, scientists are improving power generators that rely on reusable energy. The thermoelectric generator (TEG) is one type of generator that has proven to be capable of directly converting thermal energy into electrical energy using the Seebeck effect. Because they don't include any chemical products, TEGs are environmentally friendly. They also operate quietly because they don't have any mechanical components or structures, and they can be fabricated on a variety of substrates, including silicon, polymers, and ceramics. TEGs can also be incorporated into bulky and flexible devices, have extended operating lifetimes, and are position independent. Additionally, the manuscript delves into the diverse fields in which TEGs find application. These fields span from low-power domains like wearables and medical devices, to high-power domains like industrial electronics, automotive engines, and aerospace.

2.2.2 Maximum Power Point Tracking (MPPT)

Maximum Power Point Tracking (MPPT) is one of the methods that are usually used in renewable energy. This method is commonly used in industry to maximize the power extracted from the environment sources such as wind and solar from the wind turbines and solar panel. This MPPT is functioned to modify the electrical load attached to the system to collect the maximum value of power from that source. This MPPT can adjust the electricity generated by the power generator based on the changes in the environment. In instance, it can enable the device such as solar panel system to be adapted to changes in temperature or sunlight intensity. This is continuously achieved by keeping an eye on and modifying the solar panel's operational parameters to guarantee optimal efficiency.

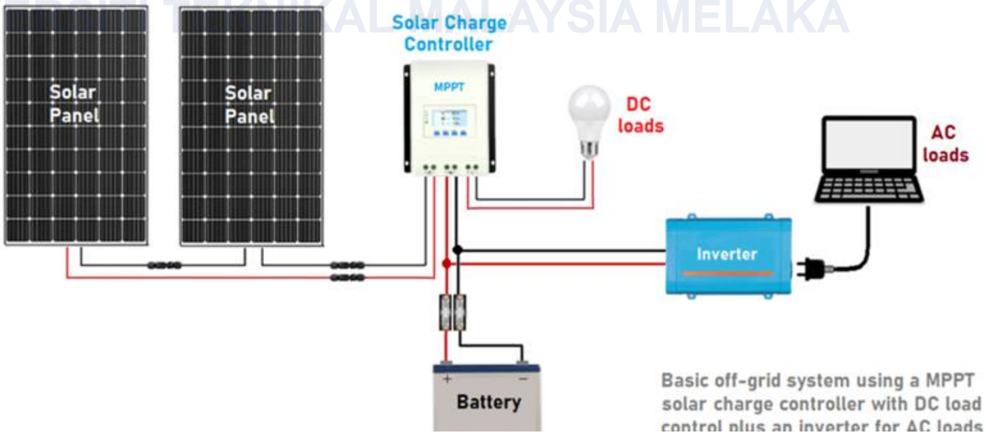


Figure 2.5: Basic off grid system using MPPT solar charge.

Figure **2.5**: Basic off grid system using MPPT solar charge. It shows the basic grid off system using the MPPT solar charge with DC load and control plus an inverter for AC loads. The MPPT technique works by measuring the voltage and current that is generated by the solar panel or other power source. This information is used to calculate the output power. By referring to this measurement, the system adjusts the electrical load to find the optimal point where the output power is maximized. This optimization process involves a continuous evaluation of the output power where the load is adjusted. This system incrementally modified the load and observes the output power result. Then, by analyzed the changes in output power, the MPPT technique can determine the best operating point to make sure the system can generate the maximum power [24].

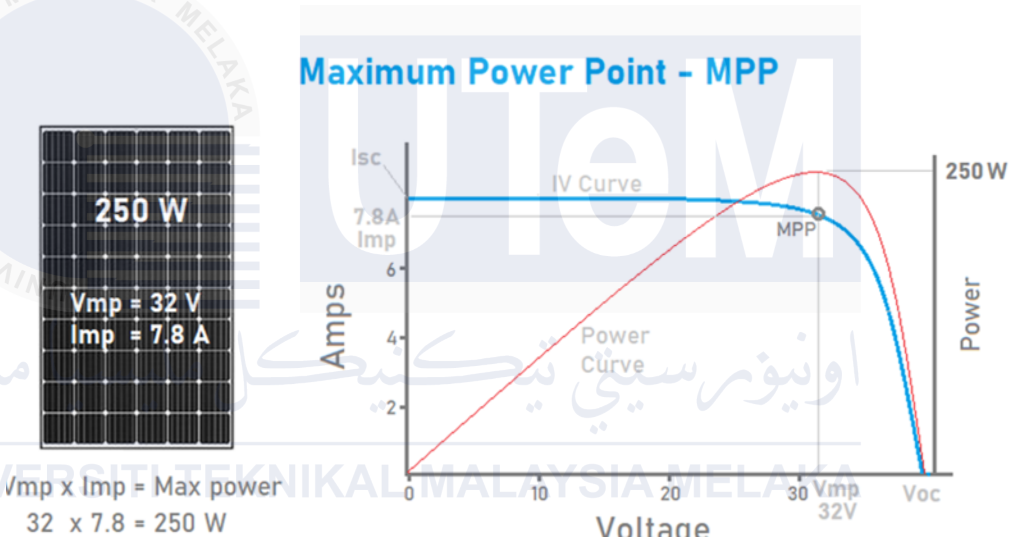


Figure 2.6: MPP operating point

By using MPPT in the system, the power generation system can track the changes in the available power and adjust it accordingly such as in Figure **2.6**. This ensures the system is operates at its highest efficiency while capture the most energy from the renewable source. Whether it’s solar panel or wind turbine, the MPPT technique helps to make the most of these clean energy sources by maximizing their power output. Thus, the MPPT technique is used to optimize the efficiency of the power generation system by controlling the electrical load to find the point of maximum power. The system can function at peak efficiency by monitoring voltage and current and making minor modifications to the load. This allows us to harness the maximum available power from renewable energy sources.

In addition, by referring to the paper “Design and implementation of a new adaptive MPPT controller for solar PV systems” [24] it has said that an adaptive control design is presented for maximum power point tracking (MPPT) in a photovoltaic system (PV). The objective of MPPT is to optimize power delivery to the load by adapting to changes in solar radiation and atmospheric temperature. A new adaptive control framework is proposed to improve MPPT performance, effectively managing uncertainties and disruptions in the PV system and environment while reducing system control complexity. The MPPT algorithm is decoupled from model reference adaptive control (MRAC) techniques to achieve stability in the entire system. The study focuses on the simulation and design of MRAC for MPPT using a boost converter, including the formulation of a mathematical model and the development of an effective MRAC. MATLAB/Simulink is used to evaluate the controller's robustness by comparing it to the state-of-the-art incremental conductance (INC) and perturb & observe (P&O) approaches under various operating conditions. The evaluation metrics include convergence time, monitoring efficiency, PV current and voltage ripple, overall efficiency, and error rates. The proposed controller has an average tracking efficiency of 99.77% and 99.69% under various temperature and radiation conditions, respectively. It achieves a fast MPP capture time of only 3.6 msec, which is approximately ten times faster than INC and twelve times faster than P&O. The MRAC-MPPT scheme also exhibits significantly lower MPP error rates compared to INC and P&O. Simulation results indicate that the presented controller performs exceptionally well under varying circumstances such as solar radiation and temperature.

Renewable energy, such as photovoltaic (PV) power, is vital for generating electricity and has become more important due to fuel shortages and environmental concerns. In the future, PV energy will be even more significant, with over 45% of global energy coming from PV arrays. However, PV systems have low conversion efficiency and the amount of electricity generated changes with weather conditions. This is due to the nonlinear I-V and P-V characteristics of PV systems. To optimize solar cell utilization and ensure the maximum power points (MPPs) of the PV module match the load characteristics, MPPT is necessary. Using MPPT can reduce the cost of energy generated by PV panels. Recently, several techniques have been suggested to track the MPP of PV systems. These methods include the fractional open circuit voltage and short-circuit current, Artificial Neural Network, fuzzy logic control, perturb and observe method (P&O), incremental method (INC), and hill climbing method (HC). Because they are simple and easy to use, these techniques are commonly used in MPPT controllers. Using PSIM and Simulink software, a model of PV module and DC/DC boost converter with the different techniques of MPPTs was utilized. The use of co-simulation between PSIM and Simulink software packages is utilized to establish FLC MPPT technique. The co-simulation is done to utilize each program to handle certain parts of the system. The response of the various MPPT techniques is evaluated in rapidly changing weather conditions. The results indicate that FLC performed the best in both MPPT techniques and P&O, INC, and HC MPPT techniques in both dynamic response and steady state in most of the normal operating range[25].

2.2.3 Point-To-Point Tracking Circuit for TEG Module Performance

Thermoelectric generator (TEG) modules can operate more efficiently when they are connected in a point-to-point tracking circuit. Heat energy can be transformed into electrical energy using a TEG module. It guarantees that the TEG module functions at its maximum power point under a range of load and temperature circumstances by utilizing the point-to-point tracking circuit to the TEG. The voltage and current output of the TEG module are continuously monitored by the circuit. After that, to maximize the output power, it modifies the electrical load. TEG modules enable converting heat into electrical energy and improve the overall performance by tracking its MPP. This is accomplished using complex algorithms and control techniques in the Point-to-Point Tracking Circuit. These algorithms analyze the voltage and current characteristics of the TEG module and adapt the system to maintain the MPP even when the temperature or connected load varies. As a result of implementing the point-to-point tracking circuit, the TEG module may run at maximum power output and boost energy conversion efficiency.

A few researchers have paid attention to the improved MPPT technique for hybrid PV-TEG system. TEGs convert heat to electricity, which is important for utilizing waste heat in industry. PV modules only convert a small portion of solar energy, with the rest being wasted as heat. A PV-TEG system combines the two technologies to improve energy conversion efficiency. MPPT is needed to modify electrical operating points effectively and precisely for optimal power collection. The MPPT technique can improve the generation efficiency from 10 to 15%[19].

To always extract the maximum power from TEG devices, it is also important to track the maximum power point (MPP). This research is aimed at evaluating the effectiveness of dc-dc converters with incremental conductance (IC) method-enabled maximum power point tracking (MPPT). The study compared the results of an IC-based MPPT approach to the results of a P&O-based MPPT approach employed by a previous researcher. The results indicated that while the IC-based approach was able to track the MPP, it had a lower efficiency than the P&O-based approach. The P&O method had a matching efficiency of 99.92%–99.95% in a temperature range of 200 °C–300 °C, while the IC method had a matching efficiency of 99.46%–99.97%. However, the IC method had higher voltage gain and converter efficiency compared to the P&O method. Therefore, using DC-DC converters can improve the steady-state performance of TEG systems and boost voltage to desired levels, leading to overall improved performance of the TEG system [26].

2.2.4 Boost Converter

A power electronic circuit called a boost converter, sometimes referred to as a step-up converter, is used to raise the voltage of a direct current (DC) power source. It is a member of the larger class of devices known as DC-DC converters, which are transformers. The boost converter output must be greater than the input voltage to make sure it functions as well. In a renewable energy system, the output voltage from the source such as TEG, and solar panel is low and not suitable for the specific application. So, by implementing this boost converter, it helps to power up the electric device or charging the batteries.

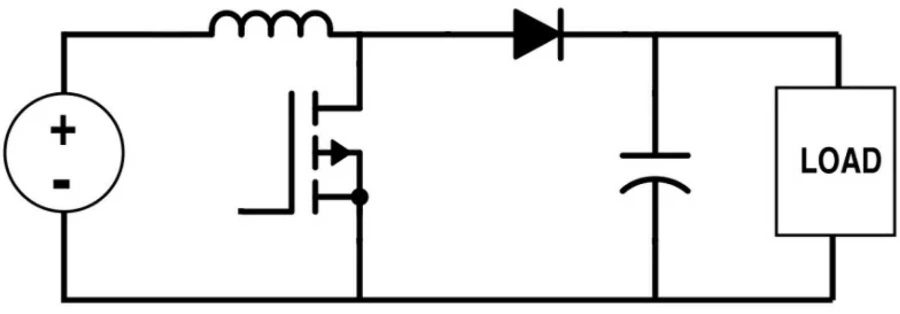


Figure 2.7: The basic component in boost converter circuit.

Figure **2.7** shows the basic component that is usually used in boost converter circuit. It contains inductance, diode, capacitor, and transistor. **Table 2.1** explains the functionality of each component in boost converter circuit.

Table 2.1: Main component of boost converter and it functions.

Component	**Function**
Switch	Controls the flow of current in the circuit by turning it on and off.
Diode	Provides a path for inductor current when the switch is off.
Inductor	Stores energy in its magnetic field during the "on" period and releases it during the "off" period.
Capacitor	Smoothens the output voltage by filtering and storing charge, reducing ripples.

In the context of a thermoelectric generator (TEG) system, a current converter plays a crucial role. TEGs convert thermal energy into electrical energy using the Seebeck effect. The generated electrical energy from the TEG is in the form of a low-voltage and low-current signal, which is not suitable for direct use in most applications. Therefore, a boost converter is employed to amplify or transform the TEG's low-current voltage to a higher current level that can be utilized effectively[27]-[29]. Additionally, the TEG is often combined with the MPPT circuit to optimize the output power of the TEG. The MPPT circuit continuously adjusts the load impedance to operate at the maximum power point (MPP)[30]. Thus, it ensures that the TEG operates at its highest efficiency and extracts the maximum available power from the thermal energy source.

The world's energy demand has increased due to industrialization and population growth. Fossil fuels are near exhaustion and have resulted in harmful greenhouse gas emissions. Recovering waste heat can provide energy for daily needs, especially in transportation. Power electronics have led to high energy-efficient systems like electric vehicles and thermoelectric technology. Thermoelectric generators can convert heat into electric energy and offer low-cost, green energy. However, their efficiency is still low and requires further research to improve their performance. To improve the efficiency of TEG systems, researchers are exploring new TE materials and studying the relationship between TEG devices and heat exchangers. The major challenge for TEG systems is their low efficiency, so it's important to extract the maximum power from them. Power conditioning methods like impedance matching and dc-dc converters can be used to achieve this. Impedance matching balances the internal and external resistances of the TEG system, but it's difficult to achieve without special electronic devices. DC-DC converters with maximum power point trackers (MPPT) help achieve a stable voltage and maximum power output [31].

Energy harvesters convert ambient energy into electrical energy, and thermoelectric energy can be harvested from any structure with a temperature difference between two points. This is done by using a thermocouple that produces a voltage proportional to the temperature difference. However, low-power electronic circuits require at least 1 V DC, which is much higher than the 50 mV DC produced by thermoelectric generators. To solve this, a DC-DC boost converter is used to convert the low voltage to a higher voltage. This is a circuit that takes a lower voltage as input and provides a higher voltage as output. The efficiency of the boost converter is the major design challenge in low-power energy harvesting systems. In this paper, an efficient digital DC-DC boost converter operating in DCM mode is presented. The dead time of the DCM mode is minimized adaptively to improve efficiency, and an active diode circuit is used to prevent the flow of reverse current and reduce power loss. The proposed circuit provides an efficiency improvement of 21% compared to the existing boost converter circuit, with an efficiency of 72.59%[31]

2.2.5 Solar Power Generation

Solar power generation circuits have the functionality to convert sunlight into usable electrical energy. It is basically employed in solar panel systems to harness the power of the sun and provide electricity for several applications. The circuit consists of components such as solar panels (primary component) which are made up of multiple solar cells. It contains photovoltaic material that converts sunlight directly into energy through the photovoltaic process. When sunlight hits the solar panel, the photovoltaic materials within the cells absorb the photons (particles of light), which excite the electrons within the material. This generates a flow of electrons, creating a direct current (DC) electrical output[32].Besides that, to make this DC electrical output useful, the solar power generation circuit also has one important component which is charge controller. It regulates the charging of the batteries or the direct supply of power to electrical loads. This charge controller ensures that the batteries are charged optimally and protects them from overcharging[33]. An inverter, which changes the DC electricity produced by the solar panel into alternating current (AC) electricity, may also be a part of the circuit. The most common type of power used in residential and commercial settings is AC electricity. In general, solar power generating circuit technology allows sunshine to be converted into electrical energy that may be used. It produces DC electricity by harnessing the photovoltaic effect, which can then be processed further by parts like charge controllers and inverters to supply power for a range of uses [34].

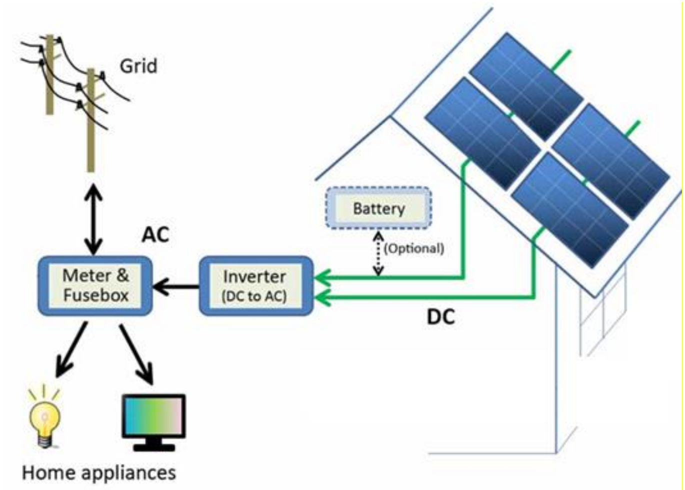


Figure 2.8: Typical grid connected PV solar system.

Figure **2.8** illustrates the typical grid connection with the PV solar system. The solar panel captures the sunlight intensity and stores it in the battery to make produced a stable output. Then, it is connected to the inverter to convert the DC to AC before using it for the home appliances. Difference and Similarities of MPPT Circuit with Solar Power Generation.

2.2.6 Difference and Similarities of MPPT Circuit with Solar Power Generation

The MPPT circuit and solar power generation have related concepts in the field of renewable energy, however they have a different purpose and play distinct roles within solar panel systems. The MPPT circuit is a technology that is used to optimize the output power of solar panels. It continuously monitors and adjusts the operating conditions. The MPPT circuit ensures that solar panels operate at maximum power point by generating the highest amount of electrical power from the available sunlight. The MPPT circuit achieves this by employing advanced algorithms and control techniques to extract the maximum energy from varying weather conditions[34].

In the meantime, solar power generation refers to the overall process of converting sunlight into usable electrical energy. It includes the use of solar panels which are composed of photovoltaic cells that directly convert sunlight into electricity. Solar panels absorb the sunlight and generate DC electrical output through the photovoltaic effect. Then, the DC electricity proceeds to other processes through components like charge controllers and inverters to make it suitable in powering electrical devices and systems.

Moreover, the MPPT circuit and solar power generation are centered on utilizing solar radiation to produce energy. Both circuits use the photovoltaic effect and solar panels to turn solar energy into electrical energy. They contribute to the larger objective of lowering reliance on non-renewable fossil fuels and increasing the use of renewable energy sources. Nevertheless, the primary differences are found in their functions inside the solar panel system. To be more precise, the MPPT circuit maximizes the solar panels' power production to guarantee optimal efficiency[36]. In contrast, solar power generation includes all aspects of energy production from sunshine, such as the use of solar panels and other parts to transform and transfer the electricity generated for practical applications[37].

In summary, the MPPT circuit is a technology that optimizes the power output of solar panels, while solar power generation refers to the broader process of converting sunlight into usable electrical energy. Both concepts contribute to harnessing renewable energy and reducing dependence on non-renewable sources, but they have distinct roles within a solar panel system. The comparison between MPPT circuit and solar power generation can be referred to in **Table 2.2**

Table 2.2: Comparison between MPPT circuit and solar power generation

Aspect	MPPT Circuit	Solar Power Generation
Purpose	Maximizing energy output	Converting sunlight into electricity
Functionality	Adjusts operating point	Converts sunlight into electricity.
Component	Part of the solar power system	Overall process of energy conversion.
Goal	Optimize power output	Generate electrical energy.
Impact	Enhances system efficiency	Reduces reliance on fossil fuels.
Environmental Benefit	Maximizes renewable energy	Minimizes greenhouse gas emissions.
Contribution	Enhances solar panel performance	Utilizes sustainable energy sources.

CHAPTER 3

METHODOLOGY

3.1 General overview

This chapter present the method that used in Improve the performance of TEG. This chapter will cover the approach in designing a suitable circuit to reach the desired output for this project. This chapter started with the flow chart and block diagram for the whole TEG system and followed by experiment setup for objective 1, simulation, experiment setup for objective 2 and the prototype test This chapter contains 2 main parts which are for the simulation process and prototype test. For both parts, a total of four major steps are discussed which includes the TEG configuration, MPPT circuit design, boost converter circuit and combination of full circuit. For the simulation part, software such as MATLAB and Simulink Software, OrCAD and Multisim are used in this thesis.

3.2 Flow chart of overall system

. The process of developing a flowchart for this project is the first step in the methodology and development process of improving the output of thermal energy harvesting for higher level applications. This flowchart is a main guideline for this project because it provides a visual representation of the entire project. It helps to make the project become easier by following the sequence of steps. This flowchart is started by defining the sequence of steps or activities that indicate the logical order in which activities should be completed first. It also acts as project planning because it can break down the complex process into a manageable step and make sure this project can be done in the specific time.

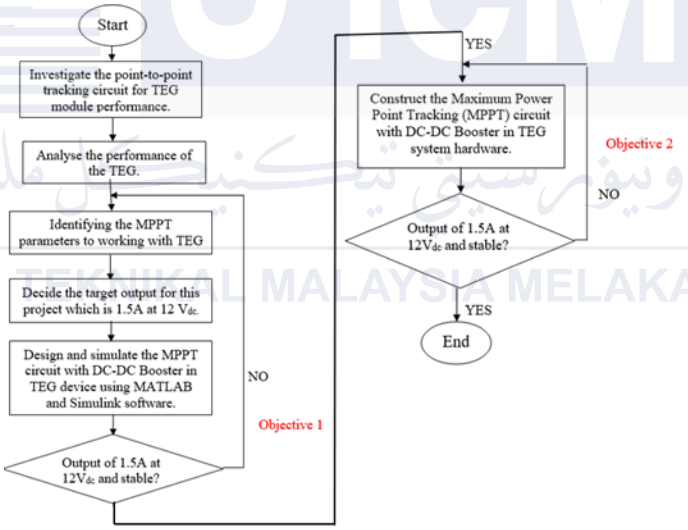


Figure 3.1: Flowchart of the project implementation

Figure 3.1 illustrates the whole process that was used and needed to be done in this project. This flowchart is divided into 2 parts and each part covers the aim for this project. The process of this project started by investigating the point-to-point tracking circuit for TEG module performance. By doing this, Performance of the TEG can be analyzed and used for this project. For this process, the TEG configuration and temperature value also need to be considered as it can affect the TEG output performance. Then, the MPPT parameter such as the algorithm used need to be identified. This is because each of the MPPT algorithms has its own advantages. From these 2 processes, the desired output can be determined before the design and simulation process is done. For this project, the first objective is to achieve the desired output for the whole system is 1.5A at 12V DC, and make sure it is stable to be used. If the desired output cannot be achieved, the identification of the MPPT process will be done again as shown in figure 3.1. Thus, the previous process covered the method to achieve the objective in this project.

Next, objective 2 is to construct the TEG system with additional circuits such as MPPT and boost converter circuit. This process is a continued process from the designing and simulation process. The prototype for this circuit is done when the simulation part is achieving objective 1 for this project. At the end, the circuit will be tested to make sure that desired output is reached and if it did not reach the desired output level, the circuit will be constructed again such as shown in **Figure 3.1**

3.3 Block diagram

Block diagram is used to provide a system of process that be used in this project. It offers an overview of the component and its connections. In this project, there are 3 main components which are TEG module, MPPT circuit and boost converter circuit. These 3 components have owned their task in this project as shown in **Table 3.1**

Table 3.1: The component and its functionality

Component	Functionality
TEG module	Act as a supply for this project.

MPPT	Track the maximum power tracking that has produced from the supply and optimize the energy by adjusting the operating point of the supply.
Boost converter	Boost the output voltage to a higher level from the input voltage.

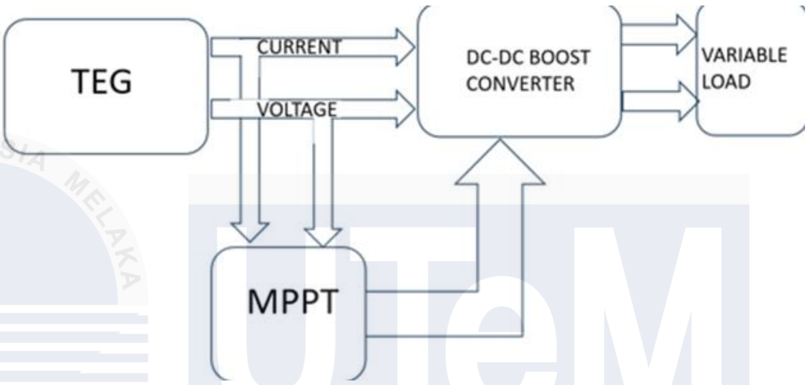


Figure 3.2: Bock diagram of project implementation

Figure **3.2** illustrates the connection between the circuit connection that was used in this project. This project utilized the TEG as a supply. This TEG module converts heat from waste heat to electricity from the temperature difference between two TEG plates which is hot and cold side[38]. This module implies the Seebeck effect and generates electricity[39], [40]. However, the TEG module generates the low output, and it needs this additional circuit to make sure it can be used to increase the output performance and its efficiency for higher level usage. The implementation of additional circuits such as MPPT and boost converter in TEG system can increase the overall performance and its efficiency.

The MPPT helps to optimize the energy harvesting by adjusting the operating point of the supply. It helps to maximize the power output. In this project the current and voltage from the TEG is send to MPPT to make sure it can track the maximum power that has generated from the TEG[38], [41] . The other advantages of this MPPT are straightforward implementation, easy to install and small size[42]. In addition, the boost converter increases the output voltage for the higher-level usage application. It maintains high energy efficiency while minimizing the loss during the voltage conversion process[43].

3.4 Experimental setup for objective 1

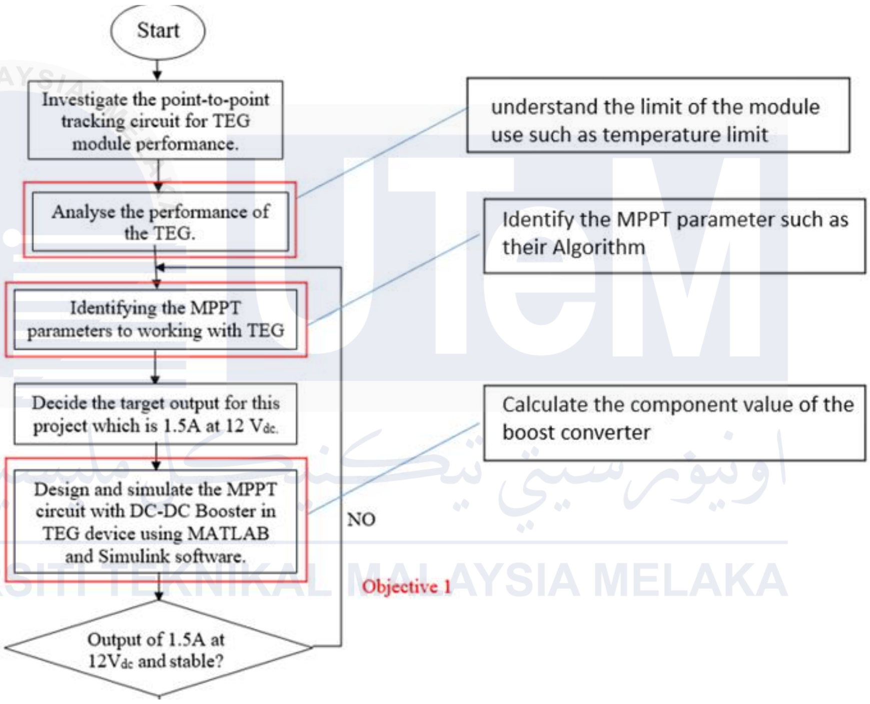


Figure 3.3: Flowchart for objective 1

In this project, objective 1 is focused on the simulation of the MPPT performance circuit integration to increase the output performance of the TEG system. The flowchart in Figure **3.3**explains the process to achieve objective 1.

3.4.1 TEG performance

First, the point-to-point tracking circuit for TEG module performance was investigated. The aim is to optimize the power output, improve the efficiency, adapt to changing conditions, ensure long-terms stability and protect the TEG module by not exceeding its limit. This TEG was chosen by referring to their datasheet. In this project, TEC-12706 module was chosen. The datasheet for this module can be referred in **Table 3.2**[44]. This module was chosen because in this project the Hot side temperature used in range 100°C to 150°C and the cold temperature is 0°C to 60°C. Then, TEG’s performance is examined. The purpose of the analysis is to comprehend the module's limits, including the temperature limit. Overstepping the limit increases the risk of damage to the TEG module, which affects the entire system.

Table 3.2: TEC-12706 technical specification

Properties	**Value**
Max Hot side temperature, T_h	138°C
Max cold side temperature, T_c	-17°C
Max voltage	16.4V
Matching load output current	6.4 A
Matching load output power	60W
Seebeck coefficient	53mV/K
Load matching resistance, R_{IN}=R_L	1.98 – 2.30Ω
Length (mm)	40
Width (mm)	40
Thickness (mm)	3.9

3.4.2 MPPT algorithm selection

Then, the MPPT parameter in TEG system was then identified. The crucial parameter for MPPT is their algorithm. MPPT has a several algorithms and each algorithm has its own advantages and disadvantages. Here are several the example of MPPT algorithm:

1. Perturb and Observe (P&O) Algorithm
2. Model Predictive Control (MPC)
3. Incremental Conductance Algorithm

4. Hill Climbing Search

5. Fractional Open-Circuit Voltage (FOCV)

6. Hill Climbing Search

However, the selection of MPPT algorithm can be considered from a several aspects which are system dynamic to consider characteristics of the renewable energy and how it behaves under different conditions, cost, and complexity of the MPPT circuit. Simple algorithms usually are cost effective and easy to implement while the more advanced the algorithm, the cost and complexity of system might increase.

	MPPT ALGORITHM USED						
Journal	Perturb and Observe (P&O)	Incremental Conductance (INC)	Fractional Open Circuit Voltage (FOCV)	Constant Voltage (CV)	Hill Climbing	Artificial Intelligence (AI)-based Algorithms	Advantage
Review on Comparison of Various Maximum Power Point Tracking Algorithms,2018 by Risha singh, Richie Sharma, Priti	✓ ✓		✓	✓			- The most widely used MPPT control Techniques - simple implementation
Conventional and Soft-Computing Based MPPTMethods Comparisons in Direct and Indirect Modes for Single Stage PV Systems, 2018 by Ekrem Kandemir, Selim Borekci , Numan Sabit Cetin	✓ ✓	✓ ✓				✓	- Convergence speed to reach MPP: Indirect mode faster than direct mode for ideal environment condition. The convergence speed is 2.38 times faster for P&O. - Tracking accuracy: direct mode>indirect mode P&O = increase 2.8% INC = increase 3.1 %
Review on MPPT Techniques in Solar System 2022 by Ali Jawad, Ameer Khan, Suhair Hussein, Imran Mousa.	✓	✓	✓ ✓			✓ ✓	High Tracking accuracy: artificial intelligence. Inexpensive Cost implement: FOC Simple complexity to tuning: FOC
Comparison between neural network and P&O method in optimizing MPPT control for photovoltaic cell 2019 by Ahmed G. Abdullah, Mothanna Sh. Aziz, Bahar A. Hamad	✓					✓ ✓	ANN scheme can give fast track the MPP under steady state and very small peak overshot is noted when sudden varying in irradiation or temperature happen, ANN has very small oscillation around MPP, while very high oscillation is noted in P&O method, this is increase in power losses
Analysis and comparison of PV Array MPPT technique to increase output power 2021 by Ritu Singh, Rakesh Yadav, Dr. Lokesh Varshney	✓ ✓	✓	✓ ✓			✓ ✓	Efficiency: fuzzy logic controller Speed: fuzzy logic controller Cost: FOCV Low Complexity: P&O, FOCV
Comparison of Different MPPT Control Strategies for Solar Charge Controller 2020 by Parag K. Atri, P.S. Modi, Nikhil Shashikant Gujar	✓ ✓	✓ ✓	✓				Low Complexity: P&O, FOCV Fast Coverage Speed: INC Efficiency: INC

Figure 3.4: A review on MPPT algorithm

Nonetheless, parameters such as MPPT algorithm were chosen in this project. This project uses Perturb & Observe algorithm for the MPPT circuit. This is because P&O was easy to implement. The selection of this algorithm is chosen after many papers have been reviewed such as show in Figure **3.4**. The targeted output for this project was 1.5A at 12Vdc.

3.4.3 Boost converter circuit

Then, after the selection of the MPPT algorithm, the boost converter is needed to step up the voltage in this TEG system. The design of this boost converter starts from determining all the parameter used such as in **Table 3.3** and based on the boost converter formula. The aim is to find the component value such as inductance and capacitance value.

Table 3.3: Parameter and its value

Parameter	**value**
Voltage supply, Vs	5V
Voltage output, Vo	12V
Current Output, Io	2A
Switching frequency, f	50kHz
$\Delta Vo/Vo$	0.01

$$D = 1 - \frac{Vs}{Vo} \tag{3.1}$$

$$Vo = Io \ x \ Ro \tag{3.2}$$

$$Lmin = \frac{D(1-D)^2 R}{2f} \tag{3.3}$$

$$L = 2Lmin \tag{3.4}$$

$$C \geq \frac{D}{R(\Delta Vo/Vo)f} \tag{3.5}$$

First, the duty ratio can be calculated by substituting the value Vs and Vo in the (3.1. From that formula, the value of the duty ratio is 0.583. Next, the value of the Ro can be calculated by substituting the value of Vo and Io into (3.2. The value of Ro is 6 ohms. Afterward, the calculation value of inductance is 12.17uH after referring to the (3.3 and (3.4. Then, value of capacitance is calculated by referring to (3.5 and it is 194.33uF. All the calculation values are recorded in **Table 3.4**

Table 3.4: calculation value

Parameter	**value**
Duty cycle, D	0.583
Output resistor, Ro	6Ω
Inductance value, L	12.17uH
Capacitance value, C	194.33uF

3.5 Simulation

This process or method helps the project by imitating and modelling the operation of real-world systems over time. Simulation provides the experiment analysis. So, it helps to test the hypothesis and analyze the impact of different variables. It allows us to evaluate the output result before the process of prototype is done. This process use includes modern tools which are MATLAB and Simulink software, Mult., and OrCAD. This software is used in this project to design and simulate the circuit for TEG system.

3.5.1 TEG Configuration

Before starting to design the full system of TEG system, it is important to identify the available resources such as component datasheet, the material used and the configuration. For this part, it started by determining the value for the TEG properties and its configuration which are in series or parallel condition. First, the TEG properties such as hot and cold temperature are selected as shown in **Table 3.5**. Then, the value for TEG module needs to be chosen before deciding it configuration. For this project, the number of TEC-12706 modules used is 4 modules. This decision to use 4 modules resulted in a 5 configuration of TEGs which are 1 TEG, 2 Series TEG, 2 Parallel TEG, 4 Parallel TEG, 2 TEG Parallel with 2 TEG. Then, from this configuration and the TEG parameter, the MATLAB and Simulink Software is used to simulate their Output performance. The result and analysis for this part can be referred to in 4.2.1.

Table 3.5: TEG parameter selection

PROPERTIES	VALUE
HOT SURFACE TEMPERATURE, Th	130°C
COLD SURFACE TEMPERATURE, Tc	30°C
SEEBECK COEEFICIENT	53 mV/K
THERMAL RESISTANCE	1.95 K/W
LOAD MATCHING RESISTANCE, RIN = RL	1.98 – 2.30 Ω
LENGTH (MM)	40
WIDTH (MM)	40
THICKNESS (MM)	3.9

3.5.2 MPPT circuit design

The MPPT circuit design is started by selecting the algorithm first. In this project, the MPPT algorithm used is the Perturb & Observe algorithm. This algorithm was chosen because it is simple to design and effective for many applications. The concept and flow of this algorithm need to be understood first. So, this MPPT can have a very good impact on the TEG system.

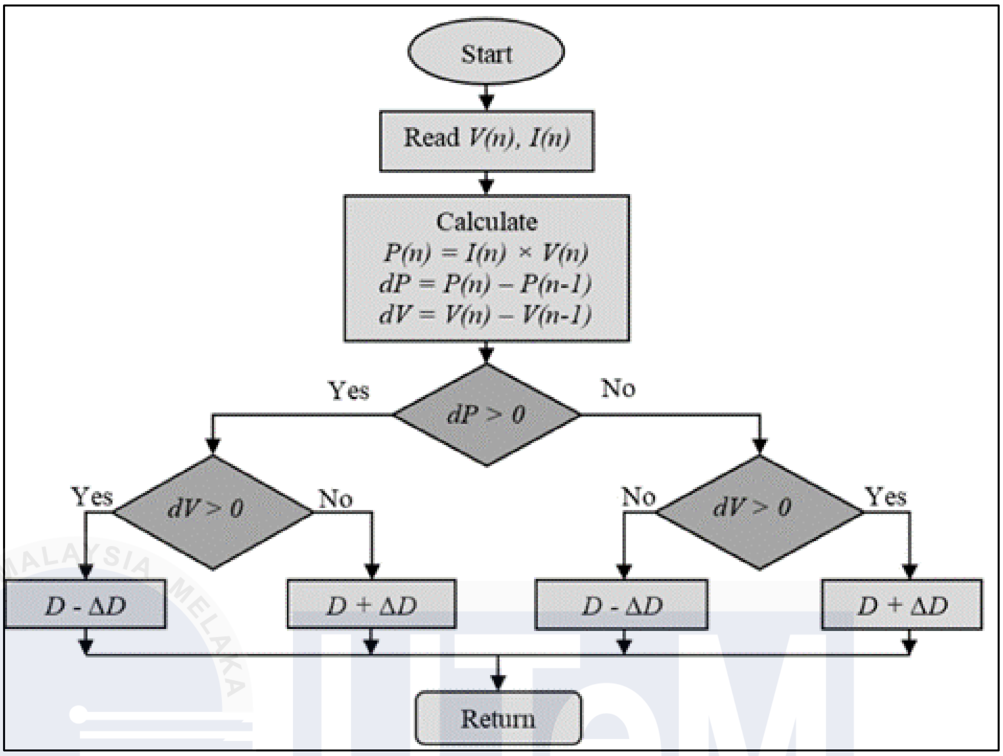


Figure 3.5: Perturb & Observe algorithm.

Figure **3.5** illustrates the Perturb & Observe algorithm flow and process. The P&O approach is typically employed to track the MPP. This method introduces a small disturbance to cause the PV module's power to fluctuate. Periodically, the PV output power is measured and contrasted with the preceding power. The same procedure is followed if the output power rises. Otherwise, the perturbation is reversed. The PV module or the array voltage is perturbed by this technique. To determine whether the power is increasing or decreasing, the voltage of the PV module is changed. The PV module's operating point is on the left of the MPP when a rise in voltage results in an increase in power[45]. Therefore, to accomplish MPP, more disturbance is needed in the right direction. On the other hand, if a rise in voltage results in a fall in power, this indicates that the PV module's operating point is to the right of the MPP and that additional disturbance to the left is necessary to reach the MPP. This MPPT circuit was designed and simulated by using MATLAB and Simulink Software is used to simulate their Output performance. The result and analysis for this part can be referred to in 4.2.3.

3.5.3 Boost converter circuit

Next, the boost converter circuit is used to increase the output voltage. This circuit helps to step up the voltage in the TEG system. So, it is suitable for higher level usage applications. Based on 3.4.3, the component value is calculated and recorded in **Table 3.4**. By referring to this value, the simulation for the boost converter can be done. For this project, the boost converter was simulated by using the OrCAD and Multisim software and the result and analysis for this part can be referred to in 4.2.2

3.5.4 Combination of full circuit

The TEG module and additional circuit are combined into 1 system. This system is the final system for this project. It contains TEG, MPPT and boost converter circuit. This system will be used to charge the Li-ion battery. The aim of the battery is to make sure the output performance of the system is stable before it can be used for the higher application. This simulation for the TEG system was simulated by using the MATLAB and Simulink software and the result for this part can be referred to in 4.2.4

3.6 Experimental setup for objective 2

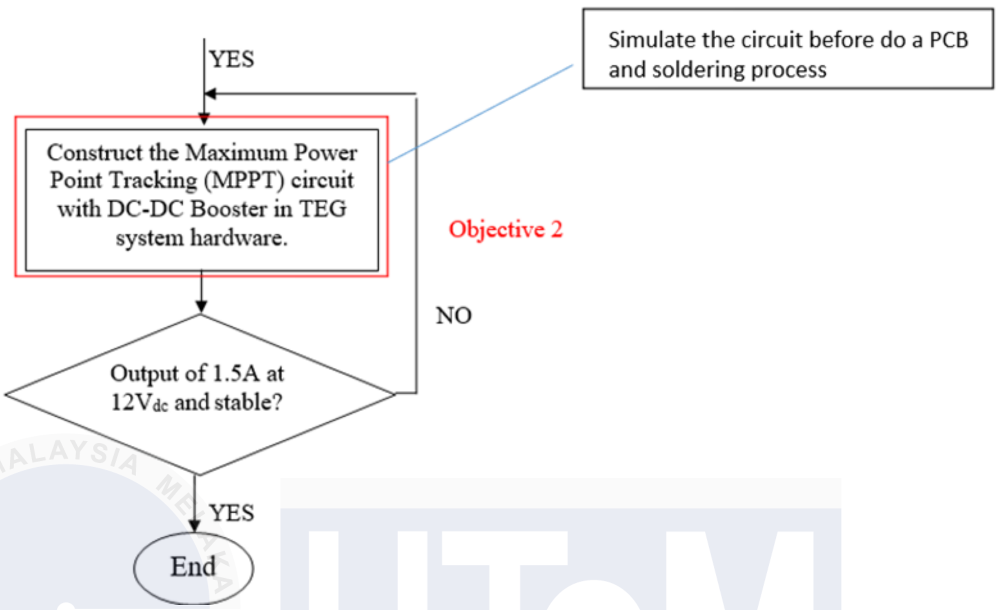


Figure 3.6: Flowchart for objective 2

Figure **3.6** illustrates the flowchart for objective 2 in this project. Objective 2 is the continuous from objective 1. However, Objective 2 is focused on the hardware construction of the MPPT circuit with Dc-Dc booster in TEG system. This system will be constructed again if it does not achieve the desired output performance for this project, which is 1.5A and 12 V DC.

3.7 Prototype Test

This process or method helps the project by constructing the model or product. This prototype is the evidence to validate and prove the concept that was used in a project. By constructing the model or prototype, it can verify the functionality of the system. For this project, the TEG system has been constructed into a prototype.

3.7.1 TEG Configuration

For the prototype test, the parameters such as Hot side and cold side temperature were selected as shown in **Table 3.6: TEG parameterTable 3.6**. The source for the hot side is dry iron and for cold side is water in room temperature. Since there are 5 configurations of TEG, all the configuration has been tested and the result is recorded in 4.3.1.

Table 3.6: TEG parameter

Hot Side, T_h (°C)	125 - 135
Cold Side, T_c (°C)	30 - 35
Max Temperature Difference, T_d (°C)	105

3.7.2 MPPT circuit design

Based on the simulation part, the MPPT circuit for this project is replaced by the module with the same algorithm. The reason for choosing the module is because of its efficiency and reliability. The existing MPPT modules are designed to operate under a variety of conditions that have been validated in real world scenarios. For this project, the MPPT module use is CN3791.

3.7.3 Boost converter circuit

From the previous part of the simulation, the boost converter has been constructed and PCB. However, the construct circuit just functions when the input supply meets the requirement such as mentioned in calculation part. For example, when the input voltage and current does not reach the requirement, the circuit cannot function well. So, to overcome this problem, the boost converter circuit module was used. For this project, the module was XL6009. However, the selection to use this converter is also good because the output can be adjusted since it has adjustable voltage step up level.

This converter input has been set up to fulfill the requirement of the MPPT module output.

3.7.4 Combination of full circuit

The prototype for the whole TEG system is TEG module, MPPT module CN3791 and boost converter module XL6009. This module relates to each other to make sure the system is complete. Then, this prototype for the whole TEG system is tested and the result has been recorded in 4.3.3

CHAPTER 4

RESULTS AND DISCUSSION

4.1 General overview

This chapter consists of 2 main sections which are simulation and prototype test. for both topics, it has four sections covering TEG configuration selection outcomes for both series and parallel configuration, voltage incremental outcome, the maximum power point tracking (MPPT) outcome, and prototype utilization by users. It summarizes the significant finding related to the TEG output, and the comprehensive evaluation and analysis conducted.

4.2 Simulation

This part is related to the result for the simulation test by using modern tool software such as MATLAB, Simulink, OrCAD, and Multisim. It consists of 4 subtopics which are TEG configuration outcomes, Voltage incremental outcome, maximum power point tracking (MPPT) outcome, and overall, TEG system outcome.

4.2.1 TEG configuration Outcomes

In this section, it reflects the content about the result for configuration of the TEG. The Voltage and Current in this thesis were generated by Thermoelectric Generator (TEG) which is TEC-12706. A thermoelectric generator is a device or component that can convert heat directly into electrical energy by using the Seebeck effect. The output of this TEG depends on several factors such as the temperature difference and TEG configuration. For this project, the number of TEG modules used was 4. So, it will produce 5 configurations such as mentioned in 3.5.1Therefore, this configuration of TEG is decided to be manipulated variable and temperature difference as a constant variable. As mentioned in the previous chapter, this parameter as shown in **Table 4.1**was used for this part. The detailed result for each part can be referred to in the own subtopic.

Table 4.1: The TEG parameter used in simulation.

PROPERTIES	VALUE
HOT SURFACE TEMPERATURE, Th	130°C
COLD SURFACE TEMPERATURE, Tc	30°C
SEEBECK COEEFICIENT	53 mV/K
THERMAL RESISTANCE	1.95 K/W
LOAD MATCHING RESISTANCE, RIN = RL	1.98 – 2.30 Ω
LENGTH (MM)	40
WIDTH (MM)	40
THICKNESS (MM)	3.9

The detailed result for each part of TEG configuration can be referred to in their own subtopic that start from 4.2.1.1 to 4.2.1.5. Based on the overall analysis for the TEG configuration such as shown in **Table 4.2**, it shown that the TEG configuration effect the output voltage and output current. From **Table 4.2**, we can analyze that the current increase when the TEG is in a parallel configuration while the Voltage is increase when the TEG is in series configuration. This result is approved the Kirchoff voltage and current law[46].

Kirchoff Voltage Law (KVL) stated that the sum of voltage drops around any closed loop is equal to the total voltage drops around that loop. The idea of energy conservation is the basis of this law. According to this, the total energy injected into a closed loop and the total energy released within the loop are equal. So based on the result in **Table 4.2**it approved this concept by showing that voltage is increase when the TEG is in series condition.

Kirchhoff's Current Law (KCL) states that the total current entering a junction (or node) in a circuit is equal to the total current exiting the junction. KCL is based on the principle of the conservation of electric charges. It implies that the total charge entering a junction is equal to the total charge leaving the junction. So based on the result in **Table 4.2** it approved this concept by showing that current is increase when the TEG is in parallel condition.

Therefore, to achieve the desired output for this project, which is 1.5A at 12V DC, the configuration of 2 TEG parallel with 2 TEG is the best choice. This is because this configuration generates more current. To step up the current is more challenging than voltage. As current increases, the voltage drops across conductors and components also increases due to their inherent resistance. This can lead to undesired losses and affect the efficiency of the system. Stepping up the voltage is more straightforward because voltage can be raised through passive components like transformers without necessarily raising current.

Table 4.2: Comparison between TEG Configurations

CONFIGURATION	V_{OUT} **(V)**	I_{OUT}**(A)**	P_{OUT}**(W)**
1 TEG	2.65	1.152	3.053
2 SERIES TEG	5.3	1.152	6.107
2 PARALLEL TEG	3.533	1.536	5.428
4 SERIES TEG	10.6	1.152	12.21
2 TEG PARALLEL 2 TEG	7.067	1.536	10.56

4.2.1.1 1 TEG configuration

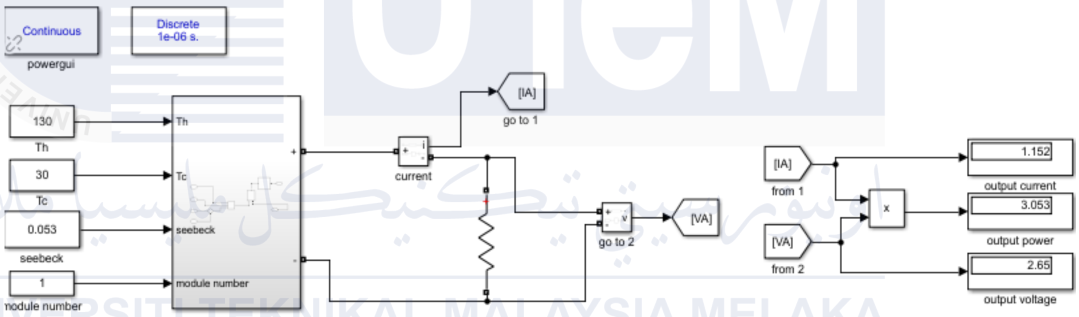


Figure 4.1: Simulation result for 1 TEG configuration

Figure **4.1** shows the simulation for 1 TEG configuration. The result shows that the 1 TEG with the specification in **Table 4.1**generated 2.05V and 1.152A with the power 3.063W. It is quite impressive that TEG can generate power from just using the heat.

4.2.1.2 2 Series TEG configuration

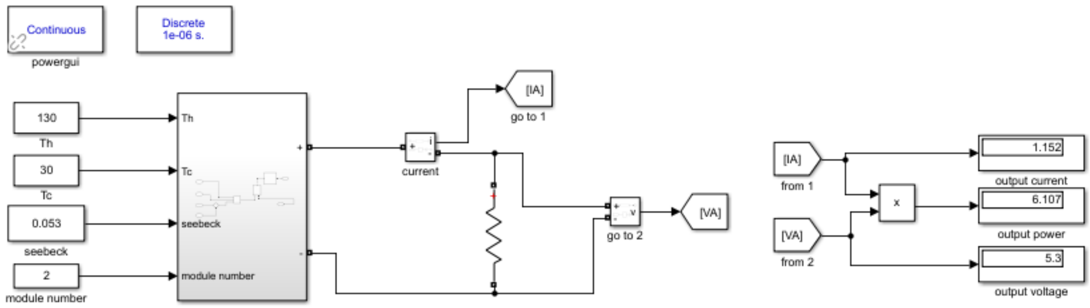


Figure 4.2: Simulation result for 2 series TEG configuration

Figure **4.2** shows the simulation for 2 series TEG configuration. The result shows that the 2 series TEG with the specification in **Table 4.1**generated 5.3V and 1.152A with the power 6.107W.

4.2.1.3 2 Parallel TEG configuration

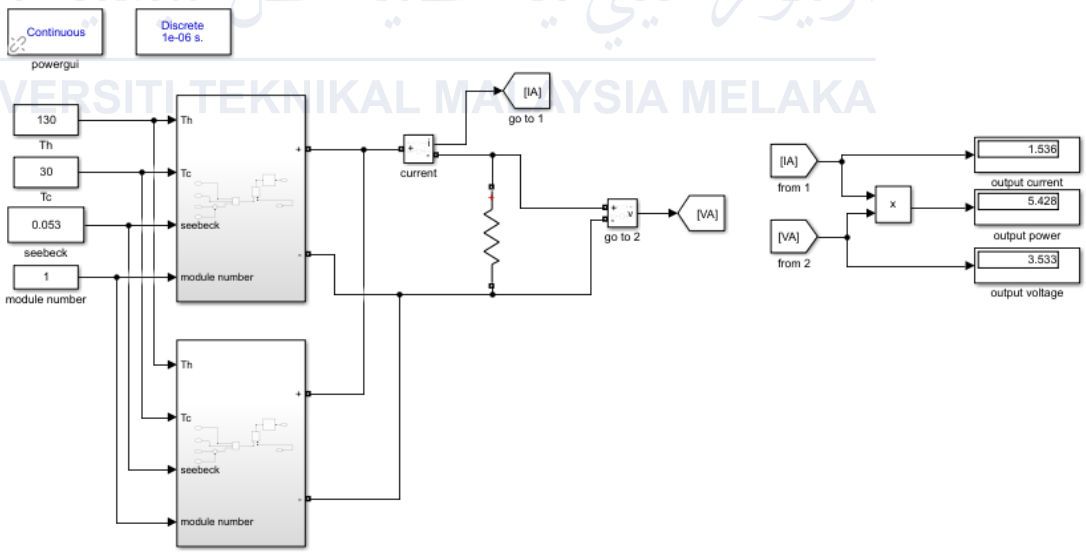


Figure 4.3: Simulation result for 2 parallel TEG configuration

Figure **4.3** shows the simulation for 2 parallel TEG configurations. The result shows that the 2 parallel TEG with the specification in **Table 4.1** generated 3.533V and 1.536A with the power 5.428W.

4.2.1.4 4 Series TEG configuration

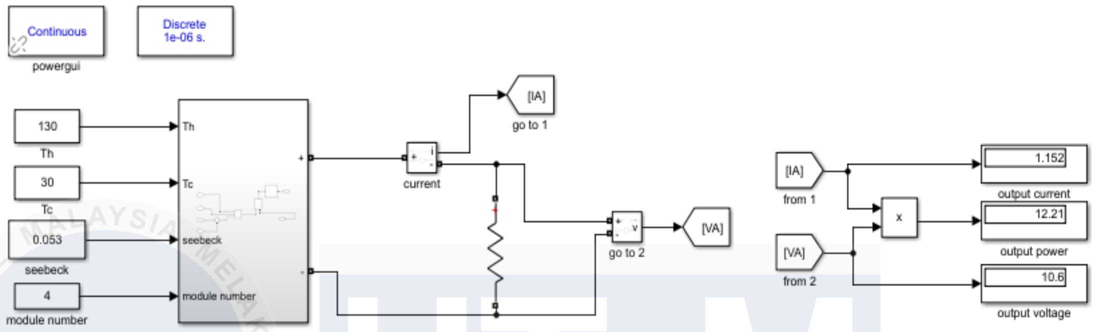


Figure 4.4: Simulation result for 4 series TEG configuration

Figure **4.4**shows the simulation for 4 series TEG configuration. The result shows that the 4 series TEG with the specification in **Table 4.1**generated 10.6V and 1.152A with the power 12.21W.

4.2.1.5 2 TEG Parallel with 2 TEG configuration

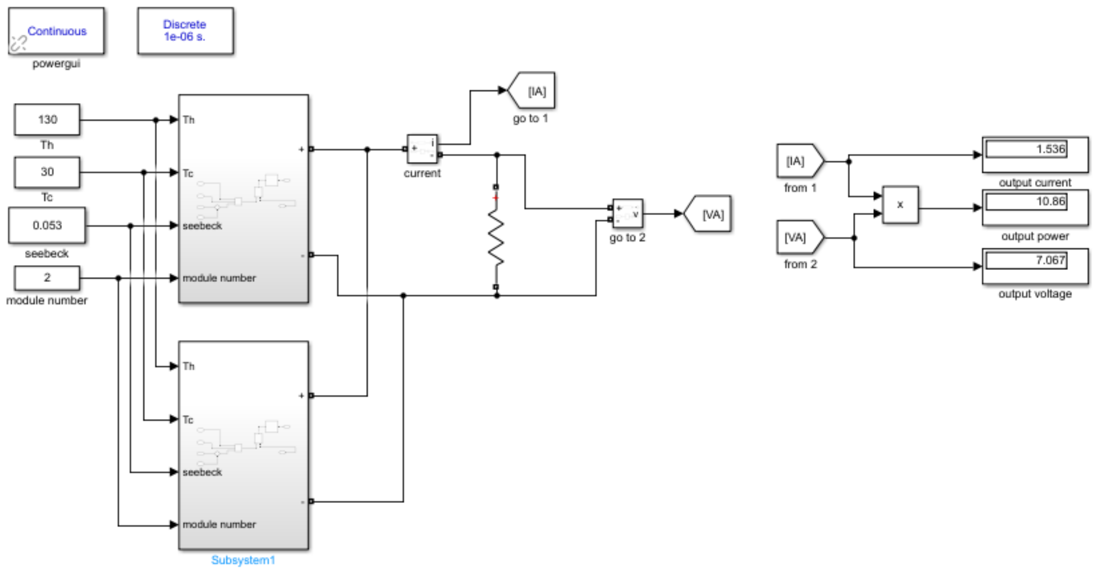


Figure 4.5: Simulation result for 2 TEG parallel with 2 TEG configuration

Figure **4.5**show the simulation for 2 TEG parallel with 2 TEG configuration. The result shows that the 2 TEG parallel with 2 TEG configuration with the specification in **Table 4.1** generated 7.067V and 1.536A with the power 10.56W.

4.2.2 Voltage incremental Outcomes

This subtopic discusses the outcomes of the simulation of boost converter. Based on the calculation in chapter 3, the simulation for this part has been done by using Multisim software. The result for this part is recorded in **Table 4.3**

Table 4.3: Multisim result for boost converter

	Input	Output
Voltage (V)	5V	8.05V
Current (A)	1.63A	1.34A
Power (W)	8.15W	10.747W

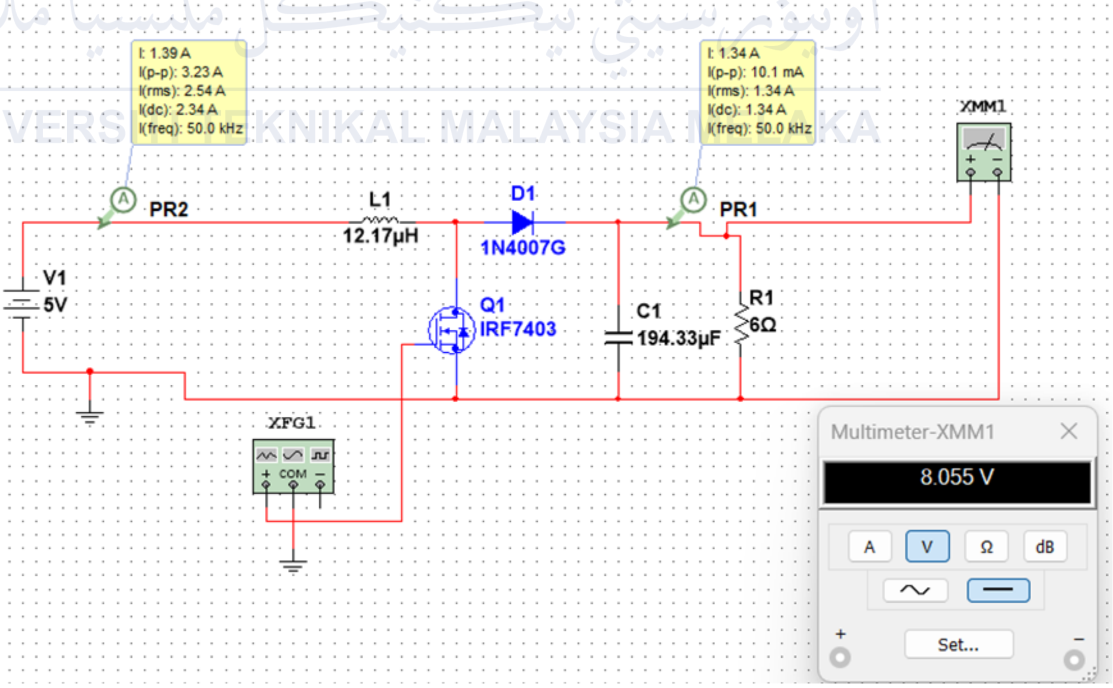
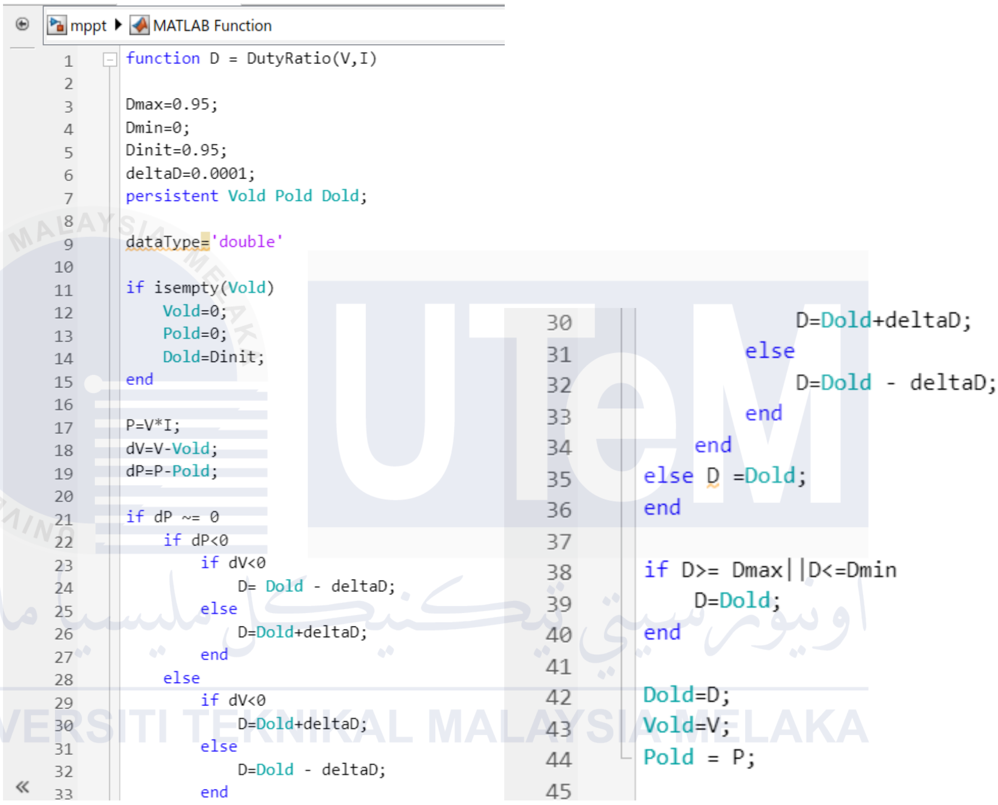


Figure 4.6: Simulation for boost converter in Multisim software

Figure **4.6** shows the Simulation for boost converter in Multisim software. To measure the voltage, the multimeter must connect in parallel with the load and to measure the current, the multimeter must connect in series with the load.

4.2.3 Maximum power point tracking (MPPT) outcome



```
mppt ▸ MATLAB Function
function D = DutyRatio(V,I)

Dmax=0.95;
Dmin=0;
Dinit=0.95;
deltaD=0.0001;
persistent Vold Pold Dold;

dataType='double'

if isempty(Vold)
    Vold=0;
    Pold=0;
    Dold=Dinit;
end

P=V*I;
dV=V-Vold;
dP=P-Pold;

if dP ~= 0
    if dP<0
        if dV<0
            D= Dold - deltaD;
        else
            D=Dold+deltaD;
        end
    else
        if dV<0
            D=Dold+deltaD;
        else
            D=Dold - deltaD;
        end
```

```
            D=Dold+deltaD;
        else
            D=Dold - deltaD;
        end
    end
else D =Dold;
end

if D>= Dmax||D<=Dmin
    D=Dold;
end

Dold=D;
Vold=V;
Pold = P;
```

Figure 4.7: The MPPT code for the P&O algorithm

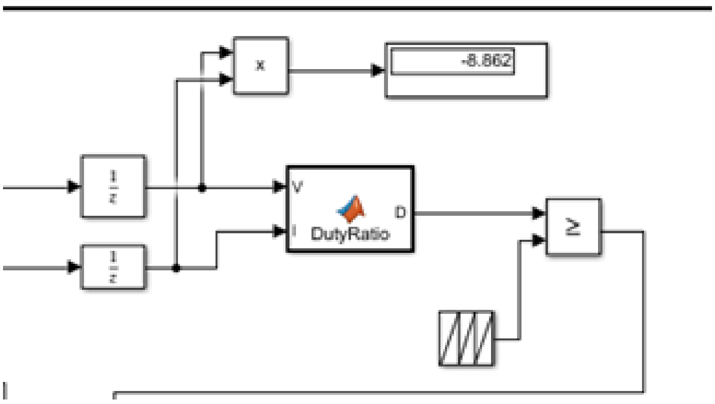


Figure 4.8: The MPPT circuit for the 2 TEG parallel with 2 TEG configuration

Figure 4.7 shows the MPPT code for the P&O algorithm. This MPPT circuit, as shown in Figure **4.8** is connected to TEG. The aims are to make sure it can optimize the performance of the whole system, especially from the TEG input. So, the overall system can be at higher performance.

4.2.4 TEG system Outcome

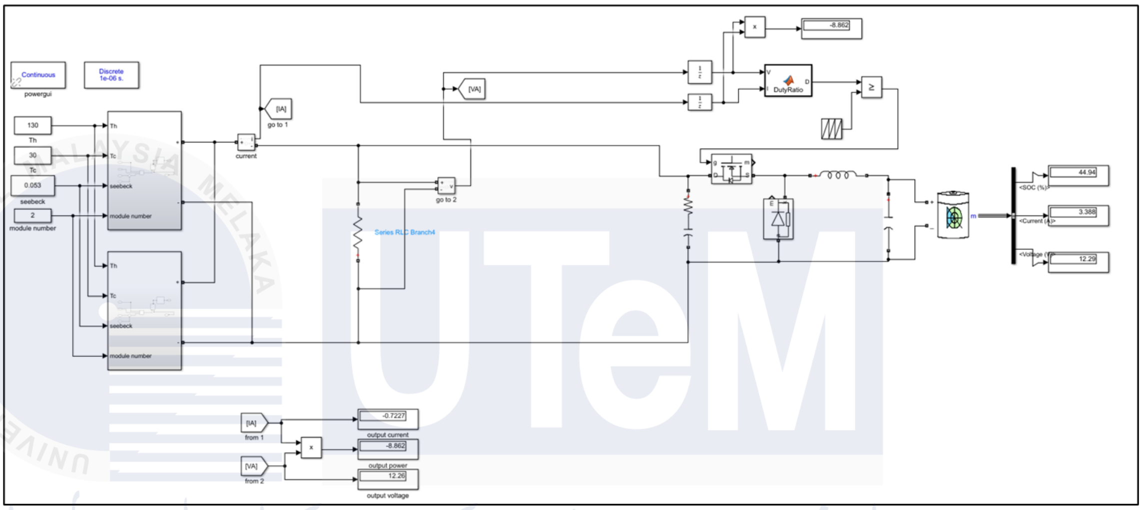


Figure 4.9: Simulation for overall TEG system outcome

Figure **4.9** shows the simulation for overall TEG system outcome. This overall system is a connection between TEG, MPPT and boost converter. The input from the TEG is low which can be referred in **Table 4.4**. So, by implementing these 2 additional circuits, it can help the overall performance of the TEG system. The output from the boost converter is connected to the battery. This is because this system will be used to charge a battery before going to user. By doing this, the output can be stable to use for higher application usage such as charging a phone. However, in this simulation, many factors are not to be considered such as temperature for hot and cold side of TEG. in simulation this temperature can be control and the value is fixed but for the practical this temperature value is little bit hard to control. For example, the cold side will become hot after a few minutes cause of the heat transfer, but this scenario does not occur in the simulation. Therefore, the result for simulation and practical test may be slightly different to each other.

Table 4.4: Result for overall TEG system

	Input	Output
Voltage (V)	12.26	12.29V
Current (A)	0.7227	3.38A
State of charge (SOC)	-	49.44%

4.3 Prototype test

This part is related to the result for the prototype test by constructing the circuit using the TEG module (TEC-12706), MPPT module (CN3791) and boost converter module (XL6009). It consists of 4 subtopics which are TEG configuration outcomes, Voltage incremental outcome, maximum power point tracking (MPPT) outcome, and overall, TEG system outcome.

4.3.1 TEG configuration Outcomes

In this section, it reflects the content about the result for configuration of the TEG. The Voltage and Current in this thesis were generated by Thermoelectric Generator (TEG) which is TEC-12706. This TEG module has been tested by using iron at the hot side and water at the cold site indicate a difference temperature. So, the Seebeck effect can occur, and the electricity can be generated from the heat. **Table 4.5**shows the TEG parameter that was used for the testing process. The part has tested all the TEG configuration. This specific test for each configuration can be referred to in their own subtopic.

Table 4.5: The TEG parameter used in simulation.

PROPERTIES	VALUE
Hot surface temperature, Th	125-135°C
Cold surface temperature, Tc	30-31°C
Max Temperature difference, T_d (°C)	105

Based on the overall analysis for the TEG configuration such as shown in **Table 4.6**. It shown that the TEG configuration effect the output voltage and output current. From **Table 4.2**, we can analyze that the current increase when the TEG is in a parallel configuration while the Voltage is increase when the TEG is in series configuration. This result is approved the Kirchoff voltage and current law[46].

Table 4.6: Result for the TEG module configuration

CONFIGURATION	V_{OUT} (V)	I_{OUT}(A)	P_{OUT}(W)
1 TEG	0.8	0.75	0.6
2 SERIES TEG	1.25	0.10	0.125
2 PARALLEL TEG	0.15	0.25	0.037
4 SERIES TEG	9.59	0.77	7.38
2 TEG PARALLEL 2 TEG	6.0	1.45	8.7

Kirchoff Voltage Law (KVL) stated that the sum of voltage drops around any closed loop is equal to the total voltage drops around that loop. The idea of energy conservation is the basis of this law. According to this, the total energy injected into a closed loop and the total energy released within the loop are equal. So based on the result in **Table 4.2** it approved this concept by showing that voltage is increase when the TEG is in series condition. Meanwhile, Kirchhoff's Current Law (KCL) states that the total current entering a junction (or node) in a circuit is equal to the total current leaving the junction. KCL is based on the principle of conservation of electric charge. It implies that the total charge entering a junction is equal to the total charge leaving the junction. So based on the result in **Table 4.2** it approved this concept by showing that current is increase when the TEG is in parallel condition.

Therefore, the arrangement of 2 TEG parallel with 2 TEG is the optimum alternative to obtain the needed output for this project, which is 1.5A at 12V DC. This is because of the setup producing higher current. It is more difficult to step up current than voltage. Due to the intrinsic resistance of conductors and components, as current increases, so do the voltage drops across them. This may result in unintended losses and have an impact on the system's effectiveness. Because passive components like transformers can raise voltage without necessarily raising current, stepping up the voltage is simpler.

4.3.1.1 1 TEG configuration

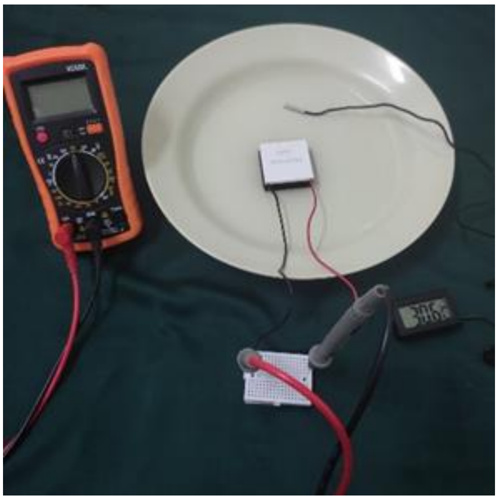


Figure 4.10: Initial condition before measurement

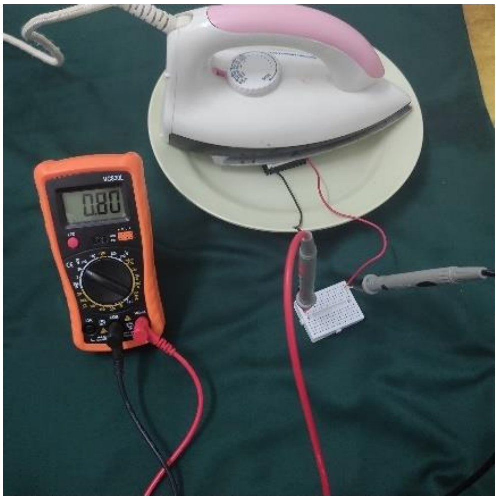


Figure 4.11: Voltage measurement

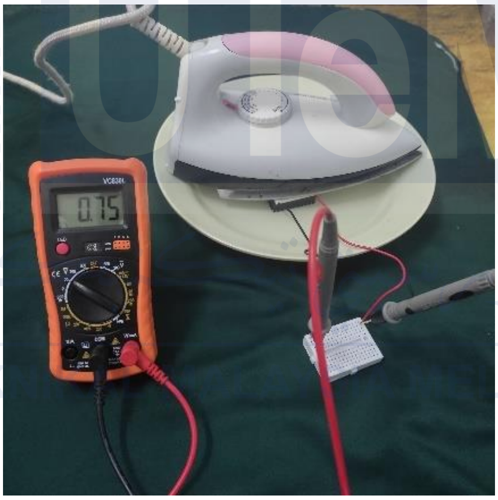


Figure 4.12: current measurement

Figure **4.10** visualizes the initial condition for prototype measurement. Figure **4.11** depicts the TEG voltage measurement and Figure **4.12** illustrates current measurement from the TEG. This voltage was measured by aligning the multimeter probe parallel to the Thermoelectric Generator (TEG) while the current was measured accurately by aligning the multimeter probe series to the Thermoelectric Generator (TEG). based on the measurement 1 TEG with the specification in **Table 4.5** generated 0.8V and 0.75A with the power 0.6W such as shown in **Table 4.7**.

Table 4.7: Output result for 1 TEG configuration

Voltage Output V_o (V)	0.8
Current Output I_o (A)	0.75
Power Output P_o (W)	0.6

4.3.1.2 2 series TEG configuration

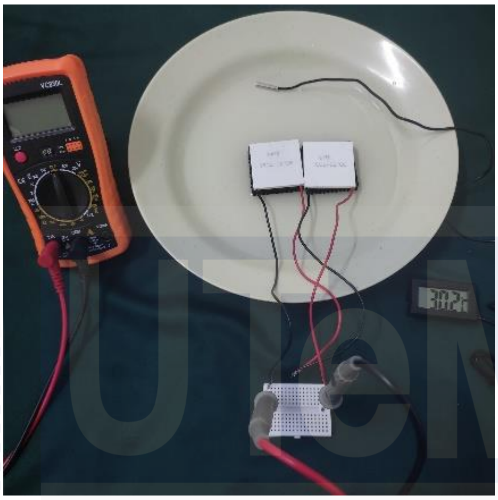


Figure 4.13: Initial condition before measurement

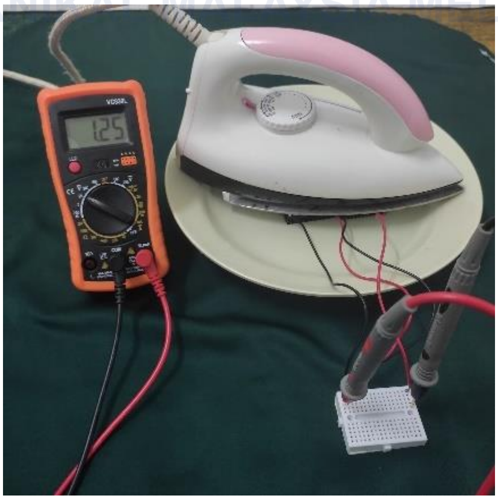


Figure 4.14: Voltage measurement

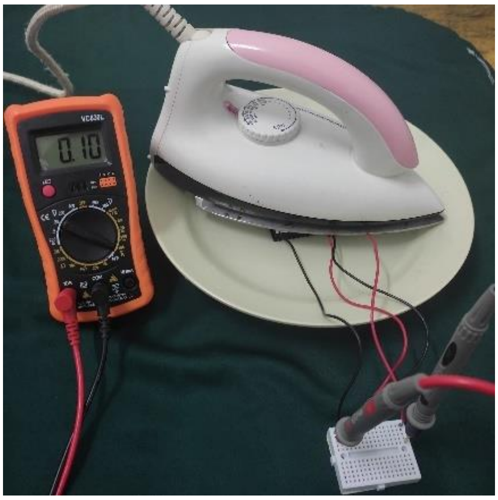


Figure 4.15 current measurement

Figure **4.13** visualizes the initial condition for prototype measurement. Figure **4.14** depicts the TEG voltage measurement and Figure **4.15**illustrates current measurement from the TEG. This voltage was measured by aligning the multimeter probe parallel to the Thermoelectric Generator (TEG) while the current was measured accurately by aligning the multimeter probe series to the Thermoelectric Generator (TEG). based on the measurement 1 TEG with the specification in **Table 4.5** generated 1.25V and 0.10A with the power 0.125W such as shown in **Table 4.8**.

Table 4.8: Output result for 2 series TEG configuration

Voltage Output V_o (V)	1.25
Current Output I_o (A)	0.10
Power Output P_o (W)	0.125

4.3.1.3 2 Parallel TEG configuration

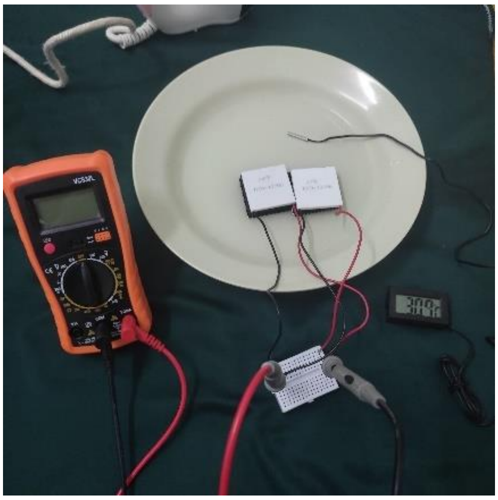


Figure 4.16: Initial condition before measurement

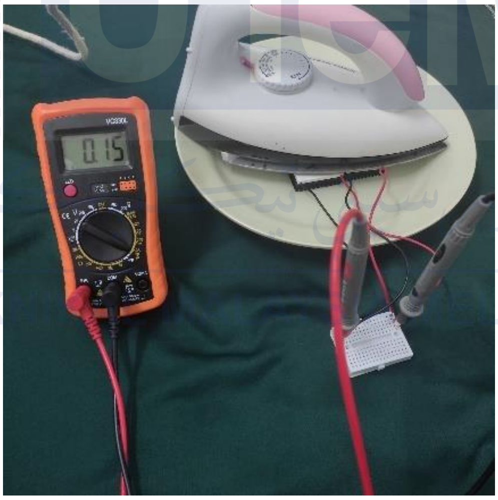


Figure 4.17: Voltage measurement

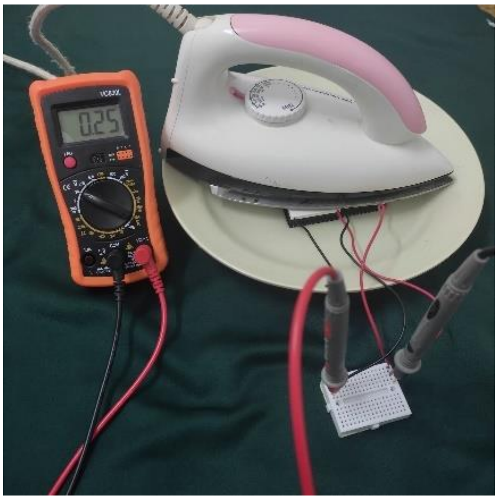


Figure 4.18 current measurement

Figure **4.16** visualizes the initial condition for prototype measurement. Figure **4.17** depicts the TEG voltage measurement and Figure **4.18** illustrates current measurement from the TEG. This voltage was measured by aligning the multimeter probe parallel to the Thermoelectric Generator (TEG) while the current was measured accurately by aligning the multimeter probe series to the Thermoelectric Generator (TEG). based on the measurement 1 TEG with the specification in **Table 4.5** generated 0.15V and 0.25A with the power 0.037W such as shown in **Table 4.9**.

Table 4.9: Output result for 2 Parallel TEG configuration

Voltage Output V_o (V)	0.15
Current Output I_o (A)	0.25
Power Output P_o (W)	0.037

4.3.1.4 4 Series TEG configuration

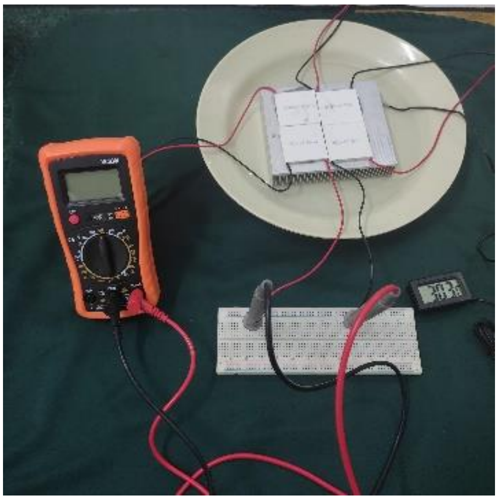


Figure 4.19: Initial condition before measurement

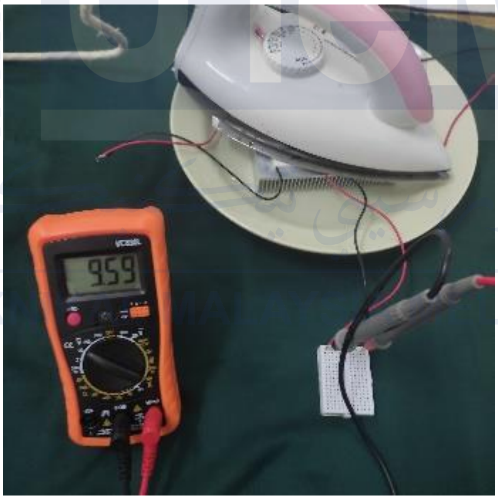


Figure 4.20: Voltage measurement

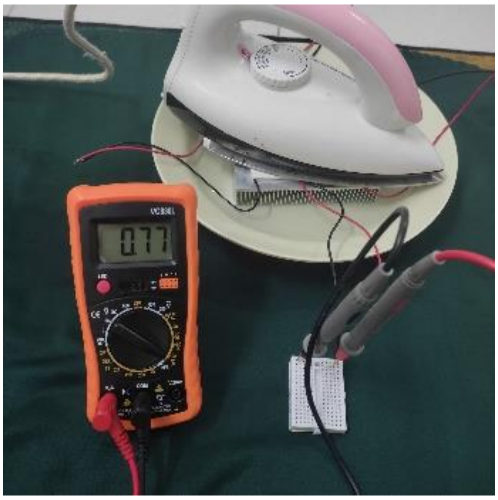


Figure 4.21 current measurement

Figure **4.19** visualizes the initial condition for prototype measurement. Figure **4.20** depicts the TEG voltage measurement and Figure **4.21** illustrates current measurement from the TEG. This voltage was measured by aligning the multimeter probe parallel to the Thermoelectric Generator (TEG) while the current was measured accurately by aligning the multimeter probe series to the Thermoelectric Generator (TEG). based on the measurement 1 TEG with the specification in **Table 4.5** generated 9.59V and 0.77A with the power 7.38W such as shown in **Table 4.10**

Table 4.10: Output result for 4 series TEG configuration

Voltage Output V_o (V)	9.59
Current Output I_o (A)	0.77
Power Output P_o (W)	7.38

4.3.1.5 2 TEG parallel with 2 TEG configuration

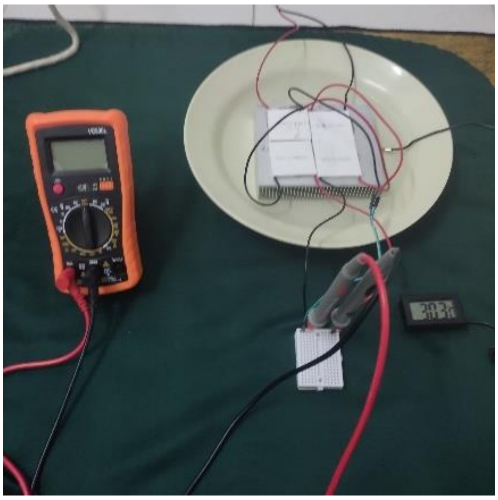


Figure 4.22: Initial condition before measurement

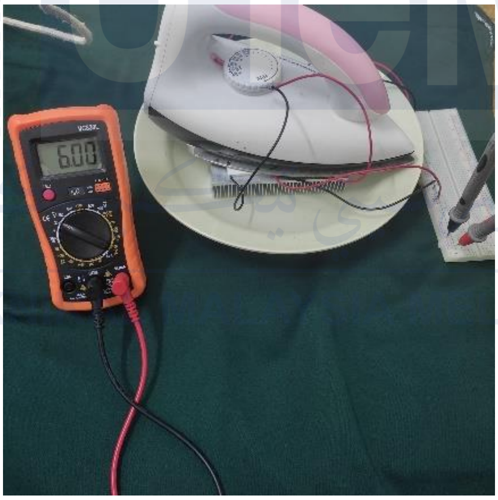


Figure 4.23: Voltage measurement

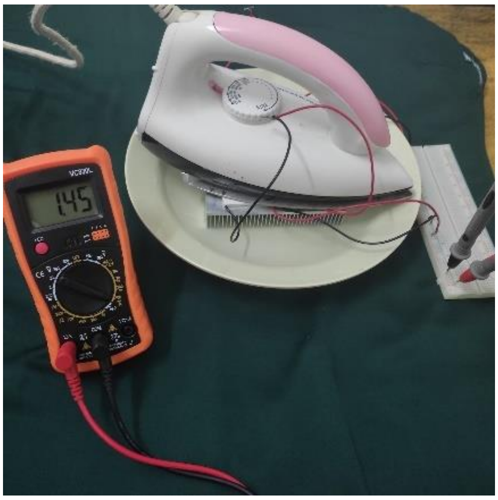


Figure 4.24 current measurement

Figure **4.22** visualizes the initial condition for prototype measurement. Figure **4.23** depicts the TEG voltage measurement and Figure **4.24** illustrates current measurement from the TEG. This voltage was measured by aligning the multimeter probe parallel to the Thermoelectric Generator (TEG) while the current was measured accurately by aligning the multimeter probe series to the Thermoelectric Generator (TEG). based on the measurement 1 TEG with the specification in **Table 4.5** generated 6.0V and 1.45A with the power 8.7W such as shown in **Table 4.11**.

Table 4.11: Output result for 2 TEG Parallel 2 TEG configuration

Voltage Output V_o (V)	6.00
Current Output I_o (A)	1.45
Power Output P_o (W)	8.7

4.3.2 Voltage incremental Outcomes

This part explains and describes the section which deals with stepping up the voltage. The "Voltage Incremental Steps" section is defined by a thorough study and discussion of the systematic procedure involved in modifying or increasing voltage levels within a specific context or system. From the previous part, the XL6009 was used as Dc-Dc boost converter to step the supply from the TEG before it connected to the next part. For the prototype test, the use of boost converter XL6009 instead of the own circuit is because of the own circuit has a limit feature. For example, it has a design to meet the requirement of 5V as a supply input. If it does not meet the requirement, the circuit is not functioning. The other reason for selecting XL6009 module is because it has a feature to control the level of step voltage.

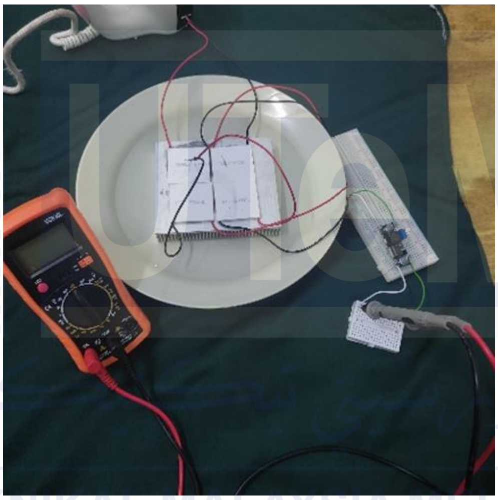


Figure 4.25: Initial setup

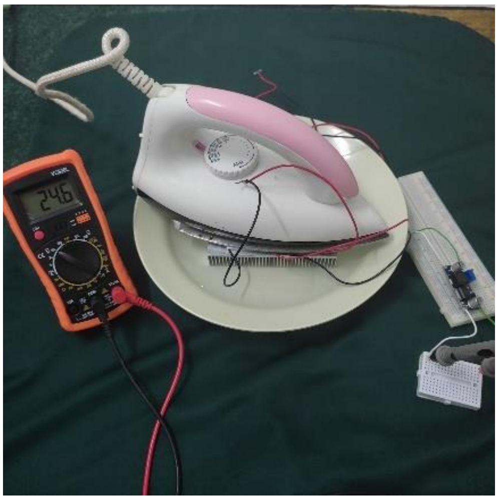


Figure 4.26: Voltage measurement

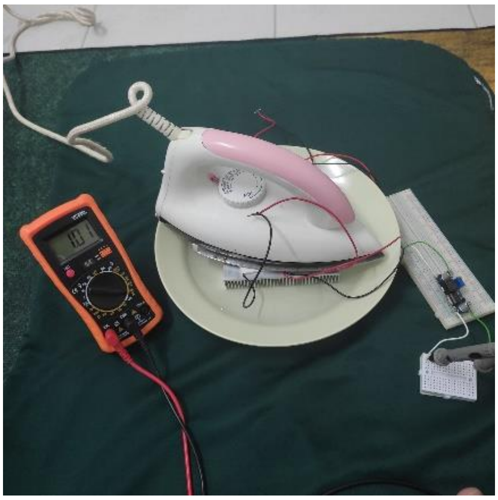


Figure 4.27: Current measurement

Figure **4.25** shows the initial setup and the connection of the XL6009 Dc-Dc booster connected with the TEG. Figure **4.26** show the voltage measurement output from the Dc-Dc booster. Figure **4.27** show the current measurement output from the Dc-Dc booster. The voltage that produced was 24.6V The current that produced was 1.01A. The power from this booster is 24.8W and the data for this measurement is recorded in **Table 4.12**

Table 4.12: Output data for the XL6009 Dc-Dc booster

Voltage Output V_o (V)	24.6
Current Output I_o (A)	1.01
Power Output P_o (W)	24.8

4.3.3 MPPT outcomes and the overall TEG System

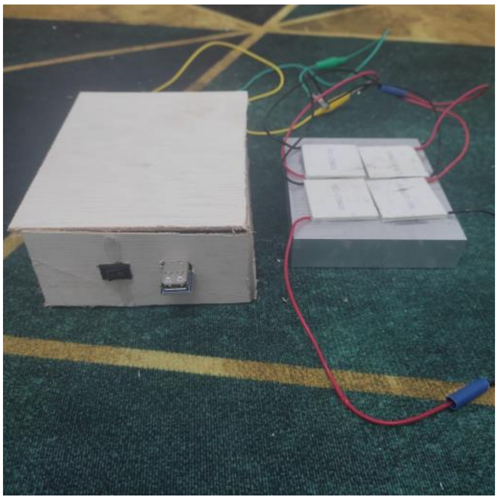


Figure 4.28: The Full prototype

Figure **4.28** shows the full prototype of the TEG system. In this prototype, it is the complete connection between TEG module, MPPT and boost converter circuit. This project is choosing the TEG configuration is 2 TEG parallel with 2 TEG. The full result for this overall TEG system can be referred to **Table 4.13**. The MPPT output is connected to the lithium battery to ensure the output performance of this system is stable before applied it to the load. Based on table 4.13 the MPPT output voltage is 15V and output current is 1.02 A. It also shown this system have 70.46% efficiency.

Table 4.13: The result for overall performance

	TEG	**BOOST CONVERTER**	**MPPT**	**USB**	**System Efficiency**
Voltage (V)	4.3	14.5	15	4.05	
Current (A)	1.05	0.8	1.02	0.34	
Power (W)	4.52	11.6	15.3	1.37	70.46%

CHAPTER 5

CONCLUSION AND FUTURE WORKS

5.1 General overview

This chapter presents the conclusion for all previous chapters. It summarizes the result and the functionality of the entire project. Further investigation is carried out to offer guidelines and suggestions for future development if future candidates wish to pursue the study and creation of new circuits for improved TEG system output performance in energy harvesting applications.

5.2 Applications

This project is suitable to be used as a renewable energy source because it converts waste heat energy to electrical energy. This harvested energy also can then be used to supplement the battery power, extending the battery life, or even eliminating the need for frequent recharging. Thermal energy can be benefit to power up other electric devices such as charging phones or smartwatches. The harvested electricity can reduce the overall energy consumption and improve the overall efficiency of the operation.

5.3 Future works

To improve the efficiency of the project, the number of TEG modules can be increased. By increasing the number of the TEG module, it can reduce the number of temperature difference between hot and cold side. For example, this project uses a 4 TEG module with temperature difference at 105 degrees Celsius to generate the overall output performance at 15V and 1A. However, this output performance can also be obtained using a lower temperature difference with condition the number of TEG used is increase. In addition, this project uses water at room temperature for cold sites. This water needs to be replaced when it becomes hot, and the process needs to be repeated for each time this TEG wants to use. So, to overcome it, this method can be improved by replacing the water with the dc fan. Therefore, the cold site will have constant temperature.

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