ANALYSIS OF ENERGY HARVESTER CIRCUIT FOR A THERMOELECTRIC ENERGY HARVESTING SYSTEM (TEHS) AT ASPHALT PAVEMENT

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2023

DECLARATION

I declare that this report entitled "Analysis of Energy Harvester Circuit for A Thermoelectric Energy Harvesting System (TEHs) At Asphalt Pavement" is the result of my own work except for quotes as cited in the references.



Date : 13 JANUARY 2023

APPROVAL

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

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Date

13 January 2023

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DEDICATION

First and foremost, I am very grateful to all the family members for their valuable guidance and support in the completion of this project in its entirety. I would like to express our deepest appreciation to all those who provided us the possibility to complete our Integrated Design Project. A special gratitude we give to our supervisor, Dr. Khairun Nisa Bt Khamil whose contribution in stimulating suggestions and encouragement and help I am lot in this project and with much appreciation too because she gave the knowledge about this project to use all required equipment and the necessary materials to complete the project. Besides, not to forget our coordinator of this PSM Project, Dr. Mas Haslinda who keep reminding us about the important things that must be done before the due date and always give us moral support to complete our project and the knowledge that gives us the idea to complete this project. Finally, gratitude goes to all my friends who directly or indirectly helped me to complete this project

ABSTRACT

The overriding challenge of our time are manifold from climate change, global energy shortages, and even environmental pollution. The search for renewable energy sources that are economical, efficient, and clean is vital. For this purpose, industries have looked at the environmentally friendly usage of renewable energy from many angles including in pavement harvesting. Choosing the right power management circuit for harvesting energy with a thermoelectric generator is an important element. However, most of the energy harvesting (EH) circuits on the market are typically designed to meet solar harvesting applications. Commercial EH circuits typically have an MPPT ratio of 0.7-0.85 for PV cells and 0.5 for TEG. As a result, if it is used with a thermoelectric source, a stable output cannot be obtained. Therefore, this project aims to analyze, an EH circuit that is designed for thermoelectric energy harvesting on asphalt pavement and to analyze the cold-start performance of the power management circuit. To confirm the feasibility of the energy harvesting project with a thermoelectric generator, the project has been tested in the laboratory with asphalt pavement. Based on the result simulation, IC SPV1050 able to fully charge to 4V between 3 to 8s, however LTC3105 able to charge faster than SPV1050 between 0.19s to 0.21s but only able to reach 2.4 V. However, the

results in laboratory experiment show SPV1050, able to charge 4.1 V for about 1 hour, while LTC3105 unable to charge to 44 mV. These results show that ICs with a charge pump type of cold start are able to boost and charge the voltage much faster than transformer's type. In conclusion, the difference in IC energy harvesting in terms of cold start, component use, technical issues from the circuit board and etc can have an effect on the desired voltage reading and make the charging process faster to help increase the performance of the power management circuit



ABSTRAK

Cabaran yang dihadapi manusia hari ini adalah kurangnya tenaga global, berlakunya perubahan iklim, dan juga pencemaran alam sekitar. Dengan adanya pembangunan tenaga baharu, serta pengunaan tenaga yang sedia ada yang menjimatkan, bersih dan cekap ia dapat memberi potensi yang bagus dalam penjanaan kuasa. Industri telah mengkaji pengumpulan perlindungan alam sekitar dan penggunaan tenaga boleh diperbaharui dari pelbagai perspektif termasuk dalam penuaian turapan. Teknologi penuaian tenaga menjadi topik utama kajian antara disiplin dalam penuaian turapan. Memilih litar pengurusan kuasa yang betul untuk menuai tenaga dengan penjana termoelektrik adalah elemen penting. Walau bagaimanapun, kebanyakan litar penuaian tenaga (EH) di pasaran biasanya direka untuk aplikasi penuaian tenaga suria. Litar EH komersial biasanya mempunyai nisbah MPPT 0.7-0.85 untuk sel PV dan 0.5 untuk TEG. Akibatnya, jika ia digunakan dengan sumber termoelektrik, output yang stabil tidak boleh diperolehi. Oleh itu, projek ini bertujuan untuk menganalisis, litar EH yang direka untuk penuaian tenaga termoelektrik pada turapan asfalt dan untuk menganalisis prestasi permulaan sejuk litar pengurusan kuasa. Untuk mengesahkan kebolehlaksanaan projek penuaian tenaga dengan penjana termoelektrik, projek ini telah diuji di makmal dengan turapan asfalt. Berdasarkan hasil simulasi, IC SPV1050 mampu mengecas sepenuhnya kepada 4V antara 3 hingga 8s, namun LTC3105 mampu mengecas lebih pantas daripada SPV1050 antara 0.19s hingga 0.21s tetapi hanya mampu mencapai 2.4 V. Manakala, keputusan dalam eksperimen makmal

menunjukkan SPV1050, boleh mengecas 4.1 V selama kira-kira 1 jam, manakala LTC3105 tidak boleh mengecas hanya mencapai 44 mV. Keputusan ini menunjukkan bahawa IC jenis pam cas mampu meningkatkan dan mengecas voltan lebih cepat daripada transformer. Kesimpulannya, perbezaan penuaian tenaga IC dari segi permulaan sejuk, penggunaan komponen, isu teknikal dari circuit dan sebagainya boleh memberi kesan kepada proses bacaan voltan yang dikehendaki, dan menjadikan proses pengecasan lebih cepat untuk membantu meningkatkan prestasi litar pengurusan kuasa.



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CHAPTER 1

INTRODUCTION



This chapter will briefly describe project introduction, objective, problem statement, scope of work and Importance/Significant.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

1.1 Introduction

The energy harvesting sector is rapidly growing. In Japan, China, Europe, and North America are main market leaders and the components of energy harvesting are expected to be worth more than 4 billion by 2020, which is significant given that the market was only 79.5 million in 2009, indicating a 73 percent annual growth rate. Most companies invest in energy harvesting for various purposes, for example, some companies want to reduce the cost of generating their systems. Although the energy generated is minimal, the upfront expense of using energy harvesting can be paid for in the long run, depending on the lifespan of the system [1]

Harvesting energy from asphalt pavements has shown promise in generating green electrical energy. Asphalt pavements are one of the most prominent components of civil engineering infrastructure. In Malaysia, to do the energy harvesting process is very suitable. According to Ismail & Ahmed (2009) Malaysia is a country endowed with a natural climate, where the average solar radiation of 4500kWh/m2 and sunlight of 12 hours/day process low-grade thermal energy that can benefit all [2]. In addition, according to the Malaysian Meteorological Department (2018) there were few seasonal temperature fluctuations in Peninsular Malaysia and East Malaysia, with the greatest average temperatures in April and May and the lowest average temperatures in December and January. Most of the road developments in Malaysia are paved with flexible and rigid asphalt, which is ideal for Malaysia's climate and influences it positively [3]. The heat absorbed by the asphalt road, which absorbs incident solar radiation, makes it an important source for energy harvesting with a total paved road length of 82,144 kilometers [4].

According to the Sze, (2015) World Economic Forum, Malaysia's roads are among the best in the world, ranked alongside Korea and better than some European countries. Roads in Malaysia that connect districts, villages, and even states have grown rapidly every year for the convenience of Malaysians [5]. With a good road structure in Malaysia, it can benefit the country by using it as a source of energy. Available energy sources can produce energy such as solar radiation, mechanical energy produced by moving vehicles or pedestrians, and geothermal energy. There are two main types of energy harvesting systems used for energy harvesting from roadways thermal and mechanical-based systems. The first type is called solar radiation and thermal gradients convert solar energy from asphalt pavements into electrical energy. A thermoelectric generator (TEG) and an asphalt solar collector (ASC) are used in the thermal gradient system, whereas photovoltaic techniques are used in the solar radiation system to generate electricity [6]. According to Roshani et al,. (2016) piezoelectric harvesters and electromagnetic systems, such as hydraulic, electromechanical, and micro-electromechanical systems, are examples of mechanical-based energy harvesters [7].

1.2 Problem Statement

Power consumption keeps increasing day by day due to high demand from users. According to Twaha et al,. (2017) Energy harvesting is a way to save and minimize electrical energy. Energy harvesters are converters that convert ambient energy into electrical energy, such as thermal energy, wind energy, solar energy, water energy, kinetic energy, vibration energy, and acoustic energy [8].

TEGs (thermoelectric generators) are devices that convert heat into electricity. One of the difficulties with TEG is that the power generated is unstable, necessitating the use of a proper power conditioning mechanism before it is supplied to the load. Furthermore, the maximum power point (MPP) must be tracked to ensure that maximum power is always extracted from TEG devices [8]. And due to this, EH circuits available in the market are normally designed to cater to solar application harvesting applications. Typically, the commercial MPPT circuit ratio was set to 0.7-0.85 for PV cells and 0.5 for TEGs. Hence if it is used to use the thermoelectric source, a stable output cannot be achieved. In this paper by Khamil et al., (2020a) ,ECT310 was able to step up the voltage by more than 5V but it took long hours to charge. Most of the commercial EH circuit is used to meet the needs of solar energy substances and programmed to meet a 0.7 to 0.85 MPPT ratio, so when the MPPT input is unstable, charging becomes challenging [9].

Another researcher Cabiling & Cristi, (2013) most EH circuits incorporated a cold start process to turn on the power to start the main boost converter, and among the methods used are transformers, mechanical switches, charger pumps, and low power oscillators. Each commercial EH circuit such as LTC3105, ECT310, and BQ25504 used a different cold-start method. For example, LTC3105 uses the stepup transformer to allow it to boost input voltages as low as 250mV. In contrast, BQ25504, cold-starts used a DC-DC boost charger that requires VIN from TEG as low as 600 mV. However, once the cold start operates at the minimum value to boost, it affects the charging capabilities and takes a longer time [10]. Thus, in this project, various cold-start methods are investigated on how they will influence the input from TEG once it operates and starts to charge.

1.3 Objective

- 1. To analyze the cold-start performance of the energy harvesting (EH) circuit.
- 2. To investigate the charging capabilities between the commercial EH circuit that is designed for solar and the circuit that is designed for Thermoelectric generator.

1.4 Scope of work

This project aims to analyze energy harvester circuit for a thermoelectric energy harvesting system (TEHs) at asphalt pavement. Simulations and experiment investigation are required to achieve the project objective. The main hardware for this project is using power management IC for energy harvesting, thermoelectric generator, and cooper Bussmann's supercapacitors. For Phase 1 using PSpice & LT Spice software to simulate the circuit for power management circuit and collect all relevant data for this project and make an analysis from the simulation. From the simulation results in Phase 1, data are compared to experiment results in Phase 2.

1.5 Importance/Significant

The TEG generates electrical energy if there is a temperature difference between its surfaces. TEGs are also environmentally friendly and have no moving parts. Furthermore, they are long-lasting and silent, scalable, and emit no greenhouse gases. Their main disadvantage, on the other hand, is their low conversion efficiency of 10% [11]. However, the low conversion efficiency may be overestimated due to the use of TEGs for energy recovery. TEG output voltage must be regulated because it varies continuously with temperature differences. If global energy demand continues to rise, environmental concerns about today's energy sources will persist, as will the need for renewable energy sources, and TEGs will remain one of the sought-after research topics [12].

CHAPTER 2

BACKGROUND STUDY



The literature review chapter's primary purpose is to expand upon the context and background of the study. This chapter will explain the past research about Analysis of energy harvester circuit for a thermoelectric energy harvesting system (TEHs) at Asphalt Pavement. Research in books, newspapers, journals, and articles is used in this chapter.

2.1 Basic principle of a thermoelectric generator

Thermoelectric generators are commonly used to convert thermal energy into electrical energy and are based on the Seebeck effect. TEGs have numerous advantages, including design simplicity, the absence of moving parts, a long lifetime, long service life, and environmental friendliness. According to Kauzlarich et al., (2007) TEG does not emit greenhouse gases during the generation of electricity, making it environmentally friendly. As a result, TEG has gained increasing attention because it largely meets the public's needs as a green and flexible source of electrical power [13]. In study by Champier et al., (2011), TEG generate electrical energy each time there is a temperature difference in the TEG environment. They are not like solar (PV) panel in that day-night, rainy sunny days do not inhibit electricity production [14].

In study by Jaziri et al., (2020) TEG is made of thermopiles that are connected to increase the power output. A voltage is generated when a temperature difference is established between the hot and cold ends of the semiconductor material [15]. Riffat & Ma, (2003) this voltage is referred to as the Seebeck voltage, and it is proportional to the temperature differential [16]. According to Yahya et al., (2020) thermoelectric generator can operate in electrical power generation mode, where TEG in power generation mode can create voltage when there is a temperature difference (Δ T), where the side of TEG follows the seebeck effect [17]. The Seebeck effect occurs when there is a temperature difference that passes through a conductor and produces a voltage at the end of the conductor. TEGs or Seebeck generators generate voltage that is proportional to the temperature differential between the two metal junctions [18]. By using the seebeck coefficient in equation 1, the ratio of voltage developed to the temperature difference is related to intrinsic property of material.

$$S = -\frac{\Delta V}{\Delta T} = \frac{V_{hot} - V_{cold}}{T_{hot} - T_{cold}}$$

S = Seebeck Coefficient $[\mu V/K]$

 $\Delta \mathbf{V} = \text{Voltage Difference } [\mathbf{V}]$

 $\Delta \mathbf{T}$ = Temperature Difference [K]



Figure 2.1: Thermoelectric Generator circuit [17]

According to Rohit et al,. (2017) The amount of power generated by the TEG is determined by the temperature difference between the TEG different sides ($\Delta T = T_{hot} - T_{cold}$). Heat is transferred to the other when one surface is kept at a higher temperature, reducing the temperature difference [19]

The TEG device has two sides which are cold side and the hot side. This device provides the temperature differential, (DT). The voltage generated at the TEG output terminals can be utilised to power an external circuit, which supplies power to an external electrical load. A single TEG can generate 1 to 125 W of power. Using more TEGs in a modular connection can boost power up to 5 kW and temperature up to 70°C.

1

In Orr et al., (2016) studies, the heat source is the system where heat is lost to the heat sink. One example of a heat source is the heat pipe, where the TEG device is used in conjunction with the heat pipe in the recovery system. This heat pipe's system is passive, meaning it has no moving parts and a high heat transfer capacity. [20]. Another researcher from Ando Junior et al., (2018) the cold source is the heat transfer system, which includes heat exchangers such as coils, radiators, heat sinks, and cooling blocks. This process is useful to obtain a larger temperature difference across the TEG to improve heat dissipation across the TEG [21].

However, Kütt et al., (2018) presented DC-DC converter power electronic circuit designed to convert a direct current source from one voltage level to another. Because the TEG's output voltage is low or not constant, a DC-DC converter is required to boost the TEG's output voltage, which depends on the number of TEGs in series and the TEG features to correspond to the external load requirements. The Maximum Power Point Tracking (MPPT) algorithm must be implemented within the DC-DC converter controller. To improve actual system feasibility, it is necessary to harvest as much electric output power as possible from TEGs, because the effectiveness of TEG operation can be assessed by evaluating DC-DC converter operation and MPPT control. To store energy, Dc load is used and connected to a supercapacitor or rechargeable battery where the battery stores DC voltage in charging mode and DC electrical power in discharge mode. The DC load (battery) on the TEG usually operates at 12 V and the output voltage of the TEG device on the MPPT must be higher [22].



Figure 2.2: Block diagram of a thermoelectric energy harvesting system [23].

2.2 TEG on Asphalt Pavement

2.2.1 Previous Research on Asphalt Pavement

Previous study Wu & Yu, (2012) from have reported that the temperature difference between the pavement surface and the surrounding soil can generate electricity. In the study conducted as well, the TEG was attached to an asphalt concrete layer on one side and a plate embedded in the soil on the other. However, this design exposes the TEG to traffic loads, which may reduce its lifespan. Based on the result, they were able to obtain 4.5 mJ of energy in 90 seconds 0.05 mW [24].

Previous research from Datta et al., (2017) developed a prototype for thermoelectric energy harvesting in asphalt pavement. Using 3 components, which is a set of TEGs, the Z-shaped copper plate which means to transfer mechanism and heat collector and using the aluminum heat sink. From that, the TEG hot side is attached to the bottom copper plate to collect heat from the asphalt pavement and transfer it to the lowest layer. And from another side of the TEGs were attached to the heat transfer plate and an aluminum heat sink filled with soil. This paper attempts to show that 64mm x 64mm TEG is able to produce 8 an hour to generate 10mw of electricity. In addition, the estimated recoverable power density for each square foot pavement section is 16 mW and the daily energy accumulation of the prototype is 0.5 kWh [6].

Another researcher Tahami et al., (2019) develop a new thermoelectric generator system that converts the thermal gradients between the pavement surface and the soil below it into electricity. The system consists of a coolant module, heat collector, and thermal electric generator. The importance of thermal gradient in thermoelectric system generators is proven by the correlation between thermal gradient and power, a higher temperature difference produced more electrical energy. from that they are able to generate the energy harvester system electricity by average power 29mW per day [25].

Next, Khamil et al., (2020b) investigate the effects of heat conduction using different shape structures in the subterranean level to achieve a high-temperature difference between the top and bottom plate of the TEHs [26]. In addition, another researcher Khamil et al., (2021) used asphalt pavement to make useful electrical energy. By developing an H-shape element in subterranean cooling they are able to achieve high-temperature difference. Based on the result, when compared to the single rod cooling element, the H-shape cooling element improves differential temperature by 75%. It indicates that the conduction shape factor (S) may have affected the heat distribution in the cooling element by employing a top plate with a 100 x 200 mm dimension and an extra 8 C of T than the top plate with a 65 x 200 mm dimension [27].

The author W. Jiang et al., (2017) developed a road thermoelectric generator system to generate electricity when there is a temperature difference between the

road surface and the ambient air and to test the energy capacity both indoors and out. According to the results, the output voltage of asphalt (300 mm x 300 mm) is 0.4 V during the winter season, with a temperature difference of 15 C, and 0.6-0.7 V during the summer season, with a temperature difference of 25-30 C. As a result, in 8 hours, a road with a length of 1 km and a width of 10 m can produce 160 kWh of energy [28].

Another research performed by W. Jiang et al., (2018) used a three-module asphalt structure that included thermoelectric conversion, cold end cooling, and heat conduction. The module converts heat absorbed in asphalt pavement into electrical energy and reduces the temperature of the pavement surface. The output results indicate that an asphalt pavement with a 0.564V electrical output may generate 33 kWh of electrical energy in a single day during the summer when the pavement area is $10000 m^2$ [29].

Another study from Zhu et al., (2019) for asphalt pavement is that they discuss thermoelectric effects, pavement temperature field and investigate the configuration of thermoelectric energy harvesting system used in asphalt pavement. In this paper also, it is stated that thermoelectric effect for energy harvesting is very suitable to be implemented but needs to have a lot of effort in improving the efficiency of thermoelectric devices. In addition, this study uses the SHTE-AP method, which can reduce high-temperature diseases on asphalt pavements. Renewable thermal energy generated by asphalt pavement can be converted to electrical energy through TEG. Based on the study done related to the temperature field on the asphalt pavement says that the temperature gradient in the asphalt pavement structure is high enough to generate electricity through TEG [30].

2.3 **Power management circuit IC**

A power management integrated circuit (PMIC) is a circuit that controls power on electronic devices or in modules on devices that operate at different voltages. The PMIC is in charge of controlling battery charging and sleep modes, as well as DC-to-DC conversion and voltage scaling up and down. On PMICs, users can find lowdropout regulators (LDO), pulse-frequency modulation (PFM), pulse-width modulation (PWM), power FETs, and real-time clocks (RTC). A typical PMIC contains one or more switching DC-to-DC converters, such as buck or boost converters, and linear regulators, such as LDO.

2.3.1 Previous Research on using Power management IC

According to Twaha et al., (2016) the output voltage from the thermoelectric generator is low, so to design a circuit must have a power management circuit. It is made comprised of a DC-DC step-up converter. Several methods are mentioned that can be used to stabilize the voltage generated by the TEG to improve the system's overall performance. The selection of a DC-DC converter affects the overall performance of the system, so a proper criterion must be followed to select the best converter [31]. Tawil & Zainal, (2018) stated a DC-DC converter is an electrical circuit that transforms a direct current (DC) source from one voltage level to another, either to step up or down the voltage. There are two types of converters, buck converters that reduce DC voltage and boost converters that increase DC voltage. To achieve this step-down or step-up property, they both employ inductor energy and a switching device. A boost converter is used in the power management circuit to modulate the fixed voltage required. The DC-DC step-up converter is triggered when the voltage reaches 3V. The power management device will manage the voltage output until it reaches the required voltage to turn on the wireless communication

module. The input can be chosen using a switch that allows to choose between TEG and PV. PV input is recommended for usage during the day due to its ability to capture solar light energy and because the time required to turn on the DC-DC stepup converter is less than that of TEG. [32].

Another study by Morais et al., (2020) they are using the EM8900 as a DC-DC Converter with input voltages ranging from 5 mV to 200 mV. The input impedance of the EM8900 can range from around 0.7W to 35W. Step-up transformers with turn ratios of 1:20, 1:50, and 1:100 are supported by the EM8900. The results show that when only one TEG was used, the Em8900 output power remained zero until the temperature gradient (DT) across the TEG reached about 1.7°C, and then increased to a maximum output 1.02 mW when the temperature gradient was 2.5°C. With two TEGs in series, the EM8900's onset operation occurred at a significantly lower temperature gradient of 0.5°C, but the higher input impedance of the two TEGs in series results in the maximum output power being reached only at 3.25°C. It is important to note that one additional series TEG actually reduces the EM8900's onset of operation from 1.7°C to 0.5°C, but due to the greater output impedance of the series arrangement, a 40% higher temperature gradient is required to attain the maximum output power. Furthermore, the most of these temperature gradients are only a few degrees, and while TEGs can harvest them, the resulting output voltages are extremely small, only a few mV, necessitating the use of DC-DC converters to boost them to usable levels. As a result, at ultra-low voltages, the output impedance of the TEG ensemble influences not only the amount of energy scavenged but also the onset temperature of energy harvesting [33].

Next research is from Webb, (2021) uses the ADP5091 as a power management circuit. They show how to harvest thermoelectric energy from the temperature difference between the ocean surface and the surrounding air. The device was tested by changing the temperature input from the hot plate and chilled heat sink, as well as the time required to charge a 15 F capacitor from 2.9V to 3V. The tests have been carried out with a hot plate, a freezer-chilled heat sink, a 3V power supply to simulate the backup battery, and a DMM connected to the ADP5091's PGOOD pin. The experiments with the energy harvesting circuits demonstrated that the ADP5091's charging capability, when connected with a temperature differential input to the TEG, can charge an energy storage device. As a result, the temperature inputs must be higher than the temperatures commonly observed between the ocean surface and the ambient air. To avoid interference from the DMM on the capacitor directly, the PGOOD pin on the energy harvester chip was used instead to ensure that the capacitor was fully charged. It was assumed that the ADP5091's input impedance from this pin was high enough to prevent the DMM's leakage current from affecting any circuitry affecting capacitor charging [34].

Another research by Siew Yun & Swee Leong, (2018) has developed a

circuit for the charge pump and LTC3108 IC chip by using TEG as input. The charging pump takes 6 minutes to raise the circuit to 4.06V from a TEG input of 1.18V. The LTC 3108 circuit, on the other hand, only takes 10 seconds to increase the voltage to 4.92V. The circuit is then connected to a decade resistance box. In terms of power output, the two circuits produce the same amount. However, the corresponding load of the LTC 3108 circuit is 20k, but the corresponding charge pump load is only 50 [35].

Another researcher Mullen et al., (2015) has been doing an experiment to experimentally demonstrate the lowest T, measured across the TEG (Δ TEG) at which the embedded processor functions to enable for wireless communication by connecting a single TEG of 449 couplings to an embedded processor via a power conditioning circuit. According to the result, when a 0.6°C Δ TEG temperature difference is placed across the thermoelectric module, an input voltage of 23 mV is generated, which is sufficient to activate the energy harvester in around 3 minutes. When the energy storage capacitor is fully charged, the power source would provide enough electricity to operate an entire low-power sensor system with wireless data communication. The LTC3108 power converter enables the use of fixed thermal gradients, such as between a cold sink and a warmer environment or a warm source in a cooler environment. According to Table 1, researcher also compared commercial energy harvesting ICs and concluded that the LTC 3108 was chosen because it has the lowest activation voltage and able to charge a supercapacitor [36].

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Component	Activation voltage for cold start	Maximum input voltage	Energy storage	Voltage Regulation	MPPT
SPV1050[37]	500mV	5.5V	Supercapacitor/ battery	Programmable	Hardware set
LTC3108 [38]	20mV	500mV	Supercapacitor	2.2V	None
MAX17710 [39]	750mV	5.3V	Battery	Programmable	None
BQ25504 [40]	330mV	3V	Battery	No Regulation	Programm able

 Table 2.1: Comparison commercial energy harvesting IC [36]

According Markiewicz et al., (2020) they make a comparison between commercial IC for ultra-low power boost converters with battery management for energy harvesting applications (ADP5090, SPV1050 and LTC3108). Based on the table below show that, The SPV1050 provides more features than the LTC3108 and ADP5090. Furthermore, it can function in both buck and boost mode, and it is the most cost-effective option. The main disadvantage is the comparatively high leakage current of 0.8A. Because LTC3108 and ADP5090 have lower input voltages than SPV1050, they are more suitable for our case at 5°C, where the selected TEG provides around 190 mV. The LTC3108 has a good cold start voltage of 20mV. Besides that, the ADP5090 IC is less satisfactory than the LTC3108, because it has a minimum voltage of 100 mV and a cold start voltage of 380mV, which is equivalent
to 10 degrees Celsius. Furthermore, it is quite expensive in comparison to other ICs [41].

Table 2.2: Comparison between commercial IC for ultra-low power boostconverters with battery management for energy harvesting applications [41]

	ADP5090	SPV1050	LTC3108
Parameter	[40]	[35], [36]	[36]
Minimum input voltage	380	550	20
Input voltage	0.1-3.3	0.15-18	0.02-0.5
Battery terminal charging threshold	2.2-5.2	2.2-5.3	5.25
Leakage current at BAT pin [nA]	15	800	100
Leakage current at BAT pin Vsys=0V [nA]	0.5	1	-
Standby current [Ua]	سيتى 8.9	اويتولم	6
Efficiency @ V IN= 0.02 V [%]	IALAYSIA N	IELAKA	35
Efficiency @ V IN= 0.01V [%]	40	-	25
Efficiency @ V IN= 1 V [%]	85	85	-

Another study from Xia et al., (2019) used commercial unusual chips, LTC3108 and BQ25504, to develop circuits and use converted electricity to power electronic devices. The purpose of a power management system is to convert a small amount of electrical energy into a higher voltage for electronic use. Furthermore, it helps in the movement of electronic loads by converting the energy generated from microwatts to milliwatts . Having a wider range of applications, the LTC3108 has an acceptable lower voltage. However, due to the lack of an MPPT function, the integrated converter cannot adjust its internal resistance to obtain a resistance match between the converter and the input voltage source. As a result, the system can only function with a low internal resistance of the input source and has a low efficiency. The other integrated converter BQ25504's incorporated programmable MPPT feature allows for substantially more energy to be captured via resistance matching. Furthermore, the battery protection function contributes to the chip's intelligence and expands system application. Nonetheless, the high cold-start voltage of 330 mV necessarily requires a large temperature difference to exist for a period of time in order to drive BQ25504 to exit the cold start period. When the system enters the normal operating mode, it accepts input voltages as low as 80 mV. As a result of the 104 mV input voltage from the TEGs applied to the human body and the 65s transmission period, 302.7 uW power can be harvested in the supercapacitor [42].

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2.4 Cold startup

The important point in a boost converter system is the start-up voltage. To achieve a low start-up voltage, the transistor's threshold voltage must be low. Low threshold voltage, on the other hand, contributes to high transistor off-state leakage loss. The transient response of output voltage to reach steady state is influenced by the start-up voltage. If a low start-up voltage can be achieved, the boost converter can be triggered in less time. The start-up time is the time interval for the transient period.

2.4.1 Previous Research about cold startup

According to Bose et al., (2019) the cold-start or start-up time is defined as the time it takes to turn on and start the primary boost converter by determining the ability of the low-power start-up voltage multiplier to power the inductive boost converter's start-up control circuits. While the rise time of the final output depends on the inductor current and the output load cap, most of the start-up time is consumed by the slow, low-voltage cold-start. A cold-start circuit is needed to drive the voltage booster with a depleted storage element [43].

Another researcher by Scheidl & Pott, (2021) the cold-start circuit powerful way to boost the system, allowing it to self-sustain. The simplest implementation would be to drive the booster using the source signal. However, the supply frequently produces insufficient voltage to power the booster in the first place. One alternative is to use a mechanical switch. The mechanical switch, which is activated by random motion, is used for the initial cold start. For its higher impulse capability, a different energy domain (the mechanical domain) is used here from a theoretical viewpoint. However, after a cold start, the mechanical switch remains in the circuit and can prevent operation. Furthermore, this method is only applicable to inductive boost converters, which are typically not integrated. Following that cold-start method use transformers, which has the advantage of achieving high efficiency after a cold-start with the same transformer. Inductors and transformers, on the other hand, generate magnetic fields that can interfere with other chip components and build large components that are incompatible with the desired form factor. Next, charge pumps are switched capacitor circuits that can provide very efficient conversion and are easily integrated. Charge pumps provide a method of boosting that uses only integrated parts and has a high achievable efficiency [44].

X. Jiang et al., (2018) employed a 70-mV start-up voltage to start the inductive boost converter by charging a storage capacitor, which is known as charge pump storing. A cross-coupled Pelliconi charge pump was implemented by the researcher. To reduce the start-up voltage, the Dickson charge pump is cascaded until it reaches 24 stages, with voltage monitoring has been eliminated [45].

Another research from Carlson et al., (2010) they have been implemented a startup solution for voltage booster which is through a pre-charge load. The disadvantage of using a storage element is that it will disable the converter for long periods of time. When the output voltage reaches a certain level, the capacitor is used to reset the voltage booster. Despite the fact that the capacitor has been completely discharged, the switch capacitor circuit can still generate 600 mV to start the booster [46].

The initial issue in designing a TEG PMIC is to support as low a cold-start voltage as possible. Many efforts have recently been taken to reduce the cold start voltage. Another study by Im et al., (2012) used a transformer to obtain a 40 mV startup voltage. However, the transformer is undesirable because of its bulky size

and increased system cost [47]. According to Goeppert & Manoli, (2016) boost converter using auxiliary charge pump circuits is more optimal and required only a simple inductor instead bulky transformer. But the converters in can only perform cold start with TEG voltages above \sim 70 mV and achieve low efficiency (58%) [48].

A mechanical switch was used in another study by Ramadass & Chandrakasan, (2010) to achieve a starting voltage of 35 mV, additional chip inductors and capacitors are used to reduce efficiency to 58% as an additional component for mechanical switches [49]. On a 65-nm technology, Lim et al., (2018) also employed a Colpitts oscillator with two off-chip inductors to produce a startup voltage as low as 40 mV. [50]. Another approach by Weng et al., (2013) to get a cold start from 50 mV, an additional auxiliary converter with a total chip area of 1 mm2 was used [51].

2.5 Boost Converter

A DC-to-DC converter is an electrical circuit that changes the voltage level of a direct current (DC) source. It is an electric power converter with power levels ranging from extremely low small batteries to very high large batteries. According to Hasan & Yasir (2013) DC-DC converters are also important in energy harvesting systems and also in mobile electronic devices such as cellular phones, laptops, etc. where they are supplied by power from batteries primarily. This electrical device has several subs -circuits where each sub -circuit has a different voltage than the voltage supplied by the battery. This DC-DC converter offers a way how to increase the partially lowered battery voltage and from that it can save space without using a lot of battery to reach the desired voltage level [52]. According to Twaha et al., (2017a) there are several kinds of type DC-DC Converter, one of them is Boost converter. A boost converter is also known as a step-up converter since it increases the voltage supplied. The boost converter has the same components as the buck converter, but it produces a higher voltage than the source voltage. Boost converters start voltage conversion by passing current through a closed inductor switch. The switch is then closed, leaving the current with no other path to take than through a diode which functions as a one-way valve. The current then wants to slow down extremely quickly, and the only way it can do so is by increasing the voltage at the end that connects to the diode and switch. If the voltage is high enough, the diode opens, and current cannot flow back through it. This is the basic fundamental of a boost converter. Table 2.3 below show the characteristic, application, advantage , limitation of the DC-DC converter that suitable to use [53]. For this project will be focus on DC-DC boost converter that required in energy harvesting.

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Converter	Characteristics	Application	Advantages	Limitation	
Boost	 Convert from low voltage to Higher voltage Load current smaller than the input current Most commonly used Middle and low level in the conversion network 	• Suitable for TEG with unstable internal resistance and output voltage	• Precise and flexible conversion factor	 Requires a large inductance To get high efficiency 	
Buck	 Converts from a higher voltage to a lower voltage. PWM controlled 	• A lower voltage level is needed to supply the load	• Precise and flexible conversion	 High voltage ripples at the output Higher flux density due to Large size of inductance 	
Buck boost	 Increased and decreased the output voltage Load voltage is inverted 		• input voltage can be higher or lower than the regulated output voltage	-	
Push- Pull	 High level conversion of high power Step-up and step- down tasks Multiple output due to the transformer isolation 	 High power application (range of kWs) Fairly good efficiency 	 Less likely to cause saturation than in the fly-back converter · Hence smaller size 	 More complex MOSFETs must be able to handle twice the input voltage Hence used for low voltage application 	
Cu'k	 Middle level conversion Continuous output current Can boost or buck the voltage 	• Suitable for sensitive environments	 Stable input and output terminal currents Easy to cancel ripples (By adjusting inductors) Emit less RF noise 	-	
Fly back	 Transformer is used. Multiple output can obtain Output energy is stored as magnetic energy and released to the load later. 	• Multiple outputs are required	 No separate inductor is needed since the transformer is used for storage Cost effective 	• Very high peak currents	

 Table 2.3: Type of DC-DC Converter [53]

According to Chen & Kok, (2019) they were able to show the relationship between the TEG output voltage and the boost converter circuit with various temperature gradients formed between the TEG. The comparison of the voltage before and after being boosted up by the DC-DC converter circuit at various Temperature is shown in the result. The temperature gradient formed across TEC is proportional to both output voltages. The output voltage of the circuit increased from 0.961V to 2.378V at 10°C of T. When the temperature difference increases to 15°C, the output voltage reading of the circuit shows a quick rise, but the voltage appears to saturate in the range of 3.125V to 3.143V.

Based on the results of previous studies that have been revealed above a little bit can be used in producing this project, among which is a reference on energy harvesting using TEG at asphalt pavement. The use of asphalt can help to produce heat energy to convert into electricity energy that can be used in small electronic devices. The selection of materials in the experiment can be used to help increase the thermal temperature of the TEG which has hot and cold side, and it can increase the output voltage compatible with the increase in differential temperature. In addition, the use of TEGs that provide low voltage input cannot be used for power electronic devices [54]. By using a power management circuit is needed to generate from low input voltage to get the higher output voltage. But most of the power management circuits in the market are designed for solar and when used on TEG, the ratio of teg cannot be achieved. In addition, the use of the cold start method is also very important in this power management circuit, this is because each power management circuit has a different cold start that can give the ability of a circuit in giving the desired results. This cold start functions as is to boot strap the system when there is insufficient energy stored in the storage element. So, references from previous

studies can help provide useful information so that experiments can be conducted based on theory and the correct use of materials. Therefore, in these studies, the power management circuit chosen to be studied in this experiment is SPV1050 and LTC3105 will investigate which of the commercial PMIC suitable for thermoelectric harvesting from asphalt pavement.



CHAPTER 3

METHODOLOGY

This chapter will explain the flow chart, financial management in purchasing the materials and components for the project, the details about the materials,

components, and prices stated clearly. MALAYSIA MELAKA

3.1 **Project flowchart**

The procedure to be followed in this project is to identify and collect relevant information, such as from websites, journals, and books. Next, the EH circuit will be designed using PSpice & LT Spice software to simulate the process and compare the results with evaluation board on PSM 2. This project will also analyze EH circuit for thermoelectric energy harvesting on asphalt pavement using a Power management Circuit IC SPV1050 with cold-start performance and compare it to other commercial Energy Harvesting Circuit LTC3105 to obtain a reliable result. Following that, the data will be analysed about the study's findings.



Figure 3.1: Project Flowchart

3.2 Background research of Power Management Circuit

In this experiment, the Figure 3.2 shows the two ICs used in this experiment, among them is an ultra-low power energy harvester and a battery charger with embedded MPPT and LDO for Power management circuit (SPV1050) and a 400mA Step-Up DC/DC Converter with Maximum Power Point Control and 250mV Start-Up (LTC3105). The SPV1050 is an ultralow-power, high-efficiency energy harvester and battery charger that implements the MPPT function and integrates buck-boost converter switching elements [37]. The SPV1050 device allows for the charging of any battery or supercapacitor, including thin film batteries, by monitoring the end-of-charge and minimum battery voltages to prevent over discharge and long-term battery life. Thus, LTC3105 is a boost converter optimized for high impedance, very low voltage input power source and allow for relatively high impedance, very low voltage input power sources. It allows to quickly evaluate the LTC3105 boost converter and LDO regulator[55]. These two ICs will be used to improve low input voltage to high output voltage of the energy harvesting system. This power management circuit will operate if the TEG input reach up initial start-up to 0.5V for (SPV1050) and 0.25V for (LTC3105).



Figure 3.2 : Power Management Circuit for SPV1050 and LTC3105

3.3 Software

3.3.1 PSpice for TI (Cadence)

SPICE (Simulator Program with Integrated Circuit Emphasis) is a computer program used to simulate the behavior of electrical networks. This program is primarily directed for integrated network (IC) planning. The input data of this program, referred to as the input-deck is a file whose contents are the display of the circuit to be computed. This includes the network topology as well as the parameter values of each circuit element, such as current source (I), voltage source (V), resistance (R), capacitance (C), and inductance (L). This network view is referred to as a netlist. For this project, this software is used to simulate a circuit to see the results of how the SPV1050 will affect the TEG output that generated with a DC-DC boost converter that convert low voltage to high voltage [56].



Figure 3.3: PSpice for TI software [57]

3.3.2 LTspice software

LTspice is software used for high-performance circuit simulation programs, to enable users to draft, test and analyze the performance of circuit design. LTspice allows users to learn some basic instructions that are easy to understand, which has an integrated schematic, waveform viewer and functions that are easy to understand.



Figure 3.4: LTspice Software [58]

3.4 Data acquisition tool

3.4.1 TC-08 thermocouple data logger

The TC-08 thermocouple data logger is designed to be used with any thermocouple that has a small thermocouple connector to measure a wide range of temperatures. Pico offers a diverse assortment of thermocouples. The effective temperature range of this thermocouple is 270 °C to +1820 °C the actual temperature range depending on the thermocouple used. Temperature measurements may be made fast and precisely with the TC-08 thermocouple data logger. The TC-08's quick conversion time allows it to capture up to 10 temperature readings per second, and its high (20-bit) resolution allows it to detect minute temperature changes. The TC-08 can retain a better than 0.025 °C resolution for Type K thermocouples throughout a 250 °C to +1370 °C range [59].



Figure 3.5: Pico log TC-O8 thermocouple [59]

3.4.2 NI USB-6001/6002/6003

The National Instruments USB-6001/6002/6003 is a full-speed USB device with eight single-ended analogue input (AI) channels that can alternatively be configured as four differential channels. There are two analogue output (AO) channels, 13 digital input/output (DIO) channels, and a 32-bit counter as well.



Figure 3.6: National Instrument USB-6001/6002/6003 [60]

3.5 Procedure Setup Experiment

Figure 3.7 below shows the equipment & materials that will be used in completing this project. Among them are Soil, asphalt, halogen lamps, top plate, bottom plate, H-Shape rod, and TEG module. Materials such as Plate for Top and Bottom are to heat and cool the TEG module which will be placed in the middle and clamped with both plates like a sandwich. The Picolog temperature reader to monitor the temperature, and NI-DAQ USB 6003 is used to read the open circuit voltage (V_{oc}) from the TEG module. This project also used a box simulator measuring (500 mm x 1500 mm) by place the asphalt box and also the soil that was placed half of the box simulator because to imitate the road construction configuration and halogen lamps as heat resources for this project.



3.5.1 Material for experiment

Table 3.1 & Figure 3.8 below show the dimensions of the materials used in this project. On the plate part, by using aluminum type measuring 150 x 200 mm (Top Plate) with 2mm thickness, it works to absorb heat (top plate) from the temperature of asphalt and halogen lamps power 1000 W. The plate on the top used is larger than the plate on the bottom because it can touch the asphalt surface. According to Khamil et al., (2020a), the asphalt influenced the top plate (Temperature Hot), and the soil will remain constant. While the bottom plate measuring 100 mm x 200 mm will be welded together with the H-Shape to cool the TEG's cold part. This is due to the reason that the cold part of the TEG will work to cool and dispersed the heat. The bottom of the plate will also be protected with foam to keep it from being in contact with the asphalt [9].



Figure 3.8 : Simulator box setup for the experiment UNIVERSITI TEKNIKAL MALAYSIA MELAKA Table 3.1: Dimension of material

Material	Dimension (mm)			
H - Shape Rod	Radius			
Aluminum (Top Plate)	150 x 200 x 2			
Aluminums (Bottom Plate)	100 x 200 x 2			
РСМ	100 x 200 x 2			
Asphalt	320 x 320 x 100			
Soil	320 x 320 x 100			
TEG module	30 x 30 x 5			
Halogen lamp	450			

3.5.2 Configuration of TEG

Figure 3.9 below show 3 TEG type APH-127-10-25-S arranged cascading module to module. According to Khamil et al., (2019), the cascaded TEG provides a higher output temperature difference compared to cascaded side by side and single module. And it can also provide a higher output value when connected with a Power management circuit but on the condition that it needs to reach the start-up value of each IC to work [61]. This experiment also uses 3 TEGs connected in series. According to Yusop et al., (2014) series connection will allow the current to be high compared to parallel connection and the TEG cascade connection allows an increase in voltage because the thickness of the TEG can affect the value of the voltage [62]. This is due to the fact that parallel TEG connections will have lower voltage and greater currents, resulting in I2R or Joule heat losses.



Figure 3.9: TEG type APH-127-10-25-S

3.5.3 Phase Change Material



Figure 3.10: PCM Box

Phase change material (PCM) is a product that is able to control the temperature in a way that stores and provides heat energy during the melting and freezing process that is it changes from one phase to another. When PCM is coupled together with asphalt pavement it can work to control cracking through asphalt self-healing. Phase change materials are used as a cooling method for the cold side of TEG. The material for PCM is Calcium Chloride Hexahydrate (CaCl2- 6H2O), which is placed in a container attached with an H-shape and a bottom plate in order to keep a stable temperature that will give a higher value of temperature difference between the top and bottom plates. The higher the temperature difference, the greater the open circuit voltage (V_{oc}) [25].

3.5.4 Configuration of Asphalt



Figure 3.11 : Box hold Asphalt

Figure 3.11 shows the box that has been designed with diameters for the Base (320 x 320) mm and Sides (320 x 100) mm will hold the asphalt and the model while doing this project. In the middle of the base box, a hole is also made to insert half of the H-shape so that it is in contact with the soil for the cooling element process. Next, for this experiment also , the type of Asphalt that be used is Cold mix asphalt. This type of asphalt is usually used for small-scale repairs or patches. It does not require heating and bags of asphalt can be poured directly on potholes or cracks to prevent damage from spreading. It can also be used for emergency patching or repairing broken or potholed road surfaces [9].

3.6 Social design criteria

The idea of energy self-sufficient roadways should be implemented to support efforts toward energy sustainability. Energy harvesting from roadways plays an important role in this context and has received a lot of attention. In particular, in the context of climate change adaptation, the use of road energy harvesting technology is likely to increase public awareness of the importance of renewable energy. The implementation of road energy harvesting technology should also help reduce air pollution and improve public health. By offering clean and affordable energy that can be used immediately for various purposes, including domestic use, and charging mobile electronic devices, this energy use can also positively impact well-being and social amenities [63]. This project will provide a high-efficiency power generator to replace power source utilization and is applied on any asphalt road pavement especially in rural areas to enhance and improve the quality of life of the society and community. Furthermore, by following the established rules and regulations, the materials used in the experiment are safe and can be used in this energy harvesting experiment.



CHAPTER 4

RESULTS AND DISCUSSION



This chapter presents the findings of this study and the report to be concluded which were obtained from the various analyses. Also, a summary of the studies has been presented and each study is discussed in this chapter.

4.1 Simulation Testing

4.1.1 Schematic Diagram





Figure 4.2: Circuit Diagram for LTC3105

Figures 4.1 and 4.2 show the schematic diagram for SPV1050 & LTC3105. The Power management IC Energy Harvesting and TEG are used to control the entire project circuit. For all components used in circuit, product characteristics are determined from the outset of project selection. The components used are supercapacitor, capacitors, resistors, inductors, and others.









c) 5 F

Figure 4.3: Simulation results for supercapacitors charging using Power Management Circuit, SPV1050

For figure 4.3, since the data are more than reach the exceed limit of data in excel, the graph cannot be converted into standardized format like the other graph. These graphs are extracted directly from PSpice software. From the graph, by setting the current value of 100uA taken from real experiment value of Khamil et al., (2021), SPV1050 has shown similar rapid charging for supercapacitors value from 0.01F, 0.1F and 5F [64]. The output shows that the power management IC SPV1050 can reach 4V if employing 3 supercapacitors of 0.01F, 0.1F, and 5F when the TEG input is set to 500mV.



Figure 4.4: Simulation results for supercapacitors charging using power management circuit, LTC3105

As for Figure 4.4, it requires 1ms to reach steady state for LTC3105 to charge 0.1F, 0.01F, and 5F of supercapacitors in compared to SPV1050. In transient analysis the two very important parameters are print step and final time. Hence, time steps here in the simulation is not indicating the real time in experiment [65]

		SPV1050		LTC3105	
VTEG	Supercapacitor	Voltage Output	Time Step to Reach	Voltage Output	Time Step to Reach
		(Vo)	(V 0)	(V 0)	(V 0)
500 mV	0.01 F	4V	8 s	2.4	0.19s
500 mV	0.1 F	4V	4 s	2.4	0.20s
500 mV	5 F	4V	3s	2.4	0.21s

Table 4.1: Comparison IC SPV1050 and LTC3105 in simulation

Based on the simulation circuit between the power management circuit (PMC) between LTC3105 and SPV1050 that show in Table 4.1, it was found that the SPV1050 circuit has a higher charging voltage reading of 4V, compared to the LTC3105 IC which is only capable of 2.4V. This is because for use on small electronic devices, 3.3 V is required for electronic devices to operate [66]. For IC SPV1050, the pump charging method is used for the initialization of the power management circuit and will be active mode when it reaches a value of 0.5V from the TEG source. According to Lee J et al., (2006), the charge pump circuit uses a capacitor to increase the low input voltage to get the higher output voltage. Because the TEG voltage is insufficient to start a simple electrical device, the boost converter can be started when the capacitor is charged up until the voltage level changes. Hence, the utilization of a charge pump in the power management circuit for energy harvesting TEG helps to make it possible for the startup of a boost converter in a short interval of time. The energy extracted from the TEG source can be harvested by the charge pump while the output is connected to a supercapacitor while doing an experiment in the laboratory. While the LTC3105's initial startup input is 0.25 V

when using the cold start method transformer. According to Scheidl A et al., (2021), the use of transformer will give the advantage of being able to achieve high efficiency after a cold-start process with the same transformer, by using a transformer it can control and stabilize the voltage transmission and transformers provide highly efficient and long-distance power transmission, which helps to step up the voltage to a higher level on the output [44]. Hence, the cold start charge pump is much more suitable for environmental sensing. With that, the simulation results will be used as guidance for next experimental investigation.

4.2 Laboratory Testing

This experiment was conducted in the Lab, and a simulator box was designed that resembled the design of road construction, using 1000 W halogen lamps as a heat source. Data readings for Temperature, open circuit voltage (V_{oc}) and Voltage charging supercapacitor will be monitored for 14400 seconds equal to 4 hours and the data readings were taken every 60 seconds (1 minute) by using Picolog (data for Temperature) and NI-DAQ (data for V_{oc} and V_{CAP}). This experiment will look at how the different types of energy harvesting ICs differ in cold start performance and are able to charge according to the time set.



Figure 4.5 : Temperature profiles for laboratory experiment.

As illustrated in Figure 4.5, the temperature during this 4 hours of experiment increases continuously due to the effect of using the lamp as a heat source and in a controlled environment. The controlled environment was the simulator box as seen in Figure 3.8. Hence, the constant temperature.

SPV1050 & LTC3105							
	Top Bottom Middle Asp				Тор	Temperature	
	Plate °C	Plate °C	Plate °C	°C	РСМ	Difference	
					°C	°C (DT)	
Min	25.252	25.712	26.382	25.123	25.744	0.015	
Max	61.621	56.826	50.535	73.982	54.335	11.301	
Average	56.272	49.289	41.887	65.641	46.018	7.007	

Based on the Table 4.2, the temperature on the Asphalt section increases rapidly when the lamp is turned on, which is close to 73 degrees Celsius for 4 hours, while the temperature between the top plate that is connected to the top of the TEG also increases by 61 degrees Celsius. The temperature difference between the top plate and the bottom plate has an effect on the voltage increase in the TEG, during the experiment the temperature difference between the top plate and the bottom plate is only 12 DT. Due to the use of static lamps, it affects the temperature of the bottom plate, the Top PCM, and also the Middle plate. According to Khamil et al. (2021), the data from the paper show, if the experimental test in the field, the bottom of the TOP Plate and asphalt, and the DT will be higher than in the laboratory and it can affect the TEG voltage increase [27]. In Figure 4.5 show that the longer the time taken, the closer the temperature difference (DT).

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Figure 4.6: Voltage Boost for IC SPV1050

Another function of the Power management Circuit is that it can step up and stabilize the output until the V_{oc} is lesser than the minimum required [67]. As seen in Figure 4.6, from V_{oc} has able to boost using SPV1050 to 4V, when V_{oc} reached 500mV. VBOOST 00 0.3 Boosted Voltage (VBoost) SIA ME KNIKAL MAI ΔΚΑ 0.25 0.2 0.15 0.1 0.05 0 0 2000 4000 6000 8000 10000 12000 14000 Time (s)

Figure 4.7: Voltage Boost for IC LTC 3105

While in Figure 4.7 illustrated the boost voltage using LTC3105 only reached to 68mV when V_{oc} is 0.25V.

	SPV1050			LTC3105		
	Min	Max	Average	Min	Max	Average
Voltage						
Open	-0.012	0.674	0.471	0.000561	0.242	0.222
Circuit,V _{0C}	0.012					0
(V)						
Voltage	-0.300	5.23	3.98	-0.00041	0.001528	0.000687
boost (V)						
Time	ALAYSIA	5 minutes	8		Not reache	d

Table 4.3 : Comparison Voltage Boost between SPV1050 and LTC3105

Table 4.3 shows the comparison voltage boost between SPV1050 and LTC3105. From that, IC SPV1050 can boost voltage until 5.23V for 5 minutes compared to IC LTC3105 which cannot boost at certain times.



Figure 4.8: Open circuit voltage from TEG and capacitor voltage for SPV1050



Figure 4.9: Open circuit voltage from TEG and capacitor voltage for LTC3105

For this experiment, to investigate the charging capability between IC SPV1050 and LTC3105, 3 super capacitors were selected to be performed in this experiment. Among the supercapacitor values are 5F, 0.1F and 0.01F. Figure 4.8 and 4.9 shows the open circuit voltage (V_{oc}) and the charging voltage (V_{CAP}) value according to the type of IC selected.



Figure 4.10: Output voltage for SPV1050

Figure 4.10 above shows a graph for V_{oc} . For IC SPV1050, according to the datasheet, when the V_{oc} initial startup reaches 500mV, the voltage drops and becomes unstable due to the supercapacitor, where the characteristic of

supercapacitor will cause the voltage to change when the energy is delivered [68]. The supercapacitor will be in active mode and start the charging process until it reaches 4 V, and after the first start up, the input voltage from V_{oc} can range between 150mV and 18V.The time taken for the charging process for IC SPV1050 is also 4 hours using a 0.01F supercapacitor [37].



Figure 4.11: Close up view of the output open circuit voltage for SPV1050 MPPT (T-Tracking)

In addition, as can see from the graph Figure 4.11, when the MPPT mode is active, the SPV1050 IC will stop switching for 400 ms (sample time) every 16 seconds (tracking time). During the sample period, the IC SPV1050 will also reach a high impedance state and be stored on the (C_{REF}) with a charging capacitor.



Figure 4.12 : Close up view of the output voltage for SPV1050 when V_{EOC} pin trigger

Figure 4.12 show, DC-DC will therefore switch back after the sampling time has passed. The switching phase DC-DC converter also will be stop once the voltage at the store pin triggers the V_{Eoc} and continue until the V_{STORE} value drops below the internal hysteresis-defined threshold. It can be said that this process is a part of the MPPT algorithm.



Figure 4.13 : Open circuit voltage, Voc for LTC3105

Figure 4.13 show the result of V_{OC} for LTC3105, just only able to reach until 250mV. As can see from the graph, due to process charging, the voltage seems unstable because the effect of the supercapacitor.

Table 4.4: Comparison between SPV1050 and LTC3105 in terms of Voltage
Output, V_0

Voltage Open Circuit,V _{OC} (V)		SPV1050	LTC3105			
	Min	Max	Average	Min	Max	Average
0.01F	0.008	0.589	0.402	0.018	0.285	0.242
0.1F	0.012	0.605	0.204	0.003	0.258	0.242
5F	0.167	0.563	0.222	0.027	0.255	0.146

Table 4.4 shows the comparison between two IC in terms of voltage open circuit, As can be seen, the voltage open circuit for IC SPV can reach 500 mV, compared to IC LTC3105 which is only able to reach 250 mV. According to the datasheet of SPV1050,the open circuit voltage value is not stable due to the switching process of the charge pump. So, the experiments in the laboratory acquired the same result, that is why the V_{oc} seems unstable.



Figure 4.14: Capacitor charging voltage for SPV1050

As seen in Figure 4.14, from supercapacitor charging voltage has able to charge using SPV1050 to 4.1V when using 0.01F, and 0.1 F capacitor.



Figure 4.15: Capacitor charging Voltage for LTC3105
While in Figure 4.15 illustrated the capacitor charging voltage using LTC3105 cannot charging when using 0.01F, 0.1F and 5F capacitor. Moving on, another power management circuit such as BQ25505, compared to Khamil et al. (2021), this power management circuit is also unstable but, after the supercapacitor store reaches at 1.8V, Open circuit voltage (V_{oc}) value will become more stable. Therefore, the time taken to charge the supercapacitor at 4 V is approximately 12 000 seconds, within 3.5 hours [27].

Table 4.5: Comparison between SPV1050 and LTC3105 in terms of Voltage charging

Voltage	WALAYS/4	SPV1050			LTC3105	5
Charging,	Min	Max	Average	Min	Max	Average
V _{Cap} (V)	-	KA				
0.01F	-1.743	4.103	3.79	0.041	0.047	0.044
0.1F	0.008	4.097	2.827	0.039	0.044	0.042
5F	0.231	0.358	0.311	0.208	0.223	0.217
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Based on Table 4.5, all results were obtained after completing the experiment. These 3 parameters of supercapacitor have been chosen to investigate the charging result. As can see, the supercapacitor of 0.01F and 0.1F for IC SPV1050 are able to charge until it reached (V_{Eoc}) which is ~4V, but for 5F, it is not able to charge, and the result does not achieve the target. It is different in the LTC3105 IC show in Figure 4.15, where the three supercapacitors used are not capable of charging until they reach a (V_{Eoc}) value of 3.3V [55].

	Time to reach Max V _{EOC}		
	SPV1050 max (4 V)	LTC3105 (3.3V)	
0.01F	1 Hour	Not reached	
0.1F	3.75 Hour	Not reached	
5F	Not reached	Not reached	

Table 4.6: Time taken to reach Max (V_{Eoc}) within 4 hours of experiments.

Throughout the experiment, the data shown in the Table 4.6, time was also taken to study the ability of each IC for the charging process according to the type of supercapacitor used. For the 0.01F supercapacitor, the time taken to charge ~4V is less than I hour compared to 0.1F, only 3.75 hours and the 5F supercapacitor does not reach the value of charge. While for the LTC3105 type IC, the three supercapacitors cannot charge at the specified time. In addition to that, each power management circuit energy harvesting circuit has a different cold start, where it can affect the results during the process experiment. the SPV1050 IC uses a charge pump as a method to start up, while the LTC3105 IC uses a transformer, this method will affect the overall performance of each circuit used.

According to Abdelaziz et al. (2012) because the output from the Thermoelectric generator is very low, less than 1V so it cannot be used for power up in electronic devices, so the cold start method can help in raising low voltage to high voltage [69]. For IC SPV1050, the type of cold start used is the charge pump type, according to Peng et al. (2014) a type of DC-DC converter called a charge pump circuit, uses a switched capacitor technique to either raise or lower the input voltage level [70]. The charge pump also uses a capacitor to achieve high voltage, since the charge pump also helps to start the circuit to achieve from low input to get a higher

voltage. Meanwhile during experiment using LTC3105 the performance of cold start transformer make the IC not achieved the voltage to charge and reached the high voltage.

$$Error \% = \frac{Simulation - Experiment}{Simulation} x \ 100$$

The difference between the results of the simulation and the experiment in the laboratory has been examined and the percentage error calculated in the equation above. External disturbances, human factors, materials, and other variables can all influence the results when undergoing process analyses, but perhaps the results of field experiments are more accurate than any results obtained from simulations. As a result, the percentage for the IC SPV1050 is approximately 20% in comparison to the simulation where the maximum value in the experiment result reaches 5V compared to the simulation which is only 4V. However, the LTC3105 have a big gap due to unable to charge for the assigned 4 hours during the experiment.

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4.2.4 Environmental and sustainability

The TEG generates electrical energy if there is a temperature difference between its surfaces. TEGs are also environmentally friendly and have no moving parts. Furthermore, they are long-lasting and silent, scalable, and emit no greenhouse gases. Their main disadvantage, on the other hand, is their low conversion efficiency of 10%. However, the low conversion efficiency may be overestimated due to the use of TEGs for energy recovery. TEG output voltage must be regulated because it varies continuously with temperature difference. If global energy demand continues to rise, environmental concerns about today's energy sources will persist, as will the need for renewable energy sources, and TEGs will remain one of the hottest research topics.

TEG does not emit greenhouse gases during the generation of electricity, making it environmentally friendly. As a result, TEG has gained increasing attention because it largely meets the public's needs as a green and flexible source of electrical power. They generate electrical energy each time there is a temperature difference in the TEG environment. They are not like solar (PV) panels in that day-night, rainysunny days do not inhibit electricity production. This project is support SDG goal 7 which it can ensure access to affordable, reliable, sustainable, and modern energy for all [71].

CHAPTER 5

CONCLUSION AND FUTURE WORKS

This chapter will summarize interpret, integrate, theories, recommend or apply, and lastly make some suggestions for further research.

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5.1 Conclusion

This experiment has been carried out in a laboratory, where there are materials used such as halogen lamp, asphalt, H-Shape PCM, and also picolog and DAQ software. This experiment was performed according to the height of the lamp level from the asphalt position and the output voltage analysis of both ICs. The height of the lamp level is taken at a distance of 45 cm.

Several objectives of this project have been achieved, among which is to analyze the cold-start performance of the new energy harvesting (EH) circuit. The cold start effect in the power management circuit allows us to know which method can be used as a guide in terms of weaknesses as well as advantages when doing this experiment. The IC used in this experiment, namely LTC3105 and SPV1050, have different types of cold start. This different type of cold start can make a process affect the amount of voltage required, and the time it takes to boost & charge. For the LTC3105 IC, it uses a cold start transformer, while the SPV1050 IC uses a charge pump type cold start. For the LTC3105 cold start type transformer requires an input voltage of at least 250 mV for the power management circuit to act in the charging process and boost to a better voltage, while the SPV1050 requires an input voltage of TEG 500mV.

Next is, to investigate the charging capabilities between the SPV1050 and LTC3105. Based on the results shown in chapter 4, 3 supercapacitors are used to test the ability of each IC for charging. Among the supercapacitors used are 0.01,0.1,5F. The SPV1050 IC can charge at a total voltage of ~4V on the 0.01F and 0.1 F supercapacitors, compared to the LTC3105 IC which is unable to charge for 4 hours for the experiment time. So based on problem statement 1 stated that energy harvesting circuit that design to solar for LTC 3105, the result cannot be able to charge because according to datasheet the voltage input should achieve 0.6V, while SPV1050 it can charge and achieve the MPPT ratio for teg 0.5, and the charging voltage does not drop even though the voltage from input is unstable. The increase in input voltage on the TEG also depends on the differential temperature. The higher the temperature difference, the higher the laboratory, the total temperature difference is only 12 C between the Top Plate and the Bottom plate.

As a conclusion, the difference in IC energy harvesting in terms of cold start, component use, technical issues from the board and so on can have an effect on the desired voltage reading process, this matter needs to be done carefully in order to obtain the desired result.

5.2 Future works

Several features are required at the end of this project to improve the performance and functionality of the circuit. By using a thermoelectric energy harvester system, it can help give energy to the world to be well controlled without wasting it. It is very necessary because it is an environmentally friendly material and very reliable in forming energy that is able to provide convenience to humans in using it. So, the future work that can be stated is to design a circuit purposely with TEG's source that able to charge and boost rapidly. In addition, adding more TEG helps to increase the voltage and current, to make the charging process faster and it will help the performance of the power management circuit.

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APPENDICES









ALAYS/A			
Pin No	Name	Туре	Description
	E C	6	
1	MPP	¥1	• Max. power point tracking voltage sense pin.
F			• To be connected to the voltage source
			through a ladder resistor
	SALW O		
2	MPP-SET	L	• Max. power point setting voltage pin.
-	مليسيا مالاك	5	• To be connected to the MPP pin through a
U	INIVERSITI T	EKNI	ladder resistor. Connect to STORE if MPP function is not required.
3	MPP-REF	Ι	• Max. power point reference voltage pin.
			• To be connected to a 10 nF capacitor.
			• Connect to an external voltage reference if
			MPP function is not required.
1	GND	GND	Gignel ground nin
-	Give	UND	
5	LDO1_EN	Ι	• If high, enables LDO1.
6	LDO2_EN	Ι	• If high, enables LDO2.
7	BATT_CHG	0	Ongoing battery charge output flag pin (open
			drain).

			• If low, it indicates that the battery is on
			charge.
			• If high, it indicates that the battery is not on
			charge.
8	BATT_CONN	0	• Battery status output flag pin (open drain).
			• If high, it indicates that the pass transistor
			between the STORE and BATT pins is open
			(battery disconnected).
			• If low, it indicates that the pass transistor
			between the STORE and BATT pins is
			closed (battery connected).
9	EOC	Ι	• Battery end-of-charge pin.
			• To be connected to the STORE pin through a
	WALAYSIA 4		resistor divider between EOC and GND.
10	UVP	I	Battery undervoltage protection pin.
EK		S.A.	• To be connected to the STORE pin through a
12	<u>ا ا ا ا ا ا ا ا ا ا ا ا ا ا ا ا ا ا ا </u>		resistor.
	0		
11	LDO1	0	• 1.8 V regulated output voltage pin.
5	Mo hunde	4	and in musical
12	LDO2	0	• 3.3 V regulated output voltage pin.
12 U	NIVERSITI T	EKNI	KAL MALAYSIA MELAKA
15	CONF	1	Configuration pin.
			• Boost configuration: to be connected to the
			voltage supply source.
			• Buck-boost configuration: to be connected to
			ground
14	BATT	I/O	Battery connection pin
17	Ditti	цО	• Battery connection pin.
15	STORE	I/O	• Tank capacitor connection pin.
16	IN_LV	Ι	• Low voltage input source.
			• It must be connected to the inductor for both
			boost and buck-boost configuration.

17	NC	-	• Not connected.	
18	PGND	PGND	• Power ground pin.	
19	L_HV	I	 Input pin for buck-boost configuration. Boost configuration: to be connected to ground. Buck-boost configuration: to be connected to the inductor. 	
20	IN_HV	I	 High voltage input source. Boost configuration: to be connected to ground. Buck-boost configuration: to be connected to the voltage supply source. 	
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