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An Optimized Energy Harvesting Circuit for Low-Power IoT Applications

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ABSTRACT

The concept and development of an independent energy harvesting mechanism functioning intermittently are described in this paper. A power management circuit (PMC) that is self-regulating, an energy scavenging module, a circuit for charging batteries, as well as an electronic load are all a component of the system that has been proposed. This proposed circuit is designed to attain a fixed output power with a diverse input range. In the unavailability of an additional voltage supply, the PMC can react, maintain, and smartly control the electronic load's power supply. The self-powered energy accumulating technique is expected to be used in situations when supplied power is inadequate to drive the load properly, such as Internet of Things (IoT) applications. IoT is a dispersed architecture of reduced-power, limited-storage, lightweight, and nodes that are adaptive. The majority of embedded IoT devices and low-power IoT sensors are driven by short-life batteries that must be replaced every few years. This procedure is expensive and efficient energy regulation could be critical in enabling energy savings for connecting IoT devices. Experiments with the proposed PMC show that the voltage stored in the capacitor remained mostly fixed at 3.3V at widely diverse inputs that vary from 850mV to 4V. At 3.5V input voltage, a peak efficiency of 88.67% is achieved while the load resistance considered is 230Ω.

1. INTRODUCTION

Nowadays, many applications of wireless sensors and wearable devices have exploded. Wireless Sensor Networks (WSN) which operate at relatively low power is an important part of the Internet of Things' growth (IoT). That kind of sophisticated sensors is projected to be exploited in a variety of circumstances, including environment observation (Sim & Choi, 2020; Tan, 2017), traffic supervising (Jayakumar et al., 2021), remote observation (Shyni et al., 2020), biomedical monitoring, etc. (Mayer et al., 2021). All of these applications have potential uses in a variety of fields, including bioengineering, materials engineering, communications, medicine, etc. (Gomez-Casseres et al., 2016). The Internet of Things (IoT) includes regular objects like laptops, medical equipment, cell phones, and other electronic devices, and it may one day include items as common as furniture or clothing (Udoh & Kotonya, 2018). It is an innovation that enables devices to connect by sensing, processing, and transmitting data. The sensing terminal is a vital part of the IoT that converts a variety of physical parameters, such as humidity, temperature, pressure, light intensity, and other environmental factors are converted into digital signals (Qin et al., 2018; Raad, 2020). Sensors in the IoT consume very little energy, but they are large and widely dispersed, with the capability of being movable (Krishnamurthi et al., 2020). Current advancements in wireless communications, sensors and integrated processing platforms have paved the way to design affordable, low-power compact electronics that can access the internet. These are the core features of the emerging Internet of Things concept (Bkheet & Agbinya, 2021; Marinakis & Doukas, 2018; Samie et al., 2016; Villamil et al., 2020). The rapid spread of the Internet of Things as a prospect for the electronics sector necessitates highly proficient sensor node development (Ahmad et al., 2017; Kaur & Sood, 2017). Each functional equipment in the IoT system needs a specific volume of energy to execute its functions properly (Zeadally et al., 2020). However, securing long-term power sources for such sophisticated sensors, and IoT devices, in particular, is a huge concern. Although batteries have been the most common strategy for powering wireless devices, they must be checked regularly to ensure continued functionality. Any such requirement is undesirable because the major limitations for battery-powered devices are inadequate life cycle, lower energy density, current dissipation (even when it's not being used), labor cost, and toxic disposal (Adu-Manu et al., 2018; Siddique et al., 2015), while cabled energy connections have drawbacks including the expense of wire materials, connectivity challenges for multiple devices, and electricity resistance. Conversely, wireless energy connections, have none of these issues (Vanhecke et al., 2015; L. Wang et al., 2019). Furthermore, it may be tough or even impossible to change the battery in applications with a vast quantity of IoT devices (thousands or more) (Statista, 2015). Therefore, finding a feasible way to continuously distribute such a large quantity of components is a hotly discussed research objective (Newell & Duffy, 2019).

Energy Harvesting, a way of generating energy from environmental resources is a promising option to produce constantly operated IoT modules that do not have to be recharged throughout their total operation since it provides a consistent and reliable energy supply with lower installation and maintenance expenses (Mishra et al., 2019). Ambient energy sources are increasingly playing a supporting role in meeting the constantly growing demand for wireless and portable electronic gadgets (Z. Zhao et al., 2017). Harvested energy from ambient energy sources like solar (Cabello et al., 2020), wind (Shi et al., 2021), ocean (T. Zhao et al., 2021), etc. have been employed as a power source to operate wearable devices or wireless sensors nodes (Hu et al., 2018). It is the most promising approach to extracting energy from natural resources and developing WSN devices that do not require recharging for the duration of their operation (Ababneh et al., 2019; Miglani et al., 2020). Energy harvesting is a reliable technique that may be applied either in industrial or residential applications. [29]. Several well-established energy harvesting methods including the electromagnetic effect (Yan et al., 2020), the piezoelectric effect (Z. Wang et al., 2021), and the triboelectric effect (C. Zhao et al., 2021), etc. have been established in recent years to acquire energy from the surroundings that are required to run low-power, portable smart electronics. The energy harvesting technology harvests and captures relatively small quantities of readily available energy from the surroundings. However, many energy resources are incapable to deliver the vast amounts of energy needed to power IoT gadgets (Fu et al., 2020). Moreover, using an energy harvester as an input imposes supplementary circuitry and energy regulation technologies when contrasted to both main-powered and battery-powered systems.

Energy harvesting circuits provide the advantage of extending battery life, allowing gadgets to function for longer periods perhaps forever (Procel et al., 2019). Given the features of low voltage and power of micro energy harvesting resources, and also the imbalance among the load and the source's output power level, this additional circuit is necessary. As a response, driving a wireless instrument demands a PMC, a DC/DC converter, and an energy preserver. The power management circuit's main objective is to provide highly efficient energy transfer and accumulation between both the energy harvester and the load since an energy harvester's average output power is in the μW range (Lin et al., 2020). To achieve stable output from energy harvesters for convenient applications, power management circuits are typically used. When working with low energy, circuit design should prioritize low power consumption and quick startup times (Kalaivaani & Krishnamoorthi, 2020; Priya et al., 2019; Tamrin & Ahmad, 2020). The application of the PMC in IoT equipment has stimulated attention to harvesting micropower (Muhtaroğlu, 2017; Woias, 2015). Likewise, due to their inability to respond to fluctuations in input power, most typical PMC that execute a set of criteria are inadequate for low-power energy harvesters. To ensure a constant output power, a ubiquitous adaptive power regulation circuit to extract the maximum power from it and a higher power altering capability is drawing consideration to be implemented in the wireless sensor node built on IoT (Prasad & Chawda, 2018).

To maximize energy harvesting proficiency and to produce a stable output voltage with little variation, an enhanced and effective power regulation system for ultra-low powered IoT sensors is suggested in this study. The suggested design employs a converter IC that works on the buck-boost principle which is capable of handling different input voltages varying from 850mV to 4V. Because of the PMC's unique architecture, it's been successful in retaining the output voltage steady at 3.3V and it has a conversion efficiency of 88.67% for the stated input voltage levels which makes it appropriate for the operation of IoT devices. This proposed design additionally includes a battery charging IC to preserve the optimal energy and to assist IoT equipment to operate constantly.

2. DESIGN OF THE PROPOSED SYSTEM

Figure 1 represents a schematic representation of an independent and universal energy harvesting method, which includes an ultra-low-power managing circuit, several energy harvesters, some loads, and a battery charging circuit. Due to the enormous number of nodes in an IoT infrastructure, it is necessary to stimulate the accessibility of alternative resources. Batteries are often used to power IoT nodes. As a result, the energy consumption of specific devices and the complete system (i.e., actuators, sensors, and microcontrollers) must be controlled throughout the design of an IoT setup.

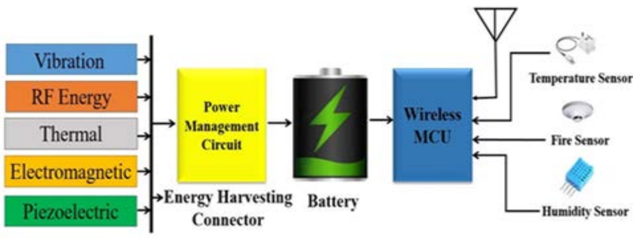

Figure 1: Schematic representation of a ubiquitous energy scavenging system

The main concern of this work while designing the circuit is to provide a regulated output voltage (3.3V in this work) from any energy harvester available in the environment. Figure 2 depicts the entire power management system, which includes an energy source, a DC/DC converter, a full-wave bridge rectifier, and a battery charging circuit. The complete circuit was designed and simulated using the LTspice XVII software.

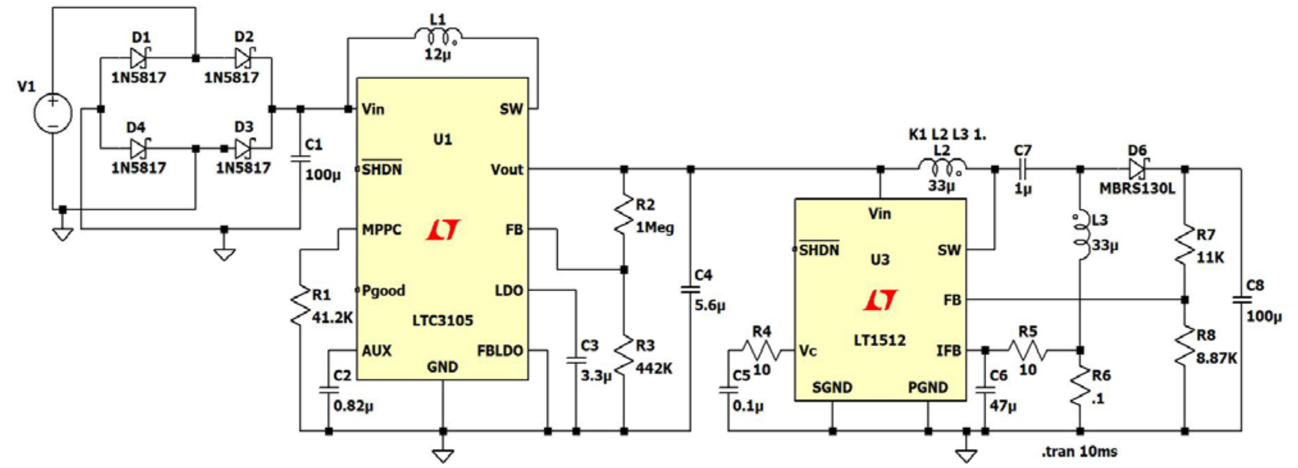

Figure 2: Circuit diagram for the ubiquitous ultra-low power management system

A. Modeling of the proposed Rectifier Circuit

Although energy harvesters generate ac voltage, whereas a power storage unit typically functions at dc to drive the sensor node load, therefore it demands an ac-dc rectifier circuit linked at both ends of the generator in the first stage. The electrical power can be harvested directly if the output voltage from the rectifier is larger than the energy storage device. The rectifying bridge circuit of the proposed system is made up of four compact Schottky diodes. The rectified input and output voltages are shown in Figure 3.

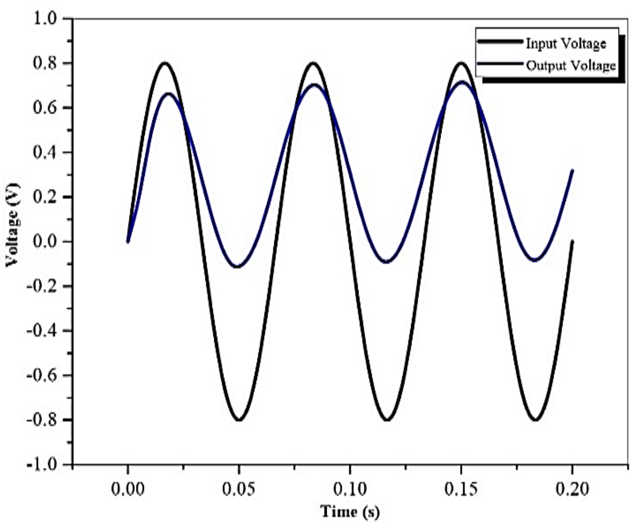

Figure 3: Input and output voltage waveforms of the rectifier

Origin 2016 software was utilized to visualize the output voltage graph. Here, the considered input voltage is 850mV, and the rectified output voltage is 772.49mV (Vpk). Conventional rectifiers based on silicon diode bridges are ineffective as an AC-to-DC conversion since energy harvesters' output voltage peaks are frequently less than 1 V_{pk}. A Schottky diode, on the contrary, can consume a lesser voltage than a regular silicon diode since its terminals only consume 0.3~0.4V. The satisfactory forward voltage loss of a Schottky diode over a conventional diode is one of its core advantages. Schottky diodes also have a quicker recovery rate than other types of diodes which makes them suitable for fast switching operations. It also works well in low-voltage scenarios since it demands lower power. Such diodes have been selected specifically for rectification since they have a modest forward voltage loss and leakage current.

B. Modeling of the proposed DC-DC Converter

The energy harvesting module produces a variable order of voltages, whereas the load circuit requires a consistent DC voltage. In some situations, however, the output voltage of the rectifier is smaller than that of the storage elements. Therefore, the generated voltage must be regulated and boosted. Moreover, since the electronic load may necessitate higher power, the harvesting module may struggle to produce suitable power consistently. The primary goal of a DC/DC converter in a compact device is to link up a battery to the different components of a system if the battery voltage does not align with the required voltage. The voltage of the battery may be either too low or too high. In that scenario, DC/DC upconversion is necessary. Consequently, if the battery voltage is relatively larger than the highest allowable feed voltage, DC/DC down conversion is necessary. However, from the perspective of efficiency, converting the battery voltage to the minimum supply voltage V_{min} required by the load is always a smart idea because of the reasons mentioned. To begin with, once a DC/DC converter is utilized, the load can be designed for the lowest supply voltage rather than the entire voltage span of the battery. In most circumstances, this will result in a better load performance. Second, driving a system component with a greater voltage supply than required is a misuse of energy. A PMC is used to recharge a storage capacitor. The suggested PMC has the feature of not requiring an external power source because it is self-powered owing to the front-end harvesting device. The PMC has an autonomous regulatory circuit that can deliver constant functional power to the load even if the accumulated power is insufficient. We utilized an LTC3105 step-up DC to DC converter in our suggested circuit design, which was capable to retain the output voltage constant at 3.3V for input voltage varies from 450mV to 4V.

C. Modeling of the proposed Battery Charging Circuit

A wireless sensor module consumes a lot more optimum power than an energy extractor can provide. The energy storage device should be used to store any excess generated energy for a prolonged period to efficiently operate the load. In the proposed methodology, we have used LT1512 Constant Current/Voltage Battery Charger to charge a capacitor. The LT1512 is a 500 kHz current mode switch regulator that has been particularly designed to generate a constant-current/voltage battery charger. It has a current sensor feedback circuit in addition to the conventional voltage feedback node for precisely managing the output current of a flyback topology charger. The LT1512 has a peak switch current of 1.5A. For a single lithium-ion cell, this permits charging currents of up to 1A. As a storage element, a capacitor C8 with a capacitance of 100F is considered, which stores energy for proper use of quick power output bursts. To inhibit energy dissipation from the load, the load's capacitor should be disconnected during the energy storage phase, and it can only be reconnected if the energy generated is adequate to run it.

3. SIMULATION AND RESULTS

Figure 4 demonstrates the output voltage of the PMC. The input of the energy harvester is a sinusoidal voltage with a magnitude of 850mV, a frequency of 15Hz, and a DC offset voltage of 0V. Three different capacitors (5.6F, 10F, and 15F) are considered at the PMC's output to produce the best possible regulated voltage. The utmost output voltage is 3.3V when a 5.6F capacitor is adapted, as presented in the picture. If the 10F and 15F capacitors are employed, still, the output voltage falls below 3.3V. Because the 5.6F capacitor can generate a stable output voltage of 3.3V, it's been chosen particularly.

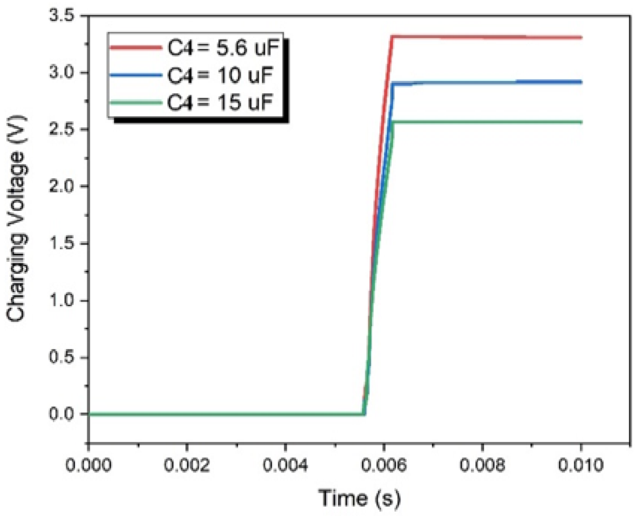

Figure 4: Regulated output voltage graphs for different charging capacitors

The output voltage from three different charging capacitors (47F, 100F, and 150F) is shown in Figigure 5. The proposed battery charging IC delivers higher than 3.5V, 3.3V, and lower than 3.3V, correspondingly, at 47F, 100F, and 150F capacitance. Furthermore, reaching saturation at 150F capacitance takes some time. We chose this capacitor since the IC can generate a stable voltage of 3.3V with a capacitance of 100F.

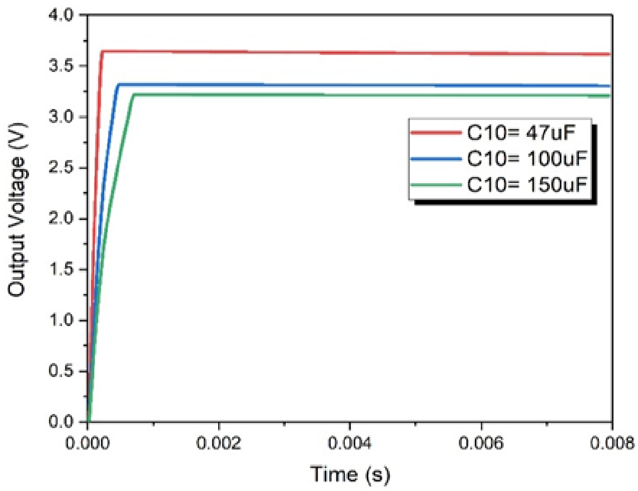

Figure 5: Output voltage graphs for different capacitors considered as batteries

The energy harvester's characteristics are used to determine output power, output voltage, optimum load, and resonant frequency. The energy harvester's output voltage is shown in Figure 6 when the frequency varies from 5Hz to 50Hz. The least possible voltage is below 1V for frequencies ranging from 0Hz to 14Hz, while the highest voltage goes between 3.30V to 3.35V for frequencies varying from 15Hz to 50Hz, as shown in the figure.

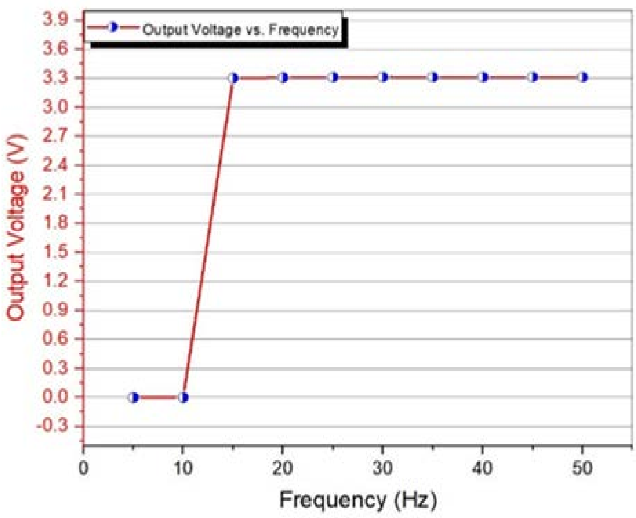

Figure 6: Output voltage at the different input frequencies

Figure 7 shows the load voltage and output power vs. load resistance curves. It is clear to visualize that the voltage level steadily rises with increasing load, reaching 3.3 V at 230 Ω. at that stage, the highest power was delivered to the load. At a load resistance of 220k Ω, the peak output power is 68.5W. The $P=V^2/R_L$ equation can be utilized to approximate the imminent power output of an energy harvester.

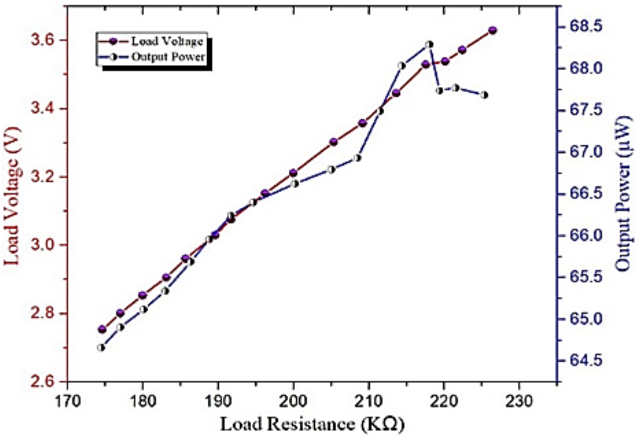

Figure 7: Load voltage and output power waveform vs. load resistance

The output power waveform as a parameter of the duty cycle is illustrated in Figure 8. The highest power can be generated by the energy harvesting system to a battery throughout a variety of duty cycles, as presented in this diagram. Moreover, the voltage that passes across the voltage multiplier from the energy harvesting system is consistently at the ideal duty cycles.

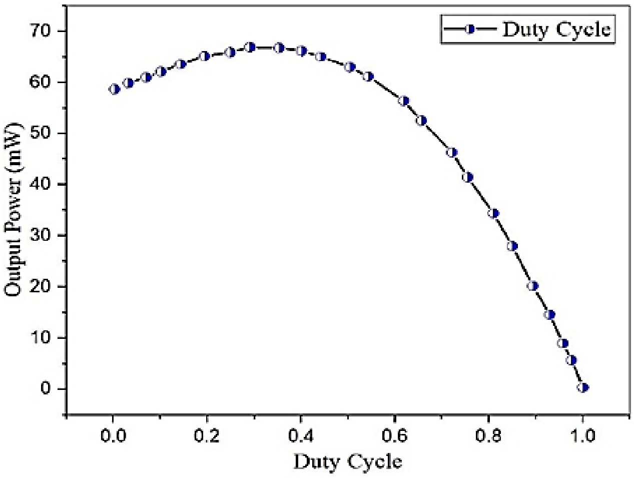

Figure 8: Output power as a factor of the duty cycle

Switching regulators transform one voltage to other by momentarily accumulating energy and then delivering it at various voltages to the output. To convert one voltage to another, the switch pauses the transfer of current to energy-storing equipment, such as a capacitor or an inductor. A switching regulator is equivalent to a transformer. As a result, energy wastage is reduced. To deliver energy from the source to the output, an inductor is used. Figure 9 shows the input voltage vs. power conversion efficiency graph of the suggested PMC. Efficiency can be obtained by dividing the output power by the input power. When the output power equals the input power, the power conversion efficiency is 100 percent, and the regulator loses no energy. This is the ideal state, but it is unreachable. From the figure, it can be seen that from 0.85V to 2.5V, the power conversion efficiency is low because in that case, both the output and input power is low hence lower efficiency is obtained. When the input voltage increases from 2.5V to 3.5V, the ratio of output and input power becomes higher, and therefore significantly higher power conversion efficiency is achieved which is 88.67%. In (Safwat & Ibrahim, 2021) and (Leeuw & Srivastava, 2021), the peak efficiencies reported are 91.6% and 74.21%, respectively which are slightly higher and considerably lower, respectively than our proposed circuit. After 3.5V, since the input power is increasing but the output power remains fixed, the efficiency is getting lower as seen in the figure.

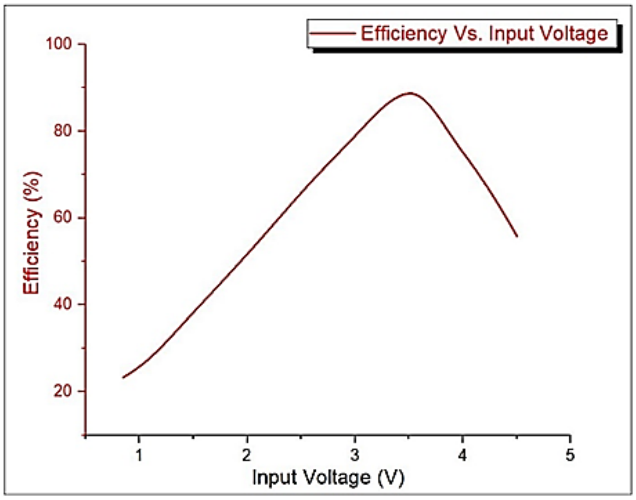

Figure 9: Input voltage vs. circuit efficiency graph

To the best of the author's understanding, among the other circuit works that have been reported, this suggested power regulation circuit delivers one of the best outcomes. Table 1 shows an analysis of the suggested power management circuit and multiple harvesting circuits.

Table 1
Analysis of the performance of several energy harvesting technologies

Reference	Mechanism	Output Voltage	Power Density
Zhang et al., 2019	Triboelectric	3.5V	16.780mW/m3
Li & Jing, 2021	Electromagnetic	2.8V	0.240mW/m3
Uchino, 2018	Piezoelectric	2.33V	0.0013mW/m3
Fang et al., 2021	Hybrid	1.06V	1.580mW/m3
This work	Universal	3.3V	23.60mW/m3

The prices of different parts of the system obtained from different electronic device manufacturers are shown in Table 2. Both the LTC3105 and LT1512 account for the majority of the entire device costs. The LTC3105 is a highly effective DC/DC converter that can harvest and regulate energy from a very minimal input voltage source.

On the other hand, the LT1512 is a 500kHz switching regulator that has been specifically designed to build a continuous-current/continuous-voltage battery charger.

Table 2
Cost calculation of the suggested method

Materials	Provider	Qty.	Price/Qty.	Subtotal
LTC3105	Analog Devices Ltd.	1	$5.30	$5.30
LT1512	Analog Devices Ltd.	1	$3.28	$3.28
Schottky Diode	Cheng Industrial Ltd.	5	$0.05	$0.25
Resistor	Cheng Industrial Ltd.	8	$0.01	$0.08
Capacitor	Cheng Industrial Ltd.	8	$0.08	$0.64
Inductor	Cheng Industrial Ltd.	3	$0.30	$0.90
			Total	**$10.45**

4. CONCLUSIONS

For this research, we built a universal ultra-low-power control circuit that can be used in a variety of harvesters. Any harvester, such as electromagnetic, piezoelectric, and others, will benefit from it. The proposed approach is more efficient than existing generally available power management circuit works. This unique circuit design results in excellent effectiveness and a quick start-up phase, making it ideal for low-energy scavenging purposes with minimum power dissipation. The highly functional energy extractor with low power regulation shown here is a suitable solution for developing a more durable and practical self-powered mechanism that can work with a wide range of ambient insufficient mechanical energy and fit into a variety of application scenarios. The proposed PMC is designed to preserve and regulate electrical energy produced without the use of an additional supply, as well as self-control capacitor charging.

Currently, the Internet of Things (IoT) is serving as an extremely essential aspect of our daily activities, grabbing worldwide attention and bringing up plenty of new opportunities. It's an exciting concept for networking equipment, where the extent of interactions between devices grows every year. With the substantial rise of IoT systems, it is also crucial to recognize sustainable, dependable, and sources of energy that are inexpensive for operating the batteries of sensors, as this research concentrates on ultra-low-power managing circuits for energy harvesters. The issues and approaches utilized to circumvent energy harvesting have been addressed in particular. The components that make up a robust energy-scavenging system are examined in this research. A full-wave bridge rectifier, a battery charging circuit, a DC-to-DC converter, and a precise energy storage system are among them. To begin, we created an AC-DC rectifier incorporating a Schottky diode, a battery charging system, and a reliable and safe voltage regulator that may deliberately reduce system expense while extending battery lifespan. A sensor is necessary to remotely monitor wave height.

To wirelessly send sensor information, a wireless sensor node is essential. The suggested ultra-low-power control circuit can be utilized to make sure that the wireless sensor node receives consistent power. When supplied power from the environmental source is unsatisfactory or unreliable to immediately turn on the electronic equipment, it is an ideal alternative for microelectronics and IoT-focused devices which are self-dependent on the intermittent functioning method.

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