Journal of Engineering Science and Technology
24th EURECA 2025 Special Issue April (2026) 57 - 68

SMART POWER MANAGEMENT CIRCUITS FOR RF ENERGY HARVESTING SYSTEM

WEI RONG LOW, MANEE SANGARAN DIAGARAJAN*,
WEI HOWN TEE, INTAN IZAFINA IDRUS

School of Engineering, Taylor's University, Taylor's Lakeside Campus, No. 1 Jalan Taylor's, 47500, Subang Jaya, Selangor DE, Malaysia
*Corresponding Author: manee.diagarajan@taylors.edu.my

Abstract

RF energy refers to the radiofrequency energy which generates from the wireless communication sources such as Wi-Fi routers, broadcast towers, Bluetooth devices, and others. It considered as ambient energy source which can be utilised as an efficient energy solution to sustain low power, battery-less devices. This solution can be achieved by converting the ambient radio frequency signals into usable DC power. However, in order to make this concept function efficiently, a smart power management circuit is essential. The power management circuit consists of energy storage elements, voltage regulation, and load management systems that dynamically adapt to fluctuations in the input source, thereby providing a stable power supply. This paper presents the design and development of smart power management circuit (PMC) for RF harvesting circuit through software simulation. The LTSpice software was used to perform most simulation during research and development stage for the circuit design. The PMC was driven by a multifunction IC which enabled functions of power conditioning and load management. The designed system was able to handle two inputs and two outputs depending on the varying RF signals to maximise energy conversion and minimise power losses. The PMC operated with an input voltage below 1V and can be boosted to a voltage level of 5V. This work contributes to the advancement of autonomous, energy-efficient systems for ubiquitous low-power applications.

Keywords: Energy harvesting, Power management, Radio frequency, Wireless power.

1. Introduction

Power management is one of the important circuits in a RF energy harvesting system which come after RF signal harvesting, impedance matching network, and rectification or voltage multiplier. Before going into the power management circuit, it is necessary to understand what RF energy harvesting is, how it operates. Radio frequency energy harvesting (RF-EH) is a technology that uses electromagnetic waves from a variety of sources, including mobile phones, Wi-Fi signals, and broadcast television, to generate wireless power for battery-free devices, making it a possible alternative energy source for future applications [1]. The technique entails harvesting RF energy with a receiving antenna and transforming it into usable direct current voltage using rectification [1]. The efficiency of RF-EH systems is determined by several parameters, including the receiving antenna design, the ambient power density of RF sources, and the efficacy of energy harvesting circuits [2]. With developments in electrical technology, RF-EH units can achieve high efficiency while requiring minimum current and voltage, making them appropriate for a wide range of applications that value wireless power transfer and environmental sustainability [3].

RF energy harvesting has a long history, reaching back nearly a century, with recent advances focusing on optimising energy consumption in a variety of fields, including telecommunications. Researchers have been investigating the potential of RF energy harvesting to power low-energy devices in remote places without the need for regular battery changes by utilising ambient RF signals from bands such as GSM and Wi-Fi. The progress of RF energy harvesting technology has resulted in the creation of high-efficiency RF energy-harvesting chips capable of capturing ambient RF energy, converting it into usable energy, and storing it in energy storage devices such as supercapacitors or rechargeable batteries [4]. This type of energy can be categorized as renewable energy contributing to SDG 7, affordable and clean energy. These improvements promise to enable self-powered IoT devices wirelessly, providing a potential solution for future smart devices and sensors.

Figure 1 depicts an RF energy harvesting system, which generally comprises an antenna for energy capture, an impedance matching circuit for efficient power transfer, an RF-to-DC converter, and a power management circuit. This paper will focus on the design and implementation of the power management circuit, as highlighted in red in Fig. 1.

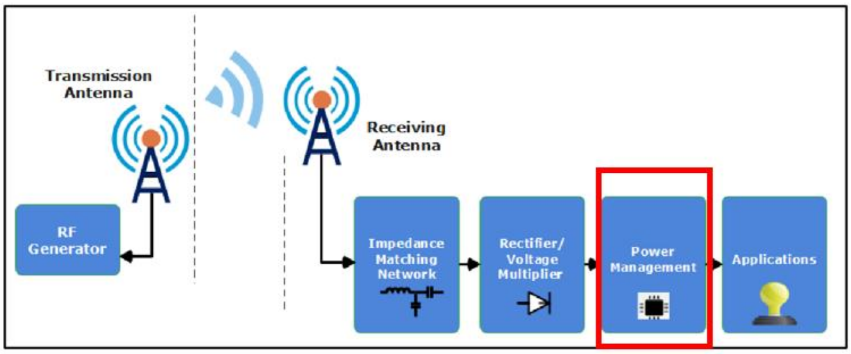

Fig. 1. Block diagram of RF energy harvesting system.

A power management circuit is essential for the harvested RF energy to be efficiently converted and utilized for the desired load. To construct a smart power management system, there are various primary type of power management systems for RF harvesting system which is DC-DC conversion system, energy storage system, power conditioning system, maximum power point tracking system (MPPT), and energy management controller.

The first DC-DC conversion system here is responsible for the buck, boost, or buck-boost converter. By effectively converting energy from ambient sources, a buck-boost converter is an essential component of energy harvesting systems. The buck-boost converter's main function is to control the output voltage, enabling a steady power supply even if the ambient energy source's input voltage fluctuates [5]. This is necessary to power a variety of applications that need a steady and dependable power source, like embedded sensors, remote wireless sensors, and wireless sensor networks (WSN). When low input voltage levels are present in micro-power energy collecting devices, the buck-boost converter is especially helpful. It is an essential part of self- sufficient and sustainable energy systems because it effectively controls power conversion, ensuring that the energy is harvested, stored, and used to power electronic equipment [5].

Followed by that, an energy storage for the power management system is also essential. The type of energy storage can be capacitors, supercapacitors, batteries, and others. Despite this, the selection of an appropriate energy storage for each different energy harvesting system also crucial which include the factors like energy and power requirements, size and weight constrain, environmental conditions, costs, cycle life, and durability. To effectively harness renewable energy sources and meet the world's growing energy demands, energy storage technologies are critical [6]. However, it is not limited to have only single energy storage for the power management system. Multiple and multitype storage can be integrated and work with algorithms to form a Hierarchical energy storage system.

Moving on to the power conditioning system, voltage regulators are being exploited to maintain a steady voltage level of input voltage fluctuations or load variations [7]. They are essential to the stable and dependable operation of electronic equipment. These regulators are crucial to extend the lifespan and improve the functionality of the system by shielding delicate parts from harm caused by overvoltage or undervoltage situations [8]. Voltage regulators improve the overall efficiency of the system by supplying a steady power supply, which permits various parts and circuits to operate consistently.

Furthermore, MPPT system is another important factor to construct excellent ambient energy harvesting system. The objective of MPPT system is to increase the overall efficiency of the system and assists in obtaining the most power possible from energy transducers [9]. The MPPT system is implemented to precisely measure the maximum power point voltage and thus increase the energy conversion efficiency and results in improved performance with longer operating durations for harvesting sources.

The last primary power management system will be the energy management controller or known as power management integrated circuits (PMICs). This unit integrates multiple power management systems and functions mentioned above into a single chip. Therefore, it can standalone perform various power management system activities [10].

This objective of the paper is to design and develop an ultra-low power energy harvesting boost converter with threshold-based activation. It is designed to maximize RF energy harvesting by optimizing the circuit's responsiveness to varying input RF levels. By combining these approaches, the system ensures efficient power capture and allocation, maintaining optimal energy availability for load requirements while safeguarding sufficient reserves in storage for periods of low RF input with an input as low as 1V.

2. Methodology

2.1. Overall research design

The entire research design of this project relies on the combination of various methodologies to find the most thoroughly investigated and validated proposed smart power management system with threshold-based activation boost converter and dynamic prioritization algorithm to manage energy distribution between storage element and load for RF energy harvesting. The design incorporates four approaches: experimental, comparison, simulation, and case study. Given the research objectives and methodologies involved, this study primarily adopts a quantitative approach. The circuit design is based on the power management integrated circuit (PMIC), LTC3106, as illustrated in Fig. 2.

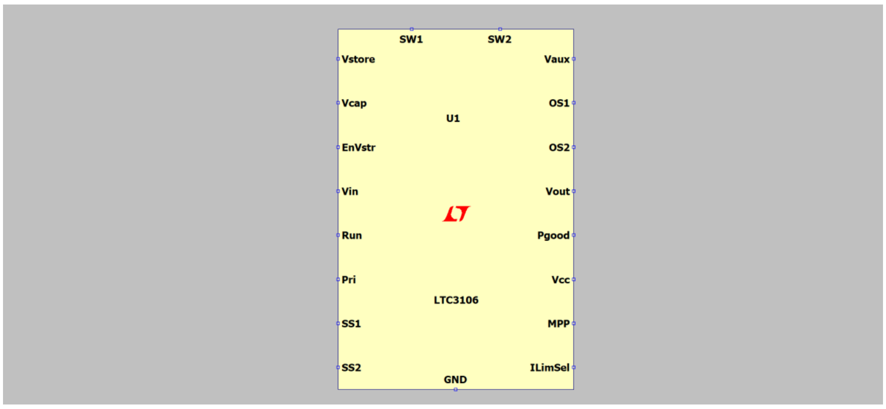

Fig. 2. Pin configuration on PMIC LTC3106.

Figure 3 shows the internal configuration of PMIC LTC3106 in the form of block diagram. The final power management circuit will be constructed based on this PMIC LTC3106.

2.2. Programmable output voltage

This PMIC, LTC3106 provides the programmable output voltage function which maximum output voltage value can be set by performing different circuit connections as shown in Fig. 3. The output voltages can be chosen from either 1.8V, 2.2V, 3.3V, or 5V by manipulating the connection for pin OS1 and OS2 as shown in Table 1 [8]. In this case, 5V output voltage circuit connection will be configured by connecting OS1 and OS2 to VCC with a decoupling capacitor rated at 0.1µF as shown in Fig. 4.

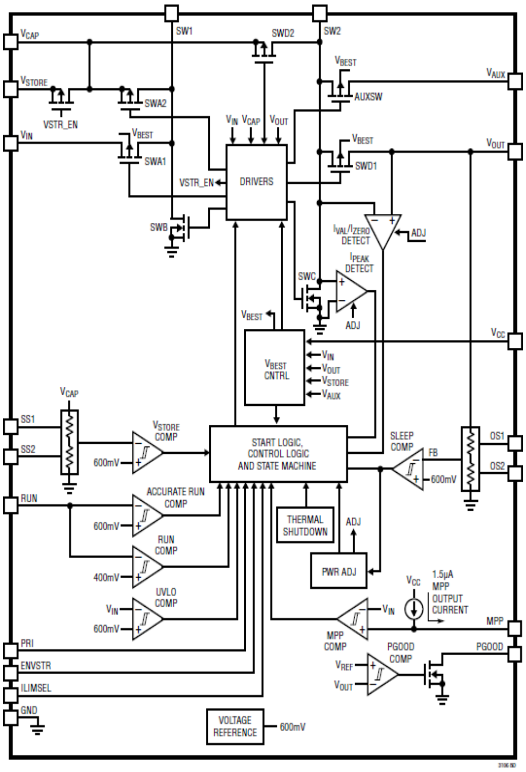

Fig. 3. Block diagram of internal configuration for PMIC LTC3106 [11].

Table 1. Output voltage selection [11].

OS1	OS2	Output Voltage
0	0	1.8V
0	V_{CC}	2.2V
V_{CC}	0	3.3V
V_{CC}	V_{CC}	5V

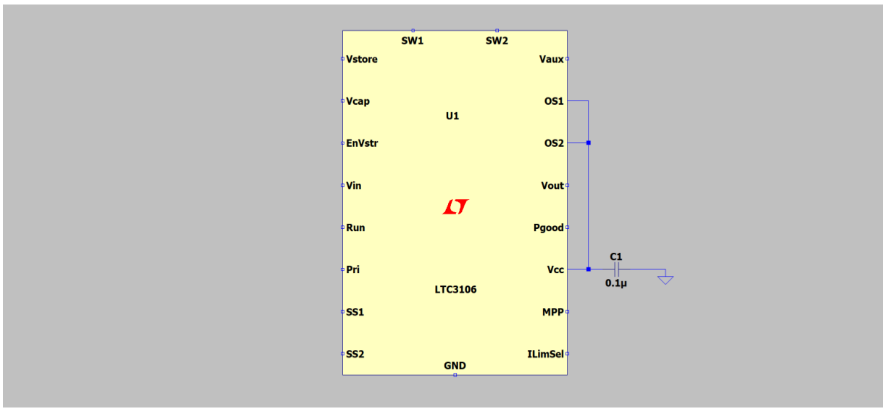

Fig. 4. PMIC circuit connection for pin OS1 and OS2.

2.3. Maximum power point (MPP) control

This function allows user to activate MPP comparator for maximum power point control by connecting a resistor from pin MPP to GND [11]. Alternatively, the function can be disabled by directly connecting pin MPP to the VCC pin. As mentioned, a resistor is needed to enable the MPP control, thus it is important to decide resistor's value through mathematical calculation. From the datasheet provided for PMIC LTC3106, the MPP pin is having an internal output current of about 1.5μA [11]. Therefore, by applying Ohm's law, V=IR, the resistance value can be calculated by pre- defining the MPP voltage value. In this case, 0.5V MPP voltage is being used to identify resistance value. The calculation is as shown in the Eq. (1) to Eq. (3). The resistance value obtained from the calculation is 333.33kΩ. Since it is a floating value, a resistor of 333kΩ will be used instead as shown in Fig. 5.

$$V = IR \tag{1}$$

$$0.5V = 1.5\mu A * R \tag{2}$$

$$R = 333.33k\Omega \tag{3}$$

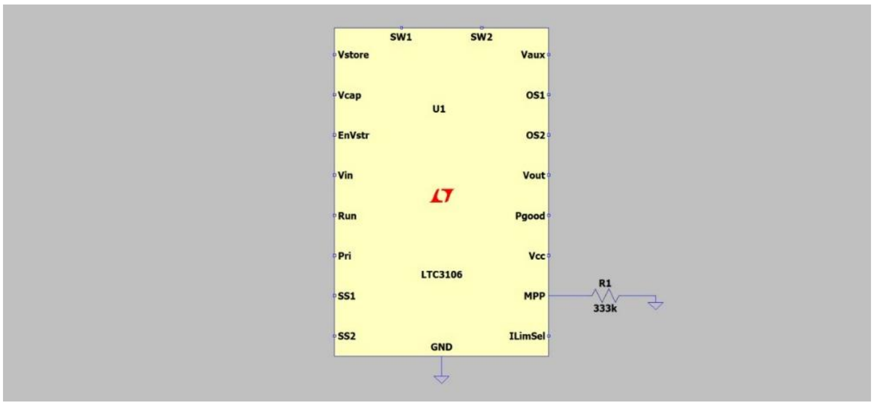

Fig. 5. PMIC circuit connection for pin MPP.

2.4. SS1 and SS2 (storage select)

These two pins are responsible for VSTORE selection programming inputs. There are multiple circuit connections between these two pins to select overvoltage and undervoltage values for VSTORE/VCAP and the corresponding battery type. The selection is as shown in the Table 2.

Table 2. Output voltage selection [11].

PRI	SS1	SS2	VSTORE/VCAP OV	VSTORE/VCAP UV	BATTERY TYPE
0	0	0	4V	2.78V	Li Carbon
0	0	VCC	2.9V	1.9V	2x Rechargeable NiMH
0	VCC	0	3V	2.15V	Rechargeable Li Coin Cell
0	VCC	VCC	4V	3V	Li Polymer/Graphite

In this work, SS1 and SS2 will be connected to the VCC which overvoltage and undervoltage value will be 4V and 3V respectively while Li Polymer/Graphite battery type will be used. Overvoltage value is the voltage level that energy storage will stop charging and vice versa for undervoltage. This overvoltage and undervoltage rating are essential for battery used in energy harvesting applications as it helps to protect battery for being overcharge and over drained which results in battery degradation or damage. Figure 6 shows the circuit connection to accomplish the overvoltage and undervoltage settings for storage elements mentioned above.

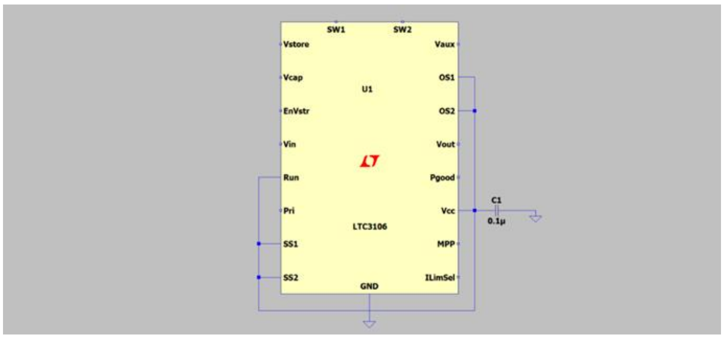

Fig. 6. PMIC circuit connection for pin SS1 and SS2.

2.5. SS1 and SS2 (storage select)

To achieve the objectives mentioned before using the LTC3106 programmable power management integrated circuit, sets of circuit connections are needed to apply. Figure 7 shows the complete PMIC circuit connection based on the footprint of LTC3106 using the software LTSpice [9].

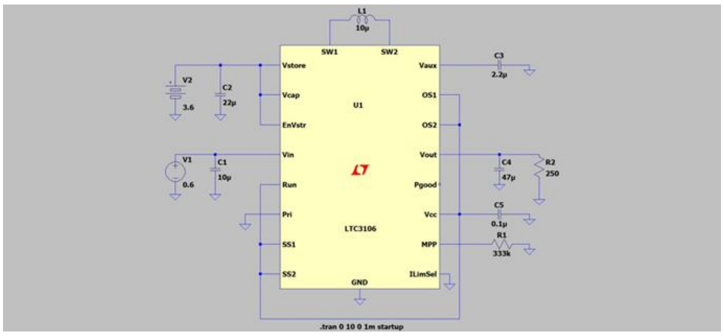

Fig. 7. Complete PMIC circuit connection.

Referring to the Fig. 5, pin VSTORE and VCAP are interconnected with pin EnVstr (Enable Storage) to activate the function of storing energy in batteries or supercapacitors [11]. For the pin SW1 and SW2, there are interconnected using an inductor to allow the operation of boost converter [11]. For the application of capacitor, C3 at pin Vaux, it is applied to power the internal circuit of PMIC LTC3106. While the remaining capacitors are responsible to smoothen and stabilise the voltage input and output by reducing noise and ripple.

3. Results and Discussion

In this paper, the results and discussion will be based on the simulation that has been done using the software LTSpice. The reason of using LTSpice instead of other simulation software is due to its wide variety of open resources that can be obtained. For this section, the results and discussion will be split into 3 parts. Since the PMIC LTC3106 having the features of dual input, the simulation will be run with either input or both inputs together. For all parts in results and discussions, the voltage level used will be very low between 0.1V and 1V because this project is targeted to boost voltage generated from RF energy source which is very low to a voltage level that can power low voltage sensor.

3.1. Boosting input from VIN

The first set of simulations are being run to measure the output voltage that can be generated by the boost converter integrated in the PMIC LTC3106 by relying only on the input voltage from harvested energy. The results are as displayed in the Table 3.

Table 3. Output voltage with only voltage supply from Vin.

Vin (V)	Vstore (V)	Vout (V)
0.1	0	0
0.2	0	0
0.3	0	0
0.4	0	0
0.5	0	0
0.6	0	0
0.7	0	0
0.8	0	0
0.801	0	3.61
0.81	0	3.63
0.85	0	3.75
0.9	0	3.88
1	0	4.13

From the Table 3, when the input voltage is at 0.8V, the PMIC will not generate voltage to the output pin. However, when the input voltage slightly exceeded 0.8V at 0.801V, there will be voltage generated at the output pin. These can be proven by the Figs. 8 and 9.

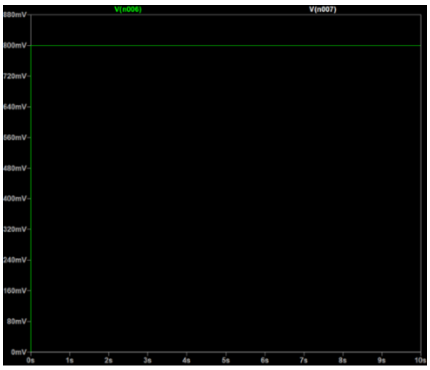

Fig. 8. Input (0.8V-green) and output (0V-white) waveforms.

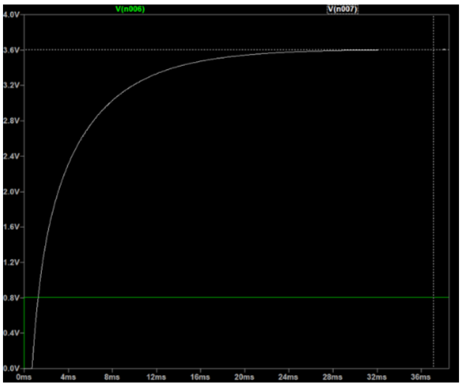

Fig. 9. Input (0.801V-green) and output (3.61V-white) waveforms.

From that onwards, any increases in input voltage will increase the output voltage as well. The highest input voltage being tested here is 1V which RF energy could most probably supply at its maximum.

3.2. Boosting input from VSTORE

This set of simulations will test on the reliability of powering load using only energy stored in the battery through pin V_{STORE}. The PMIC LTC3106 is capable to pre-programme for the undervoltage (UV) and overvoltage (OV) for storage elements as mentioned before in Table 3. The UV and OV value of energy storage for this project is set to be 3V and 4V respectively. Table 4 shows the simulation results for output voltage with only voltage supply from V_{STORE}.

Referring to Figs. 10 and 11, it can be clearly seen that when voltage output from battery is 2V, there will be no output voltage while on the other than when voltage output from battery is 3V output voltage from PMIC will be around 5V. This was due to the pre-programmed setting that mentioned previously which energy storage will stop discharging when voltage level drops below 3V as a protection. Additionally, the reason that 5V output from battery is not included in this simulation is because the overvoltage of 4V has prevented the energy storage to have voltage value beyond that limit.

3.3. Boosting input from VIN and VSTORE

The last set of simulations will test the PMIC LTC3106 in dynamically choosing power supply from two different input by detecting the voltage values. Referring to Table 5, the simulations will be testing for the output voltage with Vin from 0.1V to 1V and each Vin value with Vstore of 3V, 3.5V, and 4V.

Table 4. Output voltage with only voltage supply from Vstore.

Vin	Vstore	Vout
0	1	0
0	2	0
0	3	4.98-5.02
0	3.5	4.98-5.02
0	4	4.98-5.02

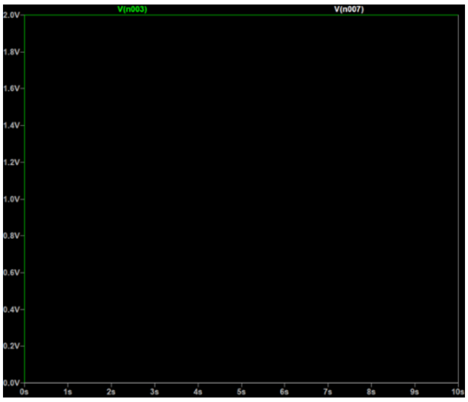

Fig. 10. Input (2V-green) and output (0V-white) waveforms.

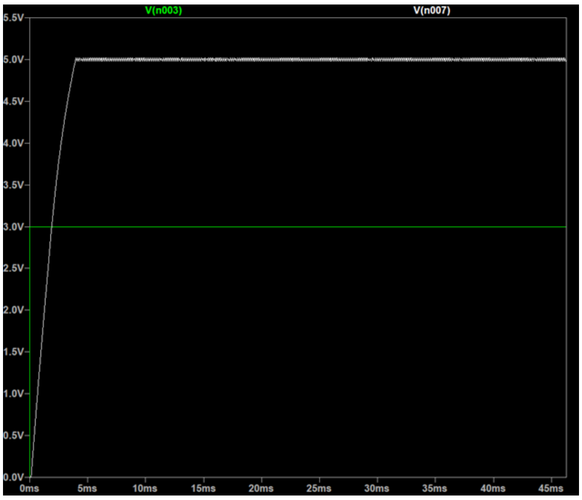

Fig. 11. Input (3V-green) and output (±5V-white) waveforms.

Table 5. Output voltage with supply from Vin and Vstore.

Vin (V)	Vstore (V)	Vout (V)		Vin (V)	Vstore (V)	Vout (V)
0.1	3	4.98-5.02		0.6	3	2.99
0.1	3.5	4.98-5.02		0.6	3.5	2.99
0.1	4	4.98-5.02		0.6	4	2.99
0.2	3	4.98-5.02		0.7	3	3.31
0.2	3.5	4.98-5.02		0.7	3.5	3.31
0.2	4	4.98-5.02		0.7	4	3.31
0.3	3	4.98-5.02		0.8	3	3.6
0.3	3.5	4.98-5.02		0.8	3.5	3.6
0.3	4	4.98-5.02		0.8	4	3.6
0.4	3	4.98-5.02		0.9	3	3.88
0.4	3.5	4.98-5.02		0.9	3.5	3.88
0.4	4	4.98-5.02		0.9	4	3.88
0.5	3	2.62		1	3	4.14
0.5	3.5	2.62		1	3.5	4.14
0.5	4	2.62		1	4	4.14

As shown from the results recorded in Table 5, when voltage value from Vin pin is between 0.1V and 0.4V, the output voltage is around 5V. This is due to voltage value at Vin is too low and PMIC LTC3106 dynamically choses Vstore as the voltage supply for boost converter. Thus, the boost converter in PMIC is boosting Vstore voltage value of 3V, 3.5V, and 4V to an output voltage of 5V. Once the voltage value at Vin reaches 0.5V which close enough to the threshold voltage value of 0.6V, the PMIC switches the voltage supply from Vstore to Vin. Therefore, from 0.5V Vin onwards, the boosted output voltage will be lower than Vin voltage level from 0.1V to 0.4V. For Vin voltage from 0.5V to 1V, to boosted voltage is about 4 times from its initial voltage value which is sufficient to power low power sensor. This hence proves that the designed PMC is optimum for RF energy harvesting applications.

Figure 12 displays and prove the discussion above regarding to the relation between output voltage and input voltage referring to Table 3. For this line graph, the voltage level from Vstore is ignored as they provide the same output when varying from 3V to 4V.

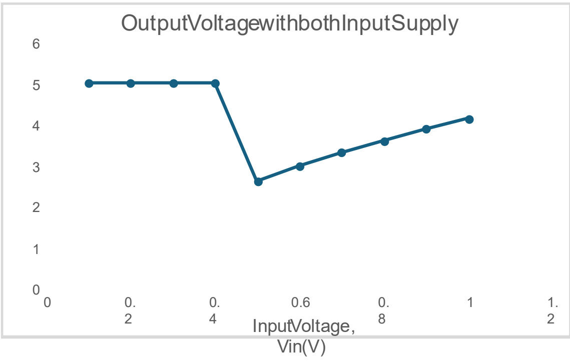

Fig. 12. Output voltage vs. input voltage.

4. Conclusion

This paper presents the design and implementation of a smart power management circuit for RF energy-harvesting applications. The idea will be to convert ambient RF signals emanating from sources like Wi-Fi and Bluetooth into a stable DC power supply for powering low- power devices. The PMC will be based on the ultra-low-voltage buck-boost converter LTC3106 as the main power management integrated circuit.

The PMC integrates major power management functions like DC-DC conversion, energy storage, power conditioning, and MPPT. Each of those has a very important function when it comes to energy harvesting and distribution: The DC-DC converter will regulate the output for a wide range of input voltages, while MPPT will optimize the power transfer provided by RF sources with varying amplitude. The following design allows programmable overvoltage and undervoltage thresholds that enable the protection of the battery from overcharging and/or deep discharging.

LT Spice simulations confirm PMC functionality to dynamically prioritize either VIN or VSTORE input sources for maximum energy efficiency and a steady output. When VIN becomes too weak, operation is smoothly transferred to take power from VSTORE to amplify output for the attached load. This adaptive power approach enables our reliable low power supplies targeting low-energy applications such as wireless sensor networks-a truly sustainable solution which minimizes battery dependency. It will also contribute to developing autonomous, low-power energy systems that can have promising applications in future IoT cases over both remote and battery-free environments.

Acknowledgement

This research was supported by Taylor's University through the Taylor's Internal Research Grant Scheme – Impact Lab Grant (TIRGS-ILG/1/2024/SOE/002)

References

1. Ibrahim, H.H. et al. (2022). Radio frequency energy harvesting technologies: A comprehensive review on designing, methodologies, and potential applications. *Sensors*, 22(11), 4144.
2. Mostafa, M.G.; Motakabber, S.M.A.; and Ibrahimy, M.I. (2016). Design and analysis of a buck-boost converter circuit for piezoelectric energy harvesting system. *Proceedings of the* 2016 *International Conference on Computer and Communication Engineering* (*ICCCE*), Kuala Lumpur, Malaysia, 204-207.
3. Szut, J.; Piatek, P.; and Pauluk, M. (2024). RF energy harvesting. *Energies*, 17(5), 1204.
4. Khan, N.U.; Ullah, S.; Khan, F.U.; and Merla, A. (2024). Development of 2400–2450 MHz frequency band RF energy harvesting system for low-power device operation. *Sensors*, 24(10), 2986.
5. Bzzou, M.; Bekali, Y.K.; and Bhiri, B.E. (2025). RF energy-harvesting systems: A systematic review of receiving antennas, matching circuits, and rectifiers. *Engineering Proceedings*, 112(1), 48.
6. Guerrero-Vásquez, L.F.; Chacón-Reino, N.A.; Tenezaca-Angamarca, S.D.; Chasi-Pesantez, P.A.; and Ordoñez-Ordoñez, J.O. (2025). Advancements in antenna and rectifier systems for RF energy harvesting: A systematic review and meta-analysis. *Applied Sciences*, 15(14), 7773.
7. Nijisha, P.; and Shidhin, M. (2023). *Power harvesting and storage system*. In Nijisha, P.; and Shidhin, M. (Eds.). *Supercapacitors and their applications*. CRC Press.
8. Hu, Y.; Luo, A.; Wang, J.; and Wang, F. (2019). Voltage regulation and power management for wireless flow sensor node self-powered by energy harvester with enhanced reliability. *IEEE Access*, 7, 154836-154843.
9. Rashid, A.H.A.; Ahmad, B.H.; Aziz, M.Z.A.A.; and Nornikman, H. (2024). Rectenna for radio frequency energy harvesting: A review. *ELEKTRIKA-Journal of Electrical Engineering*, 23(1), 12-17.
10. Yun, E.J.; Park, J.T.; and Yu, C.G. (2022). A maximum power point tracking interface circuit for low-voltage DC-type energy harvesting sources. *Bulletin of Electrical Engineering and Informatics*, 11(6), 3108-3118.
11. Analog Devices Inc. (2024). LTC3106EUDC#PBF. Retrieved November 17, 2024, from https://www.digikey.my/en/products/detail/analog-devices-inc/LTC3106EUDC-PBF/5819080