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REDEFINING SMALL-SCALE ENERGY HARVESTING: PSO-ENHANCED MICRO-NOTCHED TURBINES AND RF RECTENNAS FOR AUTONOMOUS LOW-POWER DEVICES

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Abstract
The significant strides made in science over the past century have led to the development of technical industries, primarily driven by advancements in miniature electronic circuits. The continuous decrease in power consumption is due to technology that enables electronic systems to be smaller. According to Intel, power management becomes more difficult as the size of electronic gadgets reduces. Several forms of energy are available that could supply power to low-energy applications. The creative notched turbines' experimental setup presents ideal characteristics; hence, they are best for optimal power production. When the MiNT technology is introduced into a system to evaluate power delivery, as in this analysis, it becomes a unique system that can generate usable energy. The power supply tracking system of this developed energy-harvesting device relies on maximum power point tracking, a significant component of the implemented system. Environmental conditions affect the physical dimensions and performance of the productive power output of many energy-producing devices, imposing limitations that must be considered.
Investigators applied simulations and measurements to confirm the analysis process and results, which indicated a tug–nose micro–notch turbine system that enhanced the maximum power point tracking system (MPPT). An improved MPPT system utilizes PSO (particle swarm optimization) and the emulating resistor technique to reduce hardware size and increase power efficiency (PSO). This energy-collecting equipment features a micro-notch design, and a smaller version is equipped with an upgraded MPPT for all testing purposes. A PSO (particle swarm optimization) with a resistor emulation method enhances power

efficiency and reduces the physical size of the maximum power point tracking system (MPPT). Research applications using the suggested control method can run successfully with as few energy sources as possible because this enhanced system and systems with low resistance load power it. The successful culmination of this research will enable many Energy and Power harvesting systems to improve their power management and control capabilities of their integrated circuits, thereby constraining end devices and application systems.

INTRODUCTION

As energy demands increase across compact and low-power electronic systems, efficient, small-scale energy harvesting solutions have become paramount. Traditional energy sources, such as fossil fuels, oil, and gas, are not only environmentally damaging but are also projected to be depleted by mid-century, intensifying the urgency for alternative power strategies [1]. Renewable energy sources, including solar, thermal, hydroelectricity, and wind, are not fully exploited despite their environmental benefits and sustainability [2]. Energy harvesting systems (EHS) that utilize these renewable sources provide interesting possibilities, particularly when used with highly advanced power control circuits.

Micro-notch turbine-based EHS has shown promise in recent research, as an upgraded Maximum Power Point Tracking (MPPT) system is employed to enhance conversion efficiency and reduce physical footprint [3]. The addition of Particle Swarm Optimization (PSO) and resistor emulation in MPPT enables intelligent power extraction with minimal hardware requirements, making the system well-suited for compact applications such as IoT devices, wearable electronics, and implantable medical systems [4]. This enhanced MPPT mechanism dynamically responds to changes in load and inconsistencies with sources, resulting in more efficient operation with lower hardware requirements [5]. Simulations and physics measurements have confirmed the feasibility of such systems in ensuring high-energy output at constrained conditions in low-resistance environments where conventional systems fail [6]. To achieve autonomous operation and self-sufficiency in energy-critical environments, researchers are striving to integrate control units and power management circuits into the system architecture, thereby integrating the circuit itself into the system rather than as a supporting component. Figure 1 illustrates the basic configuration of a typical EHS, comprising a power source, power control and management circuitry, and the target load. Unlike finite, non-renewable resources, these systems can utilize free and renewable energy at any time. Additionally, by incorporating intelligent control mechanisms, these systems are scalable and capable of meeting current requirements. This study proposes an improved design and experimental validation of an energy harvesting system centered on micro-notch turbines, augmented with a maximum power point tracking (MPPT) controller based on particle swarm optimization (PSO). The project will address the increasing need for energy from smart sensors, medical devices, IoT systems, and autonomous vehicles. It also aims to address existing limitations in energy-harvesting technology and overcome them through advanced simulation and hardware prototyping.

2. LITERATURE REVIEW

The development of miniaturized, effective, and sustainable energy sources has emerged as a pivotal aspect of designing future generations of power systems, particularly for portable electronic devices and implantable biomedical applications. These systems require low maintenance, a long service life, and physical compatibility with the physiological environment. The micro-notched turbine has become a favourable system innovation with volumes under 15 mm3 [1], [4]. This turbine comprises two integral components: the rotor and the turbine casing. These have been carefully engineered to convert mechanical and electrical power, mainly through fluidic and biomechanical means. The micro-notched turbine's geometry and structure are peculiar, enabling interactions between high-pressure fluids and reducing the turbulence and energy loss. The ability to shorten its form and the possibility of biocompatibility make it a suitable solution for integrating tissues or organs in a living organism, thus minimizing the system's environmental footprint [6]–[8]. New studies are investigating the biocompatibility of materials, including medical-grade polymers and titanium alloys, to promote biointegration and enable the in vivo use of turbines with minimal risk over long-term periods [9]. Strategic size optimization, 3D micro-printing, and laser cutting, which are precise, have made such systems less promising in constricted biological environments [10]. The rapid growth in miniaturised electronic circuits has been crucial to this field, and breakthroughs have been made in several areas such as wearable electronics, medical telemetry, and embedded sensor systems. However, the latter has not been proportionately reflected in the evolution of corresponding compact energy sources. Despite the advances in energy density provided by battery technologies, these systems lack the flexibility to serve wireless and implantable systems, as charging or replacement (which is often invasive) is a requirement [7], [11]. The literature increasingly suggests that mechanical-to-electrical energy conversion could be a viable alternative for powering such systems. This type of energy can be utilized within biosensors or control systems without dependency on chemical batteries [8], [12]. Micro-turbines, specifically those operating at low pressure or in microfluidic environments, can produce enough energy for these purposes.

These systems can also mitigate the biological risks associated with the degradation or leakage of an implanted battery, providing a safer and more sustainable power source. A comparison overview of different energy harvesting mechanisms, as presented in Table 2.1 from the source material, reveals that various technologies are available. These include piezoelectric resonators, photovoltaic panels, thermoelectric modules, and RF-based systems, which have varying energy conversion efficiencies and specific application constraints [3], [6], [9]–[13]. Piezoelectric and RF harvesters can succeed in intermittent energy conditions, but photovoltaic systems need adequate light and thus cannot work in embedded or enclosed systems. There is an increasing trend to purchase portable and implantable medical devices as digital healthcare and remote monitoring technologies advance. The resulting challenge has been the research emphasizing energy harvesting systems that are efficient, miniaturized, and compatible with the environment and physiology [14], [16]. This requirement highlights the need for turbine systems to strike a balance between performance and eco-design, as well as material sustainability.

Despite their promise, conventional microturbine technologies are plagued by severe limitations, including strict input flow specifications, limited geometrical shape, and difficulties in integrating microfluidic platforms [9, 17]. The Banki and Pelton impulse turbines are legacy designs that utilize fluid jets from nozzles striking rotor blades. While these designs are effective in an industrial setting, their output depends on high-pressure and heavy structural gages to prevent splash-back. They are unsuitable for biomedical or embedded environments [18], [19]. On the other hand, the micro-notched turbine is designed with a casing and blade type that is more specifically suited to run in a low-pressure environment, thereby enhancing the volumetric pressure on the rotor surface without the necessity of a direct jet's impact. This increases the rates of fluid intake, pressure stabilization, and overall energy conversion efficiency, which are critical characteristics desirable in bio-integrated systems or lab-on-chip devices [15]-[20]. The distinctive merits of the micro-notched turbine, including its decreased size, increased conversion efficiency, and flexible casing design, make it a game-changing technology in the field of sustainable and implantable energy options. Furthermore, the turbine harnesses biomechanical energy from natural body movements and organ functions, aligning with the trend towards green and autonomous energy platforms that do not rely on finite forms of energy.

As research continues, the integration of intelligence, i.e., intelligent Maximum Power Point Tracking (MPPT) algorithms such as Particle Swarm Optimization (PSO), will enhance the feasibility of micro-turbine energy harvesters. These algorithms dynamically adjust the energy extraction parameters in response to changes in the environment, the load's changing parameters, or user-specific physiological conditions [21]. Carrying out a synergistic integration of adaptive power control circuits and biocompatible mechanical structures may form the basis for implantable electronics and smart biosystems, which can be deployed for long-term use. In the end, a new convergence of mechanical engineering with bio design and power electronics, applied to an actual, not notional, mechanical artifact and micro turbine, presents a robust solution for powering the next generation of intelligent, self-aware, and environmentally conscious systems. It is expected to bring innovation in areas such as digital healthcare, smart agriculture, and environmental sensing.

3. Methodology and Design

The effectiveness of any energy-harvesting system, and in many ways, its sustainability are directly proportional to the suitability of its Maximum Power Point Tracking (MPPT) function, which acts as a pillar of the power management circuit, as shown in Figure 1. The MPPT system ensures that maximum power is extracted from the energy source and transmitted safely to the load with minimal energy loss. In mechanical-to-electrical conversion systems, e.g., mini-notched turbines, captured energy must first be converted into direct current (DC) before it is stored in energy reservoirs, such as batteries or supercapacitors, or directly powers end-user devices. This conversion is necessary for compatibility with most low-power electronics and biomedical systems, which usually work on regulated DC voltages. The power management circuit (located between the energy source and the load) contributes to this conversion and is also of immense importance for sustainability and the environment's safety. The system helps optimize power flux operation by minimizing energy loss, reducing thermal footprint, preventing overheating, and extending the lifespan of the turbine and its connected devices. Moreover, MPPT systems are crucial for ensuring human safety and system functionality in delicate environments, such as those involving implantable medical devices or environmental monitoring sensors. In this manner, the mini-notched turbine, supported by a high-performance MPPT, is part of a comprehensive strategy for EHS, facilitating cleaner energy generation, reduced dependency on chemically dilutable batteries, and enabling a maintenance-free mode in a bio-sensitized or biologically integrated ecosystem, as illustrated in Figure 1.

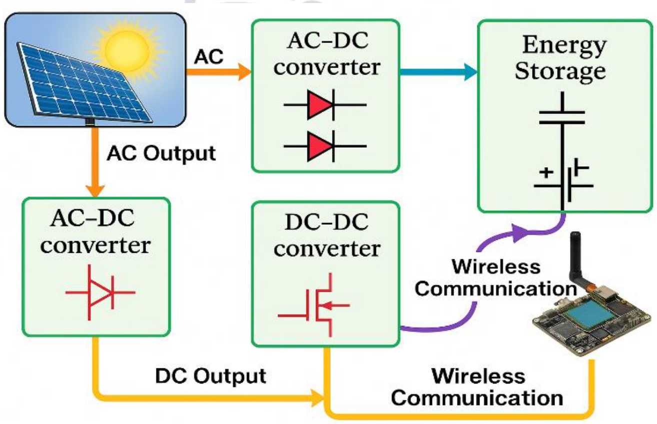

Figure 1. Basic architecture of the Energy Harvesting System (EHS).

The tremendous scientific advancements of the past century open the door to continuous technological progress in multiple arenas, especially in miniaturized circuits. As computers have shrunk, power consumption has been significantly reduced [1], while the speed of the CPU and an increase in memory capabilities have brought more capable and smaller systems. From this perspective, micro-notched turbines have become a promising form of energy, capable of converting mechanical motion into electrical energy for low-power applications [2]. These turbines are particularly useful in cases similar to biomedical situations, where harvesting energy from the human circulatory system can generate enough output to power medical monitoring devices or wireless implants. Micro-notched turbines provide a constant, self-sustaining power supply, improving the practicability and safety of implantable devices without requiring planned surgical battery extraction or replacement.

This research aims to develop a modern, innovative power generation approach that surpasses the efficiency of all currently available commercial ones. Utilizing mechanical-to-electrical energy conversion within a well-integrated system, each component can be finely tuned to achieve better energy transfer, resulting in stable and sustainable performance in a compact environment. This integration is crucial for wireless biomedical devices that require high reliability and low maintenance, as well as the ability to work seamlessly with biological systems.

When designing such a system, computer-aided design (CAD) tools are used to create the model of the micro-notched turbine's dimensions and shape. Several performance-critical aspects are explored during the CAD phase, including fluid pressure, flow rate, geophysical flexibility, and the feasibility of additive manufacturing techniques such as 3D printing [5–8]. The design process values life compatibly, and the process is modifiable to make the turbine work efficiently in various physiological and industrial conditions.

Its uniquely designed rotor is at the heart of this energy-harvesting device. Imitating the operation of an impulse turbine, the rotor is specifically designed to rotate underwater, combining the features of both impulse and reaction turbines. This hybrid approach enables the turbine to operate at a steady state, regardless of constant pressure flow, making it best suited for integration into microfluidic or circulatory systems. When the fluid enters the chamber and bumps into the blades, it releases rotational force to the rotor as it switches direction. This measure is advanced through the turbine's strategic notch design, which reflects and increases the impulse force the fluid jet creates on the blades. Decreasing turbulence between the blades promotes fluid flow, facilitating smooth turning with improved efficiency.

Furthermore, the blades themselves have a curved structure that produces an enlarged surface exposed to the fluid pressures, thus enhancing the turbine's mechanical response. This curvature facilitates the transfer of impulse, thereby improving the stability required for consistent energy production. The unique geometry of the notched turbine makes it superior in both performance and form factor compared to conventional designs. This makes it a favourable option for next-generation energy harvester applications in small and biologically sensitive environments.

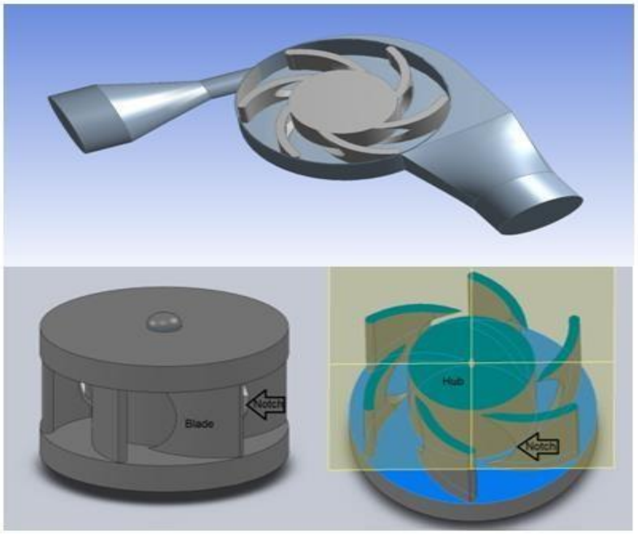

Figure 2. The mini-notched turbine's structural configuration highlights its main design features and arrangement.

In the design of the micro-notched turbine energy-harvesting system, considerations beyond the efficiency of the individual components include adaptability to various possible applications. The idea is to facilitate straightforward changes in system integration without necessitating modifications to the device structure. This is especially critical in discussing differences in inlet versus outlet scaling within a microfluidic context. Turbine compatibility with various fluidic interfaces is achieved through a highly engineered system of microfluidic closures that ensures a perfect fit into diverse spatial requirements. The design of the turbine focuses on two major components: a rotor with its blades pointing horizontally, attached to a circular frame, and a vertically curved, surrounding cage structure. The synergy between these elements helps transfer momentum from fluid motion to mechanical revolution. Internal changes in the momentum of the fluid as it passes through the turbine exert pressure on the blades' surfaces, causing them to rotate. The design also ensures that the turbine's responsiveness and efficiency are maintained across a range of operational conditions. The increased performance of the mini-notched turbine can be attributed to various critical features. An increase in hub diameter increases internal pressure in the turbine chamber, and changes in the inclination angle of the nozzle result in a more directed and effective impact of the fluid jet entering it. Additionally, the vortex blades provide turbulence control and rotational stability. Individually, each of the enhancements improves the power output by approximately 31% compared to conventional microturbine systems under similar operating conditions. Compares the volumetric dimensions of the proposed mini-notched turbine compared to commercial generators as reported in other studies [11–15], [19]. The most central power-producing component of the system is the MiNt (Micro Notched Turbine) Generator. It is designed to convert either liquid motion, such as fluid flow in microchannels, or wind energy into electrical output, alternating current (AC) or direct current (DC), depending on the generator configuration. The turbine operates with a compact generator unit, where the notched rotor blades drive an electromagnetic coil system. The power output from the system can be calculated based on the relationship between the nozzle velocity (measured in meters per second) and the resulting fluid power. This correlation, depicted in the figure, serves as a reference for estimating performance based on input fluid dynamics. Alternative methods for characterizing flow power and turbine efficiency have also been presented in the literature, offering further validation for the turbine's energy-conversion capabilities [11–14]. This fully integrated system, combining adaptive design, optimized fluid interaction, and compact energy generation, offers a scalable solution for powering miniaturized, portable, and implantable devices. It exemplifies the next generation of environmentally conscious and efficient energy-harvesting technologies, tailored for modern applications.

$$P_f = \frac{\rho Q V_n^2}{2} \quad (1)$$

In analyzing the performance of the micro-notched turbine, various critical variables are considered to determine mechanical power generation. TTT, WWW, and U1U1 represent the tangential torque, angular velocity, and tangential blade velocity, respectively. These parameters are necessary in defining the mechanical behaviour of the turbine during operation and its energy conversion efficiency. Two non-dimensional coefficients, X1 and X2, are proposed to account for the influence of design variables and fluid dynamics on the energy transfer process. Additionally, r1 is the distance from the rotor's central axis to the blade's farthest point and determines torque and velocities in the distribution of the blade's surface area. To calculate the maximized mechanical power output, these variables are combined into a derived expression, labeled as Equation (2) of the system's mathematical model. The basis of this equation is the necessity to optimize the turbine's operating conditions. By tweaking the equation – by altering design coefficients and rotational parameters – the engineers can optimize the system for maximum efficiency, maximizing the amount of energy harvested from the fluid flowing through the system.

$$\frac{dP_R}{dU_1} = V_n X_1 - 2U_1 X_2 = 0 \quad (2)$$

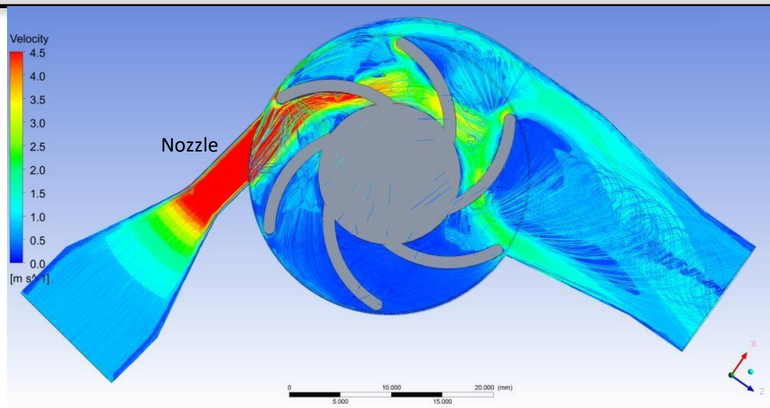

Figure 3: Simulation results of the MiNt nozzle, demonstrating flow characteristics and performance analysis.

The performance of the notched turbine generator can be evaluated in terms of three major power parameters, including:<| the possible amount of fluid power, the mechanical rotor power, and the electrical power output generated by the AC generator. These correlated power stages are depicted in Figure 4, where various energy conversion processes, from the motion of fluid to the generation of electricity, are indicated. Previous studies have suggested that an optimal system could achieve a peak efficiency of up to 75% (11). Experimental testing at a flow rate of 5000 mL/min has shown that the hydro-mechanical efficiency of the small-scale notched turbine is approximately 53%. This efficiency is defined as the ratio of the mechanical power drawn from the rotor to the total fluid power available, including the energy loss caused by fluid resistance and mechanical friction. Further analysis revealed that the resultant projected hydro-mechanical efficiency of the system is 60.23%, indicating that with more refined design parameters and improved flow dynamics, there is considerable room for improvement. Such results confirm the turbine's applicability to compact energy harvesting applications, in which a compromise between efficiency and miniaturization, as well as system integration, can be made.

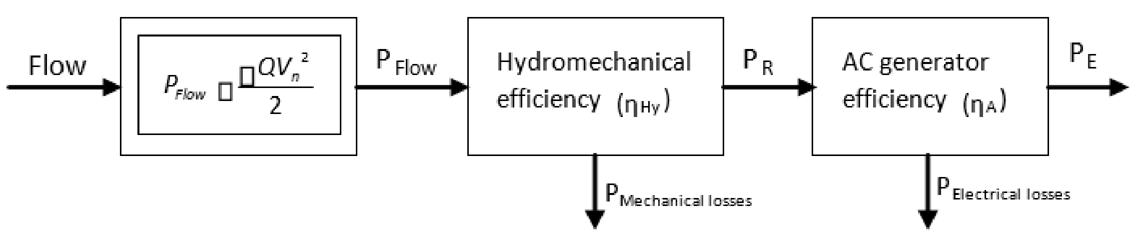

Figure 4: Flow pattern and block diagram of the MiNt turbine, illustrating operational stages and system layout.

To make an overall assessment of the performance characteristics of the Micro Notched Turbine (MiNT) system, three different turbine sizes were experimented with, which were matched against various types of generators. Tests were performed with the electrical load resistance varying. These arrangements enabled a detailed analysis of how turbine output varies under different operating conditions. The system operated at an average power output of approximately 17 mW when spun at a rotational speed of 1500 RPM, with measured values varying between 0.5 mW and 92.0 mW, depending on turbine size, generator efficiency, and load impedance. This power is sufficient to power a variety of low-power electronic applications such as wireless sensors, microcontrollers, and wearable medical devices. Figure 5. shows the power generation profile for the smallest MiNT design, tested by changing the airflow rates. The graph represents the turbine's reaction to input speeds ranging from 250 RPM to 2500 RPM, allowing it to scale its output power with flow velocity dynamically. The results support the feasibility of the MiNT system as a viable, high-performance, and adjustable energy-harvester in low-flow or variable-flow conditions.

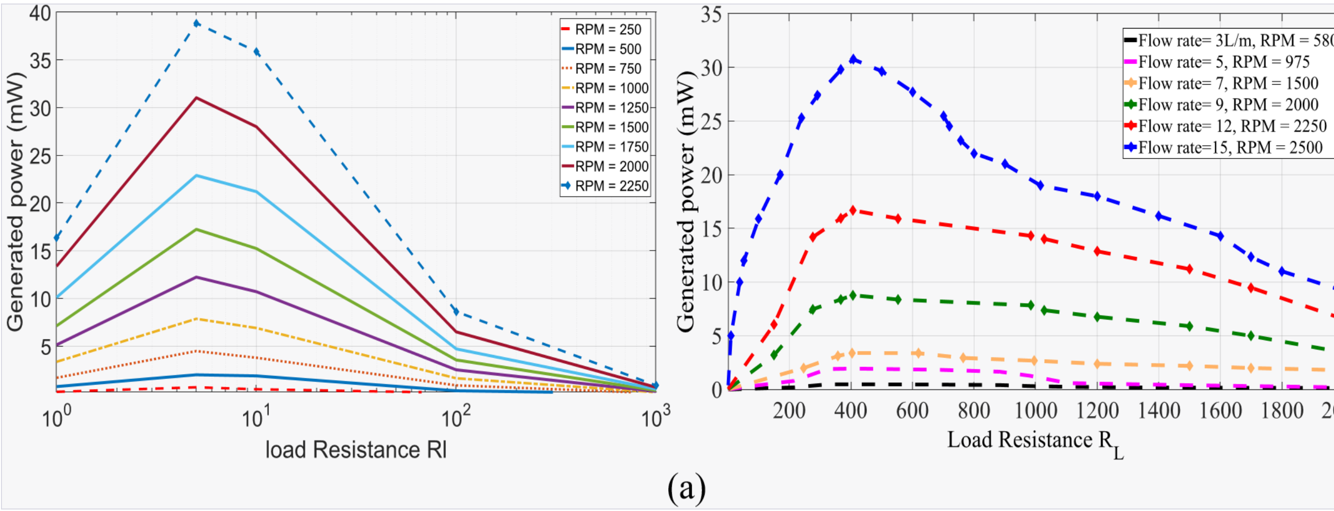

Figure 5: Power curves of the MiNt generator, plotted for various resistance values to show performance variation.

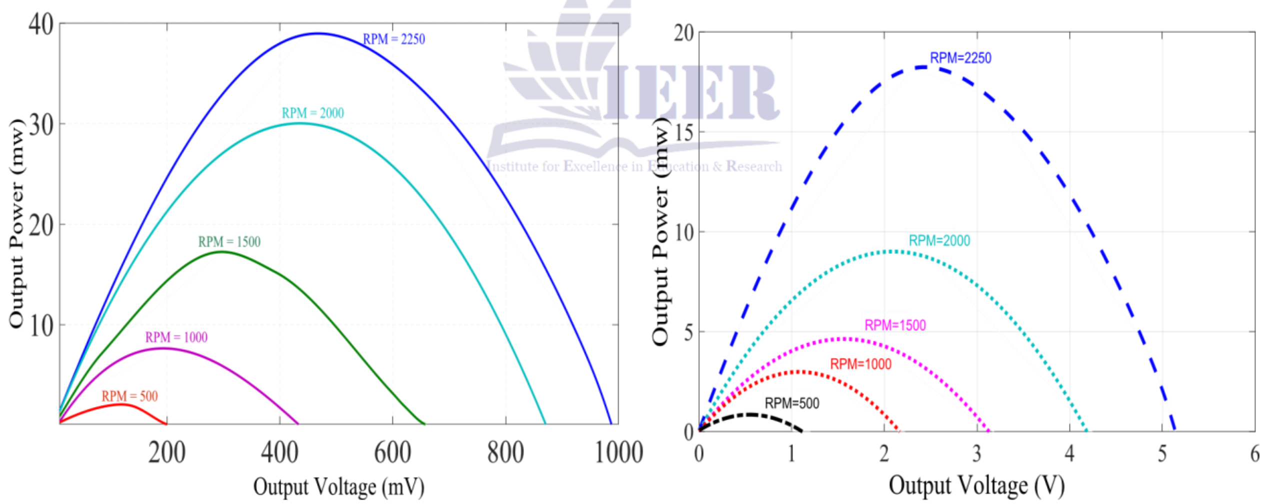

Figure 6: Power generation and output voltage measurements, showing the relationship between electrical output and system performance.

The experimental results confirm that selecting the appropriate load impedance at varying flow rates and rotational speeds significantly enhances the efficiency of the MiNT turbine. As illustrated in Figure 7, the output voltage of the small MiNT turbine varies with flow rate, demonstrating a clear correlation between optimal load matching and power output. The output voltage ranges from 0 to 1 volt, with a maximum power output of 38.8 milliwatts. These results, reported earlier [18, 35], offer essential guidelines on how to improve the performance of a turbine based on selected electrical load arrangements. The study outlines the optimum values of load impedances that yield a maximum power for every flow rate by examining the current-voltage (I-V) characteristic patterns of the turbine and test data within a wide range of flow rates. These values are the main tuning parameters for the power control and management circuit, and they help maintain energy extraction efficiency in different environments. In most cases, for any specified flow speed, there is an optimal load resistance for a turbine to output the maximum power, again strengthening the need for dynamic load adaptation when implemented in practice. What distinguishes the small notched turbine from other micro-turbines is that it has three distinct structural-functional differences. To begin with, the design's versatility enables it to function in various postures and situations within a submerged, dynamic fluid environment, making it applicable to both biological and environmental applications. Secondly, the rotor geometry of the turbine is designed correctly: On the inner proximal edge, each blade has a semicircular notch. These notches, in conjunction with the meticulously crafted blades' profiles, allow for the continuous circulation of fluids in the rotor chamber, ensuring smooth rotation and optimal momentum transmission. Lastly, the casing design enhances volumetric pressure retention, even in blades that are not directly in the fluid stream. This avoids the abrupt pressure changes that occur when fluid flows into the injection sides, which in turn ensures a gradual rerouted flow and enhances the continuity of flow and turbine stability. Combined, these design innovations endow the turbine with strength, adaptability, and efficiency as a solution to the current energy harvesting dilemma, especially in miniaturized or fluid-immersed settings where stable, uninterrupted power generation is required.

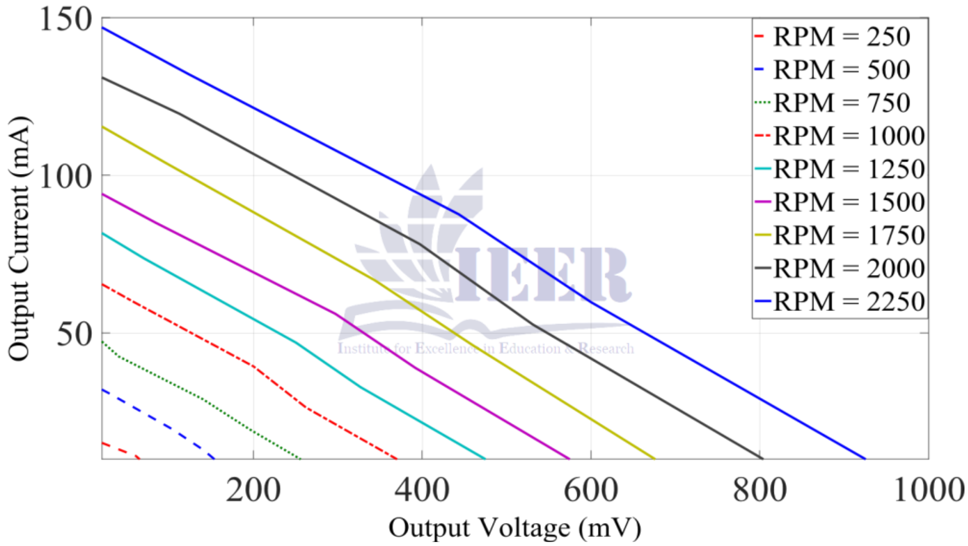

Figure 7. I-V results of MiNt at different flow rates

Recent progress in wireless energy transmission has brought significant attention to radio frequency (RF) energy harvesting systems, particularly rectennas, which convert ambient RF energy into usable electrical power. Although RF energy harvesting has been studied for several years, only a limited number of RF sources have been powerful and consistent enough to effectively power ultra-low-energy devices over extended periods [5, 7, 11]. This limitation presents a challenge for standalone embedded systems that require long-term, maintenance-free operation. The rising demand for energy-autonomous systems in fields such as healthcare, environmental monitoring, and the Internet of Things (IoT) is driving the need for innovative power solutions. To meet these demands, RF energy scavenging offers a promising path forward. However, to ensure practical usability, these devices must be not only efficient and compact but also environmentally friendly and easy to integrate into existing circuits [6]. Multiple methods have been explored for powering wireless medical devices, including inductive, capacitive, and magneto dynamic coupling. However, far-field RF energy transfer using rectennas remains a popular choice due to its simplicity, compact design, and suitability for long-range applications. The small size and low cost of rectennas, along with their ease of integration with microwave circuits, make them particularly attractive for implantable and wearable medical devices. Current research is focused on overcoming common challenges such as size limitations, efficiency loss, biocompatibility, and device reliability. These efforts aim to improve the practicality of rectennas for real-world medical applications [4–6]. Far-field RF technologies have been used for decades to power various devices, from smart sensors to drones. Efficient energy transfer in such systems depends on optimizing factors like radiation power, polarization, and alignment between the transmitting and receiving units. Although high conversion efficiencies—up to 90%—have been reported under ideal laboratory conditions [49], practical efficiency often drops significantly in real-world scenarios due to low input power, signal loss, and other environmental factors [5, 6, 19]. Strategies such as increasing antenna surface area and employing wideband antennas can help address these limitations, though broadband systems generally show lower efficiency than those designed for fixed frequencies. Additionally, path loss, antenna gain, and diode characteristics play critical roles in determining performance.

The rectenna consists of three essential components: an antenna to capture RF signals, a matching circuit to ensure optimal power transfer, and a rectifier to convert AC into DC. At the heart of the rectifier is the Schottky diode, chosen for its low power loss, fast response time, and high efficiency—crucial qualities in low-power RF energy systems. Key considerations when selecting a Schottky diode include its forward voltage, current-voltage characteristics, and maximum voltage tolerance. This study applied a voltage-doubling configuration using two high-frequency Schottky diodes to improve output voltage and system performance. Since the rectenna is being developed for biomedical use, the 2.4 GHz ISM band was selected as the operating frequency, due to its compatibility with medical applications and regulatory standards. To ensure biocompatibility, the antenna was fabricated using Roger RO4350B, a high-performance substrate known for its low-loss properties, which will be coated with biocompatible material for safe implantation. The next step in the system's development involves designing a matching network to minimize signal reflections (return loss) and enhance overall energy conversion efficiency [33].

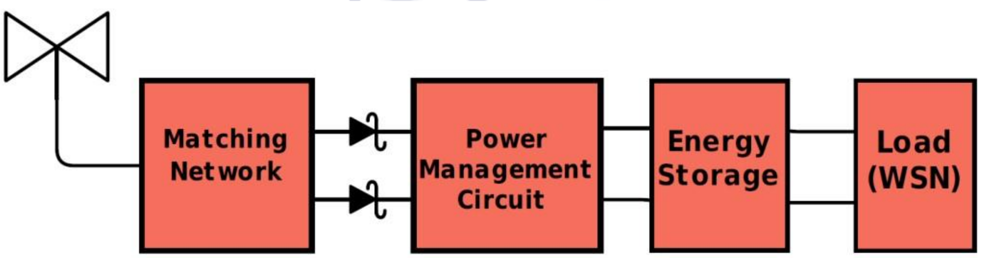

Figure 8. An RF energy harvesting system's block diagram illustrates key components and energy flow pathways.

Reports in the literature [3, 4, 8, 9, 15] indicate that the power generation capabilities of rectennas typically range between 10 µW and 1 W, depending on several influencing factors. These include the distance between the RF source and receiver, path loss, antenna gain, and the operating frequency. One commonly used performance indicator for rectennas is the RF-to-DC conversion efficiency, often called the RF-DC ratio. This ratio measures how effectively the rectenna converts incident radio frequency power into usable direct current output. It is a critical metric for evaluating the system's effectiveness in low-power and energy-constrained applications.

The power that reaches the rectenna (RF input power) depends on such parameters as the power density of the wave upon entrance and the effective aperture of the antenna. Significantly, the active area of the patch antenna is usually much larger than its physical dimensions, thanks to the fringing field, whose effects increase its ability to resonate at the desired frequency. Such an effective area is usually corrected by 2-4% for deviations [33, 57].

When designing a patch antenna, accurate estimates of its real and effective lengths are needed. These lengths are a function of variables such as operating frequency, antenna height, width, and the effective dielectric constant of the substrate material used. Such settings should be fine-tuned to ensure the antenna resonates well and absorbs as much power as possible from ambient RF signals.

The antenna plays a crucial role in the rectenna system because it is the part that receives and transmits electromagnetic energy. The evolution of the antenna can be traced back to 1842, when the magnetic nature of current was discovered by Professor Joseph Henry. This breaking revelation prompted other innovations: Edison's 1885 patent for a communication system that worked with various antenna types, A. E. Dolbear's successful long-distance code transmission during 1882, and Heinrich Hertz's invention of a balanced antenna system during 1887. Hertz's work, which provided learning that later formed the basis of modern wireless communication technologies, covered insights about the polarization of antennas.

A matching network is generally placed between the two components to have effective power transfer from the antenna to the rectifying circuit. This network reduces return loss and enhances power to the load. However, since Schottky diodes deployed in the rectifier have nonlinear current-voltage (I–V) characteristics, the input impedance of the rectifier circuit can change considerably with changes in input power level. Consequently, the proper design of the matching network has to be considered to take care of these nonlinearities, such as center frequency, characteristic impedance, expected input power, etc., to ensure impedance matching in varying environments.

In some configurations of power supply units, several rectifier circuits – voltage doublers – are connected in parallel for maximum efficiency at various power levels. These circuits are chosen based on well-documented characteristics, which are integral for keeping consistent performance in the RF energy harvesting application. These design considerations—antenna construction, impedance matching, and rectification topology—form the foundation of a well-optimized rectenna system suitable for powering modern low-energy devices.

Table 1: Comparison of conversion efficiency for different rectenna configurations (48), highlighting performance across various setups

Antenna type	Input power	Load Resistance (Ω)	Frequency (GHz)	Efficiency (%$\eta_{RF\text{-}DC}$)	Reference
Square aperture coupled patch	10 µW-100 µW	8200	2.45	15.7-42.1	[40, 60]
Patch	120mW	100	35	29	
Aperture coupled staked microstrip	100 µW	9200	2.45	34	[61]
Dipole	135mW	400	35	39	
Patch	251mW	220	2.45	40.1	[62]
Coupled microstrip rings	10mW/cm³	150	5.8	73.3	
Step dipole	100mW/cm³	250	5.8	76	
Microstrip circular sector antenna	10mW	150	2.4	77.8	[50, 52]

When the RF power input is relatively low, enhanced Maximum Power Point Tracking (MPPT) systems are utilized to improve power efficiency in RF energy harvesting applications. Passive matching techniques, such as LC networks, microstrip lines, and stub sections, are typically employed, with microstrip lines fabricated using Rogers RO4350B, a substrate known for its low loss tangent (0.0037) and dielectric constant (3.48). The matching network is optimized using the Advanced Design System (ADS) software, incorporating specifications for Schottky diodes, source and load impedances, along with components such as a DC block and smoothing capacitors. The rectifier circuit plays a pivotal role in RF-to-DC conversion, where the equivalent model of the Schottky diode—characterized by parasitic capacitance and inductance (Cp and Lp), series resistance (Rs), and junction characteristics (Rj and Cj)—guides the impedance-matching process. Efficient power control and management are equally critical, involving integration of linear and switching regulators, DC-DC and AC-DC converters, and switched capacitors, all of which contribute to regulating voltage for optimal device operation. Driven by the evolution of nanoscale circuits and Moore's Law, standard operating voltages have been reduced from 15V to as low as 1.8V to minimize heat and power dissipation in increasingly compact devices. As energy sources may not always provide stable output, advanced power control circuits are designed to operate efficiently at milliwatt-level inputs, thereby improving energy regulation by up to 7% across various voltage levels. Furthermore, factors such as I-V characteristics, load impedance, temperature, and environmental conditions (e.g., wind or fluid flow) influence the power output. A DC-DC converter placed between the energy harvester and the load can maintain alignment with the maximum power point, enhancing energy transfer. This study presents a method to improve ultra-low-power control systems by utilizing MPPT strategies, where inductor sizing and switching time are optimized through particle swarm optimization, resulting in a 10% efficiency gain in both DC-DC conversion and the overall power management system.

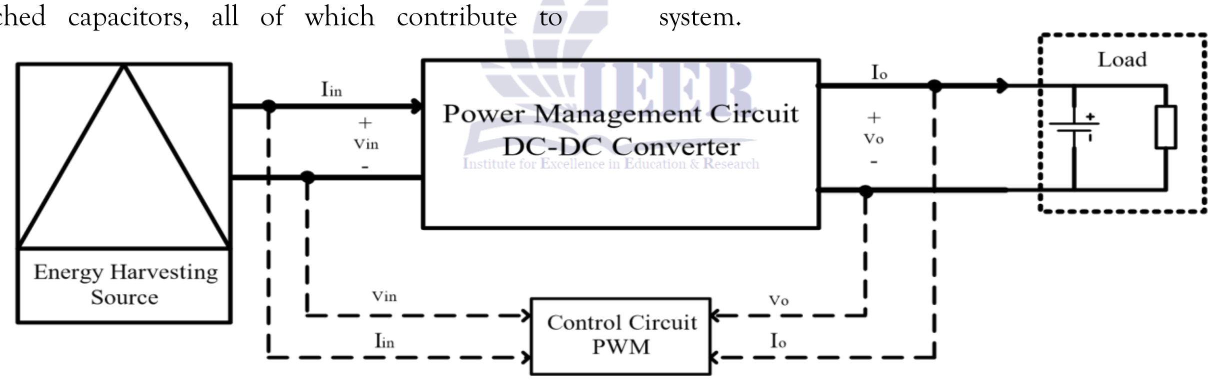

Figure 9.: Illustration of impedance matching in an EHS, achieved through a DC to DC converter for efficient power transfer.

In energy-harvesting systems, the power control and management circuit plays a vital role by utilizing a DC-to-DC converter to achieve two primary functions: it can either act as a dynamic matching network that continuously tracks and adjusts to the maximum power point (MPP) to optimize power delivery to the load, or it can modify the output voltage from the energy source to efficiently charge energy storage components like rechargeable batteries or supercapacitors. Depending on the type of energy source, the MPP can be identified using several methods. For example, flow speed and irradiation are utilized in wind and solar systems, whereas system parameter models are commonly employed in solar applications. Several MPP tracking techniques have been developed, including the differentiation method, perturb and observe (P&O), sampling techniques, feedback voltage or current-based methods, and conductance increment methods. These techniques are typically divided into direct and indirect approaches, where direct methods tend to be inefficient for compact systems, such as micro-notched turbines, due to high energy loss from repeated scanning cycles. Indirect techniques, including open-circuit voltage, short-circuit current, and lookup tables, rely on system behavior modeling such as I-V characteristics and power curves across various flow rates. Due to the size and scope of systems, a better solution is available: resistor emulation-based MPPT. This practice presents a DC-to-DC converter that facilitates impedance matching between the load and the source, thereby improving energy transfer performance without causing excess power losses. This technique was first proposed earlier in RF energy harvesting research, and it is most advantageous for compact systems, such as RF rectennas and micro-notched turbines, where the source impedance is typically of the order of 400Ω. Harvested energy is maximized when loads and impedances are equal; it declines significantly from the maximum as impedances vary from one another. Consequently, the resistor emulation approach is highly suitable for ensuring optimal performance at different flow rates and minimizing the printed circuit board size (PCB), a key priority for space-constrained applications with low power requirements. Additionally, this MPPT arrangement features a buck-boost converter, which stabilizes the output voltage by regulating the energy flow in response to real-time input and load conditions. The operation of the converter is interrelated with the actions of the inductor and capacitor of the system, thus allowing for regulated energy transfer as demands from the load vary. Ultimately, the suggested MPPT design with resistor emulation dramatically increases power conversion efficiency whilst providing an economical solution for next-generation energy-harvesting devices with a small form factor.

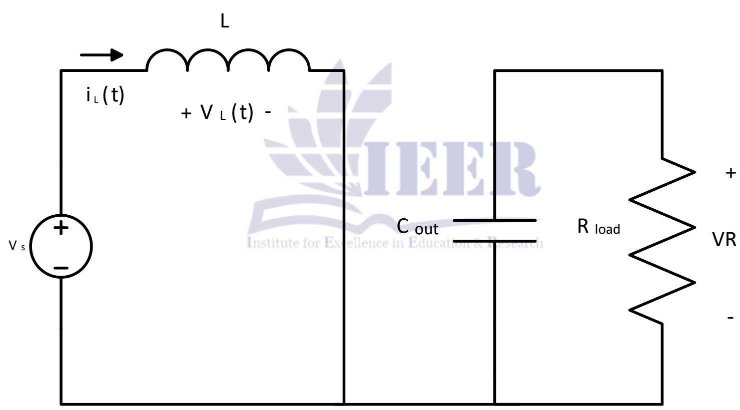

Figure 10. Boost DC to DC circuit when the MOSFET is in the on state.

illustrates its key components and operational flow. The output voltage generated by the DC-to-DC converter can be evaluated based on performance data reported in [18]. Theoretically, the output voltage increases significantly as the converter's duty cycle approaches its upper limit. However, in practical applications, this voltage is limited due to inherent power losses in the circuit components, such as switches, resistive elements, and parasitic effects, which prevent the voltage from reaching ideal levels.

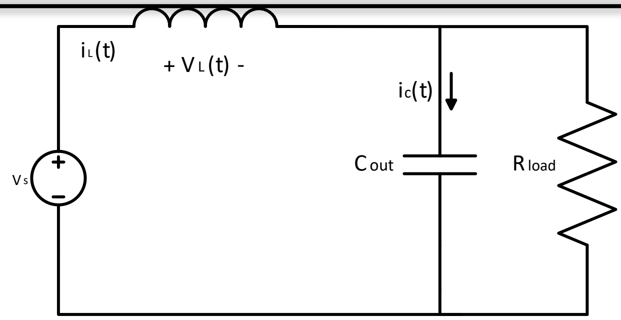

Figure 11. Boost the DC to DC circuit with the MOSFET in the off state, Showing the circuit configuration and energy flow.

DC-to-DC boost converters operate in different modes, depending on their switching behavior, primarily critical conduction mode (CCM) and **discontinuous conduction mode (DCM)**. In DCM, the switching period extends beyond the on and off durations of the MOSFET due to higher current ripple and the inductor's ability to reverse the direction of the applied voltage [23, 37, 39]. When the MOSFET is turned on, the inductor stores energy by increasing current. Once the switch is off, the inductor releases this energy through the diode until the current drops to zero. At this point, the circuit enters an idle phase, preceding the next switching cycle. This behavior results in a three-phase switching period: energy accumulation, transfer, and a non-conducting interval. As illustrated in Figure 3.5, the peak inductor current and system response depend on the timing and characteristics of each phase. While formulas exist to calculate this, practical design must consider component limitations and switching losses [36, 41, 43].

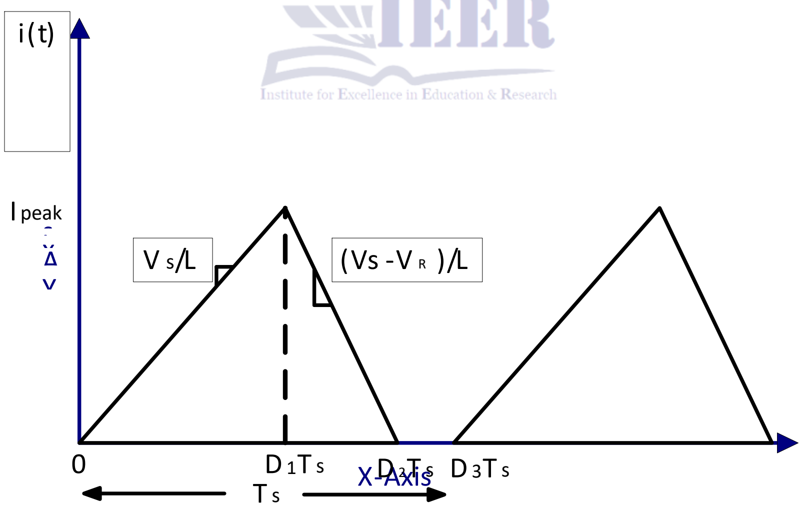

Figure 12: Waveform of the inductor current, depicting its behavior and variations over time.

The duty cycle in a DC-to-DC boost converter refers to the proportion of time during which the inductor current remains above zero within a switching period. This interval typically includes both the switch-on and switch-off durations. In the initial phase of the switching cycle, the duty cycle can be determined based on the voltage difference between the input and output, which helps establish how long the inductor needs to be energized to maintain the desired performance. It is essential to consider the peak current values and the duration for which the current flows to evaluate the average input current. The average current is influenced by several design parameters, including inductance, voltage level, duty cycle duration, and switching frequency. Once you have the average current, with the input voltage, the input power that can be developed in the boost converter can be computed by multiplying the average current by the input voltage. Further development of this power calculation involves utilizing the interaction between the parameters of the converter's genesis (inductance, duty cycle time). It takes into account the voltage regulation across a load.

In applications such as low-power CMOS VLSI systems, a switching factor, typically ranging from zero to one, is often used to define the efficiency of the converter's on/off state under dynamic load conditions. Such a factor represents the system's ability to adapt to changes in power availability and is particularly helpful during situations where power conservation and regulation are essential.

The resistor emulation method, combined with the DC-to-DC boost converter and Maximum Power Point Tracking (MPPT), provides an effective solution to improve the power efficiency of energy-harvesting systems. This strategy enables the system to operate at its optimum power point, even when power input levels fluctuate. In addition to regulating voltage, the converter functions as a dynamic impedance-matching device, which means that the internal resistance of the converter also complements the optimum resistance of the power source, such as the regulatory 400-ohm resistance used in RF rectenna designs. By keeping this impedance match, the maximization of power transfer of the source to the component or load is facilitated. The overall conversion efficiency of the system is determined by the ratio of output power to input power, typically expressed as a percentage. This metric helps quantify how effectively the energy from the source is delivered to the load. For the system to perform at its peak, the converter settings and the control circuit must be finely tuned to ensure precise matching and minimal power loss. The configuration outlined—consisting of a boost converter, MPPT circuit, and resistor emulation method—has been validated in multiple studies [25, 34, 35, 36, 48, 49], and is recognized for its ability to significantly improve energy transfer and efficiency, particularly in low-power, space-constrained applications.

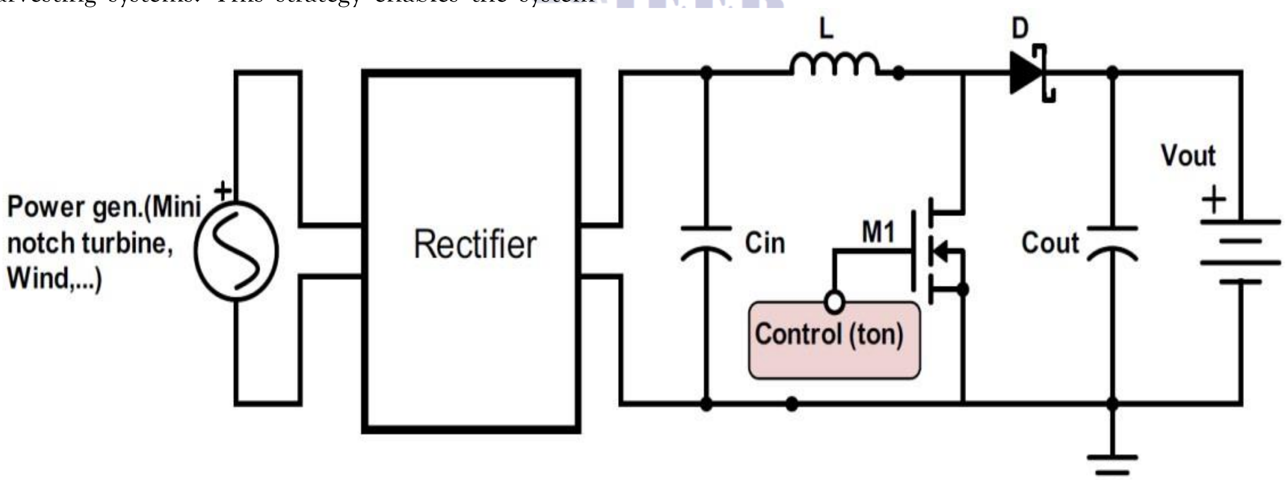

Figure 13. MPPT (Maximum Power Point Tracking) utilizing a DC-to-DC boost converter, Illustrating the power optimization process in the system.

4.1 Simulation Analysis and Results

To validate the research findings, it is crucial to ensure that all design parameters used during the optimization process remain within realistic and acceptable operational limits. The results of the optimization, including the influence of Particle Swarm Optimization (PSO) on key design variables, are summarized in Table 3.2. The optimal values for duty cycle, switching period, and inductance were identified after conducting 500 iterations or until the convergence criteria were satisfied. Simulations were performed using emulated resistances of 50 and 800 ohms, with input power levels ranging from 50 to 500 microwatts. The statistical analysis revealed variations in converter efficiency across different resistance values, with efficiencies ranging from a minimum of 80% to a peak of 91.5%, indicating strong performance consistency under varying load conditions.

Figure 14 presents a comparative analysis of the PSO-optimized MPPT and conventional MPPT techniques, evaluated at two output load resistances (210 and 760 ohms) across a broad input power range (50 to 500 microwatts). The data clearly show that the PSO-based optimization significantly outperforms traditional MPPT approaches, delivering an average efficiency gain of approximately 6.2% across the tested power spectrum and reaching a maximum efficiency of 89.8% when the emulated resistance is set to 1000 ohms. Moreover, when benchmarked against adaptive MPPT designs, the proposed method demonstrated a further 3.5% improvement in efficiency, particularly at higher resistance levels, showcasing its robustness and adaptability.

This improved converter architecture is especially compatible with energy sources characterized by low load resistance, making it suitable for ultra-low-power systems such as photovoltaic arrays, small-scale wind turbines, and micro-notched (MiNt) turbine generators. A detailed power loss analysis of the boost converter's components, specifically the transistor and diode, was conducted for the selected design parameters. The results confirm that, under increased current conditions, the dominant losses stem from conduction-related factors, primarily attributable to the combined resistance in the diodes, MOSFETs, and inductors. These findings reinforce the viability of the proposed design for efficient operation in compact, low-power energy harvesting applications.

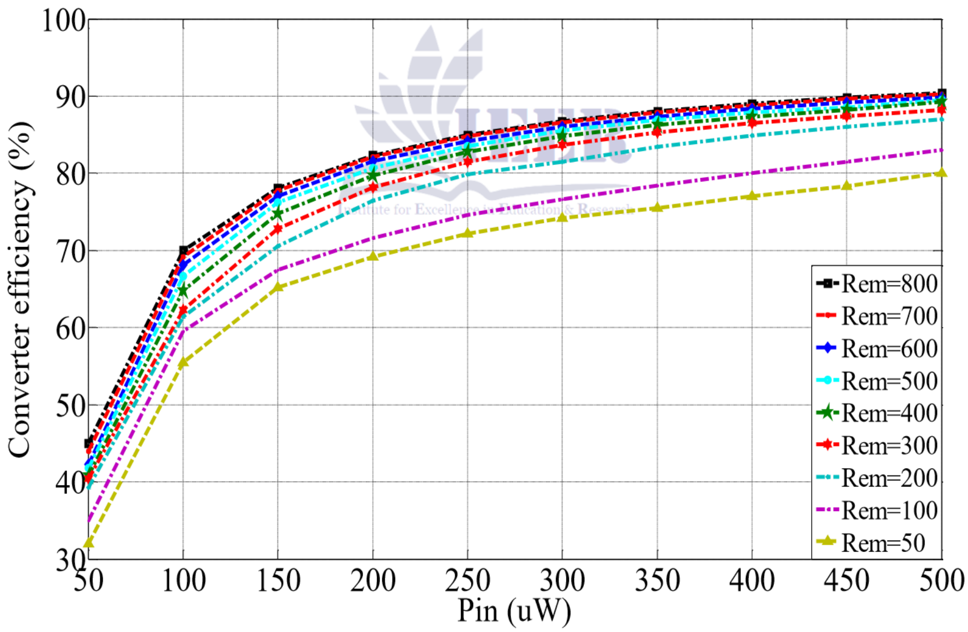

Figure 14. Results of Rem (55-850 Ω) for Pin (55 µW - 550 µW), showing the relationship between input power and the measured resistance.

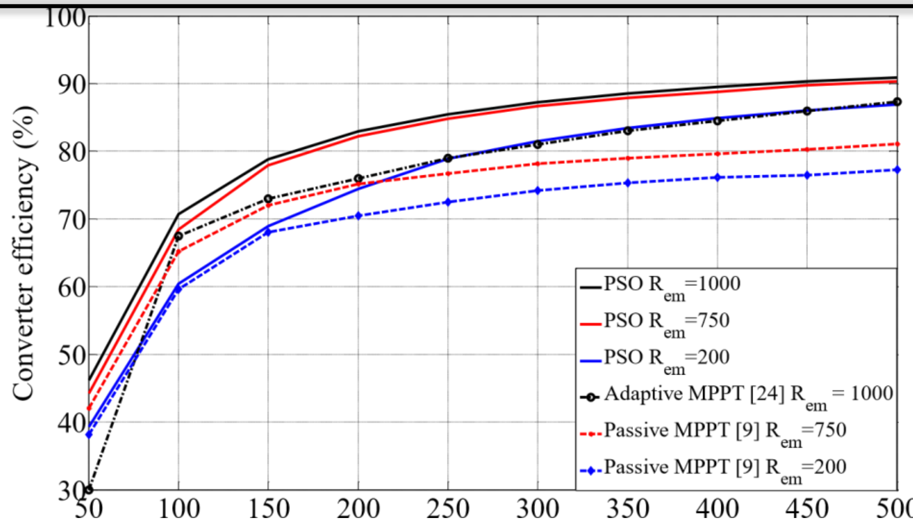

Figure 15. Comparison between PSO and passive MPPT, highlighting performance differences as referenced in [13, 16].

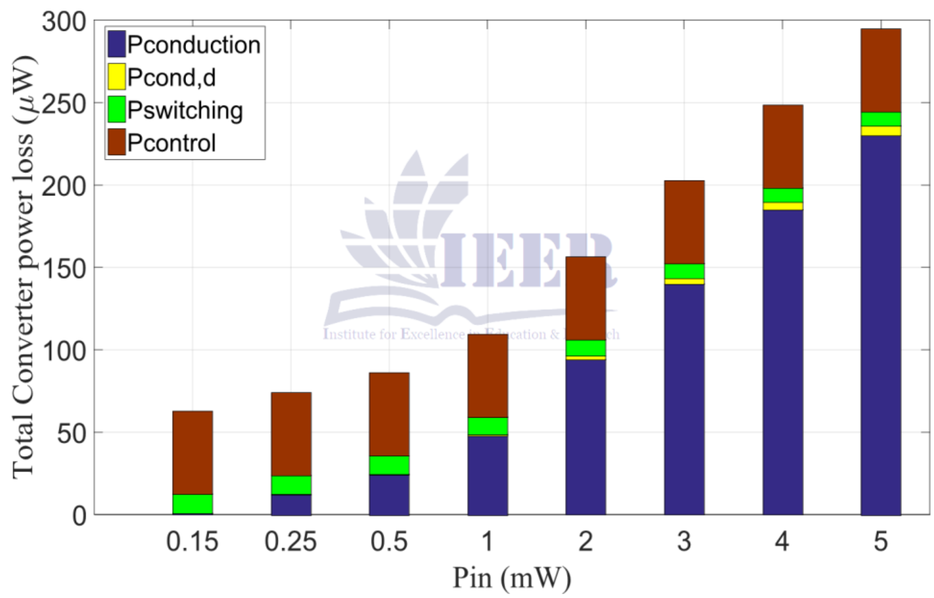

Figure 16. Calculations of power loss for varying input power, illustrating the relationship between input and power loss.

5. Conclusion:

Significant progress has been made in power electronics for low-power devices, particularly with the development of integrated circuits (ICs) tailored to support MiNT (Micro-Notched Turbine) technology. These advancements have enhanced the regulation and control of electricity generated by MiNT systems, positioning them as reliable, continuous power sources for miniature embedded applications. In parallel, researchers have proposed a method that combines boost converters with the Particle Swarm Optimization (PSO) algorithm to enhance energy regulation further and optimize the performance of energy management systems.

The compact notched turbine has demonstrated its suitability for meeting the power demands of small-scale embedded devices. Designed with a volume of 15 mm³ or less, the turbine efficiently converts mechanical energy into electrical energy using various fluids. Its design considers material compatibility, dimensional precision, and ease of assembly, with specific attention to biological and environmental applications [6–8, 19]. One promising future application is a biocompatible, implantable bio-microturbine capable of powering in vivo systems. Under equivalent testing conditions, this turbine produced approximately 35% more power than conventional micro-turbine systems.

Additionally, the RF rectenna discussed in the article offers another effective energy harvesting solution for micro-devices. The rectenna converts ambient RF energy into usable DC power via a rectifier circuit, and its performance is enhanced through an optimized power network. When the load resistance is tuned to approximately 400 ohms, the rectenna achieves a peak conversion efficiency of nearly 70%. However, many traditional energy management systems consume substantial energy, limiting their applicability in ultra-low-power scenarios.

To overcome these limitations, an optimized approach is introduced that utilizes a PSO-based MPPT (Maximum Power Point Tracking) to enhance the design of the boost converter. This method enhances DC-DC converter efficiency while minimizing power consumption across a broad range of input energy and resistance values. By treating converter efficiency as a fitness function and tuning critical parameters, such as inductance, the PSO approach delivers an average efficiency gain of approximately 7% compared to traditional systems [15, 18, 19, 26–30].

This enhanced system allows more energy to be delivered from small-scale energy harvesters to sensors and other loads. Since the design operates effectively at low simulated resistances, it is particularly well-suited for low-output renewable sources, such as photovoltaic cells, wind generators, and MiNT turbines. The simulation and analytical findings were validated using two renewable energy sources integrated with upgraded energy management circuits. The proposed architecture incorporates an advanced MPPT strategy and optimal design parameters, including an inductance of 340 H, a duty cycle period of 12.0 μs, an optimal resistance of 400 ohms, and an input power range of 15 mW to 50 mW.

The optimized DC-DC converter achieved 2–5% higher power conversion efficiency than traditional systems, confirming the effectiveness of the proposed design. Overall, the key research objectives have been met successfully. While several components of this work are already published in national and international IEEE journals, additional sections are being prepared for submission to leading IEEE publications.

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