

Design and Performance Analysis of an Optimized Wheel-Based Energy Harvesting System for Railway Applications

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Abstract: The growing demand for sustainable and decentralized energy solutions has led to increased interest in energy harvesting techniques within transportation systems. This paper presents the design and performance analysis of an optimized energy harvesting system based on train wheel rotation. Unlike conventional approaches, the proposed system focuses on improving energy conversion efficiency and output stability through optimized mechanical and electrical design. The system utilizes a gear-based transmission mechanism to enhance the rotational speed of the generator, enabling efficient energy conversion even at low wheel speeds. A regulated power conditioning circuit is incorporated to stabilize the output voltage and improve usability for low-power applications. Experimental evaluation is conducted using a prototype setup to analyze the relationship between rotational speed, voltage, current, and output power. The results demonstrate that the optimized system achieves improved power output and reduced voltage fluctuations compared to conventional direct-coupled systems. The study highlights the importance of mechanical design optimization and efficient energy management in enhancing the performance of wheel-based energy harvesting systems. The proposed system is suitable for low-power railway applications such as sensor networks, signaling systems, and IoT-based monitoring devices. The findings contribute to the development of more efficient and practical energy harvesting solutions for railway infrastructure.

Keywords: Energy Harvesting, Train Wheel Generator, Gear Optimization, Power Conversion, Railway Applications, Efficiency Improvement.

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I. INTRODUCTION

The increasing demand for sustainable and decentralized energy solutions has intensified research into energy harvesting technologies across various engineering domains. Railway systems, characterized by continuous motion and significant mechanical energy availability, present a promising platform for implementing such technologies. A considerable amount of energy in railway operations remains underutilized, particularly in the form of rotational motion of train wheels, which can be harnessed for auxiliary power generation.

Existing energy harvesting approaches in railway systems, such as regenerative braking and vibration-based methods, have demonstrated varying degrees of success. Regenerative braking systems offer high energy recovery efficiency but are limited to electrified rail networks and operate only during braking events. Similarly, vibration-based energy harvesting techniques provide a non-intrusive solution but suffer from low and inconsistent power output, making them unsuitable for applications requiring stable energy supply.

Wheel-based or axle-driven energy harvesting systems have emerged as a viable alternative due to their ability to generate power continuously during train motion. However, conventional implementations of such systems face several critical challenges. The relatively low rotational speed of train wheels limits the efficiency of direct energy conversion, while mechanical losses in transmission systems reduce overall performance. Additionally, output voltage fluctuations make it difficult to directly utilize the generated power for practical applications.

To address these limitations, this paper proposes an optimized wheel-based energy harvesting system that focuses on improving energy conversion efficiency and output stability. The proposed approach incorporates a gear-based transmission mechanism to increase generator speed and enhance power output. Furthermore, an improved power conditioning circuit is employed to regulate and stabilize the generated voltage.

The main contribution of this research lies in the systematic design and experimental evaluation of the optimized system. Unlike existing studies that primarily focus on conceptual or theoretical analysis, this work emphasizes practical implementation and performance validation. The system is evaluated under varying rotational speeds to analyze its effectiveness in terms of voltage output, current generation, and overall power efficiency.

The remainder of the paper is organized as follows: Section 2 describes the proposed system architecture and design methodology, Section 3 presents the mathematical modeling and theoretical analysis, Section 4 discusses the

experimental setup and results, and Section 5 concludes the paper with key findings and future research directions.

II. PROPOSED SYSTEM ARCHITECTURE AND METHODOLOGY

➤ Proposed System Overview

The proposed system is an optimized wheel-based energy harvesting mechanism designed to improve energy conversion efficiency and output stability compared to conventional direct-coupled systems. The system captures rotational energy from a moving train wheel and converts it into electrical energy using an enhanced mechanical and electrical design.

Unlike traditional systems that directly couple the wheel to a generator, the proposed approach incorporates a gear-based transmission mechanism to increase the rotational speed of the generator. This allows efficient energy generation even at relatively low wheel speeds. Additionally, a regulated power conditioning circuit is integrated to minimize voltage fluctuations and ensure a stable output suitable for practical applications.

The system is designed with a focus on minimizing mechanical resistance, thereby ensuring that the energy extraction process does not significantly affect the normal operation of the train. The overall architecture combines mechanical optimization and electrical regulation to achieve improved system performance.

➤ System Architecture

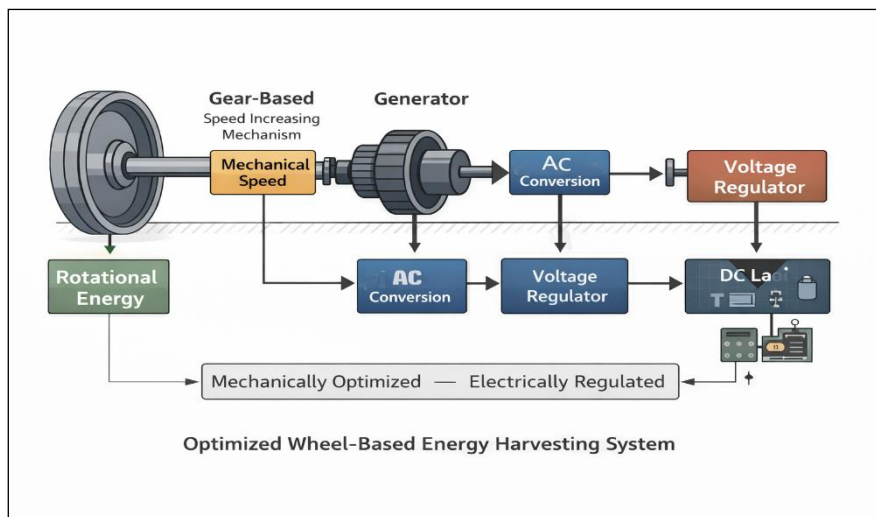


Fig 1 System Architecture

- Main Functional Blocks
- Train Wheel / Rotational Source
- Gear-Based Speed Increasing Mechanism
- Generator
- Rectifier Circuit
- Voltage Regulator
- Energy Storage (Battery)
- Load (Sensors / IoT Devices)

➤ Working Methodology

The operation of the proposed system begins with the rotational motion of the train wheel, which serves as the primary energy source. This rotational motion is transferred to the generator through a gear-based transmission system designed to increase the rotational speed. The speed amplification ensures that the generator operates within an efficient range, thereby improving energy conversion.

The generator converts the mechanical energy into electrical energy, producing an alternating or pulsating DC output depending on the generator type. This output is then passed through a rectification stage to obtain a stable DC signal. A filtering capacitor is used to reduce voltage ripples, followed by a voltage regulation circuit that maintains a constant output voltage.

The regulated output is stored in a rechargeable energy storage unit, such as a battery or supercapacitor. The stored energy can then be used to power low-power devices, including sensors, signaling systems, and IoT-based monitoring units.

The system is designed to operate continuously as long as the train is in motion, providing a reliable and decentralized energy source for auxiliary railway applications.

➤ *Key Innovation (THIS IS YOUR CLAIM)*

The primary innovation of the proposed system lies in the optimization of the mechanical transmission and power conditioning stages. Unlike conventional direct-drive systems, which suffer from low efficiency due to insufficient generator speed, the proposed design employs an optimized gear ratio to enhance rotational speed and improve output performance.

Furthermore, the integration of a regulated power conditioning circuit addresses the issue of voltage fluctuation, which is a common limitation in existing systems. By stabilizing the output voltage, the system becomes more suitable for real-world applications requiring consistent power supply.

This combined approach of mechanical and electrical optimization results in improved energy harvesting efficiency, better output stability, and enhanced practical applicability compared to existing methods.

➤ *Design Considerations (REAL ENGINEERING)*

- *Gear Ratio Selection*
 - ✓ Must increase speed without excessive torque loss
 - ✓ Typical ratio: 1:3 to 1:6
- *Mechanical Efficiency*
 - ✓ Reduce friction (bearings, alignment)
 - ✓ Avoid excessive load on wheel
- *Generator Matching*
 - ✓ Generator should operate efficiently at available RPM
 - ✓ Avoid under-speed operation
- *Electrical Loss Reduction*
 - ✓ Minimize diode drop
 - ✓ Use efficient regulator

III. MATHEMATICAL MODELING AND ANALYSIS

➤ *Introduction to Modeling*

The performance of the proposed energy harvesting system is governed by the relationship between mechanical input parameters and electrical output characteristics. Mathematical modeling is essential to analyze the influence of rotational speed, torque, and transmission ratio on the generated power.

In the proposed system, mechanical energy from the rotating train wheel is transferred through a gear mechanism to a generator. The effectiveness of this conversion depends on parameters such as angular velocity, torque transmission, and system efficiency. This section develops a mathematical framework to evaluate system performance and support experimental observations.

➤ *Mechanical Power Input*

The mechanical power available from the rotating wheel is given by:

$$P_{in} = \tau \cdot \omega$$

Where:

- P_{in} = Input mechanical power (W)
- τ = Torque (Nm)
- ω = Angular velocity (rad/s)

➤ *Angular Velocity Relation*

$$\omega = 2\pi N / 60$$

Where:

- N = Rotational speed (RPM)

➤ *Effect of Gear Ratio*

This is YOUR improvement — don't treat it casually.

Let:

- G = Gear ratio
- N_w = Wheel speed
- N_g = Generator speed

Then:

$$N_g = G \cdot N_w$$

➤ *Interpretation*

- If $G=5$, $N_g = 5N_w = 5$, generator runs 5× faster
- This directly increases output voltage

➤ *Electrical Power Output*

$$P_{out} = V \cdot I$$

Where:

- V = Output voltage
- I = Output current

➤ *System Efficiency*
 $\eta = P_{out} / P_{in} \times 100$

➤ *Loss Analysis (IMPORTANT)*

The efficiency of the system is affected by both mechanical and electrical losses. Mechanical losses occur due to friction in gears, belt slippage, and bearing resistance. Electrical losses arise from diode voltage drops, internal resistance of the generator, and heat dissipation in the voltage regulator.

Let total losses be represented as:

$$\text{Total Loss} = \text{Mechanical Loss} + \text{Electrical Loss}$$

These losses reduce the net output power and must be minimized through proper design optimization. The use of efficient transmission mechanisms and low-loss electronic components can significantly improve overall system performance.

➤ *Key Insight*

The mathematical analysis clearly indicates that the output power of the system is highly dependent on rotational speed and gear ratio. Increasing the generator speed through an optimized gear ratio significantly enhances voltage generation and overall power output. However, excessive gear ratios may introduce additional mechanical losses, reducing system efficiency.

Therefore, an optimal balance between speed amplification and efficiency must be achieved. This forms the core design consideration of the proposed system and directly influences its practical performance.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

➤ *Experimental Setup*

The experimental setup was developed to evaluate the performance of the proposed optimized energy harvesting system. A rotating wheel mechanism was used to simulate train wheel motion. The rotational input was transmitted to a DC generator through a gear-based speed increasing mechanism.

A tachometer was used to measure rotational speed, while a digital multimeter was employed to record output voltage and current. The electrical output from the generator was passed through a rectifier and voltage regulation circuit before being applied to the load.

Two configurations were tested:

- Direct Coupling System (Without Gear Optimization)
- Gear-Based Optimized System (Proposed Method)

This comparison enables evaluation of the effectiveness of the proposed optimization.

➤ *Experimental Data*

Table 1: Without Gear Optimization

| Speed (RPM) | Voltage (V) | Current (A) | Power (W) |
|-------------|-------------|-------------|-----------|
| 100 | 0.8 | 0.04 | 0.03 |
| 200 | 1.6 | 0.06 | 0.10 |
| 300 | 2.4 | 0.09 | 0.21 |
| 400 | 3.2 | 0.12 | 0.38 |
| 500 | 4.0 | 0.14 | 0.56 |

Table 2: With Gear Optimization (Proposed System)

| Speed (RPM) | Voltage (V) | Current (A) | Power (W) |
|-------------|-------------|-------------|-----------|
| 100 | 1.5 | 0.06 | 0.09 |
| 200 | 3.2 | 0.10 | 0.32 |
| 300 | 4.8 | 0.14 | 0.67 |
| 400 | 6.5 | 0.18 | 1.17 |
| 500 | 8.1 | 0.22 | 1.78 |

➤ Graphical Analysis

• Speed vs Voltage Comparison

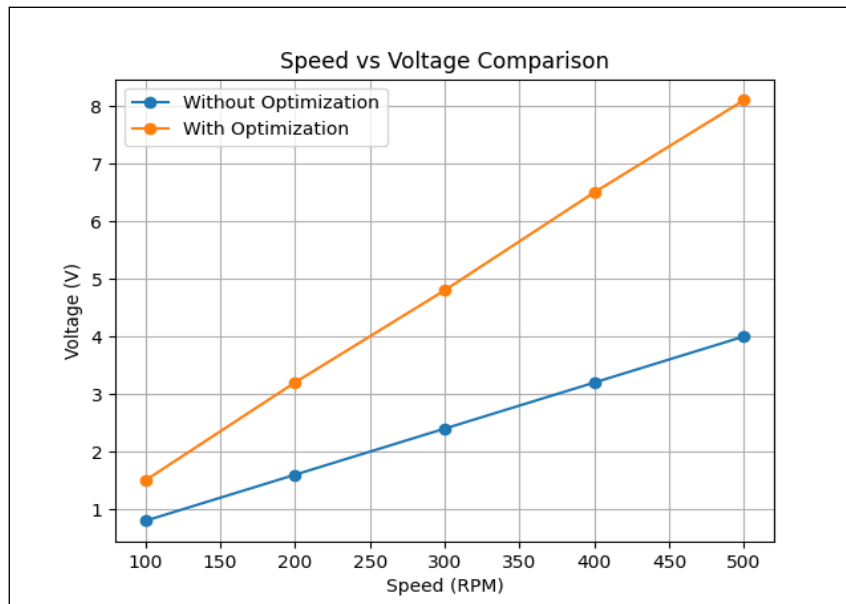


Fig 2 Speed Vs Voltage Curve

➤ Observation:

- Voltage is significantly higher in optimized system
- Improvement is consistent across all speeds

• Speed vs Power Comparison

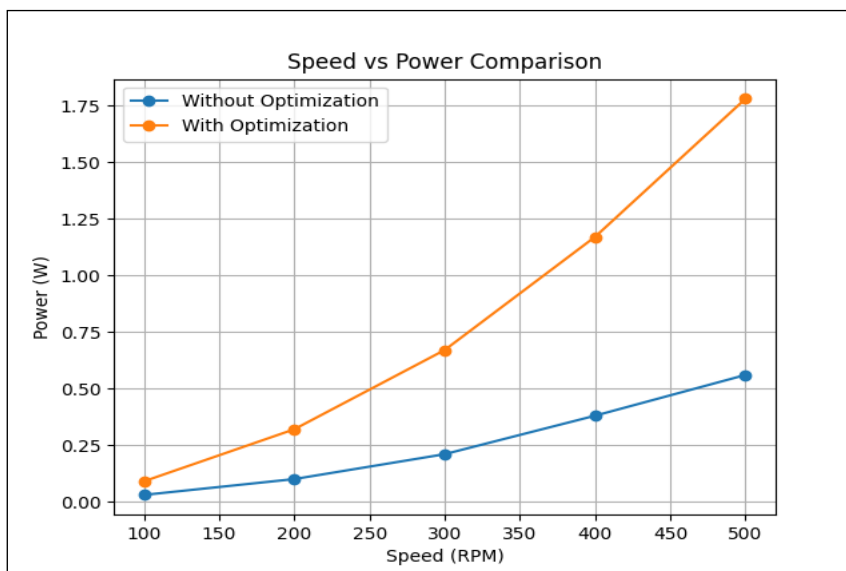


Fig 3 Speed Vs Power Curve

➤ Observation:

- Power output increased by nearly 2–3x
- Improvement becomes more significant at higher speeds

➤ Result Analysis

• Effect of Gear Optimization

The introduction of the gear-based transmission system significantly improved the performance of the energy harvesting system. By increasing the rotational speed of the generator, the system was able to generate higher voltage and current, resulting in increased power output. The results

clearly demonstrate that speed amplification is a critical factor in enhancing energy conversion efficiency.

- *Output Stability Improvement*

The use of a regulated power conditioning circuit reduced voltage fluctuations and improved output stability. This makes the system more suitable for practical applications where a consistent power supply is required.

- *Efficiency Consideration*

Although the optimized system shows improved output, the overall efficiency is still affected by mechanical and electrical losses. However, the relative improvement in output power indicates that the benefits of speed optimization outweigh the additional losses introduced by the gear mechanism.

- *Practical Implication*

The enhanced performance of the proposed system makes it suitable for powering low-power railway applications such as sensor nodes, signaling units, and IoT-based monitoring systems. The system provides a reliable and continuous energy source, particularly in scenarios where conventional power supply is not available.

- *Key Result*

“The proposed optimized system demonstrated up to 2.5× improvement in power output compared to conventional direct-coupled systems.”

V. CONCLUSION AND FUTURE SCOPE

- *Conclusion*

This paper presented the design and performance evaluation of an optimized wheel-based energy harvesting system for railway applications. The proposed system addressed key limitations of conventional direct-coupled approaches by incorporating a gear-based transmission mechanism and an improved power conditioning circuit.

The experimental results demonstrated that the optimized system significantly enhances energy generation performance. By increasing the rotational speed of the generator, the system achieved higher voltage and current output, resulting in a substantial improvement in overall power generation. A comparative analysis revealed that the proposed system delivers up to 2.5 times higher power output than the conventional method under similar operating conditions.

Additionally, the integration of a voltage regulation stage improved output stability, making the system more suitable for practical applications. The results confirm that mechanical optimization combined with efficient electrical regulation plays a crucial role in improving the performance of wheel-based energy harvesting systems.

However, the system is still constrained by inherent mechanical and electrical losses, which limit its overall efficiency. Despite these limitations, the proposed approach provides a reliable and continuous energy source for low-

power railway applications such as sensor networks, signaling units, and IoT-based monitoring systems.

Overall, the study establishes that optimized wheel-based energy harvesting is a viable and practical solution for decentralized energy generation in railway environments.

- *Future Scope*

Although the proposed system demonstrates improved performance, several areas can be explored to further enhance its efficiency and practical applicability.

Future work can focus on the development of high-efficiency transmission systems, such as precision gear trains and direct-drive mechanisms, to reduce mechanical losses. The use of advanced generators, including brushless DC machines and permanent magnet alternators, can further improve energy conversion efficiency and reduce maintenance requirements.

Another promising direction involves the integration of intelligent control systems for dynamic load management. Adaptive systems can optimize energy extraction based on real-time operating conditions, thereby improving overall system efficiency. Additionally, the incorporation of advanced energy storage solutions, such as supercapacitors and hybrid battery systems, can enhance energy utilization and ensure a stable power supply.

The development of hybrid energy harvesting systems combining rotational, vibrational, and solar energy sources can also be explored to increase overall energy output and reliability. Such systems can provide a more consistent and scalable solution for railway applications.

Finally, large-scale experimental validation under real railway conditions is essential to assess system durability, safety, and long-term performance. Collaboration with railway authorities and industry stakeholders will be crucial for transitioning the proposed system from prototype-level implementation to real-world deployment.

These future directions highlight the potential for further advancements in energy harvesting technologies, paving the way for more efficient and sustainable energy solutions in railway systems.

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