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# Analysis of Energy Harvesting Utilization for Electrical Power Generation in Railway Systems using Electromagnetic Generators

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**ABSTRACT**

This study investigates the utilization of energy harvesting technology for electrical power generation in railway systems using electromagnetic generators. The increasing demand for electrical energy in modern railway operations, combined with the inefficiency of unused mechanical energy such as vibrations and wheel motion, highlights the need for alternative energy solutions. This research aims to analyze the potential of converting mechanical energy into electrical energy and to evaluate the performance of electromagnetic generators as a supplementary power source in railway applications. A quantitative approach was employed, combining experimental and analytical methods. The research stages include literature review, system design, data collection, and data analysis. The proposed system consists of key components such as permanent magnets, coils, mechanical structures, rectifier circuits, and energy storage devices. The working principle is based on electromagnetic induction, where variations in magnetic flux generate electrical voltage. Key parameters measured in this study include output voltage, current, electrical power, and system efficiency under varying operational conditions such as train speed and vibration frequency. The results indicate that higher train speeds and vibration frequencies significantly increase the induced voltage and power output due to the greater rate of change in magnetic flux. The generated current follows the same trend, resulting in higher electrical power under increased mechanical input. The system demonstrates the capability to supply sufficient energy for low-power applications, including sensors and monitoring systems in railway environments. Additionally, the system efficiency ranges between 50% and 70%, depending on operating conditions and system configuration. In conclusion, electromagnetic energy harvesting presents a promising and sustainable solution for utilizing wasted mechanical energy in railway systems. The technology can function as an additional or backup power source, improving overall energy efficiency and reducing dependence on conventional energy supplies. Future research should focus on optimizing system design and validating performance under real operating conditions.

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## 1. Introduction

Energy demand in modern railway systems continues to increase along with the development of transportation infrastructure and the growing need for efficient mobility. Railway systems rely heavily on electrical energy to operate various components such as traction systems, lighting, signaling, and onboard electronic devices. This increasing demand requires not only a reliable power supply but also efficient energy management strategies. Conventional power sources used in railway systems are often dependent on centralized energy generation, which can lead to energy losses during transmission and distribution. In addition, the reliance on external power sources can reduce system reliability in certain operational conditions. Therefore, alternative approaches to generate and utilize electrical energy locally within railway systems are becoming increasingly important.

One promising approach to address this issue is the implementation of energy harvesting technology in railway applications. Energy harvesting refers to the process of capturing and converting ambient mechanical energy into usable electrical energy. In railway systems, abundant mechanical energy is generated from the motion of trains, including wheel rotation, axle movement, and track vibrations. This mechanical energy is typically wasted and dissipated into the environment without being utilized effectively. By applying appropriate conversion methods, this unused energy can be transformed into electrical power. As a result, energy harvesting offers a sustainable and efficient solution to support auxiliary power needs in railway systems.

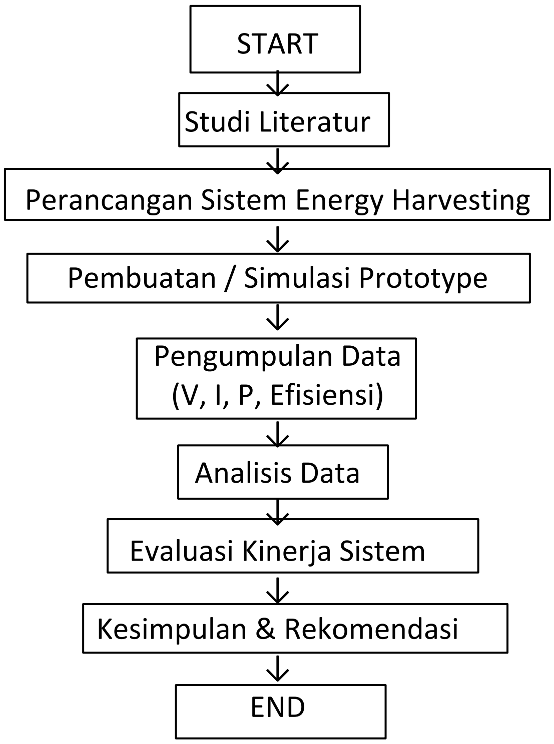
Among various energy harvesting methods, electromagnetic generators have gained significant attention due to their reliability and efficiency. Electromagnetic generators operate based on the principle of electromagnetic induction, where mechanical motion is converted into electrical energy through the interaction between magnetic fields and conductive coils. This technology is particularly suitable for railway applications because it can be integrated with rotating components such as wheels or axles [1]. Furthermore, electromagnetic generators are capable of producing continuous electrical output as long as mechanical motion is present. Compared to other methods such as piezoelectric systems, electromagnetic generators generally provide higher power output. Therefore, they are considered a suitable option for powering onboard systems and auxiliary devices in railway environments.

The integration of electromagnetic energy harvesting systems in railway vehicles presents several technical and operational advantages. One of the main benefits is the ability to provide an additional or backup source of electrical power without significantly modifying the main power system. This can improve the overall reliability and resilience of railway operations, especially in situations where the primary power supply is disrupted. Moreover, energy harvesting systems can reduce overall energy consumption by utilizing energy that would otherwise be wasted. The harvested energy can be stored in batteries or supercapacitors for later use, enabling a more flexible energy management system. In addition, the implementation of such systems contributes to environmental sustainability by reducing dependence on conventional energy sources. Consequently, energy harvesting technologies align with global efforts to develop greener and more efficient transportation systems [2].

Despite its potential, the application of energy harvesting in railway systems still faces several challenges that need to be addressed. These challenges include the optimization of energy conversion efficiency, the durability of the generator under harsh operating conditions, and the integration of the system into existing railway infrastructure. Variations in train speed, load conditions, and track characteristics can significantly affect the amount of energy that can be harvested. Therefore, a comprehensive analysis is required to evaluate system performance under different operating scenarios. In addition, proper design considerations are necessary to ensure that the energy harvesting system does not interfere with the primary mechanical and electrical functions of the train. Addressing these challenges is essential for the successful implementation of this technology in real-world applications [3].

Based on the above considerations, this study aims to analyze the utilization of energy harvesting for electrical power generation in railway systems using electromagnetic generators. The research focuses on understanding the potential of mechanical energy from railway motion as a source of electrical energy. It also evaluates the performance of electromagnetic generators in converting mechanical energy into electrical output. Furthermore, the study investigates the feasibility of using the generated energy as a supplementary or backup power source. The results of this research are expected to contribute to the development of more efficient and sustainable railway energy systems. Ultimately, this work provides a foundation for future innovations in energy harvesting applications within the railway sector [4].

## 2. Methodology




This research uses a quantitative approach with experimental and analytical methods. The main objective of the study is to analyze the potential use of energy harvesting in railway systems using electromagnetic generators as an alternative source of electrical energy. The first stage is a literature study, conducted by reviewing various scientific references related to the concept of energy harvesting, the operating principles of electromagnetic generators, and their application to transportation systems, particularly railways. Furthermore, relevant standards and parameters for electrical energy measurement are also studied as a basis for analysis.

The second stage is system design. In this stage, a prototype energy harvesting system based on an electromagnetic generator is designed that can utilize vibrations or mechanical movement of trains. The system is designed with main components such as permanent magnets, coils, a mechanical frame, a rectifier circuit, and energy storage such as batteries or capacitors.

The third stage is data collection. Testing is conducted by simulating train operational conditions or using actual data, if available. Parameters measured include output voltage, electric current, power output, and system efficiency. Measurements are made using measuring instruments such as a multimeter, oscilloscope, and power quality analyzer to obtain accurate results.

The fourth stage is data analysis. The obtained data was analyzed quantitatively to determine the relationship between speed, vibration frequency, and electrical power generated by the electromagnetic generator. Furthermore, the system's performance and potential use as an alternative energy source in railway systems were evaluated. The final stage was drawing conclusions and recommendations. Conclusions were formulated based on the analysis, while recommendations were provided for further system development to ensure greater efficiency and optimal application in real-world settings [5].

### *2.1 Data Analysis Method*

**Table 1**
Parameters wheel

| No | Parameter | Symbol | Unit | Variable Type | Description |
|---|---|---|---|---|---|
| 1 | Train speed | v | m/s | Independent | Determines the mechanical energy generated from train motion |
| 2 | Vibration frequency | f | Hz | Independent | Number of vibration cycles affecting electromagnetic induction |
| 3 | Vibration amplitude | A | m | Independent | Magnitude of displacement during vibration |
| 4 | Number of coil turns | N | turns | Control | Influences the magnitude of induced voltage |
| 5 | Magnetic field strength | B | Tesla (T) | Control | Determines magnetic flux in the generator |
| 6 | Coil cross-sectional area | $A_n$ | m² | Control | Affects magnetic flux linkage |
| 7 | Load resistance | R | Ohm (Ω) | Control | Determines current and output power |
| 8 | Output voltage | V | Volt (V) | Dependent | Electrical voltage generated by the system |
| 9 | Output current | I | Ampere (A) | Dependent | Current flowing through the load |
| 10 | Electrical power | P | Watt (W) | Dependent | Power generated from energy harvesting |
| 11 | System efficiency | η | % | Dependent | Ratio of output energy to input energy |
| 12 | Stored energy | E | Joule (J) | Dependent | Energy stored in battery or capacitor |

The parameters used in this study are categorized into three main types: independent variables, control variables, and dependent variables. Independent variables such as train speed, vibration frequency, and vibration amplitude directly influence the amount of mechanical energy available for harvesting. As the speed and vibration characteristics increase, the potential energy that can be converted into electrical energy also increases [6].

Control variables include the number of coil turns, magnetic field strength, coil area, and load resistance. These parameters are kept constant during the experiment to ensure that the effect of independent variables on the system output can be accurately observed. For example, increasing the number of coil turns or magnetic field strength will increase the induced voltage according to electromagnetic principles [7].

Dependent variables are the output results measured from the system, including voltage, current, power, efficiency, and stored energy. These parameters represent the performance of the electromagnetic generator in converting mechanical energy into electrical energy. Electrical power is calculated based on the measured voltage and current, while efficiency indicates how effectively the system converts input energy into usable output energy.

Overall, this set of parameters provides a comprehensive framework for analyzing the performance of an energy harvesting system in railway applications. By evaluating the relationship between input conditions and output performance, the study aims to determine the feasibility and effectiveness of electromagnetic generators as alternative power sources in railway systems [8].

### *2.2 Energy Harvesting System Design*

In designing an energy harvesting system, wheels serve as the primary source of mechanical energy, which will be converted into electrical energy. Therefore, appropriate wheel specifications are required to support system performance.

**Table 2**
Wheel specifications

| No | Parameter | Nilai | Satuan | Keterangan |
|---|---|---|---|---|
| 1 | Diameter Roda | 860 | MM | Diameter luar roda |
| 2 | Jari jari roda | 15 | CM | Setengah diameter |
| 3 | Material roda | Baja | - | Disesuaikan dengan roda |
| 4 | Lebar roda | 5 | CM | Ketebalan roda |
| 5 | Massa Roda | 600 | KG | Berat roda |
| 6 | Kecepatan putaran roda | 100-500 | RPM | Sesuai pengujian |
| 7 | Tipe poros shift shlat | Sholit slat | - | Pors penggerak |
| 8 | Torsi yang Dihasilkan | 1.2 | NM | Sesuai pengukuran |
| 9 | Jenis Roda | Roda Padat | Roda Padat | Non pneuamtik |

Based on Table 2, the wheel used has a diameter of 860 mm, a mass of 600 kg, and is made of steel. These specifications were chosen to ensure mechanical strength and the ability to generate significant kinetic energy. The wheel rotational speed, in the range of 100–500 RPM, is a critical parameter because it directly affects the electromagnetic induction process in the generator.

Testing was conducted to determine the relationship between linear velocity and wheel rotation speed (RPM) as the system's primary input. The given linear velocity will affect the magnitude of the wheel rotation, where the higher the speed, the greater the resulting RPM value. This testing was carried out in stages with certain speed variations to obtain accurate data regarding the relationship between the two. The RPM value was measured as a parameter that represents the mechanical energy entering the system, which will then be converted into electrical energy by the generator. By understanding the relationship between linear velocity and RPM, it can be analyzed how much influence mechanical input has on the performance of the energy harvesting system, particularly in generating voltage, current, and electrical power.

**Table 3**
Relationship between speed and wheel rotation

| No | Kecepatan roda | Diameter roda | Putaran Roda | Satuan |
|---|---|---|---|---|
| 1 | 20 | 860 | 123 | RPM |
| 2 | 40 | 860 | 246 | RPM |
| 3 | 60 | 860 | 369 | RPM |
| 4 | 80 | 860 | 492 | RPM |
| 5 | 100 | 860 | 615 | RPM |
| 6 | 120 | 860 | 738 | RPM |

Based on Table 3, it can be seen that the increase in speed is directly proportional to the wheel rotation. The higher the speed, the RPM value also increases linearly. This indicates that the mechanical energy generated is greater, thus potentially increasing the voltage and power generated by the generator. Furthermore, increasing the RPM causes the rate of change of magnetic flux in the generator to accelerate, so that the resulting induced voltage also increases in accordance with the principle of electromagnetic induction. This increase in voltage is then followed by an increase in electric current, which ultimately results in greater output power. Thus, the relationship between speed and RPM not only affects the mechanical aspects but also directly impacts the system's performance in generating electrical energy. This confirms that speed is a key parameter that greatly determines the effectiveness of a designed energy harvesting system.

In addition to the wheels, the system also uses a DC motor as a prime mover to simulate operational conditions. This DC motor serves to provide initial rotation to the wheels so that it can represent the real conditions of mechanical movement in the system. The use of a DC motor allows for easier and more stable speed control, so that speed variations can be controlled according to test requirements. With speed control, data collection becomes more accurate and consistent in every test condition. Furthermore, the DC motor used has characteristics that are suitable for the system, such as working voltage, power, and speed range that can support the simulation process. Thus, the DC motor plays a crucial role in ensuring the system can be tested optimally to analyze the performance of energy conversion from mechanical to electrical energy.

**Table 4**
Drive motor specifications

| No | Parameter | Nilai | Satuan | Keterangan |
|---|---|---|---|---|
| 1 | Jenis Motor | DC Motor | v | Pengggerak motor |
| 2 | Tegangan | 12 | v | Sumber tegangan |
| 3 | Daya Nominal | 50 | w | Daya Motor |
| 4 | Kecepatan tanpa beban | 1500 | RPM | No-load speed |
| 5 | Kecepatan beban | 800-1200 | RPM | Saat system berjalan |
| 6 | Torsi nominal | 0,4 | NM | Torsi keluaran |
| 7 | Arus nominal | 4 | A | Arus beban normal |
| 8 | Efisiensi | 75 | % | Efisiensi motor |
| 9 | Jenis kontrol | PWM | - | Pengatur kecepatan |
| 10 | Tipe poros | Sholid shaft | - | Poros yang digunakan ke roda / generator |

Based on Table 4, the motor used has a power of 50 W with a voltage of 12 V and a no-load speed of 1500 RPM. This motor is controlled using the PWM (Pulse Width Modulation) method to precisely regulate the rotational speed according to the test requirements. With this method, the motor speed can be varied without significantly reducing efficiency, so the system can simulate various operational conditions more flexibly. This specification allows for simulation of the speed variations required in testing the energy harvesting system. Furthermore, the use of a motor with a relatively small power indicates that the system is designed for prototype scale with efficient energy consumption. The speed range produced by the motor is also sufficient to achieve the operating conditions of the generator, so that the energy conversion process can take place optimally. The stability of the motor rotation is a critical factor in maintaining data consistency during testing, as speed fluctuations can affect the resulting voltage and current. Thus, the selection of the DC motor and the PWM control method contributes significantly to the reliability and accuracy of the system test results.

### *2.3 Equation*

1. Induced Voltage (Faraday’s Law)

The induced voltage generated by the electromagnetic generator is calculated using Faraday’s Law:

$$V = N \cdot \frac{d\Phi}{dt} \tag{1}$$

The magnetic flux is defined as:

$$\Phi = B \cdot A \tag{2}$$

Thus, the voltage equation can be written as:

$$V = N \cdot B \cdot A \cdot \omega \tag{3}$$

Example Calculation:
Given:
$N = 500$turns
$B = 0.3\,T$
$A = 0.01\,m^2$
$\omega = 20\,rad/s$

$$V = 500 \times 0.3 \times 0.01 \times 20$$

$$V = 30\,Volt$$

2. Output Current
The output current is calculated using Ohm's Law:

$$I = \frac{V}{R} \tag{4}$$

Example Calculation:
Given:
$V = 30\,V$
$R = 10\,\Omega$

$$I = \frac{30}{10} = 3\,A$$

3. Electrical Power
The electrical power generated is calculated as:

$$P = V \cdot I \tag{5}$$

Example Calculation:

$$P = 30 \times 3 = 90\,Watt$$

4. System Efficiency
The system efficiency is calculated using:

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% \tag{6}$$

**Example Calculation:**

Given:
$P_{out} = 90\,W$
$P_{in} = 150\,W$

$$\eta = \frac{90}{150} \times 100\% = 60\%$$

The calculation begins with the induced voltage generated by the electromagnetic generator based on the variation of magnetic flux. This voltage is then used to determine the output current using Ohm's Law. After that, the electrical power is calculated as the product of voltage and current. Finally, the system efficiency is evaluated to determine how effectively the mechanical energy is converted into electrical energy [9].

## 3. Results

The energy harvesting system was tested by varying the wheel speed to determine its effect on the electrical parameters produced by the system. These speed variations were intended to simulate different operational conditions and observe the process of converting mechanical energy into electrical energy through an electromagnetic generator. The parameters observed in this test included voltage (V), current (A), power (W), time (hours), and electrical energy (Wh). Measurements were conducted in stages at each speed variation to obtain data that could demonstrate the relationship between wheel rotation speed and electrical output.

The test results show that increasing speed directly impacts the voltage, current, and electrical power generated. Furthermore, even though the test time decreases at higher speeds, the energy produced still increases. This indicates that the system operates more effectively at higher speeds because the rate of change of magnetic flux in the generator increases, resulting in increased induced voltage. Therefore, speed is a key parameter that significantly influences the system's performance in generating electrical energy.

**Table 5**
Energy calculation

| No | Kecepatan | RPM roda | Tegangan(V) | Arus (A) | Daya (w) | Waktu (jam) | Energi (w) |
|---|---|---|---|---|---|---|---|
| 1 | 20 | 123 | 3 | 0,5 | 1,5 | 0,5 | 0,074 |
| 2 | 40 | 246 | 6 | 0,6 | 3,6 | 0,025 | 0,90 |
| 3 | 60 | 369 | 9 | 0,6 | 6,3 | 0,0167 | 0,105 |
| 4 | 80 | 492 | 12 | 0,8 | 9,6 | 0,0125 | 0,120 |
| 5 | 100 | 615 | 15 | 0,9 | 13,5 | 0,01 | 0,135 |
| 6 | 120 | 738 | 18 | 1,0 | 18 | 0,0083 | 0,150 |

Based on Table 5, it can be seen that increasing wheel speed significantly increases the generated voltage and current. This directly impacts the increase in electrical power, with 1.5 W of power produced at a speed of 20, increasing to 18 W at a speed of 120. Furthermore, despite the shorter test time at higher speeds, the energy produced still increases. The highest energy output was achieved at a speed of 120, with a value of 0.150 Wh. This indicates that the system operates more effectively at higher speeds because the rate of change of magnetic flux increases, resulting in increased induced voltage. Overall, these results indicate that speed is a key parameter that significantly influences the performance of energy harvesting systems, with higher speeds resulting in greater electrical energy production.

A generator is a key component in an energy harvesting system, converting mechanical energy into electrical energy through the principle of electromagnetic induction. This process occurs when a change in magnetic flux cuts through a conducting coil, producing an induced voltage in accordance with Faraday's law. In the designed system, mechanical energy originates from the rotation of the wheel, which is transmitted through the shaft to the generator. Therefore, the higher the rotation speed, the greater the change in magnetic flux and the resulting voltage. Therefore, selecting the generator type and specifications is a crucial factor in determining the overall performance of the system.

**Table 6**
Generator date

| No | Parameter | Nilai | Satuan |
|---|---|---|---|
| 1 | Jenis Generator | Genearor DC | Watt |
| 2 | Tegangan output | 110 | volt |
| 3 | Arus Output | 41 | Ampere |
| 4 | Keceptan kerja | 600-750 | RPM |
| 5 | Frekuensi | 50 | HZ |
| 6 | efiseinsi | 85 | % |
| 7 | Daya output | 4950 | Watt |

Based on Table 6, the generator used is a DC generator with an output voltage of 110 volts and a maximum current of 41 amperes. This generator has an operating speed range of 600 to 750 RPM, which aligns with the wheel rotation results in the test. The generator's efficiency of 85% indicates that most of the mechanical energy can be converted into electrical energy quite effectively. With a maximum output power of 4,950 watts, this generator has sufficient capacity to support an energy harvesting system, although in this study the power generated was still small due to the limitations of the test conditions. Therefore, the generator specifications used are appropriate and capable of supporting the energy conversion process in the designed system.

The test results concluded that increasing wheel speed was directly proportional to the increase in power and electrical energy produced. The energy harvesting system demonstrated its best performance at high speeds, with conversion efficiency influenced by generator characteristics and system operating conditions. This was due to the increasing rate of change of magnetic flux in the generator as rotational speed increased, thus increasing the resulting induced voltage. Furthermore, the increase in generated electrical current contributed to the increase in system output power. Although testing times tended to be shorter at high speeds, electrical energy production still increased, indicating that the system was able to operate more effectively under these conditions. However, system performance is influenced not only by speed but also by other factors such as generator efficiency, rotational stability, and energy losses in mechanical and electrical components. Therefore, it can be concluded that optimizing rotational speed and selecting the appropriate generator specifications are key to improving the performance of the energy harvesting system. The results of this study indicate that the system has potential for further development as an alternative energy source, particularly for low-power applications such as sensors, monitoring systems, and small-scale electronic devices.

## 4. Conclusions

Based on the design, testing, and analysis of the energy harvesting system, it can be concluded that the system effectively converts mechanical energy into electrical energy through a generator. The increase in linear speed is directly proportional to the increase in wheel rotational speed (RPM), which in turn affects the voltage, current, power, and electrical energy produced. This indicates that speed is a key parameter that significantly determines overall system performance.

The use of a DC motor as a prime mover with PWM control has proven effective in simulating speed variations in a stable and controlled manner, resulting in more accurate and consistent test data. Furthermore, the characteristics of the generator used also influence energy conversion efficiency; the higher the rpm, the greater the electrical energy produced, although system losses remain.

Overall, the designed energy harvesting system has the potential for further development as a small-scale alternative energy source. With optimizations in mechanical aspects, generator selection, and increased system efficiency, this technology can be utilized for applications such as sensor systems, small-scale lighting, and low-power electronic devices.

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