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The Role of Connecting Rod Length in Enhancing Voltage Output of Translational Electromagnetic Energy Harvesters

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ABSTRACT

This study evaluates the effect of connecting rod stroke length on the performance of a translational electromagnetic energy harvester designed to convert linear mechanical motion into electrical energy. The experimental verification system incorporates a 2850 rpm AC motor linked to an eccentric plate, producing reciprocating motion of a piston embedded with neodymium magnets. These magnets travel through a fixed copper coil, inducing voltage via variations in magnetic flux density. Experiments were conducted using three stroke lengths such as 15 mm, 30 mm, and 45 mm, to across time intervals of 120, 240, and 360 seconds. Key electrical parameters, including direct current (DC) voltage, current, and output power, were measured using a digital AVO meter. Data analysis was performed using Microsoft Excel. The results indicate that the 45 mm stroke length yielded the highest electrical output, with a maximum stored voltage of 4.24 V, current exceeding 0.04 A, and power reaching 0.16 W. Voltage accumulation in highest value occurred at the first 120 seconds and declined at longer durations. It's due to magnetic losses, resistive heating, and core saturation. These outcomes highlight role of stroke length in improving induction efficiency with increase magnetic flux movement. Moreover, the diminishing performance over time suggests that thermal management and electrical load optimization are necessary to sustain output. The contribution of this study is to offer optional design strategy to generate power in low-frequency vibrational environments such as IoT system and autonomous sensing applications.

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1. INTRODUCTION

The concept of energy harvesting was developed to achieve two simultaneous goals, which are the advancement of renewable energy and the efficient utilization of energy resources [1]. The exploration of ambient energy sources (such as vibration, thermal, and acoustic signals) for energy harvesting are increase due to the international commitment to reducing carbon emissions and minimizing environmental hazard. Various techniques have been developed to capture these energies, including acoustic energy harvesting (AEH) [2-4], thermoelectric energy harvesting (TEH) [5-7], triboelectric nanogenerators (TENG) [8]-11], and vibration energy harvesting (VEH) [12-15]. Vibration-based systems may utilize piezoelectric, electromagnetic, or electrostatic mechanisms to convert mechanical movement into electrical energy. Translational motion energy harvesters represent a subclass of VEH systems that specifically convert linear or reciprocating motion into usable electrical power. The concept of utilizing one-dimensional (1D) electromagnetic vibration energy harvesters (EMVEHs) has been extensively studied [16], especially for capturing vibrations generated from human movement. Typically, these 1D harvesters employ a common design, often consisting of three coaxial magnets with opposite polarities housed in a tube, where the central magnet floats and moves relative to surrounding coils. Despite their potential, several design variations exist. Some models implement a dumbbell-shaped structure as the free magnet, while others use tightly packed multiple magnets. However, a major limitation of these 1D devices is their directional sensitivity. They are generally effective only in harvesting energy from vibrations along a single axis [17]. This restriction reduces their versatility across different real-world applications. Additionally, many of these harvesters operate within a narrow resonant frequency band, although some wideband alternatives do exist. Incorporating the concept of a translational motion energy harvester into such systems can enhance performance by efficiently converting linear motion into electrical energy. This design broadens the operational capability of the device, especially when coupled with strategies to widen the resonant frequency range. As a result, translational motion-based designs hold great promise for improving adaptability and energy output across diverse environments and motion sources.

However, existing studies have rarely addressed how variations in the mechanical configuration, specifically the stroke length of the connecting rod affect the magnitude and efficiency of the harvested electrical output. Most prior works focus on magnet and coil arrangements, while overlooking the influence of linear displacement parameters that directly govern electromagnetic interaction. This leaves a gap in the optimization of energy harvester designs that depend on reciprocating mechanisms. The objective of this study is to investigate the effect of connecting rod stroke length on the electrical output performance such as stored DC voltage, electric current, and power of a translational electromagnetic energy harvester. By evaluating multiple stroke lengths under controlled time intervals, this research aims to identify the optimal mechanical configuration for maximizing energy conversion efficiency in low-power applications.

2. METHOD

This study employs a mechanical-electromagnetic experimental setup to examine the induced voltage generated by the translational motion of a piston. A single-phase 220V, 2850 rpm electric motor drives the system by transmitting power through a 10:1 gearbox and a 120 mm diameter eccentric plate, which converts the rotary motion into reciprocating motion via a connecting rod mechanism. Two pieces of neodymium magnet attached to the piston move linearly within a coil, inducing an electromagnetic voltage due to changes in magnetic flux. The coil is composed of copper wire coated with a thin enamel insulation and wound into 1200 turns, ensuring electrical isolation between adjacent windings while facilitating efficient electromagnetic induction. The detailed experimental setup is shown in Figure 1

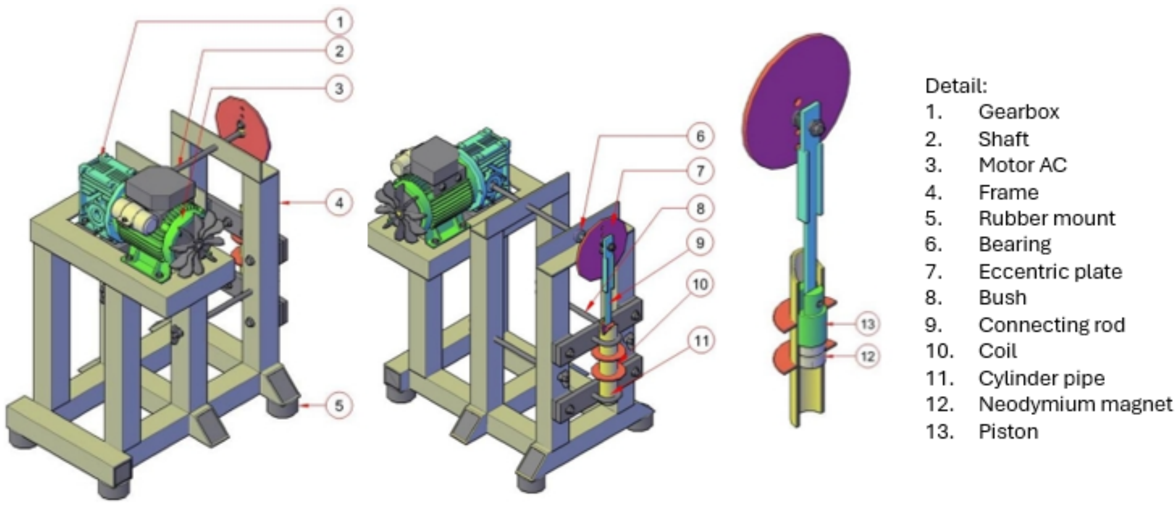

Figure 1. Experimental set-up

Based on Figure 1, voltage, current, and power were measured using an AVO meter to evaluate the electrical output of the system. The rotational speed of the eccentric plate was recorded using a digital tachometer to ensure consistency in mechanical input. The duration of each experimental run was measured using a digital stopwatch, with test intervals set at 120, 240, and 360 seconds. To assess the influence of translational motion on induced voltage, variations in connecting rod length (15 mm, 30 mm, and 45 mm) were applied. The resulting electromagnetic induction data were compiled and processed using Microsoft Excel and presented in graphical formats for analysis

To assess the electrical output of the electromagnetic energy harvesting system, a rectification and energy storage circuit was constructed as shown in Figure 2. The alternating current (AC) induced in the coil by the linear motion of a neodymium magnet was directed through a diode bridge rectifier to convert it into pulsating direct current (DC). A 12V DC capacitor was integrated into the circuit to stabilize and temporarily store the rectified voltage. The system included an AC voltmeter positioned before the rectifier, a DC voltmeter, and a DC current meter placed after the capacitor to monitor voltage and current levels. A switch was used to regulate the energy flow toward two LEDs, which served as load indicators and visual confirmation of successful energy conversion. This setup enabled real-time evaluation of the electromagnetic induction process and the effectiveness of the rectification and storage stages in a low-power experimental context.

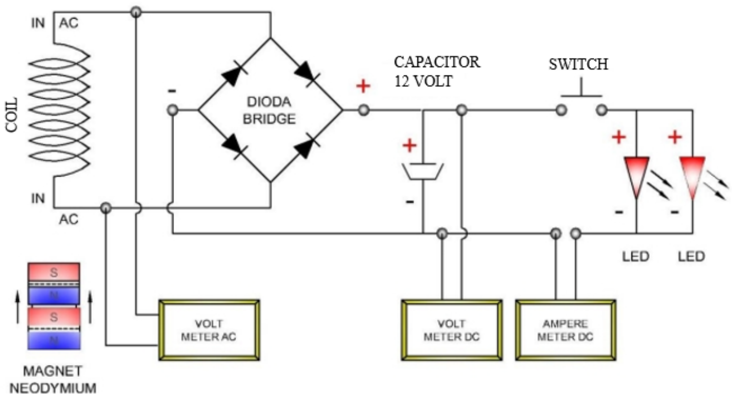

Figure 2. wiring diagram.

3. RESULTS AND DISCUSSION

Figure 3 presents the variation of stored DC voltage as a function of time for three different lengths of connecting rod in 15 mm, 30 mm, and 45 mm. The measurements were conducted over a duration of 360 seconds, with voltage values recorded at selected intervals. As illustrated, all specimens exhibit a rapid increase in stored voltage during the initial 120 seconds, followed by a plateau phase indicating stabilization. Among the three configurations, the length of 45 mm consistently demonstrates the highest stored voltage, reaching approximately 4.21–4.24 V. The 30 mm specimen follows a similar trend but with a slightly lower maximum voltage of around 3.55–3.8 V. In contrast, the 15 mm specimen shows a significantly lower storage capacity, with the voltage leveling off at approximately 1.8–2 V.

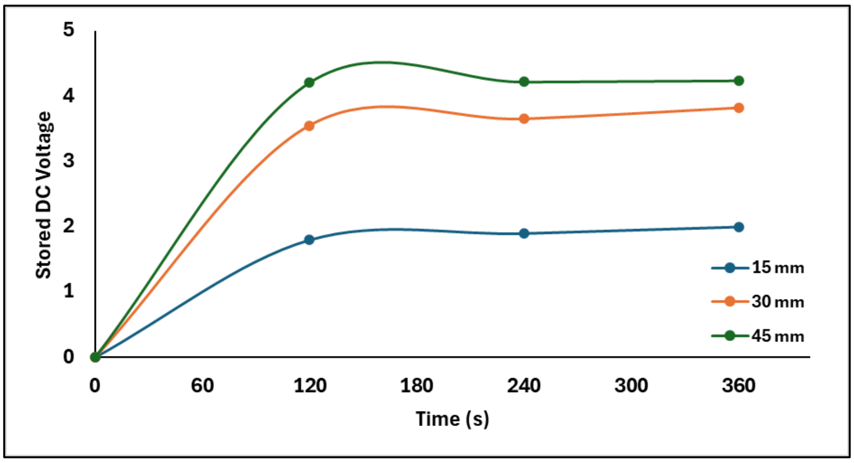

Figure 3. stored DC voltage over time for varying stroke lengths

Accordingly, an increase in the stroke length of the connecting rod specifically at 45 mm, resulted in a higher induced voltage compared to shorter stroke lengths of 15 mm and 30 mm under the same testing duration. This phenomenon is attributed to the effective voltage being induced into the coil when the direction of the magnetic force line intersects the winding through an in-and-out motion across the coil loops. Furthermore, the plateau observed after 120 seconds indicates that extending the test duration beyond this point does not significantly increase the stored voltage, reinforcing that the magnitude of voltage is more influenced by stroke length than by extended exposure time.

To further explore the energy accumulation process, the rate of voltage increase per second was also evaluated by calculating the average slope of the stored voltage over time. This was achieved by dividing the difference in stored DC voltage between two-time intervals by the duration of that interval. Measurements were taken at specific durations, such as 0–120 seconds, 120–240 seconds, and 240–360 seconds. By evaluating these rates at consistent time steps, it becomes possible to identify the point of maximum energy conversion efficiency and observe when the system begins to saturate. The resulting values are presented in Figure 4, showing a distinct peak rate before a gradual decline, consistent with system stabilization and diminishing energy conversion efficiency.

Based on Figure 4, the rate of accumulated voltage per second exhibits a distinct peak for each variation of the connecting rod stroke length (15 mm, 30 mm, and 45 mm) before gradually declining over time. The highest rate is observed in the 45 mm configuration, reaching approximately 0.035 V/s at 120 seconds, followed by the 30 mm configuration at around 0.032 V/s. In contrast, the 15 mm stroke length demonstrates a lower peak rate of approximately 0.017 V/s. After reaching their respective peaks, all curves show a decreasing trend, indicating that the rate of energy accumulation diminishes as time progresses. This trend suggests that although longer stroke lengths initially enhance voltage generation efficiency, the benefits plateau and decline with prolonged operation, possibly due to system stabilization, energy losses, and saturation effects within the storage medium.

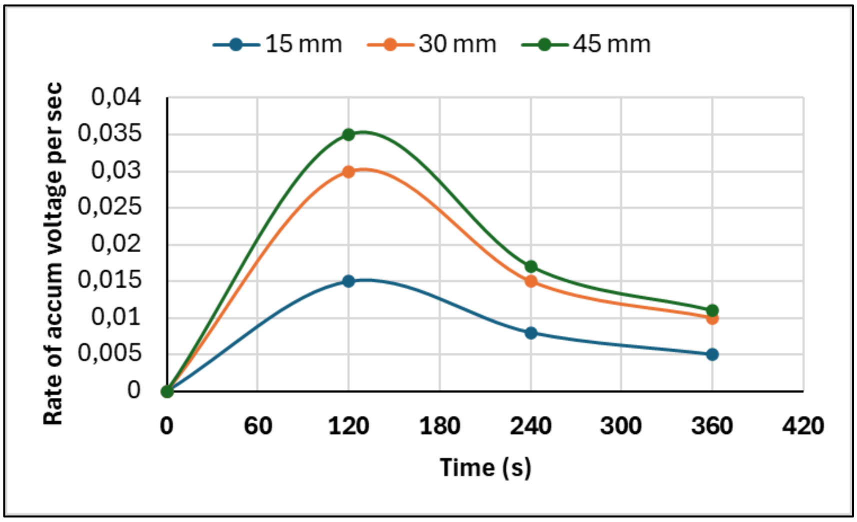

Figure 4. Rate of accumulation voltage per second

Moreover, this phenomenon may be attributed to the repetitive and steady-state nature of the mechanical motion. Once the system reaches a consistent operating pattern, the magnetic flux cutting through the coil stabilizes, leading to smaller increments in the induced voltage. Internal factors such as resistive losses in the coil and energy dissipation in the form of heat further contribute to the reduced efficiency of voltage storage over extended durations. Consequently, while the absolute stored voltage continues to increase slightly, the efficiency of accumulation declines, which is measured in volts per second, indicating a practical limit to energy gain through prolonged operation.

Figure 5 illustrates the comparison between electric current (A) and power output (Watt) for three different stroke lengths of the connecting rod. The results show a clear upward trend in both current and power as the stroke length increases. At 15 mm, the system generates minimal current and power, indicating limited electromagnetic interaction. As the stroke length increases to 30 mm, there is a noticeable rise in both current and power, suggesting improved induction performance due to enhanced mechanical displacement. The 45 mm stroke length yields the highest values for both parameters, with the electric current exceeding 0.04 A and the power reaching approximately 0.16 W. Based on the study referenced in [18], a power output of 0.18 W was achieved using a magnetically spring vibration generator. In comparison, the current research yielded a power output of 0.16 W, demonstrating a performance level that is closely aligned with the earlier study. This similarity suggests that the proposed design in this research is effective and competitive within the field of electromagnetic energy harvesting

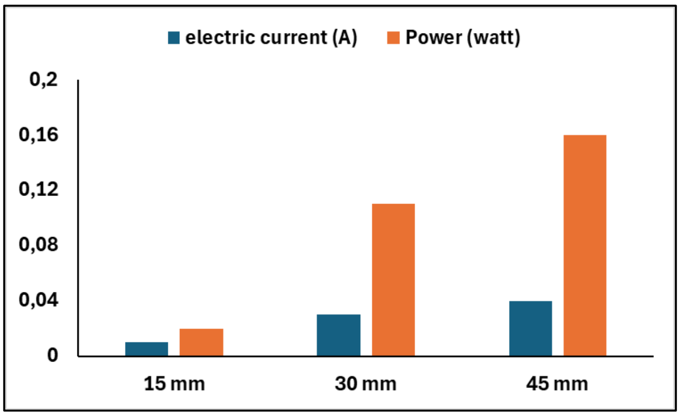

Figure 5. Electric current and Power generate in variation of connecting rod length

This trend confirms that longer stroke lengths result in stronger electromagnetic induction, which directly contributes to higher electric current and, consequently, increased power output. The enhanced performance can be attributed to the greater relative motion between the magnetic field and the coil, which increases the rate of magnetic flux change and, therefore, the induced electromotive force (EMF). These findings further validate the effectiveness of optimizing mechanical stroke parameters to improve energy conversion efficiency in electromagnetic energy harvesting systems.

The developed energy harvesting system shows strong potential for powering wearable health monitoring devices, offering a sustainable and portable energy source for continuous physiological data tracking. It can also be applied to remote structural health monitoring, where self-powered sensors are critical for long-term infrastructure diagnostics without frequent maintenance. Additionally, the system is suitable for small-scale IoT devices, enabling autonomous operation in smart environments where wired power access is limited.

4. CONCLUSION

This study demonstrates that the stroke length of the connecting rod significantly influences the electrical performance of a translational electromagnetic energy harvester. Experimental results show that among the tested configurations, the 45 mm stroke length consistently produced the highest stored voltage, electric current, and power output. The observed increase in electrical performance is attributed to the greater relative motion between the neodymium magnets and the copper coil, which enhances the rate of magnetic flux change and thus increases the induced electromotive force (EMF). Furthermore, the rate of voltage accumulation reached its peak within the first 120 seconds across all stroke lengths, after which it declined gradually. This behavior reflects a saturation effect in the system, where prolonged operation yields diminishing energy conversion efficiency due to factors such as resistive losses, thermal dissipation, and magnetic stabilization. These findings suggest that while increasing stroke length improves initial energy harvesting efficiency, system optimization must also consider operational duration to avoid inefficient energy accumulation over time.

In addition, the findings validate the effectiveness of using translational motion as a mechanism for electromagnetic energy harvesting in low-power applications. The ability to store and convert kinetic energy into usable electrical energy through mechanical-electromagnetic coupling presents a promising solution for powering small-scale electronic devices, particularly in remote or autonomous environments. Future research may focus on optimizing coil design, load matching, and material selection to further enhance performance and extend the applicability of this system under various real-world conditions.).

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