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Review Article

Design of a Power Generation System Using Energy Harvested from Exercise Equipment

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Abstract: This paper presents the design of a power generation system utilizing energy harvested from exercise machines, aiming to convert human mechanical energy generated during physical training into electrical power. Exercise machines produce mechanical energy that can be converted into electricity to supply small electrical loads. The exploitation of this energy source contributes to energy savings, enhances awareness of renewable energy utilization, and supports sustainable development. The study focuses on the mechanical design integrating a generator into the exercise machine, as well as the calculation and selection of system parameters to ensure a stable output voltage. Simulation, prototype fabrication, and experimental measurements of voltage, current, and power were conducted for validation and evaluation. Experimental results demonstrate that the system operates stably, the output voltage meets the design requirements, and the generated power is sufficient for small-scale electrical devices. These findings confirm the feasibility and effectiveness of the proposed system, indicating its potential for practical applications.

Keywords: Power Generation System, Exercise Machine, Renewable Energy, Experimental Model.

1. INTRODUCTION

Amid the continuous growth of global energy demand and the urgent need to reduce reliance on fossil fuels, renewable energy has become a central pillar of sustainable energy development worldwide. Alongside well-established sources such as solar and wind power, human motion energy harvesting has recently attracted considerable attention as a promising research direction within the domain of ultra-small distributed power generation systems. Simultaneously, the initiatives and strategic reports published by major international energy organizations—including the International Energy Agency, the Global Wind Energy Council, and the Asia Pacific Energy Research Centre—consistently emphasize that the global transition toward low-carbon and renewable energy systems is both inevitable and accelerating [1]. In Vietnam, this strategic orientation is formally articulated in Decision No. 2068/QĐ-TTg on the national renewable energy development strategy, which underscores the importance of expanding research, deployment, and practical applications of emerging renewable energy resources.

Within the domain of fitness equipment, several previous studies [2, 3], have explored the integration of electrical generators into the rotational mechanisms of exercise machines to convert mechanical energy generated by human motion into electrical energy. The harvested electricity can subsequently be utilized for applications such as lighting systems or charging low-power electronic devices. Nevertheless, the majority of these studies primarily concentrate on mechanical design considerations and fundamental energy conversion principles, while comparatively limited attention has been devoted to the optimization of power electronic interfaces and the comprehensive evaluation of output voltage stability. Furthermore, the direct utilization of the harvested energy often leads to significant voltage fluctuations and extremely low power levels, thereby limiting the practical feasibility and scalability of such systems.

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To overcome these limitations, this study proposes an alternative approach accompanied by corresponding technical solutions. Specifically, the proposed framework includes:

- A direct grid-connected micro-generation system utilizing energy harvested from exercise machines, enabling the generated power to be injected directly into the electrical grid; and
- A hybrid renewable energy configuration in which the exercise-machine-based generation system is integrated with other grid-connected renewable sources, such as solar photovoltaic and wind power systems.

This approach aims to enhance the practical applicability of human-motion-based energy harvesting while contributing to the diversification of distributed renewable energy generation systems.

2. Renewable Energy Sources

In the context of continuously rising global energy demand, fossil fuel resources such as coal, petroleum, and natural gas are increasingly revealing limitations in terms of reserves as well as their adverse environmental impacts. The combustion of fossil fuels releases large quantities of CO_2 and other greenhouse gases, contributing significantly to climate change and air pollution. Consequently, the transition toward renewable energy has become an inevitable pathway to ensure long-term energy security and sustainable development. According to the International Energy Agency [8], renewable energy currently represents the fastest-growing source in the global electricity generation mix and plays a central role in the ongoing energy transition. Major renewable energy sources include solar energy, wind energy, hydropower, biomass, and geothermal energy. The *Renewables* report published by the International Energy Agency indicates that, in recent years, newly installed renewable power capacity has consistently reached record levels, with solar and wind power accounting for the largest shares. Similarly, the International Renewable Energy Agency reports that the cost of electricity generation from solar power and onshore wind has declined significantly over the past decade, reaching price levels that are competitive with, or even lower than, those of coal- and natural-gas-based generation in many regions.

In recent years, Vietnam has been recognized as one of the fastest-growing renewable energy markets in Southeast Asia. Faced with rapidly increasing electricity demand, the gradual depletion of domestic fossil fuel resources, and national commitments to reduce greenhouse gas emissions under the United Nations Climate Change Conference (COP26), the Vietnamese government has introduced numerous policies to accelerate the energy transition. According to the International Energy Agency, Vietnam was among the fastest-growing solar power markets worldwide during the 2019–2021 period, largely driven by the implementation of attractive Feed-in Tariff (FIT) mechanisms [1].

Reports from the International Renewable Energy Agency further indicate that Vietnam's total installed renewable power capacity has increased substantially in recent years, particularly in the solar and wind energy sectors [4-8]. Within only a few years, solar power capacity expanded to several tens of gigawatts, positioning Vietnam as the leading country in the ASEAN region in terms of solar power installations. In addition, both onshore and offshore wind power projects are being actively developed, supported by the country's considerable wind potential along the central and southern coastal regions.

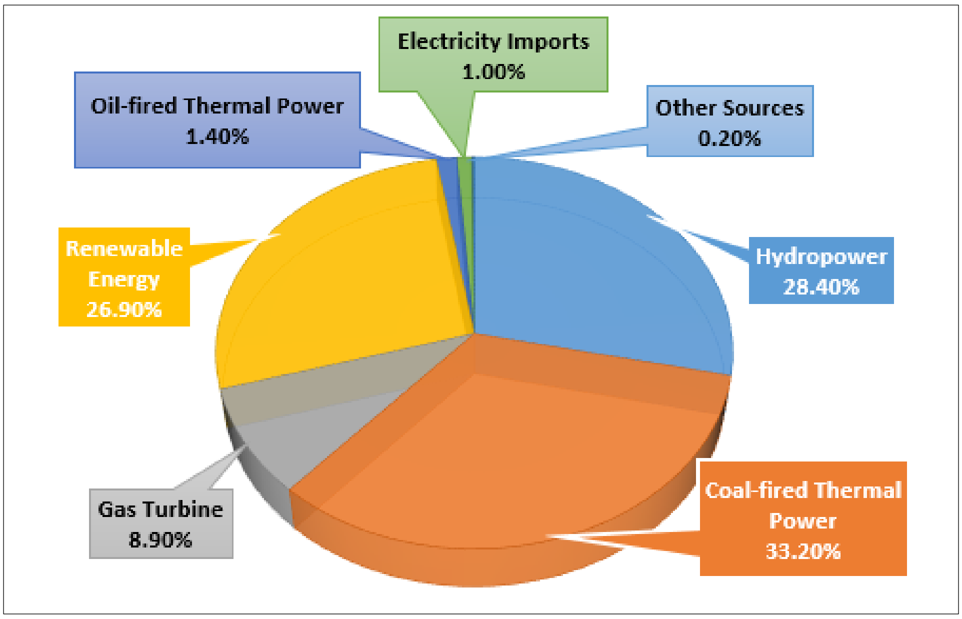

Fig. 1: Power generation mix of Vietnam in 2023

Table 1: Vietnam's electricity generation by source in 2023

Electricity Generation and Imports of the Vietnamese Power System in 2023 (million kWh)		
STT	**Power Source**	**Electricity Generation in 2023 (million kWh)**
1	Hydropower	80904
2	Coal-fired thermal power	129577
3	Gas turbine power	26315
4	Oil-fired thermal power	1267
5	Imported electricity	4191
6	Renewable energy	37922
	- of which: Wind power	11367
	- Solar power	25702
	- Biomass power	853
7	Other sources	453
	Total	280629

From a policy perspective, the Power Development Plan VIII (PDP8), approved by the Vietnamese government in 2023, clearly defines the strategic orientation of prioritizing the large-scale development of renewable energy, gradually reducing the share of coal-fired thermal power, and moving toward the goal of achieving net-zero emissions by 2050. According to analyses by the International Energy Agency, the share of renewable energy in Vietnam's power generation mix is expected to increase significantly over the coming decade, with wind and solar power playing dominant roles. Reports from the Vietnam Electricity also indicate that Vietnam has been rapidly expanding its renewable energy sector, as illustrated in Fig. 1 and Table 1.

Vietnam possesses considerable natural advantages for renewable energy development. On average, the country experiences approximately 2,000–2,500 hours of sunshine annually, providing favorable conditions for solar energy exploitation. The total solar thermal collector area increased from approximately 3 million m² in 2015 to about 8 million m² in 2020, corresponding to an energy supply of roughly 1.1 million TOE (tonnes of oil equivalent). This figure is projected to reach around 22 million m² by 2030, supplying approximately 3.1 million TOE.

In addition, with a coastline of nearly 3,400 km, Vietnam also has substantial potential for wind energy development. The estimated technical potential for wind power generation could reach approximately 24 GW. On land, the total wind power density is estimated to range from 800 to 1,400 kWh/m² per year. In coastal regions, the Central Highlands, and southern areas, the wind power potential ranges from 500 to 1,000 kWh/m² per year, while other regions typically experience levels below 500 kWh/m² per year [7].

Overall, supported by abundant natural resources, clear policy direction, and the growing attention of international organizations such as the International Energy Agency and the International Renewable Energy Agency, renewable energy development in Vietnam is entering a phase of rapid expansion. This momentum provides a critical foundation for the country to ensure long-term energy security, reduce greenhouse gas emissions, and achieve sustainable development objectives.

3. Hardware Design

3.1 System Description and Experimental Setup

In this study, the experimental implementation was conducted using a conventional stationary exercise bicycle commonly found in households and fitness centers. The bicycle features a robust load-bearing steel frame and a large-diameter rear flywheel designed to provide stable rotational inertia during pedaling. In addition, the system incorporates an adjustable resistance mechanism, allowing users with different physical conditions to regulate the pedaling load. The entire bicycle is mounted on a reinforced support frame constructed from square steel tubing. This structure is designed to ensure mechanical rigidity and operational stability, with a load-bearing capacity of approximately 50 kg, thereby ensuring safety and reliability during continuous operation.

The power generation system is implemented by harvesting the rotational motion of the rear wheel. A belt-driven transmission mechanism is employed to connect the bicycle wheel to a pulley mounted on the shaft of a DC generator. The transmission ratio between the pulleys is carefully designed to increase the rotational speed at the generator shaft, thereby ensuring that the generated voltage reaches a sufficient level for rectification and battery charging processes. This configuration enables smooth system operation, minimizes slippage, and facilitates maintenance.

A speed measurement unit is installed on the bicycle handlebar to display the pedaling speed and assist users in monitoring and controlling their exercise intensity. Additionally, an energy storage and charging module is installed at the front section of the bicycle. This module includes a rectifier circuit, a charge controller, an energy storage battery, and electrical output interfaces, such as DC USB ports and an AC output through an inverter when required. All electrical and electronic components are housed within a protective enclosure to ensure electrical safety and enhance the overall aesthetic appearance of the system.

The proposed design maintains a compact, user-friendly, and visually integrated structure while minimizing modifications to the original configuration of the exercise bicycle. Users can still freely adjust the resistance level and pedaling speed according to their fitness requirements. According to several studies [5, 6], the average mechanical power that a person can generate while cycling under normal conditions is approximately 200 W. For non-trained individuals, the output power is typically around 75 W, while trained athletes may reach 300 W, with peak power outputs potentially exceeding 500 W for short durations. These figures provide an important basis for establishing the analytical assumptions and developing the mathematical model for the integrated power generation system.

Given the design requirement of an output power of 84 W and an output voltage of 12 VDC, the specifications of the main components used in the proposed system are described as follows:

- The generator used in the system is a 12 VDC direct current generator.
- Charging for mobile devices: 5 VDC – 2 A.
- Charging for rechargeable flashlights: 5 VDC – 1 A.
- Charging for household devices such as LED lamps and electric fans (when an additional inverter is installed to provide AC output).

Battery storage capacity: … $I = \frac{P_{max}}{U} = \frac{540Wh}{12V} = 45Ah$

According to the calculation results, if the charger operates at its maximum allowable charging current, the battery can be fully charged within 1 hour.

- If the user generates an average charging power of 60 W, the battery will be fully charged in approximately 9 hours.
- If the average charging power is 80 W, the required charging time is about 6 hours and 45 minutes.
- If the average charging power reaches 150 W, the battery can be fully charged in approximately 3 hours and 36 minutes.

In this study, the research group employs a 12 VDC automotive generator (12 V alternator), which has a rated operating speed of approximately 2000–2100 rpm to ensure stable voltage generation. The system is designed with a transmission ratio of 1:5, meaning that:

Generator shaft speed=5×wheel rotational speed\text{Generator shaft speed} = 5 \times \text{wheel rotational speed}Generator shaft speed=5×wheel rotational speed.

When the bicycle wheel rotates at approximately 400–425 rpm, the belt-and-pulley transmission system increases the rotational speed at the generator shaft to its required operating range. Consequently, the generator speed reaches approximately 2000–2100 rpm, which corresponds to the nominal operating range necessary for efficient operation and stable 12 VDC output voltage.

This design demonstrates that selecting a 1:5 transmission ratio is appropriate for matching the mechanical characteristics of the exercise bicycle with the electrical characteristics of the automotive generator. When the user maintains a stable pedaling speed corresponding to 400–425 rpm at the wheel, the system operates close to its optimal working point, ensuring that:

- The output voltage reaches the rated value of 12 VDC.
- The charging current is sufficient for battery charging.
- The generator operates within its high-efficiency region.

According to physiological studies on the cycling capability of an average adult male, the pedaling speed can be estimated as follows.
Let the diameter of the bicycle wheel be:

$$25km/h \approx 416.6m/\text{minute}$$

The circumference of the wheel is therefore:

$$\mathrm{d} = 40\,\mathrm{cm} = 0.4\,\mathrm{m}$$

Assuming the cycling speed is $C = \pi d = 3.14 \times 0.4 \approx 1.25m$ vvv, the distance traveled within one minute is approximately $C = \pi d = 3.14 \times 0.4 \approx 1.25m$. From this value, the rotational speed of the wheel can be determined as:
$n = 416.6 / 1.25 = 333.2rpm$

Based on the calculated rotational speed, the transmission ratio can be determined as:
$n = 416.6 / 1.25 = 333.2rpm$

3.2 Mechanical and Electrical System Design and Implementation

a) Selection of the Electric Generator

In this study, the research team utilized an automotive alternator (12 V) as the primary device for converting mechanical energy into electrical energy within the proposed system. An automotive alternator is an alternating-current generator that integrates a diode rectifier bridge and an automatic voltage regulator, whose primary function is to supply electrical power to vehicle loads and charge the battery when the engine is operating.

The selection of an automotive alternator offers several advantages. These include a compact structural design, high mechanical durability, stable operation over a wide speed range, and high availability in the market at relatively low cost. Consequently, this type of generator is well suited for experimental energy-harvesting systems based on human mechanical motion, such as the exercise-bicycle-based power generation system proposed in this study.

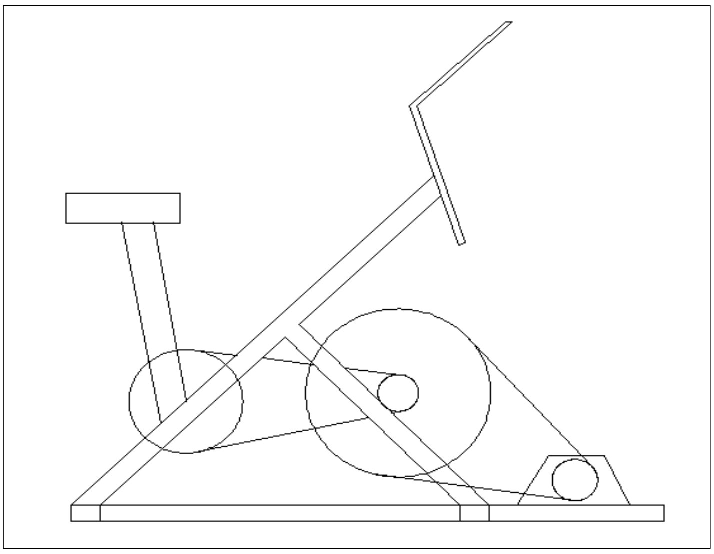

Fig. 2: Design drawing of the proposed system

Fig. 3: Mechanical model of the exercise bicycle system

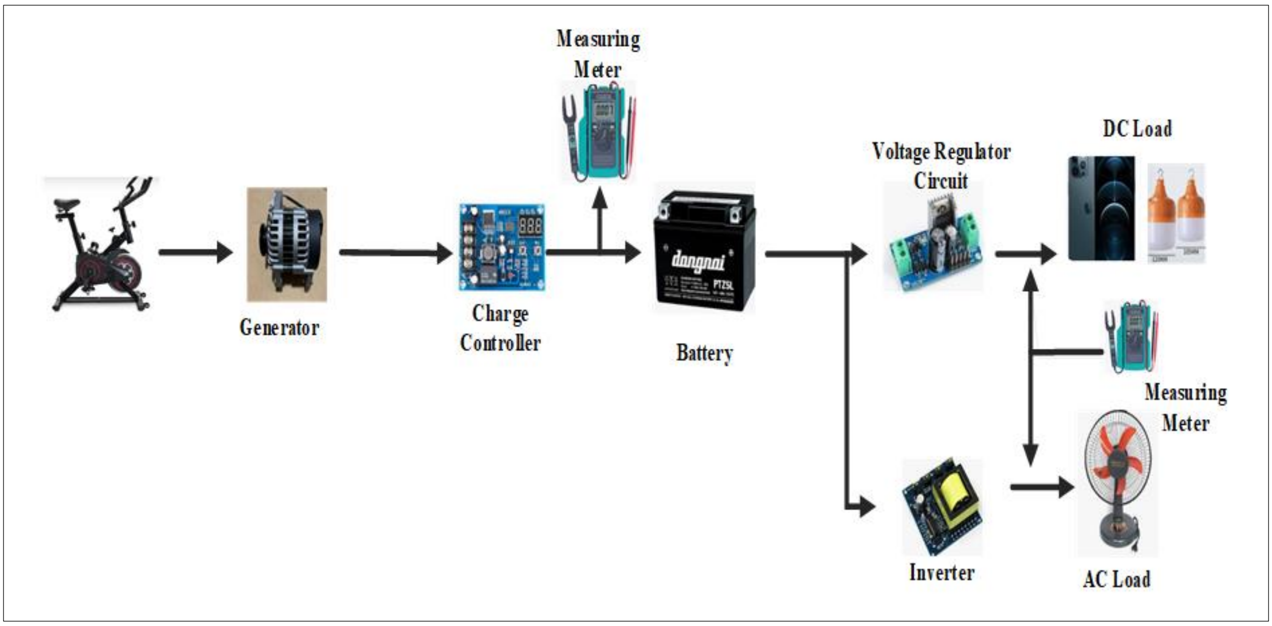

Fig. 4: Configuration of the exercise-machine-based power generation system

Operating Principle of the Electrical Circuit in the Exercise-Bike-Based Power Generation System.

The operating principle of the electrical circuit in the exercise-bike-based power generation system can be described as follows:

(1) Conversion of Mechanical Energy into Electrical Energy: When the user pedals the exercise bicycle, the rear wheel rotates. Through a belt-and-pulley transmission mechanism, this rotational motion is transmitted to the shaft of the electric generator (a 12 V automotive alternator). The rotational speed of the generator depends directly on the user's pedaling speed and the mechanical transmission ratio.

(2) Electricity Generation at the Generator: As the rotor of the generator rotates within a magnetic field, an electromotive force (EMF) is induced in the stator windings according to the principle of electromagnetic induction. The automotive alternator initially produces alternating current (AC), which is then internally rectified by an integrated diode bridge to generate direct current (DC). The resulting output voltage typically lies around 12 VDC and exhibits a near-linear relationship with the rotational speed of the generator shaft.

(3) Primary Voltage Stabilization and Regulation: The DC voltage produced by the generator is subsequently passed through a voltage regulation circuit to maintain a stable output of approximately 12 VDC. This stage is essential for protecting the battery and downstream electrical devices from potential overvoltage conditions when the pedaling speed increases significantly.

(4) Voltage Distribution and Conversion for Load Supply: From the stabilized 12 VDC source, the system distributes electrical power along two main pathways:

- One branch passes through a DC–DC step-down converter to produce a regulated 5 VDC output, which is used to supply power to mobile devices through USB ports.
- The other branch is directed to an inverter, which converts 12 VDC into 220 VAC, enabling the operation of small household appliances such as laptop chargers or low-power electric fans.

(5) Energy Storage: In parallel with supplying power directly to external loads, the stabilized DC voltage is also directed to a charging circuit that stores energy in a battery system. The battery serves as an energy storage unit, allowing the system to continue providing power when the user stops pedaling or when the rotational speed becomes insufficient to maintain the required voltage level.

Overall, the system operates according to the following energy conversion chain:

Mechanical Energy→Generator→Rectification and Voltage Regulation→Energy Storage and DC/AC Power Su pply\text{Mechanical Energy} \rightarrow \text{Generator} \rightarrow \text{Rectification and Voltage Regulation} \rightarrow \text{Energy Storage and DC/AC Power Supply}Mechanical Energy→Generator→Rectification and Voltage Regulation→Energy Storage and DC/AC P ower Supply.

This configuration enables efficient harvesting of mechanical energy generated during physical exercise while simultaneously providing a stable, safe, and convenient electrical power source for various DC and AC devices.

3.3 Experimental Results and Discussion

Through the experimental evaluation of the proposed system, the authors recorded results under two operating conditions:

1. No-load condition (no charging device connected to the system).
2. Load condition (when charging devices are connected to the system).

The experimental results collected over a 20-second measurement interval indicate that the system operates relatively stably. Under the no-load condition, the rotational speed of the bicycle wheel fluctuates within the range of 15–25 km/h and varies noticeably over time. However, despite these variations in speed, the measured output voltage (orange curve) shows only minor fluctuations, remaining within the range of 12–14 V and consistently maintaining a value close to the nominal 12 VDC. This observation demonstrates that the rectifier and voltage regulation circuits effectively maintain a stable output voltage despite variations in the input mechanical speed.

The output current (blue curve) varies within the range of approximately 5.8–6.9 A, without any sudden spikes or abnormal fluctuations. The variation in current shows a slight inverse relationship with the voltage, which is consistent with the power relationship of the load.

Similarly, under the loaded condition, no significant voltage drop or instability was observed throughout the measurement process. Overall, the experimental results indicate that the proposed system satisfies the operational requirements and is capable of providing a stable electrical supply for battery charging and load operation.

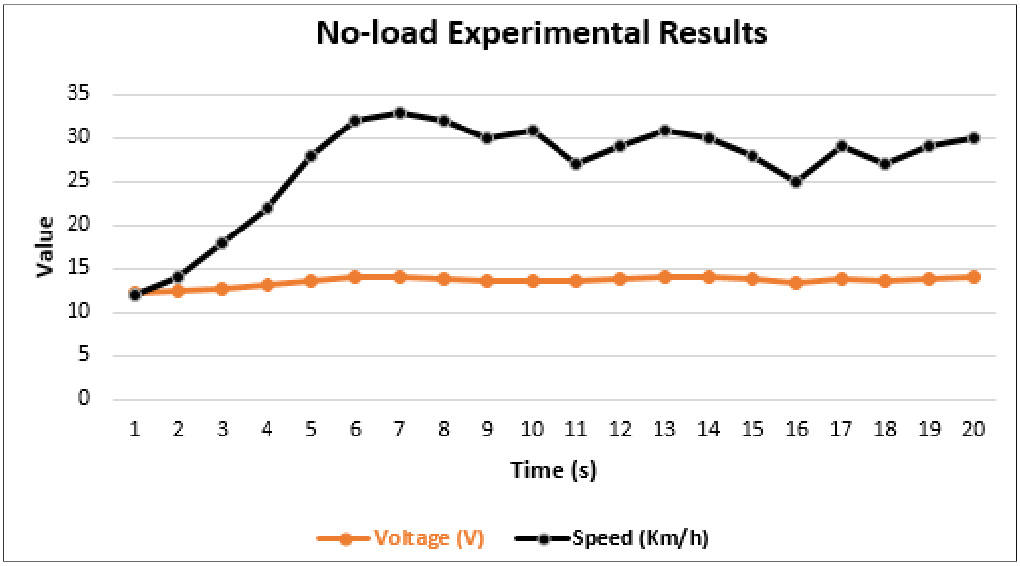

Fig. 5: Experimental results of the system under no-load condition

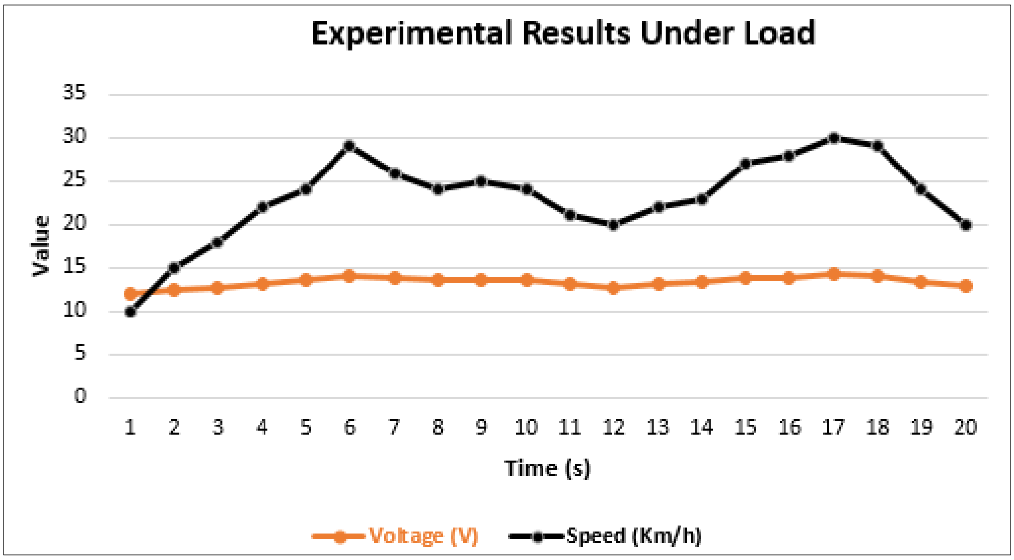

Fig. 6: Experimental results of the system under load condition

4. CONCLUSION

This paper has presented the research results and successfully proposed a solution for utilizing mechanical energy generated during physical exercise to produce electrical energy for charging mobile devices and low-power laptops. The proposed system consists of a power generation mechanism, a rectifier, and a voltage regulation circuit capable of providing a stable nominal output voltage of 12 VDC. Experimental results demonstrate that the output voltage remains close to its nominal value despite variations in pedaling speed among users. The output current supplied to the load remains within a safe operating range, and no instability was observed during system operation. These findings confirm the feasibility and reliability of the proposed model.

The primary contribution of this research lies in the development and experimental validation of a mechanical-to-electrical energy conversion system with strong practical applicability. The proposed solution not only contributes to energy conservation but also promotes awareness of renewable energy utilization. Furthermore, the system can be deployed in various settings, including fitness centers, educational institutions, and households. The outcomes of this study provide a foundation for future research aimed at improving system efficiency and expanding the power capacity of the system.

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