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A Wheel-Based Kinetic Energy Harvesting System for Efficient Battery Charging Applications

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Abstract: *The increasing demand for sustainable and renewable energy sources has led to the development of innovative energy harvesting technologies. This paper presents the design and development of a Bicycle Kinetic Energy Harvesting System integrated with an ESP32-based real-time monitoring platform. The proposed system converts the rotational kinetic energy of a bicycle wheel into electrical energy using a Permanent Magnet DC (PMDC) generator. The generated electrical power is processed through a bridge rectifier and battery charging circuit before being stored in a 12V rechargeable battery for future use. To monitor system performance, voltage and current sensors are interfaced with an ESP32 microcontroller, which continuously measures generator voltage, battery voltage, charging current, generated power, and wheel rotational speed. The ESP32 utilizes its built-in Wi-Fi capability to create a wireless monitoring interface, enabling real-time visualization of system parameters on a mobile device. The developed system provides an efficient, low-cost, and environmentally friendly solution for small-scale power generation while demonstrating the practical application of energy harvesting, battery management, embedded systems, and Internet of Things (IoT) technologies. Experimental observations indicate that the system can successfully generate, store, and monitor electrical energy produced from human-powered bicycle motion, making it suitable for educational, recreational, and sustainable energy applications.*

Keywords: Bicycle Energy Harvesting, ESP32, PMDC Generator, Renewable Energy, Battery Charging System, IoT Monitoring, Kinetic Energy Conversion, Wireless Monitoring

I. INTRODUCTION

The growing demand for electrical energy and the increasing concern over environmental sustainability have encouraged researchers to explore alternative and renewable energy sources. Conventional energy resources such as fossil fuels are finite in nature and contribute significantly to environmental pollution and global warming. As a result, the development of clean, sustainable, and decentralized energy generation systems has become an important area of research. Among various renewable energy technologies, human-powered energy harvesting systems have gained considerable attention due to their simplicity, affordability, and ability to generate electricity without producing harmful emissions.

Bicycles are one of the most widely used modes of transportation and recreational equipment worldwide. During bicycle operation, a significant amount of mechanical energy is generated through pedaling and wheel rotation. In conventional bicycles, this kinetic energy is largely dissipated and remains unutilized. By employing suitable energy conversion mechanisms, the rotational energy of the bicycle wheel can be converted into useful electrical energy. Such harvested energy can be stored in rechargeable batteries and utilized for powering small electronic devices, lighting systems, mobile charging applications, and other low-power electrical loads.

The present work focuses on the design and development of a Bicycle Kinetic Energy Harvesting System integrated with an ESP32-based real-time monitoring platform. The system utilizes a Permanent Magnet Direct Current (PMDC)

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generator mechanically coupled to the bicycle wheel through a gear transmission mechanism. As the wheel rotates, the PMDC generator converts mechanical energy into electrical energy through the principle of electromagnetic induction. The generated electrical output is passed through a bridge rectifier and filtering circuit to obtain a stable DC supply. A battery charging circuit is incorporated to regulate the charging process and safely store the generated energy in a 12V rechargeable battery.

To enhance system intelligence and monitoring capability, an ESP32 microcontroller is employed as the central control and data acquisition unit. Voltage sensors, current sensors, and wheel speed sensors are interfaced with the ESP32 to continuously monitor generator voltage, battery voltage, charging current, generated power, and wheel rotational speed. The microcontroller processes the acquired data and provides real-time monitoring through its built-in Wi-Fi functionality. Users can access operational parameters using a mobile device through a wireless web-based interface, thereby improving system usability and performance analysis.

The proposed system offers several advantages, including renewable energy generation, reduced dependence on conventional power sources, real-time performance monitoring, low implementation cost, and ease of operation. Furthermore, it serves as an effective educational platform for demonstrating the principles of energy harvesting, battery management, embedded systems, and Internet of Things (IoT) technologies. The project demonstrates the feasibility of utilizing human-generated kinetic energy for practical electrical power generation while promoting sustainable and environmentally friendly energy solutions.

The primary objectives of this research are to design an efficient bicycle-based energy harvesting mechanism, develop a reliable battery charging and storage system, implement an ESP32-based monitoring platform, and evaluate the overall performance of the proposed system under different operating conditions. The successful implementation of this system contributes toward the advancement of small-scale renewable energy technologies and smart energy management applications.

II. LITERATURE SURVEY

1. Velázquez et al. (2024) – Design of a Modular Energy Production–Storage System for a Sustainable Bicycle

Velázquez et al. proposed a modular bicycle energy generation and storage system capable of producing electrical energy at various cycling speeds. The study focused on integrating energy generation, storage, and management modules into a bicycle platform. The researchers developed an efficient mechanism for harvesting kinetic energy and storing it in rechargeable batteries for later use. Experimental results demonstrated the feasibility of generating usable electrical energy even at relatively low bicycle speeds. The work highlighted the importance of efficient power management and storage systems in bicycle-based energy harvesting applications. The study provides valuable insights into the design of sustainable bicycle energy systems and forms an important reference for the development of the present project.

2. Silva et al. (2023) – A Bicycle-Embedded Electromagnetic Harvester for Providing Energy to Low-Power Electronic Devices

Silva and co-researchers developed an electromagnetic energy harvesting system integrated within a bicycle structure. The system converts wheel rotational motion into electrical energy to power low-power electronic devices and IoT sensors. The study investigated generator design, power output characteristics, and energy conversion efficiency under different cycling conditions. Experimental results indicated that bicycle motion can serve as a reliable energy source for self-powered electronic systems. The research demonstrated the practical application of kinetic energy harvesting in smart bicycles and highlighted the potential for integrating wireless monitoring technologies.

3. Ramesh and Elangovan (2024) – Energy Harvesting from Fuel Cell Bicycles for Home DC Grids Using Soft-Switched DC–DC Converter

This research investigated the utilization of bicycle-generated energy for supplying electrical power to residential DC grids. The authors designed a power conversion system incorporating a soft-switched DC–DC converter to improve energy transfer efficiency. The study demonstrated that harvested energy can be effectively stored and utilized for

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domestic applications. The proposed converter improved voltage regulation and reduced switching losses, thereby enhancing overall system efficiency. The findings emphasize the significance of efficient power electronics in renewable energy harvesting systems and support the use of regulated charging circuits in bicycle power generation projects.

4. Nekui et al. (2024) – IoT-Based Heartbeat Rate Monitoring Device Powered by Harvested Kinetic Energy

Nekui and colleagues developed an IoT-enabled monitoring system powered entirely by harvested kinetic energy. The study integrated energy harvesting technology, wireless communication, sensors, and real-time monitoring within a single platform. The harvested energy was stored and used to power embedded electronics and wireless communication modules. The research demonstrated the capability of combining energy harvesting systems with IoT technologies to achieve self-powered monitoring applications. The implementation of wireless monitoring and low-power embedded controllers provides useful guidance for the ESP32-based monitoring architecture used in the present project.

5. Yu et al. (2024) – Ambient Energy Harvesters in Wearable Electronics: Fundamentals, Methodologies, and Applications

Yu et al. presented a comprehensive review of ambient energy harvesting technologies used in wearable and portable electronic systems. The study discussed electromagnetic, piezoelectric, triboelectric, and hybrid energy harvesting techniques along with their energy storage and management requirements. The authors highlighted the growing importance of self-powered electronic devices and real-time sensing systems. The review emphasized the integration of energy harvesting modules with wireless communication and embedded monitoring platforms, which closely aligns with the objectives of bicycle-based energy harvesting systems.

6. Snake-Scale Inspired Triboelectric Bicycle Energy Harvesting System (2024)

Researchers developed a biomimetic triboelectric energy harvesting system inspired by snake-scale surface structures for bicycle applications. The system converts biomechanical motion into electrical energy while simultaneously enabling smart health monitoring. The study reported enhanced durability, improved energy generation capability, and long-term operational stability. Additionally, the generated energy was utilized for wireless sensing and monitoring applications. The work demonstrates the growing trend of combining energy harvesting and intelligent monitoring systems within a single platform.

7. Kurt and Özer (2023) – Battery Pack and Battery Management System Design for Electric Bicycles Using ESP32

Kurt and Özer designed an ESP32-based Battery Management System (BMS) for electric bicycles. The system monitored battery voltage, charging conditions, and temperature parameters using multiple sensors. The ESP32 provided wireless communication through its built-in Wi-Fi functionality and enabled real-time monitoring of battery health. The research demonstrated the effectiveness of ESP32 as a monitoring and control platform for energy storage systems. The use of wireless monitoring, sensor integration, and battery management directly supports the implementation of ESP32 in the proposed bicycle energy harvesting project.

8. Ruiz-Guirola et al. (2024) – Intelligent Duty Cycling Management for Energy Harvesting IoT Networks

This study focused on energy harvesting IoT devices and proposed intelligent energy management techniques for maximizing battery life and improving system efficiency. The authors developed algorithms for managing harvested energy, battery storage, and wireless communication tasks. Results showed significant improvements in energy utilization and system performance under varying energy harvesting conditions. The research highlights the importance of efficient energy management strategies in self-powered embedded systems and provides useful concepts for future enhancements of ESP32-based bicycle energy harvesting platforms.

Literature Gap

The reviewed literature indicates significant progress in bicycle energy harvesting, energy storage systems, and IoT-based monitoring technologies. However, limited studies combine bicycle kinetic energy harvesting, battery charging, ESP32-based real-time monitoring, wireless user interfaces, and low-cost implementation within a single integrated platform. Therefore, the present work aims to bridge this gap by developing a compact bicycle energy harvesting

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system that not only generates and stores electrical energy but also provides real-time monitoring of voltage, current, power, battery status, and wheel speed through an ESP32-based IoT monitoring architecture.

III. METHODOLOGY

The proposed Bicycle Kinetic Energy Harvesting System is developed to convert the rotational kinetic energy of a bicycle wheel into electrical energy and store it for future use. Initially, the bicycle wheel is mechanically coupled to a PMDC generator through a gear transmission mechanism. As the wheel rotates during bicycle motion, the generator converts mechanical energy into electrical energy based on the principle of electromagnetic induction.

The generated electrical output is passed through a bridge rectifier and filter capacitor to obtain a stable DC voltage. A battery charging circuit is incorporated to regulate the charging process and safely store the generated energy in a 12V rechargeable battery. To monitor system performance, voltage sensors are connected across the generator and battery terminals, while an ACS712 current sensor measures the charging current. A Hall-effect sensor is installed near the bicycle wheel to measure wheel rotational speed (RPM).

All sensor outputs are interfaced with an ESP32 microcontroller, which continuously acquires and processes the data. The ESP32 calculates important parameters such as generator voltage, battery voltage, charging current, generated power, battery status, and wheel RPM. The processed information is displayed on a monitoring interface and transmitted wirelessly using the built-in Wi-Fi capability of the ESP32. The performance of the system is evaluated under different operating conditions by observing the generated voltage, charging current, power output, and battery charging characteristics.

IV. SYSTEM DESIGN

The proposed Bicycle Kinetic Energy Harvesting System consists of a bicycle wheel, gear transmission mechanism, PMDC generator, bridge rectifier, battery charging circuit, rechargeable battery, sensors, and an ESP32 microcontroller. The rotational motion of the bicycle wheel is transferred to the PMDC generator through a suitable gear arrangement to increase generator speed and improve energy generation. The electrical output from the generator is rectified and filtered to obtain stable DC power, which is then stored in a 12V rechargeable battery through a regulated charging circuit.

An ESP32 microcontroller is employed as the central monitoring unit. Voltage sensors are connected to monitor the generator and battery voltages, while an ACS712 current sensor measures the charging current. A Hall-effect sensor is used to determine wheel speed (RPM). The ESP32 processes all sensor data, calculates power generation parameters, and provides real-time monitoring through its built-in Wi-Fi interface. The complete system is designed to achieve efficient energy harvesting, storage, and wireless performance monitoring in a compact and cost-effective manner.

V. CONCLUSION

This research presents the design and development of a Bicycle Kinetic Energy Harvesting System integrated with an ESP32-based monitoring platform. The system successfully converts the rotational kinetic energy of a bicycle wheel into electrical energy using a PMDC generator and stores the generated energy in a rechargeable battery through a regulated charging circuit. The implementation of voltage, current, and RPM sensors enables continuous monitoring of system performance.

The ESP32 microcontroller effectively acquires sensor data, performs real-time calculations, and provides wireless monitoring through a mobile-based user interface. The developed system demonstrates a practical, low-cost, and environmentally friendly approach to small-scale renewable energy generation. The project highlights the potential of integrating energy harvesting, battery storage, embedded systems, and IoT technologies for sustainable power generation applications. Future improvements may include enhanced power management techniques, higher-efficiency generators, and cloud-based data monitoring systems.

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