Design and Development of a Smart Renewable Energy Harvesting System for Moving Vehicles

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ABSTRACT
The transportation sector is increasingly searching for renewable energy solutions Owing to growing global energy consumption and the growing environmental concerns over the use of fossil fuels. Conventional vehicles waste large amounts of energy in heat, vibration, and mechanical losses, much of which goes unused. Moving vehicles can be a source of renewable energy that can be harvested enhancing energy efficiency and reducing greenhouse gas emissions. In this we discussed about a smart system for harvesting renewable energy for moving vehicles with combined kinetic, solar, and thermoelectric energy conversion technologies using intelligent energy management strategies. This system harvests the waste energy produced during vehicle operation and converts it into usable electrical energy. Piezoelectric and electromagnetic mechanisms are used in vehicle suspension systems to achieve kinetic energy harvesting. The vehicle is equipped with lightweight photovoltaic panels on its surface to harness solar energy, and waste heat from the exhaust system is used for thermoelectric power generation. For the reliable power supply, a hybrid energy storage system, consisting of batteries and supercapacitors, is used. A smart energy management system based on a microcontroller with IoT-enabled sensors and intelligent control algorithms enables real-time monitoring and optimization of energy generation and consumption. Artificial intelligence and machine learning methods are used to improve system adaptability to different driving and environmental conditions. Development of a prototype and experimental testing in realistic driving conditions show that the proposed system is feasible, efficient, and durable. Results indicate that the harvested energy is capable of efficiently supplying auxiliary vehicle components and therefore decreasing the dependency of the main energy source. While challenges such as system efficiency, cost, and integration still exist, the proposed approach provides a hopeful pathway towards sustainable and self-powered transportation systems.

Keywords: Energy management system, kinetic energy, solar energy, thermoelectric energy, smart transportation, and renewable energy harvesting.

1. INTRODUCTION

The growing worldwide energy demand and the environmental issues related to the production of electricity from fossil fuels have made the creation of alternative energy solutions necessary. Harvesting renewable energy from moving cars offers a cutting-edge strategy for energy sustainability by combining smart technologies with cutting-edge materials to capture, store, and make effective use of energy. Design and development of an intelligent system for renewable energy harvesting are analyzed in this paper and are intended for moving vehicles using kinetic, solar, and thermoelectric energy conversion technologies.

Need for Renewable Energy Harvesting in Vehicles

A modern transportation system contributes significantly to greenhouse gas emissions and is largely dependent on fossil fuels. The transportation industry continues to be the world's biggest energy consumer despite advancements in fuel efficiency (International Energy Agency, 2022). By transforming waste energy into usable electrical energy, renewable energy harvesting in automobiles offers a practical alternative to offset energy consumption. By using this extracted energy for auxiliary vehicle functions, the vehicle's reliance on its main power source can be decreased.

Principles of Energy Harvesting in Moving Vehicles

By obtaining and converting ambient energy into electrical power that can be used, energy harvesting in moving vehicles improves transportation systems' sustainability and efficiency. In addition to energy harvesting, electromechanical, piezoelectric, thermoelectric, and electromagnetic mechanisms are the main concepts. Electromechanical energy harvesting uses regenerative suspension systems or inertial generators to take advantage of mechanical movement and vibrations in automobiles. The use of piezoelectric materials in automobile components to transform mechanical stress into electrical power. Thermoelectric harvesting uses engine heat and exhaust gas temperature gradients to generate electricity through thermoelectric generators. In electromagnetic energy harvesting, power is extracted from motion and electromagnetic fields in transmission or braking systems using inductive and resonant coupling. These techniques are employed to recover energy from sources that have been wasted. Powering onboard sensors, increasing fuel efficiency, lowering reliance on external charging sources in electric vehicles, and improving overall Vehicle performance are all examples of this energy harvesting in moving vehicles. The Internet of Things (IoT) and intelligent transportation are advanced by the use of energy harvesting technologies. by fostering the creation of self-sustaining vehicles. Energy harvesting has a lot of potential, but in order to maximize performance, issues like system integration, material limitations, and efficiency restrictions must be resolved. In order to maximize power generation in moving vehicles and open the door to more ecologically friendly and energy-efficient transportation options, future research will concentrate on improving energy conversion efficiency, creating cutting-edge materials, and putting hybrid harvesting systems into place.

1. In vehicles, energy harvesting utilizes multiple renewable energy sources such as:
2. **Kinetic Energy Harvesting:** It converts vibrations, suspension movements, and rotational energy into electrical energy using piezoelectric, electromagnetic, or regenerative shock absorber systems.
3. **Solar Energy Harvesting:** It is used to integrate photovoltaic panels into the vehicle's body or roof to capture solar energy.
4. **Thermoelectric Energy Harvesting:** It utilizes thermoelectric generators (TEGs) to convert waste of heat from the exhaust system into electrical energy.

System Design Considerations

The design of a renewable energy harvesting system should be optimized for efficiency, reliability and integration with vehicle operations. The following main components are required in system design:

1. Energy Harvesting Mechanisms

- **Piezoelectric Generators**
- **Solar Panels**
- **Thermoelectric Generators**

5. Energy Storage System

- **Super capacitors and Batteries**

- **Battery Management Systems (BMS)**

6. **Smart Energy Management System (SEMS)**

- **Microcontrollers and IoT Integration**
- **Artificial Intelligence and Machine Learning**

4. **Development and Testing using a prototype:** To validate the feasibility of a smart renewable energy harvesting system, a prototype is designed and tested under real-world conditions.

- **Fabrication of Energy Harvesting Modules**
- **Power Management and Storage**
- **Performance Testing**

5. **Challenges and Future Developments**

- Improving the efficiency & maximize output.
- **Reducing System Weight and Cost**
- Enhancing compatibility with hybrid and electric vehicles for improved sustainability.

Future work should be focused on materials development, IoT based energy management and large-scale deployment of smart renewable energy harvesting systems for commercial vehicles.

A promising solution to improve energy efficiency and sustainability in the transportation system is the integration of smart renewable energy harvesting systems for moving vehicles. Such systems can greatly reduce reliance on fossil fuels by harnessing kinetic, solar and thermoelectric energy sources and incorporating smart management technologies. Furthermore, advancements in energy conversion and storage technologies will be pivotal to realizing the maximum capacity of this innovative approach.

LITERATURE REVIEW

Xingtian Zhang et al., (2016)

The harvesting of abundant environmental energy, the demand for alternative sources of energy, has resulted in increasing attention being paid to the utilization of vibrational energy, such as track vibrations in railway systems. The present work is aimed at the development of a high-efficiency, A portable electromagnetic energy harvesting system that uses supercapacitors to convert the energy of track vibrations to electricity. Supercapacitors store generated electricity, which is then used in remote locations for safety facilities or in standby power supplies for rail-side equipment.

The proposed system includes a mechanical transmission and a regulating circuit. The one-way bearings increase efficiency by converting the bi-directional motion to unidirectional rotation. The small oscillations of the track are amplified by gears and a rack. The energy input and transmission. First use of supercapacitors in a vibration energy harvesting system. The supercapacitors can store energy from transient currents that vary rapidly and supply steady power to the external applications. The fast response of the system is demonstrated by dynamic simulations. Bench tests with an efficiency of 55.5 % have proved the practicality and efficiency of the suggested electromagnetic energy harvesting system for renewable energy applications for railroads.

Zutao Zhang et al., (2016)

In recent years, the energy source of vehicles has undergone a significant and rapid transformation, particularly in the context of electric vehicles (EVs), as a result of the increased use of renewable energy technologies. An energy regenerative shock absorber is a clever solution that converts the wasted energy in a vehicle's shock absorber into alternative energy for the vehicle itself. Existing regenerative shock

absorbers are primarily concerned with energy harvesting techniques; however, there is no such regenerative shock absorber that is suitable for extended-range electric vehicles.
This paper introduces a novel, high-efficiency energy regenerative shock absorber that utilizes supercapacitors to enhance the battery endurance of an electric vehicle (EV). The first-ever design and proposal of a renewable energy application scheme for range-extended electric vehicles (EVs) employing regenerative shock absorbers. This system replaces the conventional shock absorbers, which typically dissipate these energies through friction and heat, to capture the discarded suspension power from the moving vehicle. The vibration of the suspension input module, transmission module, generator module, and power storage module comprises the proposed system. The energy regenerative shock absorber is driven by the suspension vibration due to the road irregularities.
Then the vibration is transmitted through the mechanical transmission module. The mechanical transmission module converts the bidirectional vibration into unidirectional rotation by a gear and a rack to drive the generator module. In the power storage unit, the supercapacitor stores the regenerative energy of the shock absorber, which is used on the EV to extend its driving range. The simulation and lab tests demonstrated that the energy regenerative shock absorber is promising and advantageous for energy generation for renewable energy applications in extended-range electric vehicles (EVs). The maximum efficiency was 54.98%, and the average efficiency was 44.24%.
Mohamed A.A. Abdelkareem et al., (2018)
Since decades, hydraulic shock absorbers have been extensively employed in vehicle suspensions to effectively mitigate the acceleration of vehicle bodies and ensure that tires maintain a good connection with the ground in the presence of road irregularities. Although energy efficiency has been a significant concern in the automotive industry since the onset of mass production in the 1900s, researchers only recognized that the energy dissipated in conventional hydraulic shock absorbers is suitable for recovery in the mid-1990s. Various varieties of energy harvesting-based shock absorbers have been conceptualized and prototyped since that time.
The regenerative suspension, which is equipped with energy-harvesting shock absorbers, has the ability to convert the energy that is typically squandered into electricity, in contrast to traditional suspension systems that suppress vibrations by dissipating the vibration energy into waste heat. This paper provides a thorough examination of vehicle suspensions that are powered by energy harvesting. In particular, it concentrates on the analytical and statistical examination of vehicle regenerative suspensions, as well as the review of concepts, designs, simulations, test apparatus experiments, and vehicle roadside tests. The advantages and limitations of the most prevalent energy harvesting systems in vehicle suspensions are contrasted. Furthermore, the report addresses the unresolved research gaps and challenging issues, and it provides recommendations for future research.
Hao Wang et al., (2018)
Energy harvesting is a promising technique that has the potential to enhance the sustainability of infrastructure and generate renewable and pure energy. The purpose of this paper is to evaluate the energy harvesting techniques that are currently in use for roadway and bridge applications.
These techniques include photovoltaic cells, solar collectors, geothermal, thermoelectric, electromagnetic, and piezoelectric systems. The energy that is extracted has the potential to generate electric energy, heat or chill, dissolve ice, power wireless sensors, and monitor structural conditions. The working principles, examples of applications, developments of prototypes, and important findings reported in the literature of each energy harvesting technology are reviewed in detail. The review provided a comprehensive overview

of the previous research conducted on energy harvesting systems, including material design, system optimization, theoretical analysis, laboratory testing, field experiments, and numerical modeling. The power output, cost-effectiveness, technology maturity level, advantages and disadvantages, and support from government and industry of various energy-harvesting technologies were compared. Lastly, future research recommendations for energy harvesting in bridges and roadways were proposed.

Hanjun Ryu et al., (2019)

Sustainable green energy harvesting systems have recently garnered significant attention due to their potential application in self-powered smart wireless sensor network (WSN) systems. In particular, the developed WSN systems have the potential to advance the public welfare; however, they will necessitate substantial and long-term expenditures to be utilized for the purpose of supplying electrical energy through transient batteries or connecting power cables. This report provides a concise overview of the most recent substantial advancements in the development of hybrid nanogenerators for a sustainable energy harvesting system. These systems utilize a variety of natural and artificial energies, including solar, wind, wave, heat, vehicle noise, and machine vibration.

The article commences with a concise overview of energy harvesting systems and subsequently provides a summary of the various hybrid energy harvesting systems, including the integration of mechanical and photovoltaic energy harvesters, the integration of mechanical and thermal energy harvesters, and the integration of thermal and photovoltaic energy harvesters. A systematic summary of the structures, working mechanisms, and output performances of the hybrid nanogenerators that have been reported is presented. The review specifically examines the individual and hybrid power performances of hybrid nanogenerators, as well as their practical implementations with a variety of device designs, to examine electromagnetic induction, triboelectric, piezoelectric, photovoltaic, thermoelectric, and pyroelectric effects. Lastly, the perspectives and challenges associated with the development of hybrid nanogenerator systems that are both sustainable and high-performing are discussed.

Sherali Zeadally et al., (2020)

The Internet is being connected to an increasing number of objects as they become more advanced, compact, and affordable. The emergence of the Internet of Things (IoT) is being facilitated by these Internet-connected objects. The Internet of Things (IoT) is a distributed network of scalable, lightweight, low-power, and low-storage nodes. The majority of embedded IoT devices and low-power IoT sensors are powered by batteries with limited lifespans, necessitating replacement every few years. Smart energy management could be instrumental in facilitating energy efficiency for the communication of IoT objects, as this replacement procedure is costly. For instance, the elimination of the reliance on batteries in IoT networks is achieved through the utilization of energy from environmental resources that are either naturally or artificially available.

In contrast to battery-powered solutions, IoT systems are characterized by their ability to scavenge an infinite quantity of energy, which ensures their longevity. Thus, we introduce energy-harvesting and sub-systems for IoT networks in this section. We have identified future design challenges of IoT energy harvesters that must be resolved in order to ensure the continuous and reliable delivery of energy, following a review of the available options for harvesting systems, distribution approaches, storage devices, and control units.

Mohammadreza Gholikhani et al., (2020)

The potential to generate electricity for a variety of roadside data collection and communication applications exists through energy harvesting from roadways. On the premise of the energy source utilized, roadside energy harvesters are broadly classified into three categories: solar radiation, mechanical energy from vehicles, and pavement heat. In the realm of harvesting technology, harvesters are classified as electromagnetic, piezoelectric, thermoelectric, pyro-electric, photovoltaic, and solar heat collectors that utilize liquid or air circulation.

The literature on each of these energy harvesting technologies is comprehensively reviewed in this paper to provide a state-of-the-art overview. It encompasses information regarding the economic considerations, prototype development, implementation efforts, and harvesting principle for each harvesting technology. The report concludes that a number of these harvesting technologies have been sufficiently developed to produce self-sustainable electrical power on the roadside.

Huicong Liu et al., (2021)

In the past decade, there have been substantial advancements in energy harvesting technology that have enabled the development of self-charging electronics and self-powered wireless sensor nodes. In recent years, hybrid energy harvesting systems have been proposed as a solution to the energy-insufficiency issue of a singular energy harvester. In addition to scavenging energy from a variety of sources, hybrid harvesting involves the conversion of energy into electricity through a variety of transduction mechanisms. In addition to enhancing the efficiency of space utilization, a rational hybridization of multiple energy conversion mechanisms can also substantially increase the power output. We have compiled an exhaustive evaluation of recent progress and representative works in hybrid energy harvesting technology, with a particular emphasis on vibrational and thermal energy harvesters, which are the primary components. This review is necessary due to the ongoing growth of hybrid energy harvesting technology. Piezoelectric, electromagnetic, tribo-electric, thermoelectric, and pyro electric transduction effects are briefly discussed, along with their typical configurations and working principles.

A diverse array of hybrid energy harvesting systems, including their mechanisms, configurations, output performance, and benefits, are developed on this foundation. Comparisons and perspectives regarding the efficacy of hybrid vibrational and thermal harvesters are offered. In anticipation of the future Internet-of-Things (IoT) era, a diverse array of potential application prospects for hybrid systems are explored, such as infrastructure health monitoring, industry condition monitoring, smart transportation, human healthcare monitoring, marine monitoring systems, and aerospace engineering.

2. OBJECTIVES OF THE STUDY

1. To design an efficient smart renewable energy harvesting system for moving vehicles.
2. To develop a system that integrates multiple renewable energy sources for maximum energy capture.
3. To optimize energy conversion efficiency for improved power generation from vehicular motion.
4. To enhance system durability and adaptability for different road and vehicle conditions.
5. To evaluate the economic and environmental benefits of the proposed energy harvesting system.

3. NEED OF THE STUDY

As the increasing of global demand for sustainable energy solutions and the growing concern over environmental pollution caused by the consumption of conventional fuels necessitate the study on the Design and Development of a Smart Renewable Energy Harvesting System for Moving Vehicles. The rapid development of the transportation industry has led to excessive consumption of energy and large-scale emission of greenhouse gases, thus making it necessary to explore alternative and environmentally friendly energy sources.

A large part of the energy generated during the operation of the vehicle (e.g. kinetic energy, vibrational energy and thermal energy) is lost and remains largely unused. By harnessing this wasted energy using smart renewable energy harvesting technologies, the overall energy efficiency can be improved and the dependence on fossil fuels can be reduced. Using renewable energy sources such as these is in line with global sustainability aims and moves towards more environmentally friendly transport.

The present study aims to investigate novel energy harvesting techniques, such as piezoelectric, electromagnetic, and solar, to generate usable electrical power from moving vehicles. The integration of these systems supports auxiliary vehicle functions, roadside infrastructure, and smart monitoring systems or can potentially feed energy back into the grid, promoting sustainability in urban mobility.

Moreover, the recent advances in the Internet of Things (IoT) and Artificial Intelligence (AI) enable real-time monitoring, optimization and adaptive control of the energy harvesting systems. The study will facilitate the development of next-generation smart transportation systems by addressing technical challenges in terms of efficiency, durability and system integration, and evaluating the feasibility of various harvesting mechanisms with the aim to improve energy sustainability, economic viability and environmental benefits.

Research Methodology

The research methodology for the design and development of the smart renewable energy harvesting system for moving vehicles is based on a systematic approach that integrates experimental, analytical, and simulation-based techniques. The first step is to conduct a thorough literature review to study the status of existing energy harvesting technologies, to identify research gaps and to provide a strong theoretical basis for the proposed system. A hybrid research design is used. This is a combination of qualitative and quantitative approaches. System design phase involves conceptual modeling and development of prototype using renewable energy sources such as piezoelectric, electromagnetic and solar energy to extract power from vehicular motion. Computational simulations are performed through MATLAB, ANSYS etc. to maximize the energy conversion efficiency and to evaluate the system performance at different operating conditions.

We experimentally validate the proposed approach by fabricating a working prototype and testing it under real-world driving conditions to assess its power output, efficiency, durability, and reliability. Sensor-based monitoring systems are used to collect data, and statistical techniques and machine learning models are employed for data analysis to enhance predictive capabilities and system adaptability.

Furthermore, the study evaluates the economic feasibility, environmental impacts and scalability of the proposed system to verify its applicability for large-scale implementation. Finally, the results are compared with the existing energy harvesting technologies to demonstrate the effectiveness and sustainability of the presented solution for energy harvesting in moving vehicles.

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