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DEVELOPMENT OF A KINETIC ENERGY HARVESTING SYSTEM FOR GENERATING ELECTRICAL POWER FROM MOVING VEHICLES

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ABSTRACT

The growing demand for electrical energy and the need to reduce dependence on conventional energy resources have encouraged researchers to investigate methods for recovering energy that is normally wasted during transportation. Moving vehicles contain substantial mechanical and kinetic energy, much of which is dissipated through braking, suspension movement, vibration, friction, and other mechanical losses. This research presents the development of a kinetic energy harvesting system designed to convert a portion of vehicle-associated mechanical motion into useful electrical power. The proposed system employs a mechanical transmission mechanism coupled with an electrical generator, followed by rectification, voltage regulation, and energy storage. Vehicle motion is transferred to the generator through suitable gears, pulleys, or a vibration-based mechanism, allowing mechanical energy to be converted into electrical energy. The generated electricity can be stored in a battery or supercapacitor and used for low-power applications such as sensors, monitoring devices, lighting, and communication systems. The study focuses on the operating principle, system architecture, energy conversion process, performance parameters, and practical limitations of vehicle-based kinetic energy harvesting. The proposed approach offers a potential pathway for improving energy utilization in transportation while supporting sustainable and decentralized low-power electricity generation.

Keywords: Kinetic energy harvesting; moving vehicles; renewable energy; mechanical energy conversion; electromagnetic generator; regenerative energy; vehicle energy recovery; sustainable transportation.

I. INTRODUCTION

The rapid expansion of transportation systems has increased the demand for energy and has intensified concerns about fuel consumption, greenhouse-gas emissions, and environmental degradation. Vehicles require substantial amounts of energy to overcome rolling resistance, aerodynamic drag, road gradients, acceleration requirements, and other losses. During normal operation, a considerable portion of the energy supplied to a vehicle is ultimately dissipated as heat, vibration, friction, or other forms of loss. This situation has encouraged researchers and engineers to investigate energy-recovery technologies that can capture useful energy without compromising vehicle safety or performance. Regenerative braking is a well-established example in electric and hybrid vehicles, but the broader concept of kinetic and vibration energy harvesting provides opportunities for recovering energy from additional vehicle motions and mechanical interactions. Kinetic energy is the energy associated with the motion of an object. For a vehicle, the available translational kinetic energy depends on its mass and velocity. Because velocity has a squared relationship with kinetic energy, changes in vehicle speed can substantially alter the amount of recoverable mechanical energy. However, the theoretical kinetic energy of a vehicle should not be interpreted as completely harvestable energy. Any practical harvesting device can recover only a portion of the available energy because of mechanical friction, generator losses, electrical conversion losses, storage losses, and operational constraints. Moreover, extracting energy from a moving vehicle produces a resisting force or torque. Therefore, the engineering challenge is to recover energy that would otherwise be dissipated while minimizing additional energy consumption.

One of the most established approaches to vehicle energy recovery is regenerative braking. In regenerative braking, the electric traction motor operates as a generator during deceleration. Instead of converting all braking energy into heat through friction, part of the vehicle's kinetic energy is converted into electrical energy and stored for later use. Recent reviews describe regenerative braking as an important technology for improving the efficiency and driving range of electric vehicles, while also identifying challenges associated with control, battery limitations, component reliability, and changing driving conditions. These findings provide an important foundation for investigating other forms of vehicle-based kinetic energy harvesting.

Another potential source is suspension movement. A vehicle suspension continuously responds to road irregularities and dynamic disturbances. Conventional shock absorbers dissipate vibrational energy primarily as heat. Energy-regenerative suspension concepts attempt to replace or supplement this dissipation mechanism with an energy-conversion device. Research on regenerative suspension has considered electromagnetic, hydraulic, piezoelectric, and other mechanisms. Such systems can potentially recover small but useful quantities of electricity while simultaneously performing suspension-related functions. The amount of recoverable energy depends on road roughness, vehicle

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speed, suspension parameters, harvester design, and the relationship between energy recovery and ride comfort. Electromagnetic generators are particularly attractive for vehicle energy harvesting because mechanical rotation or reciprocating motion can be converted into electrical power through electromagnetic induction. A mechanical transmission system can increase or decrease rotational speed before it reaches the generator. Gears, pulleys, belts, ball-screw mechanisms, or similar arrangements may be used depending on the source of motion. The generated electrical output can then be rectified and regulated before being supplied to a storage device or electrical load. The selection of the generator and transmission ratio is therefore critical because the system must operate efficiently over a range of vehicle speeds and mechanical conditions.

The proposed research focuses on the development of a kinetic energy harvesting system for generating electrical power from moving vehicles. The concept is intended primarily for low-power electrical applications rather than for replacing the vehicle's main energy source. Potential loads include wireless sensors, environmental monitoring devices, vehicle-condition sensors, indicator lights, communication modules, and intelligent transportation equipment. By generating power locally, such applications may reduce the need for frequent battery replacement or additional wiring.

A major consideration in the design is the distinction between energy recovery and energy creation. The proposed device cannot produce energy without an input; it can only convert part of the mechanical energy already present in the vehicle system into electrical energy. Consequently, the system must be designed to extract energy at appropriate operating conditions. Excessive harvesting could increase drag or mechanical resistance and reduce the overall efficiency of the vehicle. A successful design must therefore consider net energy benefit, mechanical reliability, safety, cost, weight, and ease of installation. The research is significant because it addresses the growing need for energy-efficient transportation technologies and explores an alternative source of decentralized electrical power. Unlike solar or wind systems, vehicle kinetic harvesting can operate whenever the associated mechanical motion is available. Its intermittent nature, however, makes energy storage and power management important components of the system. Batteries and super capacitors can be used to accumulate harvested energy and provide a more stable supply to low-power loads.

Overall, the development of a vehicle kinetic energy harvesting system represents an interdisciplinary engineering problem involving mechanical design, electrical generation, power electronics, energy storage, vehicle dynamics, and control. The present study therefore examines the basic system architecture, conversion mechanism, performance parameters, benefits, limitations, and future possibilities of such a system.

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II. DESIGN AND DEVELOPMENT OF THE KINETIC ENERGY HARVESTING SYSTEM

The proposed kinetic energy harvesting system is designed to capture mechanical motion associated with a moving vehicle and convert it into electrical power. The design can be implemented as a laboratory prototype and subsequently adapted for controlled vehicle testing. The principal objective is not to extract the maximum possible mechanical energy under every condition, but to obtain useful electrical output with acceptable additional resistance, compactness, reliability, and cost. The system therefore consists of a mechanical input arrangement, a transmission mechanism, an electrical generator, a power-conditioning stage, an energy-storage unit, and a low-power electrical load. The mechanical input may be obtained from wheel rotation, suspension displacement, or another controlled source of vehicle motion. Wheel-based harvesting provides relatively continuous rotational input when the vehicle is moving, whereas suspension-based harvesting is dependent on road-induced displacement and vibration. For a first prototype, a mechanical rotational input is advantageous because it can be readily connected to a small permanent-magnet DC generator. The wheel or rotating shaft can drive a gear, belt, or pulley arrangement, which then transfers motion to the generator. The transmission ratio is selected so that the generator operates within its efficient speed range without imposing excessive torque on the vehicle.

The mechanical transmission is a critical design element. Direct coupling may be simple but may not provide adequate generator speed at low vehicle speeds. A step-up gear or pulley arrangement can increase generator speed, although every additional mechanical component introduces friction and transmission losses. Bearings should be selected to minimize friction, while the frame should maintain correct alignment between shafts. The mechanical assembly should also be enclosed or protected against dust, water, vibration, and accidental contact. In a practical vehicle application, components must withstand repeated mechanical loading and temperature variations.

The generator converts mechanical rotation into electrical energy. A permanent-magnet generator is suitable for a prototype because it can generate electricity without requiring a separate field supply. Generator selection should consider rated speed, voltage, current, torque, efficiency, size, and operating temperature. Since vehicle speed changes continuously, generator output will also vary. A power-electronic interface is therefore necessary to convert the variable electrical output into a form appropriate for storage or direct use.

The electrical conditioning stage may include a rectifier, smoothing capacitor, DC-DC converter, voltage regulator, and protection circuit. When an AC generator is used, the rectifier converts the generated alternating voltage into DC. A regulator then controls the output voltage. The converter can be designed to operate over a range of input voltages so that useful energy can be obtained during different vehicle operating conditions. Overvoltage, overcurrent, and reverse-current protection should be incorporated to protect the generator, storage device, and connected load.Energy storage is important because harvested power is variable. A rechargeable battery can store energy for longer periods and provide a stable output, while a supercapacitor is well suited to short-duration power fluctuations and repeated charge-discharge cycles. A hybrid battery-supercapacitor arrangement may provide both energy capacity and high power response. The choice depends on the intended application, required voltage, expected harvested power, duty cycle, cost, and available space.

III. 3. PERFORMANCE EVALUATION, APPLICATIONS, LIMITATIONS AND FUTURE SCOPE

The performance of a kinetic energy harvesting system is determined by the relationship between mechanical input, electrical output, conversion efficiency, and the additional resistance introduced into the vehicle. A meaningful evaluation should therefore examine the complete energy pathway rather than considering generator voltage alone. The principal electrical parameter is output power, which can be calculated as the product of measured voltage and current. When the output varies with time, harvested energy should be determined by integrating the power over the test interval. Mechanical input power can be estimated from measured torque and angular velocity when a rotational configuration is used. Comparing mechanical input power with electrical output power provides an estimate of overall conversion efficiency.Vehicle speed is one of the most important operating variables. Increasing speed generally increases the available kinetic energy and may increase the rotational speed delivered to a generator. However, generator voltage and power do not necessarily increase indefinitely because electrical, magnetic, mechanical, and thermal limitations become important at higher speeds. The electrical load also influences the operating point. A very light load may produce relatively high voltage but little useful power, while an excessive load can increase generator torque and mechanical resistance. Consequently, the system must be evaluated under different load conditions to identify a suitable operating region.

Road and driving conditions also influence harvesting potential. Stop-and-go urban traffic provides frequent acceleration and deceleration events, while highway travel may provide more continuous wheel rotation but fewer braking events. Suspension-based harvesters are strongly influenced by road roughness, vehicle speed, suspension stiffness, damping, and vehicle mass. Previous studies have demonstrated that suspension energy harvesting can be affected by road classification and vehicle operating conditions. These findings indicate that a universal harvesting configuration may not be optimal for every vehicle or driving environment.

The proposed system can support a range of low-power applications. Vehicle-condition monitoring sensors are an important example because they may require continuous or intermittent electrical power. Tire monitoring, temperature measurement, vibration sensing, environmental sensing, and wireless data transmission can potentially be supported by harvested energy. Roadside infrastructure may also benefit from similar technology where vehicle-induced mechanical motion can be used to support sensors or localized monitoring devices. The ability to generate power near the point of use may reduce the need for long electrical cables or frequent battery replacement. Another application is auxiliary lighting and signaling. Small LED indicators or localized lighting systems generally require much less power than a vehicle's primary propulsion system. If energy is harvested continuously or stored during periods of motion, the system may supply these low-power loads. However, the harvested energy should be considered supplementary rather than a replacement for essential vehicle electrical systems unless extensive validation demonstrates adequate reliability.

The technology also has educational and research value. A laboratory-scale prototype can demonstrate principles of kinetic energy, electromagnetic induction, mechanical transmission, power electronics, energy storage, and control engineering. Such a prototype can be used to investigate the influence of gear ratio, generator type, load resistance, speed, and storage characteristics. It also provides a practical platform for interdisciplinary research involving mechanical engineering, electrical engineering, electronics, and renewable-energy systems.Despite these advantages, several limitations must be considered. First, the available mechanical energy is variable and cannot be treated as a continuous renewable source with fixed output. Second, extracting energy creates a reaction force or torque, which can increase the energy required to move the vehicle. Third, mechanical components introduce weight, friction, wear, and maintenance requirements. Fourth, electrical conversion and storage introduce additional losses. Fifth, the physical space available for installation may be limited, particularly in passenger vehicles. Finally, any device connected to a vehicle's mechanical system must be designed carefully to avoid compromising safety.

Economic feasibility is another important issue. A low-power harvester may be technically successful but economically unattractive if its installation and maintenance costs exceed the value of the energy recovered. Therefore, future systems should use low-cost components, simple mechanical structures, efficient generators, and robust power electronics. Modular designs could allow the technology to be installed only where sufficient energy is available.Future research can focus on hybrid harvesting architectures. A vehicle could potentially combine wheel-based recovery, regenerative braking, suspension energy harvesting, and vibration harvesting. The combined system could feed a common energy-storage unit. Intelligent control could determine which harvesting mechanism should operate under different conditions. For example, a controller could reduce suspension harvesting when ride comfort is prioritized and increase energy recovery when sufficient vibration is available.

IV. CONCLUSION

The development of a kinetic energy harvesting system for generating electrical power from moving

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vehicles represents a promising approach for improving the utilization of mechanical energy within transportation systems. Vehicles continuously experience motion, vibration, wheel rotation, braking, acceleration, and suspension movement, creating opportunities for energy recovery. Much of the associated mechanical energy is normally dissipated through friction, damping, heat, and other losses. A suitably designed harvesting system can convert a portion of this otherwise wasted mechanical energy into useful electrical power for low-energy applications.The proposed system consists of a mechanical energy input mechanism, transmission arrangement, electrical generator, power-conditioning circuit, energy-storage unit, and electrical load. Mechanical motion is transferred to the generator through gears, pulleys, belts, or another appropriate mechanism. The generator converts mechanical energy into electrical energy, after which the output is rectified and regulated.

study also highlights that kinetic energy harvesting should not be considered a method of creating additional energy. The system extracts energy from vehicle motion and therefore inevitably introduces some resistance. For this reason, maximizing electrical output alone is not an adequate measure of system performance. The design must instead maximize useful or net energy recovery while minimizing additional mechanical losses, weight, cost, and impact on vehicle performance. Generator selection, transmission ratio, power electronics, storage technology, and control strategy are therefore critical factors in achieving an effective design. Vehicle speed, driving pattern, road condition, generator characteristics, and electrical load can significantly affect the amount of energy recovered. Experimental testing should therefore be conducted under different operating conditions, and actual voltage, current, generator speed, mechanical input, and efficiency values should be measured rather than assumed. Laboratory testing using a controlled rotating rig can provide initial validation, followed by carefully controlled vehicle trials.

The technology has particular potential for low-power and distributed applications. Harvested energy could support vehicle-condition sensors, environmental monitoring, wireless communication, road-monitoring systems, and other electronic devices. Integration with smart control and Internet-of-Things technologies could enable real-time monitoring of energy production and system condition. Future designs may combine several energy sources, including wheel rotation, regenerative braking, suspension vibration, and other mechanical movements, to increase the overall availability of harvested energy. However, practical implementation requires careful attention to safety, reliability, durability, installation space, maintenance, and economic feasibility. The harvesting mechanism must not interfere with essential vehicle functions such as braking, steering, wheel operation, or suspension performance. The additional mechanical resistance must also remain sufficiently low to ensure that the recovered energy provides a genuine net benefit.

In conclusion, kinetic energy harvesting from moving vehicles offers a valuable research direction within sustainable transportation engineering. Although the recovered energy may be modest

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compared with the total energy requirements of a vehicle, it can be highly useful when targeted toward low-power applications. Continued research in high-efficiency generators, lightweight mechanical systems, intelligent power electronics, energy storage, and adaptive control can improve the practicality of the technology. With appropriate optimization and rigorous experimental validation, vehicle-based kinetic energy harvesting can contribute to energy-efficient transportation and decentralized power generation.

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