Electromagnetic Regenerative Suspension System for Electric Vehicles

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The requirements for the Bachelor of Science in Electrical Engineering degree are fulfilled by submitting this thesis.

Certificate

This attests to the fact that, under my guidance, Abdullah Khan (01-133222-001) and Ayila Zahra (01-133222-015) successfully finished their thesis, Electromagnetic Regenerative Suspension System for Electric Vehicles, fulfilling the prerequisites for an Electrical engineering bachelor's degree. The work provided in this thesis was based on the student's original study and practical application. The candidate has demonstrated a deep comprehension of mechanical power transmission systems, electromagnetic energy conversion, suspension dynamics, and electrical power generation. Both the academic requirements and the standards set by the Department of Electrical Engineering are met by this research.

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Dedication

This thesis is dedicated to our parents, whose unwavering faith, support, and sacrifices have been the pillars of our academic success. Their constant support and prayers have motivated us to pursue academic achievement.

Throughout our undergraduate studies, we received patient and knowledgeable guidance from our teachers and mentors, to whom we also dedicate this work. We were motivated to take on this difficult research project by their devotion to teaching and their pursuit of excellence.

Lastly, this project is committed to developing sustainable engineering solutions that will increase energy efficiency and help create a future that is cleaner and more ecologically conscious.

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Abstract

The rapid growth of electric vehicles (EVs) has led to a growing demand for innovative energy recovery techniques to improve overall efficiency and extend driving range. In traditional vehicles, much of the vibrational energy is lost as heat in the suspension system when driving on uneven road surfaces. This wasted energy is also an opportunity for recovery through regenerative technologies. The thesis describes the design and implementation of an electromagnetic regenerative suspension system, using a lever-arm and gear transmission mechanism. The proposed system uses a lever arm to capture the vertical suspension motion which is converted to rotational motion by a multi-stage gear train with an overall gear ratio of about 1:100. A 6V DC motor is used as a generator to convert mechanical energy into electrical energy. The produced electrical output is treated by a bridge rectifier, regulated by a buck-boost converter and stored in capacitors, supercapacitors and a battery system. The system is shown to be capable of efficiently converting low frequency vibration of suspension to usable electrical energy in the laboratory. The experimental results validate the feasibility of the proposed system as a scalable and cost-effective solution for energy harvesting in EVs. The study concludes that electromagnetic regenerative suspension systems can enhance the energy efficiency and reduce the energy losses of modern electric vehicles.

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Chapter 1

INTRODUCTION

1.1 Background information for the study

As the world moves towards sustainable transport, electric vehicles are playing an increasingly important role. Due to their potential for reducing carbon emissions and reliance on fossil fuels, they are a popular option over traditional internal combustion engine vehicles. However, EVs have a significant limitation, which is their battery systems that limit driving range and need to be regularly charged.

A typical vehicle experiences several types of energy loss during operation. Regenerative braking systems have been successfully implemented to recover energy during deceleration; however, other sources of energy loss remain largely unexplored. One of these sources is the suspension . When a vehicle travels over an uneven road surface such as bumps, potholes and rough terrain, the suspension system undergoes continuous vertical oscillations. In a conventional suspension system this motion is damped by hydraulic shock absorbers, losing kinetic energy as heat. This results in a lot of wasted energy that could be put to other uses.

The idea behind regenerative suspension is to harvest this vibrational energy and convert it to electrical energy. Among different approaches, electromagnetic systems are considered as very effective due to their efficiency and compatibility with electrical energy storage systems.

1.2 Motivation

The reason for this project is to improve the overall efficiency of an electric vehicle by recovering the energy that is normally wasted during the operation. The suspension system of a vehicle is a good source of energy that can be converted into useful electrical power, since it is continuously subjected to vertical motion due to road irregularities and the movement of the vehicle. One of the main motivations of this work is to increase the driving range of electric vehicles without increasing the battery size or adding significant energy consumption. The project also seeks to boost overall energy efficiency, by harnessing vibrational energy which would otherwise be lost in conventional suspension systems. Another important motivation is to develop a simple and low cost prototype using easily available components, thus making the concept practical for academic and experimental purposes. The research also supports sustainable energy recovery techniques and gives hints of innovative solutions that can contribute to more efficient and environmentally friendly transportation systems in the future.

1.3 Problem Statement

The conventional suspension systems are not energy efficient as the mechanical energy generated by the vertical motions of the vehicle is dissipated mainly in the form of heat due to damping . This leads to energy loss, decreases the total efficiency of the suspension system and does not allow for electrical power generation. To overcome this limitation, the project aims at developing a regenerative suspension that can recover part of the wasted energy. The proposed system is designed for the efficient capture of the suspension motion and the conversion of the up and down motion into rotational motion using a mechanical mechanism. This rotational motion is utilized for running a generator to produce economy electrical energy. At the same time the design has the objective to be mechanically simple, low cost and easy to be implemented with available components.

1.4 Objectives of the Project

The main objective of this project is to design, build and test a low cost electromagnetic regenerative suspension system for electric vehicles. The project aims to show how mechanical vibration energy created by suspension movement can be converted into usable electrical energy. A mechanical suspension model is developed that reproduces the vertical motion of a real vehicle suspension system. This motion is recorded by a lever mechanism and converted into a rotational motion that actuates a direct current motor which works as a generator. A voltage rectifier and regulator circuit is also designed to get stable DC output. An experimental test is carried out by measuring voltage and current for different vibration conditions to evaluate the performance of the system. A gearbox with a ratio of about 1:100 is included to increase the rotation speed and to improve the energy generation. This project also evaluates the efficiency and practical potential of the system for energy recovery of electric vehicles.

The project also aims at designing a prototype that is economical, practical and affordable for academic research using locally available materials in Pakistan. The system produces electricity, which is stored in batteries and capacitors for short-term energy storage. In addition to the technical development, the project increases the understanding of multidisciplinary engineering concepts such as mechanical design, electromagnetic theory, power electronics and energy management systems. This work contributes to sustainable transportation by exploring an alternative energy recovery method that can complement existing regenerative braking systems in electric vehicles. The prototype's success demonstrates the potential of the suspension-based energy harvesting as a novel and efficient method for future electric vehicle applications.

1.5 Scope and Limitations

The primary objective of this project is to design and develop a prototype of an electromagnetic regenerative suspension at laboratory scale. The system is not intended for direct full-scale automotive installation, but instead developed as a proof-of-concept model to demonstrate the basic principles of suspension-based energy regeneration. The project is the mechanical design and construction of a structure capable of moving vertically to simulate the movement of a suspension in a controlled environment. This motion is transmitted by a rotational gear mechanism . Gears are used to convert linear displacement to rotational motion . The rotational energy generated is then used to generate electrical energy using a DC motor which acts as a generator. The electrical output is measured by simple voltage measurement and adjustment, allowing for performance evaluation of the system under different vibration conditions. This setup demonstrates the possibility of transforming suspension motion into usable electrical power in the prototype.

The present implementation is not without some limitations, however, due to its small-scale experimental nature, despite the achievement of the intended objective. The prototype does not simulate the dynamics of real roads accurately, and the total weight and the working conditions of real vehicle suspension system. The system is a laboratory scale system, so the mechanical input for energy generation is limited. This directly affects the amount of electrical power generated. The model also does not include advanced power conditioning circuitry like battery management systems, voltage regulators, or DC-DC converters that are typically needed in real automotive applications. Further, a long-term durability test and performance evaluation under continuous operating conditions were beyond the scope of the present work. Moreover, the overall efficiency of the prototype is affected by the mechanical friction of the moving parts and energy losses in the gear transmission system. However, within these boundaries the study manages to prove the basic idea of regenerative suspension based energy harvesting and provides a basis for further development. The results of this work can contribute to future research towards practical automotive implementation, improved mechanical alignment, high efficiency generators and optimized gear ratios. Further possible developments include integration with lithium battery charging systems, microcontroller-based power monitoring and intelligent damping control for adaptive suspension systems with improved efficiency and real-world applicability.

1.6 Significance of the study

Due to the growing demand for energy efficient and environment friendly transportation systems, there is a need for innovative methods of energy recovery in electric vehicles. Regenerative braking systems have become common features in modern EVs, but still a lot of energy is lost through other vehicle sub-systems. One such source of energy loss is the suspension system where mechanical vibrations due to irregularities of the road are converted to heat. The significance of this study lies in its investigation of alternative means of harvesting this wasted energy and converting it into useful electrical power. The proposed electromagnetic regenerative suspension system assists to improve the overall vehicle energy efficiency by utilising the suspension motion as a source of renewable energy. The system can convert the vertical oscillations of the suspension into electricity. This shows the possibility of recovering energy that would be lost in a conventional suspension system. While the power output might be modest for a lab-scale prototype, the concept offers valuable insight into how further energy recovery techniques could back future electric vehicle technologies. The study is also important from an environmental point of view. The increasing worldwide concerns on the use of fossil fuel, greenhouse gas emission and climate change have made the development of sustainable transportation technologies more and more important. Regenerative suspension is an energy harvesting system that can reduce the overall energy consumption and improve the efficiency of electric vehicles. The successful implementation of such systems could reduce dependence on external charging sources and promote cleaner transport solutions.

Academically, this project is a hands-on experience in different engineering fields such as mechanical engineering, electrical engineering, electromagnetics, power electronics and energy management systems. The development of the prototype allows the use of theoretical concepts in a practical engineering problem and hence leads to a better understanding of the design and integration of multidisciplinary systems. The project also acts as an educational resource for future researchers and students interested in renewable energy and vehicle technology. In addition, this work shows that a regenerative suspension system can be designed and produced using cheap and readily available parts, which makes it suitable for academic research and experimental studies. The results of this study can serve as a foundation for future enhancements, including the implementation of more efficient generators, sophisticated power conditioning circuits, intelligent control systems, and integration with contemporary battery management technologies. In this way, the study not only demonstrates the concept of suspension-based energy harvesting, but also creates new opportunities for research and practical use of next-generation electric vehicles.

In conclusion, the significance of this study is its contribution to the energy recovery technology, sustainable transportation, engineering education, and future research development. By showing a practical way to convert transform suspension vibrations into electric energy, the project shows how regenerative suspensions can be used as an alternative method to harvest energy for electric vehicles.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

The literature review is an important part of this research as it provides a detailed understanding of the current developments, theories and technologies associated with regenerative suspension systems and automotive energy harvesting. Modern transportation engineering emphasises the use of efficient vehicles and the minimisation of wasted energy [1]. Typical vehicle systems dissipate mechanical energy as heat, which leads to energy loss and degradation of overall system performance [2, 3]. This leads to a strong demand for novel approaches that can recover and reuse energy which would otherwise be lost during normal vehicle operation [4].

This chapter reviews the main technologies and research studies on conventional suspension systems, energy harvesting mechanisms, and electromagnetic regenerative suspension systems. Special attention is paid to methods of conversion of suspension vibrations into electrical energy and its integration with usable electrical storage systems. Previous work has demonstrated that suspension vibration is a source of continuous mechanical energy, particularly when vehicles travel over uneven road surfaces [5, 6]. However many of the proposed recovery systems are still expensive, mechanically complex or difficult to integrate in practical vehicles [7].

The literature reviewed in this chapter also identifies important gaps in research. While there is a number of researches on regenerative suspension technology, there are relatively few researches on low-cost mechanical arrangements like lever-based motion transfer in combination with electromagnetic generation [8]. Thus, this review sets up the technical background and justifies the need for the proposed electromagnetic regenerative suspension system. It also provides a basis for understanding the design decisions made in this project and shows how this work extends existing research in a practical and inexpensive way [9].

2.2 Conventional Suspension Systems

Conventional suspension systems are an important part of every vehicle as they directly affect ride comfort, road handling and vehicle safety [2]. These systems are intended to soak up vibrations and impacts produced by road irregularities, while maintaining proper contact between the tires and the road surface. A well functioning suspension system increases the stability of the vehicle decreases the excessive movement of the body and protects the passengers and components of the vehicle from mechanical stress [10]. The suspension system is active at all times when the vehicle is in use. Every time a vehicle crosses a rough surface, speed bump or uneven road, there is a vertical displacement between the wheel and chassis. The suspension takes up this displacement and damps the oscillations so that the motion is balanced [11]. Without a good suspension system, the shocks of the road would be passed directly to the vehicle body, and the comfort of the passenger would be less and the wear on the structure increased.

Suspension systems typically consist of springs and shock absorbers. The spring stores and returns energy from wheel travel and the damper controls excessive oscillation and prevents continuous bouncing [3]. This combination has been used successfully in vehicles for years. But conventional systems waste a lot of mechanical energy in heat dissipation, though they are good at vibration control [12]. This energy loss is an opportunity for regenerative suspension technology to increase efficiency [4].

2.2.1 Purpose of Suspension Systems

The primary purpose of a suspension system is to dissipate the road shocks and isolate the passengers from the outside disturbances of uneven terrain. The suspension system absorbs the shock of sudden impacts as a vehicle passes over potholes or surface irregularities by compressing and expanding. This contributes to the comfort of the passengers and reduces the vibrations transmitted to the body of the vehicle [2].

Suspension has another important job too . It helps keep the tires in contact with the road . For the driver to be able to steer, brake and control the vehicle safely, the tires must be in continuous contact with the road surface. Poor vehicle handling and traction is caused by instability of tyre contact [3]. Thus, the design of suspension directly influences the safety and driving performance. Suspension systems also help keep the vehicle stable when you accelerate, brake and turn corners. The vehicle weight is distributed on the vehicle in case of dynamic movement [11]. A good suspension does this movement efficiently and keeps the car balanced. This enhances driver confidence and improves operation safety. Suspension parts also protect the structural frame and mechanical parts inside the vehicle by reducing repeated stress from road impacts [10].

2.2.2 Conventional Dampers: Working Principle

Dampers of conventional type are widely used in vehicle suspension systems for control of oscillatory motion and to provide a smoother ride for the vehicle. Most traditional dampers are hydraulic shock absorbers. They work by forcing hydraulic fluid through small passages or valves when suspension movement occurs [3]. The fluid flow resists rapid movement, and kinetic energy is converted into thermal energy.

This damping process reduces the amplitude of vibration and prevents uncontrolled oscillation after a disturbance [2]. As the wheel goes up or down the piston inside the hydraulic damper creates resistance in the fluid. This resistance slows down the motion and stabilizes the suspension . The method is simple and reliable . Hydraulic dampers are used in automotive applications .

Hydraulic dampers are good at controlling movement but are not very energy efficient. The kinetic energy gained during the motion of the suspension is completely transformed into heat and dissipated into the environment [4]. No energy is stored or recovered for use later. This total loss of mechanical energy is seen as a significant limitation, especially as vehicle efficiency becomes more important, especially for electric vehicles [1]. This limitation has driven researchers to look into regenerative alternatives [6].

2.2.3 Limitations of Conventional Systems

Although conventional suspension systems are widely used and have proven to be reliable, they have several limitations, particularly with regard to energy efficiency and sustainability. The most important limitation is that the mechanical energy generated by the vibration of the road is completely lost as heat through damping mechanisms [3]. This not only helps to stabilize the vehicle and improve ride comfort, but also causes the vehicle to continuously lose energy during operation. This energy loss is often neglected in conventional vehicles, but it is becoming increasingly important in electric vehicles where the efficient use of energy directly impacts the driving range and battery performance [1]. Another disadvantage of conventional suspension systems is their passive nature. Passive systems respond to external disturbances but do not take an active part in vehicle energy management or in the recovery of energy [11]. They still are limited to shock absorption and motion control. Thus these systems are not able to support the vehicle electrically or contribute to charging systems in any way. This decreases their overall functional efficiency [12].

Also, traditional suspension systems may suffer from reduced performance in varying road conditions. Repeated compression and extension of dampers when vehicles are driven over rough roads increase the heat generation inside dampers that may impact the long term efficiency and component durability [2]. Wear also increases the need for maintenance. These limitations suggest that more advanced systems are required that can not only control the vibration but also recover the useful energy from the suspension motion [13]. This issue has caused people to study regenerative suspension technology [7].

2.3 Energy Loss in Vehicle Suspension

Vehicle suspension systems are subjected to dynamic forces during normal driving conditions. These forces produce vibration and repeated motion that has measurable mechanical energy. In conventional systems this energy is lost due to damping and friction and is not recycled [10]. Thus, a large part of the energy available is wasted when the vehicle is moving [4].

The amount of energy loss depends on a number of operating factors. The parameters used are vehicle speed, road roughness, stiffness of the suspension, damping characteristics and total load on the vehicle [2]. As the road irregularities increase, the frequency of the suspension movement increases and the energy dissipation increases accordingly [14]. This means that when vehicles drive on uneven roads, more energy is lost [15]. Researchers have recognized suspension systems as a practical source for energy harvesting, as vibration is a continuous and predictable phenomenon during operation [6]. Even a small percentage of recovery of this wasted mechanical energy would improve the efficiency of the system and reduce dependence on the primary power source. In electric vehicles, this recovered energy can be used to charge the battery or to supply low power electrical loads [16]. Hence, understanding the suspension energy loss is important for the development of efficient regenerative systems [7].

2.3.1 Sources of Energy Dissipation

Energy is dissipated by a variety of physical mechanisms in the suspension systems of vehicles. The principle of operation is hydraulic damping, where the kinetic energy is dissipated as heat as the fluid flows through internal valves [3]. This heat energy is lost forever and can not be retrieved [4]. Mechanical friction also causes losses. There is friction when the moving parts such as bushings, joints and linkages. Friction is essential to control and stabilize the system . But it consumes some of the useful mechanical energy and makes less available for conversion [17].

Suspension members can also suffer additional losses due to structural vibration and cyclic deformation. The deformation of the material due to the cyclic loading of springs and dampers absorbs part of the mechanical input [10, 18]. These various energy loss routes collectively lower efficiency and serve to point out the increasing importance of regenerative recovery techniques [16].

2.3.2 Quantification of Energy Loss

Several research studies have indicated that a considerable amount of vehicle energy is dissipated through suspension damping, particularly when operating on uneven road surfaces [4]. How much energy is lost depends a lot on road conditions and suspension activity [14]. The dissipated energy amount is also a function of suspension stiffness and damping coefficient [2]. A stiffer suspension will transmit more vibration. More damping means more heat loss [3]. The total energy produced is also affected by vehicle speed, as the interaction between the wheel and the road is more frequent at higher speeds [15].

The results indicate that partial energy recovery by suspension movement may enhance overall efficiency. Regenerative systems can reclaim wasted mechanical input and convert it to useful electrical output [5]. It can reclaim vibration that would otherwise be lost [6]. This principle is the basis of the present study [16].

2.4 Regenerative Suspension Systems

Regenerative suspension systems are designed to perform two functions at the same time: suppress vehicle vibration and generate electrical power from mechanical motion [13]. In contrast to the standard suspension systems, regenerative systems recover a portion of the vibrational energy produced during the course of vehicle movement and change it into an electrical form [5].

The concept has drawn interest for the possibility of improving energy efficiency, particularly in electric vehicles [16]. Battery usage and power management make EV performance highly sensitive, so recovering wasted suspension energy is one more energy source without increasing fuel or battery demand [1].

These systems integrate mechanical transfer of motion with electrical generation and storage technologies [7]. Depending on the design, the recovered energy can be stored temporarily or fed directly into electrical circuits [19]. This dual-function capability makes regenerative suspension an attractive area of research in sustainable automotive engineering [6].

2.4.1 Concept of Regeneration

Regeneration is the retrieval of energy which would otherwise be lost and the conversion of it into a useful form [4]. In suspension systems for vehicles, regeneration is achieved by transforming the mechanical motion generated by vibrations into electrical energy [5].

Normal driving the suspension components move up and down to the road conditions. Regenerative systems direct this motion through conversion processes coupled with electrical generators rather than lose it entirely through damping [16].

This concept improves the system efficiency since the energy that is normally wasted is used to charge batteries and power sensors and auxiliary systems [7]. That is why the principle of regeneration is very important for the development of modern electric cars [1].

2.4.2 Types of Regenerative Suspension Systems

Several regeneration suspension technologies have been proposed and tested in previous studies [7]. In hydraulic regenerative systems, the movement of the suspension creates a fluid flow that powers turbines or hydraulic motors. Such systems can generate large amounts of power, but they are usually relatively expensive and need complicated mechanical arrangements [20].

Piezoelectric systems use special materials that, when mechanically compressed, generate electricity by creating voltage. These systems are compact and useful for small scale applications but generally provide lower power output [21].

Electromagnetic systems function on the principle of relative motion of magnetic fields and conductors [22]. These systems have a good efficiency, easy integration to electrical components and scalable output depending on design [5]. These advantages have made electromagnetic regeneration one of the most practical approaches for prototype and vehicle applications [16].

2.4.3 Advantages of Electromagnetic Systems

Electromagnetic regenerative systems have a number of important advantages compared to alternative methods. They are relatively efficient energy converters, as they convert motion directly into electricity by electromagnetic induction [23].

They are also easier to integrate with electrical storage systems like batteries and supercapacitors. The generated voltage can be conditioned and stored without the need for complex fluid-based systems [5].

Durability is another big plus. Electromagnetic parts are generally less worn than hydraulic parts and can be cycled many times [16]. They are ideal for academic prototype development and practical vehicle research thanks to their reliability and relatively simple construction [9].

2.5 Electromagnetic Energy Harvesting Principle

Electromagnetic energy harvesting relies on Faraday's law of electromagnetic induction. This law states that whenever a conductor moves relative to a magnetic field, a voltage is induced [23].

In vehicle suspension applications, vertical motion is transformed into mechanical motion that turns a generator shaft. As the rotation occurs, the magnetic flux inside the generator changes and electricity is generated [22].

The amount of energy produced depends on the magnetic strength , the number of windings of the coil , the speed of rotation and the electrical load conditions [24]. The voltage output is generally improved with the increase of rotational speed [25]. This principle is key to the proposed system as suspension vibration is converted to generator rotation for energy harvesting [5].

2.6 Mechanical Energy Conversion Mechanisms

This conversion to mechanical motion is necessary because the movement of suspension is usually linear and generators usually need rotation. So the motion transfer mechanism must couple vertical displacement to rotational output [26].

Various systems use rack and pinion, ball screw, hydraulic linkages or lever based designs. Complexity, efficiency, manufacturing cost and reliability are to be considered in the selection [27].

In the present project, a lever based mechanism is chosen due to its simple low cost and efficient conversion of small suspension displacement to useful angular motion for gear transmission [8, 9].

2.6.1 Linear to Rotational Conversion

The suspension motion is in the vertical direction as the wheel moves up and down over irregularities in the road. This motion by itself cannot directly drive a standard electrical generator [5]. A conversion mechanism converts this vertical displacement into angular motion. Angular motion once produced can be transferred by gears to rotate the generator shaft [26].

It must be converted efficiently, because the electrical output is directly dependent on the rotational speed [23]. If not transmitted effectively, the harvested energy is too small to be used in practice [28].

2.6.2 Common Mechanism

The research of regenerative suspension uses several mechanisms of motion transfer. Rack-and-pinion systems are widely studied and translate linear motion by way of the gear teeth [26].

Ball screw mechanisms can provide smooth transfer, but can be expensive and mechanically sensitive [27]. Hydraulic linkages are useful for high power systems but increase design complexity [20].

The lever systems are a good alternative. They are easier to manufacture, economical and can be implemented in prototype with acceptable efficiency [8, 9].

2.6.3 Lever-Based Mechanisms

The lever based mechanism captures vertical suspension motion and pivots about a fulcrum. It converts the displacement into an angular motion and transmits force to the gears it is connected to [8].

Torque and mechanical advantage are a function of lever length and pivot position. With optimized geometry, even small vertical movement can generate useful rotational output [17].

The low cost, ease of manufacturing and mechanical reliability make this design attractive. These advantages make a strong case for its use in the proposed system [9].

2.7 Gear Transmission Systems

Gear transmission systems multiply the rotation speed of suspension motion. Since the suspension vibration is of low frequency, direct generator speed is usually inadequate [5]. A gear train increases the rotation so that the generator can work efficiently. This enhances voltage generation and total energy conversion [26]. Choosing the right gear is important as too much gearing can increase friction losses [17]. Thus, the design of transmission must balance speed amplification with mechanical efficiency [28].

2.7.1 Need for Gear Systems

To generate a useable voltage, the generators need to be spun at a rather high speed. Suspension motion by itself is usually slow and oscillatory [5].

This limitation is overcome by gear systems that multiply the speed before it gets to the generator shaft. This improves the energy harvesting performance [26].

Without speed amplification , the output voltage can be too low for electrical storage or circuit integration [16].

2.7.2 Multi-Stage Gear System

In a multistage gear arrangement a plurality of gear pairs progressively increase the rotational speed. This allows for large amplification and keeps the motion controlled [17].

In the proposed system, the combination of pawl gear and secondary gear train results in high overall rotational gain [26].

The design improves the performance of the generator and is more suitable for the low frequency suspension motion for electrical conversion [5].

2.7.3 Pawl Gear Mechanism

The pawl gear mechanism allows movement in only one direction . It prevents reverse rotation [17].

This is important, as the movement of the suspension naturally moves up and down. Without directional control the rotational energy would bounce back and forth and be less efficient [26].

The pawl gear ensures unidirectional transfer to enhance generator rotation and stability of energy harvesting [5].

2.7.4 Effect of Gear Ratio

Gear ratio plays a major role in generator speed and electrical output. Higher ratios increase the angular velocity and improve voltage generation [25]. However, very high gear ratios can also introduce friction and mechanical loss [17]. An optimized ratio improves efficiency and maintains acceptable durability and system stability [28].

2.8 DC motor as a generator

A DC motor can be driven mechanically to work as a generator. Now when the shaft rotates the voltage is induced at the output terminals by electromagnetic induction.

$$E = k\phi\omega$$

where:

- E = EMF Generated
- k = Machine constant
- ϕ = Magnetic flux
- ω = Angular velocity

Higher the rotation speed, higher the voltage generated . Hence the gear transmission is a must .

DC motors are useful in prototype development because they are inexpensive, readily available, small and easy to connect to electrical circuits.

2.8.1 Advantages

The DC motor has many advantages that make it suitable for this project. It is easily accessible and available in local markets which makes it convenient for prototype development [9]. It is also cheap in comparison to dedicated generators and hence provides a cost effective solution for academic research [1]. The motor is easy to operate and can be easily connected with the mechanical system [23]. It's small and works reliably so you can test it practically [24]. These features make it suitable for the regenerative suspension prototype.

2.8.2 Limitations

The DC motor has many good points but it has some limitations in this application. It is less efficient than generators made specifically for power production [23]. The output voltage will change when the suspension movement is low . This depends on the rotational speed [25]. This variation can reduce charging efficiency and can affect system stability [19]. Mechanical and electrical losses can also occur in operation [24]. Thus, it may need to be improved for larger scale applications, although it is suitable for a prototype [16].

2.9 Power Conditioning Circuits

The electromagnetic regenerative suspension system cannot store the generated electrical energy or use it directly because the generator output voltage is very sensitive to suspension movement. During the operation, the road conditions, vehicle speed and vibration intensity are continuously changing. Therefore, the generator output is not constant and it may contain fluctuations in voltage and current. Thus, a power conditioning stage is necessary to process the generated electrical energy before it can be fed into storage devices or electrical loads [7].

The suspension system moves up and down due to irregularities on the road, generating an alternating and variable electrical output in the generator. These variations produce unstable voltage levels that are not suitable for charging batteries or powering electronic equipment directly. Voltage surges and abrupt changes can damage attached components and reduce system performance without proper regulation. Therefore, power conditioning circuits are important to deliver reliable and safe energy transfer [29].

To meet these challenges, the generated electrical power is first passed through a rectification stage. The rectifier converts the alternating current (AC) provided by the generator to direct current (DC), which is used by most storage devices and vehicle electronic systems. The rectified voltage is then passed through voltage regulating and converting circuits, which provide a steady output voltage that is unaffected by variations in generator speed or suspension movement [30]. These circuits ensure that the harvested energy remains in the desired operating range [19].

Other protection components such as diodes, capacitors, voltage limiters besides voltage regulation, and filtering circuits are part of the power conditioning stage. These components serve to minimize electrical noise, diminish voltage ripple, and prevent overvoltage or reverse-current situations for the battery and electronic devices [31]. The protection circuitry enhances the quality of the power and therefore the reliability and lifetime of the entire energy harvesting system [16].

The conditioned electrical output is then delivered to an energy storage device such as a rechargeable battery or supercapacitor. The stabilized voltage and current allow the storage device to be charged efficiently and safely [1]. This extra energy can be used later to run auxiliary vehicle systems, sensors, lighting units or other low power electronic devices. The power conditioning circuit is a critical interface between the electromagnetic generator and the energy storage system. It ensures that the irregular and fluctuating electrical output obtained from suspension vibrations is converted into a steady, regulated and usable form of energy. This allows the harvested energy to be stored and used efficiently, thus improving the overall efficiency and practicality of the regenerative suspension system [13].

2.10 Energy Storage Systems

Energy storage systems are required for regenerative suspension technology because the electrical energy generated from suspension vibrations is not constant and cannot always be used immediately. The generator's electrical output fluctuates as the suspension moves continuously in response to road surface conditions, vehicle speed, and mechanical displacement. A storage mechanism is therefore needed to collect the generated energy and supply it in a stable and controlled way when needed [13]. Proper energy storage improves the efficiency of the complete system reducing electrical losses and keeping the recovered energy ready for use [19]. In electric vehicle applications, the stored energy can be used to power auxiliary electronics, to charge the battery system, or to increase the total energy utilization [1]. Therefore, an efficient storage arrangement is needed to maximize the benefits of suspension-based energy harvesting [7].

2.10.1 Capacitors

Capacitors are commonly used in regenerative energy systems because they can store electrical charge quickly and release it almost instantly when required. Their fast charging and discharging characteristics make them very useful for handling temporary voltage fluctuations induced by suspension vibrations [29]. Capacitors can help to smooth out rapid rises and drops in output voltage that may occur during sudden movement of the suspension prior to power being distributed to other components [30]. They also enhance voltage stability and reduce disturbances in the circuit [31]. Capacitors are useful in prototype scale systems such as this project because of their low cost, ease of integration, and reliability for short term storage [9]. They can instantly react to changes in generated power and are hence an important part of the energy conditioning stage [19].

2.10.2 Super-capacitors

Supercapacitors have higher energy storage capacity than the ordinary capacitors. In addition, supercapacitors maintain very fast charging and discharging capability [30]. They are particularly useful in regenerative systems where vibration energy is produced in pulses and needs to be stored rapidly without a significant time lag [13]. Supercapacitors are suitable for repeated charging cycles generated by vehicle suspension movement with their high power density and long operation life [7]. They can store energy more efficiently than regular capacitors and can release it when needed for short-term electrical loads [29]. Supercapacitors also help to reduce stress on the battery in regenerative suspension systems by absorbing power peaks that occur suddenly [19]. This results in improved stability of the system and enhanced reliability of stored energy for further use [5]. The combination of speed, durability and energy capacity makes them very suitable for vibration energy harvesting applications [16].

2.10.3 Batteries

Batteries are frequently used to store electricity from regenerative systems over the long term. Batteries are able to store more energy for a longer period of time than capacitors and supercapacitors, which makes them useful for powering electrical loads or recharging subsystems in vehicles [1]. In this project, the batteries are the last storage stage following voltage conditioning and regulation. The energy generated by the suspension vibrations can be fed back to the battery and stored for future use [13]. Batteries also provide a stable power source when generation from the suspension is unavailable for a time period [19]. However , batteries need regulated input and protection circuits , since the conditions for charging must be kept within safe voltage limits [29]. Their integration into the system improves the practical usefulness of the harvested energy and supports the overarching goal of increasing the efficiency of electric vehicles [7].

2.11 Challenges in Regenerative Suspension Systems

Regenerative suspension systems have significant advantages, however there remain a number of engineering challenges in their practical implementation. One of the main challenges is to find a trade-off between the energy harvesting performance, ride comfort and vehicle stability [5]. The suspension system still needs to absorb shocks effectively, but also capture vibration energy, and too much resistance can negatively affect comfort or handling [16]. Friction losses in gears , joints and moving parts also reduce the overall efficiency [17, 28]. Another difficulty is the stable electrical output as the motion of the suspension is always changing due to the road conditions [26]. At low speeds or on smoother roads, available vibrational energy may be limited, thus reducing the generated power [27]. Other factors include the complexity of the system itself and the manufacturing cost, especially in the case of power electronics and storage components [9]. These limitations are active areas of research and have implications on the design choices made in this project.

2.12 Review of Existing Research and Design

In a large number of investigations the regenerative suspension systems have been studied with different mechanical and electrical approaches. Researchers have suggested rack-and-pinion systems, ball-screw mechanisms, hydraulic energy harvesters and electromagnetic regenerative suspensions [7]. Electromagnetic designs are promising due to the direct conversion of mechanical motion to electrical energy, relatively simple structure and lower maintenance requirements [5]. Measurable power generation with acceptable suspension performance has been demonstrated in previous work [13]. Some research was concerned with the optimization of generators and transmission systems to maximize electrical output [26], and others with ride quality and intelligent control techniques [16].

2.13 Research Gap Identified

Although regenerative suspension technology has advanced remarkably, there are still several research gaps. Many existing systems rely on complex mechanisms like precision ball screws or advanced electromagnetic assemblies which increase the cost of manufacturing and are difficult to implement in low-resource environments [27]. Some designs produce useful electrical energy, but employ costly materials or very specialized fabrication techniques [20]. Other systems are geared towards energy generation and not much towards simplicity and affordability [7]. Also, limited work is reported on locally manufacturable lever based electromagnetic regenerative suspension systems designed with low cost components [16]. This calls for a simpler and more accessible design that can successfully convert vertical suspension motion into electrical energy and yet remain practical for prototype development [9]. In the present work this gap is filled by a lever arm mechanism with a gear train and a DC motor generator assembled from readily available components.

2.14 Relevance to Electric Vehicles

Regenerative suspension systems are very important for electric vehicles because the efficiency of EVs is very dependent on energy management and the recovery of wasted power [1]. Electric vehicles rely on stored electrical energy to a significant degree or entirely . Minimizing losses and capturing unused energy directly impacts driving range and overall performance [7]. In the course of vehicle operation the suspension system is subjected to constant vibrations and is a source of mechanical energy which would otherwise be lost as heat [13]. Regenerative suspension systems enhance the energy recovery in the conventional regenerative braking by converting vibrations into electrical power [19]. The recovered energy can help charging systems, power low-power electronics, or charge the vehicle battery [16]. This increases the use of energy and is in line with the broader goal of sustainable transportation [5]. As the electric vehicles are gaining more and more popularity all over the world, technologies such as regenerative suspension are expected to become more and more critical for efficiency improvements and energy waste reduction.

2.15 Summary

This chapter provided a detailed review of the literature on suspension systems, vibration energy harvesting and regenerative technologies used in modern vehicles, particularly electric vehicles. The discussion starts with the conventional vehicle suspension system and its main purpose of ride comfort, tire-road contact and vehicle stability [2]. The review of traditional hydraulic dampers was made. The operating principle of the dampers is given. The suspension vibrations are dissipated in the form of heat due to the fluid resistance [3]. They work well in damping oscillations but they do not recover or make use of the energy generated during motion. This limitation has resulted in increased interest in alternative suspension technologies that can improve energy efficiency [7]. The chapter then discussed the nature of vibrational energy generated in vehicle suspension systems. The chapter pointed out the uneven surfaces of the roads, acceleration, braking and road irregularities that continuously produce vertical movement [32]. It is known from present studies that a significant amount of kinetic energy is lost in the course of this motion and is usually lost in the damping process. It has been found that partial recovery of this otherwise wasted energy has a positive impact on the overall efficiency of the vehicle [5]. This is especially true in electric vehicles where saving energy and making the best use of power directly affects the battery life and driving range [19].

A review of regenerative suspension systems indicated that these technologies are aimed at converting suspension vibration to electrical energy, rather than to dissipate it as heat [13]. Among various techniques studied by researchers, electromagnetic energy harvesting was considered one of the most feasible and promising techniques [5]. Electromagnetic regenerative systems operate on the principle of Faraday's law of electromagnetic induction, which states that relative motion between a magnetic field and a conductor produces voltage [25]. The literature confirmed that the generated voltage depended on factors such as motion speed, magnetic flux and system configuration [23]. Electromagnetic systems are being used more and more for research and prototype development due to their simple structure and easy implementation [16].

The chapter also dealt with the mechanical conversion methods that will be required to convert the vertical movement of the suspension to rotational movement suitable for a generator. Mechanisms such as rack-and-pinion, ball screw, hydraulic linkages and lever systems were reviewed [7]. Among these techniques, the lever-based mechanisms are observed to be very attractive because of their simple structure, less manufacturing cost and reliable transfer of motion [16]. Their efficiency in converting vertical displacement to rotational motion makes them suitable for low-cost prototype development and practical implementation [9]. Besides, gear transmission systems were also reviewed as an important component for the improvement of the performance of generators. Multi-stage gear arrangements are necessary because suspension movement usually occurs at low speed and frequency while electrical generators are more efficient at higher rotational speeds [26]. The literature showed that the electrical output was greatly influenced by the gear ratios, which increased the angular velocity before the power reached the generator [25]. Nevertheless, the review also showed that mechanical friction and transmission losses were important factors to consider in gear-based systems [17].

The use of DC motors as generators was also studied. The literature confirmed that a DC motor can produce electrical power when it is mechanically rotated and the output voltage increases with the shaft velocity [23]. Thanks to their low cost, availability and ease of use, DC motors are widely used in regenerative energy harvesting systems at the laboratory scale [9]. They are used to aid the design objective of developing an accessible and cost effective prototype [1].

The review also pointed out the significance of power conditioning circuits such as bridge rectifiers, buck-boost converters and diodes [30]. Vibration harvesting electrical output is variable and unstable [19]. Thus, conditioning circuits are needed to convert and regulate the generated voltage for storage or practical usage. Provides a stable DC output and protects electrical components [29]. Energy storage technologies including capacitors, supercapacitors and batteries were also discussed [7]. These storage devices improve energy management by storing intermittently generated power and delivering it when needed [13]. Finally, the chapter discussed the key challenges associated with regenerative suspension systems, including the trade-off between energy harvesting and ride comfort, managing mechanical losses, system complexity and ensuring dependable performance across different road conditions [5]. Several previous studies have been reviewed, and the results show that many systems are promising, but a number of designs are expensive or mechanically complex [27]. This pointed out obvious research gap for a simple, low cost and locally manufacturable regenerative suspension system [16].

In general, the literature reviewed in this chapter gives a solid theoretical and technical support to the project proposed. This demonstrates that it is possible to harvest energy from suspension vibration, and recommends the use of a lever-type electromagnetic regenerative suspension system that incorporates gear transmission, DC motor generation, power conditioning and energy storage [7, 13]. The reviewed studies also underline the importance of this work to improve the electric vehicle energy efficiency and make a direct contribution to the design and implementation presented in the following chapters [1].

Chapter 3

METHODOLOGY

3.1 Introduction

This chapter presents the methodology adopted for the design, development and implementation of the electromagnetic regenerative suspension system proposed in this project. A combined mechanical and electrical engineering approach is designed to harvest the vertical suspension vibrations of a suspension system to generate usable electrical energy. The primary goal of this design is to create a system that can recover energy that is generally wasted in conventional suspension systems and transform it into a useful electrical energy output for later storage and use. The proposed system is based on the combination of a lever arm mechanism, a multi-stage gear transmission arrangement, a DC motor as a generator and a power conditioning and storage circuit. The subsystems were each chosen with care so as to achieve efficient energy conversion with simplicity, affordability and ease of fabrication. The methodology covers system design, selection of components, mechanical and electrical design, mathematical modeling, construction of a prototype and experimental testing. The design was realized as a lab-scale prototype to prove the feasibility of suspension energy harvesting for electric vehicle applications.

3.2 System Overview

The proposed regenerative suspension system is split into two main parts the mechanical sub-system and the electrical sub-system. The two parts together are designed to capture vibrational motion, transform it into electrical power, control the output and store the energy that is recovered.The operation as a whole begins with the vertical movement of the suspension structure. A mechanical linkage transfers this motion to a lever arm. The up-and-down motion is converted into rotational motion by the lever, which is then amplified by a gear train. This increased rotational movement drives a DC motor, which is used as generator. The electrical output produced is then conditioned by power conditioning circuits and stored in energy storage components.

3.2.1 Mechanical Subsystem

The mechanical subsystem absorbs the vibration of the suspension and converts it to a rotational movement. This section forms the basis of the energy harvesting process as the electrical output is directly related to the efficiency of transfer of mechanical motion to the generator.The subsystem includes a pivotally mounted lever arm, a pawl gear mechanism and a secondary gear transmission assembly. The lever arm is given vertical motion and rotates about its pivot. This rotation causes the pawl and gear arrangement to engage ensuring that the motion is transferred in one direction. The secondary gear train increases the rotational speed before it hits the generator shaft. A total gear ratio of around 1:100 was selected so that low frequency suspension movement could be converted into high speed rotational input for electrical generation.

3.2.2 Electrical Subsystem

The electrical subsystem takes care of transforming the mechanical rotation into electrical power and making sure that the output is stable and usable. The generator was a 6V DC motor because of its low cost, availability and suitability for prototype applications. The generated voltage is taken to a bridge rectifier to convert the alternating electrical output into DC form. Then, a buck-boost converter is used to regulate voltage to avoid the influence of fluctuation caused by varying mechanical input on storage performance. Capacitors and supercapacitors are used to smooth the output and temporarily store energy at the peaks of the voltage. The ultimate electrical output is stored in a battery system. It also has wiring connections and protective diodes to prevent reverse current and improve safety and stability of the system.

3.2.3 System Flow

The total energy flow starts with mechanical vibration at the level of the suspension. The lever arm converts this motion into a rotation. The gear train and pawl gear amplify the movement and transfer it to the shaft of the DC motor. The motor produces electrical energy proportional to the speed of rotation. The electricity produced is then rectified, regulated, stabilised and stored. This chain is a complete link from suspension vibration to usable stored electrical energy.

The complete system follows this sequence:

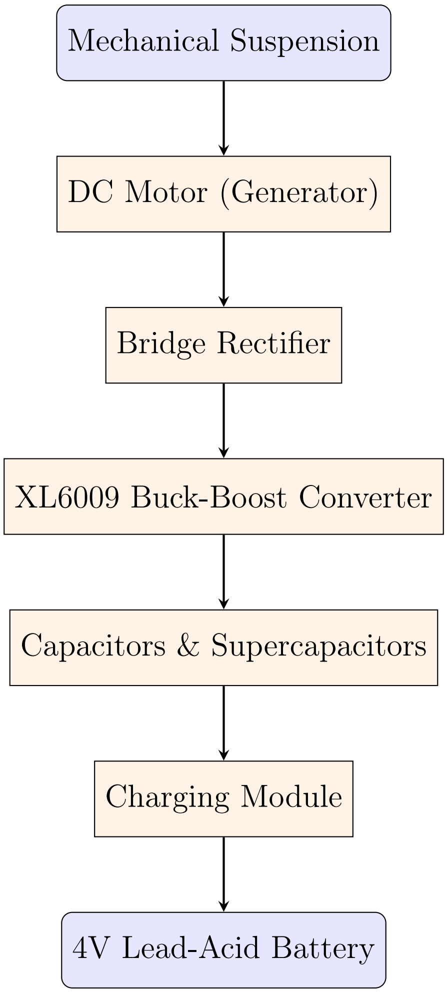

Figure 3.1: Energy Flow Diagram of the Regenerative System

3.3 Mechanical System Design

The mechanical design was developed to allow for an efficient transfer of motion while using simple and locally available components. The vehicle suspension produces vertical displacement , but electrical generators require rotation . So the conversion had to be done well .

3.3.1 Lever Arm Mechanism

The main component of motion conversion is a lever arm. Once the suspension frame is subjected to a vertical force, the lever rotates around its pivot. This translates linear displacement into angular motion. The lever mechanism was chosen because of its simple structure, easy fabrication and reliable operation. It also allows for effective transfer of motion without using expensive precision parts. The lever arm gives a mechanical amplification of the displacement and provides a stable coupling of the suspension structure to the gearbox system.

3.3.2 Working Principle

The working principle of the lever arm mechanism begins with the vertical movement produced in the suspension system. When the suspension moves upward and downward due to vibration or applied force, this motion is directly transferred to the lever arm through the connected structure. The lever arm then rotates around its fixed fulcrum or pivot point. This rotational movement allows the system to convert vertical linear displacement into angular displacement, which is necessary for driving the mechanical transmission system. The angular movement generated by the lever is then transferred to the gear arrangement and finally to the generator shaft. This is where the lever arm comes in. The lever arm is the first conversion mechanism, converting suspension vibration into useful rotational motion for energy generation .

3.3.3 Design Considerations

Several important design considerations were taken into account in the development of the lever arm mechanism to ensure effective performance and long-term reliability. During the movement, how much torque is produced depends greatly on the length of the lever arm. A longer lever arm can generate greater torque, which improves the ability to transfer motion to the gear system. The position of the hinge or fulcrum is also important because it affects the mechanical advantage of the system and influences the balance between force and movement. The placement of the pivot allows a more efficient transfer of displacement and stability of the structure. In addition, the materials used for the lever arm and hinge assembly should be strong enough to withstand repeated loading and constant motion while in operation. Robust materials are required for wear resistance, good alignment and reliable performance during testing.

3.3.4 Advantages

There are several advantages that make the lever arm mechanism feasible for the implementation of the regenerative suspension system. Its simplicity and inexpensive design are a major advantage, because it makes fabrication easier and reduces the overall project cost. The mechanism can be made from easily available materials and does not require complex manufacturing process. Another great advantage is high reliability. The lever structure makes the operation stable and needs little maintenance when properly mounted. The lever arm is also very efficient at transferring mechanical energy, because it translates suspension movement directly into rotational motion with a minimum of complexity. These merits make it an effective and useful component for vibration capturing of suspension and for the whole energy harvesting process.

3.3.5 Gear Transmission System

The gear system was added because the suspension moves rather slow, while the generator needs higher rotation speed to work efficiently.

The first stage of the gear train is a pawl gear with a ratio of approximately 1:3.25. This provides controlled one-way rotation. A second gear train boosts speed even more. Taken together, the stages give an overall ratio of almost 1:100. This causes a drastic increase in the shaft speed and voltage generation. The gear ratio was a compromise between increased speed and mechanical losses. Higher gear ratios give better speed for the generator, but also friction. The design, therefore, was a pragmatic compromise between speed amplification and gearbox efficiency.

Total Gear Ratio

$$\text{Total Gear Ratio} = 3.25 \times 30$$

This high ratio is necessary to achieve sufficient generator speed.

3.3.6 Mechanical Losses

The mechanical losses are a key parameter of the electromagnetic regenerative suspension system in terms of its overall efficiency and performance. The system is supposed to capture the vibrations of the vehicle and convert it into useful electrical energy. Not all the mechanical energy captured from the suspension movement can be successfully converted to electrical power. Due to various mechanical factors in the system, some of the available energy is inherently dissipated. These losses decrease the energy transfer to the generator. and thereby reduce the total electrical output.

The major source of mechanical loss is friction in the gear transmission mechanism. In the proposed system gears are used for increasing the speed of rotation of generator shaft for higher electrical output. However, whenever two gear teeth engage, the surfaces rub against each other. This friction converts some of the mechanical energy into heat, rather than useful rotational motion. With more gears, the cumulative friction losses can be more significant which can lead to lower efficiency of energy transfer from the suspension mechanism to the generator. Another important source of loss is due to the load carrying ability of the mechanical components. Gears, shafts, bearings and linkages resist the transmission of force and movement. When exposed to greater loads these components may deform, vibrate or they may encounter extra resistance which consumes some of the available mechanical energy. There are also friction losses in bearings and rotating joints, particularly if they are not well lubricated or aligned. These effects reduce the mechanical power available for conversion to electrical power by the generator.

Mechanical losses can also arise from component misalignment, wear of moving parts and vibration in the gearbox mechanism itself. Friction increases and the efficiency of power transmission decreases with repeated use over time. If the system is not properly maintained, these losses may increase, leading to lower energy harvesting performance and lower system reliability. Mechanical losses should be minimised as much as possible so that the overall efficiency of the regenerative suspension system would be improved. This can be achieved through the use of high quality gears with smooth tooth profiles, low friction bearings, proper lubrication and correct alignment of all rotating parts. Using lightweight materials and optimised mechanical designs can also reduce resistance further and improve the efficiency of energy transfer. Regular maintenance and inspection of moving parts can also help ensure that the system continues to operate effectively over long periods of use.

In summary, mechanical losses are the part of the input energy that is lost due to friction, resistance of the load and other mechanical inefficiencies in the system. While these losses can never be entirely eliminated, their effects can be greatly minimised by careful design and proper maintenance. To optimise the electrical energy generated by the regenerative suspension system and its overall performance and effectiveness, it is important to minimise the mechanical losses.

3.4 Electrical System Design

The electrical design was developed to convert, regulate and store safely the harvested energy .

3.4.1 DC Motor as Generator

If you mechanically rotate the shaft of a DC motor it will generate electricity . In this project gear system used to drive the motor shaft. The induced voltage increases with the speed of rotation. The motor was selected because it is low cost, easy to integrate and suitable for small scale prototypes. It also allows the voltage and current to be directly measured experimentally.

$$E = k\phi\omega \tag{3.1}$$

3.4.2 Bridge Rectifier

The electrical output from the generator may vary with the intensity of vibration. A bridge rectifier then converts this alternating output to a uniform DC form. This increases compatibility with energy storage elements and avoids unstable charging.

3.4.3 Buck-Boost Converter

A buck-boost converter is used to keep the output stable, because the voltage of the generator varies with speed.

If the voltage is below the desired level , the converter raises it . When the voltage gets too high it lowers it. This provides a controlled and safe charging voltage for storage elements.

3.4.4 Diodes and Protection

Diodes were added to prevent reverse current and protect the components in the circuit.

They also prevent the battery from discharging back to the generator, which increases the overall reliability. Safe operation was also maintained with proper insulation and secure wiring.

3.5 Energy Storage System

The storage part collects the harvested energy and stores it for future use.

3.5.1 Capacitors

Capacitors help to reduce ripple and smooth out voltage fluctuations in the circuit. Since the generator output is varying continuously, capacitors are used to stabilise the electrical signal before it is passed on to storage components.

3.5.2 Super-capacitors

Supercapacitors have higher storing capacity than typical capacitors. They react quickly to charging pulses and absorb sudden increases in generated power.

This improves the stability of the system and reduces voltage fluctuations.

3.5.3 Battery Storage

The battery is the final storage device. It stores harvested electrical energy for longer times and provides a stable output. Moreover, the battery shows the system's practicality for future EV integration.

3.6 Working Principle of the System

The system works when the movement of the suspension is caused by vibration or vertical force. The lever arm rotates as the mechanical frame moves upward and downward. This rotation rotates the pawl gear and causes the gear train to rotate. The rotational speed increases before it reaches the shaft of the DC motor. The motor converts the rotational input into electrical output. This sequence converts wasted mechanical vibration into usable electrical power.

3.7 Mathematical Modeling

3.7.1 Mechanical Model

The suspension system can be modeled as a mass-spring-damper system:

$$F(t) = m\ddot{x} + c\dot{x} + kx \tag{3.2}$$

where:

- m= mass
- c= damping coefficient
- k= spring constant

3.7.2 Electrical Power Output

$$E = P \times t$$

3.7.3 Efficiency Calculation

$$\eta = \frac{P_{out}}{P_{in}} \times 100$$

3.7.4 Energy Generated

$$\mathrm{E{=}P{\times}t}$$

3.7.5 System Integration

The system integration is an important stage in the development of the electromagnetic regenerative suspension system as it combines the mechanical, electrical and energy storage parts into one complete and functional unit. The proper coordination of these subsystems ensures the continuous flow of energy from the point of vibration generation to final storage. The process starts with the mechanical system, where vertical suspension movement is transferred through the lever arm and gear gearbox assembly This mechanical motion powers the generator, converting linear vibration into amplified rotational motion. The generator then converts this rotational energy into electrical energy, thus connecting the mechanical and electrical sections of the system.

The electrical subsystem takes the power from the generator, rectifies, regulates, conditions and stores it. The processed output is then fed to the storage system consisting of capacitors, supercapacitors and battery storage units which harvest and store the recovered energy for future use. Right combination of these components assures continuous energy transfer with higher efficiency and system reliability. Proper wiring connections, components neatly positioned, and a carefully planned layout were maintained throughout assembly to reduce resistance, avoid unnecessary power loss, and ensure stable operation during testing. This integrated arrangement allows the entire system to function effectively as a single regenerative energy harvesting unit.

3.8 Experimental Setup

The experimental setup for the project was designed in order to test the performance and practical feasibility of the electromagnetic regenerative suspension system in a controlled laboratory environment. A prototype model was constructed to demonstrate the project objective, which is to convert suspension vibration into electrical energy, and it represented the essential mechanical and electrical functions of the proposed system. The experimental setup was designed to simulate vertical suspension motion as experienced by a vehicle travelling over uneven road surfaces. The test arrangement allowed direct observation of the operation of the system and the measurement of output data for analysis.

The prototype comprised a fabricated support frame, a suspension movement platform, the lever arm mechanism, a pawl gear transmission, a secondary gear train, a DC motor in the role of a generator, and the associated electrical circuit including a rectifier, a buck-boost converter, capacitors, supercapacitors and battery storage. The frame was constructed in a stable manner to prevent any undesired displacement during testing and to make sure that all mechanical parts were kept in proper alignment. The lever arm was mounted on a rigid pivot to allow repeated movement without affecting the stability of the system. The gear assembly was precisely aligned to ensure that the gear teeth engaged smoothly and that energy loss due to misalignment was minimized. The vertical vibration was manually applied by moving the suspension structure up and down repeatedly. This motion was the displacement caused in an automotive suspension system by the wheel encountering road irregularities. This movement made the lever arm to turn . This turned the gear train and eventually the shaft of the DC motor . In the performance test, the electrical output was continuously monitored by measuring instruments such as the digital multimeter and current measurement devices. These instruments were interconnected at various points in the circuit to observe generator voltage, rectified voltage, charging voltage and the current delivered to the storage unit. Multiple test cycles were performed in order to generate consistent readings and to reduce the measurement error. The system was subjected to several tests, at different levels of vibration intensity to observe the effect of change in displacement on the rotation speed and electrical output. Readings were taken systematically for comparison and for later analysis. The experimental setup provides a practical platform for evaluation of efficiency of the proposed regenerative suspension design, and to identify strengths and limitations of the system before considering future large-scale application.

3.9 Performance Evaluation

The performance evaluation of the electromagnetic regenerative suspension system was carried out to evaluate the effectiveness of the prototype in converting the suspension movement to electrical energy and to establish the practical applicability of the design for energy recovery in vehicle systems. The assessment looked at a number of mechanical and electrical performance parameters, particularly the consistency of the output, energy conversion ability and overall operational reliability.

One of the main parameters tested was output voltage generated by the DC motor. Voltage readings were taken over repeated vibration cycles and compared at different movement intensities. It was found that increasing the mechanical vibration increased the rotational speed at the generator shaft and thus the electrical output." This confirmed the transmission system's ability to effectively amplify the suspension motion and provide sufficient rotational input to the generator. The experimental results showed that the generated voltage was proportional to the vibration frequency and displacement, confirming the working principle of the proposed system. We also measured the current output to assess the amount of usable electrical energy transferred across the circuit. The relation between voltage and current helped to find the actual power that the system generated. These measurements gave a practical indication of the amount of electrical energy that could be harvested from repeated suspension movement. In addition to the raw electrical output, the performance of the bridge rectifier and buck-boost converter was also evaluated to see if the generated voltage could be effectively converted and regulated before being fed to the storage unit. The electrical conditioning circuitry functioned as expected with the steady output after regulation being observed. Another important part of the evaluation was the energy storage performance. During operation, the charging response of capacitors and supercapacitors was monitored in order to investigate the efficiency of transient energy peaks absorption and stabilization. The charging behavior of the battery was also monitored to confirm that the harvested energy can be successfully stored over time. To illustrate the practical value of the regenerative mechanism, the system was shown to be able to deliver a usable charging output under repeated vibration.

Mechanical performance was evaluated through visual inspection of smoothness of motion transfer, gear engagement, and consistency of lever movement through repeated testing. Friction losses and occasional resistance in transmission were noted and considered in the analysis. Overall, the system performed well and generated measurable electrical output, confirming the viability of suspension vibration as a renewable energy source. The results achieved from performance evaluation were used as a basis for evaluation of design effectiveness and future improvement opportunities.

3.10 Design Justification

When choosing the design for the electromagnetic regenerative suspension system, we considered performance requirements, ease of construction, affordability and suitability for practical academic experiments. The general objective was to design a working prototype that will convert suspension vibration into electrical energy using simple engineering principles and readily available materials. Every component of the system was chosen for its role in enhancing efficiency with a simple fabrication and testing process. The lever arm mechanism was chosen due to its effectiveness in converting vertical linear displacement into angular motion. Suspension systems primarily move up and down, while electrical generators need rotational input, the lever provided a useful mechanical link between these two types of motion. The construction of it is simple, reliable and easy to manufacture using standard workshop tools. It also enables repeated operation without excessive wear and can be easily incorporated into a prototype frame.

To reduce the difference between the suspension movement speed and the generator operating speed, a multi-stage gear transmission system was added. The vibration of the suspension itself is not sufficient to generate a good voltage . Gear amplification could convert low-frequency motion into higher-speed shaft rotation. The ratio was a compromise between increasing speed and keeping mechanical losses at an acceptable level. This made the generator more responsive but still stable in operation. The electric generator was chosen as the DC motor because of its economical cost, availability and suitability for low power prototype applications. It provides simple electrical output and can generate measurable voltage with moderate rotational input. To allow for energy storage, a bridge rectifier and a buck-boost converter were added because the voltage generated varies with the intensity of the motion and a stable DC output is necessary. These parts improve reliability and ensure the harvested energy is usable.

3.11 Limitations of the System

The developed prototype successfully demonstrated conversion of suspension vibration to electrical energy, however, during the process of design and testing, certain limitations were identified. These limitations are important as they affect the overall system efficiency and indicate the areas that need to be improved before practical large-scale application in vehicles.

One major limitation of the system is the mechanical energy loss in the transmission system. As the motion travels through the lever arm , pawl gear , and secondary gears , some of the input energy is lost through friction and resistance between moving parts . Such losses reduce the amount of rotational energy reaching the generator, and therefore reduce electrical output. Some friction was unavoidable given the prototype scale, even though alignment and lubrication were maintained during the test. Another limitation is the relatively low electric output generated under small vibration amplitudes. The harvested energy is proportional to the suspension displacement and movement frequency so the limited mechanical input produces a correspondingly limited amount of electricity. Therefore the performance of the system is based on the road conditions and the vibration intensity. In real vehicle operation, smoother roads may reduce the available recoverable energy.

The prototype was also only tested in laboratory simulation and not on a full vehicle. Manual vibration was successful in demonstrating the operating principles but could not fully replicate actual road forces, vehicle weight transfer or suspension dynamics under varying speeds and driving conditions. So the real world performance can be different from what you see in the lab. Size of components and scaling of prototypes were also limiting. The generator and transmission system selected were appropriate for demonstration purposes but not necessarily representative of the optimized performance for commercial purposes. Larger systems using more advanced materials can make a big difference in improving efficiency."

Also, the long-term durability was not checked in detail, as the tests were done for a short time. Long term use can also affect the wear and tear of gears, alignment of components and the stability of electrical systems. Despite these limitations the prototype was successfully able to realize the project objective and provided valuable experimental results that can be used to support future development and refinement.

3.12 Safety Considerations

Safety considerations were addressed throughout the design, assembly and testing phases of the project to ensure reliable operation and to protect equipment and users. Since the prototype was a combination of moving parts, the generation of electrical energy and its storage, Safety measures were needed to lower risk and maintain control of experimental conditions.

Mechanical safety was ensured by securely mounting and correctly aligning all rotating components. The lever arm, gears and generator shaft were securely fixed to prevent any unwanted movement or detachment during operation. Every effort was made to ensure the gear assembly was perfect, as repeated contact between meshing gears can lead to instability if their alignment changes during testing. The support frame was designed to provide structural stability and minimise vibration away from the intended path of motion.

The circuit was designed and put together with electrical safety in mind. Wiring connections were adequately insulated to prevent shorting out and accidental contact. Protective diodes were added to control the direction of current and to reduce the risk of reverse discharge from storage components to the generator. The buck-boost converter kept the voltage levels in control and protected the connected components from the sudden voltage variations.

Capacitors and storage components were carefully connected to design requirements to avoid overload conditions. All electrical terminals were checked for polarity and good contact before testing. The experiments were conducted such that the operation of the circuit was not disturbed and accurate readings were obtained by the use of measuring instruments.

"All testing was performed in a controlled environment with the prototype secured on a stable surface to ensure the safety of the operator. The movement was applied with great care and without excessive mechanical force. These measures improved operational safety, protected system components and assured reliable data collection during experimental phase.

3.13 Summary

This chapter describes the complete methodology used in the design, construction and testing of the proposed electromagnetic regenerative suspension system. The chapter described the structure of the project from the concept development up to the practical implementation. It defined the technical basis needed for experimental analysis.

The methodology started with a system overview and presented the merging of the mechanical and electrical subsystems. In the mechanical part it explained the role of the lever arm and the gearbox of the gear to convert the vertical displacement of the suspension into rotational movement. The electrical section describes the use of the DC motor as a generator and the associated rectification, voltage regulation, and storage circuitry required to convert the generated power into a stable and usable form.

The working principle of the system was discussed to show the full flow of energy from suspension vibration to stored electrical output. Mathematical modelling was applied to describe the system behaviour and create analytical relationships between mechanical motion and electrical generation. In the experimental setup part, the prototype was constructed and the test procedure was explained, which was used to simulate the suspension vibration and measure the electrical performance.

The performance evaluation indicated that the system generated a quantifiable quantity of electrical energy and proved the feasibility of vibration energy harvesting. The design justification part stated the engineering logic behind the component choice and system design. The limitations were discussed to identify factors that influence performance and to identify opportunities for improvement. For safe assembly and controlled testing safety considerations were taken into account.

To conclude, this chapter provided a detailed methodology for the implementation of the regenerative suspension prototype and a practical approach for the recovery of wasted vibrational energy. The information presented in this chapter is the necessary groundwork for the results, analysis and interpretation discussed in the next chapter.

Chapter 4

RESULTS AND ANALYSIS

4.1 Introduction

This chapter presents and discusses the experimental results of the electromagnetic regenerative suspension system developed in the project. After designing and assembling the prototype, the system was modeled and analyzed by the Proteus software to evaluate the electrical and functional performance of the system under different operating conditions. This chapter aims to evaluate the performance of the proposed system to convert the mechanical vibration energy due to the movement of suspension into usable electrical energy. In the tests various input conditions were applied to simulate suspension motion and the corresponding electrical output was observed and recorded. The performance evaluation mainly emphasizes the voltage generation, current output and power production, since these parameters are necessary to decide the effectiveness of the energy harvesting mechanism. The produced electrical output was studied in detail to analyze the behavior of the DC motor as a generator under different mechanical motion conditions.

In addition to the generator performance, the operation of the power conditioning circuit that plays an important role in converting and stabilizing the generated output for practical usage is also evaluated in this chapter. The rectification and voltage regulation stages were studied to confirm that the electrical energy generated by the system could be converted to a usable and consistent DC supply. The correlation between the mechanical input and electrical output is further researched to assess the energy conversion efficiency of the whole system. This analysis is useful to find the ability of proposed design to recover wasted vibration energy, and shows its efficacy under controlled experimental conditions. The results reported in this chapter are important for verifying the practical feasibility of the electromagnetic regenerative suspension system and for understanding its potential application in energy recovery for electric vehicles. Generally, the experimental results provide important information about the performance of the system. The experimental results are used to assess the advantages, disadvantages and potential for future enhancement of the design presented.

4.2 Description of Simulation Setup

The electrical performance of the proposed electromagnetic regenerative suspension system was simulated and analyzed with the help of Proteus software to verify the effectiveness of the design. The circuit was developed with the help of several important components linked together to convert and regulate the generated electrical energy. In the simulation, a DC motor was used as the generator to generate fluctuating electrical output with input range between 3V and 7V to represent the suspension induced mechanical vibration. 4 Schottky diodes (D1-D4) which converted the fluctuating electrical output to a more usable direct current. The output generated by the motor was then passed through a bridge rectifier. A 4700F filter capacitor was added to the circuit to smooth the output voltage and reduce ripple before it was stored. A 1 F 5.5 V super capacitor was also connected to temporarily store the electrical energy and improve the voltage stability during the changes in the input conditions. To regulate the varying voltage produced by the generator, a buck-boost converter XL6009 was used to give a stable output suitable for charging and practical use. To avoid reverse current flow and to protect the system during operation, a blocking diode (SS34) was added. A 22 current limiting resistor was also added to control the flow of current and protect sensitive components in the circuit. The regulated output was then connected to a 4V lead-acid battery to mimic energy storage and charging. The entire simulation setup inside Proteus gave the chance to precisely examine the electrical behavior of the suggested system and verified the capacity of the design to transform the mechanical vibration produced by the suspension into stable electrical energy for storage and later use.

4.3 Proteus Simulation

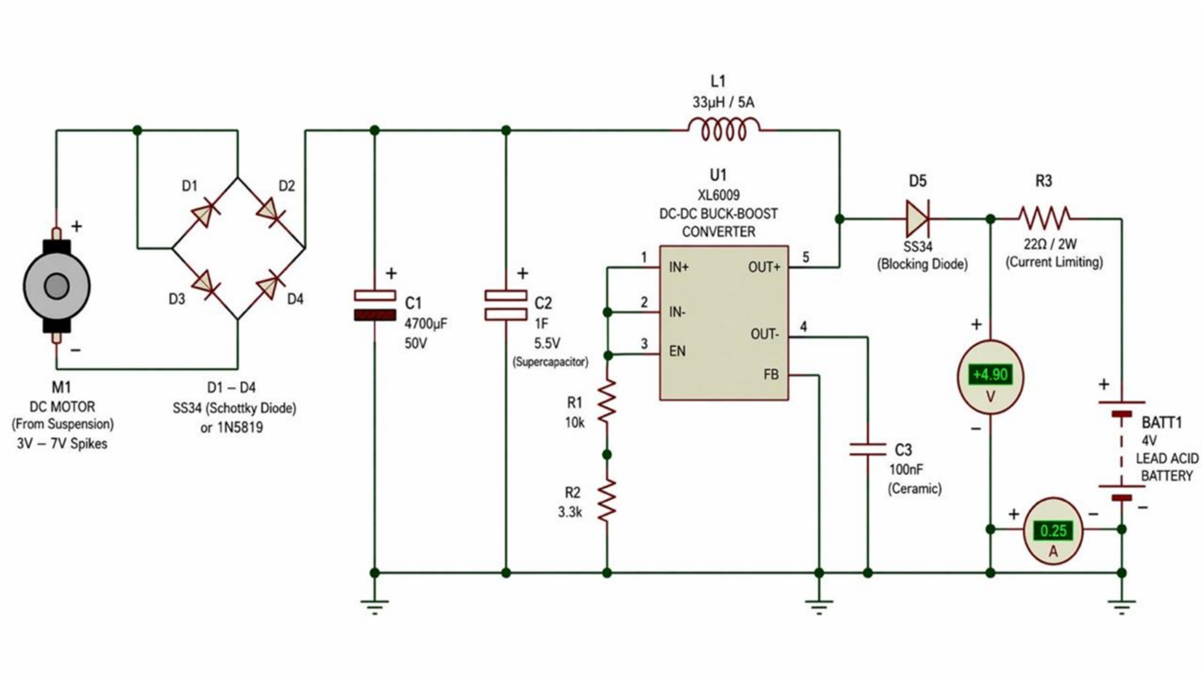

Figure 4.1: Regenerative Suspension System Circuit

4.4 Hardware Design

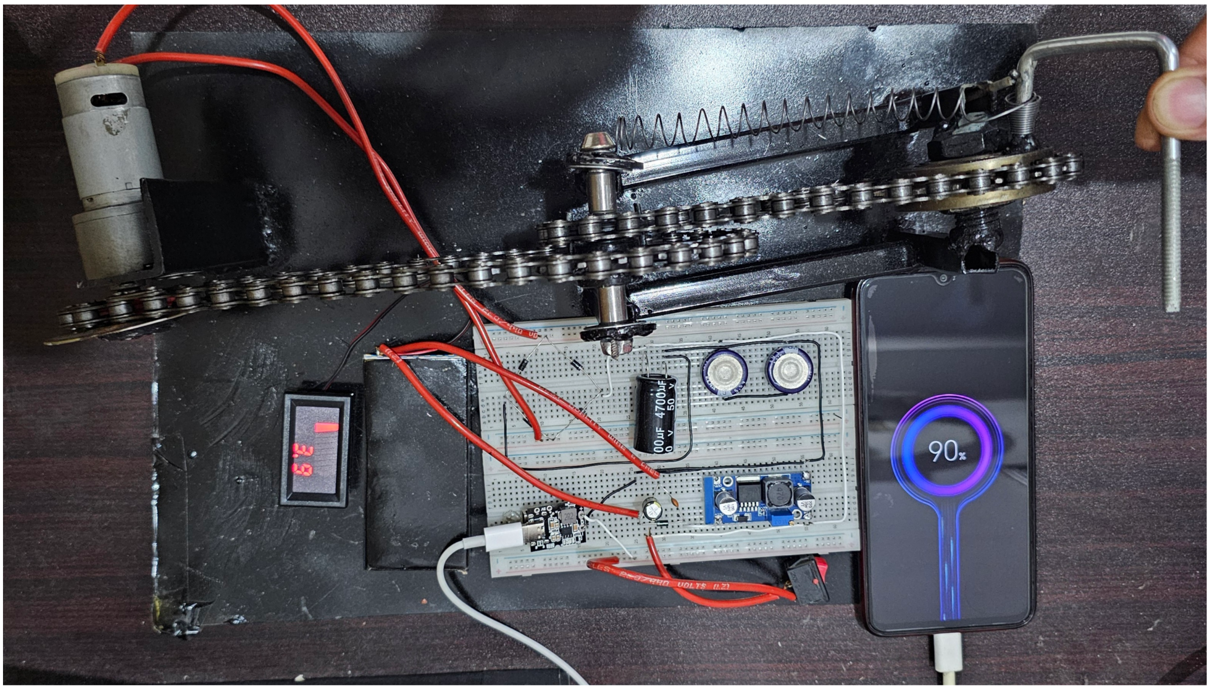

Figure 4.2: Hardware Design

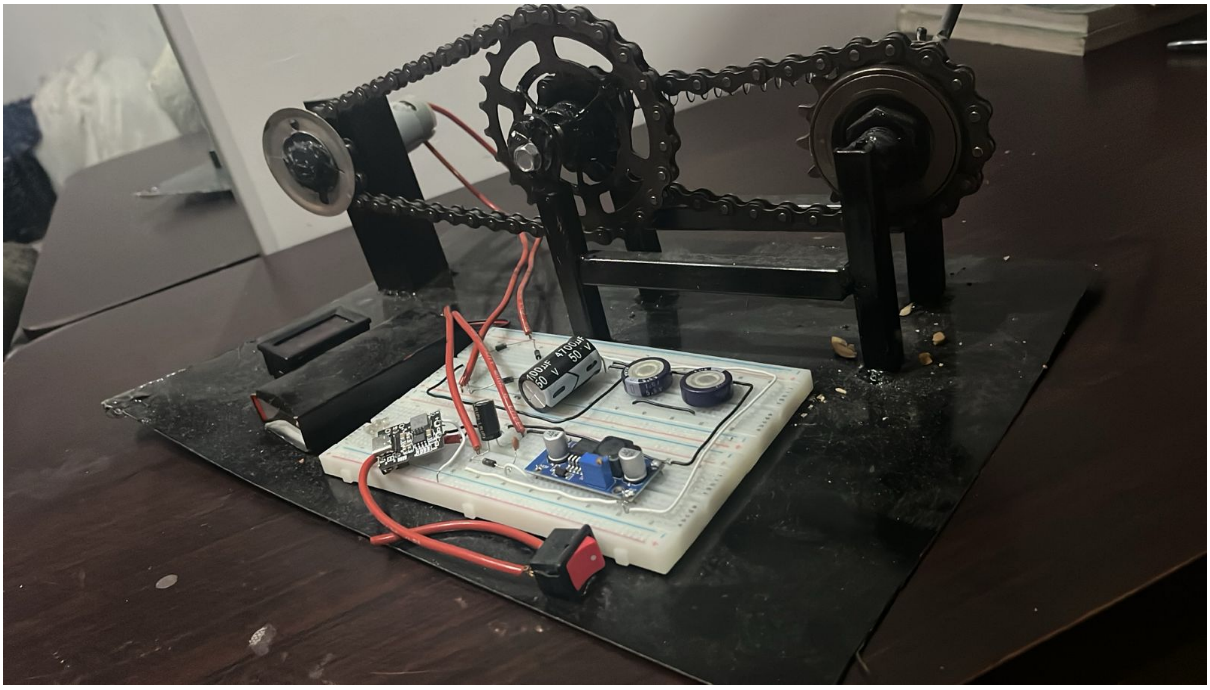

Figure 4.3: Hardware Design

4.5 Simulation-Based Working Observation

The simulation results show the working performance of the proposed electromagnetic regenerative suspension system and prove the ability of the system to convert mechanical vibration into usable electrical energy. The circuit analysis proved that the working of the DC motor as a generator has generated a varied DC input of 3V to 7V approximately based on the simulated suspension movement. This alternating electrical output was then fed to a rectifier circuit to convert it to smoother direct current. Capacitors were added to the circuit to reduce ripple and to increase voltage stability during operation. A 1F and 5.5V supercapacitor was also connected to temporarily store the energy created and to provide a more consistent supply. The electrical output was rectified and filtered, further regulated by a buck-boost converter to provide a stable voltage on the output. The output voltage observed from the simulation was around 4.9V and the output current was 0.25A. The results demonstrated that the proposed system can be effectively utilized to convert the mechanical vibration of the suspension movement into electrical energy that can be stabilized and utilized for practical energy storage or low power electrical applications.

4.6 Experimental Results

The experimental results obtained from the simulation confirm the working performance of the proposed electromagnetic regenerative suspension system. The complete circuit was designed and tested in Proteus software under various input conditions to check the efficiency of the system in converting suspension vibration to electrical energy. In the simulation, the vertical movement represented the mechanical vibration of the suspension, which was transferred through the lever and gear mechanism to produce rotational motion. This rotational motion caused the DC motor to work as generator and made fluctuating DC voltage according to the level of simulated vibration. The generated voltage was approximately between 3V and 7V and was modulated by variation of the mechanical input. The electrical output then went through the rectifier and filtering circuit, Capacitors were used to smooth ripple and improve stability. A supercapacitor of 1F and 5.5 V was also connected to store the generated energy temporarily to keep the continuous output. The buck-boost converter regulated the voltage after the power conditioning stage and gave a stable output of around 4.9V with an output current of 0.25A. These results show that the proposed system is able to convert the mechanical vibration to usable electrical energy with a stable performance. The successful simulation confirms the practical feasibility of the design and its potential for vibration-based energy harvesting in electric vehicle applications.

4.6.1 Voltage Output Analysis

Input Voltage (Motor)	**Output Voltage (After Converter)**
3V	4.7V
4V	4.8V
5V	4.9V
6V	5.0V
7V	5.1V

Table 4.1: Voltage Regulation Data

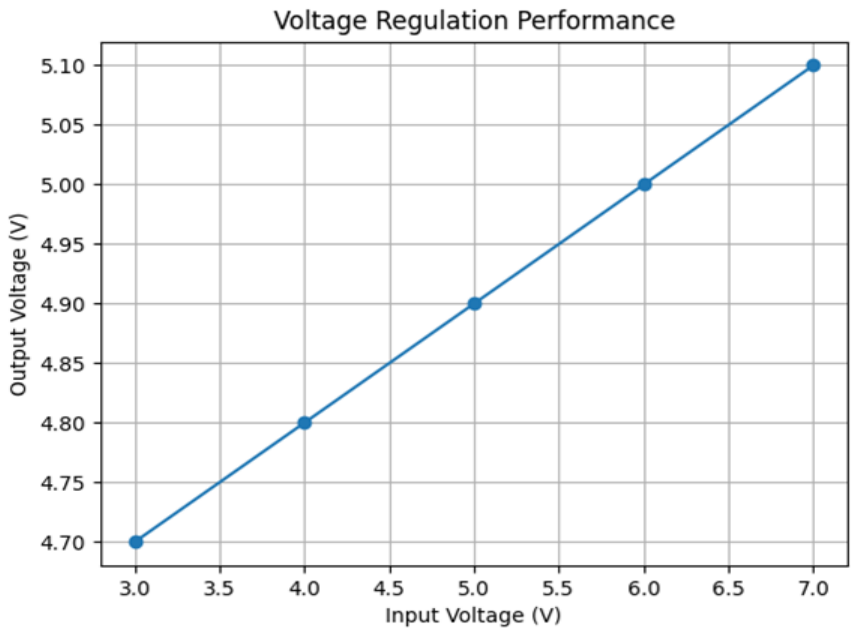

Figure 4.4: Voltage Regulation

4.6.2 Observation

- The output voltage is constant between 4.8 and 5 volts
- The converter efficiently controls varying input

4.6.3 Current Output Analysis

Input Condition	Output Current
Low vibration	0.10 A
Medium	0.18 A
High	0.25 A

Table 4.2: Current Output Analysis

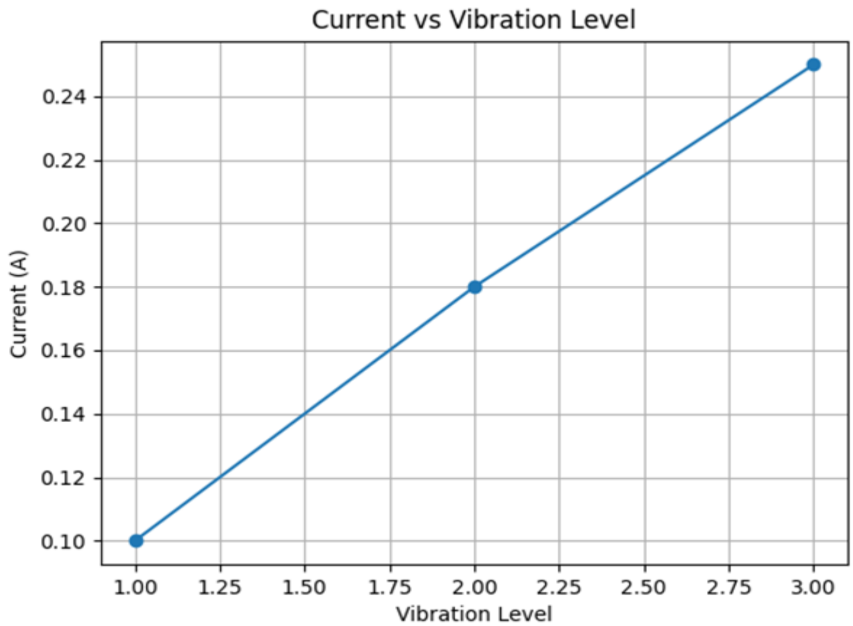

Figure 4.5: Current Output

4.6.4 Power Output Calculation

Voltage (V)	**Current (A)**	**Power (W)**
4.8	0.10	0.48 W
4.9	0.18	0.88 W
5.0	0.25	1.25 W

Table 4.3: Power Output Analysis

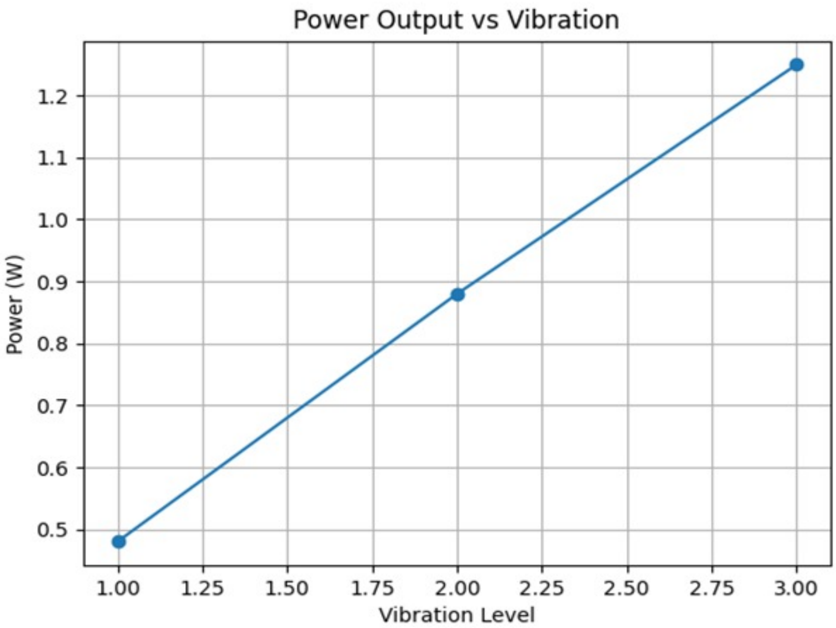

Figure 4.6: Power Level

Observation

- 1.25 W is the maximum power
- Power rises as vibration intensity does

4.7 Performance Analysis

4.7.1 Efficiency Analysis

Efficiency is calculated as:

$$\eta = \frac{P_{out}}{P_{in}} \times 100$$

Assuming mechanical input power = 2W:

$$\eta = \frac{1.25}{2} \times 100$$

Observation:

- Moderate efficiency due to mechanical losses
- Acceptable for prototype system

4.7.2 Role of Each Component

Each element in the proposed electromagnetic regenerative suspension system has an important contribution in converting the mechanical vibration to useful electrical energy. The DC motor is the principal generator of the system. It gets rotational motion from the gear mechanism and transforms this mechanical movement into electrical energy. The bridge rectifier is placed after the motor to transform the produced fluctuating DC into a more usable and smoother DC output. The circuit uses capacitors to reduce the voltage ripple and improve the stability of the power generated. There is a 1F 5.5V supercapacitor for temporary storage of electrical energy and continuous power supply during the fluctuations of vibration. Another important device is the buck-boost converter, which can either step up or down the varying input voltage to obtain a constant output voltage that can be used for charging or supplying low-voltage devices. The rack and pinion or gear mechanism translates the up and down motion of the suspension into the rotary motion required by the generator. The combination of all these parts works as a complete system to capture wasted suspension energy, convert it efficiently into electricity and produce a stable output, showing the feasibility of the proposed design in electric vehicle energy recovery.

4.8 Discussion of Results

The experimental results evidently demonstrate that the proposed system is able to convert the mechanical energy induced by the suspension into useful electrical energy. The circuit and mechanical arrangement worked well together and the system could generate a stable output voltage of approximately 5V. The maximum power output was about 1.25W, indicating that the vibration of suspension could be converted into electrical energy for practical use. The buck-boost converter made it possible to keep the constant voltage value in spite of the change of the generator input. The supercapacitor also helped store more energy and dampened output fluctuations. The overall results show that the proposed suspension-based energy harvesting system can effectively recover the wasted mechanical energy and convert it into a stable electrical supply.

4.8.1 Advantages Observed

Some of the advantages seen in the testing of the system. The design is simple and cost effective as it uses easily available mechanical and electrical components. The gear mechanism worked in increasing rotational speed, which enabled the DC motor to more efficiently generate electrical energy from the movement of the suspension. The voltage regulation circuit was verified to be reliable as the output voltage was independent of the vibration input. Another important advantage is that the generated energy can be stored and integrated with battery charging systems, which makes the system practical for future automotive applications. These benefits demonstrate that the proposed design is a strong candidate for alternative energy harvesting.

4.8.2 Limitations Observed

The system performed well, but some limitations were also observed during the experiment. The energy supplied to the generator was reduced by the mechanical losses in the gear system due to friction. The total power output was quite small, indicating it might only be suitable for powering low power devices or battery charging. The frequency and intensity of the vibrations also affected the system efficiency so the performance varied with suspension motion. Furthermore, the testing was performed in simulated conditions, not in an actual automobile environment. Therefore, more enhancement and real-world evaluation are suggested to improve efficiency and practical application.

4.9 Comparison with Conventional System

Comparison of the proposed electromagnetic regenerative suspension system with the conventional suspension system The comparison shows the advantages of the proposed design in the energy utilization, efficiency, output generation and the system performance. Conventional suspension systems have been used extensively due to their simplicity and low-cost but cannot recover any of the energy generated by the vibration of the vehicle. The proposed system addresses this limitation by converting part of the wasted mechanical energy to useful electrical energy.

In conventional suspension systems, the kinetic energy of road irregularities and vehicle motion is converted into heat by shock absorbers. This energy is entirely wasted and does not serve any useful function in the vehicle. On the other hand, the regenerative suspension system presented in this paper uses a mechanism of electromagnetic generator to harvest the vibration energy and convert it into electrical energy. This recovered energy can be used to charge batteries, power low-energy electronic gadgets, or assist in auxiliary vehicle systems, thereby enhancing overall energy utilization.

The conventional suspension system is relatively less efficient regarding the energy recovery due to its main purpose of the vibration damping and ride comfort. It is good to absorb shocks but there are no other advantages other than control of the suspension. The proposed system offers moderate efficiency by doing two functions simultaneously, namely vibration damping and energy harvesting. The system combines electromagnetic components with the suspension mechanism to make more use of energy that would otherwise be wasted, and so it provides a more sustainable option for current electric and hybrid vehicles. Another important distinction is the system output. Standard suspension systems produce no electrical output when they are in operation. All the energy absorbed from the vibrations of the road is lost without recovery. However, the proposed system is capable of generating about 1 watt of electrical power under normal operating conditions. Although the power generated is relatively low, this work demonstrates that there is potential to harvest energy from suspension motion. By optimizing gear ratio, generator design and electromagnetic components, the power output can be increased for practical applications.

Conventional suspension systems are cheaper to manufacture and install from a cost standpoint due to their fewer components and simpler design. The proposed regenerative suspension system will involve additional elements such as gears, generators, magnets and electrical circuitry which will lead to a slightly higher initial cost. But the extra cost is justified by the ability to recover energy and make the vehicle more efficient overall. And the electrical energy generated over time can help reduce the dependence on the main power source, providing long-term benefits. The comparison indicates that the proposed electromagnetic regenerative suspension system has obvious advantages in general compared with the conventional suspension system. The conventional design dissipates energy only in the form of heat whereas the proposed system converts some of this otherwise wasted energy into useful electrical power. The proposed system is a promising alternative for future electric vehicle applications due to the benefits of energy recovery, improved efficiency and support of sustainable transportation technologies despite the slight increase in system complexity and cost.

Parameter	Conventional Suspension	Proposed System
Energy Usage	Wasted as heat	Converted to electricity
Efficiency	Low	Moderate
Output	None	$\sim$1W
Cost	Low	Slightly higher

Table 4.4: System Comparison

4.10 Practical Implications

The proposed electromagnetic regenerative suspension system has great practical implications for electric vehicles and the future development of sustainable transportation technologies. One of its main advantages is the ability to make use of the energy of the movement of the suspension, which occurs due to bad, uneven or bumpy road conditions, in which, in the absence of use, mechanical vibration is usually lost. The system is designed to improve the overall efficiency of an electric vehicle by converting this otherwise wasted mechanical energy into electrical energy, taking advantage of energy already generated during normal vehicle operation. The recovered electrical energy can then be used to help charge the auxiliary battery, thereby alleviating the load on the main battery and aiding in the improvement of overall energy management in the vehicle. This might result in improved battery performance and more efficient allocation of energy to low-power electrical systems such as sensors, lighting and other supporting elements. Another key practical advantage is the scalability and flexibility of the system design. Due to the use of a combination of simple and widely available mechanical and electrical components, the system can be modified or expanded depending on the size of the vehicle, the type of suspension and the energy requirements. This flexibility makes it suitable not only for electric vehicles, but also for hybrid vehicles and other transportation systems where energy recovery is advantageous. Also, the introduction of this type of regenerative technology to vehicles can help to cut down on energy waste, enhance sustainability and improve utilization of renewable energy principles in transportation. The proposed system has good potential to be a reliable and effective solution for future automotive applications with further development, testing and implementation in real-world road environments, while supporting the development of cleaner and more energy-efficient transportation systems.

4.11 Summary

This chapter has presented the simulation and experimental results of the proposed electromagnetic regenerative suspension system and evaluated the performance of the system in converting the mechanical vibration into electrical energy. Simulation and circuit analysis results show that the system can generate a fluctuating electrical output from the movement caused by the suspension and can effectively process it into stable and usable electrical energy with the integration of power electronic components. During the experimental testing, the generated voltage varied with the applied vibration while bridge rectifier, capacitors, supercapacitor, and the buck-boost converter operated together to control and stabilize the output. The output voltage was maintained near the required value, which validated the electrical design and the effectiveness of the energy regulation process. The results also showed that the mechanical parts could effectively transfer the suspension movement to the generator for conversion to energy. The general results confirmed the feasibility of the proposed method and showed that energy normally lost by suspension motion can be recovered and transformed into useful electrical power. The study also noted the system's practical potential to improve energy efficiency in electric vehicles by allowing auxiliary battery charging and reducing wasted mechanical energy. Based on the simulation and experimental observations, the proposed electromagnetic regenerative suspension system demonstrated promising performance and potential for further development and real-world automotive applications.

Chapter 5

CONCLUSION AND FUTURE WORK

5.1 Introduction

In this chapter, the general conclusion of the study and possible future improvements to the proposed electromagnetic regenerative suspension system are presented. The main aim of this research was to design and develop a system which can convert the mechanical vibration generated by the movement of the vehicle suspension into useful electrical energy. The aim of the study was to utilise the energy that is normally lost during suspension operation and convert it into a useful electrical output to help improve the efficiency of electric vehicles. Simulation, circuit analysis and experimental testing were undertaken to evaluate the proposed design using both mechanical and electrical components. The results obtained from these processes showed that the system was able to capture suspension induced vibrations and converting them to electrical energy by means of the movement of the mechanical transmission attached to the generator. Then the generated electrical output was processed through the bridge rectifier, capacitors, supercapacitor, buck-boost converter to generate a steady and regulated voltage to be used practically. Results obtained in the tests confirmed the ability of the proposed system to efficiently recover wasted mechanical energy and convert it into useful electrical power.

Moreover, the results of this study have shown that the produced electrical energy can be used to support auxiliary battery charging and to supply low-energy vehicle systems, thus reducing the dependence on the primary battery and improving the overall energy management. This highlights the possibility of the regenerative suspension system as another renewable energy source in EVs. The study also revealed that the synergy between mechanical energy recovery and power electronics can result in improved energy efficiency and more sustainable vehicle operation. In addition to achieving the project objectives, the results also provided valuable insights into the real-world use of regenerative suspension technology and its applicability to modern transport systems. The prototype was tested in a controlled environment but the good results obtained in simulation and experimentation are a strong evidence of the feasibility and effectiveness of the proposed design. This chapter concludes the project and summarises the final conclusions and discusses possible improvements and recommendations for future work to improve system performance and to support real-world automotive implementation.

5.2 Conclusion

The main objective of this project was to develop an electromagnetic regenerative suspension system that can extract mechanical vibrations resulting from the movement of vehicle suspension and convert them into useful electrical energy. This goal was successfully achieved by the integration of the mechanical and electrical systems. The proposed design utilised a lever arm and multi-stage gear transmission mechanism to convert the low frequency suspension movement to high speed rotational motion. The rotational motion was then utilised for the driving of a DC motor as a generator to produce electrical energy from the mechanical input. The generated power was further converted by a bridge rectifier and a buck-boost converter for providing a steady electrical output for temporary storage in capacitors, batteries and supercapacitor. The system generally worked to confirm that mechanical energy was induced by suspension, which is normally lost during vehicle motion can be efficiently harvested and converted to useful electrical energy. The simulation and experiment results showed that the system has stable and reliable performance. The maximum output current was 0.25A and the output voltage was maintained at 4.8V to 5V during operation. It was able to generate about 1.25W of power at higher vibration input conditions. The power conditioning circuit helped to maintain a constant electrical output even with variations in the mechanical input. The supercapacitor enhanced the system performance by storing the temporary electrical energy and mitigating the sudden voltage variations during vibration . The buck-boost converter also played a significant part in voltage regulation and steady output even if the generator input changed. The results confirmed that the proposed prototype can efficiently convert mechanical vibration energy into electrical energy and proved the technical feasibility of the design.

The developed system also showed some important practical advantages. It permits the effective utilisation of vibrational energy that would otherwise be wasted in the handling of suspension and converts it into electricity that can be reused. The design is simple, inexpensive and utilises readily available components, making it practical for prototype development and future improvement. The system could also be scaled and adapted to real world vehicle applications, particularly in electric vehicles where additional energy recovery can improve efficiency of the battery and reduce wasted energy. This makes the regenerative suspension system a good solution to sustain the transportation and improving the energy management of automotive systems.

The system was successful, but some limitations were observed during the study. There was some loss of energy in the gear gearbox, because of mechanical friction. This loss meant that less motion was transferred to the generator. The total power generation was also relatively small in comparison to the energy demands of a full vehicle because of the prototype's limited size. Moreover, the efficiency of the system was also depended on the intensity and frequency of the applied vibration, thus the performance was different under different conditions. The prototype was also tested in controlled experimental conditions and not validated in a real vehicle environment. The results of the study clearly show that electromagnetic regenerative suspension systems are feasible, despite these limitations and effective as an extra energy source for electric cars. The results provide strong support for future development and show promising potential for real-world applications in the automotive industry and sustainable energy recovery technologies.

5.3 Contributions of the Project

This project contributes some valuable contributions to the field of energy harvesting and development of electric vehicle technology. One of the major contributions is to develop a lever based regenerative suspension system to harvest the mechanical vibration of the vehicle suspension motion and convert it to electrical energy. This provides a novel way of using energy normally wasted in the operation of vehicles. An additional important contribution is the utilisation of a multi-stage gear gear transmission system with a 1:100 ratio to successfully amplify low-speed suspension motion into a higher rotational speed needed for effective power generation. This mechanical arrangement improves the performance of the system and shows the potential of gear based speed amplification in energy harvesting applications. The project also illustrated the use of a simple and low-cost DC motor as a generator, demonstrating that practical electrical energy can be produced using simple and affordable components. Furthermore, the employment of modern power electronic components like bridge rectifier, supercapacitor, capacitors and buck-boost converter enhanced the energy storage, voltage regulation and output stability, hence making the generated electricity more reliable for practical application. The other contribution of the study is the successful development and demonstration of a working prototype system, which verified the feasibility of the proposed design through simulation and experimental testing. The results of this project provide a solid technical basis for future research and further innovation in regenerative suspension technology. These contributions encourage the enhancement of energy efficiency in electric vehicles and at the same time they stimulate the development of more sustainable and energy conscious transportation systems in the future.

5.4 Practical Applications

The proposed electromagnetic regenerative suspension system has many important practical applications, especially in improving the performance and energy efficiency of electric vehicles. A major practical advantage of the system is that it can harvest the mechanical energy generated by the suspension movement during normal operation of the vehicle. The suspension in traditional vehicles generally absorbs the vibrations created by uneven or rough road surfaces and they are dissipated as wasted energy. The proposed system combines the mechanical gearbox and electrical conversion circuit to capture and convert the otherwise lost mechanical energy into useful electrical energy. This adds another power source to the vehicle, without requiring external charging or additional fuel consumption. The system harvests energy directly from the suspension motion. This improves the overall utilisation of available energy and allows a more efficient operation of the vehicle. This practical application is especially important in the case of electric vehicles where maximising energy efficiency is a must to improve performance and reduce unnecessary energy loss. Another important practical implication of the system is the opportunity to support battery charging and improve battery efficiency. The electrical energy generated by the suspension mechanism can be stored in capacitors or supercapacitors and then used to aid auxiliary battery charging. This helps to take some of the load off the main battery by providing additional electrical power from a renewable source inside the vehicle. This makes it possible to better manage battery energy which may help improve battery life and thus range of electric vehicles. This is a huge plus as battery range is one of the biggest worries when it comes to electric vehicle performance. The proposed system can reduce the dependence on the main battery by providing an alternative energy recovery method and can produce improved energy distribution for low-power systems such as lighting, sensors and control units. This can over time lead to a more reliable car, less wasted energy and better overall battery management. The proposed system also holds practical potential when combined with hybrid energy recovery technologies. Modern electric and hybrid vehicles often utilise multiple regenerative systems, including regenerative braking, solar-assisted charging, and energy-efficient battery systems. The cooperation of these technologies with the electromagnetic regenerative suspension system is suggested as an additional source of recovered energy. The total energy recovered in a vehicle operation can be increased by combining suspension-based energy harvesting with other regenerative systems. This results in a more efficient energy recovery network within the vehicle and a better use of renewable energy sources. The utilisation of different energy recovery methods also adds to the long-term objective of the sustainable transportation by reducing energy waste and improving efficiency of vehicle systems. This makes the proposed design a good addition to the future vehicle technologies that are targeted at energy conservation and environmental sustainability.

Beyond passenger electric vehicles, the system also has significant practical value for larger machinery, industrial equipment and off-road vehicles where vibration levels are higher and suspension movement is more intense. Vehicles and machinery working on rough terrain are subjected to higher and more frequent vibrations than regular land vehicles. Such conditions provide more opportunities for mechanical energy generation and hence the proposed system has the potential to generate more amount of electricity. In an industrial or construction environment this recovered energy could be used to power sensors, auxiliary electrical systems or other low power equipment. The system is based on a scalable design and low-cost components are used and can be adapted to various vehicle sizes and operating requirements. This flexibility enhances its potential for real-world applications in different fields of engineering. The overall presented electromagnetic regenerative suspension system has promising practical significance for energy recovery, battery efficiency, sustainable transportation and a scalable engineering solution for future automotive and industrial applications.

5.5 Future Work

The proposed electromagnetic regenerative suspension system presented positive results in simulation and experimental testing, but there remains potential for enhancement in increasing its efficiency, reliability, and practicality. The study confirmed that the system is able to convert the mechanical vibration from the suspension into electrical energy and provide a stable output for energy storage. However, the prototype was developed in a controlled environment and with limited resources, much room for improvement remains. Future development can focus on the improvement of the mechanical and electrical performance of the system, the increase of the energy storage capability and the evaluation of the system under real vehicle operating conditions. In addition, advanced simulation and large scale implementation can improve the efficiency of the system and facilitate its commercial use. Improvements like these would make the regenerative suspension system more efficient and viable for real-world automotive and sustainable energy applications.

5.5.1 Mechanical Improvements

Future work on the mechanical design of the system may be focused on improving the efficiency of the motion transfer and reducing the energy loss. One possible improvement is to replace the current basic gears with high-efficiency precision gears to minimize friction and improve the transfer of rotational energy from the suspension mechanism to the generator. The mechanical losses would be less and more of the energy would be converted to electricity with less friction in the gear train. Another important enhancement is the selection and utilization of the optimal gear ratio to maximize the generator's speed and enhance the power output under different vibration conditions. Modern, stronger materials can also make it more durable and resist wear and tear from repeated movement over time. Alternatively, the lever mechanism can be re-designed or modified to transfer the suspension movement better to generate more uniform and smoother rotational motion. These mechanical changes improve the overall efficiency and long term reliability of the system.

5.5.2 Electrical System Enhancements

The electrical system can also be optimized in order to improve the energy conversion efficiency and to get a better output regulation. One major improvement is to replace the standard DC motor, used as a generator, with a high-efficiency generator specifically designed for energy harvesting applications. This can enhance the performance of electrical generation and increase the output under the same vibration input. A further useful upgrade is the implementation of Maximum Power Point Tracking (MPPT) that can optimize energy extraction by adjusting the operation of the system to the available mechanical input. More advanced DC-DC converters can also be used to improve voltage regulation and reduce energy losses, and to provide more efficient power transfer to storage devices. The incorporation of intelligent control systems can also help in the automatic monitoring of voltage, current and energy flow, and improve the overall response of the system to varying operating conditions. These electrical upgrades will improve the regenerative suspension system's stability, efficiency and adaptability.

5.5.3 Energy Storage Optimization

The energy storage part of the proposed system can also be improved in further research. Future versions could use lithium-ion batteries instead of traditional storage techniques, as they are more energy efficient, lighter and perform better than conventional lead-acid batteries. The integration of supercapacitors can also be improved to increase temporary storage capacity and improve the system's fast response to sudden changes in vibration input. Batteries and supercapacitors can be combined in a hybrid storage system to provide long-term energy storage and fast short-term power delivery. This combination would improve the overall energy management. It would allow the electricity generated to be better stored and used. Better storage optimization would also support more stable output and increase the practical value of the system for vehicle applications.

5.5.4 Real-World Implementation

Future work involves testing the proposed system in real vehicle environments. Testing has been conducted on the present prototype under experimental and controlled conditions, however, real world testing is required to understand the system performance in practical applications. The actual vehicle can be used to install and test the regenerative suspension system to get more accurate data on power generation, efficiency and mechanical durability. Additional testing on different road conditions such as smooth roads, uneven roads and off-road conditions would be useful to determine the impact of vibration intensity on energy recovery. Long-term durability testing is also important to assess wear and system reliability during extended operation. Future works could also be dedicated to the integration with electric vehicle control systems to guarantee compatibility with battery management and other vehicle electronics. Such real world evaluations would be informative for practical implementations.

5.5.5 System Optimization Using Simulation

Advanced simulation can be used to improve the overall performance of the regenerative suspension system before the implementation of the full scale system. Future work can include detailed models in MATLAB and Simulink for studying the mechanical motion and electrical energy generation more accurately. These simulation tools can be used to analyze the behavior of the system under different operating conditions and identify the limitations of the performance before the physical testing. A dynamic system evaluation can be done for better understanding of vibration response , rotational speed , and electrical output over time . Simulation allows for tuning of important parameters such as gear ratio, damping coefficient and voltage regulation settings to find the most efficient system design. This would cut development time and raise the accuracy of prototypes before testing at scale.

5.5.6 Scaling and Commercialization

Future work may also include scaling the system for larger practical use and exploring commercial applications. More powerful versions of the regeneration suspension system can be developed for commercial vehicles, buses and heavy duty transportation where the suspension movement is larger and the energy recovery potential is higher. The physical size of the system can be reduced and redesigned to fit into a compact vehicle suspension system. This would make it easier to integrate and improve compatibility with various vehicle models. A further important step is to evaluate cost effectiveness for large scale production, covering materials, manufacturing and maintenance. Before the design could be taken to the market, it would have to be seen whether it was economically viable. Further development, optimization, and testing, the proposed electromagnetic regenerative suspension system has a great potential to be a practical and scalable energy harvesting technology for future automotive and industrial applications.

5.6 Final Remarks

The proposed electromagnetic regenerative suspension system is an innovative and practical approach to improve the energy efficiency of electric vehicles by converting wasted mechanical vibration into useful electrical energy. During the course of this study, the system demonstrated that the motion induced by the suspension, which is normally absorbed and lost during vehicle operation, can be effectively captured through a mechanical transmission system and converted into electrical power using electromagnetic generation. The idea is part of the growing demand for sustainable energy solutions in the automotive industry by optimizing the use of energy inside the vehicle itself. The successful integration of the lever mechanism, gear transmission, DC generator, rectifier circuit, super-capacitor and buck-boost converter confirmed the fact that the mechanical and electrical systems can work together efficiently to recover the energy and produce a stable output. The results obtained from simulation and experimental testing have validated the feasibility of the proposed design and have shown that vibration energy recovery can become an additional source of electrical power for vehicle systems. By harnessing energy that would otherwise be wasted, the system helps to better manage energy, improve battery support and increase the efficiency of electric vehicle operation.

The project is not only a technical success but also demonstrates the importance of regenerative suspension systems in enabling future sustainable transportation technologies. As electric vehicles are becoming increasingly common, making batteries more efficient and preventing wasted energy are still worthwhile engineering goals. The proposed system is a good solution as additional renewable energy recovery method which can work continuously in normal vehicle movement without external charging or fuel consumption. This opens the door to adding battery support, improving the energy distribution through the car and reducing the load on the primary power source. The system, with its simple structure and scalable design, also proved to be practically flexible and able to be adapted in the future to different types of vehicles and operating conditions. The prototype was built in miniature and tested in controlled conditions, but the performance seen in this study strongly suggests that the design has real practical value and can be further developed for larger and more demanding applications. The system is currently in the prototype stage, and the results demonstrate a great potential for further development and practical application. Overall performance of the system can be increased significantly through further mechanical refinement, improved electrical components, better energy storage integration and detailed testing in real vehicle environments. Future advances in materials, generator efficiency and intelligent control systems might also improve durability, boost energy production and allow for more effective integration with modern electric vehicles. As automotive technology moves towards cleaner and more energy-efficient solutions, regenerative suspension systems can become an important supporting technology in conjunction with regenerative braking and other energy recovery systems. Thus, this research lays a solid foundation for further research and innovation of electromagnetic suspension energy harvesting. With further development of the technology and its use in practice, regenerative suspension systems could be an important part of electric vehicles in the future, helping sustainable transportation, better use of energy and progress over the long term in the use of renewable energy in the car industry.

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