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Design Analysis of Regenerative Braking System

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Abstract

The research article has shed light on the basic theory and mechanism of the "regenerative braking system". The general concept of the specific mechanism and advantages and limitations of RBS have been evaluated in the study for existing literature sources. The research methodology and technical methods to assemble the setup have been described. Moreover, the testing of RBS has been illustrated n the discussion section, along with an overall concussion of the study in the end.

Keywords: RBS, CBS, kinetic energy, electric vehicles, hybrid vehicles, electric energy, energy conversion, braking efficiency, and fuel consumption.

Introduction

The research article is going to shed light on the analysis and design of a regenerative braking system which comes under one of the core mechanisms in the discipline of mechanical engineering. As opined by Liu et al. (2020), regenerative braking refers to an innovative energy transformation and recovery mechanism which slows down a moving object or vehicle rapidly by transmitting the kinetic energy into a specific form of energy that can be used right away or later when required. This method or mechanism is entirely different from the conventional braking system. In the "regenerative braking system" (RBS), an electric motor (traction motor) is usually utilised in vehicles to convert the momentum or kinetic energy and recover other forms of energy rather than losing it at the brake disc as heat. In addition, the regenerative brakes help in improving the efficiency of the vehicle and extend the lifespan of the braking system, as the mechanical parts of regenerative brakes do not wear out rapidly.

Regenerative brakes are mostly involved in electric motors that function as electric generators. In other words, the "regenerative braking mechanism" is highly effective in the conversion of an electric motor into an electric generator by generating and reserving energy from the momentum of the moving vehicles. The energy that is converted and stored from the "regenerative braking system" (RBS) is used in electric and hybrid cars and railways. For instance, the electricity recovered from the "regenerative braking system" is stored back into the "traction power supply" for future uses. On the other hand, in electric and hybrid vehicles, the regenerated energy generated through RBS is stored in the battery in chemical form, in the capacitor bank in electrical form, and in the rotating flywheel in mechanical form.

The mechanism of regenerative braking is mostly observed in fully electric and hybrid vehicles (Sathishkumar et al. 2022). It has been observed that the specific mechanism helps in converting the kinetic energy of the vehicle into the form of heat energy and then electrical energy rather than losing it, such as in the "conventional braking system" (CBS). This converted electrical energy through the RBS is utilised in charging the high-voltage batteries of completely electric or hybrid vehicles. In the conventional braking system (CBS), cars or moving object slows down due to the result of friction generated between the rotors and brake pads. However, CBS is not effective at all when it comes to the

matter of converting and storing the kinetic energy of vehicles before applying the brake. Approximately, 100% of the kinetic energy of vehicles that propels a moving vehicle in the forward direction is lost in the form of heat energy while the CBS is applied; thus, a lot of energy is wasted here instead of storing or transforming into usable forms. Contradictorily, the RBS mechanism solves the issue of losing kinetic energy while applying brakes in moving vehicles. Generally, the RBS mechanism is consistent in converting around 70% of the kinetic energy of moving vehicles into other forms of energy that can be used immediately or later when needed (Turksoy et al. 2020). In most cases, the kinetic energy is transformed into heat energy at first and then into electric power through the "regenerative braking mechanism".

Literature review

Evaluating the mechanism of the "regenerative braking system" (RBS)

It has been identified that the RBS is widely used in hybrid vehicles (HV) and electric vehicles (EV). Therefore, this chapter is going to mainly focus on the use of regenerative brakes in EVs and electric hybrid vehicles to understand the general concept of the RBS.

As per the narration of Zhou et al. (2020), regenerative braking generates electric energy from kinetic energy by reversing the procedure that forces a car to move forward. In electric vehicles, a battery pack is used to provide power to the motor or multiple motors to generate torque so that vehicles can move forward by using rotational force on wheels. On the other hand, Popiołek et al. (2019) have stated that "regenerative brakes" turns the kinetic energy into electric energy at first and then mechanical energy that ensures the spin of wheel and axles. The RBS utilises the energy of spinning wheels to reverse the direction of generating electricity, such as to the direction of the battery from the electric motor or motors. In this context, drivers need to apply pressure on the brake pedal or remove the foot from the accelerator pedal to activate the RBS. Thus, the electric motor in the RBS turns into an eclectic generator to store energy rather than wasting all kinetic energy as heat. RBS also assists in slowing down vehicles as wheels commute energy to rotate the electric motor's shaft.

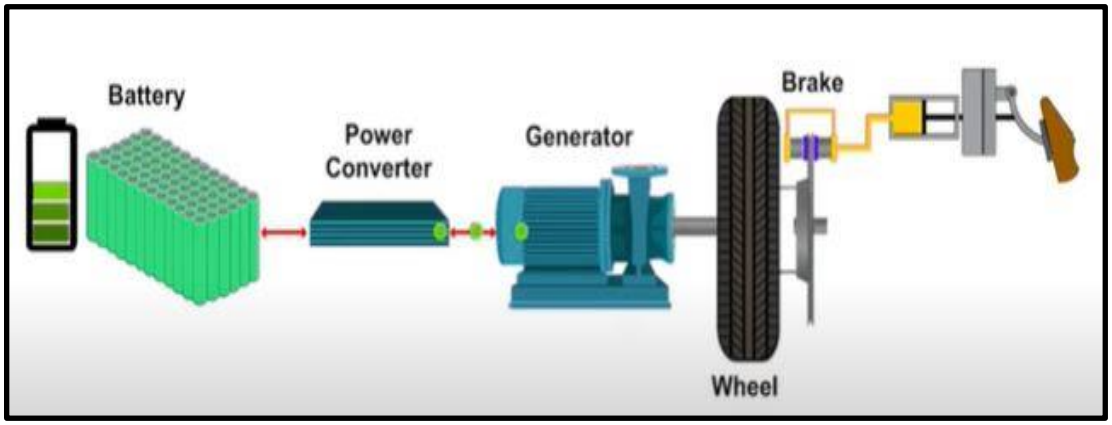

Figure 1: "Regenerative braking system"

(Source: Influenced by Zhou et al. 2020)

As per the studies of Choo and Won (2020), when a motor runs due to external forces, it is defined as an electric generator. This fundamental concept has been applied in the "regenerative braking system". In this context, a flywheel is utilised in the RBS to reverse the direction of energy generation in terms of

turning an electric motor into an electric generator. According to the consideration of Erhan and Özdemir (2021), the flywheel refers to a heavy-rotating mass that takes part in storing kinetic energy. In RBS, energy losses in the form of mechanical energy are converted into electrical energy. On the other hand, electrical energy turns into mechanical energy while charging batteries. It has been observed that the energy generated and stored in the flywheel increases with the radius, mass, and rotational speed. Henceforth, the amount of stored energy can be enhanced by increasing the angular velocity and the moment of inertia of the flywheel (Mathur et al. 2019). Thus, the RBS is considered effective in improving vehicle performance as it helps in boosting acceleration by using stored energy.

The performance of the regenerative braking can be enhanced by using advanced technology-based power components such as ultra-capacitor. Many researchers suggest that the "regenerative braking mechanism: is highly effective, especially in electric vehicles, and even includes a greater future scope. Eventually, the price of diesel and petrol has drastically enhanced across the globe while governments of multiple countries encourage countrymen to purchase electric or hybrid cars by giving subsidies and discounts to promote environment-friendly practices and reduce air pollution. As per the studies of Yadav et al. (2022), a "regenerative braking system" reduces fuel consumption by approximately 33% by converting kinetic energy into electric and mechanical energy. The utilisation of a single gear and direct drive transaxle in the RBS can maximise the efficiency of regenerative braking. Similarly, the engine needs to be disengaged with the drive wheels of vehicles while applying the regenerative brakes to eliminate ther energy loss due to engine friction. Furthermore, reducing the operation time of brakes can expand the life span of the brakes. Thus, the efficiency of RBS also reduces the maintenance and repair costs by reducing the application time to slow down moving vehicles. It has been recognised that the RBS increase the driving range up to 11-22% based on the RBS parameters and "drive cycle settings" such as energy consumption (Kulkarni et al. 2020).

Advantages of RBS

- **The increased life span of rotors and brake pads:** Regenerative brakes are efficient, providing adequate stopping force to moving wheels and axles. As regenerative brakes are mostly worked while slowing down vehicles thus, the braked pads, as well as rotors, are used with a low frequency (Jafari Kaleybar et al. 2023). As a result, the brake pads and rotors last longer between servicing and thus, the maintenance cost of car owners reduces. However, a routine check-up according to the guidelines of a manufacturing company is required even after having an enhanced lifespan of brake pads due to the RBS.
- **High fuel efficiency:** It has been noticed that hybrid vehicles still use ICE ("internal combustion engines") to utilise electric motors mostly to generate energy. On the contrary, the "regenerative braking" mechanism is efficient in keeping the battery pack of electric vehicles charged in terms so that drivers can drive smoothly without relying on engines (Mitropoulos-Rundus et al. 2021. Moreover, the RBS helps in reducing fuel consumption and thus saves money.
- **Extended driving range for electric vehicles (EVs):** The mechanism of capturing the kinetic energy and sending it back to the battery pack of EVs as electric energy can comprehensively enhance the driving range of vehicles. According to scientific estimation, the RBS can potentially extend the driving range of EVs up to hundreds of miles in a year. It not only enhances the driving range of EVS or hybrid cars but also reduces the charging time as well.

Limitations of RBS

- **Less stopping power:** Regenerative braking usually has the potential to gradually slow down and stop moving vehicles. However, it may be required much force on the brake pad to stop the vehicles compared to conventional or hydraulic braking systems (Hamada and Orhan, 2022). In most cases, drivers require to press the brake harder to stop the vehicle to get the same effectiveness as CBS.
- **Reduced efficiency at the lower velocity:** In the RBS, the kinetic energy and barking energy convert into electric energy that stores in a battery pack of EVs. However, driving at low speed refers to low kinetic energy and the requirement of low braking energy (Kivanc and Ustun, 2021). Thus, low the value of regenerative energy will be lower as well; hence, driving at low speed will not be much effective in the RBS.

Methodology

Research methodology defines the approach of conducting the entire research on the specific topic by collecting and analysing adequate relevant data in the most convenient way without facing any significant hazards. Thus, different tools and methods related to conducting research are gouging to be evaluated in the below section:

As per the views of Tamminen and Poucher (2020), research philosophy indicates the general belief that guides a researcher to make designs and execution plans for the overall research study. Generally, positivism and interpretivism paradigms are most commonly used in research works to follow a specific type of data or pattern. Positivism philosophy mostly prioritises scientific quantitative approaches, while interpretivism philosophy prefers humanistic and qualitative methods. Thus, the researcher has followed the **interpretivism philosophy** in this research to take qualitative data into consideration.

It is crucial to design the research properly to select the best suitable approach for the study. As per the studies of Siedlecki (2020), research designs can be broadly categorised into two segments, including descriptive research design and exploratory research design. However, the researcher has followed the descriptive ensign here to evaluate the overall concept and technology regarding the “regenerative braking mechanism” by focusing on the qualitative data only.

As cited by Aljaroodi et al. (2020), the research approach helps in drawing the specific path for conducting the research comprehensively. Approaches can be widely classified into three categories such as inductive, deductive and abductive. However, inductive and deductive approaches are used in most research works due to the inclusion of strategic manner and comprehensiveness. The **deductive approach** has been used in this research by collecting and analysing data based on existing theory and knowledge to reach a specific conclusion.

The selection of appropriate tools for gathering information on the particular research topic plays a constructive role in determining the quality of research outcomes. Therefore, the researcher has used a secondary data collection method to collect qualitative data only. In this regard, the researcher has searched for relevant information on the RBS by searching related articles and journals from several secondary sources such as Goggle Scholar and IRJET (“International Research Journal of Engineering and Technology”) and so on.

The researcher has followed a qualitative thematic analysis based on the critical findings from the recognised studies that have already been published on electric databases. An in-depth discussion has

been made by articulating specific themes based on the key findings from the existing secondary sources.

Technical method and procedure

Components used in analysing the performance of RBS

The major components for testing and carrying out the performance of RBS are going to be enlisted below.

- Arduino
- 2 motors of 1000 rpm
- IR sensor
- Wires
- IR sensor
- Dynamo or brake gear
- 2 wheels and aluminium rods
- Voltage module
- Adhesives

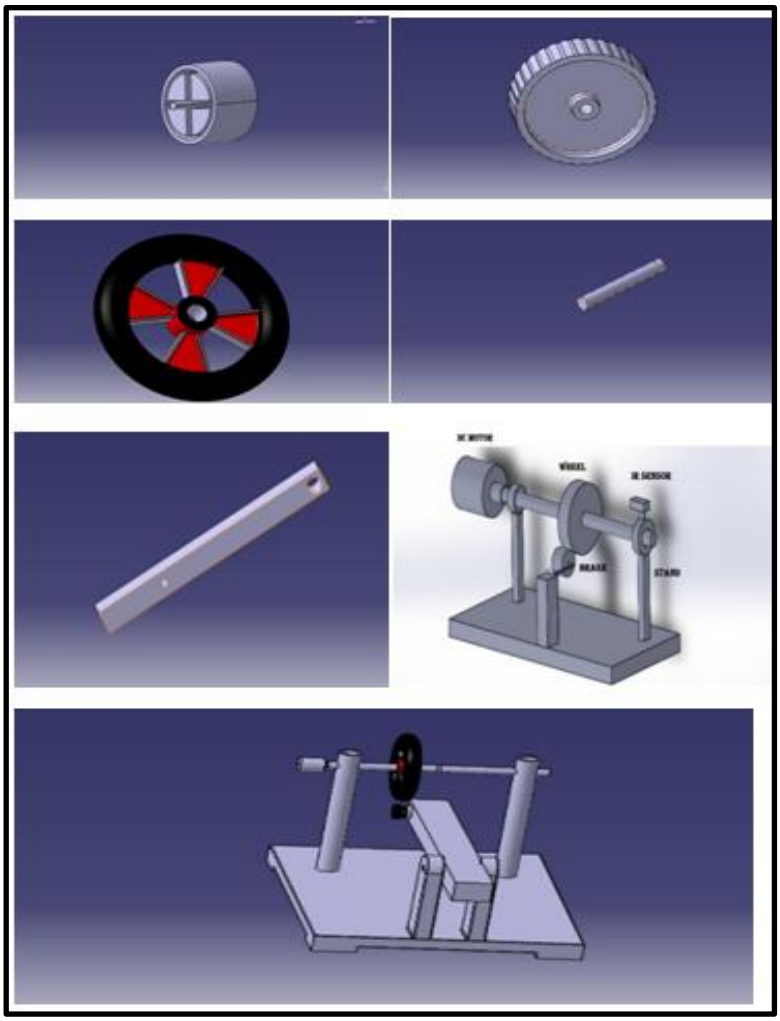

Figure 2: Important components for RBS

(Source: Kulkarni et al. 2020)

In Figure 2, the images represent specific components of RBS which are going to be enlisted below sequentially according to rows.

1. Motor
2. Dynamo
3. Wheel
4. Aluminium rod
5. Crank that supports the dynamo
6. Theoretical setup of RBS
7. Actual setup based on the Catia model

Procedure of setting up the barking system

The procedure for setting up the "regenerative braking system" goes through the following steps mentioned in the below seduction in sequential order.

- At first, 2 quantities of aluminium rods were taken to drill them at a considerable height and a specific diameter depending on the wheel shaft.
- Afterwards, a strong plywood base has been taken to fix both aluminium rods on the base. The plywood base has been drilled according to the aluminium rods' diameter, and additionally, the adhesive is used to fix those rods sturdy so that they can withstand the high-speed rotation of the wheel (Kulkarni et al. 2020).
- A drill of the same diameter has been made with the help of a "lathe machine drill" to couple the motor with the shaft. In this context, the simple arrangement of nut bolts and screws has been used for coupling the motor with the system.
- Therefore, the wheel shaft has been taken and coupled with nuts and bolts to mount the wheel to the base stand. Mechanical bushes have been taken into consideration to minimise the friction between the aluminium rods and wheel shafts. It helped in assuring a high-speed rotation of the wheel in the RBS (Kulkarni et al. 2020).
- Plywood strips, along with screws, have been utilised to make brakes by following the fundamental principle of fulcrum.
- In the end, the brake gears have been coupled with the second motor of the system by using simple nuts and bolts to attach the braking system with the motor. Finally, all wires attached to the second motor have been connected to the Arduino screen to explore the amount of generated energy as output.

Procedure related to "Arduino-based tachometer"

Specific steps are followed for assembling the RBS and attaching it to the "Arduino-based tachometer".

- The wheel of the RBS has been covered with black paper, which has a radius of 9.5 cm, and an aluminium foil strip so that the tachometer can easily detect the rotational speed of the wheel in rpm (Kulkarni et al. 2020).
- Afterwards, a Bluetooth sensor has been attached to an aluminium rod situated a the right side by using adhesive through a glue gun. Therefore, the sensor is connected to the mobile application.
- The Arduino has been attached to the "regenerative braking system".
- Afterwards, both the IR module and voltage module were connected to the Arduino to get the measure of rpm and voltage of the braking setup, respectively.

- The coding of Arduino needs to be efficient to take the appropriate readings of rpm and voltage at a particular moment simultaneously.
- Both these readings are then sent to the mobile application via Bluetooth connection.
- Finally, the MIT application shows the exact value of voltage and rpm generated by the RBS.

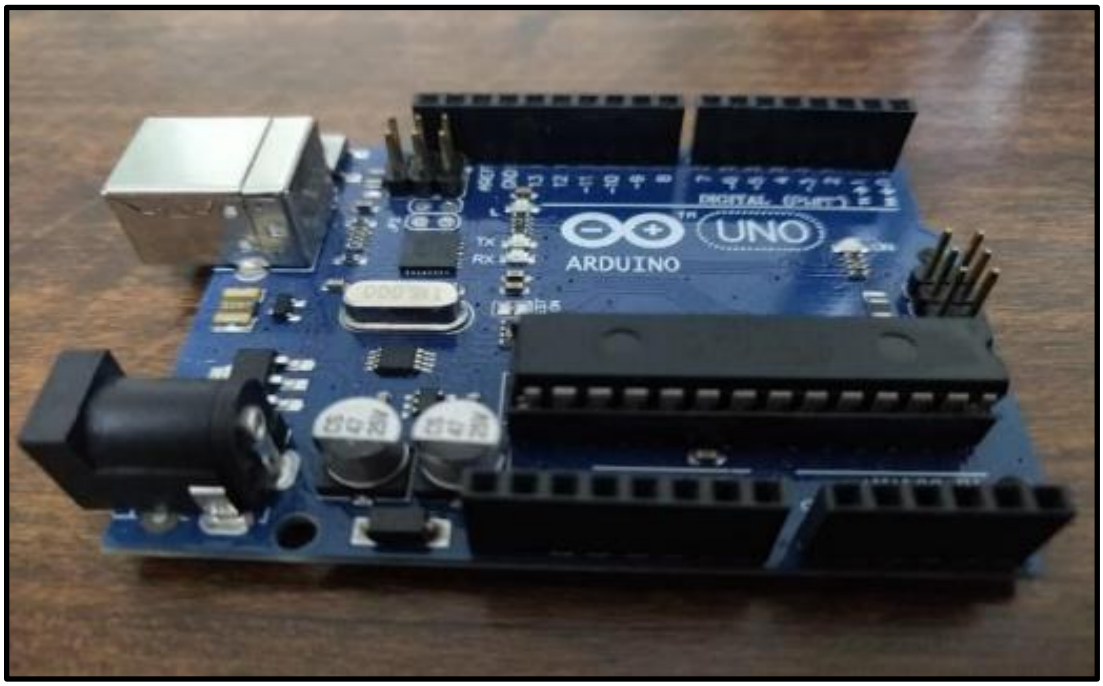

Figure 3: Arduino
(Source: Kulkarni et al. 2020)

Findings and Discussion

The RBS is developed as the supplementary and advanced braking system, which is mainly used along with "conventional braking systems" to enhance the efficiency of braking in stopping cars and restoring the kinetic and concerning braking energy in the form of electric energy. Generally, the developed RBS runs thrice to test the overall effectiveness of the setup. As opined by Kulkarni et al. (2020), the first run has been done to get an idea regarding the parameters related to the motor and the wheel. In this first run, a wheel of 250 grams is used with a rotational speed of 500 rpm. The aim of the first run was the coupling of the setup wheel; however, the motor was unable to generate the required speed. In the second run test, the wheel was mounted on the plywood base stand attached to two aluminium rod that was taken while assembling the setup. For the second time, the motor of 750 rpm has been applied, but it was again unable to meet the needed benchmark of speed generation. In the third run test, a motor with 1000 RPM has been used to generate the required speed and this time, it was successfully achieved. However, 2 mechanical bushes were used to cut down the friction between aluminium rods and the wheel shafts. It significantly helps in smoothening the angular and rotational flow of the wheel. As opined by Saiteja et al. (2022), RBS can be used along with conventional braking to maximise braking efficiency and turn the major proportion of kinetic energy into electric energy to maximise the driving range by reducing fuel consumption in hybrid vehicles.

Conclusion

The "regenerative braking system" has been widely used in recent times in electric and hybrid vehicles. However, the proportion of conventional fuel-based vehicles all over the world is significantly high compared to EVs. It has been recognised that the RBS is not widely used in fuel-based vehicles as it requires much force compared to a "conventional braking system" (CBS) to stop a car. Thus, the efficiency of braking is still required further improvement to substitute CBS on a large scale. Besides this, the conversion of electric energy from kinetic energy is lower when a driver drives a car at a low speed. Thus, it is essential to maintain a consistent minimum speed to regenerate adequate electric energy to charge the battery pack. On the other hand, the world is transforming towards green practices and environmental-friendly renewable energy in terms of reducing pollution and global warming. Thus, the transportation sector is significant turns to electric vehicles (EVs). Therefore, RBS has become very effective in converting braking energy into a usable form of electric energy to enhance the driving range and reduce fuel consumption. It also enhances the lifespan of braking pads by reducing the frequency of friction between rotators and brake pads. However, the extensive use of the RBS in high-speed vehicles, especially in petrol and diesel engine vehicles, is still a matter of scepticism, and thus, future research and further improvement are required.

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