

IOT-Enabled Regenerative Braking System with Dual Battery Management and Protection for Electric Vehicles

**Laxman Bhukya¹, Mohammed Ilyas Abbas², Md Inthiyaz³,
Naga Prabhas Yalla⁴, Errojula Abhishek⁵**

Department of Electrical and Electronics Engineering, Methodist College of Engineering and Technology, King Koti, Abids, Hyderabad, Telangana

Abstract

This paper proposes an enhanced regenerative braking system for electric vehicles, which includes IoT-based monitoring and dual battery management. Regenerative braking turns the vehicle's kinetic energy into electrical energy while braking and stores it in the battery, increasing overall energy efficiency and driving range. During braking conditions, a Permanent Magnet DC (PMDC) motor operates as a generator to convert mechanical energy into electrical energy, which is then boosted to a suitable level for battery charging using a DC-DC boost converter. The system uses a dual battery design with adaptive switching and protective features to improve reliability and lifespan. The system is designed such that the battery with higher voltage supplies power to the load, while the battery with lower voltage is charged during regenerative braking, ensuring efficient energy management and proper utilization of stored energy. A sophisticated control algorithm dynamically distributes braking energy between mechanical and regenerative brakes while maintaining safety and stability. This approach improves energy recovery efficiency, enhances battery utilization, and provides a reliable solution for small-scale electric vehicle applications.

Keywords- Regenerative braking, Dual battery management, IoT technology, Electric vehicles, Energy recovery.

1. Introduction

The growing demand for energy-efficient and sustainable transportation has led to significant advancements in electric vehicle (EV) technology [1]. However, one of the major challenges in EV systems is the loss of kinetic energy during braking, where energy is dissipated as heat in conventional braking mechanisms [2]. This energy loss reduces overall system efficiency and limits the effective utilization of available energy resources [3]. Regenerative braking systems provide a promising solution by converting kinetic energy into electrical energy during braking and storing it for future use, thereby improving efficiency and performance [4, 5].

In regenerative braking, the electric motor operates in generator mode during deceleration, producing electrical energy proportional to the speed of rotation [6]. This generated energy can be utilized for charging energy storage devices; however, the generated voltage is often insufficient for direct charging and requires proper conditioning using power electronic converters [7]. Additionally, the effectiveness of energy recovery depends on the control strategy and system design, which must ensure smooth transition between motoring and generating modes without affecting system stability [8].

Despite the advantages of regenerative braking, conventional systems primarily rely on a single battery for both energy storage and load supply [9]. This leads to inefficient energy management, increased stress on the battery, and reduced lifespan due to continuous charging and discharging cycles [10]. Additionally, the lack of proper monitoring and control mechanisms further affects system reliability and safety [11]. These limitations highlight the need for an improved system that can efficiently manage energy flow while ensuring safe operation [12].

Several research works have explored regenerative braking techniques using DC and BLDC motors along with power electronic converters for energy recovery [13]. Existing approaches focus on improving voltage regulation and storage efficiency; however, limited attention has been given to intelligent battery management using multiple batteries and real-time monitoring [14]. The integration of IoT technology in such systems has shown potential for enhancing monitoring capabilities, but its application in dual battery regenerative systems remains limited [15].

In this paper, an IoT-enabled regenerative braking system with dual battery management and protection for electric vehicles is developed to address the above challenges. The proposed system utilizes a PMDC motor for energy generation, a boost converter for voltage enhancement, and an Arduino-based control mechanism for intelligent battery switching. An ESP32 module is incorporated to enable real-time monitoring of system parameters, improving overall system control and reliability.

The key contributions of this work are summarized as follows:

1. Development of a regenerative braking system for effective energy recovery during braking conditions.
2. Implementation of a dual battery management system for efficient energy utilization and continuous load supply.
3. Integration of IoT-based monitoring using ESP32 for real-time observation of system parameters.
4. Enhancement of system reliability through controlled switching and protection mechanisms.

The remainder of this paper is organized as follows: Section 2 describes the proposed system and overall methodology. Section 3 presents the hardware implementation. Section 4 explains the working principle of the system. Section 5 discusses the experimental results and analysis. Finally, Section 6 concludes the paper.

2. Proposed System and Methodology

The proposed system is designed to recover energy during braking conditions and efficiently manage power using a dual battery configuration integrated with IoT monitoring. The overall system structure is illustrated in Fig. 1, where the red lines represent power flow paths and the blue lines represent data and control signals.

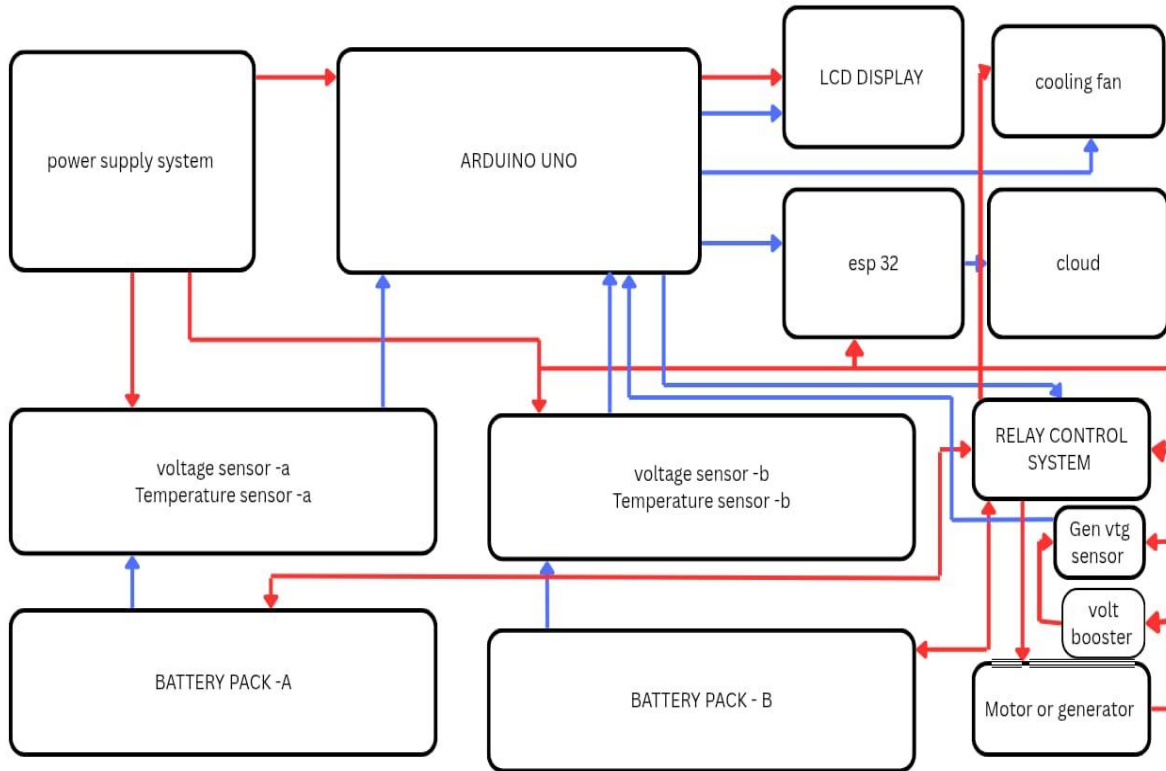


Fig. 1 Block Diagram of Proposed System

The system consists of two battery packs (Battery A and Battery B), voltage and temperature sensors, a PMDC motor operating as a generator, a DC-DC boost converter, a relay control system, an Arduino UNO, an ESP32 module, an LCD display, and a cooling fan. During regenerative braking, the motor converts mechanical energy into electrical energy, which is then stepped up using the boost converter to a suitable level for battery charging.

The Arduino UNO acts as the central controller of the system. It continuously receives input data from voltage and temperature sensors connected to both battery packs. Based on these inputs, the controller determines the operating condition of each battery and executes the control logic. The relay control system is used to switch between the two batteries such that the battery with higher voltage supplies power to the load, while the battery with lower voltage is charged using the regenerated energy.

The generated voltage from the motor is monitored using a dedicated voltage sensor before being regulated through the boost converter. The regulated output is then directed to the appropriate battery via the relay

control system. This ensures efficient energy utilization and proper distribution of power within the system.

For monitoring and user interaction, an LCD display is interfaced with the Arduino UNO to show real-time parameters such as battery voltages, generated voltage, and temperature. Additionally, an ESP32 module is integrated to enable IoT-based monitoring by transmitting system data to the cloud, allowing remote observation and analysis.

To maintain safe operating conditions, temperature sensors continuously monitor the thermal state of the batteries, and a cooling fan is automatically controlled when the temperature exceeds a predefined threshold. This prevents overheating and ensures system reliability.

Overall, the proposed methodology combines energy recovery, intelligent battery switching, real-time monitoring, and thermal management to achieve an efficient and reliable regenerative braking system suitable for small-scale applications.

3. Hardware Implementation

The hardware implementation of the proposed system is designed to effectively recover, regulate, and store energy generated during braking conditions while ensuring reliable operation. The overall hardware setup of the system is illustrated in Fig. 2, which includes a Permanent Magnet DC (PMDC) motor, a DC-DC boost converter, an Arduino UNO, relay modules, dual battery units, voltage and temperature sensors, a cooling fan, and an ESP32 module for IoT-based monitoring.



Fig. 2 Hardware Setup of the Proposed System

The PMDC motor plays a key role in the system by acting as a generator during braking conditions. When mechanical energy is applied to the motor shaft, it generates electrical energy based on the principle of electromagnetic induction. However, the generated voltage is typically low and varies with speed, which makes it unsuitable for direct battery charging. To address this issue, a DC-DC boost converter is employed to step up the generated voltage to a level suitable for charging the battery.

The control of the system is managed by the Arduino UNO, which continuously monitors important parameters such as battery voltage and temperature using the respective sensors. Based on these inputs, the Arduino controls relay modules to perform intelligent switching between the two batteries. The relay-based switching mechanism ensures that only one battery supplies power to the load while the other battery is charged, thereby improving energy utilization and system efficiency.

The dual battery configuration enhances system reliability by distributing the load and charging operations. This approach minimizes stress on individual batteries and supports continuous system operation. The temperature sensor helps in detecting thermal variations, and the cooling fan is activated when required to maintain safe operating conditions. Additionally, the ESP32 module [16] is integrated into the system to enable IoT-based monitoring, allowing real-time observation of system parameters such as voltage and temperature. This enhances system transparency and enables better supervision.

Overall, the hardware implementation ensures efficient energy conversion, controlled energy management, and reliable operation of the regenerative braking system.

4. Working Principle

The working principle of the proposed system is based on regenerative braking, where the kinetic energy of the motor is converted into electrical energy during braking conditions. The operation of the system can be broadly classified into two modes: normal driving mode and regenerative braking mode. In the normal driving mode, the battery with higher voltage is selected to supply power to the motor, enabling its rotation and driving the load. At the same time, the second battery with comparatively lower voltage remains isolated from the load and is available for charging.

In the regenerative braking mode, when braking is applied, the motor operates in generator mode due to the inertia of the rotating shaft. As a result, mechanical energy is converted into electrical energy based on the principle of electromagnetic induction. When the armature rotates within the magnetic field of the permanent magnets, an electromotive force (EMF) is induced in the conductors. The generated voltage is proportional to the angular speed of the motor and is expressed as $E=k\omega$, where E is the generated EMF, k is a motor constant, and ω is the angular velocity.

Since the generated voltage is generally low and varies with speed, it is fed into a DC-DC boost converter to increase the voltage to a level suitable for battery charging. The boosted output is then directed to the battery with lower voltage through relay-based switching, ensuring effective energy storage during braking.

The Arduino UNO [17] continuously monitors the voltage and temperature of both batteries and controls the relays to perform intelligent switching. The control logic ensures that at any instant, the battery with higher voltage supplies the load while the battery with lower voltage is charged, thereby achieving efficient energy utilization and balanced battery operation.

The voltage sensor provides real-time feedback for monitoring battery levels, while the temperature sensor ensures safe operation by detecting thermal variations [18]. When the temperature exceeds a predefined threshold, the cooling fan is activated to maintain safe operating conditions. Furthermore, the ESP32 module enables IoT-based monitoring, allowing real-time tracking of system parameters such as voltage and temperature. Thus, the proposed system effectively captures and utilizes the energy generated during braking, improving energy efficiency, battery performance, and overall system reliability.

5. Results and Discussions

This section presents the experimental results obtained from the developed regenerative braking system with dual battery management and IoT monitoring. The system was tested under different operating conditions to observe battery voltages, generated voltage during braking, and temperature variations. The obtained results were displayed locally on the LCD and also monitored remotely using the Thing Speak cloud platform.

5.1 LCD Based System Monitoring

The developed system provides real-time monitoring of important parameters using a 16×2 LCD display. The LCD displays the voltage levels of both batteries, generator output voltage, and the temperature measured using the DHT11 sensors.



Fig. 3 LCD Display Showing Battery Voltages, Generated Voltage and Temperature

During system operation, the LCD shows the voltage of Battery 1 (B1), Battery 2 (B2), generator voltage (G), and temperature (T). An example output obtained from the system is shown in Fig 3, where Battery 1 voltage is approximately 11.6 V, Battery 2 voltage is 9.6 V, the generator voltage is around 12.3 V, and the temperature is 32°C.

The displayed results indicate that the system is successfully measuring and displaying the operating parameters in real time. The voltage values also confirm that the system correctly detects the battery with higher voltage to supply the load, while the battery with lower voltage is available for charging.

5.2 Generator Voltage during Regenerative Braking

The regenerative braking mechanism allows the PMDC motor to operate as a generator during wheel deceleration. When the wheel rotates due to mechanical motion, electrical energy is generated and can be utilized to charge the battery with lower voltage.

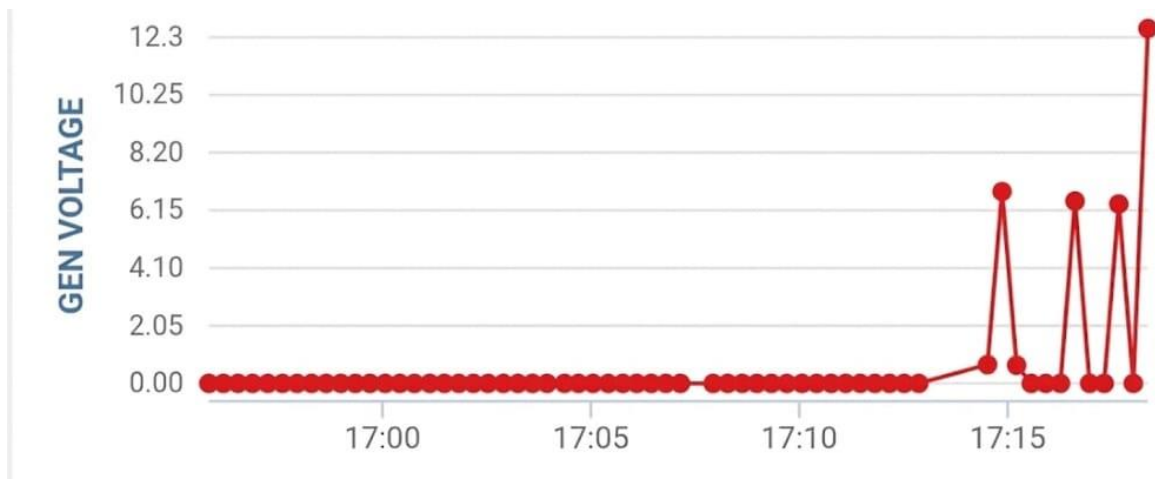


Fig. 4 Generator Voltage Monitoring Using ThingSpeak

The generator voltage obtained during testing is shown in Fig 4 through the ThingSpeak cloud monitoring interface.

The graph shows that the generator voltage remains near zero during normal operation when no braking energy is available. However, when the wheel is rotated or braking occurs, the generator voltage increases and reaches value 12.3 V depending on the wheel speed and mechanical input.

These results confirm that the system is capable of successfully converting mechanical energy into electrical energy during braking conditions.

5.3 Battery Voltage Monitoring

The voltage levels of both battery packs were continuously monitored and recorded using the voltage sensors connected to the Arduino microcontroller. The collected data was transmitted to the ThingSpeak cloud platform for visualization.

The variation of Battery 1 voltage over time is shown in Fig 5.



Fig. 5 Battery 1 Voltage Monitoring Graph

The graph indicates that the voltage of Battery 1 remains around 11.3 V to 11.6 V, showing slight variations due to load conditions and charging behaviour. These variations confirm that the battery is actively supplying power to the load during system operation.

Similarly, the voltage variation of Battery 2 is shown in Fig. 6.



voltage is observed in the ThingSpeak monitoring graphs, as shown in Fig. 4, which confirms that the system successfully produces electrical energy during braking conditions. This generated energy is then directed towards charging the battery with lower voltage through the relay switching mechanism.

The results recorded shows that Battery 1 maintains a voltage range of approximately 11.4 V to 11.6 V, indicating that it is primarily responsible for supplying power to the load during system operation, as illustrated in Fig. 5. On the other hand, Battery 2 maintains a voltage range of approximately 9.6 V to 9.8 V, which indicates that it operates under charging conditions when regenerative energy becomes available, as shown in Fig. 6. The implemented dual battery management logic ensures that the battery with higher voltage supplies power to the load while the battery with lower voltage is charged using the regenerated energy. This intelligent switching mechanism improves overall system efficiency and ensures balanced utilization of both battery packs.

Temperature monitoring is also implemented in the system to ensure safe operation of the batteries. The DHT11 temperature sensors continuously monitor the temperature near the battery packs. The experimental readings indicate that the temperature remains within a safe operating range during system operation, as depicted in Fig. 7. In case the temperature exceeds the predefined threshold value, the cooling fan is automatically activated through the relay module to maintain safe operating conditions. This feature enhances the reliability and safety of the overall system.

Another important feature of the proposed system is the integration of IoT-based monitoring using the ESP32 microcontroller and ThingSpeak cloud platform. The ESP32 module collects the measured data from the Arduino and uploads it to the cloud using Wi-Fi connectivity. The ThingSpeak platform then visualizes the data in the form of graphs for parameters such as generator voltage, battery voltages, and temperature. This allows users to monitor the performance of the system and analyse the behaviour of the system over time.

The experimental results clearly demonstrate that the developed system is capable of effectively performing energy regeneration, dual battery management, and real-time monitoring. By utilizing regenerative braking energy, the system reduces energy wastage and improves the overall energy efficiency of the system. Therefore, the proposed system can be considered a practical and efficient approach for improving energy utilization in electric vehicle applications and other energy recovery systems.

6. Conclusion

The proposed IoT-enabled regenerative braking system with dual battery management has been successfully designed and implemented to improve energy efficiency in electric vehicle applications. The system effectively converts kinetic energy into electrical energy during braking using a PMDC motor operating in generator mode, and the generated energy is regulated through a boost converter for battery charging. The dual battery management strategy ensures that the battery with higher voltage supplies the load while the battery with lower voltage is charged, enabling continuous operation and efficient energy utilization. The integration of voltage and temperature monitoring enhances system safety, while the cooling mechanism maintains stable operating conditions. Additionally, IoT-based monitoring using

ESP32 provides real-time visibility of system parameters. The experimental results validate the effectiveness, reliability, and practicality of the proposed system for small-scale electric vehicle and energy management applications.

Disclosure Statement

The authors declare that there is no conflict of interest regarding the publication of this paper.

References

1. J. Zhang, L. Wang, and H. Chen, "Review of regenerative braking systems for electric vehicles," *Energies*, vol. 11, no. 3, 2018.
2. J. Cao and A. Emadi, "A new battery/ultra-capacitor hybrid energy storage system for electric vehicles," *IEEE Transactions on Power Electronics*, vol. 27, no. 1, pp. 122–132, Jan. 2012.
3. S. Tie and C. W. Tan, "A review of energy sources and energy management system in electric vehicles," *Renewable and Sustainable Energy Reviews*, vol. 20, pp. 82–102, Apr. 2013.
4. M. Ehsani, Y. Gao, S. E. Gay, and A. Emadi, *Modern Electric, Hybrid Electric, and Fuel Cell Vehicles: Fundamentals, Theory, and Design*, 2nd ed. Boca Raton, FL, USA: CRC Press, 2018.
5. C. C. Chan, "The state of the art of electric and hybrid vehicles," *Proceedings of the IEEE*, vol. 90, no. 2, pp. 247–275, Feb. 2002.
6. A. Emadi, Y. J. Lee, and K. Rajashekara, "Power electronics and motor drives in electric and hybrid vehicles," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 6, pp. 2237–2245, Jun. 2008.
7. N. Mohan, T. M. Undeland, and W. P. Robbins, *Power Electronics: Converters, Applications, and Design*, 3rd ed. New York, NY, USA: Wiley, 2003.
8. R. W. Erickson and D. Maksimović, *Fundamentals of Power Electronics*, 2nd ed. Boston, MA, USA: Springer, 2001.
9. B. K. Bose, *Modern Power Electronics and AC Drives*. Upper Saddle River, NJ, USA: Prentice Hall, 2002.
10. A. Khaligh and Z. Li, "Hybrid energy storage systems for electric vehicles," *IEEE Transactions on Vehicular Technology*, vol. 59, no. 6, pp. 2806–2814, Jul. 2010.
11. M. Yilmaz and P. T. Krein, "Review of battery charger topologies for electric vehicles," *IEEE Transactions on Power Electronics*, vol. 28, no. 5, pp. 2151–2169, May 2013.
12. D. Andrea, *Battery Management Systems for Large Lithium-Ion Battery Packs*. Boston, MA, USA: Artech House, 2010.
13. H. He, R. Xiong, and J. Fan, "Evaluation of lithium-ion battery models for state of charge estimation," *IEEE Transactions on Vehicular Technology*, vol. 60, no. 4, pp. 1461–1469, May 2011.
14. L. Atzori, A. Iera, and G. Morabito, "The Internet of Things: A survey," *Computer Networks*, vol. 54, no. 15, pp. 2787–2805, Oct. 2010.
15. O. Hersent, D. Boswarthick, and O. Elloumi, *The Internet of Things: Key Applications and Protocols*. Hoboken, NJ, USA: Wiley, 2012.
16. Espressif Systems, "ESP32 Technical Reference Manual," 2023.



17. Arduino, “Arduino UNO Rev3 Datasheet,” 2022.
18. V. Vorperian, *Fast Analytical Techniques for Electrical and Electronic Circuits*. Cambridge, U.K.: Cambridge University Press, 2002.
19. S. M. Savaresi, M. Tanelli, and C. Cantoni, *Active Braking Control Systems Design for Vehicles*. London, U.K.: Springer, 2010.
20. J. M. Miller, *Propulsion Systems for Hybrid Vehicles*, 2nd ed. London, U.K.: IET, 2008.