Design and Analysis of Regenerative Braking System in Electric Vehicles

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ABSTRACT

The regenerative braking system in electric vehicles is an advanced energy recovery technology that enhances overall efficiency by converting kinetic energy, typically lost during braking, into electrical energy for battery storage. Unlike conventional friction-based braking systems that dissipate energy as heat, the proposed design employs a DC motor operating in dual mode—acting as a motor during propulsion and as a generator during deceleration. The recovered electrical energy is conditioned through power electronic components such as rectifiers, MOSFET-based control circuits, and DC-DC converters to ensure stable voltage regulation and safe battery charging. This approach not only improves vehicle energy utilization and extends driving range but also minimizes mechanical wear, reduces maintenance costs, and supports sustainable transportation. By optimizing energy conversion and storage, the system contributes significantly to the development of environmentally friendly and energy-efficient electric mobility solutions.

Keywords— Regenerative Braking, Electric Vehicles, Energy Recovery, DC Motor, Power Electronics, Battery Charging, Energy Efficiency, Sustainable Transportation, MOSFET Control, Dual Mode Operation.

I. INTRODUCTION

Electric vehicles (EVs) have emerged as a promising solution to address the growing concerns of environmental pollution, fossil fuel depletion, and energy efficiency in the transportation sector. Unlike conventional internal combustion engine vehicles, EVs operate using electrical energy stored in batteries, which powers an electric motor for vehicle movement. While EV technology offers several advantages such as zero tailpipe emissions and reduced operating costs, improving overall energy efficiency remains a key challenge. One of the major areas of energy loss in EVs occurs during braking, where kinetic energy is typically dissipated as heat in traditional friction-based braking systems.

In conventional braking systems, the vehicle's kinetic energy is converted into thermal energy through friction between brake pads and discs or drums. Although this method is reliable and widely used, it results in significant energy wastage and increased wear and tear of mechanical components. This not only reduces system efficiency but also increases maintenance costs and shortens the lifespan of braking parts. These limitations highlight the need for a more efficient braking approach that can conserve energy while maintaining vehicle safety and performance.

The system integrates mechanical, electrical, and electronic components to achieve controlled energy conversion and storage. Power electronic devices such as MOSFETs, rectifiers, and DC-DC converters are used to regulate and condition the recovered energy before it is fed back into the battery. Additionally, a control mechanism ensures smooth switching between driving and braking modes, allowing the system to operate efficiently under different driving conditions without affecting vehicle stability.

Overall, the regenerative braking system plays a crucial role in enhancing the performance and sustainability of electric vehicles. By recovering energy that would otherwise be lost, it not only improves energy efficiency but also reduces mechanical wear and environmental impact. This technology represents an important step toward the development of smarter, greener, and more energy-efficient transportation systems for the future.

II. AIM AND OBJECTIVES

Aim:

The main aim of the regenerative braking system in electric vehicles is to design and develop an efficient energy recovery mechanism that converts the kinetic energy of the vehicle during braking into electrical energy, which can be stored back in the battery system. This aims to improve overall energy efficiency, extend driving range, and reduce energy wastage in conventional braking systems.

Objectives:

The primary objectives of the proposed regenerative braking system in electric vehicles are as follows:

1. Energy Conversion: To design a system that effectively converts kinetic energy into electrical energy during braking instead of dissipating it as heat.

2. Efficiency Improvement: To enhance the overall energy efficiency of electric vehicles by recovering and reusing braking energy.

3. Dual-Mode Motor Operation: To implement a dual-mode operation of the electric motor, enabling it to function as both a motor during driving and a generator during braking.

4. Control Mechanism: To develop a control mechanism using electronic components such as MOSFETs and relays for smooth switching between driving and regenerative braking modes.

5. Power Conditioning: To ensure proper power conditioning using rectifiers, capacitors, and DC-DC converters for safe and efficient battery charging.

6. Reduced Mechanical Wear: To minimize wear and tear of mechanical braking components, thereby increasing their lifespan and reducing maintenance costs.

7. Enhanced Vehicle Performance:

III. LITERATURE SURVEY

Regenerative braking systems have been extensively explored as a key technology for improving the energy efficiency of electric and hybrid vehicles. Traditional braking systems rely on friction between brake pads and discs to slow down or stop the vehicle, which leads to the complete conversion of kinetic energy into heat. This energy is wasted and cannot be reused, resulting in lower overall system efficiency. Literature consistently highlights this limitation as one of the major drawbacks of conventional braking systems and emphasizes the need for energy recovery-based alternatives.

Research in electric traction systems shows that electric motors possess the inherent capability to operate in two modes: motoring mode and generating mode. In motoring mode, electrical energy from the battery is converted into mechanical energy to drive the wheels. In generating mode, the process is reversed, allowing mechanical energy from the rotating wheels to be converted back into electrical energy. This dual functionality forms the fundamental principle of regenerative braking systems and has been widely adopted in modern electric vehicle designs.

Studies related to power electronics emphasize the importance of energy conditioning during regenerative braking. The electrical energy generated by the motor cannot be directly stored in the battery due to variations in voltage and current characteristics. Therefore, components such as rectifiers, DC-DC converters, MOSFET switches, and filtering capacitors are used to regulate and stabilize the energy before storage. Literature also highlights that efficient power conversion is critical to minimize losses and ensure safe battery charging during regenerative operation.

Control system research in regenerative braking focuses on managing the transition between mechanical braking and regenerative braking. It is widely noted that regenerative braking alone is insufficient at low speeds or in emergency conditions, making hybrid braking systems essential. Therefore, intelligent control strategies are required to balance braking force between regenerative and friction systems based on vehicle speed, battery state of charge, and load conditions. This ensures safety while maximizing energy recovery efficiency.

Another important area discussed in literature is the impact of regenerative braking on battery performance and lifespan. While regenerative systems improve energy efficiency, improper charging can lead to issues such as overvoltage, thermal stress, and reduced battery life. Hence, proper battery management systems are essential to regulate charging current and maintain safe operating conditions. Literature also suggests that controlled regenerative charging can improve battery cycling efficiency by reducing deep discharge cycles.

Mechanical system studies indicate that regenerative braking reduces the dependency on friction-based braking components, thereby decreasing wear and tear on brake pads and discs. This results in lower maintenance costs and improved system durability. However, it is also noted that mechanical brakes remain essential as a backup system to ensure complete stopping capability under all driving conditions.

Overall, literature strongly supports the integration of regenerative braking systems in electric vehicles as an effective solution for improving energy efficiency and sustainability. While challenges such as conversion losses, control complexity, and battery limitations still exist, continuous advancements in power electronics, control strategies, and energy storage systems are making regenerative braking more efficient, reliable, and widely applicable in modern transportation systems.

IV. RESOURCES / COMPONENTS USED

Sr. No.	Component Name	Specification / Description	Function in System
1	Battery	48V / 12Ah Lithium-ion	Supplies power to DC motor during driving and stores regenerated energy during braking.
2	DC Motor	500W, 24–48V	Converts electrical energy to mechanical energy (driving mode) and vice versa (generator mode).
3	Controller Circuit	MOSFET-based PWM Control	Manages motor operation, throttle input, and switching between drive and regenerative modes.
4	Rectifier	Bridge Diode Configuration	Converts AC output from generator mode to DC for battery charging.
5	Filter Capacitors	470µF / 100V	Smoothens DC voltage by reducing ripple after rectification.
6	DC-DC Converter	Step-down type, 48V → 12V	Regulates voltage for safe battery charging and auxiliary circuits.
7	Throttle Sensor	Hall-effect type	Controls motor speed during driving mode.
8	Brake Switch	Mechanical / Hall Sensor	Detects braking action and triggers regenerative mode.
9	Monitoring Unit	LCD / IoT-based	Displays system parameters such as voltage, current, and battery status.
10	Wheels & Shaft Assembly	Coupled with Motor	Provides mechanical motion and kinetic energy recovery during braking.

V. METHODOLOGY

The proposed regenerative braking system is developed through a structured, multi-phase approach emphasizing energy flow design, control logic implementation, and conversion efficiency. The methodology ensures seamless transition between driving and braking modes while maintaining system stability and energy recovery efficiency.

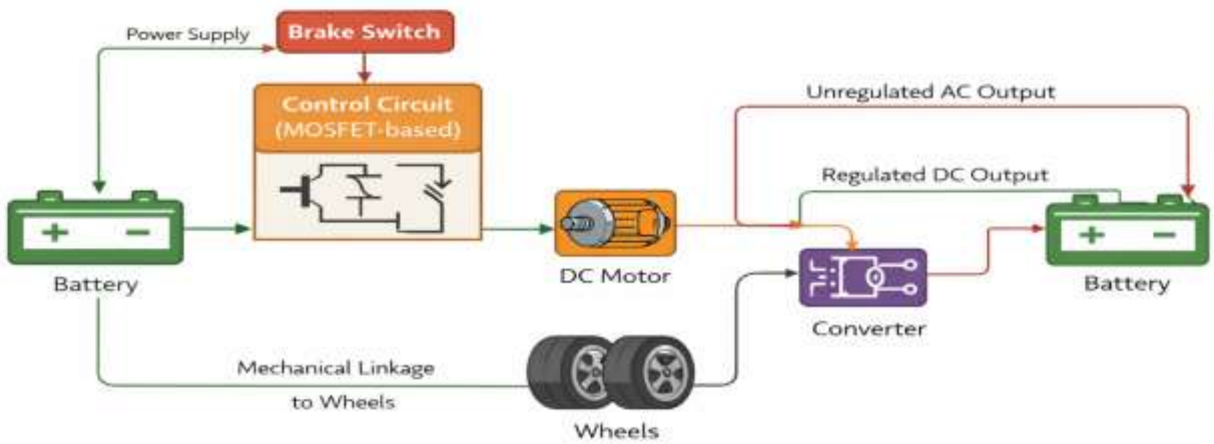

Fig.5.1 System Architecture of Regenerative Braking System.

A. Energy Flow Design

The initial stage involves designing the basic energy flow structure of the system. The electric vehicle operates in two distinct modes — **Driving Mode** and **Braking Mode**. In **Driving Mode**, electrical energy stored in the battery is supplied to the DC motor through a MOSFET-based control circuit. The motor converts electrical energy into mechanical energy, driving the wheels. Speed and torque are regulated using a potentiometer-based throttle input, ensuring smooth acceleration and optimal power usage.

B. Control Mechanism Implementation

The second stage focuses on the control logic that governs the transition between driving and regenerative braking modes. The control circuit uses **MOSFETs, relays, and brake switch signals** to manage switching operations. When the brake is applied, the circuit disconnects the motor from the battery and reconfigures the connections to enable reverse energy flow. This ensures the motor safely operates as a generator without disturbing system stability or causing electrical transients.

C. Energy Conversion Process

The third stage deals with the conversion and conditioning of the recovered energy. During braking, the kinetic energy of the rotating wheels is transmitted back to the DC motor, which functions as a generator. According to electromagnetic induction principles, this mechanical motion is converted into electrical energy. However, the generated output is unregulated and may contain AC components or voltage fluctuations, requiring further processing before it can be stored.

D. Power Conditioning and Storage

In this stage, the generated electrical energy is processed for safe storage. The unregulated AC output from the generator is first converted into DC using a **bridge rectifier**. A **filter capacitor** smoothens the DC voltage by reducing ripple. The regulated DC output is then passed through a **DC-DC converter**, which ensures proper voltage levels for battery charging. This step is crucial for maintaining battery health and maximizing energy recovery efficiency.

E. System Testing and Validation

The final stage involves testing and validating the system performance under various operating conditions. Parameters such as **voltage, current, braking efficiency, and energy recovery rate** are monitored using sensors and a display unit. The system is evaluated for smooth transition between modes, minimal energy loss, and stable operation. Experimental results confirm that the regenerative braking system effectively recovers a significant portion of kinetic energy, thereby improving overall vehicle efficiency.

VI. FLOWCHART

The system initiates by performing the initialization of all integrated modules. Subsequently, it executes continuous monitoring of the vibration sensor to detect abnormal events. Upon identification of an accident, the system acquires the corresponding GPS coordinates, which are simultaneously rendered on the LCD display for real-time visualization. Furthermore, an emergency alert containing the precise location details is transmitted via the GSM communication module to designated recipients, thereby ensuring timely assistance.

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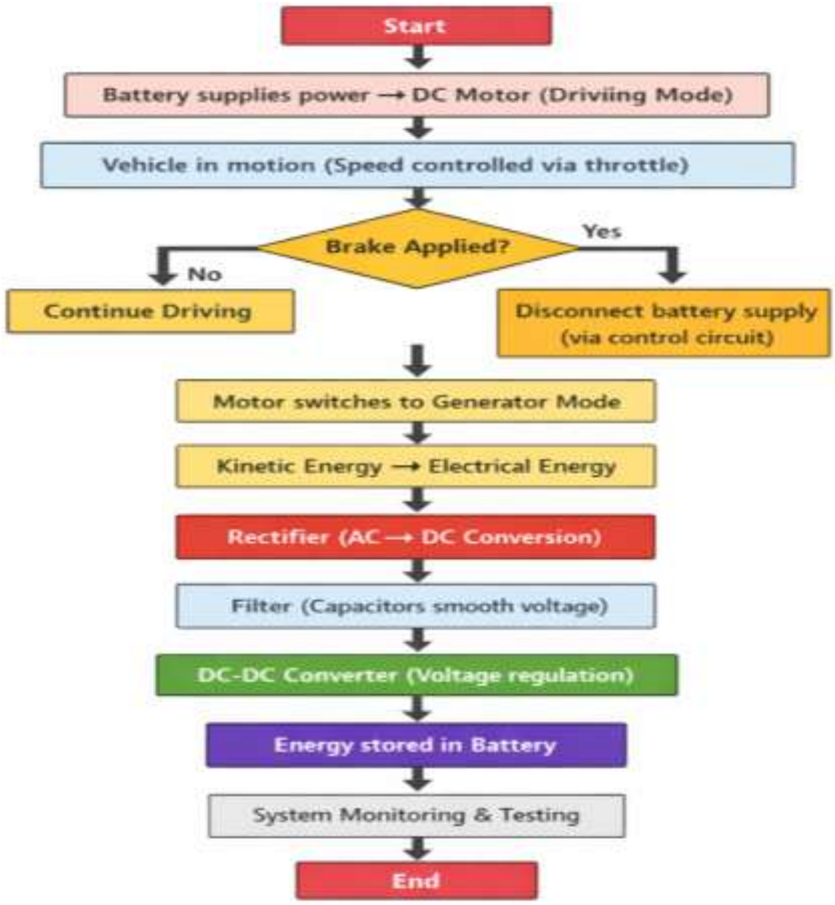

Fig.6.1. Flowchart of the Regenerative Braking proposed System.

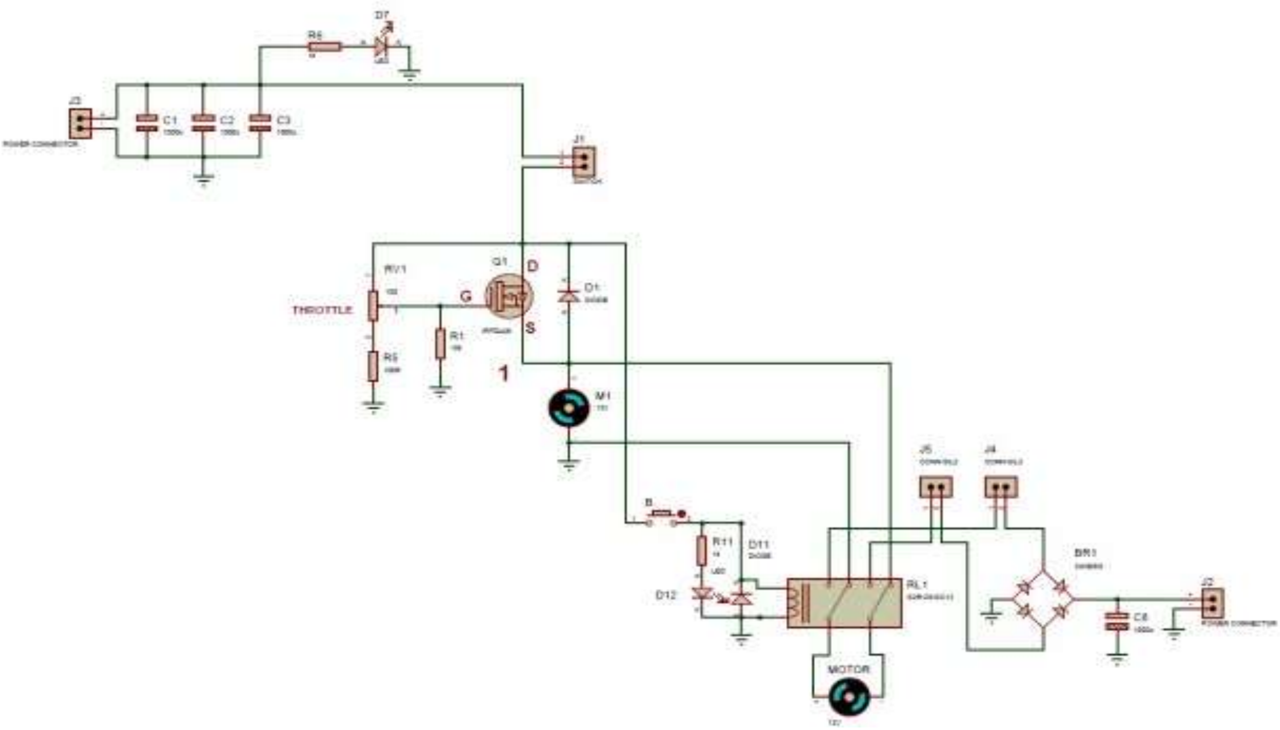

Fig.6.2. Circuit diagram of the Regenerative Braking proposed System.

VII. RESULT AND DISCUSSION

The implementation of the regenerative braking system in electric vehicles demonstrated successful energy recovery during braking conditions. It was observed that when the brake was applied, the DC motor effectively switched from motoring mode to generating mode, confirming proper dual-mode operation. In this state, the kinetic energy of the rotating wheels was successfully converted into electrical energy, validating the working principle of regenerative braking.

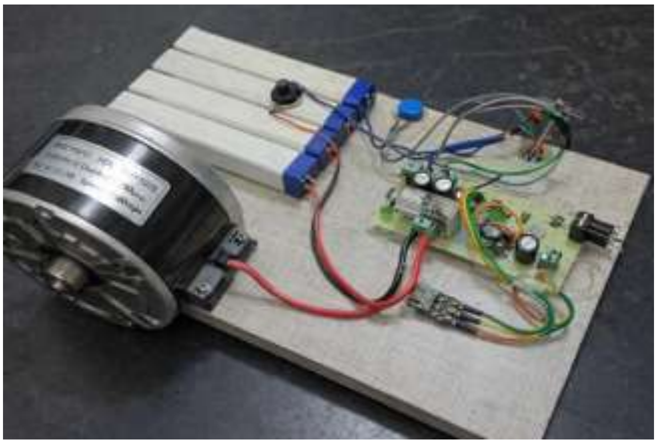

Fig. 7.1 **Model Setup**

The generated electrical energy was processed through the bridge rectifier, filter capacitors, and DC-DC converter, ensuring a stable and regulated output. This conditioned energy was successfully stored back into the battery, resulting in partial recharging during braking cycles. The system exhibited measurable improvement in battery voltage during repeated braking operations, indicating effective energy recovery.

Experimental observations revealed a noticeable improvement in overall energy efficiency compared to conventional braking systems, where kinetic energy is completely dissipated as heat. In the proposed system, a portion of this energy was reused, leading to better energy utilization and reduced dependency on external charging sources. Additionally, the load on friction braking components was reduced, resulting in lower wear and improved mechanical durability.

The control system, comprising MOSFETs, relays, and brake switch circuitry, performed efficiently by ensuring smooth and accurate switching between driving and braking modes. No significant delay or instability was observed during operation, confirming the reliability of the switching mechanism. Overall, the system successfully achieved its objectives of energy recovery, efficiency improvement, and partial battery charging, validating the feasibility of regenerative braking in electric vehicle applications.

VIII. CONCLUSION AND FUTURE SCOPE

The regenerative braking system for electric vehicles successfully demonstrates an effective method of recovering kinetic energy that is otherwise wasted in conventional braking systems. By converting this energy into electrical form and storing it in the battery, the system significantly improves the overall energy efficiency of electric vehicles. This makes the technology highly beneficial for extending driving range and optimizing energy usage. The integration of electrical, electronic, and control components such as DC motors, MOSFETs, relays, rectifiers, and converters ensure smooth and reliable operation. The dual functionality of the motor as both a drive unit and a generator forms the core of the system, enabling efficient energy conversion during braking conditions.

In conclusion, the regenerative braking system is a highly effective and practical solution for modern electric vehicles. It enhances energy efficiency, supports sustainable transportation, and contributes to environmental conservation. With further advancements in power electronics, battery technology, and control systems, the performance and efficiency of regenerative braking systems are expected to improve even further in future applications.

REFERENCES

[1] C. Qiu and G. Wang, "New evaluation methodology of regenerative braking contribution to energy efficiency improvement of electric vehicles," *Energy Conversion and Management*, vol. 119, pp. 389–398, 2016. [Online]. Available: https://doi.org/10.1016/j.enconman.2016.04.058 (doi.org in Bing)

[2] J. W. Dixon, M. Ortúzar, and E. Wiechmann, "Regenerative braking for an electric vehicle using ultracapacitors and a buck-boost converter," *IEEE Transactions on Industrial Electronics*. [Online]. Available: https://ieeexplore.ieee.org/document/1184975

3] M. T. X. Wen and D. T. K. Tien, "Analysis of a hybrid mechanical regenerative braking system," *MATEC Web of Conferences*, vol. 152, pp. 1–15, 2018. [Online]. Available: https://doi.org/10.1051/matecconf/201815201015 (doi.org in Bing)

[4] Q. Y. Zhang and J. Huang, "Research on regenerative braking energy recovery system of electric vehicles," *Journal of Interdisciplinary Mathematics*, vol. 21, pp. 1321–1326, 2018. [Online]. Available: https://doi.org/10.1080/09720502.2018.1477070 (doi.org in Bing)

[5] W. Zhao, G. Wu, C. Wang, L. Yu, and Y. Li, "Energy transfer and utilization efficiency of regenerative braking with hybrid energy storage system," *Journal of Power Sources*, vol. 427, pp. 174–183, 2019. [Online]. Available: https://doi.org/10.1016/j.jpowsour.2019.04.084 (doi.org in Bing)

[6] Y. Zhang et al., "An effective regenerative braking strategy based on PSO and ACO for electric vehicles," in *Proc. IEEE ISIE*, 2019. [Online]. Available: https://ieeexplore.ieee.org/document/8781425

[7] L. Qi et al., "An electro-mechanical braking energy recovery system based on coil springs," *Energy*, vol. 200, 2020. [Online]. Available: https://doi.org/10.1016/j.energy.2020.117523 (doi.org in Bing)

[8] D. W. Zeh et al., "Maximizing energy harvesting in electric vehicles through optimal regenerative braking utilization," Ph.D. dissertation, Univ. of Nevada, Reno, 2020. [Online]. Available: https://scholarworks.unr.edu/handle/11714/7432 (scholarworks.unr.edu in Bing)

[9] Y. Xiong et al., "Decoupled regenerative braking system for electric city bus," *Mathematical Problems in Engineering*, 2020. [Online]. Available: https://doi.org/10.1155/2020/8859346 (doi.org in Bing)

[10] M. Kane, "Global plug-in electric car sales doubled in February 2022," *InsideEVs*, 2022. [Online]. Available: https://insideevs.com/news/572688/global-plugin-car-sales-february-2022 (insideevs.com in Bing)

[11] C. C. Chan, "The state of the art of electric and hybrid vehicles," *Proceedings of the IEEE*, vol. 90, no. 2, pp. 247–275, 2002. [Online]. Available: https://doi.org/10.1109/5.989873

[12] J. Larminie and J. Lowry, *Electric Vehicle Technology Explained*. Wiley, 2012. [Online]. Available: https://www.wiley.com/en-us/Electric+Vehicle+Technology+Explained-p-9780470090695 (wiley.com in Bing)

[13] I. Husain, *Electric and Hybrid Vehicles: Design Fundamentals*. CRC Press, 2011. [Online]. Available: https://doi.org/10.1201/9781420054002 (doi.org in Bing)

[14] S. Ehsani, Y. Gao, and A. Emadi, *Modern Electric, Hybrid Electric, and Fuel Cell Vehicles*. CRC Press, 2018. [Online]. Available: https://doi.org/10.1201/9780429496405 (doi.org in Bing)

[15] A. Emadi, K. Rajashekara, S. Williamson, and S. Lukic, "Topological overview of hybrid electric and fuel cell vehicles," *IEEE Transactions on Vehicular Technology*, 2005. [Online]. Available: https://ieeexplore.ieee.org/document/1495855

[16] J. Moreno, M. E. Ortuzar, and J. W. Dixon, "Energy management system for a hybrid electric vehicle," *IEEE Transactions on Industrial Electronics*, 2006. [Online]. Available: https://ieeexplore.ieee.org/document/1642629

[17] L. Xu, J. Hua, and X. Chen, "Regenerative braking control strategy for electric vehicles," *IEEE Transactions on Vehicular Technology*, 2011. [Online]. Available: https://ieeexplore.ieee.org/document/5741167

[18] H. Gao, Y. Chen, and X. Deng, "Optimal control of regenerative braking system," *IEEE Transactions on Control Systems Technology*, 2013. [Online]. Available: https://ieeexplore.ieee.org/document/6231166

[19] S. Zhang and C. Mi, "A review of regenerative braking techniques," *IEEE Transactions on Vehicular Technology*, 2014. [Online]. Available: https://ieeexplore.ieee.org/document/6786390

[20] M. Ehsani, K. M. Rahman, and H. A. Toliyat, "Propulsion system design of electric and hybrid vehicles," *IEEE Transactions on Industrial Electronics*, 1997. [Online]. Available: https://ieeexplore.ieee.org/document/650338

[21] Y. He, M. Chowdhury, and P. Pisu, "Optimization of energy recovery in regenerative braking," *Applied Energy*, 2012. [Online]. Available: https://doi.org/10.1016/j.apenergy.2012.01.074 (doi.org in Bing)

[22] B. Wang, X. Liu, and Y. Wang, "Control strategies of regenerative braking for EVs," *Energy Procedia*, 2017. [Online]. Available: https://doi.org/10.1016/j.egypro.2017.03.118 (doi.org in Bing)