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REVIEW ARTICLE

A review of regenerative brake control strategies for electric vehicles under varying road conditions

Qianqian Li[1,2], P.M. Heerwan[1,3]* and M.I. Ishak[1]

[1]Faculty of Mechanical and Automotive Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, 26600 Pekan, Pahang, Malaysia
[2]College of Vehicle Engineering, Huanghe Jiaotong University, Jiaozuo, Henan, 454000, China
[3]Center for Automotive Engineering, Universiti Malaysia Pahang Al-Sultan Abdullah, 26600 Pekan, Pahang, Malaysia

Abstract - Regenerative braking system (RBS) is a technology that converts a vehicle's kinetic energy into electrical energy during braking, significantly improving energy efficiency, increasing driving range, and reducing emissions to contribute to environmental sustainability. However, RBS has certain limitations and disadvantages, including the complexity of its components, high implementation costs, space constraints, and compatibility with other vehicle components. Additionally, the effectiveness of RBS is influenced by external factors such as temperature variations, road conditions, and driver behaviour. The objective of this paper is to discuss regenerative brake control strategies on various road surfaces. In this review, the priority of journal and conference proceedings on the regenerative topic over the past 10 years has been examined. To optimise energy recovery, researchers have proposed various regenerative braking control strategies, including fuzzy logic, proportional-integral-derivative, fractional-order proportional–integral–derivative, model predictive control, and sliding mode control. The significance of these control strategies for the future of electric vehicles cannot be overstated, underscoring the need for further research and development in this area. Furthermore, the study of regenerative brake control strategies in slippery road conditions needs improvement, as controlling wheel lock while simultaneously enhancing regenerative brake energy recovery is complex. The review found that the regenerative brake strategy performs best on dry asphalt. Integrating RBS with the control system can prevent skidding, thereby improving braking performance. These research findings underscore the importance of regenerative brake control strategies for electric vehicles.

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1. Introduction

The automotive industry has experienced tremendous economic growth; however, it has also created global challenges, including energy shortages, environmental pollution, greenhouse gas emissions, road accidents, and traffic congestion [1]-[5]. To mitigate some of these effects, researchers are currently developing electric vehicles (EVs) with zero-emission properties. EVs are distinguished by their ability to reduce greenhouse gas emissions and air pollution, thereby promoting environmental sustainability [6]-[8]. They are also more energy-efficient than internal combustion engine vehicles, as they use energy more effectively to propel them [9]-[10]. As they use electrical energy, EVs help reduce reliance on finite fossil fuel reserves, thereby improving energy security [11]-[12]. Moreover, research on EV infrastructure has accelerated battery development, charging, and the integration of smart grids, thereby advancing technology [13]. The widespread adoption of EVs can also boost economic growth by creating jobs in the renewable energy and automotive industries, thereby facilitating sustainable development [14]-[15]. EVs are powered by electric motors that draw electricity from rechargeable batteries [16]. The motor converts electrical power into mechanical power to drive the vehicle, resulting in zero tailpipe emissions and reduced environmental impact [17]. EVs have many benefits, such as much lower carbon emissions, which create a more favourable energy environment [18]. Moreover, EVs use advanced battery technologies that can be charged with renewable energy, are more efficient, reduce lifecycle emissions, and produce less heat through regenerative braking [19]. EVs can also mitigate the risks posed by volatile oil prices and geopolitical conflicts by reducing reliance on foreign oil and diversifying transportation energy sources [20]. They play a vital role in shifting to a more secure, sustainable, and resilient energy system through clean energy sources and innovative technologies [21]. Moreover, EVs are less expensive to operate than traditional internal combustion engine vehicles because they require less maintenance, thereby reducing long-term costs [21]. EVs also operate more quietly because they lack internal combustion engines [22]. Their electric motors provide smooth, rapid acceleration without gear shifting, due to the instant torque delivery [23]. Furthermore, regenerative braking in EVs enhances the driving experience and has the potential to reduce noise pollution in urban areas [21], [24]-[26].

Despite their advantages, EVs also have drawbacks. These include energy density, power density, and battery lifespan, which can limit driving range compared to traditional vehicles, making them less practical for long-distance travel [17], [21]. Additionally, the upfront cost of purchasing an EV can be higher than that of traditional vehicles due to the cost of expensive battery components, though this is offset by lower long-term operating costs [19], [21]. Furthermore, battery production involves mining raw materials and energy-intensive manufacturing processes. Moreover, the disposal of EV batteries can pose environmental challenges if not managed sustainably [19], [21]. Given the significant value of

***CORRESPONDING AUTHOR P.M. Heerwan** | | ✉ mheerwan@umpsa.edu.my

regenerative braking technology for energy conservation and driving optimisation in electric vehicles, and the complex and variable nature of real-world road conditions, this study aims to comprehensively summarise the current state of research on regenerative brake control strategies for electric vehicles. This review systematically classifies and analyses various control strategies, discusses how diverse road surfaces affect the operational performance of regenerative braking systems, and summarises the technical advantages, limitations, and applicable scenarios of existing control methods. Furthermore, this paper aims to identify the key technical challenges that limit the stable and efficient operation of regenerative braking systems under variable road conditions. Ultimately, it provides a clear reference and feasible development direction for the optimisation and engineering application of regenerative brake control strategies, with the purpose of improving energy recovery efficiency, ensuring braking safety, and promoting the further popularisation and technical upgrading of electric vehicles.

2. Regenerative Brake System

One of the key advantages of EVs is the regenerative braking system (RBS) [27]-[30]. RBS is a technology designed to recover and store kinetic energy dissipated during vehicle braking processes [31]-[32]. Figure 1 represents a simplified schematic of the energy flow of an EV with RBS [33]. When the brakes are applied, the kinetic energy produced by the wheel braking is transmitted through the transmission system to the motor. The motor then converts this kinetic energy into electrical energy to charge the battery.

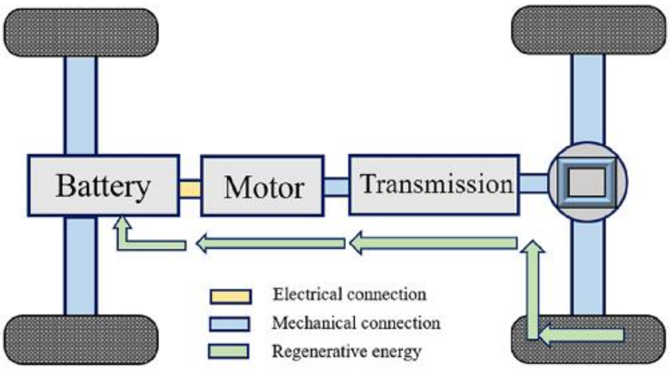

Figure 1. Energy flow of EV with RBS [33]

2.1 Regenerative Braking System Components

The RBS generally comprises mechanical and electrical components, as well as a control system (Figure 2) [34]. To ensure energy recovery, braking stability, and comfort during braking, the brake recovery controller receives the brake signal from the driver when the pedal is depressed. Subsequently, the controller employs an appropriate management strategy to oversee the brake, motor, and battery, allowing the wheel's braking energy to be channelled through the motor and into the battery.

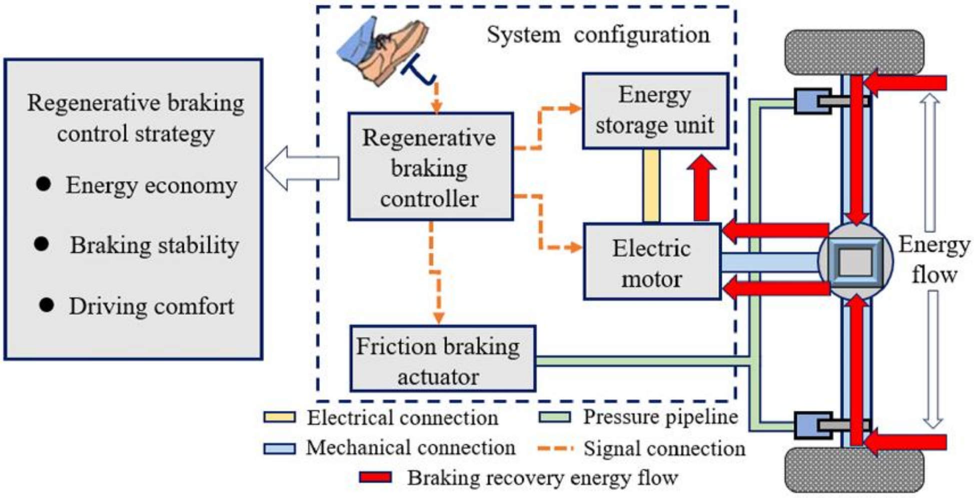

Figure 2. Logic framework of regenerative braking for EVs [33]

The RBS integrates various mechanical components, including coil springs for energy regeneration, a transmission mechanism with interconnected gears, and a control mechanism with an electromagnetic clutch and pawl component [34]. On the electrical side, the RBS comprises an ultracapacitor or battery as an energy storage system (ESS) [35]-[36] and a motor-generator unit [37]-[38] that work in conjunction [32], [39]-[41]. Furthermore, the kinetic energy recovery system uses a power converter to connect the ultracapacitor or battery to the motor [42]-[43]. This is achieved using an advanced control system that monitors vehicle and road conditions and driver braking requirements, and identifies the most appropriate ESS to operate during braking [32]. All these elements work together to increase energy efficiency, driving range, and overall braking performance in EVs [44].

The integration of anti-lock braking systems (ABS) and brake-by-wire into RBS is a key requirement for the practical implementation of this system [45]. Two fundamental control requirements must be met for ABS integration: first, a fast transition between regenerative and friction braking to electrically lock the wheels; second, coordinated control of energy recovery efficiency and anti-lock braking performance through slip-ratio closed-loop control. This is necessary to prevent regenerative braking from interfering with ABS, which modulates braking force, such as temporarily disabling regenerative braking during ABS activation to allow the wheel slip ratio to be accurately controlled [46]. The braking commands sent to the actuator by brake-by-wire systems (e.g., electrohydraulic braking, electromechanical braking) are delivered as electronic signals, enabling the dynamic coupling of energy recovery and mechanical braking. Their electrohydraulic or electromechanical actuators allow precise adjustment of friction braking force, enabling the collaborative distribution of torque between electromechanical and regenerative braking. An example application scenario is the prioritisation of regenerative braking in low-speed situations and the use of brake-by-wire systems to quickly provide braking force in high-speed emergency braking events [47]. To complete the process of effective integration, three major technical issues must be overcome: First, consistency of feel in the braking system; in other words, the introduction of a pedal force feedback compensation system to counteract the perceptual differences caused by regenerative braking engagement. Second, assurance of functional safety, which implies hardware redundancy (e.g., brake-by-wire systems use a second motor to actuate the brakes, and energy recovery modules have independent power supplies) and fault-tolerant control measures (e.g., brake-by-wire systems provide full braking authority in the event of regenerative braking failure). Third, adherence to the ISO 26262 functional safety standard, which is the general standard used to verify system reliability [47].

2.2 Regenerative Braking System Functionality

The main aim of the RBS is to harvest the energy lost during braking [48]-[49], store it in an ESS, and reuse it for other purposes, including recharging batteries [50] or supplying additional propulsion. The major functional features of RBS include energy recovery, braking performance, extended driving range, and control strategy. The first application of RBS was in hybrid electric vehicles (HEVs), which had constraints on motor torque and transmission efficiency, although it has potential for broader future applications. RBS has been used in HEVs to reduce brake energy consumption, thereby improving vehicle fuel efficiency when employing energy management methods. However, the energy recovery efficiency of HEVs is constrained by motor torque and gearbox efficiency. On the other hand, in plug-in electric vehicles (PEVs), the RBS torque can be fully harnessed because the vehicle's power is exclusively provided by the electric motor. PEVs can be categorised by the layout of their motors. The single-axle integrated-drive vehicle (Figure 3) simplifies RBS design by providing straightforward transmission chains. In this setup, the energy recovery efficiency is influenced by friction-brake intervention on the drive shaft, while the RBS focuses on the torque distribution between the driveshaft and the driven shaft. Enabling four-wheel regenerative braking and achieving greater energy recovery efficiency for a dual-motor PEV can be achieved by controlling the front and rear motors and the axles' differentials. Furthermore, four-wheel independent drive vehicles can achieve precise, adaptable motor control, which has increasingly become a focal point of EV research.

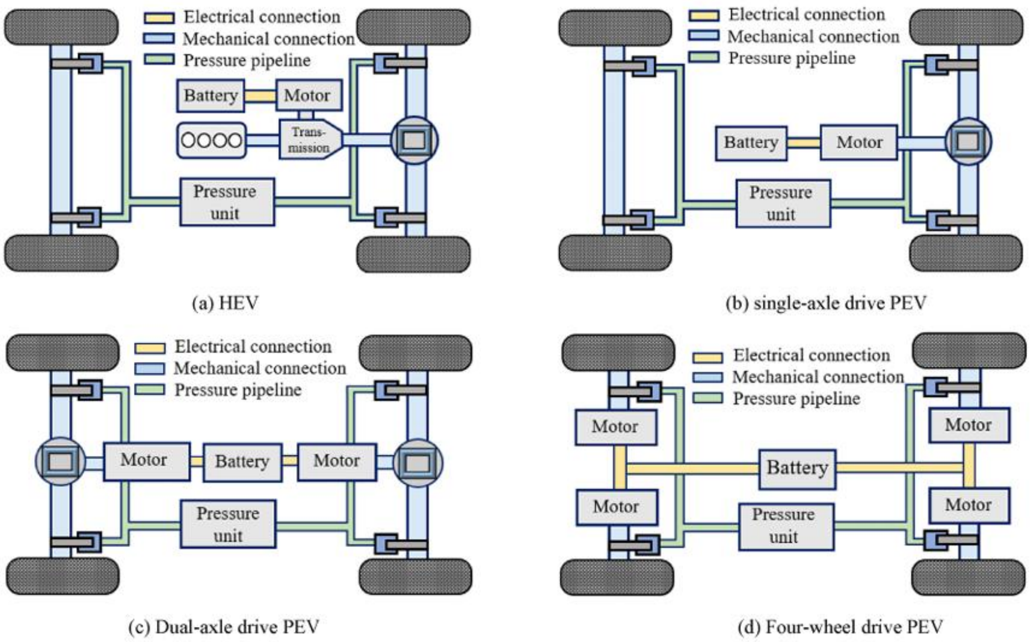

Figure 3. RBS application in EV: (a) HEV, (b) single-axle drive PEV, (c) dual-axle drive PEV, and (d) four-wheel drive PEV [33]

The RBS captures and stores energy that would otherwise be dissipated as heat during conventional braking, thereby enhancing overall energy efficiency [51]-[54]. This system successfully combines regenerative and friction braking systems to enhance brake performance, providing better control and stability during deceleration manoeuvres [54]-[55]. This means that the recovered energy can be used to drive the car, reducing battery dependency, and as a result, increasing the vehicle's range [47]. In addition, the RBS features a sophisticated control strategy, carefully crafted to maximise energy recapture, enhance braking stability, and improve driving comfort across a variety of braking conditions. This guarantees the efficient operation of the system and its integration with other vehicle systems [56]-[57]. The effective operation of a brake energy recovery system depends on the strong dynamic interconnection between the brake control system and the vehicle's subsystems. Of these interactions, the battery subsystem has a decisive limiting effect on the regenerative braking power ceiling, as reflected in its state of charge (SOC) and state of health (SOH) metrics. In particular, SOC-based control logic should be introduced to prevent overcharging at low SOC and energy overflow at high SOC. At the same time, the dynamic response properties of regenerative braking torque are directly controlled by variations in the battery's internal resistance [58].

The speed-torque characteristic and efficiency map of the traction motor, as the central energy-conversion element, essentially define the system's energy-recovery potential. Operational strategies are typically adjusted to take advantage of the motor's high-efficiency operating region. The motor has better energy conversion efficiency at low speeds, and regenerative braking should be prioritised. Conversely, low-speed conditions require a trade-off between regenerative efficiency and braking performance to achieve both energy recovery efficacy and braking safety. The thermal management subsystem is intrinsically coupled to the brake control system [59]. The thermodynamic loads imposed throughout the braking cycles affect the three key system functions: battery charge–discharge efficiency, motor operating characteristics, and friction braking stability [60]. The thermal management subsystem adjusts braking intensity by managing heat dissipation and transmits real-time component temperature information to the central control system. This temperature feedback enables active control of braking force distribution to eliminate the risk of thermal degradation. The interactions among the battery, motor, and thermal management subsystems determine the power–time profile of brake energy recovery. Three fundamental performance factors are directly controlled by this integrated coupling: vehicle braking dynamics, energy recovery efficiency, and system operational safety. Combined, these subsystems constitute a complex yet hierarchically structured system-level interaction mechanism that underpins the entire functionality of the brake energy recovery system.

3. Control Strategy for the Regenerative Braking System

Efficient control strategies are essential for optimising RBS performance in EVs [61]-[63]. A well-designed control strategy can enhance regenerative braking efficiency [64]-[66], ensure stable braking processes, improve braking comfort [67-69], and enhance battery performance [70]-[72].

3.1 Proportional-Integral-Derivative Control

The proportional-integral-derivative (PID) control, which stands for proportional–integral–derivative, is a widely used feedback control system in engineering [73]-[78]. It regulates the system's response by adjusting the input based on the error between the required set-point and the actual response [79]-[81]. The proportional (P) term responds to the current error, the integral (I) term deals with the accumulation of past errors, and the derivative (D) term predicts future errors based on the current rate of change [82]-[83]. The P term determines the reaction to the current error, the I term eliminates residual error by accumulating past errors, and the D term anticipates future errors to provide a more stable control response [84]-[85]. Thus, PID controllers not only eliminate steady-state errors but also maintain voltage regulation, ensure system stability, respond to dynamic changes [88], and prevent voltage violations under different operating conditions [87]. Duong et al. [85] used PID controllers to control a simulation model of RBS based on driving cycles such as FTP75, NEDC, EUDC, and ECE-R15. The results showed that the recovered energy can reach 4.8 kWh, depending on the initial deceleration velocity, the acceleration variation, and the duration and distance of the driving cycle [88] A fractional-order proportional–integral–derivative (FOPID) controller applies the use of fractional-order calculus to control applications. It builds upon the traditional PID controller by incorporating fractional calculus, making it more flexible and offering better performance in system control. FOPID controller parameters are optimised through the Wolf-based Elephant Herding Algorithm, a hybrid optimisation algorithm that combines the ideas of Grey Wolf Optimisation and Elephant Herding Optimisation. Unlike the classical PID controller [89], the FOPID controller offers more sophisticated control features enabled by fractional calculus, enabling superior performance and flexibility in regulating complex systems [90]-[91]. Aboshosha et al. [87] used an FOPID controller to model a BLDC motor, and the results show that FOPID controllers provide superior performance compared to PID controllers. It highlights the reality that the FOPID control system is applied within the metaheuristic optimisation system for EVs, and a statistical comparison with PID control reveals its superiority [92].

PID control schemes have significant robustness issues under operating conditions with uncertainty or component faults. One of the main uncertainties arises from variations in the battery subsystem, such as a low SOC directly limiting regenerative braking power and high internal resistance delaying the regenerative braking torque response [93]. Such battery-related disturbances amplify the fundamental drawbacks of PID control, where the P term is prone to overshoot in the braking force output, and the accumulation of error terms in the I term causes the actual distribution of braking forces to deviate from nominal optimal values. PID control performance is also degraded by sensor noise. The D term amplifies sensor signal distortion, leading to high-frequency oscillations in braking torque and negatively affecting both ride comfort and braking stability. At the same time, persistent control offsets arise from the long-term integration of noise elements in the I term, further degrading the accuracy of braking force control. One of the critical fault situations affecting PID control reliability is sensor performance degradation. The PID controller will detect distorted state-feedback signals, reducing stability margins as it adjusts based on an incorrect estimate of the deviation. Such anomalies can manifest as physical performance risks, such as increased braking range, or even as a temporary system malfunction [93]. A synergistic optimisation framework is required to overcome these robustness limitations, incorporating three fundamental technical measures: adaptive PID parameter tuning (to dynamically adjust to different operating conditions), advanced filtering algorithms (to suppress sensor noise), and fault-tolerant control strategies (to overcome sensor or component degradation). This combined strategy enhances PID control performance under complex conditions, ensuring the stability and reliability of the brake energy recovery system.

3.2 Fuzzy Control

Fuzzy logic control is a control system that uses fuzzy logic to model the relationship between input and output variables [94]-[95]. Its main elements are fuzzy variables, fuzzification, knowledge bases, reasoning machine, and defuzzification [96]-[97]. The fuzzy controller determines the proportion of regenerative braking force to total braking force as a function of vehicle speed, state of charge, and braking force [98]-[99]. The strength of fuzzy logic control and its ability to handle the nonlinear dynamics of complex systems have earned it popularity in applications across control systems, robotics, and artificial intelligence [100]. Lv et al. [79] proposed an interval type-2 fuzzy logic controller to determine the optimal total braking torque to achieve optimal slip rate and optimal energy recovery efficiency under various and complex road conditions. The simulation findings affirm that this controller can achieve the ideal regenerative braking energy recovery efficiency on both split- and joint-μ road surfaces, enhance slip-rate control, and exhibit outstanding robustness [101]. The fuzzy neural network combines fuzzy logic and neural networks to improve the performance of control systems [102]. It uses a self-tuning algorithm to optimise the membership function parameters, thereby providing efficient energy recovery during braking. This controller increases brake energy recovery by distributing electric and hydraulic braking forces based on braking intensity, vehicle speed, and battery SOC. The fuzzy neural network control method has been shown to achieve excellent energy recovery efficiency across different operating conditions [103]. It accounts for the effect of battery SOC on regenerative braking performance, vehicle speed, and brake intensity, and constructs a three-input single-output fuzzy controller to allocate hydraulic and electric braking forces. The preference for fuzzy neural networks stems from their robustness to external shocks and parameter variations, as well as their ability to solve complex, nonlinear, and fuzzy problems [104]-[105]. To build a fuzzy neural network controller, the fuzzy controller's process is optimised using a self-tuning technique to construct membership function parameters. In NEDC and FTP-75 configurations, the brake energy recovery control strategy using fuzzy neural networks is an effective means of recovering braking energy, achieving efficiencies of 14.52% and 39.61%, respectively [106].

Fuzzy control strategies have been shown to be particularly robust in situations where the operating environment is characterised by uncertainty or component faults [107]. One of their strong points is their flexibility in the face of fluctuations in the battery subsystem, where fuzzy control, unlike model-dependent control, does not require accurate mathematical models of battery SOC and SOH. Rather, it uses adaptive regenerative braking control based on heuristic fuzzy rule bases (e.g., "low SOC reduces regenerative braking proportion"). This rule-based system is automatically immune to the overcharging risks caused by model mismatches, which is a severe drawback of the traditional PID control. Fuzzy control also exhibits strong anti-interference behaviour in the presence of sensor noise. The inherent equivalent filtering effect of fuzzifying raw sensor signals is that it reduces the influence of high-frequency noise on the distribution of braking torque. The property is a good way to reduce torque oscillation caused by the amplification of noise derivatives, a major flaw in PID control systems. When sensor performance is compromised, fuzzy control ensures braking safety through specific rule-based reasoning. For instance, the rule "large deviation between actual and target braking force enhances friction braking compensation" enables the controller to compensate for distorted state feedback signals. Fuzzy control is more adaptable to operating conditions with degraded sensor accuracy than traditional control strategies, which depend on high-precision state feedback. The main basis for these merits is the nonlinear mapping of fuzzy control, which is built on linguistic variable rules. This natural property allows brake energy recovery systems to maintain control stability and adaptive performance in a complex, dynamic operating environment, a capability superior to that of model-based control in unstructured or fault-sensitive situations.

3.3 Neural Network Control

Neural network control refers to the application of neural networks to control dynamic systems, often used across fields such as robotics, automotive systems, and industrial processes [108]. It can learn complex patterns and relationships from data, making it suitable for modelling and controlling nonlinear systems. The use of neural networks in control systems enables adaptive, intelligent decision-making, improving efficiency and reliability. Therefore, it can be utilised in the energy management system to optimise power flow between energy sources and converters, dynamically achieving optimal power distribution in EVs and enhancing overall vehicle performance [109]. Neural network controls have been successfully applied to optimise energy recovery in EVs For instance, a convolutional neural network has been used to estimate the energy or power consumption of EVs [108]. In another study [109], a regenerative energy braking scheme was proposed to transfer braking energy to hybrid energy storage (HES) devices.

Control strategies based on neural networks offer unique data-robustness benefits in operating conditions with uncertainties or component faults. A fundamental benefit of neural networks is that they can be trained to generate highresolution nonlinear mappings between battery state variables (SOC, SOH) and the regenerative braking torque requirement, either via offline training or online learning. This data-driven approach enables adaptive power distribution without relying on precise battery electrochemical models, a key limitation of traditional model-based control. Notably, even under the worst battery operating conditions (e.g., low SOC with overcharging risks, high internal resistance inducing torque response delays), neural network controllers can ensure an optimal balance between energy recovery efficiency and battery operational safety [110]. This is made possible by the acquired mapping relationship, which captures the dynamics of complex batteries and braking performance needs, which are hard to emulate with linear control frameworks. Neural network control also exhibits better anti-interference behaviour in the presence of sensor noise. The noise in sensor signals at high frequencies (e.g., electromagnetic interference with wheel speed sensors) is automatically filtered out by the network's hidden-layer feature extraction. Unlike the noise amplification caused by the D term in PID control, neural network controllers produce much smoother braking torque profiles, thereby improving control accuracy and ride quality. In applications where sensor performance is declining, or signals are distorted (e.g., slip-ratio sensor accuracy degradation), the generalisation ability learned by neural networks through training on historical data can be used to reliably infer actual vehicle states from incomplete or distorted feedback signals [111]. Combined with redundant sensor fusion approaches, this inferential ability provides robustness to the distribution of braking force during energy recovery. Together, these features make neural network control strategies particularly effective at system-level robust control of brake energy recovery systems operating under complex, unstructured conditions, and more adaptive to dynamic uncertainties and fault-resilient than traditional control strategies.

3.4 Model Predictive Control

Model predictive control (MPC) is a common component of the control strategy in energy management systems of EVs. The solution to the present control action in MPC is obtained by solving an online optimisation problem using a predictive model of the system. It accounts for system dynamics, constraints, and objectives to forecast future behaviour and optimise control actions over a finite time horizon [112]. With the integration of MPC into energy management systems, electric vehicles can achieve better energy management, system efficiency, and performance. MPC helps maintain a stable DC bus voltage, defines converter reference currents, and effectively tracks them. Additionally, MPC enables efficient energy management in multi-input, multi-output DC–DC converters and enhances powertrain performance in battery EVs. It also provides galvanic isolation between the input sources and the load, increasing the converter's power density and ensuring safety in high-power applications. MPC offers simple control techniques and bidirectional power-flow capabilities, making it suitable for single-port converters and responsive to load-step changes, thereby improving system responsiveness [113].

Researchers have utilised MPC to control RBS. Li et al. [80] employed MPC to track a designated route in the middle-level controller, incorporating an energy recovery strategy for the RBS of intelligent four-wheel independent-drive EVs to maximise recuperative energy. The results, when compared with others, indicate a potential 12.04% improvement in regenerative energy [80]. A reinforcement learning-based stochastic MPC technique for energy management in plug-in hybrid EVs. Additionally, the suggested strategy yields higher fuel economy, comparable to that of the stochastic dynamic programming method, as verified by numerical simulation results. Furthermore, the consistent state of charge across various reference trajectories indicates that the proposed approach performs well for web applications requiring fast computation times. MPC is characterised by a theoretical core rooted in system-predictive modelling, in which control actions are determined by the online solution of constrained optimisation problems. In practical simulation studies, MPC integrates system dynamics, operational constraints, and control objectives to predict future system behaviour and optimise control inputs. This aligns closely with the theoretical principle of receding horizon optimisation for achieving optimal control performance [114]. From the perspective of stability margin, MPC guarantees the stability of the closed-loop system during control implementation by explicitly incorporating constraint boundaries (e.g., braking torque limit, battery current limit) into the optimisation model. This is an effective mechanism to reduce the risk of system instability due to over-control, and the stable nature of system operation, as evidenced by the simulation results, provides empirical support for this theoretical benefit. Regarding dynamic response, MPC preprogrammes control paths using predictive models and can react more quickly to changes in the system's state than traditional control strategies. The rapid adaptive change in vehicle braking states, observed in simulations with transient changes in operating conditions, confirms this attribute.

High robustness is also observed in MPC when faced with uncertainty or component errors, due to its rolling-optimisation nature and its ability to handle multiple constraints. To address the dynamics of battery state variations, MPC predicts SOC dynamics using either an equivalent circuit model or a data-driven model and, in turn, optimises regenerative braking force allocation through a combination of robust optimisation techniques (e.g., ellipsoidal constraint-based models). Although operating in extreme battery conditions, such as low SOC and the risk of overcharging, or high internal resistance resulting in delayed torque response, MPC prevents battery damage by pre-optimising the regenerative power trajectory. In sensor-noise interference scenarios, MPC is typically integrated with Kalman filtering for state estimation, thereby attenuating the impact of sensor noise (e.g., wheel-speed signal glitches) on predictive accuracy. Unlike the direct feedback mechanism of PID control that is prone to noise amplification, MPC's multi-step predictive framework inherently smooths braking torque output profiles [115]. For sensor performance degradation scenarios (e.g., slip-ratio sensor accuracy degradation), MPC compensates for distorted state feedback via the iterative correction feature of rolling optimisation. Furthermore, sensor fault-diagnosis logic can be embedded in the MPC framework to dynamically switch to redundant prediction models or adjust the prediction horizon. This integrated approach maintains a balance between braking force regulation and energy recovery efficiency throughout the braking process, rendering MPC particularly suitable for robust control under multi-objective constraints in brake energy recovery systems.

3.5 Sliding Mode Control

Sliding mode control (SMC) is a robust control technique utilised in energy management systems for EVs. SMC is a nonlinear control method that aims to drive the system state onto a predefined sliding surface and maintain it there to achieve the desired performance. This control strategy is particularly effective in handling system uncertainties, disturbances, and variations in EV operations. By ensuring robust control of energy distribution within the vehicle, SMC enhances stability and efficiency across various driving conditions. Implementing SMC in energy management systems allows EVs to achieve improved energy utilisation, reduced emissions, and an enhanced overall driving experience. Researchers have also used SMC to control RBS. In a study [116], the SMCs found in EVs created numerous opportunities for energy recovery. An anti-lock braking system based on an SMC that maintained the ideal wheel slip during regenerative braking has been proposed [117]. In this proposal, chattering was reduced by implementing an exponential law. An improved SMC that incorporated a braking-force observer and a vehicle dynamics model was introduced in another study [118]. Its co-simulation was generated using the Simulink and CarSim toolkits. In another study [113], SMC and a traditional proportional–integral controller was combined to form a hybrid conventional controller unit. SMC is based on the core theoretical principle of driving the system state trajectory onto a predefined sliding surface and maintaining it there to achieve the desired control performance. In simulation studies of uncertainties and external disturbances in EV operation, SMC demonstrates the ability to quickly bring the system state to the sliding surface, thereby guaranteeing the stability of regenerative energy distribution control [113]. Within the framework of robustness theory, SMC has inherent capabilities for disturbance rejection and model-uncertainty suppression. Simulation results provide substantial evidence of this theoretical quality, demonstrating that the control system maintains high performance even under variable operating conditions, including varying road-surface friction coefficients and changes in dynamic loads. Because of its exceptional robustness, SMC offers unique benefits in situations involving uncertainties or component faults. In addressing the issue of battery state variation, SMC mitigates interference from changes in internal battery resistance and defective charge–discharge characteristics during regenerative braking torque. This is done by creating a sliding surface independent of battery state parameters (SOC, SOH) and the need for accurate battery electrochemical models [119]. To mitigate the risk of overcharging at low SOC, SMC limits regenerative power by employing efficient switching to ensure battery safety.

SMC is theoretically noise-insensitive to sensor noise interference. Nonetheless, high-frequency noise is increased by the inherent chattering effect in practical implementations (e.g., electromagnetic interference from speed sensors on each wheel). To address this trade-off, SMC is typically integrated with auxiliary optimisation techniques, such as boundary-layer approximation or integral sliding-mode design, which mitigate chattering while preserving the robust regulatory capability of braking torque [101]. In sensor performance degradation scenarios (e.g., slip-ratio sensor accuracy degradation), the finite-time convergence property of SMC enables effective compensation for distorted state-feedback signals. Furthermore, the design of high-order sliding surfaces reduces the controller dependence on high-precision state feedback. This integrated design allows SMC to maintain a robust balance between braking force distribution and energy recovery efficiency in EV brake energy recovery systems, making it particularly suitable for complex operating conditions characterised by strong nonlinear disturbances [101].

3.6 Predictive Control

Zhang et al. [101] introduced an innovative predictive control technique to optimise energy recovery during braking in four-wheel pure EVs. This technique integrates dynamic programming and adaptive cubic exponential prediction to estimate vehicle velocity and braking intensity, accounting for the dynamic characteristics of an electrohydraulic combined braking system. The results indicate that under gradual braking conditions, this control approach, which aims to improve energy recovery efficiency, outperforms both the ideal and multi-stage brake-force distribution methods. The innovative predictive control method enhances energy efficiency by forecasting future output values based on the system’s past and current states, thereby improving energy utilisation in fuel-cell EVs. This approach enables swift adjustments to real-time changes in driving conditions, ensuring adaptive responses to unforeseen obstacles during vehicle operation. Furthermore, it effectively handles complex nonlinear systems such as vehicle dynamics, enabling the simultaneous achievement of braking safety, yaw stability, and roll stability while adhering to system constraints. Predictive control strategies exhibit robustness to uncertainty and component faults, owing to their inherent multi-step rolling and constrained optimisation capabilities. To address state changes in batteries, predictive control anticipates SOC changes using either equivalent circuit models or data-driven modelling methods. It adapts regenerative braking force allocation using advanced optimisation algorithms (e.g., stochastic model predictive control). In low-SOC cases, it pre-constrains the charging power ceiling to reduce the risk of overcharging, while in high-internal-resistance cases, it can compensate for torque delays with pre-optimised power trajectories [101]. Predictive control is frequently combined with state estimators (e.g., Kalman filters) when sensor noise is present, so that historical feedback data is used alongside model-based predictions. This combination is useful for reducing the effects of sensor noise (i.e., random perturbations in accelerator signals) in generating control commands [120]. In contrast to the immediate feedback of PID control, which is prone to amplifying noise, the multi-step predictive aspect of predictive control inherently smooths braking torque production profiles and eliminates actuator chattering, thereby improving control stability [120].

Predictive control corrects state feedback deviations caused by sensor performance degradation or signal distortion (e.g., deterioration in slip ratio sensor accuracy) [121], leveraging the iterative correction capability of rolling optimisation. Moreover, the fault-diagnosis modules can be integrated into the control framework to adaptively adjust predictive model parameters. This combined design balances braking force regulation and energy recovery efficiency during braking, making predictive control particularly appropriate for robust control applications with numerous physical constraints (e.g., battery current limits and actuator torque constraints) [122]. The effectiveness of advanced predictive control for RBS has been demonstrated in relevant research. For example, Kakouche et al. [92] proposed a hybrid control system that integrates fuzzy-logic energy control (for operating multiple power sources, such as electric vehicles) and torque predictive control (for use with motor direct torque control within a model predictive control system). The excellent performance of the proposed strategy was explicitly demonstrated through MATLAB/Simulink simulation results across various driving cycles and was empirically supported for use in RBS. This is a trade-off between energy recovery efficiency and braking comfort, a technical issue in the design of brake energy recovery systems [123].

4. Summary of the Control System for the Regenerative Brake System

In summary, the control systems efficiently allocate brake torque based on driver input and system states, ensuring excellent energy regeneration and safe braking, as indicated in Table 1. The efficiency of regenerative braking energy recovery is influenced by tyre contact with different terrains, which affects tyre thermal and wear states. Strategies that consider variations in the tyre-to-ground adhesion coefficient can improve energy recovery efficiency. To more clearly demonstrate the performance of different control strategies in the RBSs of EVs, an in-depth comparison is conducted from three dimensions: performance, complexity, and limitations, combined with an analysis of vehicle dynamics and road conditions. The resulting comparison is structured in Table 2.

Table 1. Comparison of different control RBS strategies

Control	References	Finding
FC	[94], [96]- [109]	Effectively recovers braking energy, reaching energy recovery efficiencies of 14.52% and 39.61%.
PID	[73]- [88]	The energy recovery during deceleration can vary, reaching up to 4.8 kW·h, depending on factors such as the initial velocity, changes in acceleration, and the duration and distance of the driving cycle.
FOPID	[87]-[89] [124]-[126]	It has more flexibility and improved performance than PID control.
NEC	[108]-[111]	It can learn complex patterns and relationships from data, making it suitable for modelling and controlling nonlinear systems to improve efficiency and reliability.
MPC	[112]-[115]	It can improve regenerative energy by 12.04% compared with others.
SMC	[116] – [119]	This innovative technology enables enhanced energy utilisation, leading to lower emissions and an overall improved driving experience. Furthermore, it enhances energy recovery efficiency during braking, contributing to more sustainable, efficient driving performance.
NPC	[119] – [120]	This technology excels in managing complex, nonlinear systems such as vehicle dynamics. It ensures the simultaneous achievement of optimal braking safety, yaw stability, and roll stability, all while strictly adhering to system constraints.

Regenerative braking strategies exhibit varying performance behaviours under different vehicle dynamics and road conditions, underscoring the importance of this performance in ensuring vehicle control reliability. For example, fuzzy neural network control and pure neural network control strategies with strong learning abilities exhibit better capability to handle transient nonlinear dynamic changes in vehicle operating states. Fuzzy and sliding mode control strategies offer significant robustness benefits under complex road conditions (e.g., slippery pavements) and help maintain the vehicle's braking performance within reasonable limits. However, the practical engineering implementation of these strategies is limited by several technical issues, including sensor time delays, which are a major concern. The signal delay of wheel speed and acceleration sensors is usually between 5 and 20 ms, causing a lack of synchrony between control commands (e.g., target braking torque allocation) and actual vehicle behaviour (e.g. real-time wheel slip ratio). This problem is important in ensuring the accuracy of control and safety and is therefore important to engineers in the field of vehicle responsiveness. Control performance is further limited by actuator limitations. Regenerative braking torque is necessarily limited by motor power rating and battery SOC constraints, and cannot be optimised in real time to the main variable, torque allocation. In friction braking systems, the hydraulic pressure build-up takes 100–300 ms, which can lead to longer braking distances due to transient torque deficiency during emergency braking. Thermal constraints are also a major problem in practical implementation, as they directly affect the stability of the control system. Prolonged braking periods cause a high temperature rise in friction pads, leading to a 10%–30% decrease in the braking coefficient (fade coefficient: 0.1–0.3) due to thermal degradation. At the same time, the regenerative braking feature is usually disabled when the motor windings' temperature exceeds 120 °C to prevent insulation damage. The two phenomena interfere with the synchronised distribution of regenerative and friction braking torques, thereby compromising vehicle dynamic stability.

Table 2. Comparison of different control RBS strategy performance

Control Strategy	Energy recovery efficiency	Response speed	Robustness	Complexity	Limitations	Applicable scenarios
PID Control	Varies depending on operating conditions, reaching up to 4.8 kW·h at most (fluctuates under different conditions)	Moderate, dependent on parameter tuning	General, high requirement for model accuracy	Low, easy parameter adjustment	Limited ability to eliminate steady-state errors, poor adaptability to complex working conditions	Simple systems with stable working conditions and accurate models
FOPID Control	Higher than PID control, with significant performance improvement after parameter optimisation	Relatively fast, capable of quickly responding to changes	Good, enhanced adaptability due to fractional-order calculus	Moderate, requires optimization algorithm for parameter setting	Large computational load of the optimization algorithm	Complex dynamic systems
Fuzzy Control	Can reach 14.52% – 39.61% under complex road conditions	Fast, capable of quickly handling nonlinear relationships	Strong, excellent at dealing with uncertainties	Moderate, rule-based design requires experience	Depends on expert experience for rule design, with limited accuracy	Systems with nonlinearity and many uncertain factors
Fuzzy neural network control	Can reach 14.52% and 39.61% under NEDC and FTP-75 settings	Fast, with strong self-learning ability	Strong, excellent adaptive ability	High, complex training process	High demand for computing resources, long training time	Complex and variable systems requiring adaptive control
Neural network control	Can optimise energy recovery, with the specific efficiency varying according to the model	Relatively fast, strong learning ability	Relatively strong, good at nonlinear modelling	High, complex model training	Depends on a large amount of data, the generalisation ability needs to be improved	Complex nonlinear systems
Model predictive control	Can improve efficiency by 12.04% compared with other strategies	Moderate, time-consuming online optimisation calculation	Good, takes system constraints into account	High, requires accurate models and fast computing	Large computational load, high real-time requirement	Systems with multiple constraints and requiring optimisation control
Sliding mode control	Improves energy utilisation and recovery efficiency	Fast, strong ability to suppress interference	Strong, outstanding robustness	Moderately high, parameter design requires skills	Chattering problem exists, affecting control accuracy	Systems with strong uncertainties and large interference
Predictive Control	High and relatively stable; optimised via real-time state prediction (e.g., ~5.2 kW·h under dynamic conditions)	Moderate to variable: ms-level for linear systems; tens of ms for nonlinear systems (limited by online optimisation)	General (with feedback correction); enhanced via RMPC/AMPC for small perturbations	High, requires accurate modelling; intensive online optimisation; skilled tuning + high-performance hardware	Trade-off between real-time performance and complexity; model-dependent; cumbersome tuning; high hardware cost	Multi-variable/multi-constraint systems; medium-slow dynamic scenarios (e.g., automotive energy management, industrial process control)

Two main technical solutions are suggested to address these challenges. First, model-based calibration strategies are proposed that incorporate sensor-delay compensation modules, actuator-response constraint boundaries, and thermal-fade degradation models into the control scheme. This increases the accuracy of the simulation models and the similarity between offline optimisation and real-world performance. Second, sophisticated control optimisation techniques are essential for strengthening systems. In sensor-delay problems, state observers (e.g., Kalman filters) are used to predict the vehicle's dynamic states and eliminate time-delay errors. In the event of actuator constraints, a safety-prioritised torque allocation policy is followed, with braking stability taking precedence over energy recovery efficiency when actuator performance limits are exceeded. In the thermal case, a coordinated control mechanism is introduced between the thermal management system and the braking controller to dynamically regulate torque distribution based on real-time temperature feedback from friction pads and motor windings, thereby steering future research directions. Based on the above, the following changes are suggested for improving regenerative braking strategies.

Further studies are required to develop real-time adaptive road-condition sensors using in situ sensors, including tire-mounted accelerometers and AI-based camera and LiDAR detection systems. This would enable dynamic resetting of optimal slip thresholds without requiring recalibration of the road surface category (ice, wet, etc.). This type of technology allows precise control of the slip, even in mixed or transient road conditions, such as when a patch of ice is encountered on a dry highway. Future EV braking control needs to strike a balance among ride, tyre life, and battery health, using multi-objective optimisation with scenario-dependent weights. Combined with real-time road detection (in situ sensors/AI+LiDAR), it dynamically optimises slip thresholds for accurate control in mixed/transient conditions. For autonomous EVs, AD trajectory planning should be combined with regenerative braking control. Predictive braking uses the AD's environmental perception (e.g., distances to vehicles in front of it and traffic lights) to adjust regenerative torque and slip thresholds in advance, thereby reducing abrupt braking and enabling maximum energy recovery. Platoon-based regeneration, coordinated by the AD platoon, involves inter-vehicle braking to maximise overall energy recovery (e.g., sequential regenerative braking to minimise unnecessary kinetic energy loss). The constant slip range necessitates high-frequency torque changes (millisecond-level response). Future studies can focus on co-designing control algorithms with future hardware, including power electronics, to enable regenerative inverter control and more accurate torque adjustment. In-wheel motor systems can be distributed so that each wheel can be controlled separately in slip and respond to asymmetric road conditions (e.g., left wheels on wet asphalt, right wheels on dry concrete), which current centralised systems cannot manage. New EV braking control plans need to be better validated: large-scale testing of control strategies with digital twins can replicate real-world driving conditions (extreme weather, traffic, vehicle aging) to reduce physical test costs, and fleet data analytics can use the data on deployed EVs to improve control models (e.g., region-specific optimal slip values) and detect edge cases (e.g., cold-climate regenerative brake failure) missed in lab tests. The next-generation regenerative brake control will no longer be condition-specific, single-objective stability, but will be multi-objective, adaptive, and AD-integrated systems, enabled by advances in sensing, AI, hardware, and connectivity.

5. Conclusions

In this paper, the RBS, its components, functionality, and control strategies have been elaborated. By closely examining and contrasting the results of other studies, it can be concluded that different control strategies are required for various road surfaces (dry, wet, and icy). The quantitative analysis demonstrates that the energy recovery efficiency can be greatly increased by adopting control strategies that account for variations in the tyre-to-ground adhesion coefficient. For example, the amount of energy recovered increased by up to 20% in certain situations compared to some traditional strategies. However, the current research is mainly based on numerical simulation. To further enhance the overall quality of this review, the controller could be verified on a real car or a hardware-in-the-loop system in future studies as these realistic conditions might provide different results. The factors neglected in this research model include SOC, battery temperature, and other power-related factors. These factors should be considered in a developed model in future studies, as they will allow researchers to better assess the controller's effectiveness. Further, it may be beneficial to consider other manoeuvres, such as braking through a corner, to gain a better insight into RBS. Regenerative braking performance is also influenced by road friction, which must be considered when operating the regenerative brake.

Brake energy recovery on wet, slippery road surfaces requires a solution to the inherent trade-off between safety and energy efficiency, which can be successfully balanced through high-quality tyre modelling, adaptive control, and operating condition-specific strategies that respond to vehicle dynamics. The coupling of multi-physics domains and real-time coordinated control technologies should be the priority for research, and practitioners are recommended to choose approaches related to the requirements of the vehicles: passenger vehicles should focus on the balance between ride comfort and efficacy in energy recuperation, whereas commercial vehicles should focus on braking stability and coordinated performance. The avenues for future development will be intelligent perception technologies (e.g., high-precision road-surface recognition) and intelligent, coordinated, and connected control, which will push brake energy recovery systems to a new level of safety, efficiency, and intelligence.

Existing research has tested the effectiveness of different regenerative braking controls on different road surfaces. The findings revealed that the adaptive control strategy outperformed the conventional fixed-threshold approach in braking stability and energy recovery performance. Relevant studies have shown that optimised control strategies can effectively improve regenerative braking recovery performance across diverse pavement conditions. Research findings collectively suggest that energy recovery benefits vary gradually across dry, wet, and icy road conditions when tailored control schemes are adopted. Furthermore, integrating perception of road surface conditions into regenerative braking control frameworks is widely recognised as a comprehensive means of enhancing vehicle driving safety and overall energy utilisation efficiency.

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Qianqian Li: Methodology; Analysis; Writing – original draft
P.M Heerwan: Conceptualisation; Analysis; Validation; Supervision; Writing -revise & review
M.I Ishak: Conceptualisation; Investigation; Writing-revise & review

Availability of Data and Materials
The data supporting this study's findings are available on request from the corresponding author.

Ethics Declarations
This study did not involve human participants or animals. Ethical approval was therefore not required.

Generative Artificial Intelligence Declarations
The authors claim that artificially intelligent-assisted technologies, such as generative AI, were not used to generate content, ideas, or theories. We have just utilised AI to enhance readability and refine the language. This was used with extreme human control and oversight. The authors take full responsibility for reviewing and approving the content.

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