Critical Review on Optimal Regenerative Braking Control System Architecture, Calibration Parameters and Development Challenges for EVs

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Abstract

Vehicle technology advances and the world shifts towards E-mobility, improving the performance of electric vehicles (EVs) and HEV’s is becoming the prominent focus. One of the prime topics of EV development is increasing the driving range which is the fundamental requirement. Apart from increasing the battery capacity retrieving the wasted energy during conventional braking also called as regenerative braking is a hot topic. In this context, numerous control architectures and major braking approaches are considered to examine in this study in order to create an efficient regenerative braking system (RBS). This review article intends to provide an overview of major subsystems in the RBS such as motor control system and hydraulic braking system and how it affects the braking performance is also well discussed. Additionally, it complies some of the recent research applications and systematically reviews the several braking control strategies implied. The prominent ones are fuzzy logic control, neural network, MPC, sliding mode, and adaptive control modeling approaches. These control strategies are used to enhance the energy regeneration without affecting vehicle performance. Further, this article discusses the RBS design process and its calibration variables, such as speed of the vehicle and brake force estimation, which can be used to improve braking performance. Moreover, challenges on RBS improvements are effectively addressed, coupled with brief suggestions and discussions for the growth of future RBS development. Finally, this article will hopefully help the reader to critically analyze the working of RBS and encourage to design of an efficient RBS for electro-mobility application.

Keywords: Regenerative braking system; E-mobility; brake control strategies; motor control system; hydraulic braking system.
<table>
<thead>
<tr>
<th>Abbreviations</th>
<th>Full Form</th>
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<tr>
<td>ABS</td>
<td>Antilock braking system</td>
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<td>AC</td>
<td>Alternative current</td>
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<td>ANFIS</td>
<td>Adaptive neuro-fuzzy inference system</td>
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<td>ANN</td>
<td>Artificial Neural network</td>
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<td>APP</td>
<td>Acceleration pedal position</td>
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<td>BEV</td>
<td>Battery electric vehicles</td>
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<td>BLDC</td>
<td>Brushless direct current motor</td>
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<td>BMS</td>
<td>Battery management system</td>
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<td>BPP</td>
<td>Brake pedal position</td>
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<td>CACC</td>
<td>Cooperative adaptive cruise control</td>
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<td>CAN</td>
<td>Controller area network</td>
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<td>DC</td>
<td>Direct current</td>
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<td>DTC</td>
<td>Direct torque control</td>
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<td>ECU</td>
<td>Electronic control unit</td>
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<td>EM</td>
<td>Electric motor</td>
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<td>EMF</td>
<td>Electromotive force</td>
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<td>EMS</td>
<td>Energy management system</td>
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<td>ESS</td>
<td>Energy storage system</td>
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<td>EUUDC</td>
<td>Extra urban driving cycle</td>
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<td>EVs</td>
<td>Electric vehicles</td>
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<td>FLCS</td>
<td>Fuzzy logic control strategy</td>
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<td>FNN</td>
<td>Fuzzy neural network</td>
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<td>FTP</td>
<td>Federal test procedure</td>
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<td>HESS</td>
<td>Hybrid energy storage system</td>
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<td>HEV</td>
<td>Hybrid electric vehicles</td>
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<td>HIL</td>
<td>Hardware-in-loop simulation</td>
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<td>ICE</td>
<td>Internal combustion engine</td>
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<td>ISMS</td>
<td>Intelligent sliding mode scheme</td>
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<td>IWM</td>
<td>In-wheel-motor</td>
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<td>KE</td>
<td>Kinetic energy</td>
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<td>LVTMPC</td>
<td>Linear time varying model predictive control</td>
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<td>MCU</td>
<td>Motor control unit</td>
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<td>MIL</td>
<td>Model-in-loop simulation</td>
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<td>MOOS</td>
<td>Multi-object optimization strategy</td>
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<td>MPC</td>
<td>Model predictive control</td>
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<td>NEDC</td>
<td>New european driving cycle</td>
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<td>NLTVMPC</td>
<td>Non-linear time varying model predictive control</td>
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<td>NMPC</td>
<td>Nonlinear model predictive control</td>
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<td>NN</td>
<td>Neural network</td>
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<td>PHEV</td>
<td>Parallel hybrid electric vehicle</td>
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<td>PID</td>
<td>Proportional, Integral, Derivative</td>
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<td>PIL</td>
<td>Processor-in-loop simulation</td>
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<td>PSO</td>
<td>Particle swarm optimization</td>
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<td>PWM</td>
<td>Pulse width modulator</td>
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<td>RB</td>
<td>Regenerative braking</td>
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<td>RBS</td>
<td>Regenerative braking system</td>
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<td>RL</td>
<td>Reinforcement learning</td>
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<td>RNN</td>
<td>Recurrent neural network</td>
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<td>SIL</td>
<td>Software-in-loop simulation</td>
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<td>SMC</td>
<td>Sliding mode control</td>
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<td>SMPC</td>
<td>Stochastic model predictive control</td>
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<td>SOC</td>
<td>State of charge</td>
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<td>TVSMC</td>
<td>Time-varying sliding mode control</td>
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<td>UDDS</td>
<td>Urban dynamometer driving schedule</td>
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<tr>
<td>VIL</td>
<td>Vehicle-in-loop simulation</td>
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<tr>
<td>VSE</td>
<td>Vehicle state estimator</td>
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<tr>
<td>WMD</td>
<td>Wheel-motor-driven</td>
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1. Introduction

In recent years, electric vehicles (EVs) have gained dramatic attention as alternative mobility means to internal combustion engine (ICE) vehicles. The amount of research done and the emergence of new technology pertaining to EVs are unprecedented which surely leads to the conclusion that electric vehicles are truly a green revolution [1]. Over the past couple of decades as the world is slowly shifting towards EVs, a lot of efforts are put into different research areas to collectively enhance the performance of EVs. Many developments are also done to enhance the performance of motor propulsion and other vehicle systems optimization to obtain a lively driving experience [2]. But since the importance of recuperating the otherwise lost energy during braking is identified, the concept of regenerative braking has been a prime focus as this is directly linked to improving the vehicle driving range [3]. Exploring new and advanced control logic to obtain optimal braking force distribution as well as maximized energy regeneration is hot topics in the regenerative braking domain. Nowadays RBS is equipped along with safety technologies like an anti-lock braking system (ABS), wheel slip control features, etc [4]. Regenerative braking (RB) is a way of recovering the kinetic energy while a vehicle slows down which is stored for later utilization as presented in Fig. 1. In this way, some amount of energy is recovered which in the case of conventional vehicles gets lost in form of heat and frictional energy [5]. Regenerative braking is widely implied in various types of electric vehicles like BEV, HEV, and fuel cell. The hybrid or electric car's electric motor operates in two directions: one to drive the wheels and push the vehicle, and the other to recharge the battery (generator). When the driver takes the foot off the accelerator pedal and places it on the brake, the power transfer from the motor to wheels is interrupted [6]. Now the rotating wheels induce an EMF which causes the current to charge the battery hence making the motor work as a generator. In addition to improving overall vehicle efficiency, regeneration may greatly increase the life of the braking system since the mechanical elements do not wear out as rapidly [7,8]. RB is not by itself completely sufficient to safely bring the vehicle to a halt or rapidly decelerate if required. Hence it is coupled with another braking system like friction or hydraulic based braking [9]. During and event of braking both the braking systems are used depending upon the driver's demand and hence a proper control system needs to be dedicated for the braking force distribution. To carry out these commands efficiently different control strategies are implied which are discussed further in this study [10].
Fig. 1: General structure of the braking system in EVs [2-4]

The literature study involves various researches carried on till date and also suggests the grey areas which need to be explored by future engineers to further improve the performance and significance of RBS in EVs. In [11,12], the regenerative braking capability limits of BLDC motors and their drive circuits are examined by taking into account nonlinear circuit parameters and focusing on control braking forces for optimal braking performance. To improve the braking performance a single-pedal control approach is used it can efficiently improve the energy recapture rate and extend the driving range under the different driving conditions [13]. Further, NN is used to train prediction models and optimize the predicted working conditions of EVs in order to improve their mileage capacity. As a result, it's used to improve the vehicle's working efficiency by optimizing torque distribution between different braking systems [14]. Apart from cars, regenerative braking is also implied in heavy vehicles as discussed in [15] where various braking strategies of a mining truck were compared to present the most efficient one. Also, several of the scholars have broadly studied numerous control approaches, vehicle stability, cooperation of RBS and ABS [16-18], features and control influences of hierarchical control approaches [19,20] as mentioned in Fig. 2. Besides hierarchical control strategies, optimal braking performance, regenerative efficiency approach, and their collaboration strategy have been presented [21]. To make understanding of the significance of RBS in EVs/HEVs, [22] investigated the RBS and its energy recovery capacity as compared to conventional ICE vehicles. Some studies like [23, 24] proposed a multi-input
FLC strategy for regenerative braking distribution between various braking systems in the vehicle based on real-world drive cycles. The FLC works by adjusting the sliding mode parameters based on the slip ratio tracking error between the optimal and actual slip ratios. Also, it can incorporate the best battery condition and energy recovery efficiency under a variety of vehicle driving conditions. This fuzzy SMC can improve the energy efficiency and stability of the brake in different braking conditions [25]. Moreover, the optimal slip ratio control strategy can achieve the balance between RB performance and life of the battery under various tire-road adhesion conditions. Also, it can enhance the maximum regenerative braking energy efficiency, vehicle stability and braking strength of the vehicle [26]. Then, the multi-objective optimization of RB control system is to balance among the performance of braking, braking efficiency and battery rate losses under different driving conditions. It can split maximum demand braking torque between various braking systems in the vehicle. Also, it is used to increase the efficiency of regenerative braking and reduce the battery losses on low and medium tire road adhesion conditions [27]. Further, coordinated control approach of RBS is used to achieve the optimal braking efficiency and guaranteeing the vehicle brake slip rate. The brake slip rate can track the slip-ratio tracking errors and ensure the efficient operation of the braking system. also, it can minimize the energy recover rate of the RBS and to enhance the RB energy recovery efficiency [28,29]. Similar studies were carried on in [30,31] where a NN-based technique is used to estimate the appropriate braking force split between the hydraulic and regenerative braking in the vehicle. The control strategies used have numerous approaches such as [32, 33] in which a MPC is implemented in RBS which showed better results compared to a conventional PI controller. The MPC modeling approach is used in vehicle energy management where the driver model is used to predict future power requests. It directs the friction and regenerative braking forces to meet the driver's brake request while maintaining the stability and drivability of the vehicle [34]. In order to improve the stability of the vehicle, multi-objective optimization is used to effectively enhance braking stability, life of the battery and braking comfort without compromising the energy recovery [18]. However, the limited driving range of EV is a challenging issue that must be addressed. Energy recovery is a key technique for improving energy efficiency and extending the range of electric vehicles. Under wider braking scenarios, an optimum braking force split control strategy is used to split braking torque between various braking systems of the vehicle. As a result, it can successfully achieve maximum energy recovery under various braking environments while maintaining braking performance and stability [35, 36]. In [37] with the aims of brake efficiency, stability and comfort, various cooperative control approaches were researched and their comparison was done to select the most balanced control approach. Based on such multiple ideas this review paper aims to critically present all the concepts of RBS and help bridge the gaps present in
Another critical aspect in electric vehicles is managing the energy storage while varying operating conditions. The energy storage system in typical EVs consists of sole Li-ion battery or in combination with supercapacitor or ultracapacitors also termed as hybrid energy storage system (HESS). One significant challenge which can be of concern is harnessing the transient high-power charging occurring during the regenerative braking i.e., there occurs a sudden surge in the charging current [38]. This can cause the batteries to degrade, impacting their performance over longer period of their lifetime. In this scenario the hybrid combination energy storage system comes into picture which consists of supercapacitor or ultracapacitor along with the Li-ion battery. The supercapacitors have very good power densities and are capable of harnessing the power generated during regenerative braking. In doing so the battery state of charge has a significant impact on the power absorbing capacity and the charging current of the supercapacitor based regenerative braking system [39]. The supercapacitor-based hybrid system has longer cycle life and rapid charge/discharge cycle compared to Li-ion battery. But still some limitation on the braking rate occurs if the supercapacitor isn’t operated within a certain range of SOC because of the current limitation of the power electronic converter used to charge the supercapacitor. This issue can be considered for future development of supercapacitors for efficient application in hybrid combination energy storage systems.

The effective design and development of RBS are discovered to be a major necessity by vehicle manufacturers in the current scenario for the effective performance results of EVs. An effective RBS extends the driving range by improving battery capacity by recovering lost energy during the braking. Because of its extremely transient behavior, RBS is considered to be a more complicated design in EV, making energy management between regenerative and hydraulic braking systems more challenging. As a result, efforts towards the continued development of more effective RBS technology are now necessary. This type of study would aid in better understanding the interrelationships among the RBS multiple control systems. Furthermore, such an evaluation effort will pave the way for improving the overall performance of the RBS in EVs. There have been a lot of research activities and studies done in specific sectors pertaining to regenerative braking. Many research and review articles have focused on individual topics of control strategies used in RBS, and its design considerations, etc. But very few literature papers have provided a complete overview and critical analysis of the RBS as a whole [40-43]. The different literature gaps as shown in Fig. 3, keeping that in mind, and to bridge the gap this paper attempts to provide a critical review on all the aspects involved in an efficient RBS. In this context, the objective of the current work is to conduct a critical analysis of control system architecture, brake control modeling approaches, calibration parameters, and
the RBS design and development process. In addition, this study seeks to provide several modeling strategies for brake energy optimization, such as FLC, NN, MPC sliding mode, and adaptive control. The novelty of this study originates from the aggregation of research that have explored RBS control system architecture with various modeling approaches for brake energy optimization, as well as this work defined the RBS design and development process. Also, this study explicates challenges arise during design and development of regenerative braking system in the EVs. Fig. 4, Depicts a summary of the structure and flow of the current review paper. Finally, the conclusion of the stated objective will provide readers with information and a critical perspective on the design and implementation of an effective RBS for EVs. This study, among other things, can help in certain crucial areas and indicate areas where future research should be concentrated.

**Cooperative control of braking systems**
- Discussion on control effects and regeneration efficiencies of the different control cooperative strategies
- Issues on brake comfort, safety, brake comfort, efficiency and energy recovery rates

**Regenerative braking control challenges**
- Discussion on current developments in regenerative braking technology
- Issues and challenges on advancement of various braking control strategies

**Development of regenerative braking in EVs**
- Discussion on energy recovery, integration with ABS, and vehicle stability
- Some research issues and key challenges in regenerative braking are discussed

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**Fig. 2: The current state of review works in RBS of EVs [16-18]**
Fig 3: A schematic representation of the research gap and original contribution of the work [40-43]

Fig. 4: A schematic representation of a structured summary of the review work
2. Control system architecture of regenerative braking system in EVs

Electric vehicles require an efficient braking controller for optimal braking performance and safety. The purpose of RBS is used to improve the regenerative energy efficiency, braking stability, and performance in the vehicle [44]. The control architecture of the RBS has various subsystems such as brake controller, regenerative brake controller along with brake control strategies, etc as shown in Fig. 5. Regenerative braking is one of the important systems in the functioning of an electric vehicle (EV). In EV, the braking controller receives numerous real-time inputs from various sensors present in the vehicle such as wheel speed, BPP, battery SOC, motor, battery, and other vehicle inputs [45]. These inputs are used to predict the vehicle required braking force, vehicle state, brake state, etc. Also, these inputs are used to calculate and manage the braking force between the various braking systems in the vehicle. In addition, the motor and battery inputs are used to control and manage the demand torque in the vehicle and other factors like temperature, speed, voltage, etc. Along with these inputs, the regenerative braking controller receives other external sensor inputs from the various control modules (such as transmission, battery, motor and vehicle) in the regenerative braking system [46,47]. Based on these received inputs from the various sensors, the regenerative braking controller operates to maximize the regenerative braking efficiency and optimal usage of the stored battery power. After proper calculations, the respective output signals are sent to the motor control unit and also to optimize the braking working status and operating state of the vehicle [48]. Based on these sensor signals, the control systems in the RBS will perform the appropriate control actuation to various systems.

Then, the regenerative braking controller is responsible for processing various sensor inputs received from the vehicle and providing output as per the driver requirements. The various sensor signals are sent to the driver model unit, it is used to predict the vehicle state of motion, brake state, and stability [49]. The predicted sensor signals are sent to the braking control unit, which is used to estimate the required mechanical braking torque of the vehicle. Further, the braking control unit output signals are sent to the regenerative braking controller which estimates the required regenerative braking force and brake state (includes regenerative braking, hydraulic braking, and combination of both braking systems) of the vehicle [50]. To control and estimate the regenerative braking force various brake control strategies (fuzzy, neural network, model predictive, sliding mode control, etc) are used, which are used to improve the performance of the regenerative braking controller [51,52]. Also, these control strategies are used to optimize the braking force distributions between regenerative braking and hydraulic braking system in the vehicle. Also, which is depends upon the various sensor inputs (BPP, speed, SOC) from the driver [53]. For example, in the case of hard brake, the hydraulic
brakes will also function simultaneously with the regenerative braking. Finally, the optimal braking force is sent to the motor control unit, when the brakes are applied or the accelerator pedal is not engaged the EM acts as a generator to produce current from the rotational motion of the wheels and this current is stored in the battery after power conversion for later utilization [54]. The RBS also does the energy and power analysis in how to effectively distribute the stored energy to the various vehicle systems with maximum efficiency. Hence, it is very necessary to have a complete understanding of the RBS including all the major control modules which are involved in processing the input information. Such critical analysis can be done using the entire architecture of the RBS which will help the researchers to understand the process flow of input data and the related major modules involved in decision making. Also, the readers who are new to this concept can easily grasp the essence of regenerative braking and its importance in EVs. It can even aid the researchers to identify any loopholes within the control system and focus on improvement of any particular area of the RBS.
Fig. 5: Control system architecture of RBS in EVs
3. Regenerative braking control strategies in electric vehicles

The braking controller is used to optimize the braking performance between regenerative and hydraulic braking in the vehicle. To attain the enhanced braking performance between braking systems, different modeling approaches such as fuzzy logic, neural network, model predictive, sliding mode, and adaptive control are used as stated in below individual sections.

3.1 Fuzzy Logic Control modeling approaches

FLCS is an important control system that is depending on the features of the electric vehicle system. In general, the FLCS works according to the different sensor commands (SOC, Speed, BPP, etc) from the vehicle based on the preset logical rules. Since in a moving vehicle the input parameters are constantly changing this control approach can be very useful in distribution of brake torque between braking systems [55]. The various sensors input (speed, SOC, BPP) information are provide to the fuzzy logic controller, and it is used to calculates the optimal brake force between different braking systems in the vehicle [56]. Then, it split and distribute the optimal braking force between hydraulic and regenerative braking systems in the vehicle. Also, it always tries to maximize the energy recuperation to serve the purpose of regenerative braking as shown in Fig. 6. In fuzzy logic control, there are different modeling approaches employed for brake force distribution [57], slip ratio control [58], and maximum braking energy recovery such as Sugeno’s FLC [59], fuzzy slip ratio control [26], reinforcement learning approach [60], applied to fuzzy Q-learning [61], Mamdani type FLC, nonlinear fuzzy logic with PID control and fuzzy logic with parallel topology [62], as mentioned in Table 1. Regenerative braking force generally depends upon the driver’s braking intention which means that if the braking force is large the vehicle is required to stop immediately within a short distance and if the braking force is less, then the vehicle can be decelerated slowly without any urgency [63]. When the driver presses the BP, the controller distributes the braking force between the wheels according to the input and driving conditions. Also, in some cases, a combination of fuzzy and PID controllers is employed in the regenerative braking strategy which can split the mechanical and electrical braking force dynamically [64]. Also, it can increase the driving range of EVs while maintaining braking quality. As discussed in [65], the reinforcement learning (RL) method is another modeling approach used to adjust and improve a fuzzy logic model for regenerative braking by tuning the model for a specific EV using actual data gathered from field tests [66]. In modern vehicles, an anti-lock braking system (ABS) is a common feature and in these systems, a fuzzy slip ratio controller is used to obtain the optimal slip ratio and avoid wheel skidding [67, 68]. On the other hand, a major concern is that for efficient results, an extensive testing is required.
with hardware for validation of the system. During the validation, a lot of manual tuning is essential which is time consuming and complex for large scale applications. The application of fuzzy logic control strategy causes the distribution of maximum braking torque between frictional and electrical braking is not achieved. Consequently, the efficiency and performance of the braking decreases in modeling of RBS. The splitting of braking torque between various braking systems can be affected by different vehicle parameters such as speed, SOC and braking requirements. With the FLC, the braking torque can be controlled over a short range of operating conditions and it can keep the battery SOC within certain range of driving conditions. To counter these issues, the self-learning neural network can have good scope since they learn with each passing operation and can become more precise an overtime.

Fig. 6: Fuzzy logic control system in RBS for EVs
<table>
<thead>
<tr>
<th>Modelling Approach</th>
<th>Major Outcomes</th>
<th>Ref.</th>
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<tbody>
<tr>
<td>PID with fuzzy logic control</td>
<td>• It can achieve more dynamic distribution of braking force between different braking systems in the vehicle.</td>
<td>[56]</td>
</tr>
<tr>
<td>FLC with braking force distribution strategy</td>
<td>• By implication of FLC approach in modelling RBS, the distribution of brake torque is achieved between the different braking systems and it recovers more amount of energy during braking.</td>
<td>[57]</td>
</tr>
<tr>
<td>FLC for brake energy recovery strategy</td>
<td>• It can increase the energy recovery efficiency of the regenerative braking system and it can achieve superior vehicle braking performance, and safety.</td>
<td>[58]</td>
</tr>
<tr>
<td>FLC with SOC strategy</td>
<td>• Higher energy recuperating and higher vehicle system efficiency is possible through the FLC combines with SOC.</td>
<td>[69]</td>
</tr>
<tr>
<td>Distribution of braking force using FLC</td>
<td>• Improvement of power and economic performance of EV by the application FLC strategy for brake force distribution.</td>
<td>[60]</td>
</tr>
<tr>
<td>Sugeno’s fuzzy logic controller</td>
<td>• It can enhance the braking performance based on various driver’s inputs like vehicle speed, SOC and braking torque.</td>
<td>[61]</td>
</tr>
<tr>
<td>Reinforcement learning (RL) approach with fuzzy-Q-learning</td>
<td>• Improved regenerative braking factor obtained by application of reinforcement learning to adjust and improve the braking performance. Also, it can achieve maximum amount of amount of energy recuperation.</td>
<td>[62]</td>
</tr>
<tr>
<td>Fuzzy slip ratio control strategy</td>
<td>• It can reduce braking distance and stop time along with slip ratio control for optimal braking torque. Also, it can reduce the slip ratio tracking errors between optimal and actual slip ratios.</td>
<td>[63]</td>
</tr>
<tr>
<td>FLC with PID in ABS control</td>
<td>• It can keep the battery SOC within a certain range and recovers the maximum brake regenerated energy throughout a driving cycle.</td>
<td>[64]</td>
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<tr>
<td>Nonlinear FLC with PID control</td>
<td>• The fuzzy with PID control ensures dynamic distribution of mechanical and electrical braking forces in the vehicle.</td>
<td>[65]</td>
</tr>
<tr>
<td>Brake control with FLC</td>
<td>• It can split optimal brake force between the wheels and improve the brake energy recovery efficiency. Also, it can extend driving range of the vehicle.</td>
<td>[66]</td>
</tr>
<tr>
<td>FLC with wheel slip for ABS</td>
<td>• It can reduce the wheel slips by adjusting the slip ratio tracking errors and also, it can control the braking torque over a range of operating conditions for the anti-lock braking system.</td>
<td>[67]</td>
</tr>
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</table>
3.2 Neural Network Control Modelling approaches

Neural network (NN) is a type of intelligent control algorithm which is widely known for its strong capacities of self-learning, adapting, and organization and hence it is outstanding for the control of non-linear systems [69]. In this control strategy have 3 layers (input, hidden, and output layers) of neurons that process the input data and provide the necessary output according to the modelling approach. The data acquired as per the driver demand (Speed, BPP, SOC) is processed as per thoroughly pre-trained models in the neural network. This results in providing an accurate control signal (braking torque) to carry out the actuation between the respective braking systems as shown in Fig. 7. Similar to other controls in the neural network too there are various modeling approaches like NN-based drive control [70], NN with sliding mode control [71], ANN-based methodology [72], fuzzy neural network strategy [73], ANN with PI controller [74] as presented in Table 2. Compared to an ANN model, FLC is much more dependent on the membership functions but ANN is particularly used to maximize the available energy for recovery [75]. In this approach the deceleration and speed are considered as input parameters and a portion of the front wheel-braking force is obtained as output [76]. Further, the number of layers and neurons vary in different modeling approaches, such as in NN based SRM drive control strategy [77] the ANN has 3 layers and the hidden layers have 5 neurons. The energy recovery, in this case, is higher when the braking torque is high. Moreover, the NN self-adaptive system comprises back propagation and a radial basis function, their function being to adaptively regulate the constraints of the PID controllers online and establish a non-linear prediction model and achieve parameter prediction [78]. This hybrid technique was tested and it was seen that better regeneration efficiency, control effect, and energy recovery was achieved. Another approach is the fuzzy NN control strategy, wherein an independent four wheel-motor-driven (4WMD) EV was modelled for application of this control strategy [79, 80]. In this approach, the total of five-layered NN was used to map relations between inputs and outputs to calculate the allocation of front and rear RB torque and friction braking torque [81]. Also, the ESS in an electric vehicle has to be as efficient as the regenerative braking system and for that, a HESS along with ANN control approach for braking force distribution is seen to be adopted in the study [82]. Further, NN controls the system must be put through a lot of training so that it gets accustomed to the actual road conditions inputs and the control logic becomes more efficient and faster [83]. Moreover, an appropriate NN structure is achieved through experience and trial and error approaches, which can be a concern if enough model training is not done. The NN approach is used to predict and distribute appropriate braking force between different braking systems, but it cannot achieve stability and reliability of the vehicle. During the regenerative braking less amount of energy
can be recaptured due to the lack of model training as resulting in decreased driving range of the vehicle. Further, the optimal NN brake controls approaches are used to operate motor at higher efficiency zone to recover the high amount of braking energy, but it incapable to handle the steady state tracking errors in different operating conditions. In such cases the MPC is used to anticipate future events for eliminate the steady state tracking errors in various driving conditions.

Fig. 7: Neural network control in RBS for EVs
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<tr>
<th>Modelling Approach</th>
<th>Major Outcomes</th>
<th>Ref.</th>
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<tr>
<td>NN with drive control strategy</td>
<td>• It is used to predict and distribute appropriate braking force between different braking systems and also, it can achieve stability and reliability of the vehicle.</td>
<td>[70]</td>
</tr>
<tr>
<td>NN with self-adaptive PID</td>
<td>• It can be recuperated more amount of energy during braking as a result in increased driving range of the vehicle.</td>
<td>[71]</td>
</tr>
<tr>
<td>ANN-control approach</td>
<td>• It is used to find the appropriate braking force split between friction and regenerative braking and rear-front axles.</td>
<td>[72]</td>
</tr>
<tr>
<td>NN with sliding mode controller</td>
<td>• It improves energy efficiency at different operating speeds and also reduce the various steady-state tracking errors in the vehicle. Also, it can improve the stability, reliability, and driving range of an EV.</td>
<td>[73]</td>
</tr>
<tr>
<td>Multilayer perceptron ANN</td>
<td>• It is used to find the appropriate braking force split between friction and regenerative braking and rear-front axles.</td>
<td>[74]</td>
</tr>
<tr>
<td>NN with RB controller</td>
<td>• Based on the prediction of future states, it improves energy efficiency and braking performance of the vehicle.</td>
<td>[75]</td>
</tr>
<tr>
<td>ANN based vector control strategy</td>
<td>• It is used to estimate the braking force split between hydraulic and regenerative braking as per the input parameters for maximum regenerative torque.</td>
<td>[76]</td>
</tr>
<tr>
<td>NN with Sliding mode control</td>
<td>• It possesses strong self-adaptability and recovers more energy in the braking process. Also, it improves regeneration efficiency, stability and reliability of the vehicle.</td>
<td>[77]</td>
</tr>
<tr>
<td>NN with model predictive control</td>
<td>• It can recover the maximum braking energy through regenerative braking and also, it can ensure brake safety and comfort.</td>
<td>[78]</td>
</tr>
<tr>
<td>NN with energy recovery strategy</td>
<td>• The NN-driven system handles the braking torque ripples accurately and it can split optimal braking torque between various braking systems in the vehicle.</td>
<td>[79]</td>
</tr>
<tr>
<td>FNN braking control strategy</td>
<td>• The optimal FNN braking control makes the motor operate in its higher efficiency zone to recover more regenerative braking energy and charge the battery.</td>
<td>[80]</td>
</tr>
<tr>
<td>ANN with PI controller</td>
<td>• ANN with PI controller is utilized to control the braking force split between the wheels of the EV and also, it can improve energy regeneration by 20%.</td>
<td>[81]</td>
</tr>
</tbody>
</table>
3.3 Model Predictive Control modeling approaches

Model predictive control (MPC) is a progressive method that is used to control a process and deal with it efficiently by satisfying multiple constraints in complex automotive systems [84]. It also has a unique ability to predict future events and can take control actions accordingly and due to these favouring characteristics MPC’s are used in various vehicle control processes including the RBS as shown in Fig. 8. The process flow in MPC comprises of feeding the input signal data to the prediction algorithm which gives optimised output signals of the braking state and the distribution of braking power between regenerative and hydraulic braking system in the vehicle. Included in MPC are various modeling approaches such as nonlinear MPC [85], stochastic MPC [86], and MPC with vehicle state estimator approach [87], PSO-based nonlinear predictive control [88], two-level MPC as mentioned in Table 3. Nonlinear MPC is widely recognized for its ability to manage nonlinearities or restrictions when dealing with difficult optimization problems [89]. Moreover, it combines all control objectives into a single formulation, and the control settings are simple to tune [90]. Nonlinear MPC’s are often combined with certain algorithms like the PSO-based nonlinear MPC as mentioned in [91]. The PSO- nonlinear MPC is adopted to realize the required force and moment with brake torque allocation and pressure regulation along with vehicle stability control features like to calculate required longitudinal force, lateral force, etc [92]. In-vehicle operation the driver behavior can be represented as a stochastic system since the driving conditions are random and unpredictable. The stochastic MPC modeling approach is used in vehicle energy management where the driver model is used to predict future power requests [93]. Since stochastic MPC is based on online numerical optimization, the driver model can be learned online, hence allowing the control algorithm to adapt to different driver’s behaviors [94]. The MPC controller can also be merged with a vehicle state estimator (VSE) which calculates the road friction, vehicle motion states, tire normal forces, etc [95, 96]. Also, the MPC controller directs friction and regenerative braking forces to meet the driver's brake request while maintaining the stability and drivability of the vehicle [97]. The MPC is combine with VSE it can successfully maximizes energy recuperation in relation to drivability demands, and completely provides the whole braking force demanded by the driver [98]. Moreover, the MPC requires high computation power for controls the various operation in the vehicle. It is used to track the driver's intentions and optimize steering and braking coordination, but it cannot eliminate the vehicle wheel spin problem in various driving conditions [80]. Further, it successfully maximizes the energy recuperation in relation to the various driver demand, but it is incapable of handling linear and nonlinear MPC designs for the combination of wheel spin and braking torque distribution between different braking systems. While maintain energy
regeneration efficiency the MPC does not provide faster transient response to driver demands. Also, it requires suitable trained model for the controlling of various braking operation, it depends on high accurate system model for eliminating the errors. it can be advantageous if the disturbances and uncertainties observed are reduced along with a simple calculation approach. This is a special characteristic of the sliding mode controller; it can be used to eliminate the non-linearities and disturbances in different driving conditions.

Fig. 8: Model predictive control in RBS for EVs
<table>
<thead>
<tr>
<th>Modelling Approach</th>
<th>Major Outcomes</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPC with torque distribution strategy</td>
<td>The optimal split of braking torque on front and rear axis is achieved for improved road adhesion along with maximum energy recovery during braking.</td>
<td>[85]</td>
</tr>
<tr>
<td>NMPC control approach</td>
<td>The NMPC is able to recuperate more regenerative braking energy and it improves regeneration efficiency, stability and reliability of the vehicle</td>
<td>[86]</td>
</tr>
<tr>
<td>MPC with VSE approach</td>
<td>The MPC and VSE combination successfully maximizes energy recuperation in relation to various drivability demands in the vehicle.</td>
<td>[87]</td>
</tr>
<tr>
<td>Model predictive control allocation</td>
<td>The MPC provides faster transient response, while maintaining the energy regeneration efficiency of the vehicle.</td>
<td>[88]</td>
</tr>
<tr>
<td>PSO with nonlinear MPC</td>
<td>A novel steering and braking control strategy is proposed to track the driver's intentions and optimize steering and braking coordination.</td>
<td>[89]</td>
</tr>
<tr>
<td>Nonlinear MPC with torque distribution strategy</td>
<td>Due to its ability to split brake torque intelligently to the wheels and recovers more energy without sacrificing the vehicle's performance.</td>
<td>[90]</td>
</tr>
<tr>
<td>MPC with quadratic programming</td>
<td>The optimal power can be split according to the system dynamics and it can ensure brake safety, strength and stability.</td>
<td>[91]</td>
</tr>
<tr>
<td>Linear and nonlinear MPC strategy</td>
<td>The linear and nonlinear MPC designs is used to reduce the wheel slip errors by adjusting optimal and actual slip ratios. Also, it can recover maximum regenerative braking energy during braking and charge the battery.</td>
<td>[92]</td>
</tr>
<tr>
<td>MPC approach for blending of braking systems</td>
<td>It states that the controllers smartly blend regenerative and friction braking for maximizing the regenerative braking while simultaneously preserving vehicle stability and delivering the exact requested braking force.</td>
<td>[93]</td>
</tr>
<tr>
<td>Stochastic model predictive control</td>
<td>It can reduce the linear and nonlinear steady state errors by adjusting optimal brake force between braking systems.</td>
<td>[94]</td>
</tr>
<tr>
<td>Two level MPC</td>
<td>A two-level MPC approach in a F1 car powertrain is implemented for the minimum lap time energy management.</td>
<td>[95]</td>
</tr>
<tr>
<td>Nonlinear MPC strategy</td>
<td>It can be presented for the front steering angle compensation and distribution of traction force in 4WD EVs. Also, it can achieve higher energy efficiency and optimal brake distribution between braking systems.</td>
<td>[96]</td>
</tr>
</tbody>
</table>
3.4 Sliding Mode Control modeling approaches

SMC is a nonlinear control approach that forces a non-linear system to slide along a cross-section of its normal performance by applying discontinuous control signals and altering the dynamics of a nonlinear system as shown in Fig. 9. The SMC works based upon the required brake strength which estimates the braking torque required and feeds the data to the controller. Further the SMC optimises the braking torque signals and depending on the brake torque requirement it is distributed braking force between various braking systems in the vehicle. Then, the sliding mode control along with other modeling approaches is used in regenerative braking such as Adaptive SMC [99], intelligent sliding mode scheme (ISMS) [100], SMC with fuzzy logic control approach [101], and Time-varying sliding mode control (TV-SMC) [102] which are mentioned in Table 4. Out of the above-mentioned modeling approaches, SMC with FLC is designed to change the sliding mode parameters based on the slip ratio tracking error between the desired slip ratio and the actual slip ratio [103]. By estimating the brake torque, the suggested torque distribution may incorporate the optimal battery state and energy recovery efficiency [104]. To tackle the problem of motor torque control during regenerative braking operation in EVs, the adaptive SMC strategy is employed and it is observed that the chattering phenomenon can be eliminated as compared to other controllers like smooth SMC and high-gain PID controller [105]. Chattering is often observed in traditional SMC which is occurrence of oscillations of finite frequency amplitude. These oscillations are actually undesirable and hence chattering is a harmful phenomenon which leads to low accuracies in control systems. The fast dynamics which are often ignored in ideal control models cause this issue [106, 107]. Also due to the oscillations, the mechanical parts which respond to the oscillations may wear and get damaged, in case of regenerative braking this can affect the motor parts and unnecessary damage can occur. To avoid this, the adaptive SMC method acts as a good solution which can maintain the braking efficiency without having negative effects on overall vehicle performance. Similar to adaptive SMC, the fuzzy SMC is also a modified SMC control method which reduces chattering effectively with the parameter optimization FLC [108, 109]. Another control strategy for RB in EVs and HEVs is the intelligent sliding mode scheme (ISMS), which has a basic logic torque limiter that maintains significant energy recovery without overcharging the battery pack and produces a good tracking of requested slip during an extreme braking situation with high braking performance [110, 111]. Similarly, to enhance regenerative braking performance in electric vehicles with SRM [112], the MOOS [113, 114] is proposed to improve regenerative braking performance under sliding braking conditions. Under sliding braking situations, this MOOS-based management technique may substantially improve brake smoothness, expand working distance,
and lengthen the battery lifespan of EVs [115, 116]. This control approach can attain maximum energy efficiency and performance in different braking conditions. during the vehicle operation optimal slip trajectory, chattering, modelling errors and external disturbances are major problems in the SMC. The optimal slip trajectory changes based on the surface conditions of the vehicle during vehicle operation because driving conditions are constantly changing. Moreover, the chattering is also one of the major concerns in SMC, Chattering is a common occurrence in traditional SMC and is caused by oscillations of finite frequency amplitude. These oscillations are actually unacceptable, and thus chattering is a harmful phenomenon that leads to low accuracies in control systems [106]. Also, another issue in the SMC is external disturbances in different braking and operating conditions of the vehicle. To avoid these parametric uncertainties, the adaptive SMC method is a good solution for maintaining braking efficiency without affecting overall vehicle performance.

Fig. 9: Sliding mode control in RBS for EVs
<table>
<thead>
<tr>
<th>Modelling Approach</th>
<th>Major Outcomes</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sliding mode control (SMC) with FLC approach</td>
<td>• This method aimed at obtaining adequate energy efficiency and performance in different braking conditions and also it can achieve better stability and energy recovery.</td>
<td>[102]</td>
</tr>
<tr>
<td>Adaptive SMC</td>
<td>• The adaptive SMC strategy tackles the issue of motor torque control during the regenerative braking mode.</td>
<td>[103]</td>
</tr>
<tr>
<td>Intelligent SMC</td>
<td>• It can achieve high energy regeneration efficiency and effective braking performance of an EV.</td>
<td>[104]</td>
</tr>
<tr>
<td>Sliding mode control algorithm</td>
<td>• The Sliding mode control is capable to combine the pneumatic ABS control and help to preserve the slip ratio of the vehicle in more accurate and ideal range.</td>
<td>[105]</td>
</tr>
<tr>
<td>RB control with MOOS</td>
<td>• A comprehensive balance is achieved between the braking comfort, working distance and battery life of EV by the implication of braking control based on multi-objective optimization of drive system.</td>
<td>[106]</td>
</tr>
<tr>
<td>TV-sliding mode control</td>
<td>• As compared to a conventional SMC the TV-SMC produced better results which track an optimal slip trajectory.</td>
<td>[107]</td>
</tr>
<tr>
<td>SMC based on $H_\infty$ theory</td>
<td>• It is more robust and shows superior dynamic performance as compared to others, it is widely suitable for the nonlinear control of EV.</td>
<td>[108]</td>
</tr>
<tr>
<td>Two-time-scale brake control with sliding mode</td>
<td>• The desired performance is maintained by this controller even in varying road conditions including external disturbances, modelling errors and also CAN-induced time-varying delays.</td>
<td>[109]</td>
</tr>
<tr>
<td>Super twisting algorithm with SMC</td>
<td>• Quick response to the driver’s demands, maximum use of regenerative braking energy and effectively improve vehicle drive range without sacrificing the brake power.</td>
<td>[110]</td>
</tr>
<tr>
<td>Sliding mode robust controller</td>
<td>• The aforementioned control technique has the potential to improve dynamic performance and robust stability. Using the controller, you can even increase your driving range.</td>
<td>[111]</td>
</tr>
<tr>
<td>Wheel slip control with SMC</td>
<td>• In both accelerating and braking operations performed on a slippery surface, experimental results indicated good slip regulation and robustness to shocks.</td>
<td>[112]</td>
</tr>
<tr>
<td>Sliding mode with sensor-less control</td>
<td>• The PLL with a modified control function has improved the speed and position estimation using a SMO and the regenerative braking capability of the PMSM drive shows effective battery charging.</td>
<td>[113]</td>
</tr>
</tbody>
</table>

Table 4: Summary of various sliding mode control modelling approaches in RBS
3.5 Adaptive control modeling approaches

This type of control strategy relates to a controller which works based on a control law that adapts itself to changing conditions, and which has to adapt to continuously changing and uncertain parameters in the system [117]. In the case of regenerative braking, the varying parameters are related to the driver conditions like deacceleration, torque demand, speed, battery SOC, etc. These input parameters are taken care within the controller with the help of driver model unit as shown in Fig. 10. The respective output signals are sent to the optimum power control unit, which splits the brake force between the vehicle's braking systems based on driver demand. Then, the adaptive control employs various modeling approaches for maximizing the energy recuperation efficiency such as adaptive MPC [118], modified direct torque control [119], adaptive neuro-based FLC [120], back-stepping based adaptive controller [121], and adaptive fuzzy control [122] as mentioned below in Table 5. According to a study aimed at control of regenerative braking of a downhill cruising EV, the adaptive MPC is designed which can realize the adaptive control of the braking systems with the change of the road gradient, stability, and robustness [123]. Similarly, in another experimental investigation on RBS in an EV, a baseline robust controller will be generated using the 2-step back-stepping-based design technique to emphasize the model uncertainties associated with the RBS [124]. To decrease model uncertainties caused by vehicle loads, SOC, vehicle velocity, braking power, and road surface circumstances, parameter adaption utilizing the least-squares estimation technique will be applied [125]. Additionally, in a BLDC motor EV, modification of the switching pattern will increase the efficiency of the conventional direct torque control (DTC) system as well as recuperate braking energy [126]. Using this modified DTC, negative torque is supplied to the motor while brake, producing electrical energy that is transmitted via reverse diodes to charge the storage device [127]. Furthermore, to take intelligent control to the next level, an adaptive neuro-based fuzzy control system is employed, which can update the membership function parameters and linguistic rules directly from data to improve system performance [128]. The combination of NN with fuzzy logic systems is useful since it can be trained and hence self-learn and improve. As a result, it employs a fuzzy framework to represent information in an interpretable manner and derives learning ability [129]. Also, the distribution of the braking force accurately as per the changing demand is one of the very fundamental functions of proper regenerative braking phenomenon, and an integrative control strategy [130] helps achieve that by sensing the brake pedal position and the braking intensity. Finally, the braking force splitting approach is executed to control the braking forces of regenerative and hydraulic braking cooperatively [131]. In CACC strategy improves the overall vehicle braking performance, regenerative braking energy, and safety. As seen, the adaptive
control can be achieved in combination with other prominent control strategies like FLC, NN to obtain the best performing control system. Though adaptive controllers can handle unknown parameters but they lack the ability to learn over the time and improve themselves. The self-learning ability can be very fruitful in long run as the control system will obtain a very wide operational dataset and use is accordingly for optimal results. Hence the learning-based controls is a hot research topic and is implemented for smart transportation systems.

Fig. 10: Adaptive control in RBS for EVs
<table>
<thead>
<tr>
<th>Modelling Approach</th>
<th>Major Outcomes</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>RBS control with PWM</td>
<td>• This control approach is used to produce higher braking current and pursue robust braking force.</td>
<td>[118]</td>
</tr>
<tr>
<td>Adaptive MPC algorithm</td>
<td>• The RBS and mechanical braking system can be used co-ordinately by the adaptive model predictive control.</td>
<td>[119]</td>
</tr>
<tr>
<td>Adaptive regenerative braking controller</td>
<td>• In this study the development of an integrated braking controller that maximizes regenerative braking power for an electric vehicle with a motor at its front axle has been presented.</td>
<td>[120]</td>
</tr>
<tr>
<td>Modified direct torque control</td>
<td>• This control method showed the good performance and improvement in the returned energy to the batteries.</td>
<td>[121]</td>
</tr>
<tr>
<td>Adaptive regenerative braking controller</td>
<td>• To prevent the vehicle from losing control, the controller distributes an ideal RB torque as well as additional mechanical friction brake torques.</td>
<td>[122]</td>
</tr>
<tr>
<td>Observer based hierarchy controller</td>
<td>• The upper layer controller monitors the intended vehicle velocity, while the lower layer controller monitors the lower layer controller's signal and increases energy recovery.</td>
<td>[123]</td>
</tr>
<tr>
<td>Adaptive neuro based FLC</td>
<td>• By using the control logic, the RBS can dynamically distribute the electrical and mechanical braking force is achieved.</td>
<td>[124]</td>
</tr>
<tr>
<td>Cooperative adaptive cruise control (CACC) strategy</td>
<td>• The CACC method increases the platoon's overall regenerative braking energy by around 16.5%, providing drivers with significant economic benefits.</td>
<td>[125]</td>
</tr>
<tr>
<td>Energy efficient adaptive cruise control</td>
<td>• By altering the gap between the leading and following cars, this control approach may maintain high regenerative braking effectiveness while also providing smooth acceleration and deceleration.</td>
<td>[126]</td>
</tr>
<tr>
<td>Back-stepping based adaptive controller</td>
<td>• It illustrates that, even in the presence of parameter variations, the brake control input can precisely reflect the vehicle driver's braking purpose, and the output vehicle can effectively track the target vehicle.</td>
<td>[127]</td>
</tr>
<tr>
<td>Adaptive fuzzy control algorithm</td>
<td>• The algorithm instructs the motor to deliver sufficient regenerative braking torque at all times in order to meet the braking needs of the driver.</td>
<td>[128]</td>
</tr>
<tr>
<td>Integrative braking control strategy for adaptive control</td>
<td>• The approach controls the both braking systems forces based on the braking strength, allowing the motor to run at maximum capacity.</td>
<td>[129]</td>
</tr>
</tbody>
</table>
3.6 Learning-based control modeling approaches

The learning-based control algorithm is another modeling approach which learns itself over time to achieve perfection in braking performance. Few of these strategies were implied in RBS and they also showed promising results. One of it is the Fuzzy Q-learning algorithm which indicated that the strategy can easily adapt to various driving cycles and optimal regenerative braking motor torques can be obtained [132]. Furthermore, it is known issue that SRM causes torque ripples which can be corrected by using iterative learning control which continuously checks with reference torque and the controls the current with optimal torque controller [133]. Further, the model predictive iterative control approach helps achieve fast convergence rate by considering the time-wise feedback control along with real time processing capacity [134]. The specialty of iterative learning is that it learns from previous errors stored in the memory. Moreover, iterative learning control is implied in antilock braking, as the motor torque gets optimized to keep the tire slip in maximum traction region [135]. Similarly, a smart regenerative braking system based on reinforcement learning algorithm automatically controls the regeneration torque of the motor to slow down the vehicle by recognizing the deceleration conditions [136]. Another reinforcement learning based is used to adjust and improve the fuzzy logic model which showed improved performance and even the regeneration factor (ratio of energy recovered to the total braking energy) can be obtained which is otherwise difficult to be measured [137]. Similar model-free reinforcement learning method helps manage the battery current flows which equips the controller with the information related to peak power and regenerative power demand [138]. Learning-based controls in braking also acts as advanced driver assisting systems in control methods related to intelligent vehicles. Wherein, cloud platforms are used for data storage and communication so that there is no limitation in computing power of the control system. Intelligent systems can also enable interaction between vehicle and help enhanced energy management based on live road performance. In order to promote sensorless design of braking control system, a hybrid learning-based method is developed to classify the brake intensity levels and estimate the brake pressures. This will assist the controls and energy management during the regenerative braking [139]. Similarly, while driving at traffic lights q-learning algorithms derive optimal speed profiles which consider all real time parameters using vehicle to infrastructure (V2I) communication. The predicted speed profiles decide the vehicle braking actions depending on the road conditions and this is experimentally verified to give better results [140]. These learning-based approach in RBS can prove effective in many ways since they are closely related to human learning behaviour and tend to improve over time.
3.7 Comparative assessment of various braking control strategies in EVs

All the above discussed control methodologies are unique in their way and hence their application of them varies to some extent. Table 6 summarises the benefits and drawbacks of various control approaches for EV brake energy optimization. For an instance, FLC systems are known for their ease of computation and the simplicity in applying updates to commercially produced vehicles whereas the quality is completely dependent on the professional level of a specialist who sets them up [141]. Hence, we can say that the FLC application is favoured for simplicity and feasibility and showed significant improvement in power and economic performance [142]. Another controller familiar for its strong capacities of self-learning and self-adapting is the neural network controller. Due to multiple layers of neurons that enhance its learning abilities, it is outstanding for the control of nonlinear systems which is often a case in actual braking scenarios [143, 144]. NN outperforms in terms of response time, steady-state tracking error, and can increase the stability and reliability of EV. Further, The MPC approach can deal with complicated optimization issues as well as nonlinearities and restrictions in the regenerative braking control system in an effective manner [145]. Consider an EV that has to control numerous signals involving speed, deceleration, torque demands, etc., and other inputs making the whole system very complex and hence can sometimes cause computational complexities [146, 147]. MPC approaches can be successful in extreme braking circumstances because they intelligently mix regenerative and friction brakes to enhance regenerative braking while maintaining vehicle stability [148]. An important task of ABS during braking is controlling the slip ratio in the optimal range to prevent wheel lock-up and a sliding mode controller focuses on detecting this tendency of lock-up [149]. Its robustness and invariance make it capable to handle nonlinearities and it is excellently insensitive to model error and constraints change of controlled object and external trouble during intense operating conditions [150]. Owing to its disturbance rejection characteristics and helping maintain slip ratio SMC plays an important role in improving braking performance. Furthermore, under the adaptive control technique, the system adjusts the intensity of regenerative braking when the accelerator pedal is released based on the driver type and intention [151]. Although adaptive controller is capable of dealing with unknown parameters but it lacks of ability to learn and improve themselves over time. The self-learning ability can be very fruitful in long run as the control system will obtain a very wide operational dataset and use is accordingly for optimal results. These learning-based approaches in RBS can be beneficial in a variety of ways because they are closely related to human learning behaviour and tend to improve over time. It guarantees the stability of the system as per changing conditions [152, 153]. In addition, the performance analysis of various motors with numerous control strategies for brake energy recovery in EVs
as mentioned in Table 7. Many researchers combine two or more control strategies to obtain the best results of both. Such approaches lead to efficient and stable control systems and as a result, the energy recovery is improved. Finally, all of these mentioned strategies are unique in their own ways and have different effects on the energy recovery and braking performance. Hence, a critical review of these control strategies is essential since it can assist in verifying the accuracy in various operating conditions and the maximum energy recovery along with better braking performance. By weighing the advantages and disadvantages of each control approach researcher have the opportunity to design the optimal control models for most efficient energy recuperation and smooth braking. In the review it is observed that many research works adopted a combination of different control methods to produce better results. Such initiatives can benefit from detailed review studies for them to pursue and will act as a guideline for developing better RBS in near future. Moreover, as observed, the different control techniques implied in RBS have their own pros and cons and hence it is of utmost importance to choose the correct control approach. Here, it can compare these strategies based on model complexity, development cost, extent of accuracy, performance, etc. The parallel comparison among the all parameters of these control strategies provides insight on how to obtain best possible results in braking performance. By such critical review the positive qualities of numerous control strategies can be combined in order to obtain more efficient control strategy. As per the chosen control approach the specific output signals are given to the respective components for energy recovery while braking which are discussed in further section.
Table 6. Advantages and disadvantages of various control approaches for brake energy optimization in EV

<table>
<thead>
<tr>
<th>Control strategy</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuzzy logic control</td>
<td>• Fuzzy logic control is a cost-effective controls technique.</td>
<td>• They are fully reliant on human expertise and understanding.</td>
<td>[57-61]</td>
</tr>
<tr>
<td></td>
<td>• The user interface is easy to understand and interpret even for a non-expert control engineer.</td>
<td>• A lot of manual tuning is required which is time consuming when consider complex large scale of application.</td>
<td></td>
</tr>
<tr>
<td>Neural Network</td>
<td>• After NN training, the data may produce output even with incomplete information.</td>
<td>• Design an acceptable network structure, skill and trial and error are needed.</td>
<td>[73-77]</td>
</tr>
<tr>
<td></td>
<td>• Artificial NN learn from identical events and make decisions based on them.</td>
<td>• According to its structure, ANN requires processors with parallel processing capabilities.</td>
<td></td>
</tr>
<tr>
<td>Model predictive control</td>
<td>• It is used to regulate a variety of processes, including those with non-minimum phase, long delay, or open-loop stability.</td>
<td>• A suitable model is required of the process i.e., high dependence on accurate system model.</td>
<td>[86-90]</td>
</tr>
<tr>
<td></td>
<td>• It can handle multi-variable, input and output processes along with single-input and output ones.</td>
<td>• Derivation of control law is complex.</td>
<td></td>
</tr>
<tr>
<td>Sliding mode control</td>
<td>• Applicable on wide range of non-linear systems (including higher order).</td>
<td>• Limited to single input systems.</td>
<td>[100-105]</td>
</tr>
<tr>
<td></td>
<td>• SMC is a robust control technique which is used to control systems with uncertainties.</td>
<td>• Chattering occurrence is an undesirable phenomenon in this control approach.</td>
<td></td>
</tr>
<tr>
<td>Adaptive control</td>
<td>• Parameters can be changed fast in response to changes in process dynamics.</td>
<td>• The required design for employment is enormous.</td>
<td>[120-124]</td>
</tr>
<tr>
<td></td>
<td>• Are easy to apply and have good stability.</td>
<td>• Appropriate model of the system is needed.</td>
<td></td>
</tr>
<tr>
<td>Type of motor</td>
<td>Control strategy</td>
<td>Vehicle model</td>
<td>Driving cycle</td>
</tr>
<tr>
<td>--------------</td>
<td>------------------</td>
<td>---------------</td>
<td>---------------</td>
</tr>
<tr>
<td>Brush less DC motor (BLDC)</td>
<td>PID with fuzzy logic control</td>
<td>EV</td>
<td>UDDS</td>
</tr>
<tr>
<td></td>
<td>FLC with PI controller</td>
<td>EV_HESS</td>
<td>EUDC, FTP</td>
</tr>
<tr>
<td></td>
<td>Neural network with self-adaptive PID</td>
<td>EV</td>
<td>UDDS</td>
</tr>
<tr>
<td></td>
<td>ANN control</td>
<td>EV</td>
<td>US06_HWY</td>
</tr>
<tr>
<td></td>
<td>Neural network with SMC</td>
<td>EV</td>
<td>FTP75</td>
</tr>
<tr>
<td></td>
<td>Sliding mode robust controller</td>
<td>State-space model of EV</td>
<td>Urban drive cycle</td>
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<td>Back-stepping based adaptive controller</td>
<td>Hybrid-electric bus</td>
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<td>Switched reluctance motor (SRM)</td>
<td>FLC with braking force distribution strategy</td>
<td>Nissan LEAF</td>
<td>Real-time VIL cycle</td>
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<td>Permanent magnet brushless DC motor (PMSM)</td>
<td>Fuzzy logic algorithm</td>
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<td>Brake control with FLC</td>
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<td>MPC with torque distribution strategy</td>
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<td>Traction motor</td>
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<td>Multilayer perceptron ANN</td>
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<td>Model predictive control with in-wheel-motor</td>
<td>EV with 4-IWM</td>
<td>FTP</td>
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<td>CACC strategy</td>
<td>EV_CACC</td>
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4. Regenerative braking system controller outputs

The essential output of the braking demand is estimated by using a braking controller based on numerous modeling approaches (Fuzzy, MPC, NN, SMC, etc). These approaches are used to split braking demand torque between regenerative and hydraulic braking systems in the vehicle. The outputs of the regenerative braking controller (braking torque demand) are sent to motor and hydraulic control systems in the vehicle as discussed in below respective sections.

4.1 Motor control system

The electric motor is the main driving unit that propels an EV and also acts as a generator during energy recuperation conditions. The motor control unit (MCU) acts as the brain in controlling all the operations of the motor and managing the outputs for delivering maximum torque and power [154]. The braking controller receives inputs from various vehicle systems and MCU is used to optimize the braking demands between braking systems in the vehicle as shown in Fig. 11. The various inputs from the driver, battery, motor, and other accessories input signals are communicated to the controller through the CAN bus [155, 156]. According to the driver requirement by sensing the drive mode and the pedal positions the braking torque demand is calculated. Along with the torque calculation, the motor rotor position input is also fed to the controller, and based on these the motor speed can be varied [157]. The pulse width modulator (PWM) generator gives the proper signals to the driver circuit which performs the motor working [158]. Simultaneously, the switching table also receives the signal of the motor rotors position. Finally comes the inverter which converts the DC to AC and feeds it to the motor for propulsion [159]. The driver continually controls the speed with the pedal, while all other regulations for absorbing or renewing energy are managed internally [160]. The driver instruction serves as a speed reference input to a motor control unit (MCU), which in turn drives a controller. During regenerative braking, the motor acts as a generator, converting the generated current to direct current and charging the battery [161]. In this way, the motor-inverter interaction is very critical since the drive conditions may continuously change and the inverter has to adapt to the changing situation. Simultaneously, the driver receives all the information on the instrument cluster as different indicating lights. It also displays warning signals if a fault in any of the subsystems is detected by the diagnostic system so that necessary action can be taken immediately [162, 163]. All the internal signal transmission and communication is achieved through the CAN as it serves as the prime communication medium between various systems in the vehicle [164]. Here, the communication with the battery management system (BMS) is necessary because if the SOC falls below a certain level, the MCU will receive a signal to control the motor work in the generator to charge the battery, hence making sure that the SOC doesn’t drop below a certain
value [165]. Finally, the required output is sent to the vehicle, and also braking controller is sent the driver braking demand to the hydraulic braking system as mentioned in the following section.

4.2 Hydraulic braking system

As discussed earlier, a regenerative brake usually co-exists with the friction brakes. The control strategy determines the brake force distribution between regenerative and friction braking as per the driver requirement [166, 167]. Friction braking comes into working if an immediate deceleration is required to slow down or stop the vehicle. EVs have a separate hydraulic system consisting of brake fluid, master cylinder, pistons, and fluid flow channels for this type of friction braking actuation [168, 169]. Depending on the output from the brake controller as per the driver demand, the brake fluid is displaced from the master cylinder. This further engages the pistons at the brake calipers which holds the disc brakes and brings the vehicle to a halt immediately [170, 171]. There are pressure sensors in the hydraulic line which monitor the fluid pressure and give constant feedback to the controller. The overall braking force is delivered by the friction and regenerative braking torque which can be represented as in equation (1) [172],

\[ T_{\text{total demand}} = T_{\text{regenerative}} + T_{\text{friction}} \]  

(1)

Where \( T_{\text{total demand}} \) is the total braking demand of the vehicle, \( T_{\text{regenerative}} \) is the regenerative braking torque and \( T_{\text{friction}} \) is the friction braking torque provided by the hydraulic braking system [173]. During the deceleration, the regenerative brake and the frictional brake work effectively together and the braking deceleration very gradually, ensuring the vehicle's efficient braking performance. In this section the discussion includes outputs of RB controller (regenerative and hydraulic braking torque) is sent to motor and hydraulic control systems in the vehicle. However, the idea behind the section is to make the reader aware of the execution of the braking action. As it’s known that there must be a balance between both hydraulic and regenerative braking for effective brake performance. Since the vehicle motion is dynamic in nature, the outputs depend upon the driving conditions, driver inputs and even on the battery state [174]. The vehicle braking performance and the amount of energy recuperation depends on this distribution of braking torque between the braking systems (motor and hydraulic systems) in the vehicle. For these the major output braking systems are the motor which recuperates energy and the supplementary hydraulic braking system for fast vehicle stopping. It is the harmonic co-existence of these control systems that ensure proper braking action (i.e., there must be a balance between both friction and regenerative braking for effective brake performance) in EVs.
Fig. 11: The overview of motor control system with regenerative braking in EVs
5. Calibration parameters in regenerative braking system

The RBS is associated with numerous calibration parameters including speed, brake force estimation, brake force distribution, etc as shown in Fig. 12. These are used to enhance the braking performance as well as output parameters including state of charge, demand power, etc. In the next section, numerous RBS calibration parameters are discussed in more detail.

5.1 Lookup table for driver torque and vehicle speed

Calibration of driver’s request torque and vehicle’s speed is essential to accomplish the different vehicle objectives. It influences important outcomes such as braking performance, speed, BPP, demand torque, etc [175]. The initial phase in RBS calibration is the calculation of various vehicle variables for constructing standard speed and driver request torque look-up tables. The driver’s request torque and vehicle speed lookup tables are generated based on the acceleration and brake pedal position of the vehicle [176]. These lookup tables are used to calibrate the driver’s request torque and vehicle's speed based on the driver's accelerating and braking inputs [177]. Also, it is used to estimate and optimize the future brake commands based on the vehicle's recent state and it enhances the vehicle's overall braking efficiency [178]. Furthermore, it optimizes the speed inaccuracies in the vehicle based on the different sensors commands from the vehicle, as a result in significant improvement in the braking performance [179]. Moreover, these lookup tables are used to calibrate the variations in the braking force estimation and splitting between a different braking system based on the driver’s demand power and actual speed of the vehicle as explained in the following sections.

5.2 Lookup table for brake force estimation

In general, braking force estimation in RBS calibration is crucial in determining optimal braking force between friction and regenerative braking in the vehicle. It affects significant outcomes such as SOC, braking performance, and output characteristics of the vehicle [180]. The RBS calibration procedure begins with the creation of a baseline look-up table for calculating brake force between friction and regenerative braking systems. It is used to enhance brake energy efficiency and also, increases vehicle operating range. With the support of braking force split coefficients, brake force estimation, and velocity, the braking force estimation lookup table is created [181]. It optimizes the flexibility and force proportion of braking between braking systems to maintain vehicle braking safety. Further, it ensures the best braking performance while capturing as much energy as possible throughout the braking operation. Moreover, it calibrates the impact of braking behavior and its properties such as speed of a vehicle, braking force, deceleration rate, etc [182]. Also, it provides instantaneous information by recognizing the driver's braking intention based on the opening of the BPP, speed, battery state of charge, etc [183]. As a result, the RB is determined based on vehicle
state and brake pedal position, as well as braking dynamics of the vehicle, maximum RB power, etc. Finally, the purpose of this lookup table is to optimize brake energy recovery and prolong EV driving range while meeting EV braking performance and stability standards [184].

5.3 Lookup table for brake force distribution

The brake force splitting between friction and regenerative braking systems is a critical lookup table of the RBS that must be calibrated. It has a substantial influence on key outcomes including demand brake force, vehicle status, speed, braking power, deceleration rate, etc [185]. The first step in RBS calibration is to estimate the parameters for the creation of a baseline brake force distribution look-up table. The estimation of vehicle characteristics, such as brake pedal opening and speed of the vehicle is crucial for recognizing braking intention. The brake pedal opening reflects the driving aim, while the speed indicates the degree of brake urgency [186-188]. It is estimated using the following parameters: speed, vehicle status, pedal angle, battery state of charge, vehicle braking behavior, maximum energy recovery, torque, etc. According to the vehicle's current state and brake pedal position, the required braking force is distributed between friction and regenerative braking in the vehicle. These calibration parameters are used to enhance acceleration performance, deceleration rate, and state changes between braking and driving, etc. It continuously searches for the best compromise among the different brake energy recovery modes in the electric vehicle. Further, it optimizes the deviation between the required and actual velocity of the vehicle, and also, it calibrates the different energy recovery modes during RB operation [189]. Moreover, the regenerative braking system includes additional lookup tables based on the vehicle type, battery SOC, brake selection, and other vehicle system characteristics. These lookup tables are used to calibrate the effective outputs of the vehicle in aspects of performance and energy recovery. Since the vehicle operation is dynamic in nature and the act of braking cannot be predicted but is instantaneous, so the calibration of the various mentioned parameters is quite essential. These parameters are directly affecting the different outputs characteristics of the vehicle and therefore readers must have knowledge of the role of lookup tables. Hence, the calibration of the control system parameters being important topic is discussed showcasing the role of lookup tables in RBS. Furthermore, the section that follows explains the RBS design and development procedure, which is intended to assist the optimization of the vehicle lookup tables.
Fig. 12: Various look-up tables in regenerative braking system for EVs

**Look-up tables associated with vehicle speed and demand torque**
- It calibrates the vehicle speed inaccuracies and future braking demands
- It calibrates the driver’s demand torque and vehicle speed
- It enhance the vehicle overall braking efficiency

**Look-up tables associated with vehicle braking force estimation**
- It calibrates the impact of braking behaviour and w.r.t. speed, deceleration, etc
- It calibrates optimal braking force between braking systems
- It optimize brake energy recovery during braking operation

**Look-up tables associated with vehicle braking force distribution**
- It enhance acceleration performance, deceleration rate between braking and driving
- It calibrates the different energy recovery modes during RB operation
- It calibrates optimal braking force split between braking systems

**Other look-up tables associated with regenerative braking system**
- It calibrates the driving cycle, vehicle type, brake selection, vehicle system characteristics, etc
- It calibrates battery state of charge (SOC) errors in the vehicle
- It calibrates the gear selection and transmission errors in the vehicle
6. Development process of regenerative braking control system

An efficient RBS is necessary to assure the vehicle's safety and robustness against abrupt braking and stability. A regenerative braking virtual simulation environment is required to assist with vehicle calibration and validation, as shown in Fig. 13, which also depicts the many steps involved [190]. The procedure consists of four phases; the first phase is to calculate the numerous parameters of the vehicle, as well as other critical factors such as the motor, battery, brake, etc. With the support of these multiple parameters, different systems in the vehicle will execute the necessary control operations [191]. Then, during the second phase, the vehicle influential input characteristics are used to build an efficient RBS model. In model-in-loop (MIL) simulation, the base RBS model is used to improve the accuracy of the original model and to predict the performance of the updated model. The purpose of this phase is to verify and enhance the vehicle's numerous models [192]. Then, the control parameters of the braking system are improved with the help of a generated model to increase brake performance under different energy recovery modes. Further, the control characteristics of the battery and electric motor (EM) have been fine-tuned for better power across a wide operating range [193]. This RB model is designed to coordinate different driver actions such as optimal braking power, brake energy recovery modes, etc. This model ensures that optimum data for each model is regularly updated as well as the elimination of errors.

Moreover, in the third phase, the RB model optimal data is sent into the software platform for simulation and testing of the vehicle. The first phase in the simulation process is to perform software and processor-in-loop (SIL & PIL) simulations. In Software in loop simulation, the optimized models are converted to codes and function individually in their energy recovery working modes [194, 195]. The aim of this phase is to run and evaluate the models source code on real-time systems. It is necessary to incorporate the vehicle total driver’s demand brake torque and different energy regeneration modes. During energy regeneration, the RBS model is used to calculate the driver’s demand brake torque based on several sensor commands from the vehicle. Based on the real-time sensor commands, the controller unit (processor in loop (PIL) simulation) is used to estimate the essential driver’s brake torque in the vehicle [196]. Then, the brake controller is used to distribute the optimal brake torque between hydraulic and regenerative braking systems. Also, it can estimate the vehicle operating state for maximum braking by observing the driver's request.
Fig. 13: Development procedure of regenerative braking system in EVs
Moreover, the second phase of simulation is testing simulated and fine-tuned models in the vehicle using hardware-in-loop (HIL) Simulation. To eliminate defects in the enhanced models must check the self-generated program with hardware in a loop simulator. Each HIL simulator operation necessitates the validation of simulated and optimized models. If mistakes are discovered during the validation process, the costs associated with erroneous models are reduced [197, 198]. This validation approach continually analyses and verifies better models by utilizing real-time technology. In the RBS development procedure, vehicle-in-loop (VIL) simulation is the final phase, which comprises inserting optimized models with controllers into the vehicle and verifying and calibrating the finished product. This way, before a real-time model is implemented, it can be analysed for its performance. Hence, this development stages play crucial role because nearly every time the designed RBS has to be verified for its performance and has to follow the mentioned process [199]. Moreover, this procedure integrates various modelling tools and techniques for recreating the regenerative braking model in a virtual analytical environment, which is required for successful testing, calibration and validation of the model. Also, it covers a broad spectrum of applications in different segments such as the design phase which includes the simulation, control system design, etc. If there are any faults in the developed control system models it is detected in the validation process and it can be corrected in early steps itself [200]. Due to advanced simulation platforms the control models can be tested numerous times using real-time drive cycles allowing the developers to make necessary changes and test in quick intervals. This RBS development process increases the model perfection, eliminates the model inaccuracies and improve the performance of the vehicle. Further, the obstacles encountered throughout the RBS development process are detailed in the next section.

7. Challenges in designing and developing a regenerative braking control system

The RBS has various beneficial impacts on brake and vehicle output parameters, as detailed in previous sections. However, a few issues are mentioned during the design of RBS such as energy recovery, distribution of braking energy, braking stability, maximum regenerative braking, system integration, brake controller design, control strategy optimization, brake control, emergency braking, and response time for all operating conditions [201-204] as illustrated in Fig. 14. More consideration should be given to the RBS design process, particularly in terms of energy recovery during the braking phase. Also, the braking energy distribution between brake systems is more complex due to its brake safety and stability in the vehicle [205]. It affects the energy efficiency and braking performance of the RB system. Hence, the challenge on the RB stability and design of the controller is more difficult because
of incorporation among the other current braking systems (ABS, VSC, etc) in the vehicle [206]. The estimation of wasted energy during braking is required to develop an effective RB controller and anticipate energy efficiency [207]. Then, the energy efficiency of RBS, which is based on several control techniques, may be influenced by the suitable hardware controller. In addition, different control approaches influence the various energy recovery modes and brake energy distribution between both brake systems in the vehicle under all operating conditions [208, 209]. The braking force distribution has two phases: the first is to split the maximum forces between the wheels, which affect braking stability, second is to split the brake force between the regenerative and friction braking, this influences the amount of braking energy that may be recovered. Moreover, the brake control and energy distribution between both brake systems become more complex, when the RBS is to improve regenerative brake efficiency and boost the range of EV [210]. The brake control during emergency braking is become much more complex than that of a friction and regenerative braking system. Besides, RBS is able to optimize power demand fluctuation and manage the brake energy distribution to meet the driver’s braking demand in the vehicle.

Fig. 14: Challenges in design and development aspects of RBS in EVs [205-208]

Furthermore, a few obstacles arise during the development of RBS, such as parameter identification, modeling, optimization, etc. The preliminary or influential input and output parameters of the vehicle such as real-time speed, torque requirement, brake force distribution,
battery SOC, etc are influences the vehicle's braking performance under different operating conditions. Moreover, the operating point estimation, system optimization, braking efficiency, and stability present additional obstacles throughout the model development process [211]. It has an impact on the vehicle's braking efficiency, comfort, stability, and dependability. Also, the simulation might be influenced by improved models in the vehicle under various operating conditions. However, simulation incorporates a number of optimization techniques that may be used to analyze the performance of power flow, stability, distribution, etc [212]. As a result, addressing the aforementioned problems can aid in the efficient design and implementation of RBS to achieve maximum energy efficiency, superior vehicle braking performance, and safety. During the design and development of RBS, several challenges arise, including energy recovery, braking stability, system integration, brake controller design, modeling, optimization, and response time for all operating conditions. Hence it is necessary to address all these issues as each one may have a significant effect on the performance if not corrected properly. As discussed earlier, the design and testing stage is essential as it allows to verify the models and remove the possibilities of any system failures. Also, continuous research work is carried to ensure that such issues in RBS are eliminated for improved vehicle performance since it has a direct effect on the component life. The future research prospects in RBS revolve around addressing such challenges and implementing those developments in future EVs. As a result, addressing the aforementioned problems can aid in the efficient design and implementation of RBS to achieve maximum energy efficiency, superior vehicle braking performance, and safety.

8. Summary and future scope

This review article is a compilation of numerous studies focused on the energy recovery of EVs. It gives the reader a broad overview of the RBS and its related components in a holistic manner. The studies reviewed in this paper are based on experimental work which is performed with the intent to improve the RBS performance and efficiency. This performance specifically depends on the control system architecture of the vehicle RBS which includes the interrelation among hardware and software subsystems like motor, battery, brakes, etc. Moreover, in-depth investigation is performed on the brain of the entire RBS i.e., the brake controller wherein various control strategies (fuzzy logic control, neural network, model predictive, sliding mode, adaptive control and learning-based control) are discussed and their key functions are elucidated. These control approaches are used to enhance energy regeneration while maintaining vehicle performance. In FLC approach is used to improve the regenerative braking performance with respect to steady state errors and recovers maximum possible energy (25%) during braking. Further NN is self-adaptability and recovers more
energy (24%) in the braking process. Also, it improves regeneration efficiency, stability and reliability of the vehicle. Moreover, MPC and SMC are used to track the driver's intentions and optimize steering and braking coordination, but it cannot eliminate the vehicle wheel spin problem in various driving conditions and it successfully maximizes the energy recuperation. In SMC, the external disturbances in different braking and operating conditions of the vehicle are one of the issues. To avoid these parametric uncertainties, the adaptive SMC method is a good solution for maintaining braking efficiency (32%) without affecting overall vehicle performance. In addition, adaptive and learning-based control approaches are used to handle unknown parameters but they lack the ability to learn over the time and improve themselves. These approaches are dynamically distributed the braking energy between various braking systems in the vehicle and also, it can achieve maximum regenerative braking energy (35%) during braking and deacceleration. It is observed that every control strategy has its advantages and disadvantage. Also, to gain maximum output some research studies showed an implication of a combination of strategies in their modeling approaches. Furthermore, the fundamental operational behavior of other vehicle systems like Motor control, hydraulic control also plays a decisive role in performance evaluation. These systems' optimal functioning is also necessary because they are responsible for energy storage and transmission during vehicle operation. Moreover, RBS associated with various parameters like speed, brake force estimation, etc which are used to improve the output characteristics of the vehicle. Then, the real-time RBS development procedures, as well as essential features of regenerative braking for the effective operation of EV, have been studied. The review study also emphasizes various challenges on the design and development of efficient RBS. This review article attempts to enlighten a broad overview of the RBS and investigate the performance dependence on various components. Evolving technologies in the E-mobility domain will encourage the readers to bridge some research gaps and we can hope to see improved energy recovery techniques in near future. Higher energy conversion rates can ensure an extended driving range which is the demand of time seeing the promising shift towards E-mobility. Further mentioned are some suggestions on which future studies can be carried out to enhance the performance of the RBS.

1. Future research should concentrate on the real-time use of the maximum adhesion offered by the ground, as well as a quicker and more reliable controller, to meet the drivers' braking demands sensitively and correctly, and to achieve shorter braking distances and faster energy recovery.

2. To reduce transmission losses and boost efficiency, new inventions in the form of new electric motors may be developed and installed in many automobiles, which can help in
saving energy for a greener future. Another area for development is to reduce the weight of the system, which would boost efficiency and reduce energy consumption.

3. More study is needed to solve the problem of regenerative braking and ABS mutual collaboration. One interesting area for researchers to look into is how to eliminate torque variation in a vehicle that employs non-zero RB torque during ABS events. Furthermore, all-wheel RB systems and the regulation of RB on the road with a split adhesion coefficient may be of interest as research topics.

4. Currently, new and additional braking technology includes the electro-mechanical brake, electric-hydraulic brake, etc. The integration of the RBS and regular FBS appears to be problematic due to the latter's delayed reaction. However, an advanced braking system must respond quickly and work flawlessly at high speeds. As a result, more study should be done on the combination of the RBS and the advanced braking system.

5. The development of a fully electronic brake-by-wire hybrid braking system is currently in progress. In this system, the motor and braking force on wheels can be individually and cooperatively controlled. While driving on any road, this braking system is completely used to quickly slow down the vehicle, maintain vehicle stability and recover the maximum braking energy. It is also integrated with the steering system to ensure vehicle stability.

6. To achieve optimum energy efficiency in EVs/HEVs, the EMS is essential. However, for the time being, EMS is entirely dependent on onboard sensor data. We can develop intelligent energy management and recovery system if we consider using off-board information to optimize the energy flow under any dynamically fluctuating road traffic. As a result, additional research should be concentrated on intelligent energy management and recovery systems that will increase the energy savings achieved by regenerative braking.

Credit author statement

Pemmareddy Saiteja: Writing – original draft, Atharva sanjay wagh: writing – review & editing. B Ashok and Mohamed Emad Farrag: Conceptualization, Investigation, Data curation, Project administration, Validation, Formal analysis, Writing – review & editing.
Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

Acknowledgement

The authors would like to thank the Management of Vellore Institute of Technology, Vellore for the facilities provided during the execution of this work. This research is supported by the funding from Royal Academy of Engineering, United Kingdom under the scheme of Transforming Systems through Partnership (Grant No: RAE TSP - T2\100100).

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